DOUBT AND CERTAINTY IN CLIMATE SCIENCE

ALAN LONGHURST

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About the author

Alan Longhurst is a biological oceanographer who has studied the ecology of the continental shelf of the Gulf of Guinea (1954-63), and the trophic structure and flux of energy through the pelagic ecosystems of the eastern Pacific (1963-71), the Barents Sea (1973), the Canadian Arctic (1983-89) and the Northwest Atlantic (1978-94). He coordinated the international EASTROPAC expeditions in the 1960s and directed the NOAA SW Science Center on the Scripps campus at La Jolla (1967-71), the Marine Ecology Laboratory at the Bedford Institute of Oceanography (1977-79) and was Director-General of that Institute (1970-86). He has published 80-odd research papers and his most recent books are "Ecological Geography of the Sea" (Elsevier, 1998 & 2007) and "Mismanagement of Marine Fisheries" (Cambridge, 2010).

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ALAN LONGHURST

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Preface

The possibility that anthropogenic emissions of carbon dioxide might be accumulating in the atmosphere first attracted serious attention in the 1930s, but it was not until the post-war expansion of science funding in the United States that it became a public issue. Because it was thought that the oceans might hold as much as fifty times more CO_2 than the atmosphere, and because the residence time of CO_2 there was only a matter of conjecture, it was appropriate for the director of the Scripps Institution of Oceanography in California – Roger Revelle – to suggest that a formal monitoring programme should be mounted without delay.[1]

Accordingly, he found funds in 1958 to hire a young postdoc from CalTech – Charles Keeling – to establish CO_2 monitoring stations during the upcoming International Geophysical Year, itself another of Revelle's good ideas. It was hoped that the data would provide information on the global background level of CO_2, so the stations were to be on a mid-Pacific mountain on Hawaii, in Antarctica and aboard a Scripps ship. Four continuous gas analysers for use during the IGY were purchased with funds from the US Weather Bureau and it was hoped that the data from these would quantify a global background level of CO_2 and its rate of change.

As a student at CalTech, Keeling had become interested in the apparently strong variability of atmospheric CO_2 concentrations, and had devised a new measurement strategy by observing CO_2 levels many times each day at pristine sites in the Californian mountains. He quickly found a diel signal that he conjectured was related both to the photosynthesis/respiration cycle of plants and probably also to the diel stability cycle of the lower atmosphere. He also confirmed the highly variable concentrations of urban areas, measurement of which had led to previous assumptions that no background level could be expected.

But Keeling's new data hinted that a background level of about 310 ppm might be general, and it was the interest of his new measurements that led to the post he was offered at Scripps to participate in the IGY[2]. Once routine measurements began, the existence of this background was confirmed, and it also became clear that CO_2 was steadily accumulating in the atmosphere, just as it continues to do today - although it still does so without saturating the ability of oceanic and terrestrial vegetation to utilise a constant fraction of each year's accumulation. This confirmed Revelle's intuition that CO_2 might be accumulating, and also confirmed his fears concerning the potential effect of this on the ocean's carbonate system, which was one of his main scientific interests.

Not long after Keeling's data had begun to confirm his expectations, Roger Revelle left for Harvard, where one of his students was the young Al Gore, who was much impressed by his lectures on carbonate chemistry and its relation to the data

[1] *Revelle, R. and H. Suess (1957) Tellus 9, 18-27.*
[2] *Scripps Institution archives, Keeling autobiography.*

coming from Mauna Loa. One may speculate how different things might be at present if these two had not met in this way, and if the Florida federal election recount of 2000 had not been called off....

I was fortunate enough to be recruited by Scripps in 1963, just a few years after Charles Keeling and, although my work was in a different field, I quickly learned about the new CO_2 results, which were already being discussed at Scripps. But they made no headlines because in those years there was clear evidence that the global climate was cooling rather than warming. In 1975, comments were made on a state of affairs that curiously mirrors our own "*…climatologists are pessimistic that political leaders will take positive action…and concede that...spectacular solutions…might create more problems than they solve…The longer planners delay, the more difficult it will be to cope with grim reality"*.[3]

The widespread trend of glacier advance and of sea ice expansion was also noted in an article in Science News which suggested that "*The unusually beneficial climate of the past few decades may be degenerating, facing humanity with a new challenge to survival" and* recalled the bitter winters at the end of the 18th century, during the American Revolution, when the freezing coastal waters of New York immobilised the British fleet, and the revolutionary army hunkered down in frozen fields in New Jersey.[4] Interestingly, although the writer also discussed CO_2, urban heat and other anthropogenic effects, he associated the cooling climate trend of those decades principally with changes in the degree of cyclonicity in the westerly winds.

A different explanation for the advance of glaciers was also being discussed because there was reason to believe that our present interglacial period, already 11.6 thousand years long, might be drawing to a close, because the length of previous interglacials had been about 50% of the precession period of Earth in its orbit, or about 11,000 years. This suggestion is also still with us, although now tempered with solid computation concerning the radiative forcing of atmospheric concentrations of CO_2.[5]

But when glaciers began to retreat again and air temperature data suggested that a warming trend had set in, everybody quickly forgot about ice ages and the scientific community rapidly stirred itself into action to study the radiative consequences of CO_2 accumulation. Science funding followed novelty, as it always does, so the Canadian research group in which I was then working at the Bedford Institute of Oceanography easily obtained funds to go to sea as part of the international Joint Global Ocean Flux Study (JGOFS) to evaluate the role of the planktonic ecosystem in global carbon budgets, and we were well supported by the Canadian government of the time. Within a few years, I was able to participate in an international programme of observations of carbon flux through the spring surge of phytoplankton in the Northwest Atlantic, and of the vertical flux of this organic carbon in the eastern tropical Pacific and in Canadian Arctic seas. These studies led to one of earliest analyses of the role of the marine biosphere in the global carbon cycle – and to the then-fashionable hunt for the apparently missing sink for carbon emissions. I concluded that predicted perturbations of the oceanic

[3] *Newsweek, 28 April 1975*
[4] *Douglas, J.H. (1975) Science News 107, 138-140.*
[5] *Kukla, G.J. et al. (1972) Quat. Res. 2, 261-269.*

"biological pump" by climate change were more likely to reinforce, than mitigate, the rate of increase of anthropogenic CO_2.[6]

In a word, like my colleagues, I was hooked…

But more recently, I became troubled by what seemed to be a preference to view the climate as a simple system, presently perturbed by anthropogenic carbon dioxide, rather than as a highly complex system having several dominant states, each having a characteristic return period imposed on gradual change at millennial scale. The research of H.H. Lamb and others on the natural changes of regional and global climate of the Holocene appeared to be no longer of interest, and the evidence for anthropogenic climate change was being discussed as if it was reducible to change in a single value that represented global surface temperature. The complex relationship between solar cycles and regional climate states on Earth that was central to classical climatology (and is still being discussed in the peer-reviewed literature) had been replaced with a reductionist assumption concerning radiative balance, and the effective dismissal of any significant solar influence.

I found this rejection of an entire body of scientific literature troubling, and looked for a disinterested discussion of the balance between natural and anthropogenic effects, but could not find what I wanted - a book that covered the whole field in an accessible and unprejudiced manner, and that was based solely on the scientific literature: I found text-books on individual topics aplenty, together with a flood of others, either supporting or attacking the standard climate change model, but none that was based wholly on studies certified by peer-review - and whose author was inquisitive rather than opinionated.

One thing led to another and this text is the result. My intention has been to examine the scientific literature that both supports – and also contradicts - the standard description of anthropogenic climate change, and its effects on Earth systems: I undertook the task with an open mind concerning the interpretation of the evidence presented in individual research reports, and collectively by those who have been tasked to report to governments on the progress of climate change and to predict future states. Because of my experience, this review leans very heavily on discussion of the role of the oceans in controlling climate states, but I make no apology for this: their role is central and critical and too often ignored.

For this task, I have only very occasionally consulted the many Internet sites that contribute to the debate, and have clearly identified my handful of references to such material. On the other hand, I have made extensive use of the original and processed data on surface temperatures taken both ashore and at sea, are archived by public agencies and are available to researchers.

Anthropogenic modification of climate, especially of micro-climates, is undoubtedly occurring but I have been unable to convince myself that the radiative contribution of carbon dioxide can be observed in the data, although modellers have no trouble in demonstrating the effect. The question of remediation in response to this is left strictly to one side, as being a political rather than technical issue: the means to respond exist, or can be made to exist, but the forces that maintain us on our present course are very powerful. Because readers will be familiar with them, I have also left to

[6] *Longhurst, .R. (1991) Limnol. Oceanogr. 36 (8) 1507-1526.*

one side some events that very unfortunately brought discredit on climate science but I must admit that they have caused me to be slightly diffident of expert opinion.

Certainly there will be some who will question my motive in undertaking this task, but I assure them that I have been impelled by nothing other than curiosity and have neither sought nor received financial support from any person or organisation in the preparation and distribution of this eBook. I am grateful to those who have discussed some individual issues with me, or who have provided data or reprints of their work, but because of the intolerance of non-conformism which now invests climate science, they may prefer not to be named - but they know who they are, and I thank them one and all.

My title is chosen in homage to Prof. J.Z. Young's '*Doubt and Certainty in Science*', so influential when I was a student in the early 1950s.

Chapter 1

THE CRISIS IN CLIMATOLOGY

"Philosophers of science have repeatedly demonstrated that more than one theoretical construction can be placed upon a given collection of data". [7]

It has been clear since the 1970s that climatology was passing through a crisis in the sense of Thomas Kuhn, as a new paradigm - that of '*climate change*' - came progressively to dominate the normal science. Whether or not we are witnessing the replacement of the classical paradigm for climatology, the rapidity of the adoption of '*climate change science*' as a term to describe the activities of very many earth scientists has been remarkable.

Equally remarkable is the progressive move of the concept of climate change into the public sphere as a policy issue and as a political priority to support, or - in some jurisdictions - to avoid like the plague. In the new volatile mix of science, industrial interests and politics that is associated with the concept of climate change, normal climatology became irrelevant because once the genie of the radiative effects of CO_2 was out of the bottle, "*researchers, policy-makers and activists have claimed that climate science requires a global policy agenda of top-down, UN-sponsored, international agreements*". [8]

Science alone has not been able to create such an outcome, because conservative politicians and some industrialists have done everything in their power to prevent it, under the belief that government should not interfere in the economic evolution of society. So scientists and others who are convinced that modification of our energy use is urgent have been induced to make very confident predictions concerning future climate states, and of disasters to come, in the belief that a mounting weight of evidence would gradually overwhelm opposition to the establishment of national climate policies.

It is this context that the activity which we now call climate change science has evolved and flourished in universities and other research centres, where it now absorbs a very large fraction of the total financial support to the earth sciences offered by research funding agencies in most nations.

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[7] *Kuhn, T.S. (1962) "The structure of scientific revolutions", U. Chicago Press.*
[8] *Sarewitz, D.(2010) Nature 464, 29 doi:10.1038/464028a to which this section owes much.*

1.1 - 'Climate change' science: a new paradigm or a new community?

During most of the 20th century, climate science consisted of two main streams: the search for understanding of climate normals - or periodic average conditions - and also the historical study of past climates at all time scales. The first stream sought evidence in observations of air and sea surface temperatures and in the changing pattern of atmospheric circulation, while the second stream sought its data in historical writings or archaeological research, and also in proxy evidence of past conditions in cores of sediments or polar ice, and in analysis of annual growth rings in trees, stalactites and corals. Other research was concerned with the astronomical forcing of ancient and modern climates caused by changes in solar irradiance, by vulcanism and by impact events. Anthropogenic affects on climate states were not yet of general concern.

The first volume of the Journal of Climate in 1988 illustrates this situation very well; in the 12 monthly issues, I can see only two papers that discuss anthropogenic effects, while the remainder have titles like "*Synoptic activity in the Arctic basin*" or "*Interannual Variations in the Southern Hemisphere Circulation*" and so on; studies of atmospheric circulation patterns or the succession of regional droughts and rainfall were prominent in the titles.

Yet the seeds of what was to dominate the literature today had already been planted much earlier with the studies of Arrhenius,[9] Tyndall and Fourier in the 19th century that introduced the concept of the CO_2 greenhouse effect, a concept that was matured by the work of Callender in the mid-20th century who first linked fossil fuels, CO_2 emissions and global warming.[10] Such suggestions induced the start of a compilation of the comprehensive global surface temperature records that would be essential to investigate the concept of anthropogenic influence on climate state. These data, and the warming they seemed to indicate, became central to the invasion of the paradigm of "climate change" into climatology; the reliability and significance of the data were not questioned – even if today they remain very uncertain, as will be discussed in Chapters 3 and 4.

From the early 1970s onwards, public money began to flow in support of climate change studies, both in government laboratories and university institutes, who modified their institutional structure and programmes accordingly: many existing research departments were transformed to attack the new tasks with the new funds now available. At Scripps, where Roger Revelle organised the first serious CO_2 monitoring facility, the largest research department is now entitled "*Climate, Atmospheric Sciences and Physical Oceanography*" and in 2014 it comprised 42 professors and research scientists, 20 post-docs, and 47 graduate students, who write about 100 proposals annually - and tokk in $48 million in a recent year in external funds from state and federal science granting agencies. Similar reorganisation has been adopted in many research establishments, to enhance and manage the flow of financial support for research on climate change. Financing of these research groups is entirely dependent on the continued support of government funding agencies and hence on the level of concern of governments - and of their voting public - for anthropogenic climate change research; it would not be surprising, then, if such organisations were rather sensitive to any criticism of the accepted model.

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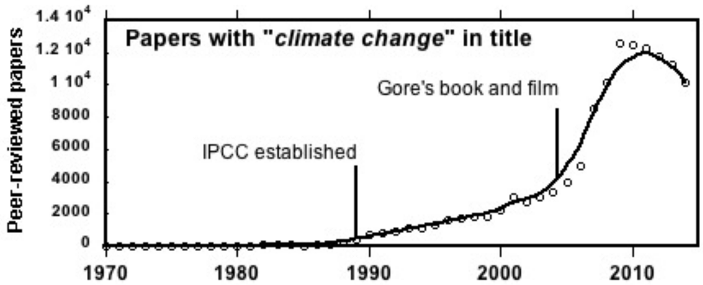
[9] *Arrhenius, S. (1896) Phil. Mag. J. Sci. 5, 237-276*

[10] *This section owes much to the essay of Morloff, J.C. et al. (2015) Phil. Trans. Roy. Soc. A 365, 2741-2776.*

During the 1980s, a series of international conferences carried forward the paradigm of anthropogenic climate change and forced the attention of science funding agencies on the issue. The first World Climate Conference in 1979 was followed by a succession of WMO, UNEP and ICSU conferences that culminated in the establishment by the UN General Assembly of the Intergovernmental Panel on Climate Change - the IPCC, of which much will be said in later chapters - in 1988. In the same years, international protocols on remedial action began to be discussed by governments and this increased public awareness of the potential consequences to them of a warming world.

Almost immediately after the establishment of the IPCC, the scientific community reacted with a rapid but sustained increase in the number of studies devoted to 'climate change', and this term rapidly became a code for concern for the future environment.



In the new century, this trend accelerated very strongly for a few years; it is not easy to attribute cause to this sudden change, but these were the years that followed the publication of the Gore book and film "*An Inconvenient Truth*" and they were also the years of the sudden flowering of web-based discussion concerning climate change when many influential internet-sites were established: RealClimate (2004), Climate Audit (2005) and WattsUpWithThat (2006) and others. The influence of these on public opinion, and their role in bringing the issue of climate change into the social environment, should not be underestimated.

Curiously, since about 2010, the number of papers whose titles refer to climate change directly has progressively declined although there is no clear reason why this should have occurred: perhaps the community simply become more sophisticated in its choice of words? Or did the staff of funding agencies become more knowledgeable about the complexities of the issue? In any case, the lack of a sustained plateau does not detract from the singularity of the pulse of interest in the term during the first decade of the century.

At first sight, this incursion of "climate change" into the literature might appear to represent a paradigm shift, in the Kuhnian sense, in climatology but this is appears not to be the case: normal climate science continues its habitual course. The current issue of Journal of Climatology contains only two papers whose titles would have seemed novel 25 years ago: the remainder, except for greater emphasis on evaluation of models, would have fitted comfortably into the list of titles of the first issue in 1988. Rather, what we have is a new and parallel paradigm for climatology that has evolved from the activity of the IPCC and is closely associated with, and necessary for, international discussion of palliative measures. It has also created very strong growth in certain sectors of research and in certain groups of researchers who would not have, 30 years ago, thought of themselves as climatologists.

What appears to have happened is that a new community has established itself within the earth sciences that has "*undergone similar education....absorbed the same technical literature and drawn many of the same lessons from it. As a result the members...see themselves and are seen by others as the men uniquely responsible for the pursuit of a set of shared goals, including the training of their successors...communities of this sort are presented as the producers and validators of scientific knowledge*".[11] Those earth scientists whose work is relevant to climate change but who do not participate in the community (and there are many such) risk ostracism; if they criticise the simple paradigm in discussions or in their writings, they risk worse.

The acceptance of unrestrained critical comment, behind a cloak of anonymity, on the web-sites has led to some very unpleasant exchanges and accusations, and it has now become very difficult to discuss the standard model of anthropogenic climate change in any critical sense without giving offence to some – and perhaps to many. Even if the scientific consensus may not be quite as solid as has been suggested, those who have serious doubts are clearly in a small minority.[12] But free and open discussion is just as essential in this, as in any other scientific discipline, if the truth is to be found; it shouldn't need to be said yet once again, but what may be called healthy scepticism is an essential ethic of science. T.H. Huxley long ago wrote that this is "*the highest of duties; blind faith the one unpardonable sin*" of the improver of natural knowledge – which is, in the end, the first responsibility of a scientist.

Yet many scientific societies (on behalf of their members) the world over have endorsed the authority of the IPCC and the relevance of its conclusions; the web-site of many carries a statement that endorses the reality of, and dangers associated with, anthropogenic global warming. While some individual scientists are free thinkers with regard to this question, their collectives generally conform to the standard model. Even if the Royal Society has modified its original flat statement with a more open position on the causes of climate change, as requested by a group of Fellows, there remains little residual attachment to what was previously printed on their Philosophical Transactions: "*… it is an established rule of the Society, to which they will always adhere, never to give their opinion, as a Body, upon any subject, either of Nature or Art, that comes before them".* Also very largely forgotten is their motto "*Nullius in verba*", usually taken in this context to translate as "*nothing upon another's word*".[13]

1.2 - Estimating the levels of certainty in scientific information

There are two principal sources of information on climate change and each offers different levels of confidence that we may place on statements concerning anthropogenic effects: (i) conclusions expressed by the IPCC in its formal Assessments of the progress and future of climate change, and (ii) peer-reviewed communications in the scientific journals. The IPCC offers us a range of levels of certainty in making its judgements, while the journals offer us no such nuance: if it is published, we are asked to

[11] *Kuhn, T. (1962) Ibid.*

[12] *Anonymous comment is today accepted in places where it is inappropriate, as on the weekly internet version of Nature.*

[13] *But it is given a stronger meaning in my Conington's Horace: "Whats my sect? Why none: I've taken no mans shilling; none…owns me for his son".*

assume that it is correct - which, by experience, we know is not always the case - while the levels of certainty stated by the IPCC remain largely untested.

The International Panel on Climate Change (IPCC) is a UN agency with a very limited mandate: *"to assess…the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation".* Because it has no formal mandate to investigate or review other causes of climate change, it is quite proper that the scientists who participate in the assessment should be experts in anthropogenic effects on climate, and should be concerned principally with radiative effects in the atmosphere of carbon dioxide molecules and of particulates. Conversely, there is no reason for experts in, say, solar influences on climate to be involved in the work of the IPCC and it is reasonable to think that this is likely to constrain their collective opinion to point in certain directions.

Perhaps surprisingly, the first Assessment Report in 1990 stated that, in their judgement, *" global mean surface air temperature has increased by 0.3 to 0.6 ^{o}C over the last 100 years....The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus the observed increase could be largely due to this natural variability; alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming. The unequivocal detection of the enhanced greenhouse effect is not likely for a decade or more."*

But in subsequent Assessments over the next 20 years or so, research on the anthropogenic effects has strengthened the collective opinion that natural effects are sufficiently trivial that they can essentially be ignored. If the initial mandate of the IPCC been wider, the spectrum of expertise involved in the discussions would have been correspondingly more extended, and the judgment of the most recent Assessment perhaps not so unambiguous; a greater involvement of general climatologists and astrophysicists in the discussions would have ensured that the record of natural climate change in the past was more fully explored, and this might have prevented the undue attention that has been placed on the climate of just the most recent decades that has, in fact, occurred.

The formal expressions of opinion of the IPCC are contained in a series of quadrennial Assessments Reports, supplemented by reports on special topics. Recent Assessments have been drafted by three Working Groups: WG1 assesses the scientific aspects of the climate system and climate change, WG2 assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it, and WG3 assesses options for mitigating climate change through limiting or preventing greenhouse gas (GHG) emissions and enhancing activities that remove them from the atmosphere.

We are mostly concerned here with the 4th Assessment Report of 2007 and also the 5th, issued in autumn 2013. The 4th Assessment involved the participation of 18 Coordinating Authors (responsible for content) and 106 Lead Authors, who drafted the texts of each of the 10 Chapters. These were appointed to the IPCC by 27 (of the 151) member nations, but almost exactly half of them were from just three: the USA, the UK and France. In addition, each chapter lists a larger number of contributing authors who were asked to supply specific scientific or technical information, graphics and so on. Also listed for each chapter are 2-3 review editors, some of who are also listed as authors.

Lead authors have an additional very heavy responsibility, imposed by the requirement that each Assessment should express in a standard manner the level of certainty that they place on each aspect of the science that is to be reviewed. For this purpose, the IPCC has evolved a formal system of quantifying such judgements that is described in AR5 as follows – *"Likelihood as described in Table 1 provides calibrated language for describing quantified uncertainty. It can be used to express a probabilistic estimate of the occurrence of a single event or of an outcome (e.g. a climate parameter, observed trend, or projected change lying in a given range). Likelihood may be based on statistical or modeling analyses, elicitation of expert views, or other quantitative analyses:*[14]

Virtually certainly correct …………..>99% probability
Very likely correct……………………..>90% probability
Likely correct…………………………..…>66% probability
More likely than not………………… ..>50% probability
About as likely correct as not………....33-66% probability
Unlikely correct…………………………..… 0-33% probability
Very unlikely…………………………………<10% probability
Exceptionally unlikely…………………..<1% probability"

This table is an unusually complex version of what is known in the military intelligence community as a set of "*words of estimative probability*", a concept that stems from an essay of Sherman Kent, who discussed the inappropriate use in CIA national intelligence estimates of difficult-to-quantify statements, such as *"It is almost certainly a military airfield".* Kent pointed out that words like "*almost*" have no uniform quantitative meaning, so he proposed that estimates of certainty should be formalised for operational decision-making.[15] But, for the system to work, the user community must be trained in its use; this presumably occurred at the CIA but the readers of the IPCC reports (and those who quote from the reports) have not been trained and commonly misinterpret the special meaning given by IPCC to everyday words: *"laypeople"* it as been shown *"interpret IPCC statements as conveying probabilities closer to 50% than intended by the IPCC authors"*.[16]

The process by which their own texts are reviewed by the IPCC is complex and has been much discussed both in the formal literature and on web sites; two sets of reviews are involved, from experts and from governments. These reviews are subsequently available for public inspection for a period of 5 years, but it is not always easy to locate them; however, those for WG2 remain open for inspection and offer interesting insights.

To get the flavour of this process, I looked at the final Expert Comments on the 2nd order draft, and under Section #4 "Ecosystems, their properties, good and services" I found a strange mix of comment, some of which had apparently remained unanswered. For example, Eric Kasischke, (University of Maryland) commented: *"I do not feel the present report does justice to the complex issues related to climate warming in arctic and boreal regions, in particular, the lack of a coherent and complete discussion of recent observations that permafrost is warming, the role of permafrost in a variety of important*

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[14] *IPCC AR5, Note for Lead Authors.*
[15] *Kent, S. (1964) Words of Estimative Probability, CIA Stud. Intell. (Fall 1964 issue)*
[16] *Budesco, D.V. (2014) Nat. Clim. Change 4, 508-512.*

ecosystem processes…..." and so on. This elicited no response from the lead authors, but when Oscar Abbink commented that the "*Section on past climates (4.2.1) lacks a clear message. In my opinion, there should be a clearer statement on the lessons learned from past climate changes, namely, that rapid climate changes do exist, and ecosystems are not able to adapt to those changes on a short time scale*" the authors responded: *"Text revised substantially and incorporated into a more comprehensive section on climate variability".*

In fact, the great majority of comments were editorial and textual rather than substantive, and, as is inevitable in any exercise of this kind, some comments revealed a national sensitivity; the USA remarked, for instance, that "*The connection between climate change and people using water sources contaminated with Arsenic or Fluoride is unclear. A fluorosis case in Niger was due to a shallow, not a deep well. The poisoning story is dramatic and tragic, but the connection to climate change is not clear*", to which the authors replied quite simply "*Request in opposition to several made by another reviewer*". It is hard not to conclude that the participants from Niger preferred to blame a domestic problem on climate change.

The material used in this book comes almost exclusively from papers published in major peer-reviewed journals, rather than from the IPCC Assessment Reports: more than 70% of my 600-odd citations are to just seven journals: *Nature, Science, Geophysical Research Letters, Journal of Geophysical Research, Proceedings of the National Academy of Science, Philosophical Transactions of the Royal Society,* and *Journal of Climate*. Only about a dozen are to work published in journals that some might say have an editorial prejudice. I have referred only rarely to informal web sites and then mostly to check specific information that I knew I could find there, preferring to rely on the old-fashioned mode of scientific discussion in formal journals. But, despite my reliance on the core journals in each relevant discipline, the works that I have selected for discussion represent neither the absolute truth nor the last word. Where I have been aware of opinions different from those that I quote, I have discussed the lack of agreement. I have not searched the web sites and blogs for counter-arguments to my sources; if you look for them, I am confident that you will find them, such being the nature of science today.

That my sources are essentially from the major peer-reviewed journals may surprise those who have read the Nature essay on "*The Scientific Consensus on Climate Change*". This was based on a reading of 928 peer-reviewed papers having the words "*Global Climate Change"* in their abstracts and, of these, none were judged to disagree with the consensus position.[17] Yet this result is not quite as significant as claimed: rather few of the papers relevant to climate change that I have consulted included those exact words in their abstract, even though many explicitly disagreed with a concept, an observation or an interpretation implicit in the standard climate change model. The peer-reviewed climate change literature is richer, more diverse and more contrarian than Nature's essayist understands, and most papers contributing to the subject offer no explicit opinion on the central issue. Nor is it easy to comprehend the volume of published discussion today: for 2013 alone, I found that more than 18,500 scholarly papers - not all peer-reviewed - contained both '*global climate change*' and *'anthropogenic'* in their texts!

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[17] Oreskes, N. (2004) Nature, 306, 1686.

Recent investigation of the extent to which formally-published results in pharmaceutical science are refuted by later studies is, frankly, shocking: "*it can be proven*" wrote John Ioannides of this field not so long ago "*that most claimed research findings are false*". He showed that positive bias in the original studies and negative bias in the refutations are both involved, that this effect is especially high in hot, new fields, and also that *"the greater the financial and other interests and prejudices in a scientific field, the less likely the research findings are to be true*"[18].

Unfortunately, climate change research fits both of these moulds: the interests, both of society and of individual researchers during their careers, are not negligible. This problem is deeply rooted and has been commented on in a paper published in a respected source, Wiley InterScience: "*Climate science, as articulated through the authoritative IPCC, became linked to and synonymous with a single policy agenda, the UNFCCC-Kyoto process, starting in 1992. Indeed, this policy regime explicitly evolved as a response to and outgrowth of the scientific conclusions of the IPCC. Any scientific conclusion consistent with the possibility of 'dangerous anthropogenic interference with the climate system' could be understood as an endorsement of the UNFCCC regime because it was the only available option. Climate policy became understood as having one central goal: emissions control monitored and enforced at the national level as part of a top-down, coordinated international governance regime. Climate science served one main purpose: to advance that regime*".[19]

So we are faced with the question of how to verify and evaluate the published works of climatologists individually, but also collectively within the IPCC.

For this, much is made of the mechanism of peer review of scientific findings as warranty that a sufficient level of certainty has been achieved to demonstrate that expensive and socially disruptive remedial action must be undertaken immediately. The context in which much science, including environmental science, is performed today has clearly corrupted peer review towards supporting a socially-acceptable interpretation of observations: in the present context, climate science is not *"inherently self-correcting"* and it is not correct to say that *"incorrect or incomplete scientific concepts do not survive repeated testing against observations of nature*" as suggested by IPCC4.

In the past, it was always thought proper (at least among people with whom I worked) to accept the strictures of peer-review of your texts - if your paper was rejected by your chosen journal, you simply trashed it and chalked it up to experience. But now it seems to be normal to resubmit to a second – or a third, or a fourth journal – papers that have been rejected by the first. Today, probably few scientific projects that are carried through to a formal text are, in fact, never published because of rejection by peer review.

This undesirable end is rendered even more likely by the current proliferation of journals, in response to the high profitability of science publishing, which is in a period of rapid change. The long-established core journals, based on subscription revenues, are under criticism for exorbitant pricing and manipulation of readership and, indeed, some have been making extraordinary profit margins that would be the envy of any industry. In response to these practices, some mathematicians have boycotted an important

[18] *Ioannides, J.P.A. (2005) PloS Medicine 2, e124*
[19] *Sarewitz, D. (2012) DOI: 10.1002/wcc.126*

scientific publishing house, and have turned to the open-access literature.[20] But the problem with this solution is that the original and respectable open-literature journals have been joined by a flood of newcomers, many of which have been described as 'predatory' in their dealings with those who agree to write and edit for them. Of the approximately 16,000 new open-access journals, it has been estimated that about 25% fall into the predatory category, having questionable practices concerning hidden page charges, or the offer of a proportion of the journal's revenue to those who agree to be on the editorial board!

In any event, one doesn't have to read very far to find evidence that a progressive collapse of peer-reviewing - at least in those fields where controversy or financial interests are involved - today puts in doubt the reliability of results published even in very respectable journals in all branches of science. I have read papers, in fields in which I have some experience, that have been so clearly erroneous – and so clearly designed to make headlines in the press - that I lost my faith in the peer-review process some years ago and suggested that "*in-group reviewing*" was now seriously affecting the veracity of papers published in even major journals.[21] And I find that I am not alone in that opinion. Consider this, from a little book by Laurent Ségalat, ex-CNRS geneticist: *"...in order to have the best cards in your hand, you must exploit a detestable and shameful trick of the profession: the possibility of suggesting to the editor the names of suitable reviewers...if the editor uses your names you have a 50% greater chance of your paper being accepted...from this flows the creation of little circles of people who help each others publications".*[22]

This attitude is also addressed in the following text, remarkably written by the senior editor of *The Lancet*, one of the most respected journals in the medical field, and one which itself has an unusually strict procedure for peer-review: "*Editors and scientists alike insist on the pivotal importance of peer review. We portray peer review to the public as a quasi-sacred process that helps to make science our most objective truth teller. But we know that the system of peer review is biased, unjust, unaccountable, incomplete, easily fixed, often insulting, usually ignorant, occasionally foolish, and frequently wrong".*[23]

Despite such evident truths, some people take the authority of journal editors very literally; a little book was published recently by a group of French academics, who asked "*Why are the climatologists so exasperated*"? The reason, they suggested, is that climatologists publish in peer-reviewed journals so that "*this control by their peers guarantees the progress of their knowledge*" while, on the contrary, criticism of their results is "*expressed in the media instead of being submitted to proper journals as is the custom in all scientific disciplines*".[24] This, it seems to me, is an astonishingly naïve attitude, yet I have to believe that it represents the opinion of the authors.

In this context, it is necessary to raise the question of the level of scholarship of some contemporary writers; I take it as given that scientists are – or should be – scholars, in the sense of one who possesses a broad and critical understanding of the

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[20] Arnold, D.N. and H. Cohn (2012) arXiv:1204.1351v1 [math.HO] 5 Apr 2012 and see also Taylor, M. et al. (2008) The Siege of Science. Ethics Sci. Env. Polit. 8, 17-40

[21] Longhurst, A.R. (2007) Fish. Res. 86, 1-5.

[22] Ségalat, L. (2009) "La Science à bout de souffle?" - Éditions Seuil, pp. 107.

*[23] Horton, Richard (2000). MJA **172** (4): 148–9. PMID 10772580*

[24] "Climat: une planète et des hommes" E. Orsenna & M. Petit (eds); Cherche-Midi, 2011.

literature of their topic. But there are signs that this standard is eroding, a problem that has been investigated directly by examining subsequent citations to a selected group of prominent fisheries conservation studies, each of which had been formally challenged in a refereed journal.[25] This analysis showed that not only is citation rate of a paper unaffected by the publication of a challenge, but also that subsequent citations rarely noted that the work being cited had been challenged. In fact, only 5% of subsequent citations were in any way critical of the original paper and, worst of all, 8% of subsequent citations appeared to believe that the challenge had been a paper supporting the original! Clearly, in this case, studies had been cited without having been read or understood.

The authors of this investigation pointed out that the high profile studies they chose to investigate were all predictive of future catastrophic declines in fish stocks, which raises an interesting question - are predictions of future disasters so much expected of science today that we no longer feel it necessary to read them critically? If that is the case, then the probability that we can reach certainty concerning prediction of the future course of anthropogenic climate change - which is undoubtedly real even if it may not be well described by the standard climate change model - may be very low indeed.

1.3 - Numerical climate simulation

Models are, and must continue to be, central to the IPCC's evaluation of our impacts on climate, yet – as the 4th Assessment Report points out – model predictions are "*intrinsically affected by uncertainty*" in two ways: (i) our incomplete knowledge of the climate state, and therefore (ii) incomplete description of the initial state in the equations from which the simulation departs. Instability must result and prediction cannot be extended into an indefinite future, because we cannot know at what point the model has become chaotic. All this, of course, is well known and goes back at least to Lorenz's "*Problem of deducing the climate from the governing equations*" - but knowing what the problem is doesn't get us very far in judging to what extent we can trust any prediction of future climate states that is based on numerical simulation.[26]

But a recent comparison of the performance of 11 coupled climate-carbon models concerning the sensitivity of terrestrial and oceanic carbon cycles to anthropogenic release of CO_2 is salutary: the individual models were formulated by teams in 10 different research centres to evaluate the coupling to be anticipated between climate change and the global carbon cycle.[27] Each model was forced by historical emissions and the anthropogenic emissions of CO_2 for the 1850–2100 time period and carbon cycles of oceans and continents were simulated separately. As expected, all 11 models agreed in suggesting that the addition of anthropogenic CO_2 to the atmosphere would reduce the capacity of natural systems to absorb the anthropogenic fraction and progressively increase the airborne fraction. This finding was approved by the IPPC4 report, which used it as a basis for suggestions concerning future climate states and temperatures.[28]

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[25] *J.A. Banoby, et al. (2011) Ecosphere 2(3) 1-11.*
[26] *Lorenz, E.N. (1964) Tellus, 16, 1-11.*
[27] *Friedlingstein, P. et al. (2006) J. Climate 19, 3337-3353*
[28] *IPPC4 Chapter 10, p. 750*

But the spread of the estimates of the increase in the airborne fraction was impressive: projected to the end of the 21st century, most models offered estimates between 50 and 100 ppm, but the end-points of the spread were at 20 and 200 ppm. Nor did the models agree whether the greatest sensitivity of natural systems would occur at high latitudes or in the tropics, or even in the oceans or on land! One cannot but agree with the authors that: "*To reduce the large uncertainties in climate–carbon cycle projections, it is critically important that carbon cycle models are more completely constrained by observational data*".

Unfortunately, not only did these 11 models offer a spread of results far too wide to be believable or useful, but even the point on which they all agree – that the anticipated anthropogenic perturbation would saturate the ability of natural systems to take up the additional CO_2 – seems not to be validated by the 70 years of observations now in hand. These show that the fraction of anthropogenic CO_2 that remains in the atmosphere each year, to progressively increase total concentration there, has remained constant: both anthropogenic and natural concentrations have increased in due proportion.

Recent studies concur that the trend in the fraction of anthropogenic CO_2 from all sources, not only the combustion of fossil fuels, that remains in the atmosphere is rather stable at 0.44% with an increase of only 0.3%.yr^{-1}, which is not significantly different from zero: no trend in the relative size of this fraction can therefore be detected.[29] The natural carbon cycles, both ecological and physical, have been able to accommodate to the presence of anthropogenic CO_2 in the atmosphere. It is no surprise to have confirmation that earth systems are more complex and resilient than models pretend, and in the light of these observations there seems no reason to suppose that the <1.5^{o}C extra warming by the end of the 21st century predicted from the saturation of natural carbon cycles will actually occur: it could well be much more, or much less, depending on which formulation you choose to believe.

And the level of confidence in the predictions of complex simulation models has an interesting differential distribution between those who design them and who are those mandated to use them, but do not have the technical competence of the first group; this distribution of what we might call relative confidence in the prediction of models has been studied in the field of missile trajectory simulation.[30] Here, mandated users show the highest levels of confidence, because of their association with the technological programmes that require the model predictions. But some of those who are directly involved with designing the models – rather than those use their projections - have a significantly lower esteem for, or confidence in, their output. This attitude has been found among those who design general climate models (GCM) by McKenzie, a social scientist who was embedded in one of the most important centres of this activity – the US National Center for Atmospheric Research at the University of Colorado at Boulder. His study confirmed that modellers sometimes think and speak about their creations in terms of the real world: asked if this was the case, one modeller told McKenzie *"Yes. Yes. You have to be constantly careful about that…it is easy to get caught up in it, you start to believe that what happens in your model must be what happens in the real world. The danger is that you begin to lose some objectivity on the response of the*

[29]*AR5 6.3.2.4 and. Knorr, W.(2009) Geophys. Res. Lett. 36, doi:10.1029/2009GL04061*

[30] *MacKenzie, D (1990) "Inventing Accuracy: a Historical Sociology of Nuclear Missile Guidance", MIT Press.*

model…". Another remarked "*You start referring to your simulated ocean as 'the ocean'…*" – and so on. [31]

The most extreme statement of doubt concerning the performance of models of natural systems encountered in this study was the physicist who remarked that his "*students know more and more about computer reality and less and less about the real world – if the assumptions behind some simulations were flawed my students wouldn't even know where or how to look for the problem*". McKenzie also suggests that although most nations support only a single group that is capable of drafting GCMs, the US supports several who must compete for funds and tend, therefore, to acquire the habit of speaking and thinking very confidently about their own product.

More fundamentally, climate models only with difficulty integrate the fact that global climate (like the New York Stock Exchange) is an open system of which the components and the forcings are in a constant state of flux over both short and long time scales; it is logically impossible to predict the future performance of such systems with certainty: "*Verification and validation of numerical models of natural systems is impossible. This is because natural systems are never closed and because model results are always non-unique*" wrote Oreskes in 1994. [32] AR5 referred to this concept only with the very modest reminder that *"This...places important limits on the understanding of many of the inferences in the Earth sciences*". Ignored is the logical impossibility of demonstrating the truth of any proposition except in a closed system in which the all the components are precisely known and quantified, as in symbolic logic and mathematics. Earth scientists understand that their observational data (and parameters derived from them) are imprecise and incomplete and that it is rarely possible to quantify their divergence from reality.

It is also essential to distinguish between *validation* (of the structure of a model) and *verification* (of its results); the former process simply concerns examination of the structure of the model against the real system - and is relatively simple - while the latter compares output against observations. Paradoxically, as Oreskes suggests, more weight can be given to the negative result of a mismatch with observations than to a positive result - for which there must always remain the possibility that the model is incomplete - because there may be elements of which the modeler was ignorant when writing code. So even if a model is capable of simulations that conform to past observations, it may still not predict future states correctly for several reasons, of which the most obvious is that these may lie outside the range of the observational data of past states and may involve interactions different from those observed in the past. The global climate is subject to a wider range of forcings than can be recognised in any model, and some of these may hold surprises.

But, despite the fact that the structure of the modelled climate system used in the very first IPCC assessment could only be described as simplistic, the results obtained were used to predict future conditions quantitatively.[33] *"Based on current model results"*, the 1990 assessment predicted, *"and under IPCC Business-as-Usual emissions…a rate of increase of global mean temperature during the next century of about 0.3°C per decade…will result in a likely increase in global mean temperature of about 1°C above the present value by 2025 and 3°C before the end of the next century".* It is commonly

[31] *Lahssen, M. (2005) 'Seductive simulations?' Soc. Stud. Sci. 35/6 895-922*

[32] *Oreskes, N. et al. (1994) Science 263, 643-645 - to which this section owes much.*

[33] *APPC 4th report, Chapter 1, Figure 1.2*

assumed by the public that this and later predictions are based on what is often referred to as 'the IPCC model', but this is not exact. In fact, the projections for the 4th Assessment were made by reference to 23 atmosphere-ocean coupled General Circulation Models that had been formulated in 15 research centres in 8 different countries. As would be expected, the prediction of future climate states by these models under any particular scenario varies rather widely, so the final IPCC prediction itself represents no more than a statistic (termed the 'Mean Model') that is computed as the RMS error within multi-model monthly fields. This technique demonstrates, for instance, that uncertainty in outgoing SW radiation from the surface of the planet, as computed by the range of 23 models, lies somewhere between 15 and 22 W m^{-2}, which is a very significant variance! Happily, the Mean Model statistic lies closer to observations than does any single model, for reasons not yet understood[34].

Then, the same WG1 report remarks that "*Water vapour feedback is the most important feedback enhancing climate sensitivity"* and a more recent study confirms that the strength of this feedback is consistent with what is expected from changes in the water vapour mixing ratio[35]. Feedback from clouds and surface albedo are positive, while the only negative (and thus stabilizing) feedback is that of the temperature response that exhibits strong regional anomalies; between-model differences in cloud feedback is the largest source of uncertainty of predictions.

But, unfortunately, models perform even less satisfactorily if phase transitions of water vapour and the release of latent heat during cloud formation are included in model formulation. Trenberth[36] discusses the representation of cyclonic circulation and the formation of hurricanes in global climate models and concludes that while the general distribution of tropical storms can be "*somewhat simulated*", maximum winds and vortices are not realistic even in fine-scale (110 km) resolution and *"given the missing hurricane processes, the climate models therefore compensate in other ways*" and this raises the question of whether projections of climate changes can be realistically depicted in the absence of tropical storms? The role of clouds in climate sensitivity is an undeveloped field, largely because of the extreme difficulty of observing the evolution of cloud cover, and this is a problem that will require discussion in a later chapter: the dynamics of cloud cover may be one of the critical uncertainties in understanding climate history. Such a suggestion appears to be in harmony with the report of WG1 of the last IPCC assessment: "*…the spread of climate sensitivity estimates among models arises primarily from inter-model differences in cloud feedbacks"* and "t*he relatively poor simulation of clouds in the present climate is a cause for concern*".

One recent study of these problems went so far as to suggest that "*the sensitivity of the climate system to an imposed radiation imbalance remains the largest source of uncertainty in projections*" of future climate, probably due to natural and undescribed cloud variation, so that "*radiative forcing resulting from temperature changes (feedback) cannot be easily disentangled from those causing temperature change (forcing)*" in satellite observations.[37] You might expect that this contribution would be unpopular with some in the climate science community, but it would be difficult to have anticipated

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[34] *This section is based on IPCC 4th Assessment, WG1: The physical science basis - Chapter 8 – Climate models and their evaluation (Randall, D.A. and R.A. Wood).*

[35] *Soden, BJ and IM Held (2006) J. Climate 19, 3354-3360.*

[36] *Trenberth, KE and J. Fasullo (2007) J. Geophys. Res. 112, D23107*

[37] *Spencer, R.W. and W.D. Braswell (2011) Rem. Sens. 3.*

the storm of protest that followed its publication. Because it appeared to constitute a serious rebuttal of IPCC projections, it was widely and extravagantly reported in the press and 56,000 pdf copies were downloaded in the first 30 days after publication! The editor of the journal later commented that: "…*comparable studies published by other authors have already been refuted in open discussions and to some extent also in the literature, a fact which was ... unfortunately, not picked up by the three reviewers*".[38] He suggested that perhaps the paper should not have been published and then, weirdly, he resigned his editorship....

This episode illustrates very well both the range of opinion within the relevant scientific community concerning important topics and the intensity with which conflicting opinions are held and defended in the peer-reviewed literature. It also illustrates very well the difficulty the community faces in establishing certainty in one topic and then moving on to the next: this difficulty will be encountered and discussed in each and every one of the succeeding chapters. Doubt is not often replaced by certainty.

[38] *It was Trenberth et al (2010) Geoph. Res. Lett. 37, doi: 10.1029/2009GL042314*

Chapter 2

RADIATIVE FORCING OF ATMOSPHERIC PROCESSES

"I receiv'd a draft…of an Act against the nuisance of smoke in London, to be reform'd by removing severall trades which are the cause of it and endanger the health of the King and his people".[39]

The surface heat budget of the Earth is maintained by the balance between solar radiation that warms the surface, and the radiation of this heat back to space. This balance is largely controlled by surface reflectivity and by the transparency and gaseous composition of the atmosphere, some molecules being transparent to both short and long wavelength while others absorb the longer wavelengths. Inertia is imposed by the changing heat content of the ocean. Although the rates of accumulation and loss of heat by the Earth must be dependent on cyclical variation in the strength of solar radiation, this is usually assumed to be a minor factor so that, as Andrew Lacis has it, "*Atmospheric CO_2 is the main control knob governing atmospheric temperature*".[40] This argument permits only a minor (if any) role for the variable sun, and this only at secular scale; I shall return to this issue in later chapters and examine here only the role for what are termed well-mixed GHGs – although we shall find that CO_2 is not really as well-mixed as is usually assumed.

At the top of the atmosphere, Earth receives about 342 $W.m^{-2}$ of solar radiation of which about 40% is in the visible part of the spectrum. About one-third of this is scattered or reflected by clouds and at the surface, or is lost in heating dust particles and the molecules of radiatively-active gases. Consequently, only about 168 $W.m^{-2}$ reaches the surface, where a part heats the solid ground and ocean water, the rest being directly or indirectly returned as IR back radiation or as the latent heat flux of evaporation.

Back-radiation to space from the Earth includes some reflection of visible light from cloud tops, ice and the ocean, but is otherwise dominated by IR radiation (both from the atmosphere and from warmed surfaces) with which the molecules of radiatively-active gases react on its return passage up through the atmosphere. Many discussions of the effect of radiatively-active gases ignore the fact that the atmosphere is heated in this way by both incoming and outgoing radiation.[41]

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[39] *John Evelyn, 11 January, 1662*
[40] *Lacis, A.A. (2010) et al. Science 330, 356-359.*
[41] *e.g. "Le Climat à decouvert", (2011, CNRS editions), p. 50-52: this appears to be a public statement on climate change science by this organisation.*

The mono-atomic molecules (O_2 and N_2) comprising the bulk of the atmosphere are transparent both to incoming solar and outgoing thermal radiation while the radiatively-active, or greenhouse gases (GHGs) are those whose molecules are excited to a higher energy level when impacted by a photon within one or more characteristic wave bands This energy is then re-emitted almost instantaneously as the molecules return to their low-energy state, thus increasing the temperature of the atmosphere and so radiating some energy back to space. These gases are all bi-atomic (CO_2, CH_4, H_20, and so on), although industrially-produced complex molecules, such as the CFCs, may also be radiatively active. The individual GHGs not distributed uniformly in the atmosphere, either with respect to latitude or altitude nor yet seasonally, and each molecule has a characteristic longevity in the atmosphere, ranging from 7-9 days in the case of water vapour to 30-95 years in the case of CO_2.

Finally, and perhaps most importantly, what is not so well understood is that the effect of increasing concentrations of GHGs – including that of CO_2 – is not linear, but logarithmic: a doubling of the CO2 concentration will not double the radiative effect of that gas in the atmosphere. The radiative effect of the 280 ppm present before the Industrial Revolution in rural areas and at high altitude locations had a radiative effect of about 3.45°C, but to double the present concentration to (say) 400 ppm, would increase its radiative effect only to about 3.9°C…..*caveat lector!*

2.1 - Radiative forcing by active molecules

The troposphere now carries a complex population of natural and anthropogenic particles and molecules which influence air temperature very variously; emphasis is commonly placed on the role of anthropogenic carbon dioxide in the global warming that has undoubtedly occurred since the 19th century but, as I shall discuss in this chapter, this is over-simplistic. Really, the situation is very much more complex than that.

Central to this discussion is the definition of the *climate sensitivity* (ΔT_{2X}) of a molecule or particle; this is usually expressed as the effect on atmospheric temperature of a doubling of the initial concentration of agent x. The CO_2 molecule is only one among many agents that together determine the response of the atmosphere to short wavelength solar radiation and the long-wave radiation induced by the warming of air, ground and water; those of greatest concern are the so-called Kyoto Protocol gases: carbon dioxide CO_2, methane CH_4, nitrous oxide N_20, hydrofluorocarbons HFCs, perfluorocarbons PFCs and sulphur hexafluoride SF_6.

The atmosphere does not act as a single reaction chamber for these molecules, nor is it a volume in which their concentrations change along a simple vertical gradient. Rather, although air pressure decreases continuously from the surface to the boundary of outer space at about 100 kms altitude, it is layered into zones that have characteristic conditions, cloud types and responses to radiatively-active particles and molecules.

Here, we shall be concerned mainly with the troposphere that extends to the tropopause at 9-17 km, depending on latitude, and with the stratosphere that extends up to about 50 km at the stratopause. The troposphere is dominated by weather systems that actively redistribute surface heat and so cools progressively upwards to around -50°C at the tropopause; on the contrary, the stratosphere warms progressively upwards and vertical motion is relatively restricted, partly by the existence of the layer of ozone that occurs in the lower stratosphere at 20-35 km altitude.

Curiously, models suggest that cooling will be produced by the presence of the GHG molecules in the stratosphere: one of the earliest prediction from GCMs of the effect of doubled CO_2 was of a peak cooling of about 11^{o}K at the stratopause.[42] The mechanism for cooling lies in balance between the absorption of upwelling radiation emanating in the troposphere - thus warming the stratosphere – and the increased emission of infrared radiation within the stratosphere - thus cooling it. "*The net effect*" write Seidel et al. "*at a given altitude depends on the spectral properties of the gas and the upwelling radiation, at the wavelength of interest*".[43]

You might have thought that good agreement would by now have been reached on the specific warming effects of radiative gases and aerosols on the temperature of the atmosphere, but much uncertainty remains. My reading of the literature suggests to me that not all those people who write about the projected consequences of increasing anthropogenic CO_2 understand the simple fact that the effect of the radiatively-active gas molecules in the atmosphere is not linear. This is because the main 14.9 micron absorption band of CO_2 was already naturally saturated in the atmosphere prior to industrialisation, so that the consequence of adding further CO_2 to the atmosphere is proportional to the natural logarithm of the fractional change in concentration.

Further, the most appropriate value for the consequences of doubling CO_2 concentration remains uncertain and there has been much discussion since early estimates were proposed in the range of 1.5-4.5K; the AR4 of the IPCC used a value of 2.8 (2.2-3.8). Some of the higher values that have been proposed in the past cannot now be reconciled with palaeoclimate evidence, and the most recent estimate that I have seen suggests a rather lower sensitivity of 1.7-2.6K.[44]

The radiative forcing, positive or negative, attributed to each active agent was briefly summarised by IPCC AR4 as follows:

		+W/m2	***-W/m2***
Well-mixed greenhouse gases:			
	CO_2	+1.66	
	CH_4	+0.48	
	N_20	+0.16	
	CFCs, HFCs	+0.34	
Stratospheric ozone			-0.05
Tropospheric ozone		+0.35	
Stratospheric H_2O		+0.07	
Aerosols			
Black carbon (soot)		+0.34	
Sulphate aerosol			-0.40
Fossil fuel aerosol			-0.20
Nitrate aerosol			-0.10
Mineral sand aerosol			-0.10
Albedo			

[42] *Manabe, S and R. Wethereld ((1967) J. Atmos. Sci. 24, 241-259.*
[43] *Seidel, D.J. et al.(2011) Clim. Change 2, 592-616.*
[44] *Schmittmer, A. et al. (2011) Science 334, 1385-1388*

Land use albedo		-0.20
Snow albedo (soot)	+0.10	
Aircraft contrails	+0.01	
Cloud albedo		-0.70
Solar irradiance, ground level		+0.12
Radiative balance	**+3.70**	**-1.55**

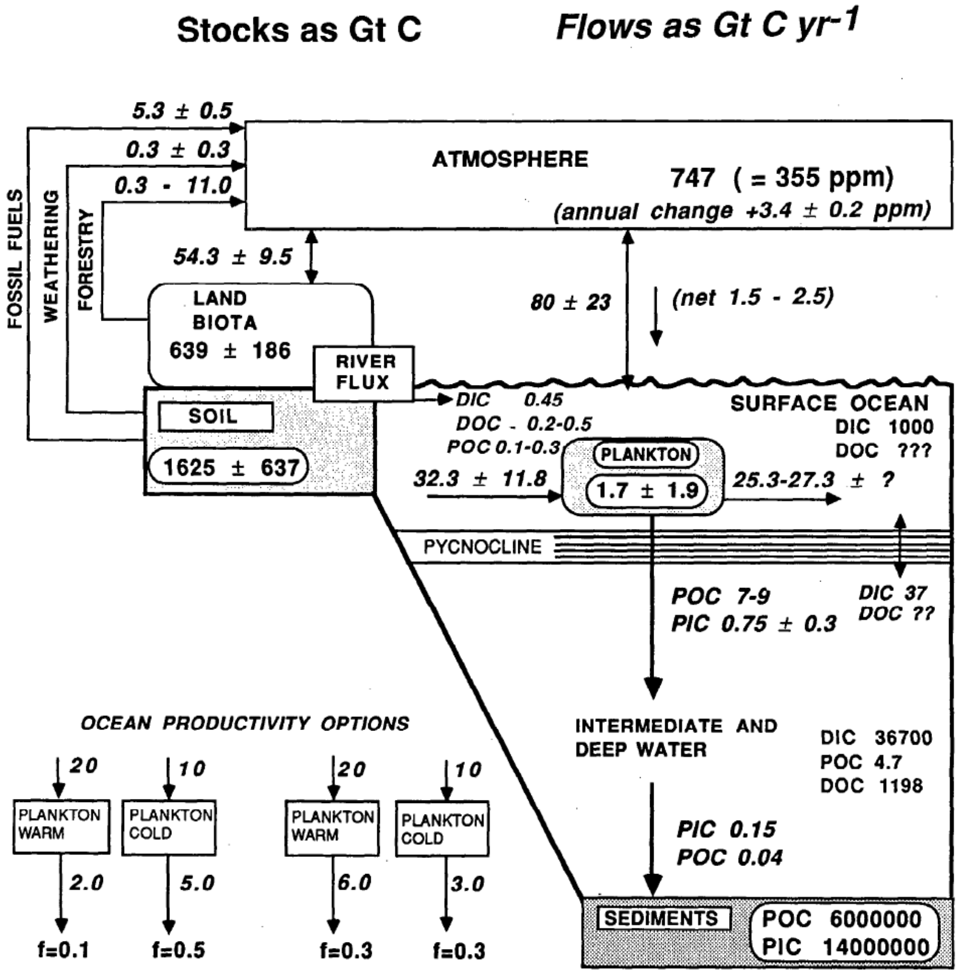
This simple table conceals great complexity and much uncertainty, because although the AR4 of IPCC assigns some confidence to an estimate of an overall radiative balance of 1.8 Wm^{-2} and also suggests a rather high level of confidence in the value assigned to CO_2, this is not the case for all items: desert dust aerosols, for instance, are very prominent in some large regions, but their radiative effect is quite uncertain and is given as -0.10 ± 0.20.

It is very easy to miss the main point illustrated by this table: that the radiative forcings listed are but very small perturbations on the dynamics of Earth's energy budget and the 342 $W.m^{-2}$ of solar radiation received at the top of the atmosphere is the principal motor that forces the climate systems of the planet, by non-uniform heating processes within the atmosphere and at the land and sea surfaces. Of the incoming solar radiation, 10.3 $W.m^{-2}$ is absorbed by ozone in the stratosphere causing regional warming, strongest above equatorial regions, 58.1 $W.m^{-2}$ is absorbed by water vapour in clear air, 147 $W.m^{-2}$ heats the surface, while 24 $W.m^{-2}$ is absorbed by clouds which also reflect 65 $W.m^{-2}$. The difference between quiet and active sun conditions (see Chapter 3) is about 0.5 $W.m^{-2}$ at the top of the atmosphere, which is equivalent to about one-third of the total radiative forcing of CO_2.

Consequently, the warming effect of all of the radiatively-active components of the atmosphere, even including CO_2 and water vapour, are trivial compared to solar effects. It is the Sun that drives the climate machine and it is against the effects of a varying Sun that we attempt to quantify the effect of the anthropogenic increase in CO_2 concentration.

Although water vapour is the most abundant radiative molecule in the atmosphere, it is not habitually listed in tabulations of GHGs, because it is a naturally-occurring molecule that is strongly cycled by evaporation and precipitation within the troposphere and acts rather as feedback than forcing. I shall devote a special discussion to its significance below, but it will now be appropriate to discuss some of the radiative agents individually.

***2.2 - Carbon dioxide* -** Although this molecule is released by the metabolism of living organisms, and captured during the photosynthetic growth of terrestrial and oceanic plants, it is present in the atmosphere and ocean principally because of primitive outgassing from the mantle of the planet, a process that continues today at subduction sites of tectonic plates, and also by volcanism. Slow, progressive drawdown of this CO_2 from levels of 4500-7000 ppm during the Cambrian, and 1000-2000 ppm during the Jurassic and Cretaceous periods was caused by the sequestration of carbon by living organisms into calcareous stromatolite-building and other cyanobacteria in shallow seas, releasing sufficient free oxygen to permit the oxidation of reactive elements in the rocks (e.g. Fe to Fe oxides) to permit the evolution of the modern biosphere which then - by progressive incorporation of carbon in coal, black shale and carbonate rocks - created the modern atmosphere that contains around 750 ppm of CO_2. But this is not a stable condition, because during the Pleistocene glaciations, CO_2 concentration fell sufficiently low (180-220 ppm} that "*severe and sustained*" carbon starvation can be observed in the fossil wood of high-altitude junipers at a site in North America.[45]



This is a simple diagram, resulting from the hunt for the missing carbon sink that occupied some of us in the 1980s, but it illustrates the complexity of the fluxes and reservoirs of carbon; more emphasis than usual in such diagrams is placed on processes in the ocean, where the reactive reservoir above the pycnocline is very large indeed, of order 900-1000 Gt.[46] '*Ocean productivity options*' refers to the ratio of inorganic to total nitrogen used in different models of phytoplankton production.

Like all such diagrams, it should be read with one salient fact in mind: annual flux from anthropogenic sources is less than 5 ppm and, of this, only about 2 ppm remains within the atmosphere annually - which is a very small addition indeed to the approximately 350 ppm accumulated in the atmosphere. It should also be noted that

[45] *Ward, J. et al. (2005) Proc. Nat. Acad. Sci. 102, 690-694*
[46] *Longhurst, A.R. (1991) Limn. Oceanogr. 36 (8) 1507-1526*

computations of the size or each reservoir have evolved somewhat since this diagram was drafted in 1990.

The total annual primary productivity of both terrestrial and marine photosynthesis, and hence their uptake of CO_2 from the atmosphere, is rather similar but, at geological time scales, marine biota have accumulated much more carbon dioxide in marine deposits and calcareous rock (40 x 10^6 Gt), than land plants have stored as oil, coal and peat (3-7 x 10^3 Gt): the same pattern continues today, despite the great difference in living biomass of the terrestrial and oceanic plants. Organic matter produced by forests and other terrestrial ecosystems goes to relatively transient sinks in peat and forest litter, whence it can readily be remobilised into the atmosphere, but the flux of organic detritus from the oceanic ecosystem goes directly to the deep ocean floor, where stockage is essentially forever. In shallow tropical regions, the shelf deposits contain a very high percentage of calcium.

Early evaluations of the fate of anthropogenic CO_2 in the atmosphere assumed rather small rates of uptake by the ocean, of order <1 gT C yr^{-1} and required a major sink in the terrestrial biosphere due to the regrowth of forests.[47] Today, it is usually assumed that the imbalance between anthropogenic CO_2 emitted and the annual increase observed in the atmosphere is almost entirely due to oceanic uptake, now thought to be of order 2.2 gT yr^{-1}; it has also been suggested that in the 19th and 20th centuries the ocean took up about 118 gT of carbon from the atmosphere, or about half of all anthropogenic emissions.[48]

The global background of atmospheric CO_2 is controlled by a wide range of natural processes, all of which are highly variable and respond to a variety of environmental forcings: CO_2 is very readily added to, or removed from the global atmosphere by changes both in forcing originating outside the earth system and also to changing relationships within that system. The relatively massive increase in the release of anthropogenic to the atmosphere during the 20th century does not appear to have saturated the natural carbon cycles, the increase in the atmospheric fraction of CO_2 being so slight as to be insignificant.

The seasonal pattern of plant growth dominates the annual cycle of CO_2 in the atmosphere, a cycle which is relatively simple on the continents and involves the annual dying-off of seasonal vegetation at high latitudes after the growing season and the episodic death of vegetation during droughts and in forest-fires; the progressive stockage of this organic carbon as coal and peat is a long-term process. Evasion of CO_2 from the ocean is more complex, although the long-term stockage in ocean sediments is a more immediate process. Uptake of CO_2 into the oceanic DIC pool involves both simple solution at rates determined by the partial pressure[49] at the sea surface and by chemical reaction, resulting in three forms: dissolved CO_2 (1%), bicarbonate HCO_3 (91%), and carbonate $CaCO_3$ (8%). Surface mixed-layer water in a stable water column is stripped of dissolved CO_2 by phytoplankton growth until nutrient-limitation intervenes, when partial pressure balance is achieved across the sea surface. But where wind-stress drives upwelling of deep water having a high content of the dissolved gas to the surface, the partial pressure of CO_2 in the ocean becomes higher than in the atmosphere and flux of CO_2 to the atmosphere occurs.

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[47] *Siegenthaler, U. and J.L. Sarmiento (1993) Nature 365, 119-125*

[48] *Gruber, N. et al. (2006) J. Geophys. Res. DOI 10.1029*

[49] *Partial pressure is the gas phase pressure that would be in equilibrium with the dissolved phase.*

Once the Mauna Loa and other time-series had become routine, Charles Keeling turned his attention to the cyclical nature of the variability observed in the data, at longer periods than the strong annual cycle. In a historical paper with Revelle, he showed that there was a clear influence of the El Niño-Southern Oscillation on atmospheric levels of CO_2.[50] This climate index records the relative strength of the Pacific trade winds and therefore the intensity of the upwelling of deep water to the surface along the eastern equatorial region, off the coasts of California and Peru, and in some other regions; these regions therefore are characterised by high partial pressure at the sea surface and high flux rates of CO_2 across the sea surface to the atmosphere. This results in a minor peak in the tropospheric concentration of CO_2 at 5°N-5°S in the otherwise rather simple trend from high northern values (339 ppm) to low values (336 ppm) over Antarctica.

But, during episodes of El Niño conditions, the trade winds fail and upwelling ceases, so that the surface water mass stabilises and is rapidly stripped of available dissolved CO_2 by the growth of phytoplankton; part is removed as sinking organic material and is not recycled within the mixed layer. Consequently, the strong flux of CO_2 to the atmosphere from the equatorial eastern Pacific that occurs under normal trade wind conditions is much reduced and is perhaps even no longer a regional anomaly. "*Nevertheless*" wrote Keeling and Revelle "*atmospheric carbon dioxide continues to increase during El Niño years, at a faster rate than at other times"*. This observation is consistent with the modification of regional climates that are characteristic of Niño conditions and the enhanced probability of droughts and forest or bush land fires. Others have also found a similar relationship between ENSO conditions and the rate of increase in atmospheric CO_2 content, with a suitable lag in the South Pole data.

Subsequently, Keeling continued these investigations and confirmed the relationship: *"We now discerned patterns related to El Nino events in the $^{13}C/^{12}C$ isotopic ratio of atmospheric CO_2...these isotopic variations must mainly reflect CO_2 exchanges with vegetation on land. Oceanic exchange of CO_2 with the air does not cause significant isotopic fractionation, whereas....vegetation on land does. The dominant cause of an anomalous rise in CO_2 concentration during El Niño events appeared to be a release of CO_2 to the air by vegetation and soils."*.[51]

Recently, after a long interval, the relationship between sea surface temperatures and atmospheric CO_2 has again been the subject of analysis of the phase relation (leads/lags) between periods of rapid change of atmospheric CO_2, of sea surface temperature and of air temperature from 1980-2011.[52] Phase relations between rates of change in the NOAA global average monthly CO_2 data and the eight standard SST and SAT data archives from the NCDC, from NOAA and from CRU/Hadley were analysed individually; for this analysis, the annual cycle was removed and the data transformed to 12-month running means. From this was calculated DIFF12, for which the difference between adjacent monthly values indicates relative rates-of-change in the original data.

The strongest values for DIFF12 occur in relation to the anomalously strong 1998 Nino event, and it is clear that in relation to this event the peak rate of increase in SST is followed by peak rates in SAT and in CO_2 increase, the lag being about one year between

[50] *Keeling, C.D and R. Revelle (1985) Meteoritics 20, 437-450: this journal has been entitled Meteoritics and Planetary Science since 1995; this issue is not archived by the Society.*
[51] *Keeling, C.D. (1998) Ann. Rev. Energ. Env. 23, 25-82.*
[52] *Humlun, O. et al. (2013) Global and Planetary Change 100, 51-69*

apparent cause and effect. The author does not invoke any mechanism other than a transfer of heat from ocean to atmosphere during trade wind failures, and the main interest of the paper is its confirmation of a rate increase at later Niño events than those studied by Keeling.

2.3 - Methane - The principal ingredient of domestic natural gas, CH_4 is produced by the metabolism of microbiota associated with decaying marsh and other vegetation and is widely released from marshes, peat bog terrain and some marine sediments; it is also released by ruminants, which utilise similar microbiota in their digestive processes. The atmospheric background concentration of methane is currently of order 1.7-1.8 ppm, and therefore much lower than that of CO_2 at around 390 ppm. Because both molecules are involved in many biological processes and are therefore strongly temperature-dependent, CH_4 tracks CO_2 concentrations at geological time-scales in the ice-core record. The question of which gas leads and which follows (or of cause and effect) is therefore relevant, as in the case of water vapour and CO_2 already noted.

The resident time of CH_4 in the atmosphere is relatively short compared with CO_2, of order 12 years. After a short period of stasis (that was not predicted by IPCC models) the recent resumption of increase in concentration is most likely associated with high Arctic seawater temperatures and unusually high precipitation in the tropics.[53]

In the present climate era, sources of atmospheric CH_4 are both permanent and episodic, and they include important anthropogenic sources. Increasingly, the petroleum industry loses CH_4 to the atmosphere during the transmission of natural gas from sources to consumers, while emanations from flooded rice-paddies are also on the increase; agribusiness is now heavily dependent on intensive raising of cattle, pigs and poultry in crowded conditions and release from such sources is of concern. The increase in radiative forcing caused by the increase in atmospheric CH_4 since the mid-16th century has been calculated at 0.07 Wm^{-2}.[54]

It has been suggested that a warming Arctic Ocean would lead to increased emanations from the melting of frozen methane clathrates known to exist deep below the sea-floor at temperatures near their freezing point, and this problem is discussed in Chapter 8. What seems not to have become an issue concerning potential climate disasters is the fact that the Black Sea contains a very large methane reservoir in its interior, fed both from bottom seeps and from anoxic decay of sinking organic matter produced in the upper, oxygenated 100m of the water column. Below this depth, methane concentrations are about 11nM. Although the consequences of an overturn of the water column of the Black Sea have been discussed in the past this has been in relation to equally massive potential release of H_2S that is now capped below the upper mixed layer.

2.4 - Nitrous oxide. The N_2O molecule is present in the atmosphere at approximately the same concentration as CO_2 and follows a linear trend of increase that is not inflected by natural changes in the environment. It is produced in natural and agricultural soils during the nitrification:denitrification process, and under the effect of synthetic nitrogen fertilisers that have become an essential for intensive agriculture; the linear increase of this molecule in the atmosphere may reflect the almost linear increase

[53] *Dlugokencky, E.J. et al. (2009) Geophys. Res. Lett. 36, L18803.*
[54] *Myhre, G. et al. (2007) Geophys. Res. Lett. 34, L01807.*

in the production of these fertilisers. N_2O has a radiative effect significantly higher than CO_2.

2.5 - Water vapour - There has been some informal grumbling that the importance of CO_2 is being exaggerated by the climate science community compared with the effects of water vapour in the atmosphere, whose radiative consequences are 2-3 times greater than that of CO_2.[55] But this suggestion ignores the reality of the different dynamics of CO_2 and water vapour.

Water vapour may be the most active greenhouse molecule, but its residence time in the atmosphere is very brief and, because it is dependent on temperature, it is more unevenly distributed above the Earth's surface even than CO_2: higher concentrations occur at low altitude and latitude and preferentially over the ocean. Tropical surface air is hot and humid in areas of seasonal rainfall, while mountain air is relatively dry at all latitudes.

So the response of water vapour to natural forcing and its radiative activity are unique among atmospheric constituents, as is the rapidity with which it undergoes a phase-transition to liquid water and falls to the surface as rain or snow, modifying as it does so the regional thermal regime. It is therefore appropriate that the presence of water vapour is treated as a simple feedback in climate models, enhancing the radiative effect of CO_2 by a large fraction, although usually no allowance is made for any dynamic interaction with the atmosphere. Also largely ignored is progressive human intervention in the cycle of evaporation, condensation and precipitation, an intervention that is direct and may be rapid. Land-use change associated with irrigated agriculture increases the humidity of the lower troposphere in tropical regions, while regional deforestation induces an equivalent reduction in evaporation – and hence in subsequent rainfall both within and outside the forested region.[56] Climatic consequences of human intervention are also induced in the stratosphere through the reaction between methane (CH_4) and the OH radical in the stratosphere, resulting in an increase in the density of stratospheric H_2O molecules.

Moreover, there is evidence that the enhanced rate of warming after 1980 and the stasis after 2000 in global surface temperature follows a pattern that is consistent both with observed changes in the water vapour content of the stratosphere and with the assumption that increases in water vapour cool the stratosphere but warm the troposphere This is observed to have decreased by about 10% after the year 2000 and reduced the rate of anthropogenic radiative warming during the following decade. It has been suggested that these changes are likely to have offset the forcing by CO_2 and other GHGs by about +30% and by -25%, respectively, during the two decades before and after the year 2000.[57]

The authors of this study caution, however, that it is *"not clear whether the stratospheric water vapour changes represent a feedback to global average climate change or a source of decadal variability"* and they point out that current models are not very skilful in representing interactions in the stratosphere, which emphasises the importance of observational data. These conclusions seem very clear, and well-supported by the observations, but they also seem to ignore the possibility that the

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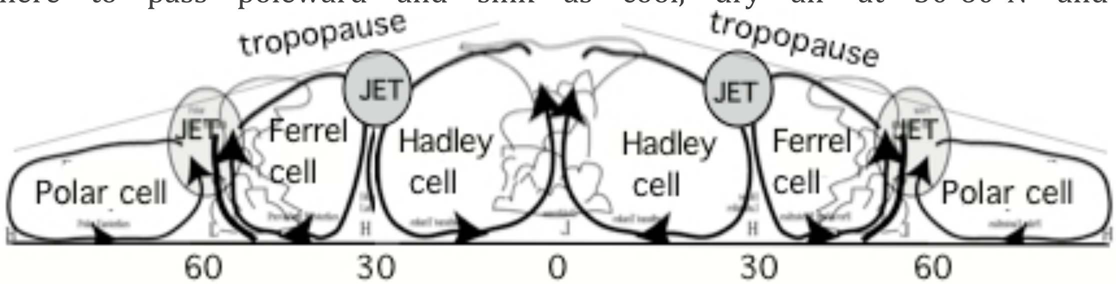
[55] *IPCC Assessment Review 5 (2013)FAQ 8.1.*
[56] *AR4, Chap. 1, section 2.5.5*
[57] *Solomon, S. et al. (2010) Science 327, 1219-1223*

1985-2010 surface temperatures are aliased by both the 1997-98 Niño and also the Pinatubo eruption.

Water vapour is also deeply implicated in other critical processes in the atmosphere, principally those of latent heat fluxes, rainfall and evaporation, although recent discussion suggests an even more fundamental process associated with the rapidity of phase transitions of the H_2O molecule. By such means, water vapour in the atmosphere represents a store of potential energy equivalent to the dissipative power of the entire general atmospheric circulation. [58]

The basic mechanism by which heat is transported from low to high latitudes in the atmosphere is strongly dependent on these phase transitions. The structure of global wind systems is based on three zonal wind belts that form the tropical, mid-latitude and polar convective cells in which relatively warm, humid air rises on one flank of the cell and dry, cold air sinks on the other. The strongest of these features, the Hadley cells, associated with the Trade Winds, lie at the solar equator in the humid tropics where warm, moist air rises very strongly to near the top of the troposphere, there to pass poleward and sink as cool, dry air at 50-60°N and S. [59]



In the Hadley cells, the strongly rising humid air is rapidly cooled, so that water vapour condenses to form towering cumulus clouds as occurs whenever vertical motion is imparted to a volume of air, which must expand as it rises and may therefore be cooled below its dew point (usually at the base of the forming cloud) so that small water droplets are formed around condensation nuclei, progressively to aggregate into raindrops. This process involves the consequent release of latent heat during the transition from gaseous to liquid states during the development of thermals, especially over flat landscape; under ideal conditions such a cloud will continue to develop until it runs out of water vapour, which will be delayed if the air entering the cloud base is humid.

Recently it has been suggested that another, equally important but neglected, process must participate in the development of rising air within clouds, due to the reduction in atmospheric pressure, proportional to the fraction of molecules that have condensed into liquid raindrops. This process must induce dynamic lift within the air mass beyond what is caused by the release of latent heat, and - in the case of a large region that is crowded with developing cumulus, as in the humid tropics - will reduce regional atmospheric pressure and strengthen winds originating in regions of higher pressure. It is also suggested that this is one of the main factors in the mechanism of cloud formation although, as the authors of this study point out, "*Remarkably, these*

[58] *Makariova, A.M. et al. (2013) Atmos. Chem. Phys. 13, 1039-1056.*
[59]*http://tornado.sfsu.edu/Geosciences/classes/m503/m503_Sp05/GeneralCirculation.html*

effects of condensation and evaporation on air pressure through the removal or addition of air molecules have been overlooked by the scientific community." [60]

Thus, where cumulus formation is very active - as over tropical forested regions - the consequence of the reduced pressure within each cloud will significantly enhance the strength of air transport from adjacent regions of higher atmospheric pressure and higher humidity: as the authors of one study put it, humid air will flow from donor to receptor regions. This mechanism must be characteristic of conditions over the tropical ocean, where cumulus is an important component of the cloudscape and (as the authors emphasise) also over forested regions where the nature of the forest canopy and the degree of seasonality in plant growth will determine the relative strength of the effect, which depends on a supply of moist air at low altitude.[61]

In the absence of clouds, total solar energy received at the surface would increase by approximately one-fifth and the ensuing heating would only be partly compensated by outgoing IR radiation. This effect is not uniform with latitude but follows the general pattern of cloud cover that is characteristic of each climate zone; high tropical cumulus affords the greatest cooling, while the low, stratiform cloud cover of polar regions has a warming effect due to downward longwave radiation from the cloud deck itself.[62] Even very modest changes in cloud cover are computed to have significant effects on global air temperatures; a simple calculation suggests that a 1% decrease in cloud cover will increase surface air temperature by at least 0.33°C, in line with more complex computations.[63]

Many authors have pointed out that condensed water vapour, in the form of clouds, dominates the global thermal budget. The effect of clouds is approximately an order of magnitude greater than that of all anthropogenic greenhouse gases, yet (as shall be discussed in Chapter 8) our knowledge of global cloud cover, and of how it changes, is so poor that "*we currently do not know whether clouds are changing so as to mitigate or exacerbate anthropogenic greenhouse warming*".[64] And that is a problem that has no easy or quick solution, so it is generally simply ignored – including by those drafting GCMs.

The critical problem facing us here is uncertainty about how condensed water vapour in the form of clouds behaves and how the atmosphere responds to its presence. "*Limited understanding of clouds is the major source of uncertainty in climate sensitivity but also contributes substantially to biases in modelled climate systems*" reported a White Paper of the WCRP in 2012, specifying this problem as the Grand Challenge facing climate science. "*At present, it is not known whether changes in cloudiness will exacerbate, mitigate or have little effect on the increasing global temperature caused by anthropogenic greenhouse radiative forcing*" was the conclusion of a Strungman Forum report in 2009.

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[60] Makarieva, A.M. et al. (2013) Atmos. Chem. Phys. 13, 1039-1056 and Makarieva A.M. and V.G. Gorschov (2010) Int. J. Water 5, 365-385.
[61] http://www.atmos-chem-phys-discuss.net/10/24015/2010/acpd-10-24015-2010-discussion.html, and see also discussion at "The Air Vent", posted on 10 October 2010.
[62] Mueller, M. et al. (2011) Rem. Sens. 3, 2305-2320.
[63] Svensmark, H. Space Sci. Rev. 93, 155-166 and G.E. Marsh, pers. comm.
[64] Norris, JR (2009) in Strungmann Forum Report MIT Press ISBN 978-0-282-01287-4

2.6 - Sulphur dioxide and volcanic activity: a special case

The role played by vulcanism and sulphur dioxide in controlling global surface temperature is not much discussed by AR5 although it is noted that volcanic eruptions are "*the dominant natural cause of externally-forced climate change on the annual to multi-decadal time scales*", but discussion is anecdotal and primarily concerned with the consequences of recent and very large events: it is also difficult to separate the effects of SO_2 originating in eruptions from the effects of anthropogenic SO_2. In the recent literature, emphasis has been placed on the cooling effect of volcanic dust veils perhaps because stratospheric warming events due to three explosive volcanic eruptions are prominent in radio-sonde and satellite data in the last decades of the 20th century

What we may call the simple SO_2 hypothesis is based on the fact that sulphate aerosols in the troposphere, originating in the combustion of coal and petroleum, reflect sunlight and also act as condensation nuclei for cloud formation: the net effect is a cooling of the lower atmosphere, so it will be useful to look briefly at the potential effects of atmospheric sulphate to modify air temperature and to shape the pattern of its increase during the 20th century. Sulphate emissions during the 20th century reflect the continued mining of coal and the atmospheric concentration increased continuously until offset by the introduction of sulphate removal from oil products in the final decades of the 20th century; a small increase in recent years is the result of renewed combustion of coal in China. Emissions of sulphates from coal are seasonal, peaking in northern winter, and their effects are regional with anomalously high concentrations over eastern Europe and China; the effect of emissions is relatively ephemeral, because typical residence times for industrial SO_2 in the lower troposphere are only 2-3 weeks.[65]

To these anthropogenic emissions of SO_2 content in the atmosphere must be added the emissions from explosive volcanic eruptions that inject massive amounts of this gas into the stratosphere, where it becomes more widely dispersed than at ground level, and where it has a longer residence time. Cooling mechanisms in the stratosphere depend on similar chemical transformations as in the lower troposphere that result in reflection of solar radiation back to space. The occurrence of volcanic eruptions is neither regular, nor random in space or time so that no general consequence is easily stated; if no major eruption occurs anywhere over a period of several decades – as occurred during the middle of the 20th century - atmospheric cooling should occur as ambient CO_2 is progressively reduced by oxidation by hydroxyl radicals.

The dynamics of volcanic ejecta are complex: SO_2 reaching the stratosphere quickly achieves near-uniform distribution globally, forming a reflective sulphur aerosol which reduces solar radiation in the troposphere, while causing a significant and rapid warming effect at these levels through absorption of solar infrared radiation. Large eruptions, isolated in time, cause cooling within the stratosphere as noted above: the unexpected 1991 eruption of the apparently dormant (because its slopes were forested) Mt. Pinatubo in the Philippines was the most recent example of this process. Such Plinian eruptions, that eject gas and dust to very high altitudes, may occur also in groups over a short period, and collectively eject sufficient SO_2 as to overwhelm the oxidising capacity of atmosphere - and so induce accumulation of radiatively-active gases, including CO_2. It is perhaps relevant that a group of Plinian eruptions occurred from

[65] *Barrie, L.A. et al. (1984) Atmosph. Envir. 18/12, 2711*

180-143 BC, just prior to the start of the Roman warm period, and also at 818-838 AD, just before the Mediaeval warm period.

Volcanic activity is, at least in part, a response to external forcing, including changing loads of seawater over the sea bed near island volcanoes, changing vertical stresses associated with earth tides, and of earth movements associated with plate tectonics and mountain building. Thus, the Pavlof volcano in the seas off Alaska erupted 13 times in the period 1973-1984 and each of the 13 events occurred between September 9 and November 20 - and four of them occurred on dates between November 4 and 15; this pattern is explicable only by changing compressional stress by tidally-driven differential ocean load.[66] Earth movements may also trigger eruptions, as has been recorded in California or – in the case of Mt Wrangell in Alaska – such movement may paradoxically quieten the seismicity rate for an extended period.[67] Finally, a study of the timing of almost half-a-million earthquakes in the NEIC catalogue confirms that they may respond directly to earth tides: a correlation (>99% confidence level) was obtained for the timing of these events and the phase of the earth tide. The mechanism involves a response to ground uplift and the reduction of stress within the lithosphere, although the responses to the two major classes of earthquake (strike-slip and thrust faulting) are not identical.[68]

On the geological time scale, periods of unusually strong earth tides may initiate or sustain movement of the tectonic plates that may continue over a very long period; these movements may cause enormous floods of basalt, like those that form the Deccan Traps on the west coast of India, and other places associated with sea-floor spreading, such as Iceland and Reunion; such events have occurred several times during the geological history of Earth, and will do so again.[69] Very strong earth tides presumaby occurred at Milankevitch periods and should have induced a response in the frequency and magnitude of volcanic eruptions – and the geological evidence shows that this did indeed occur at the termination of interglacials. The super-eruption of Toba in Sumatra about 70ky BP "*was the largest known explosive volcanic event in the late Quaternary. It could have lofted about* 10^{15} *g of fine ash and sulphur gases to heights of 27–37 km, creating dense stratospheric dust and aerosol clouds*".[70] Models of this event suggest there was a reduction in atmospheric clarity that was sufficient to have induced a 'volcanic winter', with perpetual snow and an acceleration of the shift to the full glacial conditions that lay just ahead.

Much attention is now paid to the Pinatubo eruption of 1991 which injected c.900 Mt of H_2O, 230 Mt of CO_2 and 15-19 Mt of SO_2 into the atmosphere, reducing net incoming radiation at the top of the atmosphere by 2.5 W m^{-2} and cooling surface air temperature by 0.5°C. To put these quantities in perspective, the average *natural* release of SO_2 is about 40-50 Mt annually, while anthropogenic release is around 60-80 Mt annually and increasing at a rate greatly exceeding that of CO_2. Such extremely high rates of emission of SO_2 must also decrease the natural rates of removal from the atmosphere of CH_4, CO_2, and other radiative gases and should increase the amount of water vapour retained in the atmosphere. After the deliberate reduction of the rate of

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[66] *McNutt, SR and RJ Beavan (1987) J. Geophys. Res. 92, 11509-115011.*
[67] *Sanchez, J.J. and S.R. McNutt (2004) Earth. Sci. Res. J. 8, 34-44.*
[68] *Metivier, L. et al. (2009) Earth Plan. Sci. Lett. 278, 370-375.*
[69] *Courtillot, V. ' Nouveau voyage au centre du Terre' (Odile Jacob, 2009, pp. 349)*
[70] *Rampino, M.R. and S. Self (1992) Nature 359, 50-52*

industrial SO_2 emissions after 1980 (done in order to reduce the impact of acid rain) the rates of increase in air temperature and methane content also began to decrease.

Effects such as these have occurred on a much grander scale in the very distant past - as in the Cretaceous pulse of rapid movement of the continental plates, with which were associated the sheet larva flows of the Deccan Traps - a mantle plume several thousands of square kilometres in extent, which released SO_2 into the atmosphere at rates calculated to be two orders of magnitude greater than from current global rates of volcanism. If this gas reached the stratosphere (which is not a given) and if there was sufficient water vapour in the atmosphere to hydrate the whole (which is also not a given) then massive atmospheric cooling would have occurred. In fact, cooling of around $2^{o}C$ is computed for this period from other evidence, although this is now sometimes attributed to the strongly reduced atmospheric CO_2 content that occurred at the same time.[71] Unfortunately, these effects of explosive volcanic eruptions on climate are not well integrated into climate change science, perhaps partly because the data describing these events, and their type and magnitude, is increasingly attenuated back into the record: this is perfectly clear in data sets such as that provided by NOAA.

Bay et al. (2004) point out that it is becoming increasingly apparent that current global climate models omit some natural forcings, and also under-estimate the threshold crossings of the climate system that eruptions may induce. They also remark that '*evidence has been accumulating for decades*' (i) that such eruptions can modify the climate system and (ii) that climate changes, induced by some other factor, may create feedback that then induces further volcanic activity.[72] This conclusion is based on the use of a dust-sensor in the analysis of deep ice cores from the Siple Dome in Antarctica, where a rigorous bipolar correlation between the dating of layers of volcanic glass shards and the onset of millennial colder stadials within Quaternary glaciations have been demonstrated with a >90% rejection of the null hypothesis. The thickening of the west Antarctica ice sheet near the end of the last glaciation appears to have initiated a cluster of regional eruptions that must have, in turn, modified levels of SO_2 in the atmosphere. The same study also suggests that additional atmospheric cooling may have been induced by oceanic draw-down of CO_2 from the atmosphere because the sulphur that accompanies Fe ejected in volcanic eruptions will increase its solubility by reducing the Fe(III) to Fe(II). This, in the iron-limited areas of the ocean - such as the Southern Ocean – is likely to induce anomalous phytoplankton blooms and hence unusual levels of carbon assimilation and draw-down of CO_2.

2.7 - Aerosols and particles, natural and anthropogenic

The populations of particles and aerosols in the atmosphere are highly diverse and are evolving very fast because of the rapid transformation of our agricultural, industrial and transportation activities. The particles are dominated by carbon (both as soot and organic material), sea salt, and mineral dust downwind from desert regions which may be transported great distances, particularly westwards across the Atlantic from the Sahara. Many of the particles reflect sunlight, and act to cool the ambient atmosphere, but carbon has special significance because both organic particles from the burning of biomass, and black soot particles from the combustion of coal, accumulate

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[71] *Royer, D.L. et al. (2004)GSA Today 14 (3): 4–10*

[72] *Bay, R.C. et al. (2004) Proc. Nat. Acad. Sci. 101, 6341-6345.*

solar heat and so warm the atmosphere during daytime. Although the individual components of aerosols are usually discussed separately, individual particles may comprise a mixture of several components, not all of which have the same radiative consequences. Sulphate aerosols scatter, rather than absorb, solar radiation and in so doing cool the atmosphere by reflecting solar radiation back to space and reducing the amount of radiation reaching the surface. On the contrary, where carbonaceous aerosols (black carbon, or BC) are abundant, both upward infrared and downward visible radiation is absorbed, resulting in increased air temperatures.

At the start of the 20th century, the troposphere had low concentrations of aerosol particles except in populated areas where coal was the fuel most commonly used for manufacture, transport and for cooking and heating. In some of these places, smoke pollution had already caused public concern much earlier, as John Evelyn recorded in London in 1662. Two periods of rapid increase in the global emissions of black carbon particles occurred after the middle of the 19th century: the first of these was the effect of the early industrialisation of Europe and North America and, after a period of stasis during the mid-20th century, there followed the consequences of the urbanisation of other regions, and their progressive industrialisation - that continues to expand in a largely uncontrolled manner.[73]

So, until mid-20th century, the atmosphere outside industrial regions was largely particle-free and transparent, as it remains today in just a few favoured regions, especially at high elevations and in the southern hemisphere. Elsewhere, the lower atmosphere is now more or less opaque because of the significant aerosol load that it carries. The term 'smog' has been found too weak to describe what has evolved in recent decades in some regions, so the term 'brown cloud' has appeared in the geophysical literature – and no other term is appropriate. Over the entire region from the northern Indian Ocean through SE Asia to China, a thick haze of industrial and agricultural aerosol may extend to 3000-5000m altitude, thus including the altitudes at which convective trade wind cumulus develops; this condition extends down to about 5-6^{o}S, at the ITCZ, beyond which there is relatively clear air.[74]

"*Most often*" note Ramanathan and the co-authors of this study of particulates "*they are composite mixtures of a core refractory material (black carbon, dust, sea salt) with a coating of organics, sulphates and nitrates*". The computed transport of black carbon and fine aerosols over the ocean eastwards from China amounts to about 75% of estimates of the amounts emitted over North America: transport from Asian sources, then, is a major source of aerosol contamination over North America..[75]

The remarkable drift of aerosol eastwards from northern China is an indication of the dimensions of the brown cloud problem; westwards drift across the Atlantic from West Africa is at least partly due to Saharan dust although countries such as Nigeria are clearly major emitters - because in rapid industrial transition. Grey areas indicate lack of data over deserts and at very high latitudes. Land use change in South America and central Africa are prominent, as is the industrialisation of some parts of west and central Africa.[76]

[73] *Lamarque, et al (2010) Atmosph. Chem. Phys. 10: 7017-7039*
[74] *NASA image*
[75] *Hadley, O.L. et al. (2007) J. Geophys. Res. 112, D05309.*
[76] *Ramanathan, V., et al. (2001) Science, 294, 2119-2124.*

The dimensions of the brown haze over India are revealed by satellite lidar; heavy aerosol loads reach up to 2500 m altitude, most concentrated in the boundary layers, and then follow the contours of the land surface up to elevations around 5000 m across the Himalayas. Direct measurements within the brown haze over the Indian Ocean by means of instrumented drones showed an enhancement of lower atmospheric heating by about 50%, while model results suggest that the regional effect of aerosols is approximately equivalent to the radiative forcing of anthropogenic greenhouse gases in the lower atmosphere. [77]

Other major consequences of aerosol contamination have also been discussed, amongst which one of the most significant is the modification of cloud cover and cloud physics. Increased aerosol concentrations are observed to increase cloud water content and cloud depth, decrease precipitation, and cause an increase in the reflection of sunlight back to space. But observations over the Indian Ocean suggest an opposite effect under some circumstances by a reduction of total cloud cover in the trade cumulus that is typical of the region, with important consequences for regional radiation balance in the troposphere.[78]

One of the most significant consequences of tropical brown haze is what has been called the 'widening of the tropics' that is associated with poleward shifts of features of the large-scale atmospheric circulation pattern: the Hadley cell and storm tracks in both tropics and sub-tropics have all shifted poleward by 2-5^{o} of latitude since 1979. When detailed aerosol physics is integrated in the models, poleward shifts are produced that are concordant with observations; this suggests that increases in warming agents such as soot produce larger consequences than CO_2, and that the recent northern hemisphere poleward shift in features of the tropical circulation are, indeed, at least partly a consequence of the black carbon burden of the lower troposphere of the tropics rather than of CO_2.[79]

Paradoxically, the heating effect of aerosols in the lower atmosphere almost balances a cooling effect at ground level that is due to what has been termed 'dimming', a global phenomenon in which aerosol contamination reduces the transparency of the atmosphere. The strength of this effect depends on the relative composition of the regional aerosol composites, so that the balance between absorptive black carbon and reflective sulphate particles determines aerosol albedo[80]. The balance between aerosol, local ground surface and cloud albedos in turn determines the extent of the net warming at the surface and is implicated in regional climate modifications. Aerosol contamination of the lower atmosphere has had important consequences for regional climate and, on the basis of the GISS 12-layer climate model, has been invoked as the cause of increased summer floods in China, increased drought and reduced winds in northern China, and moderate cooling in both India and China.[81]

One consequence of regional dimming, which has been calculated to be equivalent to a 7% reduction in solar radiation received at the surface, is the weakening of the meridional SST gradient in the Indian Ocean which in turn has weakened the

[77] *Ramanathan, V., et al. (2007) Nature, 448, 575-579.*
[78] *Ackerman, AS. Science, 288, 1042-1047.*
[79] *Allen, R.J. etal. (2012) Nature 485, 350-353*
[80] *Seinfeld, J. (2008) Nature Geoscience 1, 15-16.*
[81] *Menon, S. et al. (2002) Science, 297, 2250-2253*

monsoonal circulation and hence summer monsoon rainfall over the sub-continent.[82] Recent decreases in regional precipitation in southern Asia may, at least in part, be traced back to decreased evaporation, both from the sea and from land surfaces.

Unfortunately, the IPCC's presidential gaffe concerning Himalayan glaciers - based on speculation rather than observations - cannot be allowed to pass without brief comment: the details of the case are not important, but the retreat of Himalayan glaciers such as the Rondbuk was predicted by AR4 to result in their imminent disappearance by 2035. Not surprisingly this caused some surprise, *and retraction by the IPCC was swift and correct*. More interesting was the later observation that in the western Himalaya and, more particularly in the Karakorum range, the surge-type glaciers that characterise this region doubled the number of surges after 1990 compared with equivalent earlier periods, and some have modestly accumulated mass in recent decades.[83] These glaciers are effectively isolated by the highest peaks from the regions to the south, which are affected by particulate pollution of the lower troposphere; it is thought that they are responding to changes of snow-fall in their source regions as are perhaps a few polar glaciers (section 8.4).

[82] *Chang, C and V Ramanathan (2007) Geophys. Res. Lett.34 doi0.1029/200gl030491*
[83] *Gardelle, J. et al (2012) Nature Geoscience 5, 322-325*

Chapter 3

EARTH'S CLIMATE IS NOT A CLOSED SYSTEM

> *"It seems worthy of remarking that the greatest heat that hath been in the air this year was on the day of June when the first spot was near the middle of the Sun"*
>
> Robert Hooke, 1676.[84]

Climate science is based on an understanding that natural change occurs on all scales, both spatial and temporal, and on an assumption that at least some of these changes are forced by periodic variability in solar radiation; it on this understanding that French climatologists base *"la théorie astronomique de climate*". Consequently, the literature of climatology is rich in references to the effects of periodic changes in solar radiation, and studies on sun-climate relationships continue to be published.[85]

But although AR5 does make some reference to climate states other than our own, its assessment of the role of the Sun in recent climate change is without appeal: long-term change in solar irradiance is computed to be trivial compared with the effect of long-lived greenhouse gases. It also offers the rather extreme view that *'despite a massive literature on the subject, there is at present little or no convincing evidence of significant or practically useful correlations between sunspot cycles and the weather or climate'.*[86]

It has now become an article of belief for many that solar influence on climate state is slight or negligible and the changes such as a millennial-scale cooling of the oceans or the onset of glaciations or of lesser events such as the Little Ice Age episodes of the 17th to 19th centuries are currently attributed to other forcings than solar – even if these are appropriate to the changes. Typical of the genre is a recent study in Nature Geoscience that describes a millennial cooling of the ocean from proxy data, comparable to the millennial cooling of the arctic that matches solar output, but suggests that "*…simulations using single and multiple forcings suggest that the…trend…is not primarily a response to orbital forcing but arises from a high frequency of explosive vulcanism…via a decline in mixed-layer ocean heat content*". The reversal of the trend around 1800 is attributed to the Industrial Revolution.[87]

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[84] *thanks to D.V. Hoyt and K.H. Sherman.*

[85] *Scafetta, N. (2013) Earth-Sci. Rev. 126, 321-357 discusses 30 such studies.*

[86] *Pittock, A.B. (1978) Rev. Geophys. 16, 400-420*

[87] *e.g. McGregor, H et al.(2015). doi:10.1038/ngeo2510 or Miller, G.H. et al. (2012) doi: 10.1029/2011GL050168 are good examples of this.*

Yet this view and that of the IPCC concerning the influence of solar forcing on climate state is opposed by results obtained and opinions expressed in very many peer-reviewed studies and that divergence of opinion is the subject of this chapter.

The literature that accepts a significant role for the Sun is now sometimes decried as being contaminated by 'cyclomania', a derogative term used to describe the search for cyclical phenomena by some meteorologists today and some philosophers in the past; despite this, a recent study reaches the conclusion *"that, with few exceptions, the case for weather cycles is not proven, but an appreciation of the apparently periodic nature of climatic fluctuations is essential in understanding contemporary changes in the Earth's climate."*[88]

Why indeed should we take any relationship between solar cycles and climate seriously, given the assurance of the IPCC and so many others that variance in solar irradiance is too small to have any significant consequence for global temperatures?

Perhaps the answer lies in Dutch astronomer Huygen's two pendulum clocks that he mounted in a single cabinet in the 17th century, hoping to get an unusually precise timekeeper. He had already noted that the pendulums of such a pair persisted in swinging in unison though in opposite directions: what he called a 'strange sympathy' developed between them.[89] We now know that this was an example of coupled oscillations, which are characteristic of complex chaotic systems in which weak external forcing can bring the chaotic oscillations first into synchrony - and subsequently to follow the period of the external forcing. In the case of Huygen's clocks, the trick was in the mounting: if the cabinet had been absolutely rigid, the interaction would not have occurred. Unfortunately, Huygens' double timekeeper proved to be insufficiently accurate on a voyage to Cape Town to 'keep the longitude' with sufficient precision to win the Admiralty's prize.

Consequently, it should be no surprise to find that changes in solar irradiance, even if modest in scale, do indeed result in resonant coupling in the modulation of climate systems here on Earth. Even if the changes in irradiance associated with these cycles may be too small to be directly responsible (as emphasised by the IPCC), and even if the resonance is not reproduced in models, the circulation patterns in Earth's atmosphere and oceans do clearly include a range of frequencies with which the 11-year and longer cycles of solar radiance resonate, at least intermittently. Using Lorenz equations, a recent study demonstrates forcing of both symmetric and asymmetric systems on Earth by the solar dynamo, and concludes that *"...climate and the solar cycle can be regarded as chaotic oscillators, each with a typical frequency though with very different structures...the climate model has two unstable states (warm and cold)...solutions oscillate chaotically, flipping aperiodically from warm to cold...this interaction is represented by a one-way quadratic input from the dynamo system to the climate model, favouring the warm state."* [90]

One of the authors of this study later suggested that the IPCC position - that changes in solar irradiance are too small to modify climate on Earth - is no longer sustainable, now that a model exists for a mechanism that is capable of enhancing the effect: this study maintained that - at least up to 1850 - solar variability had been

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[88] *Burroughs, W.J. (2003) Weather cycles, real or imaginary? (CUP, New York), pp. 317.*
[89] *Birch, T. (1756) Phil. Trans. Roy. Soc. 2, 19.*
[90] *Tobias, S.M. and N. Weiss (2000) J. Climate 13, 3745-3759.*

important in determining climate and *"therefore the solar contribution to temperature change is larger than was assumed by the IPPC"*.[91] This is a suggestion that should not be neglected.

3.1 - The consequences of the variable geometry of the solar system

At geological time scales, changes in total solar irradiance (TSI) received by Earth are forced by the oscillatory motion of the Sun relative to the horizontal plane of the galaxy, each passage through the plane closely corresponding with very long cold spells on Earth.[92] These correspond to times of high extinction rates at the end of the Ordovician, Permian and Cretaceous periods when a characteristic pattern of extinction was repeated at each passage.[93] Such relationships may be, and have been, extended to other periodic motions of bodies within the solar system – and have been as readily rejected by critics, largely on analytical and statistical grounds. Yet unless these relationships are, at some level, real then we lack explanation for cyclical behaviour of Earth systems: where the phenomenon is sufficiently simple and the consequences sufficiently strong – as in ocean tides – then we accept such relationship without thinking twice; the material discussed in this section is similar in principal but has been savaged, at least in informal blog discussion. But I am reminded that each proposition found supporters in peer reviewed publications.

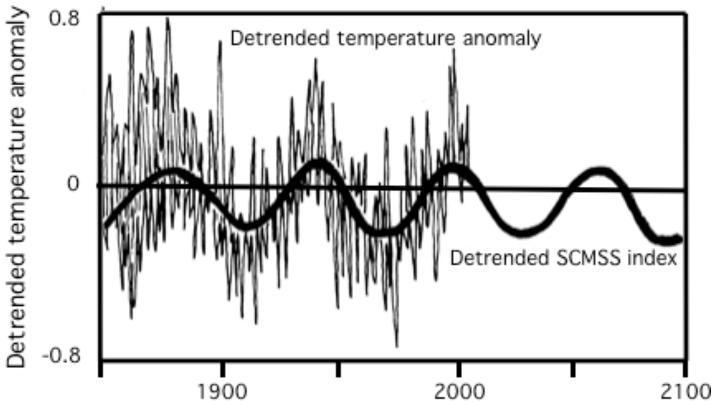
In more recent times, cycles having six frequencies can be detected in SAT data since 1850 and these can be matched to similar frequencies in the orbits of the Jovian planets, although the mechanisms are not wholly understood. The shortest cyclic activity of the Sun has a well-defined mean period of 11.1 years, the Wolf cycle, modulated by grand maxima that respond to the robust periodicity of 205 years for cosmogenic isotope abundance:[94] climatic response on Earth is observed to be associated with the 11-year cycle and weaker association is observed at the longer periods. The existence of such externally-forced physical cycles in phenomena here on Earth should be no surprise, considering we have such consequences before us twice daily in the tides on the shore, modulated monthly and at longer intervals by Sun-Moon-Earth distances.

Clearly evident is the association of the minima in annual sunspot numbers that were associated with the cold periods that occurred during the last millennium: the post-mediaeval minimum around 1350, and the minima of 1500 (Spoerer), 1645-1715 (Maunder), 1791-1825 (Dalton): this seems very clear, but one must remember that some recent studies propose that these episodes only occurred because of the triggering effect of unusually active periods of volcanic eruptions.[95]

Changes in solar radiation levels that have been observed to coincide with colder periods on Earth in recent centuries – even down to the brief colder periods of the 1860s-70s and the 1920s-30s - are caused by in internal dynamics within the Sun, which is itself strongly influenced by gravitational forces within the Solar System, that are not simple. Although the Sun is popularly considered to be the centre of mass around which

[91] *Weiss, N (2010) A&G 51, 3.9-3.16.*
[92] *Gies, D.R. & J.W. Helsel (2005) Astrophys. J. 626, 844–848*
[93] *see review of this topic by Gillman, M and H. Irenler (2008) Int. J. Astrobiol. 7, 17-36*
[94] *Weiss, N.O. (2010) A&G 51, 3.9-3.15*
[95] *Miller, H. et al. (2012) Geophys. Res. Lett. doi: 10.1029/2011GL050168*

the planets revolve, it does not lie at the exact barycentre of the Solar System but moves around this point in response to the gravitational pull of the major planets in their changing orbits, principally by the great masses of Jupiter (about 380 times that of Earth) and Saturn. The distance of the Sun relative to the barycentre follows a complex cyclic pattern of dimension about two solar diameters, within which 20- and 60-year periods are clearly evident, although each new pattern is unique. The gravitational effects of this dance modify the rotation rate of the Sun and can be matched to some climatic conditions here on Earth; the following figure shows the detrended GISSTEM global temperature record on top of the detrended SCMSS index of the 60-year periodicity of the oscillation of the Sun around the barycentre.[96]



This alignment has been remarked upon in more than one study, but it contains what one might call a 'missing variable' problem; it is perhaps necessary to detrend the GISS data only because these are heavily contaminated with anthropogenic effects other than what may be attributable to CO_2; this issue was discussed in Chapter 4.

The solar rotation rate modifies convective energy flux within the Sun, and therefore its brilliance; a latitude differential (faster at lower latitudes) in the rotation rate of the solar plasma draws out the submerged lines of force in the magnetic field into loops which may break through the surface, forming regions of intense magnetic activity, or sunspots. This process repeats itself, though with reversals, at 11-year intervals so producing complete 22-year cycles.; it is reported that solar rotation rate was exceptionally slow during the Maunder minimum when sunspots were essentially absent and global climate was cool. Hoyt and Shatten (op. cit.) have developed a combined solar-irradiance model for the past 300 years, since solar measurements could be seriously undertaken, that is based on the following observations: solar-cycle length, cycle decay rate, mean level of activity, solar rotation rate, fraction of penumbral spots and a solar activity component. The intensity of received radiance is not random over periods longer than the Wolf cycle but – one might say – untidily cyclical with periodicity at sub-secular scale, fitting the 60-80 year cycle observed in earth systems that will be discussed later.

The proportion of the radiation emitted by the Sun that is received at the top of the atmosphere is modified by the fact that the orientation of Earth's axis varies in relation to the ecliptic plane of the solar system and this controls the absolute length of each season. Nor is Earth's orbit around the Sun circular, but traces an ellipse that precesses in space according to the gravitational pull of the great planets although this has only a minor effect on levels of TSI. These changes to the geometry of the solar

[96] *From Scafetta, N (2010) .J. Atmosph. Solar-Terr. Phys. 72, 951-970. Image redrawn.*

system modify climate and weather patterns on Earth in a complex manner, some effects being very direct - as in the case of the solilunar tides in the ocean - and others less direct, as in the case of a weak external periodic forcing that may impose a matched oscillation on Earth climate systems. Consequently, changes on Earth systems are forced by changing TSI at periods that range from the 11-year sunspot cycle to that of glaciations, the consequences being recorded both in observations and in proxies for observations in sediments, tree-rings, corals or ice cores – all of which testify to the entire history of the Quaternary glaciations that were initiated about 2.5 million years ago with periodicity of 41,000 years - although the five more recent glaciations have a collective dominant period of 100,000 years. These records clearly confirm the relationship between conditions here on Earth and the cyclic changes in the geometry of the Solar system; it as been suggested that the detrended NOAA global surface temperature record marches in step with the 60-year oscillations in the variable distance of the Sun from the barycentre of the solar system since 1850.[97]

A study of proxy records of sunspot count extending back to the year 860 implies that a clear relationship between solar radiation and Earth's climate has been maintained during this period; this study is based on a model of processes that relate the ^{10}Be concentration in Antarctic and Greenland ice cores (and C_{14} in tree-rings) to sunspot number. The anomalous increase in sunspot numbers towards the solar maximum of the 20th century is noteworthy because the Sun was more active during the first half of the 20th century than at any time during the entire previous millennium: that should cause us to look at any other potential causes of climate change with the very greatest care and attention. Reconstructions of the correspondence of sunspot numbers with ^{14}C proxies of temperature suggest a remarkable correspondence of solar radiation with each of the major climate anomalies of this period: the Mediaeval Warm Period (MM), and subsequent Sporer, Maunder and Dalton climatic minima. These anomalous periods of cold, or very cold climate created major problems for society that are best documented for Europe.[98]

Although the interactions within the solar system that modify climate and weather patterns here on Earth are very complex, evidence concerning their evolution in the past can be derived from palaeo-temperature proxies. The relative abundance of *Globigerina bulloides* in varved sediments in the Southern Ocean was used in the classical demonstration that timing of glaciations responded to the 41K year period of the obliquity of Earth's equatorial plane with the ecliptic, together with the 21K year periodicity of the nutation (or wobbles) of Earth's axis around the cone of the precession of the equinoxes; the modulation of these two effects generates the dominant 100K period to which recent glaciations have responded. The authors of this remarkable paper were in the enviable position of being able to state with some certainty that: "*It is concluded that changes in the Earth's orbital geometry are the fundamental cause of the succession of the Quaternary ice ages*". Climate variance at this scale is based on three discrete spectral peaks at 23, 42,000 and 100,000 years that correspond to the effects of obliquity of the Earth's axis, of precession and of orbital eccentricity respectively.[99]

This modern study comforts that of Milankevitch who computed that solar orbital tilt (42 Kyr period) and orbital precession (23 Kyr period) together should reduce solar

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[97] *Scafetta, N. (2010) J. Atmos. Solar-Terrestr. Phys. 72 (13), 951–970.*
[98] *Usoskin, I.G. et al. (2003) Phys. Rev. Lett. 91, 211101-1-4.*
[99] *Hays, J.D. et al. (1976) Science, 194, 1121-1132.*

irradiance sufficiently to induce a response in northern hemisphere ice cover (suitably lagged by 5 Kyr to account for the slow processes of accumulation and ablation); this would, he thought, be sufficient to account for the recurrent global glacial periods already observed in the geological record: however, as discussed in section 3.7, the gravitational consequence of these changes in orbital geometry may well be an equally good candidate to explain the timing of glaciations through major changes in the strength of ocean tides.

Deep-sea sediments demonstrate the consequences for marine ecology of all these frequencies, and provide abundant evidence that global climate state has responded in the past to solar radiation levels: the abundance of *G. bulloides* in sediments of the Carioca Basin from 1650 to the present day serves as a proxy for Atlantic trade wind strength and also for the North Atlantic Oscillation index that predicts the pattern of atmospheric circulation over the North Atlantic. Periods of reduced solar output (the Maunder, Sporer minima and the low points of the Wolf cycle) correlate well with periods of strong regional upwelling driven by strong Trades in the central Atlantic.[100] On the Tibetan Plateau, very far from all oceanic influences, proxy data from sediment cores in two high-altitude lakes also demonstrate concordance between variable solar radiation and alkenone production (one of the best temperature proxies yet utilised) by specific groups of lake algae. There are, of course, the usual corrections to be applied to the samples for missing segments and a reservoir effect, but these appear to have been well resolved in this and earlier studies of regional lakes in China that show the same sequence.[101]

These data suggest very strongly (the authors quite properly put it no stronger than that) the existence of a Mediaeval Warm Period that was warmer than the present climate, and a rather clear concordance between solar radiation and Tibetan Plateau temperatures in which each of the recent minima (Wolf, Spörer, Maunder and Dalton) is faithfully recorded. Finally, observations of some Central Asia ice-core temperature data, filtered for volcanic effects, followed solar activity over the period 1250-1850, suggesting that solar influence was dominant at least until the Industrial Revolution. This would seem to be an ideal demonstration of solar effects on climate systems, but it is not so simple as that: the effect is lagged by 10-30 years in this and in other central Asian ice-core and tree-ring data and so is not compatible with a direct effect of insolation, but requiring a lag induced by transport of heat in ocean circulation (as suggested by the authors) or a simpler mechanism of differential rates of accretion and melting of ice.[102]

Such demonstrations of solar influence on climate in both distant and recent pasts are not hard to locate in the scientific literature, but they have been challenged by two very influential Royal Society studies which concluded that while there may have been a solar influence on Earth's climate prior to mid-20th century, the relationship disappeared after 1987 because "*all trends in the Sun that could have had an influence on the Earth's climate have been in the opposite direction to that required to explain the observed rise in global mean temperatures*".[103]

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100 *Black, et al. (1996) Science 286, 1709-1713.*

101 *He, Y.X. et al. (2013) China Sc. Bull. 58, 1053-1059.*

102 *Eichler, A. et al. (2009) Geophys. Res. Lett. 36, L01808, doi:10.1029/2008GL035930*

103 *Lockwood M. and C. Froehlich (2007) Proc. Roy. Soc. A doi:10.1098/rspa.2007.1880* and also *.0347*

The authors of these studies appear to ask us to abandon classical concepts such as the Maunder and Dalton climatic minima and to ignore the many studies that discuss relationships between the solar cycle and regional climate phenomena. And it is all the more surprising that some years later the senior author published a study that discussed "*solar influence on the probability of relatively cold UK winters*" during the coming 50-year period of declining solar activity: he predicted that the probability of cold winters would increase during this time.[104]

Finally, on the basis of a comparison between GISS SAT data for 1975-2005 and the sunspot numbers and solar irradiance levels, the authors remark that "*Earth's surface air temperature does not respond to the solar cycle"*.

In fact, of course, it does just that - and in many different ways, as we shall see n the next section.

3.2 - Observed consequences of the Wolf sunspot cycle

The simplest demonstration of this response may be to look at the consequences on Earth of the short 11-year sunspot cycle. After the invention of the optical telescope in the 17th century, the routine observation of sunspots has been a fascinating but frustrating pastime for astronomers, amateur as well as professional, who have looked for correlation between their numbers and natural phenomena.[105]

The abundance of sunspots, dark regions having great magnetic activity, follows an approximately 11-year return period between solar minima and maxima, corresponding to a 22-year cycle in magnetic activity and particle emission; a polar reversal occurs on the Sun at each sunspot maximum and this forms a useful indication that a cycle has really been completed and a new cycle has begun.[106] This cycle is expressed in several versions: the Group, the Zurich and the International Sunspot Number series although, for present purposes, the differences between these formulations are unimportant.[107] Sunspots also tend to aggregate into groups whose emergence is of primary significance, and this is now quantified in the *Group Sunspot Number* that shows a generally increasing trend in solar activity since 1700, leading to a modern Grand Maximum in mid-20th century that is not evident in the earlier Wolf scale.[108]

A connection has long been observed between solar radiation levels and these cycles, even though the variation during individual cycles is very small; during the period of modern satellite observations, irradiance has varied only between 1371 and 1374 $W.m^{-2}$ (or less than 0.3%), and similar values (1367 $W.m^{-2}$) are suggested by a solar irradiance model.[109] This might be thought to be too small to have any observable effect on climate or weather, and indeed correlation characteristically collapses after just a few cycles or - equally often – a relationship remains but reverses sign.[110] This is

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[104] *Lockwood, M. et al (2012) Env. Res. Lett. 6, doi:10.1088/1748-9326/6/3/034004*
[105] *Hoyt, V and KH Schatten "The role of the sun in climate change" Oxford Univ. Press, 1997, is an account that leans over backwards not to be partisan, one of the authors being a NASA scientist.*
[106] *Here, my text owes much to Leif Svalgaard's essay "Solar activity – past and present".*
[107] *See, for instance, Hathaway, D.H. et al. (2002) Sol. Phys. 211, 357-370.*
[108] *Hoyt, D.V. et al. (1994) Geophys. Res. Lett. 21, doi: 1.1029/94GL01698*
[109] *Foukal, P. and J. Lean (1990) Science 247, 556-558.*
[110] *Hoyt, D.V. and K.H. Schatten "The role of the sun in climate change" OUP, 1997.*

very clearly illustrated by solar history during the period 1850-2000 when the first five of the sunspot maxima coincided with warm maxima in the SAT anomaly series while the last four coincided with cool minima – the range of decadal temperature bandpass being about 0.15°C. Between these two periods, bandpass associated with temperature change was irregular and smaller.[111]

Finally, in the context of this discussion, it is to be noted that visible wavelength radiation is not the only solar influence on atmospheric temperature and climate; in fact, variation at UV (6-8%) and at X-ray wavelengths (100%) during each 10.7 yr solar cycle is much greater than at visible wavelengths. Because ozone in the upper atmosphere is opaque to UV, some heat is accumulated there and propagates down into the lower atmospheric circulation. This process was verified during cycle 23 which had a very high second maximum during winter 2001/2002 that caused the northern winter polar vortex to shrink and the southern polar summer vortex to collapse, perhaps contributing to the break-up at that time of the Larsen ice shelf.[112]

The frequent failure of correlation between solar radiation and natural processes on Earth is one of the most commonly used arguments against any such correlation, but there is now good evidence to demonstrate that this is exactly what you would expect from any study that is restricted to a single station, or to a small regional group of stations. This conclusion is derived from a study that used the extraordinary spatial coverage of weather stations in the continental USA (see Chapter 4), because this uniquely enables the surface air temperature field to be described in detail over a large area. The consequences of changing sunspot numbers can therefore be examined at regional scale rather than at a single site, as has usually been the case. This has been done at global scale for 226 stations world-wide, revealing a 10.6 year cycle at many stations with, at North American stations, a 0.27°C amplitude.

This result encouraged a more detailed spectral analysis of the 20th century data from almost 1200 mostly rural meteorological stations in the contiguous United States which demonstrated a clear relationship between instrumental SAT and the 11-year solar cycle.[113] Correlation (ranging from -1 to +3) was established at each reporting station between changes in surface air temperature and the modulation of irradiance during solar cycles. The pattern of this correlation was geographically coherent, rather than spatially random: everywhere west of the continental divide, the value was negative, while everywhere to the east it was positive, with highest correlation being in the centre of the continental mass to the south of the Great Lakes; immediately east of the divide (heavy line) is a narrow area of no correlation (between the two lines). Surface air temperature was found to respond with an amplitude of about 0.3°C (significantly larger than predicted by models) to the periods of the 10.7 year Wolf sunspot cycle and also of the 18.6 year Saros cycle of lunar tidal forcing in the ocean; the potential for tidal vertical mixing to cool sea surface temperature, and modify both regional and global climate will be discussed below.

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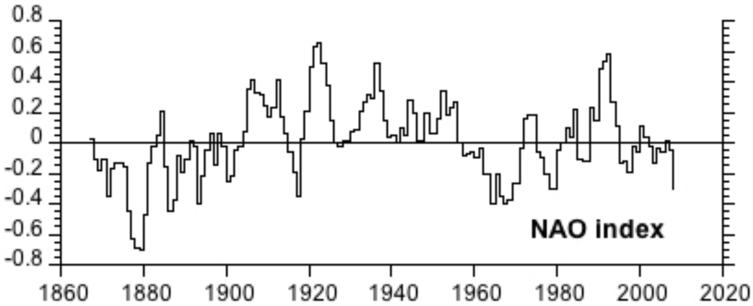
[111] *Herman, J.R. and R.A. Goldberg "Sun weather and climate" Dewer, NY 1985)*
[112] *these processes are discussed by Labitzke, K. (2004)Met. Zeitsch. 13, 263-270*
[113] *Currie, R.G. (1993) Int. J. Climatol. 13, 31-50. The map is redrawn from this authors work.*

This is not an isolated observation, because similar effects have been identified on other continents (and on other sections of the continental divide) and it is now increasingly recognised that solar influence on climate does not modify the environment – whether by rainfall, temperature, growth rate of plants or whatever takes your fancy - uniformly across the planet at the shorter periodicities but, instead, induces change in the planetary weather patterns and hence the values of the major climate indices - the Southern Oscillation, the Atlantic Meridionial Oscillation and so on. It is also fundamental to regional climate regimes that atmospheric circulation should be strongly patterned by the major meridional mountain chains on the continental masses for, without these, the Atlantic Meridional Overturning Circulation would be much weaker.[114]

This result has been confirmed by another study of 153 stations in the conterminous USA, selected for the duration and completeness of their record; this demonstrates a solid relationship during the entire 20th century between variation of a magnetic index of solar activity and variation of minimal (night-time) temperatures for each of six regions: Florida, California, Atlantic coast, Great Lakes, North Pacific and North Atlantic. In each region a maximum in night-time temperature occurred around 1950, with minima of 50% of the maximum value around 1920 and 1980, and a very good correspondence with a 1950 peak in solar activity. The same relationship has been observed in comparable data for western Europe and for Australia[115] The European study was based on 50 carefully-selected sets of station data from the ECA&ECD and GHCND archives (the criterion being that data should be missing for no more than one year during the entire 20th century),and it demonstrated very clear relationships between the solar cycle and the duration of periodic regional anomalies in the data. In this case, the relationship between SAT and sunspot numbers is (i) strongest in winter, (ii) in regions adjacent to the Atlantic and (iii) when the data have been partitioned into large climatic regions. The coastal regions of western Europe, most intimately affected by Atlantic weather, are preferentially linked to the solar cycle and this strengthens the conclusion from the North American data because the strength of westerly winds from

[114] *Binha, S. et al. (2012) Geophys. Res. Lett. 39, L02705*
[115] *Le Mouel, J.-L. et al. (2008) CR Geosc. 340, 421-30*

the ocean over Europe is a function of the sign of the North Atlantic Oscillation (NAO) which codes the pattern of wind direction in this region.



Unsurprisingly, it was in the region strongly influenced by changes in the NAO that one of the early scientific observations of the consequences of the solar cycle were made. Tasked with understanding the unreliability of Norwegian cod stocks, Johann Hjort postulated a solar influence on the functioning of the marine ecosystem inhabited by cod in the Barents Sea.[116] Both water temperature and the condition of the fish, as indicated by the oil content and weight of their livers, coincided remarkably closely with the sunspot maxima of 1886, 1895 and 1905. Modern data[117] suggest that change in oil content is untidily cyclical in these fish, with outstanding peaks in (for instance) about 1937, 1947, 1963, 1979, and 1989: of course, the modern data are less homogenous than those collected a century or more previously because they are from stocks of fish that are far less pristine in age structure caused by selective fishing mortality on older fish - so perhaps one should not expect a tidy result. The most that can reasonably be said now is that oil level in fish remains strongly variable and that most of the periods of high oil content approximately correspond with periods when solar radiation was rapidly increasing towards sunspot peak numbers.

These observations, and those of the SAT data for the United States, suggest that the small changes in solar radiation associated with the 10.7-year cycle do indeed modify the pattern of global atmospheric circulation, and that the position of the jet stream shifts accordingly.[118] Since the pattern of high and low pressure systems is complex and only partially stable, we should not expect the location of the line between positive and negative correlation to be permanent in its position or strength.

Consequently, it is not surprising that evidence should be accumulating to confirm the complexity of the resonant response of the atmospheric circulation to imposed frequencies in solar radiation.[119] Major changes in the tropical atmosphere are induced, notably the strengthening of the Hadley cell at TSI_{max}, with a consequent poleward shift of the inter-tropical convergence zones in both hemispheres; the easterly trade winds within the zonal Walker circulation also strengthen and are associated with equatorial divergence of cold water in the Pacific that is distinct from the El Niño-Southern Oscillation signal, which appears to be modified by the occurrence of solar maxima. In higher latitudes, comparable effects have been identified in the distribution of pressure over the North Atlantic, coded as the North Atlantic Oscillation. There is also some historical evidence to suggest that increased solar radiation is associated with

[116] Hjort, J. (1914) Fluctuations in the geat fisheries of northern Europe, Fred. Høst, Copenhagen.
[117] Yaragina, N.A. and C.T. Marshall (2000) ICES J. Mar. Sci. 57, 42-55
[118] *Nastrom, G.D. and A.D. Belmont (1980) J. Geophys. Res. 85, C443-452.*
[119] This section owes much to Gray, L.J. et al. (2010) Rev. Geophys. 48, RG4001/2010

positive value of the NAO while, during the Maunder Minimum, the NAO took negative values associated with cold easterly winds across Europe and consequently major anomalies in SAT across Western Europe.

3.3 - The relationship between solar cycles and regional climate modes

Studies of the relationship between solar cycles and the major indices of climate pattern are legion, go back to the earliest scientific literature, and their findings range from very simplistic ("*every year following a minimum of sun spots is an El Niño year….*") to the rather complex, such as the study which shows that the minimum phase of each solar cycle tends to be associated with negative phase NAO conditions over western Europe[120]. For this to occur, unusually cold air must form high in the tropical stratosphere that induces strong easterly flow over the Atlantic basin at mid-latitudes during cold winters. At peaks of the solar cycle, the pattern is reversed.

Of course, neither of these studies confirms anything more than the fact that regional SAT is not indifferent to the sunspot cycle: it must be emphasised that what they specifically do not do is to demonstrate that global SAT (for what that is worth as an index) responds coherently as Earth gains or loses heat; complication arises from interference with shorter cyclical patterns arising from shifts between stable states of atmospheric circulation, such as a 3-5 year response to the ENSO signal. Something of this complexity has been analysed by wavelet analysis of palaeoclimate proxy data for the large-scale atmospheric patterns (NAO, AMO, PDO and SOI, all defined by atmospheric pressure difference between two distant points); coherence has been found between periodicity of each of these and the periodicity of solar phenomena at all scales. Spectral analysis of ENSO data confirms oscillations at 11-12, 5-6 and 2-3 year frequencies and thus also confirms that coupling and interaction does occur between the inherent periodicities in oceanic and atmospheric circulations and the multiple cycles in solar irradiance that themselves depend on the complex motion within the plasma that constitutes the mass of the Sun.[121]

Despite the evidently complex resonance that is involved, some proxy evidence suggests a simple relationship between solar and ecological cycles in the ocean, comparable with Johann Hjort's cod liver oil data. The consequences of these are recorded in sediments which reveal solar periodicity: in Effingham Inlet on the British Columbia coast, varve thickness records a cycle of 11-13 years and wavelet analysis reveals cycles of 4.5, 7, and 9-12 years in diatom abundance. These frequencies suggest that the sediments record the effects of the 11-year solar cycle and the return frequency of ENSO events in the plankton of the North Pacific Ocean.[122] Very similar results have been obtained in varied lacustrine Pliocene sediments in Spain: in fact, almost the same set of cycles was found as in the North Pacific inlet: cycles of about 12 years, 6-7 and 2-3 years were recognised. The authors interpret these in the same manner as was done for

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[120] *Ineson, S. et al. (2011) Nature Geoscience doi:10.1038/ngeo1282.*
[121] *Velasco, V.M. and B. Mendoza (2008) Adv. Space Res. 42, 866-878; Nuzhdina, MA (2001) Nat. Haz. Earth Syst. Sci. 2, 83-89.*
[122] *Patterson, R.T. et al (2013) Quatern. Internat. ?? 1-16.*

the North Pacific data, as representing the effect of solar cycles on ocean/atmosphere circulation.[123]

Effects on climate processes can also be observed with longer periodicity than the Wolff cycle in response to longer periodic changes in solar radiation intensity. In sufficiently long proxy series, an amplitude modulation of the Wolf cycle can be identified at intervals of about 80 years after smoothing with an 11-year running mean, and this itself - further smoothed – exhibits the periodicity of the well-known 88-year Gleisberg cycle.[124] This has an astronomical basis, conforming to the changing position of Jupiter within the solar system: changes in the length of the cycle are related to whether that planet is approaching perihelion or aphelion.

The classical tabulation of relationships with the Gleisberg cycle is worth repeating here, because these are too frequently ignored in modern studies or dismissed as folk-lore; here is an abbreviated, but compelling, version of the tabulation of Hoyt and Shatten:[125]

Parameter	***Cycle length, years***
Central England temperature	76
Diel temperature range, Budapest	80
Prague weather	89
European winter severity	80 and 83
Ice at Iceland	80
Greenland oxygen isotopes	78
Tree ring deuterium	95
Beijing rainfall	80
Low stage, Nile	83
Nile floods	77
Caspian Sea level	80
Midwest drought	90
Midwest drought, tree rings	90
Lapland tree rings	90
Sequoia growth rate	83
California tree rings	80

A further example of this frequency in natural systems will be discussed in Chapter 10 is the apparently cyclic alternation between warming and cooling regimes in the Arctic Ocean, associated with changes in sign of climate indices, notably the NAO and the AO. Such periodicity continues to be evoked in relation to droughts and floods foretold: predictions based on Senegal River discharge cycles, Nile floods and East African lake levels (all having similar periodicity) the drought conditions in the Sahel of the early decades of the present century were verified.[126]

Despite the apparent match of the pattern of the Gleisberg cycle with natural changes in solar strength, some studies continue to reject any relationship between irradiance and climate-related variables on Earth. A recent analysis from NASA

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[123] Munoz, A. et al. (2001) J. Palaeolimn. 27, 453-463.
[124] Peristykh, A.N. and P.E. Damon (2003) J. Geophys. Res. 108, doi:10.1029/2002JA009390,
[125] "The role of the sun in climate change". Oxford, 1997, pp. 279.
[126] Youssef, S. and L.O.M. Ghilly, ICEHM2000, Cairo University, Egypt, Sept. 2000, 209- 221

compares Zurich (International) numbers, Group numbers, total sunspot area and the 10.7-cm radio data and the authors suggest that if the secular trend since the Maunder Minimum is removed "*We find little evidence for multi-cycle periodicities like the 80-year Gleisberg cycle or the two- or three-cycle periodicities*". They find the solar signal to be so noisy that it is best analysed in 13-month running means with the application of 24-month Gaussian filtering.[127] This mathematical approach suggests that the observational method, on which the above listing of proxy cycles is based, is no more than illusory: such opinions are not hard to find in the modern climate change literature and the reader will judge between these two approaches to a complex issue.

Of course, one of the principal causes for disdain today concerning any periodic relationship between solar conditions and climate variability is that GCMs fail to reproduce the observations; the 48 models used by the IPCC during their preparation of AR5 of 2014 all incorporate a rather low estimate of the intensity of solar radiation, and none simulates a trend of surface air temperature which matches the observations of periodicity in recent global surface temperature as successfully as a simple, semi-empirical mode. Although an assumption of the existence of a simple 60-year, solar-related oscillation explains the 1850-1880, 1910-1940 and 1970-2000 warming periods and the lack of warming since the year 2000, the GCMs simulate a simple warming rate of about 2^{o}C/century that continues right up to the present time.[128]

But other modelling approaches produce different results: a coupled ocean-atmosphere circulation model simulates the pattern of multi-decadal fluctuations of North Atlantic SST very well; these are found to be governed by changes in external forcing from solar irradiance and volcanic events, both of which can be specified simply during the last 600 years or so; volcanic cooling events play an important role through their effect on SST in the low-latitude regions where solar heating of surface water normally occurs in the subtropical gyre. The use of a coupled ocean-atmosphere model demonstrates that the effect of this external metronome is sufficient to account for the observations of Gleisberg periodicity in the Atlantic Meridional Oscillation of basin-scale temperature between North and South Atlantic basins (see pp. NN)[129] The AMO involves an alternation of warming/cooling between North and South Atlantic, which is recorded in many proxies on adjacent continents; using data from several of these together with a solar proxy based on ^{10}Be in Antarctic ice cores and an accepted record of volcanic forcing, there can be little doubt that during at least the last 450 years the AMO has responded closely to this combined external radiative forcing.

A recent analysis based on proxy data of the relationship between the AMO and incident radiation at the surface due to combined volcanic and solar forcing would seem to close this discussion.[130] In such cases, confirmation of a functional relationship between forcing and resultant is not just a matter of mathematically matching cycles between two variables but rather that one variable (the AMO proxy) closely tracks two irregular cycles that represent the opposing influences of solar heating and volcanic cooling. It would be hard to argue that such a match is a matter of chance or that it will not be reflected in future climate change.

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[127] *Hathaway, D.H. et al. (2002) Solar Physics 211, 357-370.*
[128] *Scafetta, N. (2013) Earth-Science Rev. 126, 321-357.*
[129] *Ottera, O.H. et al. (2010) Nature Geosc. 3, 688-694*
[130] *Knudsen, M.F. (2013) Nature Communications 5, 3323 doi:10.1038/ncomms4323*

3.4 - The 1470-year Bond cycle, and the glacial-interglacial transitions

So far, we have been concerned principally with the pattern of global surface temperature change during the last 150 years, a period for which the consensus view is that global climates have been slowly warming, a trend that accelerated during the 20th century; it is generally agreed, also, that events such as the Little Ice Age or the Mediaeval Warm Period were no more than anomalies on the general trend of surface temperatures during the Holocene, which has in the past been generally regarded as having experienced a rather stable climate, though punctuated alternating glacial advances and retreats in different parts of the world; early studies of these episodes concluded that variation in solar activity was at least a possible trigger for these events.

But proxy evidence - Icelandic glass, haematite-stained grains and cosmogenic nuclei - in North Atlantic sediment cores taken south of Greenland and to the west of Ireland, shows that periodic flooding of this region with Arctic water and floating ice has been associated with cold episodes, now termed Bond events by some, at intervals of 1470 ± 500 years throughout the Holocene. These events can be traced at similar intervals back through at least the most recent glacial period and some, such as the Younger Dryas (p. NN), have been sufficiently strong to attract much attention. The proxies also suggest that the Little Ice Age of the 17th century was not an isolated event, but the most recent, although weak, Bond event, the period of c.1100 years falling within the limits of previous intervals between cold episodes.[131] Some of these episodes were synchronous with climatic anomalies - droughts, cold periods and so on - in other regions, as far away as eastern Asia. Event 2, for example, at 2800 BP was associated with drought in the MIddle East, while Event 6 at 9400 BP correlates with glacial advances in Scandinavia and a cold epoch in China.

It is not surprising that such events should be so very well-marked on the land masses surrounding the North Atlantic, because this is the sole region in which confluence occurs between massive poleward flux of heat originating in tropical seas and major episodic flows of cold, ice-laden water from a polar ocean which result in "*rather substantial change*" in the regional surface circulation of the northern North Atlantic basin[132] They characteristically result in a 2^{o}C drop in the SST of the Northeast Atlantic as cold water from the Labrador and Nordic Seas extended much farther to the southeast than we see at the present time. The authors of this study suggest that their results imply that solar variability must be expected to influence future climates just as it has in the past.

The North Atlantic, therefore, has switched between two characteristic circulation patterns during the Holocene with a period of about 1500 years, although an analogous, though smaller, switch between two patterns occurs in the strength of the flow of North Atlantic Current water into the Arctic through the Nordic Seas at the near 60-70 year intervals of the Gleissberg cycle. These changes in zonal transport in the North Atlantic - at each time scale - have climate consequences to match. Amplification of the effects may involve the changing rate of production of North Atlantic Deep Water by winter cooling, and the consequent 'slumping' of dense water to mid-depths in the southern Labrador and Norwegian Seas. There is also close correspondence between

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[131] Bond, G. et al. (1997) Science 278 1257-1266 & (2001) 294, 2130-2136: this section owes much to these two contributions.

[132] Werner, F and J. Butikofer (2008) GeografieňSbornÌk, 113, 338-350 (after Bond, 2001)

these events and $\Delta^{14}C$ in tree-rings and therefore inferred glacial advances in Scandinavia.

Bond and his co-authors[133] expressed no doubts concerning the origin of these periodicities in a second study entitled "*Persistent solar influence on North Atlantic climate during the Holocene*", noting the close correlation between cosmogenic nuclides in unusually finely resolved drift-ice proxies in the sediment cores. At times of reduced solar irradiance, cooling occurs in the stratosphere because of changing levels of ozone, and this leads to a chain of events: the northern latitude troposphere cools, the northern subtropical jet shifts southwards and the strength of the Hadley circulation is reduced. These changes are sufficient to account for the episodic cooling of the seas between Greenland and Europe during Bond events.

There has been remarkably little reaction to these studies and inferences although they have, as we would expect, been challenged by a NOAA-led study that suggested that the coupling between solar irradiance and a cold North Atlantic may not be so close as claimed; this study was given some weight in the recent AR5 of the IPCC.[134]

3.5 - Was there a role for CO_2 in the orbitally-forced glaciations?

Since the classical demonstration of Milankevitch, the Quaternary glaciations have been very widely attributed to orbital forcing of solar irradiance but now, since our fixation on the climate consequences of CO_2, you do not have to read very far to find opinions expressed concerning the role of radiative gases in the mechanism of deglaciation. The timing of increases in CO_2 in the atmosphere at deglaciations (did this occur before, or after, the events?) generates much difference of opinion, even though modelling studies suggest that this molecule alone cannot have sustained the changes in air temperature.[135]

This question is at the core of a very influential study entitled "*Target atmospheric CO_2: where should humanity aim?*"[136]. This was based on computations of climate sensitivity for doubled CO_2 and one of its central assumptions was that both over very long time-scales and also during the Pleistocene glaciations; *"Decreasing CO_2 was the main cause of the cooling trend that began 50 million years ago, the planet being nearly ice-free until CO_2 fell to 450 ±100 ppm"*. The same argument is applied to the onset and relaxation of the Pleistocene glaciations, although the general consensus is that the cause of the Pleistocene glacial and interglacial periods was cyclical change in solar radiation, even though this involved a difference of only about 0.5 Wm^{-2}. [137]

The problem is not simple to solve since the concentration of the radiatively-active gas component of the atmosphere must have consequences for the climate of the Earth, and because it is necessary to consider some processes in the very distant past that may have involved both radiatively-active gas and also solar forcing. Some have attributed the extreme warmth of the Palaeocene-Eocene thermal maximum (a warm

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[133] *Bond, G. et al. (2001) Science, 294, 2130-2136*

[134] *Muscheler, R. et al. (2006) Quat. Sci. Rev. doi:10.1016/j.quascirev.2006.07.012*

[135] *Kohler, P. et al. (2009) Quat. Sci. Rev. doi:10.1016/j.quascirev.2009.09.026*

[136] *Hansen, J. et al. (2008) Open. Atmos. Journ. 2, 217-231.*

[137] *Berger, A.L. (1978) J. Atmos. Sci. 35, 2362-2367.*

anomaly of 5-6^{0}C during a brief period of only 10,000 years) to, among other possibilities, the massive release of CH_4 either from marine sediments [138] or else from thawing polar permafrost deposits,[139] while a sharp rise in the depth of the CCD in the oceans at that time indicates high levels of atmospheric CO_2. But this anomalous event, a little more than 55 million years ago, also coincided with a period when orbital geometry combined extremely high eccentricity and obliquity, and was therefore associated with anomalously high radiative forcing.

Thermal anomalies such as this were imposed on a slow cooling of the climate that occurred throughout the Cenozoic which been attributed to the progressive weathering of silicate rocks; this cooling trend caused Antarctic ice sheets to develop near the Eocene-Oligocene transition (c.35 Myr BP) and Arctic ice much later, near the transition to the Pleistocene. But the movement of tectonic plates and the changing spatial distribution of continents and oceans imposed non-linearity on the long-term trend, so that major roles in the control of climate are now also attributed (i) to changes in the size and location of ocean passages between land masses, (ii) to major episodes of volcanism, and (iii) to the consequences of collisions between tectonic plates, as in the case of the uplift of the Himalayan massif. It is now thought that the Oligocene glaciation (33-27 Myr BP) was related to thermal isolation of Antarctica caused by the widening of the Southern Ocean gateways, although its termination required reduced CO_2 and CH_4 levels and less snowfall, with probable reduction of ice coverage.[140]

The primary tool for dating transitions between glaciated and warmer conditions - and for understanding the role of radiatively-active gases – is the analysis of deep ice cores, mainly from the Antarctic ice domes, from which may be derived the local air temperature at the time the ice was laid down, together with concentrations of gas in the local atmosphere; reference may also be made to proxies for temperature change at mid-northern latitudes, because it is here that global ice cover is most sensitive to changes in solar radiation. Reference may also be made to deep ocean sediment cores, in which the phytoplankton cells, analysed in each varve, indicate near surface temperatures in the ocean above. Ratios of stable isotopes ($\partial^{18}O_{ice}$ and ∂D_{ice}) in the ice cores are used as proxies for local atmospheric temperatures at the time of snow formation, while CO_2 and CH_4 are preserved in the ice and progressively buried, unfortunately they are not isolated in the ice core until transformation of snow to ice occurs at some depth around 50m; so these gas inclusions are therefore younger than the enclosing ice by a period of years (known as Δage) which must be used to match the ages of CO_2 and CH_4 with the age of the ice at each depth.

In cores from sites with slow accumulation rates such as Vostok and EPICA Dome C, Δage may be as much as 2500-5200 years, while at those with faster accumulation, as at Siple Dome and Byrd, it is computed as being 200-800 years, depending on the absolute age of the ice. Further problems occur at the very deepest reaches of some cores, when the temperature of the ice may rise close to the melting point. When considering leads or lags between CO_2 and the cooling/warming cycles, the Δage problem is a principal source of uncertainty, and a constraint on the precision of estimates. [141]

[138] Higgins, J.A. ad D.P. Schreig (2006) Earth Planet. Sci. Lett. 245, 523-537.
[139] DeCono, R.M. et al. (2012) Nature, 484, doi:10.1038
[140] Zachos, J. et al. (2001) Science, 292, 686-693.
[141] A useful entry into these problems is Pedro, J.B. et al. (2012) Clim. Past 8, 1213-1221.

Our understanding of the evolution of climate took a great step forward with the publication of the studies of the ice cores from the Russian VOSTOK ice dome station in Antarctica. On this classic study is based much of our understanding of the mechanism of glaciations, stretching back over 420,000 years and four full glacial periods. [142] Even longer cores at Dome C by the EPICA group and by other teams elsewhere in the Antarctic has taken the record back eight full glacial cycles and thus to 740,000 yrs BP. The global temperatures that are based on these cores represent the result of at least 5 millions years of slow cooling of the '*Vostok equivalent temperature*' from around -1.5°C to around -4.0°C during the last glacial cycle.

The proxies for local temperature, CO_2 and CH_4 demonstrate the brevity of each warm intermission. The characteristic saw tooth pattern of very rapid warming prior to the termination, followed by a series of progressively more extreme cold events during each glaciation is very easily seen in the isotopic temperature of the Antarctic atmosphere. From these and other cores we now know that the brief warm periods, lasting perhaps as little as a few thousand years, that were characteristic of Terminations 1-4 were quite different from those of the earlier Terminations 5-8 which were significantly less saw-toothed and did not reach such high temperatures. [143]

The correspondence between the 100 Kyr solar insolation cycle at 65°N and deuterium temperatures in these cores is remarkable. These results are broadly consistent with the findings of the classical study by Hays and his colleagues of sediment cores from the Southern Ocean that first demonstrated satisfactorily the relationship between changing orbital geometry, changing solar constant and the climate regimes in the Southern Hemisphere.

The closely-similar pattern of change of Antarctic air temperature, and of CO_2 and CH_4 was one of the most notable findings of the Vostok cores and suggests that these gases must amplify the initial orbital forcing that are represented by insolation changes at 60°N) and in so doing they must contribute to forcing the glacial-interglacial cycles. These conclusions have subsequently been examined closely, and not always without prejudice, because the question of whether CO_2 concentrations led or lagged local temperature change became an issue between those who are wholly committed to the standard model of anthropogenic climate change, and those who are not. [144]

The IPCC 5th Assessment Report of 2013 expresses no doubt in the matter: "*There is high confidence that orbital forcing is the only external driver of glacial cycles. However, atmospheric CO_2 content plays an important role as internal feedback.*" One would have hoped for a more quantitative approach to internal feedbacks to orbital forcing, because since there are several other forcings that must be more significant than CO_2 – such as methane and water vapour. That "*Orbital-scale variability in CO2 concentrations…covary with proxy climate records*" of global ice volume, climate in central Asia and some ocean properties does not necessarily, one would think, demonstrate causation but nor does it question the prime role of orbital conditions or some role for radiative CO_2 effects in the glacial-interglacial transition.

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[142] *Petit, J.R. et al. (1999) Nature, 399, 429-436.*

[143] *Terminations are numbered consecutively backwards from the most recent.*

[144] *A prominent argument of the Gore film was the relationship between CO_2 and temperature at terminations, as it was in Maslin, M. (2004) "A short introduction to global warming" Oxford Univ. Press.*

In any event, the peer-reviewed literature, though not unanimous, has largely agreed (despite these complications) that the rise in concentration of CO_2 in the atmosphere lags the rise in air temperature at each glacial termination. I have consulted a file of 13 papers that directly address this issue from analysis of ice core data, and find only three that conclude that CO_2 led Antarctic temperature rise at deglaciation, though at least one does comment that the coincidence is so close that it is possible that CO_2 may have marginally led.

Fischer et al (1999) *Science 283 1712* • Terminations 1-3 • CO_2 lags 600±400 yrs
Petit, J.R. et al. (1999) *Nature 399, 429* • Terminations 1-4 • CO_2 lags 400-1000 yrs
Monnin, E. et al. (2001)*Science 291, 112* • Termination 1• CO_2 lags 800-1000 yrs
Muddelsee, M. (2001) *Quat. Sci. Rev 20, 583* • Vostok core • CO_2 lags 1300±1000 yrs
Caillon, N. et al. (2003) *Science 299, 1728* • Termination 1 • CO_2 lags 800 ± 200 yrs
Bereiter, B. et al. (2012) *PNAS 109, 9755* • Termination 1 • CO_2 lags 250-870 yrs
Pedro, J.B. et al (2012) Clim. Past 8, 1213-1221 • Termination 4 • CO_2 lags 400 yrs

Shackleton, N. (2000) *Science 289, 1897* • Vostok core • CO_2 'essentially in phase'
Luthi, D. et al. (2008 *Nature, 453, 3798* • 11 glacial cycles • CO_2 'strong correlation'
Parrenin, F. et al. (2013) *Science 339, 1960* • to 800 Kyr BP • CO_2 'closely related'

Ruddiman (2003) *Quat. Sci. Rev 22, 14* • Termination 1 • CO_2 leads or is in phase
Shakun, J.D et al (2012) *Nature 484, 49* • CO_2 unquantified lead
Lisiecki, L.E. (2010) *GRL 37, L2170* • Terminations 1-8 • CO_2 leads by 0.2-3.7 Kyr

One of the most recent of this clutch of studies, that of Parrenin, was based on the then most highly-resolved CO_2 record – that of the EPICA Dome C core – and finds clear evidence for synchrony with a lag of 600 ± 400 years at the end of the last three terminations, without minimising the uncertainties involved in ageing the entrapped air in the cores. This study "*strengthens the hypothesis that there was a close coupling between CO_2 and Antarctic temperature on both orbital and millennial time scales. The CO_2 rise could…alone account for 0.6°C of the global warming during Termination 1*".

But as you would expect, one of the most frequently cited of these papers is a simple study of proxy temperature records from both hemispheres, offered by Shakun et al. under the title *"Global warming preceded by increasing carbon dioxide during last deglaciation*". The author is also an IPCC author and although this paper has not yet been challenged formally, an informal peer reviewer suggests that the critical point – that northern hemisphere temperature increase is directly related to the CO_2 increase in the cores – is unproven. But, more importantly, his examination of the proxy data stack reveals that the quoted global temperature is heavily biased by northern hemisphere records - and it has also been suggested that the averages quoted have been incorrectly computed.[145]

Lisiecki's contribution is noteworthy for several reasons, despite his marching out of step with the consensus. He avoids the Δ_{age} problem associated with ice core gas analysis, because his analysis is based on a comparison of ice-core temperatures and CO_2 proxies from deep-sea sediments from a single domain in the South Pacific, where the bottom water mass is more stable than in the Atlantic. The result is unequivocally

[145] *http://www.sciencebits.com/Shakun_in_Nature (this is one of the very few occasions when I have chosen to quote from an unpublished source).*

stated: CO_2 usually leads terminations by 0.2-3.7 kyr, but lagged the two anomalous events at 535 and 745 kyr BP by 3-10 kyr.

The studies discussed so far reveal only the broad outline of the mechanism that controls the saw-toothed glacial terminations, which must involve processes at global scale, both in the oceans and on the continents. More detail is revealed by a study of the period from 9000-20,000 years ago, leading to the end of the Pleistocene glaciations and on into the early Holocene; a very close correlation was obtained between global CO_2 concentration and Antarctic temperatures, suggesting that Southern Ocean processes control the atmospheric CO_2 burden. On the other hand, the lag of the CH_4 profiles compared with Antarctic temperature shows that the evolution of CH_4 is distantly forced by events in the northern hemisphere, where the principal sources and sinks of methane are located. This interpretation is reinforced by the observation that the CH_4 profile closely responds to the Younger Dryas cold event at 11-12K yrs BP, when there was a rapid drawdown of CH_4 into northern wetlands; this interpretation is supported by the release of CH_4 at the onset of the warm Bølling-Allerod event at 14K yrs BP.[146]

It is now generally agreed (although the models of Koehler *et al.* dissent) that the increase in atmospheric CO_2 at each termination originates in outgassing from the Southern Ocean and is forced by changes in the strength of the northward transport of heat in Atlantic Ocean circulation, and also by the response of phytoplankton growth rates to Fe fertilisation in dust flux at the surface. This model is rooted in the observation that the largest global reservoir of CO_2 is in the oceans, being approximately fifty times larger than the atmospheric reservoir. Disequilibrium is maintained by photosynthetic accumulation of carbon by oceanic phytoplankton and its removal into the deep ocean by gravity and the active vertical migrations of herbivorous zooplankton; this 'biological pump' maintains the observed balance. It was the remarkable insight of the late John Martin that suggested that changes in the flux rate of the biological pump in the Southern Ocean responds to Fe in dust, that dust deposition is enhanced during glacial epochs, and that the enhanced biological pump must then increase the drawdown of CO_2 from the atmosphere.[147]

It is a long step from there to the complex models of processes in the Southern Ocean and elsewhere that are proposed today to describe the termination of glacial periods. These models usually agree that the increase in atmospheric CO_2 that occurs at glacial terminations may be attributed with confidence to the upwelling of carbon-rich deep water from the Southern Ocean, to the south of the Antarctic convergence. And, further, that the origin of the rich carbon content of this deep water is the high level of primary production in the regional planktonic ecosystem. Nevertheless, the Southern Ocean cannot be treated as a single Fe-depleted region: the Sub Antarctic biome, north of the Polar Front is SiO_3-limited/Fe-replete in summer, while between the southern edge of the Antarctic Current and the continent the Polar biome is consistently SiO_3-replete/Fe-limited. Between these two zones, in the Antarctic Current, the limiting nutrient changes seasonally.

The pelagic ecosystem of polar biomes is responsible for the strongest rate of vertical carbon flux, for here the phytoplankton is dominated by large cells, is rich in diatoms, and these are consumed by large copepods and euphausids, both of which produce relatively large, rapidly-sinking faecal pellets. Even here, in cold water, the

146 Monnin, E. et al. (2001) Science 291, 112-114
147 Martin, J.H. (1990) Palaeoceanography 5, 1-13.

overturn of the planktonic ecosystem is impressive – copepods alone consume up to 50% of daily plant production and, with krill, constrain the seasonal build-up of plant biomass: most production is rapidly respired by herbivores or sinks as organic carbon in faecal pellets to the sea floor. This process is the regional expression of the biological carbon pump.[148]

The models proposed for the transport of significant quantities of this carbon back to the surface at glacial terminations are complex. Distribution of foraminifera in sediment cores suggest that the strength of the biological pump responds at millennial-scale to changes in dust flux as observed in in ice-dome cores from the Antarctic. Implicated in the model of Ziegler et al.[149] are two vertical circulation cells, one close to the continent, the other further north. The first, a deep overturning circulation (0-5000m) adjacent to the ice-edge is associated with the formation of deep bottom water from which carbon-rich water returns to the surface when ice-cover retreats at glacial terminations. The second is a mid-depth overturning circulation (0-3000m), further from the ice edge, in which North Atlantic Deep Water returns to the surface there to be transformed into Subantarctic Mode Water which returns north at shallow depth. Return to the surface occurs in the Antarctic Biome mentioned above.

It is also suggested that this Southern Ocean response participates in the thermal bipolar seesaw model of Broecker, who proposed that the evolution of Greenland temperatures obtained from ice cores (which show abrupt climate variability over glacial cycles between stadial and interstadial conditions) may be explained by changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC, see p. NN). Changes in the strength of the northward transport of heat at the surface in this circulation should produce opposite temperature trends in southern polar regions, so that transitions from a weak to a strong AMOC should cause warming over the North Atlantic (otherwise recognised as a Dansgaard-Oescher event) and cooling in Antarctica.[150] The correspondence observed between these oscillations and atmospheric CO_2 and CH in the ice cores suggest that positive feedback to the termination event is associated with the seesaw mechanism of the AMOC.[151]

Toggweiler has integrated these complex relationships into a relatively simple model of the mechanism that represents the 100,000-year saw-toothed periodicity of Antarctic temperatures and of CO_2.[152] As noted above, it is generally agreed that insolation changes have, at least in the deep past, modified the global climate state through their effects on the ice sheets of the northern hemisphere and hence by the mediation of CH_4 that is released or recovered in the regions of the northern high-latitude wetlands. This model depends on the progressive cooling of the atmosphere since the Eocene thermal optimum about 500 Myr BP when atmospheric concentrations were about 20 times their present level.[153] This process culminated about 5 Myr BP when temperatures in polar oceans fell to a few degrees above or below 0^oC. Because polar oceans have an inherently low salinity, their stability is temperature-dependent

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[148] *Longhurst, A. (2007) Ecological Geography of the Sea, Chapter 12.*
[149] *Ziegler, M. et al. (2013) Nature Geoscience doi:10.10.38/NGEO1782, 5 pp.*
[150] *Broecker, W.S. (1998) Palaeoceanography 18, 1087.*
[151] *Barker, S. et al. (2011) Science 334, 347-351.*
[152] *Toggweiler, J.R. (2008) Palaeoceanography 23, PA2211 17 pp. (for subsequent citations in this discussion, please consult this paper).*
[153] *Berner, R.A. (1997) Science 276, 544-546.*

and only a very small increase above 0°C is needed to induce overturning, while a very small cooling below 0°C induces strong stability of the water column. Switching between the two states induces atmospheric CO_2 to alternate above and below the 225-230 ppm concentration set by the slow process of volcanism and weathering.

Toggweiler proposes that exchanges between atmosphere and ocean at the last termination (from about 10 to about 20 Yr BP, see p. 186) "*began with a seesaw-like fluctuation in the overturning around Antarctica which released respired CO_2 from the ocean to the atmosphere…flipped a $CaCO_3$ deficit in the deep ocean to a surplus…which led to an enhancement in the ocean's $CaCO_3$ burial…warming from the elevated CO_2 led to even more overturning and even more $CACO_3$ burial…the internal feedback…converted a relatively minor overturning fluctuation into a major transition*". This process, and its inverse, should reverse the balance between $CaCO_3$ deficit and surplus in the deep ocean with a period of about 50 Kyr. Finally, it proposed that the saw tooth form of the terminations after 100 Kyr periodicity was initiated may be due to the fact that the transitions to warm ocean conditions result in larger $CaCO_3$ changes in deep water than transitions in the opposite sense.[154]

Although this model is ingenious and has been widely quoted, it appears to require the invention of a novel internal feedback mechanism in order to force the flip-flop mechanism at the observed frequency. In fact, such a mechanism already exists, at the proper frequency, in the external orbitally-forced changes of solar radiation in the northern hemisphere; it has the right frequency, it originates in the northern hemisphere as required, and it leaves the role of CO_2 in temperature changes during glacial epochs – as required by other studies – intact. So, Occam's razor requires us to accept a time-keeping role for the Sun rather than to invent new candidates for that role, as Toggweiler does.

The matter will not rest there, and the dozen deep or so cores around the periphery of the continent that are now available for analysis will continue to yield different insights and greater detail: as I write, a new interpretation of the progress of warming in East and West Antarctica at Termination 1 has been offered that reconciles the previously-opposing views that a Northern Hemisphere trigger was (or was not) required for Southern Hemisphere warming. Cores from marine-influenced West Antarctica now suggest a more direct and active role for the Southern Ocean than had been inferred from the East Antarctic cores, isolated from maritime influences.[155]

Nevertheless, I believe that we do not need to take very seriously the proposal contained in the NASA study which I took as the starting-point for this discussion: I cannot say to what extent this suggests that we no longer have to take the question of targets for future $C0_2$ concentrations as seriously as many wish us to do. In any case, I suspect that any proposition that humanity can sufficiently agree among itself to set such a target, *and then successfully hit it*, is in the realm of fantasy.

3.6 - Predicting the climatic effects of the coming solar cycle

There is currently much interest in projecting solar/climate relationships into the near future, because we are now emerging from a period of maximal solar irradiance

[154] *Jackard, S.L. et al. (2005) Science 308, 1003-1006.*
[155] *WAIS Members (2013) Nature, doi:10.1038/nature12376*

and there has been some recent discussion on the consequences of the grand solar minimum that may be expected during the first half of the 21st century. This has raised interest in another characteristic of solar cycles: the intensity of solar radiation at their peak period is a function of the relative length of the cycle itself. Although they are formally numbered only from 1745, the 36 solar cycles for which we possess direct observations since 1610 ranged in length (measured between maxima) from 8.2 to 17.1 (mean 11.0 ±2.0) years.

More immediately, we are concerned with the very weak start to Cycle 24 that was initiated in January 2008 after an unusually long period between Cycles 23 and 24 when the sun was entirely lacking spots. It was predicted as early as 2004 that Cycle 24 would be unusually weak, and it now seems clear that indeed it will be unlike those that we have become accustomed to since global climate change became a public issue. [156]

The Maunder and Dalton minima were far from symmetrical – though separated by about the expected interval – and the 20th century Grand Maximum, that appears now to be ending, was long and included the rather cool period of cycle 20, which was of smaller amplitude than cycles 19 and 21. But there is also a simple relationship between the length of cycles and the amplitude of their maximum radiation; three consecutive solar cycles during this period were anomalously long, up to twice the nominal 11 years, suggesting a direct relationship between cycle length and intensity of solar radiation, that presented an anomaly of about 0.24%. The effect of this is seen in the proxy relationship between growth rate of *Pinus* in the Urals during the Maunder Minimum. Solar Cycles 5-8 were unusually long, 18-22 years, compared with the 11-12 year average of subsequent cycles and, moreover, Cycle 5 had an anomalous pattern which should interest us today.[157]

The hiatus observed in the surface air temperature record since the end of the 20th century came as a surprise to the climate science community, whose models had confidently predicted continuation of the strong warming that the surface data had indicated over the previous 2-3 decades. This period coincided approximately with Cycle 23, which ended in December 2008; the length of this Cycle (almost 13 years) and its weak solar maximum had already attracted attention to the following cycle, whose very slow start much remarked upon: similarities with Cycle 5 were being noted. Formal predictions of the strength of Cycle 24 before it started were strongly divided between those who expected the strength of the previous cycles to continue to grow and those who (correctly) predicted that a Grand Solar Maximum had been passed. It is now predicted that Cycle 24 will be double-peaked and perhaps the weakest since Cycle 14 at the beginning of the 20th century.

Indeed, observations of solar polarity suggest that the peak of the cycle is already behind us, because it now appears that polarity switched during the spring of 2013. The subsequent evolution of the state of the Sun suggests that Cycle 24 may not terminate until some time in 2026, for a lifetime of 18 years – anomalously long, and therefore likely cool. Pattern-matching is perhaps a mug's game, but it must be of interest to note that the pattern of Cycle 24 is anomalous, but strongly resembles that of Cycle 5 around 1650, having a very slow start followed by a rapid rise of intensity.

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[156] *Svalgaard, L. et al (2005) Geophys. Res. Lett. 32 doi:10.1029/2004GL021664*
[157] *Kocharov, G.E. et al. (1995) Solar Physics 159, 381-391*

As you would expect these days, suggestions are now appearing that this cycle represents the start of a longer-term weakening of solar output, leading to a Grand Minimum of Maunder or Dalton calibre during the coming century. Some reflection of this is starting to appear in the peer-reviewed literature, and some organisations having major public responsibilities are making enquiries of experts. I found a commissioned report on the web-site of HM Treasury in London that reported that "*Projections of weak solar maxima for solar cycles 24 and 25 are correlated with the terrestrial climate response to solar cycles over the last three hundred years, derived from a review of the literature. Based on solar maxima of approximately 50 for solar cycles 24 and 25, a global temperature decline of 1.5°C is predicted to 2020, equating to the experience of the Dalton Minimum".*

A projection of the recent evolution of sunspot count by David Archibald suggests that cooler times might be ahead as irradiance declines in 21st century solar cycles:[158] He was been criticised by some for his presumption, because he is said not to be a 'proper climatologist', so I will quote him no further but will note instead comments from the Cambridge astrophysicist Nigel Weiss whose credentials would seem to be impeccable. He has written as follows: *"The Sun has been exceptionally active for the last 80 years, but the feeble and tardy start to the current Cycle 24 has led to a flurry of speculation about what may happen next. Is this just an abnormal fluctuation, or are we about to experience a Maunder-like grand minimum?".*[159]

A recent clutch of studies from UK and Russian groups is based on analysis of reversals in the dipole field of solar magnetism at each solar cycle and based on analysis of Cycle 24, a prediction of unusually low interaction between the polar fields and hence very low numbers of sunspots – perhaps as low as during the Maunder Minimum: a significant reduction in luminosity of $3W.m^{-2}$ is predicted and this may lead to significant cooling over the 30-year period of the next solar minimum.[160]

But the AR5 of the IPCC is not very convinced: "*Most current estimations suggest that the forthcoming solar cycles will have lower TSI than the previous ones. Recent estimates of the RF between the modern minimum in 2008 and this 21st century minimum indicate a negative RF of about 0.04–0.07 W m^{-2}. However, much more evidence is needed, and at present we have a very low confidence concerning future solar forcing."* Many climatologists are also not convinced and a good example of their reaction is a recent paper from the Hadley Centre which uses a model to project forward the temperature trend observed in the GISS and HadCRUT archives over the last 50 years or so, and predicts that the response to reductions in solar radiation will be of order 0.06-0.1K which, as they say, is a small fraction of the projected anthropogenic warming of 2.55°K by the end of the 21st century predicted by the HadCM3 model.[161]

But the problem with this prediction (and of other similar projections) is that it is based on a direct continuation of the warming trend in the SAT data, which was shown in Chapter 4 to have very little to do with the consequences of GHGs in the atmosphere, but much to do with progressive urban heat contamination and land use change that are expressed in the data. Any model, such as the 'simple climate model'

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158 *Archibald, D.A. (2009) Energy & Environment · Vol. 20 (1&2), 1-10.*

159 *Weiss, N. (2010) A&G 51, 3.9-3.14..*

160 *Shepherd, S.J. et al. (2014) Astrophys. J. 46 doi:10.1088/0004-637X/795/1/46; E Popova, et al. (2013) Ann. Geophys. 31, 2023-2038*

161 *Jones, G.S., M. Lockwood & P.A. Stott (2012) J. Geophys. Res. 117, D05103*

used in this study, which is coded to conform to this projection, cannot be taken seriously as a projection of the radiative consequences of carbon dioxide.

And there are some observations that support contrary suggestions: if one abandons the contaminated GHCN station data and makes a simple regression of good station data for surface temperatures on solar cycle length during the 20th century one obtains an interesting relationship between cycle length and air temperature at these stations: the difference between short (9-10 yr.) and long (12-15 yr.) cycles being of order 1.5-2.0°C – which is very different from the assumptions of the authors from the Hadley Centre. If changes of that order should come to be imposed on the current climate we shall see similar manifestations of concern as those that preoccupied us in the mid-1970s, but this time Newsweek's headlines will be asking questions about how could science (and Science, too, for that matter) have managed to get it all so wrong?

Finally, all discussion of the consequences of Cycle 24 that I have seen has entirely neglected the fact that other mechanisms will influence the outcome; the predictability of the lunar nodal cycle makes forecasts of the relative strength of lunar tidal stress in the ocean rather simple to make - and the prediction of the lunar effect on tidal mixing is for progressively less powerful tidal streams well beyond the end of the 21st century. These will progressively reduce ocean mixing rates, will progressively increase surface ocean temperatures, and may inducing a progressive, gentle warming of the global climate - or, at least, reduce any solar-induced cooling that may intervene.

3.7 - Lunisolar tidal cycles and global temperature: neglected relationships

Indeed, variable solar radiation is not the only external agent that induces change in climate conditions here on Earth. There are other consequences for Earth's climate from its place in the Solar System, and from the changing geometry of orbiting masses whose variability must be integrated into any model – intellectual or numeric – of the evolution of global climate on all scales from years to millennia. Thus, the changing gravitational forces exerted on Earth by the masses of the Moon and Sun create a tidal effect in ocean, atmosphere and in the solid earth. The familiar, repetitive sequence of spring and neap tides in the ocean respond in their height and timing not only to gravitational effects but also to the geography of each ocean region (depth, coastal orientation, basin size) while, in the solid earth, a simple, single wave at centimetre-scale is generated by the same forces: both ocean and earth tides have important consequences for the evolution of climate that shall be discussed below.

The changing strength of ocean tides is forced by the evolution of the relative masses of Moon, Earth and Sun, the tidal force of the Moon being about twice that of the Sun because of its relative proximity. Relative distances and changing orientation of the planes of the orbits of the three bodies cause cyclical change in tidal strength and induce periodicity in weather features, so that both rainfall and air temperature respond to the 18.6 year nodal cycle. Strength of the neap/springs tidal cycle is greatest when Sun-Earth distance is smallest (at perigee) in January and July in the northern and southern hemispheres respectively. Amplification also occurs when the three bodies are in their most precise alignment (at synergy). From the evolutions of the three bodies may be derived multiples of the 18.6 year nodal cycle at periods of 93.1 years (5 cycles) and 558.4 years (30 nodal cycles) when super-tides of exceptional strength occur.[162]

[162] *Encyclopedia of Palaeoclimatology and Ancient Environments (Springer, 2009)*

Prediction of the occurrence of super-tides when the three bodies are at their very closest perigee at millennial scale (about 1800 year intervals) can also be made.

Strong tidal stress and mixing in the ocean cools the surface layers by drawing cold, deep water towards the surface, and this has consequences for surface air temperature. Some may find it surprising that one of the most closely-argued papers on this for climate state was authored by Charles Keeling, originator of the Mauna Loa CO_2 time series, towards the end of his life.[163]

The concept is not new and one of the earliest analyses of the potential consequences of variation in tidal strength was published in 1913[164] by Otto Petterson, who studied the evolution of internal waves on the pycnocline in the Kattegat, and the consequences of their breaking at high tidal velocities. This oceanographer and polymath made the first observations of cooling of surface water by the vertical mixing of cold, deep water to the surface at the overflow of the Gullmar fjord in 1911 at a peak of the 18.6-year nodal cycle, so modulating the flow of warm surface water into the Baltic.[165] He also realised that when orbital forcing was exceptionally strong, at much longer intervals, "*there must be great floods, sharp extremes of climate and great temperature contrasts*". He realised that the previous paradigm, attributable to Nansen, of a historically invariant North Atlantic climate must be wrong, and described the effects of the exceptional tides that accompany longer cyclical pattern in the Sun-Moon-Earth relationship on the relative ice coverage of the NE Atlantic. He understood the consequences of these periodic events for mediaeval and later settlement in Greenland and Iceland and noted that settlement had coincided with the start of a period of relatively low tidal forcing around the beginning of the millennium, when the first Norse settlers had found Iceland to be *"green from mountain to shore*". All this was terminated when a new epoch of maximal tide-generating force "*ruled by the perihelion node-apside…which occurred at the beginning of the 15th century*" and which brought frigid conditions to the seas around Iceland. The effects of this period of super-tides (that peaked in the 1430s) were also recorded historically in the flooding of the low-lying coasts of northern Europe (see p. NN).

It was later confirmed by Canadian oceanographers that periodically strong tidal motion does indeed reduce surface temperature on continental shelves because dissipation of the tidal force increases vertical mixing and so cools the surface layer; these observations were made on both Atlantic and Pacific coasts, thus validating the effect in two contrasting tidal regimes – semi-diurnal and mixed.[166] A relationship between tidal strength and SST has since been confirmed in other places:

(i) - in Indonesian seas, where enhanced vertical mixing of the water column during periods of strong tides occurs in both Serum and Banda Seas; perturbation of the thermocline is associated with mixing down of freshwater and heat from the surface layer and their export to the Indian Ocean;

(ii) - in the open North Pacific Ocean where the 18.6-year nodal tide mode is associated with significant and sustained changes of more that 1°C over this cycle; this process is associated with changes in SAT at Sitka, Alaska, which enables the effect to be

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[163] *Keeling, C.D. and T. Whorf (2000) PNAS 97, 3814-3819.*
[164] *Pettersenn, O. (1913) Svenska Hydrog.-Biol. Komm. Skrifter.*
[165] *Pettersen, O. (1930) The tidal force. Geogr. Ann. 12, 261-322.*
[166] *Loder, J.W. and C. Garrett (1978) J. Geophys. Res. 83, 1967-1970.*

hind-cast back to the early 19th century. In the resulting reconstruction, up to 30% of the low-frequency variance appears to be associated with the 18.6-year nodal signal

(iii) - in the Barents Sea, where the same periodicity is observed in both SST and in the physiology and reproduction of fishes, providing an alternative explanation for the periodicity observed in cod physiology and in other components of the ecology of the region. Here, the "*code of long-term fluctuations of Norwegian spring-spawning herring*" is given by the 18.6 year lunar nodal tide and its harmonic cycles.[167]

(iv) - and in the Carioca Basin, a relationship between varved deposits and the 18.6 year tidal cycle has been observed over a period of 600 years.

When Charles Keeling had accumulated several decades of CO_2 observations at Mauna Loa and the South Pole, he became interested in the periodic, quasi-decadal signal that became evident in the CO_2 background concentrations. Depending on the strength of the spline that was fitted to the detrended data, these revealed El Niño patterns or, with a stiffer spline curve, a secular trend was revealed that took lowest values around 1975. The decadal variability then led him to the tidal cycle and to note that tides provide more than half of the total power that induces vertical mixing in the ocean - 3.5 terrawatts compared with about 2.0 from wind drag at the surface. Consequently, he noted that periodicity in tidal forcing may sufficiently modulate vertical mixing - and hence SST - as to cause cyclical surface cooling at millennial scale; he also noted that the 1800-year tidal cycle has been the dominant forcing of climate change during the Holocene, and that the Little Ice Age was no more than a minor expression of this process.

Because the sequence of tidal forcing contains periodicities that can be computed as well as observed, both past and future periods of cooling are known with certainty: tidal forcing was extremely weak during the Roman and Mediaeval climate optima, but maximal between 1430 and 1610 and was therefore associated with the low air temperature of the Little Ice Age. Some have proposed that the progressive warming observed since the 19th century has been a recovery from this period due to weak but progressive increase in solar radiation: more correctly, we have two alternative (or reinforcing) explanations for this recovery, solar and lunar, because tidal forcing has become progressively weaker since the 17th century, contributing to long-term warming of the climate even as solar radiation has progressively increased. The 18-year period of the Saros cycle is reflected in cooling of surface seawater temperatures, an effect modulated at longer periods, that include peak forcings in 1880 and 1974, both being consistent with the global SAT record discussed in Chapter 4. The 1800-year cycle in the tide-raising forces shows a clear maximum that corresponds well with the period of the Little Ice Age - thus, incidentally, resolving the vexed question of whether this was a global phenomenon.

The 1795-year cycle has been identified from the ice-rafted debris record in North Atlantic and in lake sediment cores and their associated temperature proxies, supporting the suggestion of a role for tidal stress in the sudden cooling events: in Elk Lake in north-central USA for which timing of events is unusually precise, three sharp spikes of ice-rafted debris coincide very closely with 1800-year tidal events - and, moreover, coincide with dated changes of climate state in other parts of the world.

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[167] *Yndestad, H. (2003) J. Mar. Sci. 60, 1251-1264*

Keeling and Whorf point out that the next maximum of tidal forcing will occur only in 2133 and will be relatively weak so the continuing warming trend from tidal effects will be additional to any caused by increasing CO_2 in the atmosphere or other anthropogenic effects. [168] And it will only be after a further 600 years that tidal forcing - and its cooling effects on SST and SAT – will be as strong as it was around 1970; continued and progressive warming of the surface ocean is inevitable, and thus of the global surface air temperature generally, through the next several centuries. Needless to say, the proposition that tidal frequencies and their beat harmonics at millennial scale are of sufficient amplitude to generate sufficient cooling to be associated with climate perturbation, has been questioned; rather, it is suggested, dynamic processes in the atmosphere are the cause of the observed climate perturbations. However, "*low beat frequencies between tidal harmonics...cannot be ruled out by any evidence known to us; if these indeed are a factor, then the combination proposed by Keeling and Whorf is the most likely candidate*". [169]

At much longer intervals, much greater effects of the strength of tidal streams must occur. Since tidal strength is related to periodic changes in orbital relations within the solar system, it is natural to suppose that the 41,000-year variation of the obliquity of the ecliptic (the key to the Milankovic theory of ice ages) may have consequences for tidal forcing of climate state comparable to the changing solar radiation. In fact, computation shows that the deep ocean tide could act as a pacemaker to terminate ice sheets at every second or third obliquity; this would solve the difficulty of reconciling the 40-kyr obliquity period with the 100-kyr period of glaciations. Further, while solar radiation simply delivers heat to the earth's surface, the perturbation of ocean heat content and distribution by tide-producing forces modifies the poleward transfer of heat associated with the meridional overturning circulation. During glaciations, North Atlantic tides were twice as high as today and pelagic dissipation three times as strong, and '*these feedbacks dwarf the astronomic forcing*' of Milankevitch, according to Munk and Bills, who further note that, although there are complications not yet considered such as the increased depth of the shallow seas due to ice melt, and the consequent increase in tidal dissipation .....but they note that "*the numbers will not go away*".[170]

The investigations discussed here illustrate very well the depth of the divide between those climatologists who closely follow the opinions and predictions of the IPCC and those who are, one might say, freethinkers – which, I maintain, should be the hallmark of a scientist. The role of tidal mixing in ocean climate has long been a minor subject of discussion and – for some oceanographers – frustration, but 't*here is now wide agreement that tidal mixing must be taken into account in any realistic modelling of ocean properties*' to quote Walter Munk: however, the word 'tides' and 'tidal' have no place in the text of the latest Assessment Report of the IPCC except in relation to problems of changing global sea level. The studies that are quoted by AR5 seem to be out-of-touch with oceanographic analysis: I expect little light to be thrown on a complex problem when I read that "*a coupled oscillator model shows that changes in sea level on the shelf*

[168] *Keeling, CD and TP Wharf (1997) Proc. Nat. Acad, Sci. USA 94, 8321-8328, and also Keeling, C.D. Ann. Rev. Energy Env 23, 25-82.*
[169] *Munk, W. et al. (2002) J. Climate 15, 370-385.*
[170] *Munk, W. and B. Billins (2007) J. Phys. Oceanogr. 37, 135-147*

are much more effective at perturbing shelf and ocean tides than sea level changes in the deep ocean" in the summary of a paper quoted by AR5. [171]

3.8 - The Holocene CO_2 and CH_4 anomalies

Before leaving the general question of solar cycles it will be useful to return to a very interesting question posed by the ice-core data at Glacial Termination 1: why was the evolution of atmospheric temperature following this event so different from that of the three previous interglacials?

The existence of the anomaly has been known since the earliest core analyses, and it was the source of the suggestions made in the mid-1970s that the present interglacial period was already abnormally long compared with previous interglacials, and that the observed cooling that was being observed in those years (see p. 6) signalled the beginning of a new glacial epoch. This suggestion was made at a time when the pattern of only the previous three interglacials was available, but this was sufficient to tell us that Antarctic temperatures peaked only very briefly at Terminations 2-4 compared with the more extended warm period that followed the most recent Termination.

Almost everybody is now agreed that the pattern of glacial-interglacial periods is forced by subtle and cyclical changes in solar radiation whose period responds to changing orbital geometry, and – in particular – to the eccentricity of Earth's orbit around the Sun which has been progressively decreasing during the last 200 Kyr and will, over the coming glacial cycle, exhibit only about 25% of the eccentricity characteristic of the previous cycle. This will resemble the pattern of solar forcing after Termination 5, which was followed by a much longer interglacial period than Terminations 2, 3 and 4. Using this observation, it has been predicted that we may have a long interglacial ahead of us, during which climate will certainly be modified by our activities. That this has occurred already has been suggested by the establishment of a new geological era, the Anthropocene, the dating of which has caused some dissent; some suggest that the best stratigraphic marker would be in mid-20th century, with the start of massive accumulation of debris, while others prefer the start of the industrial revolution in the 19th century. But because it is probable that human activities influenced global climate long before that, some prefer to consider it to be coeval with the Holocene since the start of agriculture and animal husbandry occurred right after Termination 1.[172] The question is currently debated in geological circles and it is possible that compromise will be reached on a subdivision, to include a Paleoanthropocene era covering most of the Holocene to date.[173]

However those times may be called, when modern man emigrated from Africa his arrival on each continental land-mass (with the possible exception of Australia) coincided closely with the initiation of the Quaternary Extinction Event that involved the disappearance of almost the entire fauna of great mammals and birds within a short period from about 50-10 Kyr BP: only Africa retained some of its original megafauna of

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[171] *Muller, M. et al. (2011) J. Geophys. Res. 116 C5 DOI: 10.1029/2010JC0063*
[172] *Smith, B.D. and M.A. Zeda (2013) Anthropocene 4, 8-13*
[173] *Foley,S.F. et al. (2013) Anthropocene 4, 83-88*

giraffe, elephant, rhinoceros, hippopotamus, ostrich and so on: with a few interesting exceptions, very large animals are extinct everywhere else.[174]

The process of extinction was very rapid. The Maoris eliminated the large vertebrates of New Zealand, here only giant birds, in just 2000 years. In America, there is evidence for a progressive collapse of the megafauna from north to south over a similarly brief period starting 13.4 Kyr BP, immediately following the opening of an ice-free corridor from Asia in the Alaskan region.[175] So, although there had already been a slow and progressive loss of very large mammals during the entire Pleistocene, what happened after the most recent glaciation was exceptional, and is widely accepted to have occurred as the wave of human migration encountered naïve populations of large mammals and birds, which had insufficient time to learn that modern humans were lethal neighbours.

All this must have had a major impact on global vegetation cover and, hence, on global albedo and there is, in act, good evidence that a major modification of terrestrial ecosystems accompanied this wave of extinctions. In Australia, the drought-adapted savannah vegetation was rapidly transformed into fire-adapted desert scrub, even further reducing the rainfall in the interior of the continent.[176] But it was not necessary for humans to intervene with fire, as they may have done in Australia, for the vegetation cover to change rapidly; the loss of some American mammals, especially very large herbivores, disturbed the dispersal mechanisms of many plants, including trees, which disappeared progressively from the original vegetation: those individual trees of these species that survive today now produce seeds and other dispersal agents in great excess. The herbivores with which they co-evolved are no longer present to consume them.[177]

I can find no estimates for the consequences of these human-induced and global vegetation changes for atmospheric composition around Termination 1, but a radical proposition from Ruddiman, coming – it was said by an editorialist – "*like a bolt from the blue*" in 2003, suggested that about 8000 years ago, very early in the Holocene, some changes in atmospheric composition can be attributed to human activities. This suggestion was based on the observation that, shortly after Termination 1, atmospheric CO_2 and CO_4 concentrations began to diverge from the trajectories that had been characteristic of the previous three glacial transitions, during which atmospheric CO_2 and CH_4 concentrations had decreased steadily for several tens of thousands of years from their peak values at each glacial termination, eventually reaching significantly lower levels. The anomalous reversal of the decrease of CO_2 and CH_4 in the Holocene atmosphere at 6000 and 8000 yr BP, respectively, "*has no counterpart in any of the three previous glaciations*" as the author put it.[178] This proposal was derived from studies that compared the evolution of Antarctic air temperature and CO_2 content over the last five glacial terminations, including the anomalous rise in CO_2 after a brief period of falling concentrations after the peak temperature was reached at Termination 1. It was also found that neither temperature nor CO_2 nor yet CH_4 followed the same pattern at Termination 5 as at the following three terminations.[179]

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[174] Lyons, S.K. et al. (2004) Evolut. Ecol. Res. 6, 339-358.
[175] Martin, P.S. (1973) Science 179, 969-974.
[176] Miller, G.H et al. (2005) Science 309, 287-290.
[177] Janzen, D.H. and P.S. Martin (1991) Science 215, 19.
[178] Ruddiman, W.F. (2003) Climatic Change 61, 261-293.
[179] Toggweiler, J.R. (2008) Palaeoceanogr. 23, PA 2211. Doi:10.1029/2006PA001405,2008.

The CO_2 anomaly after Termination 1 had previously been ascribed to natural causes involving regrowth of forest cover when glacial ice cover receded, but this does not explain why the same had not occurred after earlier Terminations[180]. Ruddiman proposed that the start of the Holocene CO_2 anomaly represents the reduction of terrestrial vegetation cover as the human population turned to agriculture. And the start of the CO_2 anomaly is indeed closely contemporary with the Neolithic demographic transition because analysis of burial grounds in the Middle East, North Africa, Southeast Asia and America demonstrates a shift in relative numbers of deaths in each age class indicative of a change from static to rapidly expanding human population size. This is indicative of the adoption of sedentary life style, food storage, and stratified agriculture, after which birth rates and absolute population numbers increased dramatically. Each of the areas in which this occurred was rich in wild cereals, legumes, tree crops, tubers and animals, all suitable for domestication. [181]

The CH_4 anomaly is thought to represent the effect of the start of irrigated rice agriculture in China and SE Asia, with which it is contemporaneous, and also with the development of herding of bovine ruminants – as in the green Sahara of those times - whose digestion releases CH_4 in significant amounts.

Major change must have occurred in the terrestrial carbon pool with the beginnings of agriculture, first shifting and then progressively settled because the amount of carbon stocked in the new farmlands will have been smaller than in the pristine vegetation cover. It has not been easy to recreate the progressive transformation of forest and shrub lands into cultivated land, but the changes during the subsequent millennia in global plant cover were certainly very fundamental: examples are the desiccation of the Sahara – apparently at least partly due to human activity – and the deforestation of western Europe.

Confirmation of the effect of human activities on the anomalous increase in CO_2 appears to be obtained by the observation that changes in its concentration occurred during the collapse of global human population numbers during the pandemics of the late Roman era and the mediaeval period: agriculture was widely abandoned during these pandemics and carbon began to accumulate again in regrowth of natural vegetation.

But Ruddiman's proposition was not received enthusiastically by the climate science community, which responded with critical comment, and with counter-argument. For some authors, "*the consequences of the widespread modification of terrestrial ecosystems as farming developed are consistent with the hypothesis that human activities led to the stabilisation of atmospheric CO2 concentrations at a level that made the world substantially warmer than it otherwise would be*".[182] Others dismissed Ruddiman's proposal out of hand, suggesting (for instance) that the CO_2 anomaly was entirely due to imbalance in the oceanic $CO_2/CaCO_3$ relationships induced by uptake of oceanic CO_2 by the rapid post-glacial regrowth of forests.[183] One must wonder, though, why this should not have occurred after each previous Termination, no matter what the solar conditions might have been?

180 *Broecker, W.S. et al (1999) Biogeochem. Cyc. 14, 599.*
181 *Bellwood, P. & M. Oxenham (2008) "The Neolithic Demographic Transition"(Springer),pp. 13-30.*
182 *Kaplan, J.O. et al. (2011) The Holocene 21, 775-791.*
183 *Broecker, W.S. and T.F. Stocker (2006)Eos, 87, 27/*

It has been argued, on the basis of modelling results, that the CH4 anomaly of the Holocene deglaciation is not anthropogenic from cultivation of rice in paddies but a natural release of CH_4, mostly from southern hemisphere wetlands; simulations the Holocene and the previous Eemian deglaciation (150-130 yr BP) – when CH_4 did not increase after an initial drop – have been used to suggest that human influences on CH_4 fluxes are not required to explain the Holocene-Eemian difference; the models indicate that a modest glacial inception during the Eemian (due to differences in insolation levels during the two deglaciations) prevented a rise in CH_4 similar to that which occurred during the Holocene.[184] But this argument avoids the question of why the Holocene is anomalous with respect not only to the Eemian, but also to the three earlier glacial terminations of the Quaternary – each of which occurred at different total levels of solar radiation?

Perhaps the most fundamental criticism was made by the EPICA group[185], which suggested that marine isotope Stage 11 – the period immediately following Termination 5 (409,000 years BP) is really the best analogue for the Holocene interglacial because of its similar orbital situation to that of the Holocene and Termination 1. In this case, they noted, a new glaciation would not today be expected for another 16K years. But it is now realised that this comparison is not exact, because there is an obvious difference in insolation pattern during the two periods: the Holocene interglacial spans only a single solar maximum, while Stage 11 spanned two solar maxima due to coincidence between a minimum in orbital eccentricity and a maximum in Earth's axial tilt.[186]

For this reason, Tzedakis et al. re-examined the problem and located a more exact analogue for our present situation at the rather older sub-Stage 19c, at 777 Kyr BP, when northern summer insolation was at a minimum. At this time, ice core data show that CO_2 and CH_4 were dropping to values predicted in the absence of any anthropogenic effect, temperatures were falling and peak interglacial warmth had ended. So, the only serious difference with Holocene conditions is that CO_2 levels diverge in the two periods, exactly as we would expect them to do from Ruddiman's early Anthropocene hypothesis. [187]

This alignment also appears to be compatible with the factors constraining glacial onset discussed by the same authors, who propose that this cannot occur prior to the establishment of a 'bipolar-seesaw' (to use their term) in climate variability that requires ice-sheets large enough to discharge sufficient icebergs to the ocean to disrupt the overturning circulation sufficiently to reduce the flow of heat into the North Atlantic and to induce slow warming in the Antarctic: in a word, to induce heat flow between the northern and southern hemispheres. Applying this logic to the Earth at sub-Stage 19c – now thought by at least some to be the closest analogue to our times - gives a Holocene duration of 10.5-12.5 thousand years, and glaciation commencing with atmospheric CO_2 levels of about 240 ±5 ppm. This is, as Tsadlik et al. comment, in line with Ruddiman's hypothesis….

In the end, '*each and every aspect*' of the early Anthropocene thesis had been challenged - as Ruddiman remarked in prefacing his formal response. Nevertheless, he

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184 *Singarayer, J.S. et al. (2011) Nature, 470, 82-85*

185 *EPICA Community Members (2004) Nature, 429, 623-628.*

186 *Rohling, E.J. et al. (2010) Earth Planet. Sci. Lett. 291, 97-105.*

187 *Tzedakis, P.C. et al. (2012) Nature Geoscience Letters doi:10.1038/NGEO1358*

defended each and every one of his propositions, although he agreed that his original estimate of carbon release from early deforestation had been too large.[188]

Despite this response, the issue will surely continue to be debated, and it was the subject of a recent issue of *The Holocene*.[189] In this volume, there were suggestions that the original estimates for mid-Holocene human populations had been underestimated and that, consequently, the amount of CO_2 released by early farming, using very conservative assumptions, must be larger than first thought. To the population size must also be added new information concerning land usage by shifting agriculture that modifies very significantly the previous assumptions concerning CO_2 release. A recent review of the history of rice farming confirms that the earliest production was from wet, paddy culture in southern China as early as 6000 yr BP with a transition from dry rice culture to paddy in India by about 3000 yr BP, each shift having major consequences for the release of methane.

Ruddiman's proposal has, quite properly, been given more serious consideration by the IPCC in their 5th than in their previous 4th Assessment Report, in which it was dismissed rather summarily. In the latest assessment, no mention is made of the similarity of the Holocene with Stage 11, but reference is made to the CO_2 processes in the Southern Ocean discussed above and (curiously) to the proposition that CO_2 stimulation of natural vegetation must have progressively increased terrestrial carbon storage. Two modelling studies are mentioned, each with opposing results concerning changing land usage, and two opposite opinions are offered concerning the relationship of fires in the environment and human population density. Similarly, two natural wetland models are respectively '"*able to or unable to*" simulate late Holocene increases in CH_4 concentration![190]

But we are carefully reminded that the "*variations in atmospheric CO_2 over the past 11,000 years preceding industrialisation are more than five times smaller than the observed CO_2 increase during the Industrial era*"….

And there the matter rests for the moment.

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[188] *Ruddiman, W.F. (2007) Rev. Geophys. 45, RG4001:1-37.*
[189] *The Holocene (2010) Vol. 20 (4)*
[190] *IPCC 5th AR, paragraphs 6.2.2.1 – 6.2..2.2*

Chapter 4

CAN A GLOBAL MEAN TEMPERATURE BE MEASURED?

"…however careful the observing procedures and however carefully studied the adjustments applied afterwards to the observations, to declare a value for the world average or an area average to within some hundredths of a degree centigrade is an unattainable ideal"[191]

The agencies which are tasked with issuing regular evaluations of the progress of global warming habitually use a single value to represent a '*global mean temperature*' as the prime indicator of this process.

Curiously, together with the financial indices from Wall Street or the City, this value has become one of the most important single numbers that are used to measure change in affairs that interest us economically and socially, and, like them, it now carries heavy implications for some commodity and financial markets. But it differs from them in one very fundamental manner: financial indices are based on data whose precision is known, and whose significance is understood, so that financial crashes are not the fault of the numbers but rather of some inappropriate action on the part of the players in the game. But the single number that represents a global mean surface temperature (GMST) over land and sea - relentlessly recorded every month by several government science agencies – is based on data that are incompletely understood, that are often wrong, and collectively are perhaps meaningless. That changes in this number do not represent changes in heat content of the oceans and atmosphere is very little discussed, yet this is the quantity that is critical to understanding the dynamics of radiatively-forced climate change, be it the Sun or CO_2 that does the forcing.[192] Such are the problems addressed in this chapter.

4.1 - Consequences of patchy observations and doubtful assumptions

The term 'global mean temperature' has no formal meaning, and I have found no clear definition of it: IPCC4 simply introduces it as the *"global mean temperature over ocean and land surfaces*". Change in this value is firmly entrenched in the climate change literature, and in the public's mind, as the index of anthropogenic warming of Earth and may be variously expressed: as a mean surface air temperature (SAT) on land surfaces (without correction for elevation, be it noted) together with the sea surface temperature (SST) of the oceans. Together, these are used as the principal indicator (as the GSMT) of

[191] *H.H. Lamb (1982) Climate history and the modern world (Rutledge)*
[192] *see, for example, Essex, C. et al (2007) Non-Equil. Thermodyn. 12, 1-27*

the progress of anthropogenic global climate warming; unfortunately, these measures are incompatible, even if they are all we have.

The competence of a single value to represent mean surface air temperature above all continents, at all elevations, over both natural landscapes and cities, at all latitudes from polar to equatorial and also over ice caps, lakes and oceans is rarely questioned. But some discussion is certainly required concerning the extraordinary degree of extrapolation from such diversity to a single value, to say nothing of the problems of changing methods of temperature measurement that have been used over the century-long period for which we suppose that we have precise and accurate measurements.

This global surface temperature is expressed as the anomaly of the mean over long periods, and is assumed to be weightless, so that very small changes of the order a tenth of a degree are accepted as representing the rate and sign of global warming. Formally, this value is based on the measurement of surface air temperature (SAT) over land, and of sea surface temperature (SST) at sea and it is commonly reported as having changed by some small fraction of a degree Celsius over a few decades, or even between one year and the next.

One fundamental flaw in the use of this number is the assumption that small changes in surface air temperature must represent the accumulation or loss of heat by the planet because of the presence of greenhouse gases in the atmosphere. With some reservations, this is a reasonable assumption on land but at sea, and so over >70% of the Earth's surface, change in the temperature of the air a few metres above the surface may reflect nothing more than changing vertical motion in the ocean in response to changing wind stress on the surface; consequently, changes in sea surface temperature (and in the air a few metres above) do not necessarily represent significant changes in global heat content although this is the assumption customarily made.

As if those problems were not enough, the use of the changes in a simple mean of many local values (even if extrapolated over a global grid) to represent trends at global scale is scorned by at least some mathematicians: a global temperature, commented Essex and his co-authors "*is nothing more than an average over temperatures…as if the out-of-equilibrium climate system has only one temperature. But an average of temperature data sampled from a non-equilibrium field is not a temperature. Moreover, it hardly needs stating that the Earth does not have just one temperature. It is not in global thermodynamic equilibrium — either within itself or with its surroundings.".* They further point out that there is no reason to choose the averaging method habitually used in climate studies, and they use a small file of a dozen or so stations with very long data to illustrate the consequences of choosing one among many other possibilities: "*The global temperature statistic is also described as the average, as if there is only one kind of average…there is an infinity of mathematically legitimate options. Indeed over one hundred different averages over temperatures have been used in meteorology and climate studies with more appearing regularly. For the case of temperature, or any other thermodynamic intensity, there is no physical basis for choosing any one of these from the infinite domain of distinct mathematical options.* [193]

None of these niceties are accessible to the general public or, probably, to most of those working on climate change research – most of whom surely fail to understand the

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[193] *Essex, C. et al. (2007) J. Non-Equilib. Thermodyn. 32, 1-27*

levels of uncertainty inherent in these values, and the significance that may be placed on any 'global temperature' – yet we all encounter the concept almost daily in the public media and the scientific journals.

To the extent that we can isolate the effects of anthropogenic change in the atmosphere from the effects of natural change, then change in lower troposphere temperatures are indeed of relevance and their reduction to a single global value would be of some interest. But unfortunately, even the deceptively simple measurement of SAT or of NMAT has proved to be difficult to make with sufficient accuracy, at a sufficient number of suitable places and over sufficiently long periods, to give much confidence in the regional temperature histories that have been derived from it.

Also unfortunately, the easy availability of sophisticated data processing techniques tends to hide the fact that the original, unprocessed data obtained both ashore and afloat are themselves of very varied quality; this is not surprising since they represent daily measurements made by people having a wide range of competence and dedication, under different working and political conditions. At each observatory or aboard each observing ship, the data have been obtained, in principle, with a standard set of thermometers exposed in a standard manner and read at standard hours – but, inevitably, these standards have been followed better in some places than in others and everywhere they have evolved over time. Consequently, the resulting data are not of the quality we have come to expect from modern observation programmes, yet they are all we have against which to verify the results of numerical climate modelling.

The uncertainties that are inevitably associated with SAT data due to poor maintenance and placing of the equipment have been much discussed in the climate change literature and one of the most-frequently criticised aspects of the data has been the extent to which the specifications for the exposure of instruments has been followed, and to what extent 'best practice' for the measurement of temperature at ground level has evolved during the period of interest.

Consider just one simple characteristic of the basic measuring instrument – the mercury-in-glass thermometer.[194] Because glass is a liquid, it flows over time in such a way that meteorological thermometers may progressively indicate warmer temperatures, the rate-of-change being of order 0.1C per decade – very similar to the rate calculated for anthropogenic warming of the atmosphere by CO_2. In some cases, a correction has recently been made for some data sets, such the 200-year Hohenpeissenberg data[195], but it seems extremely probable that creeping, progressive errors have contaminated the historical data: not all station metadata record the date of changeover from mercury-in-glass thermometers to electronic measurement and not all have recorded the progressive renewals of old thermometers. There seems little probability that this can be investigated now that the adjustment of the observations and the data files derived from this process are in common use.

Even the simple, louvered Stevenson screen (containing maximum/minimum and wet/dry bulb thermometers) has been far from standardised since its earliest use in mid-19th century, and it exists today in several versions that are thought to be

[194] *Ian Strangeways, Imperial College, U. London, 13.2.10*
[195] *Winkler, N. (2009)Theor. Appl. Climat. 98, 259-268.*

appropriate for different climates.[196] How it must be exposed, and how it must be protected from local heat sources, or from the effect of the growth of vegetation nearby, is clearly stated in standard opiating procedures but is rather frequently forgotten or ignored.

It is very easy to locate installations that do not meet the basic criteria. And, consequently, a major survey of the degree to which these instrument housings were correctly placed and maintained in the United States was made by a group of 600-odd followers of the web site Climate Audit; the siting of 1007 stations of the US Historical Climate Network (about 83% of the total) was photo-documented, and each station categorised for compliance with NOAA-required procedures for these stations. This examination, which did not involve control for instrument type or daily observation schedule, showed that only 7.4% of the examined stations were sufficiently in compliance to be considered valid for climate research. The study was undertaken with the expectation (based on a much smaller sample) that a spurious warming trend would have been introduced into the data by the frequent proximity to the instrument screen of external sources of heat from parking lots, air conditioners, and so on, and also from the effect of being placed on bitumen or cement surfaces, rather than on the specified grass plot.

But the results were surprising: although poor siting was abundantly confirmed so that 70% of the USHCN stations could be expected to show significant uncertainties (2-5°C), it was found that overestimates of minimum and underestimates of maximum temperatures were similar in magnitude, so that mean daily temperatures were little affected by how well or how badly the instruments were exposed: only the very worst-sited stations tended to be warmer than the overall mean. There were also important consequences for the measurement of diurnal temperature ranges, for which the study confirmed the existence of an overall long-term downwards trend, that had been observed since mid-20th century. But, on the contrary, at "*the best-sited stations, the diurnal temperature range has no century-scale trend*". As shall be discussed in Chapter 6 such trends are commonly associated with local anthropogenic effects on low-level atmospheric particulates from the use of wood and coal for heating and cooking.

Then, the relatively small numbers of well-sited stations showed less long-term warming than the average of all US stations. Based on 30-year data sets from each station, aggregated into 5 classes of site quality, all trends (mean, maximum and minimum) differed significantly between well- and poorly-sited stations. The temperature increase at well-sited stations was 0.145°C lower than for all stations combined, while the gridded mean of all stations in the two top categories had almost no long-term trend (0.032°C/decade during the 20th century); each of the other three categories indicate a strong warming trend (0.221°C/decade).[197]

Despite all the uncertainty inherent in any practical utilisation of the instrumental data, changes in the global values for SAT and SST are now firmly entrenched in the climate change literature, and in the public's mind, as the index of warming of Earth by anthropogenic greenhouse gases, and it is tacitly accepted that the GMST represents an instantaneous average surface air temperature above all continents,

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[196] *Strangeways, I (2010) Measuring global temperatures. CUP pp. 233 (this is a good introduction to the subject).*
[197] *Fall, S. et al. (2011) J. Geophys. Res. 116, D14120*

over both natural landscapes and cities, from polar to equatorial zones, from plains to mountain-tops and over oceans, lakes and ice-caps.

This is a truly extraordinary degree of reduction of great diversity to a single value that is commonly expressed as a weightless anomaly of the mean (at each data point and also globally) over long periods; very small changes of the order of a tenth of a degree in this anomaly are taken to represent the rate and sign of change in a global mean temperature, although this term itself has no formal meaning. Despite all this, the IPCC uses a standard unit (the Global Warming Potential) for the effects of each radiatively-active gas is derivative and suggests that this would be a useful metric "*for trade-off between emissions of different forcing agents*" in establishing emission constraints "*so that multi-gas emitters (nations, industries) can compose emission constraints…by allowing for substitution between different climate agents*".

In implementing these suggestions across the diversity of land-forms and ocean conditions, the climate change community has embraced the concept of temperature anomalies as the primary expression of change in local, regional or global climatic conditions; this concept is commonly unquestioned – because it is an apparently logical first step toward some degree of homogenisation of diverse measurements. But a fundamental criticism of this technique has been made by a well-known English meteorologist, who wrote: "*The technique of using anomalies to counteract or avoid the difficulties caused by sites having different characteristics, different climates, varying altitudes and different seasons assumes that while absolute temperatures are strongly affected by these factors (which they are), anomalies are completely immune from any of them…But is this correct? An anomaly of x°C at 600m altitude does not necessarily have the same weight as an x°C anomaly at sea-level nearby…*".[198]

And so on… to which I would add that anomalies in SAT and in SST data may represent responses to two quite different forcing mechanisms, and may have two quite different consequences for the heat budget of the planet that really should not be confused – although no distinction is normally made between temperature change in the two environments. In this context, the same meteorologist remarked rather wryly, "*All one can meaningfully do is look at changes in regions of similar climate, in the same hemisphere, with the same geography, in spring, summer, autumn or winter – not all of these things at once*."

Only a small part of the daily observations made by weather stations the world over has been archived for the study of climate change and, given the ubiquity of weather forecasting, one might have hoped for better than we have - which is extremely uneven in both space and time. We might also have hoped that the internationally-recognised routine for each type of daily observations would have been strictly followed at all stations, but the reality is very different. Examination of original data records commonly shows breaks in the continuity of the data or a significant change in the mean value during just a very brief period which is unlikely to be natural, and is often considered *post facto* to be due to the move of the instrument housing to a better place (often cooler, because better sited), or to the replacement of mercury-in-glass thermometers by electronic thermistors which results in sudden cooling.[199] These changes may (or may not) be recorded in the meta-data provided by the agency concerned.

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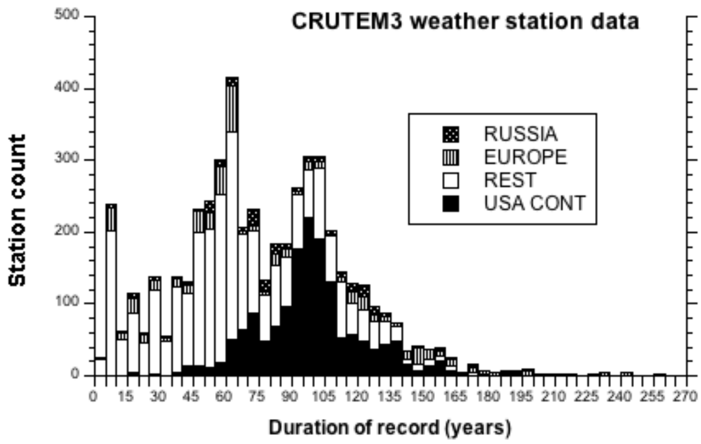
[198] *Strangeways, Ian (2010) "Measuring Global Temperatures", CUP, New York.*
[199] *Quale, R.G. et al. (1991) Bull. Aer. Meteorol. Soc. 72, 1718-1724.*

That such issues would complicate the task of computing global mean values for climate indices ought to be well understood but as recently as 1991, a study published by AGU felt that it was necessary to point out that '*From a climatological standpoint, the instrumental record is both incomplete and uneven...there is insufficient large-scale spatial and temporal coverage for us to make confident statements about climatic variability*'; this problem was judged to have introduced variability and bias into the long-term climate record. [200]

Although the gathering of archives of long-term data from weather-forecasting services for climate study goes back to the early decades of the 20th century, the requirement for such data only became urgent in the early 1990s, when understanding climate change became a research imperative. Consequently, in 1992, data from many of the weather stations that had been designated by the WMO as suitable for climate monitoring were gathered into a Global Historical Climate Network (GHCN) data archive; these comprised about 6000 temperature, 7500 precipitation and 2000 pressure stations.[201] The GHCN continues to be maintained at the NOAA National Climatic Data Centre and made accessible to researchers by US/NASA Goddard as the GISTEMP (global) data set and by the Hadley Centre of the UK Meteorological Office (with the Climate Research Unit of the University of East Anglia) as the CRUTEM and HadCRUT (land surface) and HadSST (ocean surface) data sets. These archives have been progressively enhanced by the acquisition of further national archives, some through accession to the GHCN, others more directly.

Very few of the observing stations operated routinely over long periods: for instance, the 5111 stations compiled as the CRUTEM3 archive included 32 stations that obtained routine data for >200 years while 45 stations have data for less than six years, including 4 that operated for only a single year - yet these were still included in the archive! [202] The distribution of record length in this archive is probably typical of the GHCN; the conterminous US data comprised almost half (47.4%) of all stations whose data records extend through the entire 20th century, as shown in the following figure.



The extent of the aggregation of station data into certain regions is probably not generally appreciated and the extent of the addition and removal of stations from the

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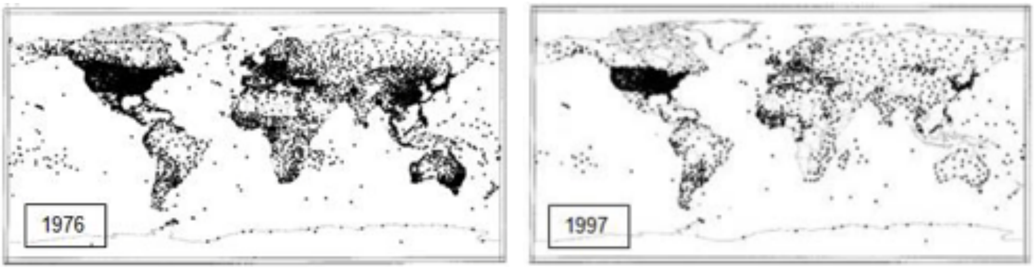
[200] *Willmot. C.J. and S.M. Robeson (1991) Geophys. Res. Lett. 18, 2249-2251.*
[201] *Peterson, T.C. and R.S. Vose (1997) Bull. Amer. Met. Soc. 78, 2837-2849*
[202] *My thanks to John Kennedy, UK Met. Office, for assistance in downloading data.*

record is certainly not much discussed, but both are very significant. In fact, the stations that have contributed to the GHCN archives are distributed very unevenly on the surface of the continents: the CRUTEM3 data included 1435 stations in the lower 48 United States, but only 74 in all of the much greater expanse of Russia! In the USA, each station represented 5,960 km^2 of surface area, compared with 190,000 km^2 in Russia. The global average is 23,740 km^2. Perhaps equally significant is the imbalance in station location because the global ratio of rural and urban stations is strongly unbalanced: there are relatively few urban stations (<10%) in the USA but these are dominant (c.90%} in data from the rest of the world.

Any use of such data requires an assumption that the flow of data from each region has originated in a sufficiently unchanging number of sites that uniformity can be assumed, both spatially and temporally but, as you might expect, this is very far from the truth; in every region the number of reporting stations whose data have entered the global data archives has changed grossly (there is no other suitable word) during the period since the first modern observations were made. The numbers of stations that have been recorded each year in the GHCN archive increased progressively during the 20th century until the late 1980s, after which the numbers of stations whose data were incorporated was rapidly reduced - even if many of these stations continued to obtain data. Below are the distributions of stations that were archived in the GHCN during the 1970s compared with the distribution of stations being accessed 20 years later.[203]



The greatest reduction in the number of stations occurred during the 1980s, although the decline continued even after the end of the century so that, of the 15,000-odd stations that were eventually incorporated into the GHCN by the mid 1960s, just 4802 stations remained in the HadCRUT3 archive in 2012 – even though some of these were not necessarily continuing to report data. Worse yet, 44% of these were in the conterminous USA,.[204]

The potential consequences of the changing pattern of station data during the 20th century are not trivial; the proportion of 5^o x 5^o grid boxes with data has never been high, but since 1980 this decreased severely, so that by 1990 only about 32% of northern hemisphere grids – and 12% of those in the southern hemisphere – contained data. This has surely been an unsatisfactory sample of the whole on which to base so much expressed certainty concerning a single global value? It has been suggested informally, using an NCAR climatology (having smaller numbers of data points than the GHCN) for the period prior to 1990, that the absolute value of the global land surface temperature (interpolated and spatially averaged) during the last century was warm-biased by changing station numbers and therefore changing station locations, both

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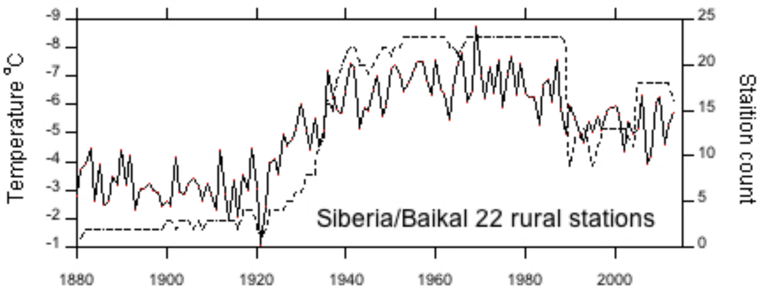
[203] *http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/images/ghcn_temp_overview.pdf and Peterson, T.C. and R.S. Vose (1997) Bull. Am. Met. Soc. 78, 2838-2849*

[204] *These numbers are a close approximation, obtained from the KNMI site.*

globally and by country. This statement has (as you might have expected) been challenged and I shall take it no further. Yet the problem had already been discussed in relatin to increasing station numbers during the period of accession of stations to the GHCN in the first half of the 20th century. [205]

But to demonstrate once again the potential effect of variable reporting station numers independently, I used the Goddard Station Locater site to select a point to the west of Lake Baikal in pristine boreal forest landscape, where I found data for 22 rural stations within a radius of 1000 kms, of which two included data for the entire 20th century and beyond, while the others were in operation only from the early 1930s to about 1990.



The resulting plot requires no comment – and is not really required - because it is self-evident that if any reporting stations are not consistent in numbers and locations change during a period of observation, there will be consequences for the data base to which they contribute whether this is reported as anomalies or as absolute values.

4.2 - Adjusting the observations, and extrapolating over a global grid

Formal numerical analysis of a global field requires that data should be available to represent the entire field, and this is evidently not the case for surface temperatures either over the continents or the oceans: data have been obtained preferentially from regions of high economic activity and stable societies and vast regions of both continents and oceans were not sampled until the satellite era. To achieve the required uniform global field the available observations are extrapolated onto a global set of grid boxes of 5^o x 5^o latitude and longitude, which provides complete coverage; however, uniformity is not achieved because the major archiving agencies use different rules for the extrapolation of data from observations to grid-boxes.

The procedures used at NASA GISS to aggregate land station data are complex and include the interpolation of values for grid boxes lacking observations, which are obtained by interpolating the mean value for all stations within 1200 kms, weighted according to their distance from the grid point, while the file is adjusted to minimize local anthropogenic effects in urban areas, using population density data or satellite night lights.[206]

Procedures at the CRU and the Hadley Centre to generate the CRUTEM archives are much simpler, and include no extrapolation of data to empty grid boxes, so they do not achieve the ideal of global coverage; these archives are relatively empty at high

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[205] See also Willmott, C.J. et al. (1991) Geoph. Res. Lett. 18, 2249-2251

[206]Hansen, J & S. Lebedeff (1987) J. Geophys. Res., 92, 13345-13372; Hansen, J. et al. (2010) Rev. Geophys. 48, RG4004

latitudes not only because observatories are relatively rare there, but also because the grid boxes themselves become so small at very high latitudes that they might fail to capture a data set even in the tropics. The divergence between the global temperature field indicated by the GISS archives, with in-filling of empty cells, and the CRUTEM archives is significant and a potential cause of misunderstanding.

The data supplied by national agencies to the GHCN are all subjected to post-accession processing and the original numbers that were recorded by observers are adjusted as a result of this process. The originating national meteorological agencies appear not to be routinely consulted concerning this process, and at least one of them insists that the original observations are correct. The adjustment process is performed independently by three agencies, whose conclusions do not always agree: consequently, one agency favours a more rapid warming in the late 20th century than the others.

Because it is unusual in stating exactly how its data are treated, the NOAA US Historical Climatology Network protocol is a useful example of these procedures: the following is the sequence of treatment of the station data by this agency:

1 - Quality control: suspect stations are found by comparing trimmed means and standard deviations with nearby stations.
2 - Adjustment for time-of-day bias due to different observing times, that may introduce a non-climatic bias into monthly means.
3 - Adjustment for instrumental bias due to the change from thermometers to transistor sensors.
4 - Adjustment for homogeneity due to random station moves and changes in local environment.
5 - Missing data adjustment uses the de-biased data from step 3 and fills in missing data by reference to nearby stations within the same grid-box.
6 – Adjustment for urban warming bias by the regression approach

The public statement concerning the adjustments to raw data used by NASA Goddard for constructing the GISTEM archive has a rather different emphasis:

1 – Elimination of dubious records is done by finding "*unphysical-looking segments…eliminated after manual inspection*" and by comparison with nearby stations.
2 – Splitting into 30^{o} latitudinal sections and then homogenisation, dropping stations with <20 years.
3 - Gridding and computation of zonal means using 5^{o} x 5^{o} grid boxes using stations in the box or, if there are none, using stations that lie within 1200 km of the centre of each box.
4 – Reformatting of SAT anomalies.

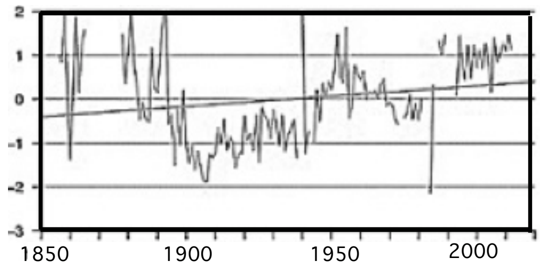
The procedures used by the U. East Anglia Climatic Research Unit generally follow the adjustment and homogenisation sequence of the USHCN and the GISS gridding technique, although no correction for urbanisation is integrated into CRUTEM archives.[207]

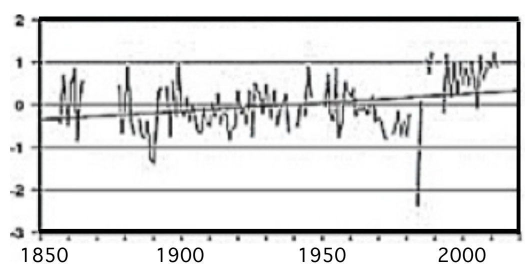
An informal synthesis has been made by Ross McKitrick of the consequences of the adjustments to the GHCN version 2 data.[208] He finds that these are mostly

[207] *Brohan, P. et al (2005) J. Geophys. Res. 111 DOI: 10.1029/2005JD00654*
[208]*http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.175.4705&rep=rep1&type=pdf*

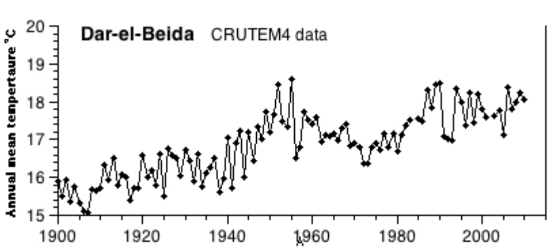
downwards in the first half of the 20th century and upwards in the second half, thus strengthening the apparent global warming trend; one would like to understand the logic for the adjustments that produced this result. Particularly, one would like to know why there is a striking increase in the volatility of the adjustments at the end of the period and, inevitably, decreasing confidence in any comparisons that might be made between this and earlier periods.

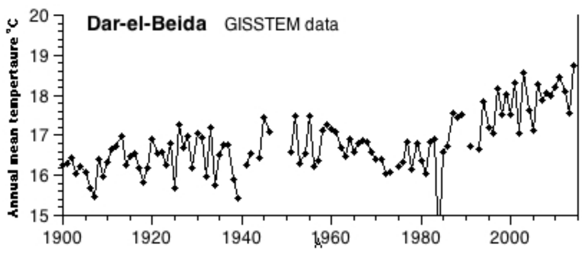
It is instructive in this context to compare some examples of the data originally archived by a national meteorological department against those now offered in the latest version of the GHCN; at the time of writing these lines, this was version 3.2.0, released in September 2012. I selected (simply because it was the first long data set in the listing) a station in Algeria: here are the original (left) and adjusted data (right) for Dar-el-Said, at 36ºN 2.3ºE, where data was obtained almost continuously from 1850 to 2012. The break that has been inserted at about 1895 during adjustment by NCDC so as to make the warm temperatures of the early years conform to later decades appears to be logical and may correspond to a station shift or instrument change, but it is not so clear why the 1950's warm period, present in so many other data sets from this climatic region (p. --), has been reduced by the elimination of a year or two of data and the shifting of others.





Consulting the operational archives of SAT, I found that this place-name is no longer recognised by the GISS Station Locater although when further search is made there and also at KNMI, a station called Dar-El-Beida is found; this contains the same data that has subsequently been adjusted and homogenised by NASA Goddard and at the Climate Research Unit of University of East Anglia: these agencies have produced two rather different interpretations of the original data.

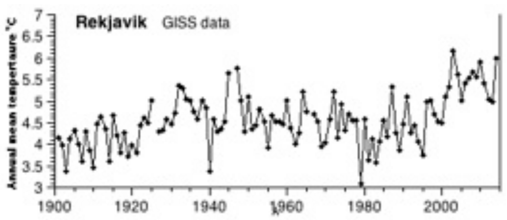


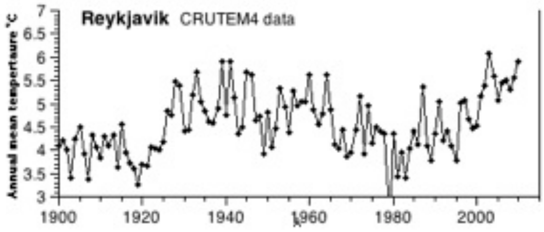


It is absolutely not clear to me how this difference should be evaluated, because the progression of warming through the 20th century - and its relation to earlier conditions - is strikingly different after processing by these two agencies: the difference in the warming trend indicated by NOAA and CRU in the second half of the 20th century is of the same magnitude as the computed radiative effects of CO_2 on global surface air temperatures over the same period.

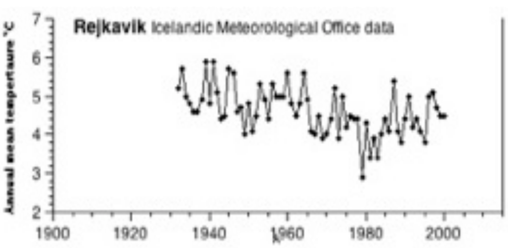
Because this might have been an isolated result, some confirmation is clearly in order; for this, I have used the data for Reykjavik, in Iceland, among others. Like the Algerian station, Reykjavik is now offered by the two operational agencies rather differently. The CRU/Hadley version is close to the original GHCN archive, while the

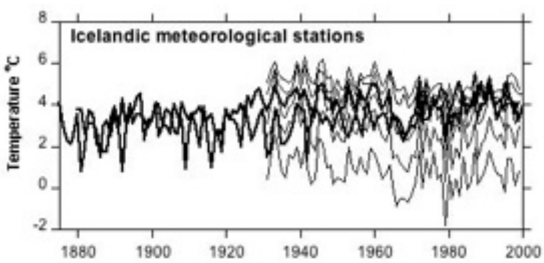
Goddard procedures have further enhanced the warming at the end of the 20th century, together with a relative reduction in the prominence of the mid-century warm period - just as in the Algerian example.





There is no reason to suppose that the Icelandic meteorological office is not as competent to eliminate observational errors and homogenise its data as anyone else, and a shorter archive is available from this source which is close to the CRUTEM version but diverges significantly from the GISTEMP version. A bundle of eight Icelandic records offered on the government web-site suggests that neither the Goddard nor CRU version may represent regional trends for Iceland correctly: there appears to be no support in this bundle for end-of-the-century warmth to exceed that of mid-century in this sub-arctic country.[209]





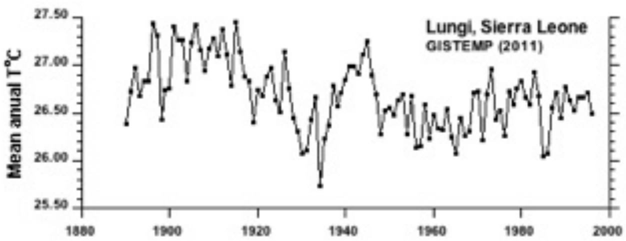
In fact, since the logic of the methods used in adjusting the data for GISTEMP and HADCRUT, one should not expect their results to be identical. Perhaps the most significant difference between the indications of the two archives is the fact that the Goddard gridding routine permits the extrapolation of data up to 1200 kms from the originating meteorological station in order to infill empty grid-cells; reduced to absurdity, this policy permits an empty grid-cell in the North Sea being infilled from observations made in the western Mediterranean!

The consequence of this policy is that GISTEMP has a coverage of almost 100% of relevant grid-cells, compared with only 65% for HadCRUT3. Consequently, data from regions with some degree of urban development or of land-use change has been extrapolated in GISTEMP to undeveloped grid-cells in steppe, forest and tundra country. Obviously, this must have significant consequences where infilling occurs across a climatic transition region as is the case at high northern latitudes, both in the coastal lowlands surrounding the Arctic Ocean and also over the ocean itself. In this region, the policy would permit an empty grid cell with its southern limit in the central Kara Sea to be infilled from data including those from, say, Tobolsk in the central West Siberian Plain, where July temperatures can reach 20°C. This is surely the origin of the frequently-made suggestion that the most rapid warming during the last 50 years has occurred in sub-Arctic regions; this issue, and the reality of the reported recent warming around the Arctic Ocean, is addressed in Chapter 10.

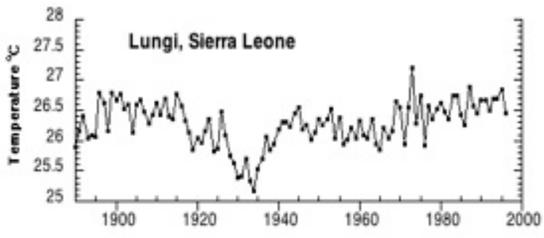
[209] *http://en.vedur.is/climatology/data/*

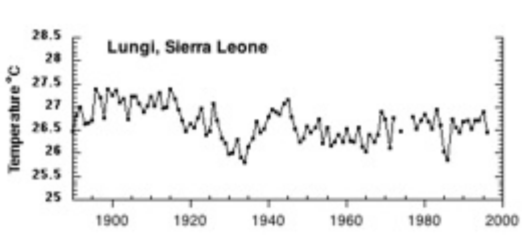
The consequence of these different procedures and assumptions is that the two principal operational data archives offer different interpretations of the progression of global warming during the 20th century over the continents. There is a very clear difference between what the Goddard and Hadley archives tell us about the progress of global warming during the 20th century and beyond: GITEMP 5-year mean data have a slope of R = 0.804, while the CRUTEM data show only an R = 0.789 slope. To what extent this divergence between the two archives is due the different method of extrapolation of data into empty cells, or to preferential adjustment of data to warmer values, is not clear, although either could explain the difference. What is remarkable, and will be discussed below, is the extent to which regional pattern of secular temperature change – when investigated with data from individual stations, rather than with gridded data – differs from this global sequence (Chapter 6).

Just occasionally, one can infer with some certainty what has probably been done, even if it is difficult to understand why it was done. Here are the data for Lungi, on the coast of Sierra Leone, that were published on the GISS Station Selector site in 2011; they appear to be unadjusted data from the GHCN.



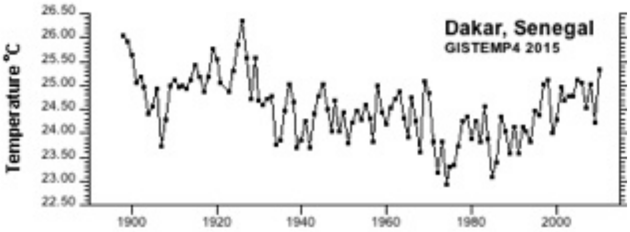
But consider how these data have been adjusted subsequently: the right-hand plot below is the currently version in CRUTEM4, while the left-hand plot is the GISTEMP4 offering. The overall cooling trend in the GHCN observations has been reduced by one agency, and removed by the other. In the extreme case, the Goddard team has dropped the temperature of the first decades by almost a full degree, and imposed an unobserved warming trend on the final 30 years of the GISTEMP series. Naturally, one wonders why this was done by just one of the two adjustment teams who processed these data.





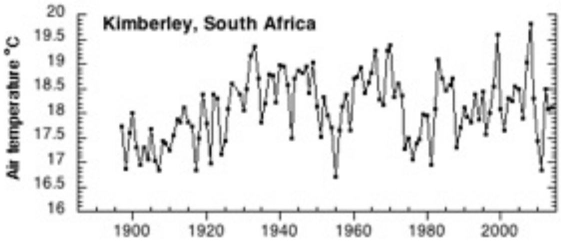
Because I am quite familiar with this place, I thought it might be interesting to look at the other stations that were available to those who adjusted this record. Lungi is a small village beside the beach (popn. 4200), its climate is maritime, it is surrounded by peasant farmlands (oil palm, plantain and cassava) and it lies well beyond any urban influence of Freetown, which is served by the single airstrip at Lungi just as it was 50 years ago. Along the appropriate stretch of the West African coast there are only four other weather stations, of which two (Conakry and Bissau) are associated with cities of 520,00 and 100,000 respectively that have grown rapidly since the 1950s, a fact reflected in their SAT data. The others (Bonthe and Boke) are located in small coastal villages and have very short data runs (1950-1970) during which the records are similar to the original data from Lungi.

But about 800 kms northward, on the coast of Senegal, the equally long data set for Dakar in GISTEMP4 suggests that a reversal occurred in about 1970 from a long, almost centennial cooling to a warming trend, and this pattern is little changed from that of the original GHCN data for Dakar.

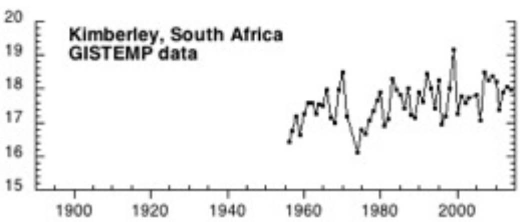


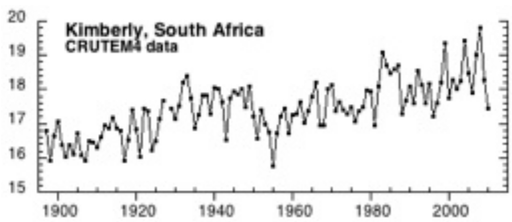
It seems likely that this trends were used in the homogenisation of Lungi data with other regional data – although the logic is not appropriate in this case: Dakar is a coastal metropolis of >1000,000 inhabitants and its climate is dominated by the seasonal upwelling of cold water in the Canary Current, close inshore. Both of these characteristics make it inappropriate to use Dakar as a model for the adjustment of Lungi data, if that is indeed what has been done.

Another unexplained oddity of the adjustment process is that some of the century-long GHCN data sets that were posted only a few years ago have since been heavily truncated in the current GISS archive. One of the strangest examples that I have found is for Kimberley, South Africa, which in 2011 was presented on the GISS Station Selector site as a long, unbroken data series from about 1890 to the present time.



The current versions of GISTEMP and CRUTEM present different interpretations of the climate of this station., both of which diverge strongly from the GHCN version. I am at loss to understand what has been done, and can find no explanation for the change in slope that has been imposed on the CRUTEM version, or for the truncation prior to 1955 of the 2015 GISTEMP file.

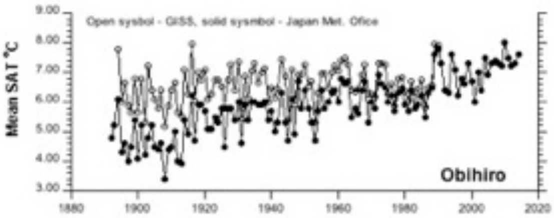


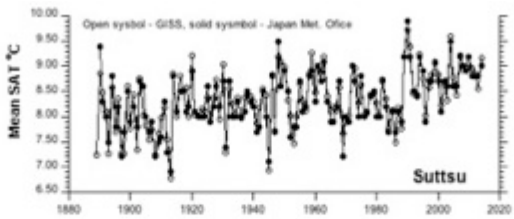


It seems clear that what is presented in the current data sets has resulted from a multitude of individual decisions, big or trivial, made by the technicians responsible for adjusting the data; the complexity and magnitude of adjusting, individually and largely by hand, as described above, several thousand data sets surely requires that a careful record must be kept and made widely known. Accordingly, at least one national meteorological service, that of Australia, has published a very clear "*how-we-did-it*" report that recounts for at least some individual stations exactly why and how each adjustment was made; the public is invited to examine the before and after data, as well as the data at neighbouring stations that were used to make the corrections.[210] It would be more difficult to do this for the several thousand stations in the GHCN than it was for 200 selected rural stations in the unusually dense Australian station network, but the present situation must inevitably give rise to questions concerning what has been done and why.

Another reminder of the uncertainties inherent in the global data sets that are in current use to monitor climate change comes from the Japanese Meteorological Agency, whose web-site offers public access to the entire current archive of meteorological station SAT data, each station being coded with its WMO Station ID number.

These data have not been adjusted, although known break-points (station moves, etc.) are indicated on the files, so it is interesting to compare them with the adjusted GISS data for the same sites: they must be very close to what was originally archived by WMO. A group of 32 stations in central Hokkaido (centered on Abashabi, 44N 144.3E) was obtained from the GISS Station Selector site, of which 11 were selected for their length of record (at least 1920-1990).





The result was extraordinary: for 5 of these stations, the GISS data were at least 1^{o}C warmer in the early years than the Japanese data, the difference progressively diminishing towards the present; in the other 6 data sets, GISS values are almost identical with the original Japanese data. In about half of the data sets, some of the early decades were deleted by Goddard. A similar experiment with Honshu data produced the same result, though less clearly. I have no suggestion to offer for these strange observations.

The anomalies discused above have not passed unperceived by others: an examination of the processing of global SAT data in the CRUTEM archives has been made by comparing these data against the indications of two reanalyses of climate evolution: the ERA-40 and the NCEP/NCAR reanalyses for the period 1957-2002.[211] The surface data incorporated in the ERA-40 were not obtained instrumentally but, instead, were derived as 2m temperatures from meteorological forecast analyses that had been constrained by observations of upper air variables and surface pressure. Even so, the ERA-40 analyses are not fully independent of data processed at CRU and Hadley, because 1500-2000 of the stations that are included in the CRUTEM archives are based on monthly averaged WMO data that contribute to the ERA-40 reanalysis. Initial quality control found and removed a few outliers and duplicates: station normals (monthly averages 1961-1990) were then generated from station data "*or inferred from surrounding station values*".

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[210] *Torok, S.J. and N. Nicholls (1996) Aust. Met. Mag. 45, 251-260*
[211] *Simmons, A.J. et al. (2004) J. Geo. Res. 109, D24115. 1-18; Brohan, P. et al. (2006) idem. 111, D12 1-21*

Comparison between the SAT observations archived by CRU and the ERA-40 reanalysis was then performed on a 5° x 5° gridded derivative; this was expressed as global and hemispheric averages in one study, and also for large regions - Europe, North America, Australia - in a second study.:

		NH	SH	Europe	N. Amer	Austr
1958-2001						
CRU		*0.19*	*0.13*	*0.17*	*0.21*	*0.14*
ERA-40	*0.13*	*0.13*	*0.04*	*0.11*	*0.14*	*-0.10*
1979-2001						
CRU		*0.30*	*0.11*	*0.46*	*0.30*	*0.01*
ERA-40	*0.27*	*0.04*	*0.42*	*0.42*	*0.28*	*-0.10*

In each case, the fidelity of the CRUTEM data to the ERA-40 reanalysis improved both with size of region, and with time, becoming very close in the final decades: here are the linear trends in °C/decade

The finding that regional matches between observed SAT and reanalysed meteorological data perform better than global matches suggests that regional analysis might be useful if performed at even smaller spatial scale, and this is discussed in Chapter 5. It will be suggested that this scale of analysis may be essential to interpret the true significance of changes observed in global surface temperatures.

However that may be, surely the adage of *caveat emptor* should be kept in mind by any scientist who uses or interprets the major global archives of surface temperature records. They are not of the quality and reliability that is ideal for the use to which they are put and they measure processes other than the one they are assumed to represent.

4.3 - Sea and land surface air temperatures are incompatible

Surface temperatures over oceans and continents respond to quite different physical processes, yet they must be integrated into a single gridded, global archive for modelling purposes; to this problem must be added the fact that the accumulated data for surface air temperatures taken over the ocean are not sufficiently comprehensive to be merged with data from meteorological stations ashore to form a unified and coherent global archive.

But most importantly, as will be discussed below, SST is sensitive to changes in vertical motion of cold water from below the thermocline such as occurs during changes in wind-driven upwelling. The consequences of changed upwelling intensity will be recorded as changes in the global surface temperature record although they have nothing to do with changes in temperature over land surfaces that are forced by changing radiative conditions in the atmosphere. This confusion appears not to have been addressed.

Traditionally, night marine temperature (NMAT) observations have been obtained almost exclusively aboard merchant ships, and from a small fleet of Ocean Weather Ships that were posted at strategic Northern Hemisphere locations for a short period in mid-20th century. But large parts of the ocean have literally never been crossed by regular shipping routes, and so are almost devoid of NMAT data.. Then, although the standardisation of observing methods and instruments ashore was undertaken quite early, the standardisation of air temperature measurement at sea was never fully resolved.

Consequently, sea surface temperature (SST) – for which the number of measurements are significantly greater and more widely dispersed than for NMAT - is now used in climate studies as a proxy. It is assumed that air temperature a few metres above the sea surface closely follows the temperature of the upper metre or so of the ocean, although this ignores the generalisation that the sea surface is slightly warmer – especially at night and especially in summer at higher latitudes – than the air a few metres above the surface. NMAT anomalies do follow the pattern of SST anomalies, but only in the open ocean and only when averaged across seasonal or annual periods, with some major regional discrepancies in tropical seas.

Unfortunately, like the procedures at meteorological observatories ashore, observing systems for obtaining SST from a moving ship evolved significantly during the 20th century, from the use in the early years of a canvas bucket and a thermometer, to the use of direct read-outs from thermo-sensors either in the seawater cooling system in the engine-room, or externally on the hull.[212] Each of these techniques is still in use today, though not many ships still use a canvas bucket.

But the long-term SST record from shipping is not without interruption, and a major inhomogeneity occurs at the end of the war at sea in 1945, when British ships again began to supply data even as US ships reduced their contribution, and this discontinuity is yet to be reconciled in the current HADSST and the ICOADS data archives. Because these data have been integrated into the global SAT series combining both oceanic and continental data then major consequences must to ensue for our interpretation of global temperature in the second half of the 20th century, depending on whether the post-1945 data are raised or whether the pre-1945 data are lowered.[213]

The end-of-the-war anomaly of 1945 is still prominent in the 20th-century record that was used in the 2013 IPCC Assessment Report and also in the HadSST3 data archive. There is now adequate data coverage of all oceans, but this was achieved only progressively and data from the southern hemisphere were too sparse to provide any useful information until the mid-20th century. Surface drifting buoys deployed by NOAA, and *Argo* profiling drifters and other automated devices, now provide the majority of the almost 10 million data points for SST that are taken directly at sea annually.[214]

Since about 1980, observation techniques changed rapidly and radically so that, paradoxically, we now have far more complete data on SST than we do for the land surfaces. Satellite sensing of radiation from the ocean surface at wavelengths within the peak of blackbody radiation – and selected for good transmission characteristics – provide monthly data at very high spatial resolution for all oceans and seas, so that seasonal and ENSO-scale events can be mapped very closely. Because these data are critical for weather forecasting, we can assume that instruments such as MODIS flown by NASA will be with us permanently. SST data, excluding those obtained by satellite sensors, are gridded before being archived in several different formats by NOAA, NASA and the Hadley Centre. In the International Comprehensive Ocean-Atmosphere (ICOADS) archive of NOAA, gridding is performed in $1^o \times 1^o$ boxes after 1960, but the

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[212] *Kent, E.C. et al (2007) J. Atmos. Ocean Tech. 24 DOI: 10.1175/JTECH1949.1: unfortunately, IPCC AR5 (Ch. 2, p. 32) incorrectly places the change from buckets to ERI at the end of WW2, and moreover gets the change the wrong way around!*

[213] *Thompson, D.W.J. (2008) Nature 453, 646-649*.

[214] *Rayner, N.A. (2003) J. Geophys. Res. 108, D14, 4407 doi:10.1029/2002JD002670.*

percentage of empty boxes is quite high in out-of-the-way but interesting regions such as the Indian Ocean.

All the same, the SST archive does reach sufficiently far back to provide critical insights into the present climate of Earth, by enabling secular-scale matching of these data with relevant proxy data that stretch back much farther. This has been done in the Agulhas Current where SST proxies were obtained from growth rings in massive *Porites* corals at Ifaty on the southwest coast of Madagascar; here, it was possible to locate two relevant SST grid boxes to monitor change in SST to which the growth of these corals will have responded; it was found that the pattern of change in SST anomalies in the instrumental data closely matches the pattern of proxy SST data from the corals. The proxy data enable a rational hind-casting of SST that extends back several centuries and well into the Maunder Minimum of the Little Ice Age that is well-expressed here.

This *Nature* study demonstrates that in this region at least "*Our new coral composite SST record…showed strong multidecadal SST variability in this important ocean current and that warming over the last three decades is not unprecedented in the context of the multi-centennial record*." [215] Unlike some well-known bundles of proxy data sets to which have been added the instrumental data, in this case there is no significant divergence between instrumental and proxy data. Moreover, the SST pattern inferred for the Agulhas Current from these proxy corals closely matches that of 20th SAT obtained from a stalagmite air-temperature proxy from the 'Cold Air Cave' in the northern Transvaal that also extends back to about 1650; this has been verified against local data for the 20th century except for one anomalous 20-year spell. Both the cave and the coral data very closely match the long SAT series for Kimberly (about 500 km from the Cold Air Cave, and both extend back well into the very cold era of the Maunder solar minimum of 1665-1710; the warm period of 1870-1900 is well-recorded at each site. A close relationship between SAT and SST at regional scale was demonstrated by SST data from the Ifaty corals that are significantly correlated with SST in the western and north-eastern Pacific coded as the Pacific Decadal Oscillation (PDO, p. NN) although the strongest relationship was with western Indian Ocean in the Agulhas retroflection region. [216]

But I have seen no real discussion of the reliability of SST as an indicator of the effects of radiative gas molecules in the atmosphere, and therefore its suitability for integration with SAT over land surfaces into a global index of the consequences of anthropogenic CO_2 release, although this would seem to be essential for a proper understanding of global temperature change. While the basic assumption that SST is an adequate measure of SAT a metre or two above the surface is correct, this does not at all imply that similar processes control changes in SST and in SAT on the continents. The surface temperature of the ocean (which is usually marginally warmer than the first metre or so of the atmosphere) does respond to the pattern of insolation in the same way as does air temperature over land surfaces, but it also changes rapidly in response to changes in wind stress.

This is independent of any radiative effect and occurs simply by wind-induced vertical motion in the upper 100m or so of the water column – or by the lack of vertical motion. Although this simple proposition is largely ignored in the climate change literature, every oceanographer knows that upwelling of cool water to the surface from

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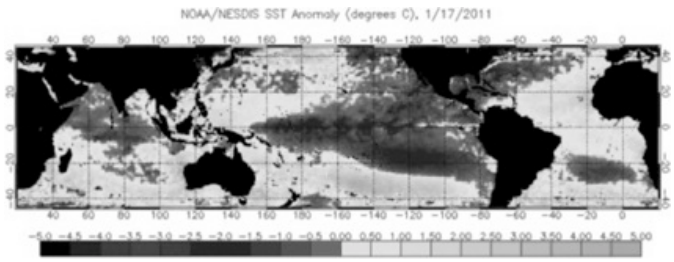
[215] *Zinke, J. et al. (2014) Nature Scientific Reports 4, doi:10.1038/srep04393*
[216] *Sundqvist, H.B. (2013) Nature Scientific Reports 3: doi:10.1038/srep01767*

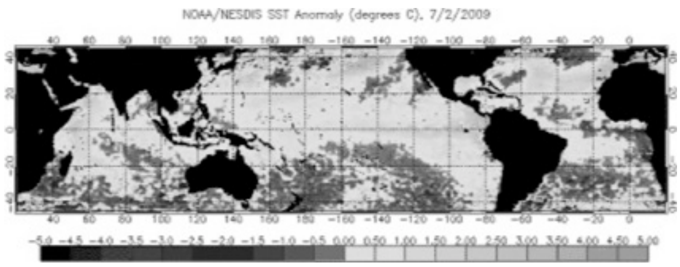
beneath the warm wind-mixed layer is induced by a variety of processes both at the coast and also far from land: these include the consequences of mesoscale eddying in the major surface flows, of wind-induced divergence at the coast, of the curl of the wind-stress and of Coriolis-based divergence of surface water masses at low latitudes and so on. It was a change in wind pattern, and not a radiative effect, that caused the warm global 'air temperature' anomaly of 1998.

Divergence of surface water occurs seasonally and episodically along 'upwelling' coasts, as off California, or in the open ocean wherever surface water is forced to diverge by wind stress, as along the Equator caused by the trade winds. These entirely natural processes have much smaller impact on the heat budget of the Earth than would seem to be indicated by the consequent changes in global SST. So the evolution of SST at annual, decadal or longer scale may tell us very little, if anything, about the evolution of global warming of the atmosphere, anthropogenic or natural.

Regional SSTs – and therefore the GSMT index – are very clearly dominated by regional oceanographic processes. One would not expect to find a similar pattern of change in Gulf Stream SST as in the Greenland Sea or in the tropical Pacific – and this is indeed the case.[217] Because the oceans cover 71% of the surface of the globe and strongly influence the climates of many continental regions, then it should be no surprise that GSMT trends are, in the long term, dominated by the global evolution of SST. But it is dangerous to reduce global SST to a single variable because this index represents the consequence of several quite different regional processes, and because changes in regional or global SST do not necessarily quantify the accompanying loss or gain of heat from the Earth.

It is a matter of popular knowledge that, quasi-periodically, the Pacific trade winds fail so that surface wind stress is relaxed, upwelling along the American coast ceases and surface water is warm over the entire eastern ocean; these are the El Niño events, long known to Peruvian fishermen who have to stay ashore because the anchovies on which they depend are no longer available.[218]





These images illustrate the extent of the consequent changes in SST globally that have direct consequences for the GSMT index, based on SST + SAT over land surfaces.

[217] *Rayner, N.A. et al (2003) J. Geophys. Res. 108 D14, 4407 & (2006) J. Clim. 19, 46-469*
[218] *Longhurst, A.R. (2007) Ecological Geography of the Sea (Academic), p. 201 et seq.*

This is why the 1998 Nino now forms such a prominent spike in the global SAT record, just before the so-called 'warming pause' of the first decades of the 21st century. As I write, the 2015 Nino is in full development, upwelling of cold water has essentially ceased and this has created a huge warm anomaly from Oregon to Chile that will is already being reflected in the GSMT anomaly. On this occasion, however, at least one major climate agency will not be attributing this to anything other than the natural evolution of climate states.[219]

These two regional patterns in SST in the tropical Pacific have long been known to be associated with characteristic regional climate patterns, and with the strength of the monsoon rainy season of India. This early attracted the attention of meteorologists, the code being broken by the Indian Meteorological Department in the 19th century. This organisation began seriously to study the possibility of prediction soon after the almost complete failure of the 1877-78 monsoon rains and the disastrous droughts that followed which may have killed 5 million people in India. It was quickly understood that this event was associated with abnormally high atmospheric pressure from Siberia to Australia, conditions that are now associated with an El Nino event in the eastern Pacific – conditions which, in fact, had been noted in 1876-1877. Later work at the IMD resulted in the use of a wider range of pressure and other data but a reliable forecast remained elusive until Gilbert Walker arrived in India and immediately undertook a deeper mathematical analysis, using pressure data from sources on all continents. Using appropriate leads and lags, he concluded that Indian monsoon rainfall could be predicted by reference to Himalaya snowfall, Mauritius pressure, mean S. America pressure and Zanzibar rainfall. This formulation was the origin of Walker's understanding that it is the variable strength of the pressure gradient along the equator between America and Asia that controls the strength of the Trades, a mechanism that is encapsulated in what has come to be called the Southern Oscillation in the tropical zone between America and Asia.

Low pressure over Asia results in strong Trade winds, transport of water into the western warm pool and strong upwelling at the American coast and along the equator. Reversal of the pattern occurs when pressure is high over Asia, trade westerly trade wind stress is relaxed and upwelling of cold water ceases. The process is now coded as the Southern Oscillation Index (SOI) which is computed as the trans-Pacific sea level pressure difference between Tahiti and Darwin, The SOI is not a simple on-off mechanism but varies so that some decades are dominated by one or other the phases, and it is the effect of the SOI that generates the dominant mode of variability in the tropical ocean and the year-to-year variability of global climate that, of course, also responds at longer intervals to the Atlantic Meridional Oscillation and the other indices of climate change discussed in Section 7.1

El Nino conditions, with low trade wind stress and hence less exposure of cold water at the surface are reflected in the global surface air temperature data as a warm anomaly but, as noted above, this does not imply that the Earth has suddenly accumulated more heat from the Sun. There will be some change in sensible heat flux at the surface between Nino and normal conditions, but it has not been shown that this is globally significant, so we should question the use of the combined SST/SAT data archives to measure the progress of 'global warming'.

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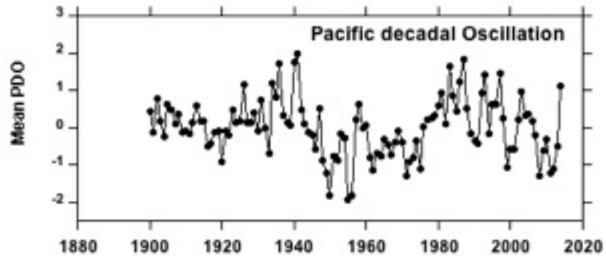
[219] *see UK Met. Office (Sept. 2015) "Big Changes Underway in the Climate System?", pp. 15*

Similar warm anomalies must be introduced into the GMST whenever upwelling ceases due to changing wind stress in the eastern boundary currents of each continent - the Humboldt and Canary Currents and the California and Peru Currents. This is also true of some other coastal regions where upwelling occurs, as off Somalia and Ghana.

At longer time-scales, large-scale changes in regional SST also occur and the "Great Pacific Climate Shift" of 1977 was much remarked for the consequences on fish distribution and abundance of a rapid cooling of SST in the central and western North Pacific and an equally rapid warming of SST in the eastern regions from Washington to Alaska: this is coded as the Pacific Decadal Oscillation (PDO).[220]



The PDO is the main mode of variability in the North Pacific and it exhibits a very different temporal pattern than the ENSO/Southern Oscillation Index and is associated with a complex pattern of forcing from the equatorial region to mid-latitudes that will be discussed in Section 7.1 below.[221]

Of course, no more than in the case of the Southern Oscillation index, one should not expect a regular, rhythmic polarity shifts in the PDO over very long periods and this is clear in North American tree-ring proxy data in which the 20th century shifts in polarity are clearly identified, as is a major and rapid double polarity change around at the start of the century. These proxy data also suggest that the contemporary states of the PDO are in no way anomalous in the millennial-scale record; [222] Unusually low values were experienced during the extrema of the Little Ice Age in the 17th century.

The 1977 shift of polarity from the cold to the warm mode of the PDO came at the end of a period during which normal trade-wind stress had dominated the equatorial region and at the inception of a period of frequent Nino conditions suggesting a connection between the two phenomena. It was one of a series of reversals of polarity of the Pacific Decadal Oscillation (PDO) that had been observed in the distribution of SST during the 20th century which were associated with an enhanced eastward transport of warm water at mid-latitudes in the North Pacific and strengthened flow in the Alaska Current into the Bering Sea. Later, weaker changes occurred in 1988/89 and 1997-98 each involving shifts in wind patterns over very wide regions and reaching significantly as far as the North Atlanti; the winter value of the NAO index shifted rapidly from a period dominated by negative to almost a decade dominated by positive values at about the same time.

These indices of climate states, each describing a characteristic pattern of high and low pressure regions – and hence the distribution of winds at the surface - are critical to an understanding of changes in regional climate states and will be discussed in several places in this text.

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[220] *Mantua, N.J. et al. (1979) Bull. Am. Meteorol.Soc. 78, 1069-1079 with NOAA image*
[221] *Newman, M. (2003) J. Climate 16, 3853-3857*
[222] *Biondi, F. et al. J. Climat. 14, 1-10.*

4.4 - Regional patterns of warming of the troposphere

Early papers by Manabe and Wethereld[223] suggested that the atmospheric temperature pattern should have a relatively simple response to the observed increases of atmospheric CO_2 content.: (i) *in the stratosphere*, a cooling of lower levels should be caused by the destruction of ozone by halogens and consequently the enhanced formation of polar clouds at great heights, and the reflection of incident solar radiation to space, and (ii) *in the troposphere*, warming was expected to occur both through the effect of CO2 and other radiatively-active molecules, and also due to the release of latent heat in the convective cloud systems that are characteristic of wet tropical climates. Dust veils from volcanic activity are anticipated to have a regional warming effect up to whatever altitude they are carried, even as they shield the surface from sunlight and so reduce air temperature at ground level where black carbon particle clouds, especially over SE Asia, must be expected to have a heating effect.

To avoid the consequences of the contamination of surface temperature data to be discussed in the following chapter, the temperature of the troposphere would be the ideal index for evaluating the radiative consequences of atmospheric CO_2 although observation of evolution of temperature in the troposphere is not simple and the record is not long. In addition, you will recollect from Chapter 2 that although CO_2 is considered to be a 'well-mixed greenhouse gas' it is, in fact, very far from being well mixed in the atmosphere and one cannot expect a uniform response to its radiative effect at all latitudes.

The seasonal dynamics of CO_2 due to accumulation in plants during the growing season and loss to the atmosphere in winter, especially in the northern, land hemisphere and its vertical transport within the tropical regions in convective cloud systems dominate the global distribution of this gas. Whether or not there should consequently be a tropical 'hot spot' high in the troposphere has been much debated.

Then, the radiative consequences of CO_2 are not the same everywhere: the observed surface warming trend in the northern hemisphere is by no means evenly distributed across all grid cells; the overall trend has been about 0.05^{o}C/decade but, curiously, just a small part of the total area (c.13% of the total) contributed >50% of the warming. Further, in winter, c.25% of the area contributes almost 80% of the total warming. These regions are the cold, dry anticyclonic regions of Siberia and North America where the contribution of CO_2 to radiative forcing is greatest relative to water vapour, and where the relative dryness of the air causes a greater proportion of visible solar radiation to be transformed into sensible, rather than latent heat. Winter temperature trends in the lower troposphere include maximal warming in the dry anticyclonic regions of central Siberia and northwestern North America; in summer, maximal warming occurs in the dry atmosphere over parts of northern Africa. More generally, the local level of warming that occurred over a recent 50-year period is a function of atmospheric pressure.[224]

So we cannot expect that the radiative effects of CO_2 will be easy to quantify at global scale in the troposphere, and even if observation techniques are theoretically capable of delivering the required data with satisfactory precision, their use is not

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[223] *(1967) J Atmos Sci 24:241–259*

[224] *Michaels, P.J. et al. (2004) Clim. Res. 14, 1-6*

simple. Nor have they been deployed for more than a few decades, so it is not easy to construct homogenous time series over sufficiently long periods to be useful for quantifying progressive change in tropospheric heat content.

The two principal sources of data are (i) radio-sondes, carried on weather balloons that penetrate the lower stratosphere to about 30km altitude and which have been used since the 1950s and (ii) microwave sounding units (variously, MSU, AMSU or SSU) carried aboard polar-orbiting satellites since the late 1970s.[225] Neither type of observation has provided the long periods of routine observation necessary to understand the thermal evolution of the atmosphere at secular scale, which is what we need to evaluate anthropogenic influences.

But even if long-term trends are difficult to specify, radiosonde data do show very strong temperature change in the lower 2 km of the atmosphere, typically a warming trend up to a thermal discontinuity, at the top of the inversion layer, above which progressive cooling occurs up through the troposphere.

Because radio-sonde operations have been financed mainly for weather forecasting by national meteorological agencies, the integrity of long time-series has been only a minor preoccupation; consequently, as instrumentation has evolved, there has been little reason not deploy the most recent type, and this has introduced discontinuities into otherwise useful long time series. The use of sounding balloons also encounters problems that are comparable to those associated with the use of meteorological instrumentation at ground level: for example, the presence of the balloon above the instrument package, and the effect of solar heating on the metal instrument casing itself, have been identified as sources of error.

Nor have the polar-orbiting satellites carrying MSU instrumentation been without their problems because two progressive errors have been found to compromise the data: equator-crossing times of their orbits have been shown to drift progressively, to the extent that the induced errors may be as large as the signal, and the orbits may also degrade to progressively lower altitudes so that the total area observed by the sensor becomes progressively smaller.

Because of the obvious interest in reconciling the rapid surface warming since the 1970s with troposphere temperature data that seem to show little warming, at least seven satellite and radio-sonde data sets, or re-analysed data sets, have been assembled: these agree in their responses to Pinatubo and the 1998 Niño, but *"differ substantially in their long-term mean trends and…actually serve to increase the spread in long-term trends, nominally increasing our uncertainty*" according to Thorne et al..[226] *"We can no longer"* continue these authors *"absolutely conclude whether globally the troposphere is cooling or warming relative to the surface"*. As an earlier study had pointed out, three separate realisations of tropospheric temperatures reported linear warming trends for the period 1973-2002 of +0.24 ±0.02, of +0.12 ±0.02 and of +0.03 ±0.05°C per decade – a spread of about an order of magnitude.

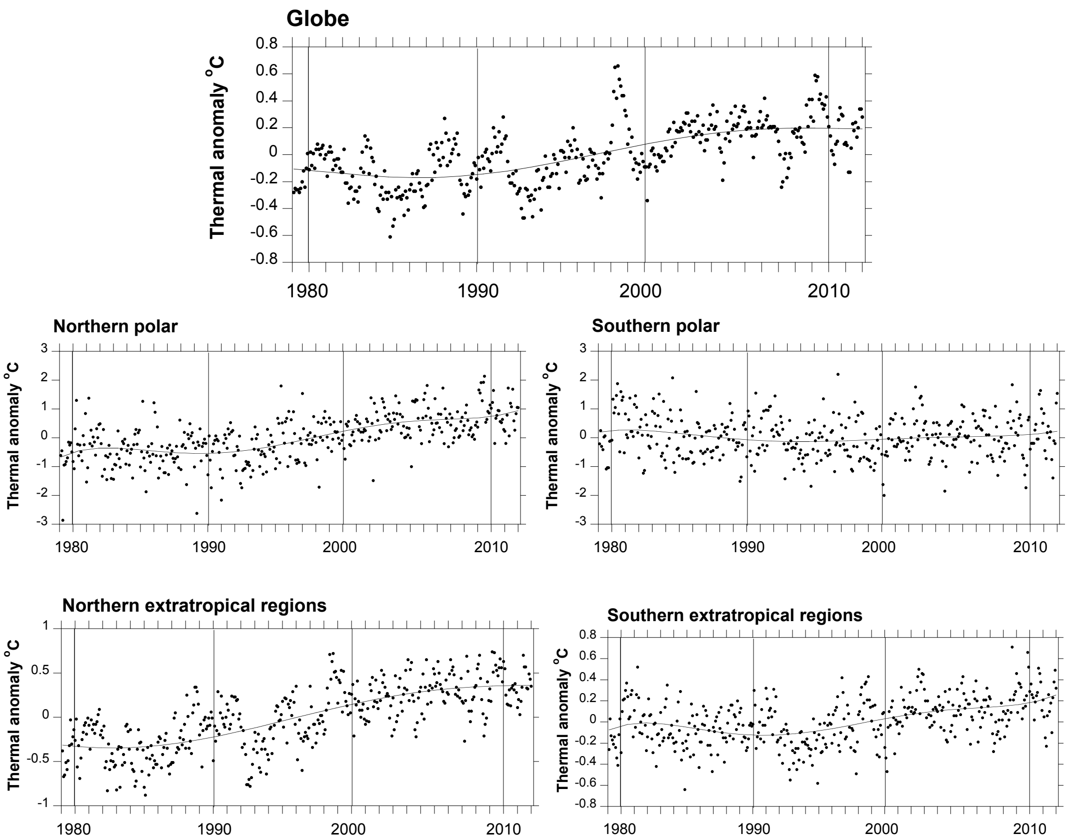
This uncertainty results from the fact that the compilers did not approach their data in an identical manner, introducing structural uncertainty during their manipulation of the raw data, each step of which may have been logical but may not have been properly recorded; further, the corrections that should be applied if a

[225] *this section owes much to Thorne, P.W. et al. (2010) Wiley Interdisc. Rev. 2, 66-80.*
[226] *Thorne, P.E. et al. (2005) Bull. Amer. Met. Soc. 86, 1437-1342.*

particular instrumental error is revealed were not always made. Thorne et al. conclude that structural uncertainty in environmental data sets is inevitable and that it is unrealistic to expect explicit resolution of the problem: *"the challenge is to quantify the true spread of solutions, given the limited number of data sets."*

Attempting to avoid such issues, because corrections have been made progressively over a long period, a comprehensive tropospheric data set has been assembled at the University of Alabama (UAH) from satellite microwave sensors for the period 1978-2012.[227] This was one of the earliest archives to have been reported and it created a significant controversy that dominated the literature for some years: the data showed a sustained cooling trend in the lower troposphere for the first decade or so of this period, contrary to expectation and contrary to what had been inferred from the principal versions of the SAT data. Progressive accession of new data required correction of algorithms, of the decay of orbits and of drift in equator-crossing time.

The UAH archive (illustrated in the following graphs) now supports the expectation that an increase in troposphere heat content should have occurred during the 20th century, but also shows that strong regional differences in lower troposphere temperatures are related appropriately to regional differences in the distribution of CO_2 concentrations.



Warming in the lower troposphere has been most pronounced in polar and extratropical regions of the northern hemisphere while, over much of the planet, warming – if it can be detected – it has been trivial during the entire period. Although the straight-line fit that is often applied to such data would suggest continuous warming,

[227] *Christy, J.R. and W.B. Norris (2004) Geophys. Res. Lett. 31, L06211 ansd see also Christy, J.R. et al (2000) J. Atmos. Oceanic Tech., 17, 1153–1170*

one would be justified in describing the global data as showing two periods, each with rather little temperature change: a cooler period prior to 1995 and a later, warmer period offset by half-a-degree or so. In the appropriate regions, the signal of the 1998 Southern Oscillation event is clearly seen. The global trend in the lower troposphere has been of order +0.08^{0}C ≠0.05^{0}C/decade since 1978 and the AR5 of 2014 assumes a simple increase in troposphere temperatures globally, initiated around 1965: there is little if any recognition that, in fact, there are significant hemispheric and regional singularities.

Thus, the trend in the troposphere in no way matches instrumental measurements made at the surface, the overall trend being shallower and lacks a 1920s-30s cooling trend that is clearly recorded in the combined GHCN, CRUTEM, GISS and BEST global data.[228] Others have, of course, noted that lower troposphere temperatures do not match trends in surface observations or as modelled, with troposphere temperature increase lagging surface observations and models at high latitudes [229], and the IPCC is quite frank about the difficulties of knowing exactly how the upper atmosphere has evolved thermally in the last half-century or so. They note that "*Based upon multiple independent analyses from weather balloons and satellites it is virtually certain that globally the troposphere has warmed since the mid-20th Century. However, there is only medium to low confidence in the rate and vertical structure. There is medium confidence in the rate of change and its vertical structure in the NH extra-tropics, while elsewhere confidence is low, particularly in the tropical upper troposphere and over the shorter period since 1979.*"

The strongly asymmetric distribution of CO_2 in the troposphere coincides very well with the general distribution of surface warming during the 20th century and beyond, even if this has been modest compared with what is indicated by surface measurements. The UAH data suggest a thermal anomaly of about 0.4^{o}C globally in the troposphere since 1980 compared with about 1.1^{o}C at ground stations, derived from the GISS surface data (see Chapter 4). There is every reason, then, to associate cause and effect in this case, while acknowledging that the atmosphere is not a simple reaction chamber containing a single radiative molecule. Moreover, as was discussed in Chapter 2, CO_2 has a very small radiative effect at the concentrations that have been observed compared to that of water vapour in the troposphere.

Nevertheless, the counter-arguments seem solid and are supported by the global distribution of water vapour; the total column climatology for 1988-1992 from the NASA Water Vapor Project clearly demonstrated the relatively high concentrations over the oceans in the humid tropics.[230] These observations also demonstrate something of the reactivity of both water vapour and CO_2 to changing patterns of atmospheric circulation as these respond to the pattern of changes in solar radiation. The almost complete failure of the trade winds in 1998 in response to changing relative strengths of the tropical high pressure cells is clearly recorded in the temperature of both the boundary layer and the troposphere.

The reactivity of water vapour to temperature is confirmed in all data sets of total column water vapour or precipitable water; seven such sets have been assembled by Sherwood and his colleagues and these clearly demonstrate an increase in the final

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[228] *AR5 Chapter 2*
[229] *Vinnikov, K.Y. et al. (2006) J. Geophys. Res. 111 doi:10.1029/2005JD006392*
[230] *Randell, D.L. (1996) Bull. Am. Met. Soc. 77, 1232-1246*

decades of the last century of 1.2-4.7%. These are observed both in global data and also in data restricted to the northern hemisphere (1 set) and to tropical regions (3 sets); there has, however, been some drying in subtropical regions.[231]

Such observations confirm the general assumption that water vapour acts as a positive feedback mechanism in the case of both warming or cooling of global atmospheric temperature whether by solar, anthropogenic, volcanic or other forcings.

4.5 - Cooling of the stratosphere

We now have detailed stratospheric data for a rather short period from MSU satellite-borne instruments, and these suggest overall stratospheric cooling from 1960-2012, punctuated by several warming episodes after volcanic eruptions. [232] The quick reaction to injections of volcanic dust particles into the stratosphere (especially at lower levels) was anticipated, as was the stability of temperature during the last 15 years of the observations when the rate of explosive vulcanism was relatively low. Cooling is evident only until about 1997-98, and is associated with seasonal ozone destruction, especially at high latitudes, where seasonal trend differences are greatest. The authors of this study concur that a gradual decrease in stratospheric water vapour occurred in the last decades of the 20th century, followed by a step-decrease in 2001 that lasted for about a decade.

Perturbations other than volcanism have also modified the stratospheric cooling trend otherwise to be anticipated; for instance, a weak response of around 2K to solar irradiance cycles has been observed at 18-25 km altitude in the stratosphere in US radiosonde data in low latitudes; this effect is not uniform either with respect to height or location, because it responds to non-uniform planetary waves that are propagated on the density discontinuity of the tropopause, preferentially in low latitudes. [233]

Potential mechanisms for observed cooling in the stratosphere other than volcanic effects have been much discussed: the simplest suggestion is that a greenhouse effect in the troposphere should slow the upward passage of heat in the infrared, trapping it at low altitudes, but it is more complex than that. To quote a NOAA account: *"ozone absorbs solar UV radiation, which heats the surrounding air in the stratosphere. Loss of ozone (by CFCs) means that less UV light gets absorbed, resulting in cooling of the stratosphere...results in the formation of more polar stratospheric clouds, which require very cold temperatures to form...allows even more ozone destruction to occur, since the reactions responsible for ozone destruction occur much faster in clouds than in dry air*".

Unfortunately, progress towards certainty in the understanding of change in stratospheric temperatures is not entirely encouraging: while I have been drafting this section, *Nature* has headlined a collective study entitled "*The mystery of recent stratospheric temperature trends*"[234]. The authors examined a new NOAA reprocessing and revision to 2008 of the UK Met Office SSU data set that previously extended only to 1998, and found that the new archive "p*rovides a view that is strikingly different from*

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[231] *Sherwood, S.C. et al. (2010) Rev. Geophys. 48, RG2001/2010*
[232] *https://www.climate.gov/news-features/understanding-climate/state-climate-2011-stratospheric-temperature*
[233] *Ramaswamy, V. et al. (2001) Rev. Geophys. 39, 71-122.*
[234] *Thompson, D.W.J. et al. (2012) Nature 491, 692-697.*

that provided by earlier data sets"'. The NOAA data now suggest an evolution of stratospheric temperature that is strikingly different from that obtained from models, especially in their latitudinal profiles; although the UK Met Office data suggest that cooling was relatively uniform with latitude, the revised NOAA now suggest greatest cooling in tropical latitudes.

The authors note that "*It is possible that the models are correct and that both SSU data sets are in error*" despite the fact that, as they point out, most models suggest that increasing greenhouse gases accelerate circulation in the stratosphere and that this should decrease ozone levels and hence induce cooling at low latitudes – as is confirmed by observation. But they also suggest that, at the present time, it is not possible to know whether the observations are in error, or whether the simulated ozone trends are incorrect. The authors leave the matter there, with some suggestions for resolving the impasse.

Chapter 5

THE OCEAN: MAIN GLOBAL SINK OF SOLAR HEAT

"It often happens that scholastic education, like a trade, does so fix a man in a particular way, that he is not fit to judge of any thing that lies out of that way; and so his learning becomes a clog to his natural parts, and makes him the more indocile, and more incapable of new thoughts and new improvements, than those that have only the talents of nature." [235]

The author of the above lines theorised in 1722 that the "*chaotic*" mountain ranges on Earth must be the aftermath of the Biblical flood, "*after the sea had overwhelmed all, and left only the ruins of the original, perfect Earth".* That was a nice fantasy, but it is not fantastic to suggest that "*scholastic education*" can restrain freedom of thought concerning massively complex problems like changes in global climate. Many of those now at work were taught the standard climate change model in their school and university courses, with all that that implies for their future thinking.

Nor would it be a fantasy to suggest that the oceans must play a dominant role in any discussion of climate because most of the solar heat retained by the planet is stored there. The relative importance of the oceans in any analysis of global climate stems from the simple fact that the thermal mass of seawater per unit volume is 3.5 x 10^{-3} greater than that of air at surface pressure, so the ocean has a heat capacity that is two orders of magnitude greater than that of the atmosphere. [236] A little solar heat is also stored in the rock and soil of the continents, but because the ocean is not a passive reservoir of heat, a good measure of the changing heat balance of the planet may be obtained through knowledge of change in the heat content of the ocean. This must be done at global scale because the radiation balance at the sea surface is not everywhere uniform, and the circulation of oceanic water masses importantly modifies the regional pattern of heat exchange.

One of the most interesting questions recently discussed is the hiatus in the long-term increase in global surface temperature data observed since the turn of the century (p. NN). Since the Earth has continued to receive solar radiation at the top of the atmosphere, "*...where exactly does the energy go?"* asked a recent study that made no reference to the possible effects of variability in incident solar radiation. [237] It has been widely suggested that the missing heat has entered the oceans, because this would enable balance to be maintained between solar radiation, its storage on Earth, and its

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[235] *Dr. Thomas Burnet , "The sacred history of the Earth", 1722*

[236] *Proc. NATO Adv. Stud. Inst., Erice, Italy, 1993.*

[237] *Trenberth, K.E. and J.T. Fasullo(2010) Science 328 316-318.*

loss to space at the top of the atmosphere. [238]

This suggestion is supported both by observations of subsurface warming in the ocean during this period – although these are not entirely satisfactory - and by simulations of heat fluxes under a constant radiative imbalance at the top of the atmosphere, using the Community Climate System Model. These suggest that decade-long periods of hiatus in atmospheric warming would occur during the 21st century, involving the uptake of heat by the ocean, especially in the upper 300m.[239] But no explanation is offered for how heat is transferred across the surface of the ocean, which is neither simple nor (as many seem to assume) just a matter of increasing the surface air temperature, or increasing the downwelling longwave radiation flux from clouds - both of which are quoted as consequences of the presence of anthropogenic radiative gas in the atmosphere. So, it may be useful to review the complex processes by which the ocean gains and loses heat.

5.1 - How does heat enter the ocean and how is it stored there?

This process is habitually presented as including four elements:

1 - Shortwave radiation (Qs) at visible and UV wavelengths from the solar disc or from scattered sky reflection in the visible part of the spectrum (0.4–0.7 μm), directly heats the interior of the ocean because seawater is relatively transparent to these wavelengths, and only a tiny fraction is reflected from the surface, so that most penetrates relatively deeply. Sunlight is detectable to 150m in the clearest (Type I) ocean water, while at 50m there still remains about 5% of the surface value. In turbid (Type 9) coastal water, sunlight is detectable only to 10m and 99% is absorbed shoaler than 5m. This is the main heating term in the budget, but the depth at which heating occurs depends largely on the abundance of plankton: a bloom of green phytoplankton cells will create local warming and prevent deeper penetration of energy to deeper water. This is usually a seasonal phenomenon at mid- and high latitudes but may occur episodically even in

2 - Longwave, or IR radiation (Qb) passes both skywards from the sea surface and downwards from the sky (more strongly below clouds) but penetrates no more 1-2 μm in seawater; in the past it has usually presented as a loss term, though this is now known not be exact.

3 - Latent heat flux (Qe) is carried by evaporated water from the sea surface to the troposphere and is very dependent on SST and, hence, on latitude. This is the major loss term in the oceanic heat budget.

4 - Sensible heat flux (Qh) is a minor loss term across the sea surface, proportional to the surface skin temperature gradient and some power of the wind speed.

Thus: $Qt = Qs - Qe - Qh \pm Qb$. [240]

The values allotted to latent and longwave fluxes in any ocean heat budget are sensitive not only to changes in SST but also to the temperature of the lower

[238] *Levitus, S. et al. (2012) Geophys.Res. Lett. 39, L10603, doi:10.1029/2012GL051106*
[239] *Meehl, G.A. et al. (2014) Nature Climate Change, in press.*
[240] *see, for instance, Dietrich, G. et al. "General Oceanography" Wiley-Interscience*

troposphere, since they are sensitive to temperature differences across the sea surface. An advective flux (Qv) would be required if regional heat budgets were to be computed.

Under most circumstances, just two fluxes dominate the balance in heat content of the upper ocean: (i) deep penetration of shortwave solar radiation into the upper layers to a depth depending on surface albedo, and on water clarity, and (ii) the loss of this heat to the atmosphere by the latent heat of evaporation above the surface of the ocean. The classic assumption of ocean physics is that of the 720 cal cm^{-2} d^{-1} of shortwave radiation that is received at the top of the atmosphere, 47.5 cal cm^{-2} d^{-1} enters the surface of the sea (22.5 directly, 10.5 by sky radiation and 14.5 from clouds), and the remainder is lost back to space by reflection from the sea surface, from cloud tops and by backscattering in the atmosphere. The component of longwave radiation from clouds represents, at about 6 W m^{-2}, " *the smallest radiative component of the surface energy budget and is less than the indirect effects of convection on the greenhouse effect of the atmosphere at the ocean surface*".[241]

These are median values, because there are major differences between heat flux at high and low latitudes, and between regions of active upwelling of cold, deep water and regions where the water column is more stable. Cooling by latent heat of evaporation, for instance, takes highest values in the warm tropical gyres (<200 $W.m^{-2}.yr^{-1}$) with lower values along the narrow equatorial upwelling band (>80 $W.m^{-2}.yr^{-1}$) of cool water in each ocean.[242] The greatest loss of heat from the ocean to the atmosphere occurs in the western boundary currents, principally the Kuroshio, the Agulhas Current and the Gulf Stream, in which warm water is transported poleward below a cooler atmosphere.

In the central Pacific, the upper ocean heat budget was quantified over an 18-month period on the 15 transects of the Hawaii-to-Tahiti shuttle experiment, and throughout this period the latent heat, sensible heat and IR fluxes were all found to be negative and nicely balanced incident solar radiation. Only heat gain by solar radiation and loss by latent heat of evaporation were judged to be sufficiently significant to quantify in the report on the experiment.[243] At higher latitudes, where sun angle changes strongly with the seasons, heat accumulation in the Gulf of Alaska is dominated by solar irradiance (Qsw, 159 $W.^{m-2}$) while all other heating fluxes total only 17 $W.m^{-2}$. In winter, heat is returned to the atmosphere largely through sensible heat flux.[244] . In the central Labrador Sea, the heat budget at OWS Bravo also contains strong seasonality in the surface flux that is imposed on a long-term loss of heat to the atmosphere. Both heat loss and gain fluxes here have a strong seasonal cycle of more than an order of magnitude: solar heating (December – 10-15 $W.m^{-2}$, June - 190 Wm^{-2}), latent and sensible fluxes together (January 90-100 $W.m^{-2}$, June 0-10 $W.m^{-2}$).

These studies are typical of the era of exploratory physical oceanography, but today we are faced with the problem of explaining an observed increase in ocean heat content in a scientific climate in which only one of two important questions is usually asked: is the observed warming anthropogenic - the 'missing heat' evoked after the flattening of the instrumental SAT curve in 1999-2000 - or is it an expression of some natural and cyclical phenomenon?

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241 *Collins, W.D. et al. (2000)J Geophys. Res. 105, 14807-14821*

242 *Weare, B.C. et al. (1981) J. Phys. Oceanog. 11, 705-717*

243 *Stevenson, J.W. and P.P. Niiler (1983) J. Phys. Oceanogr. 13, 1894-1907*

244 *Reed, R.K. and P.J. Stabeno (2001) Deep-Sea Research (submitted)*

The central contribution to solving the missing heat problem is that of Levitus, who provides "*updated estimates of the change of ocean heat content and thermosteric sea level change of the 0-700 and 0-200m layers…for 1955-2010*", based on a wide range of historical and recent data. Unfortunately, Levitus does not speculate how the heating might have occurred, but just repeats another's comment that "*the response of the earth's climate system to increasing atmospheric greenhouse gases is not simple*".

In fact, the key study of the consequences for ocean heat content of the addition of molecules of CO_2 to the atmosphere is that of Ramanatham, who broke new ground in the relatively early days of our concern over climate sensitivity. He suggested, based on some simple assumptions, that three feedback processes were involved: (i) that radiative heating by a factor of about 3 would occur in the lower troposphere because of the overlap of the CO_2 and H_2O bands in the 12-18µm region (rather than cooling, as occurs in the dry stratosphere), (ii) that although solar flux at the sea surface would be reduced, there would be a more-than-compensatory increase in the IR surface flux, and (iii) that direct radiative heating of the troposphere would occur, by a factor of about 3 for a doubling of CO_2. [245]

This translates to an increase of 15.5 $W.m^{-2}$ for a doubling of CO_2, the two direct surface fluxes together being relatively small (<3 $W.m^{-2}$) compared with the consequence of interactions within the lower troposphere (12.0 $W.m^{-2}$). This pattern has been investigated with the use of two coupled ocean-atmosphere models in which LW radiation is treated not only as a loss term from the ocean surface (as it is in classical physical oceanography) but also as a downward flux into the ocean as proposed by Ramanatham: "*by the 1990s, the downward longwave flux increases by 3.7 $W.m^{-2}$ which is not fully compensated by the upward flux of 2.2 $W.m^{-2}$, resulting in a net longwave increase of 1.5 Wm^{-2}*". It is not surprising that this flux should appear prominently in their model, because it is associated with the most discussed mechanism of anthropogenic warming: the radiative effect of CO_2. [246]

The component of downwelling longwave radiation from clouds is said to represent, at 6 W m^{-2}, " *the smallest radiative component of the surface energy budget and is less than the indirect effects of convection on the greenhouse effect of the atmosphere at the ocean surface*".[247] In any case, the positive radiative forcing of SST by long-wave emanation from low-level clouds is greatly outweighed by the effect of direct sunlight being reduced as clouds pass overhead.[248]

But, there is a body of recent observations that suggests that the physics of the ocean skin is more complex than is discussed in some older texts. [249] There is a significant difference between routine SST measurements that represent the temperature of the first metre or two below the surface, and the skin temperature of the ocean as observed by satellites.[250] We know now that a micron-scale skin layer occurs at the very surface, the characteristics of which at least partly control the rate of sensible

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[245] *Ramanatham, V. (1981) J. Atmosph. Sci. 38, 918-930*
[246] *Pierce, D.W. (2006) J. Climate 19, 1873-1900*
[247] *Collins, W.D. et al. (2000)J Geophys. Res. 105, 14807-14821*
[248] *Lockwood, M. and C. Frohlich (2007) Proc. Roy. Soc. A doi:10.1098/rspa.2007.1880*
[249] *Pierce, D.W. (2006) J. Climate 19, 1873-1900*
[250] *Zeng, X. et al. (1999) J. Geophys. Res. 104, 1525-1536.*

heat flux from the ocean at night when the atmosphere cools faster than the ocean below.[251]

Clearly, if the absorption of long wavelength sky radiation at the surface of the ocean modifies the slope of the temperature gradient across the skin layer and this will, in turn, reduce outgoing heat flux from the (usually) warmer ocean into the (usually) colder atmosphere. Very delicate observations at sea have now confirmed that longwave radiation from the passage of clouds overhead induces appropriate change in the micron-scale thermal gradient and so must reduce the flux of heat from the ocean into the atmosphere.[252] But at very low wind speeds within a warm air mass, the surface skin may no longer be cool in relation to the underlying water; in this case no heat flows into the skin layer from below and, consequently, there can be no heat loss to the atmosphere.[253]

To complicate matters still further, the micron-scale skin is eroded at wind speeds >5 $m.sec^{-1}$, which is significantly less than mean wind speed over the open ocean, so we must ask what is the balance of infra-red radiation across most of the ocean's surface, most of the time? This question is particularly pertinent now because there is some evidence to show that during recent decades both wind speed and wave height have progressively increased over the ocean at all latitudes.[254]

Unfortunately, I believe that we have no assurance that the simulation models used to predict anthropogenic warming of the ocean treat longwave fluxes at the surface of the ocean in a realistic manner, accommodating what we now know of the physics of the surface skin of the ocean. Those used by Pierce and his colleagues at Scripps to simulate heat flux into the oceans, and also the HadCM3 model, were crafted prior to our new understanding of the complications of the molecular skin of the ocean, so the surface flux mechanisms are described in very simple terms: "*fluxes of heat and momentum at the atmosphere-ocean interface are accumulated...near-surface vertical mixing is parameterised...below the mixed layer the vertical diffusivity is an increasing function of depth".* This describes a process with dimensions that are not correct for the penetration of IR heat into seawater.[255]

The 4th Assessment Report of the IPCC also seems to have had some doubts about the capability of the models available to them to handle the revealed complexity of heat flux between ocean and atmosphere. The IPCC has expressed concerns in the past about the "*capacity of climate models to simulate observed variability as well as the non-climate-related biases in the observations of ocean heat content change*". But the 5th Assessment Report of 2013 is much more confident, having eliminated (i) systematic errors in BT observations, which comprise the bulk of the historical ocean temperature data base, (ii) bias due to non-anthropogenic forcing, especially from volcanic dust veils, and (iii) by using a multi-model archive (CMIP3) through which the "*anthropogenic fingerprint in upper-ocean warming*" was observed.

But that cannot be the end of such a complex story, so some exploration of the observational evidence concerning ocean warming is appropriate to this discussion.

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251 *Minnett, P.J. et al. (2011) Deep-sea Res. II, 58, 861-868.*
252 *Minnett, P. (2006) NAS Guest Commentary: 'Why greenhouse gases heat the ocean'.*
253 *Konda, M. et al (1994) J. Oceaography 50, 17-30,*
254 *Young, I.R. et al. (2011) Science DOI: 10.1126/science.1197219*
255 *Gordon, C. (2000) Climate Dynamics 16, 147-168.*

5.2 - Progressive warming of the ocean

Whatever the precise mechanism might be, a progressive warming of the ocean during the 20th century has been reported in many studies and, indeed, there are many reasons why the heat content should not remain stable over long periods - for one thing, the acquisition of data has not been standardised over very long periods. Oceanographic data obtained with profiling instrumentation are essential for the computation of changes in heat content of the interior of the ocean, but such data are not satisfactorily distributed in space and time to represent change at global and secular scale - which is what is required. Throughout the period in which we are now interested, measuring tools have progressively evolved and measurements have been made progressively more frequently and comprehensively. It is very difficult to extract a long-term signal of change from such data and studies of the 'missing heat' issue tend to deal only with the last 10-15 years when global, timely data finally became available. This is hardly a satisfactory situation.

The general retreat from ship-board oceanographic surveys at the end of the 20th century and the bottle-casts, CTDs and XBTs that provided information on ocean temperature structure up to that time have now been replaced by large numbers of drifting, profiling and satellite-reporting ARGO floats scattered in all oceans, together with some moored arrays of buoys.[256] So although we now have a good global measure of changing heat content of the oceans in the new century, we also have a major problem of compatibility between two critical segments of observations.

The earliest comprehensive data on ocean heat content were obtained during the global oceanographic survey of HMS Challenger and these indicate that the interior of the ocean was indeed cooler in 1850 than is currently reported by the synoptically-sampled global data obtained from ARGO free-drifting, profiling, satellite-reporting floats in the 21st century.[257] But the change of heat content of the oceans since the Challenger voyage is most unlikely to have been a simple trend and, in a series of recent papers on increasing ocean temperatures that are based on classical oceanographic data, Levitus and his colleagues propose that the warming was episodic at the decadal scale, and uniform neither geographically, nor with depth. This series of studies concluded that the 0-700m layer of the oceans has warmed since 1955 at a rate of 0.27 Wm^2 and that heat content has increased by 16.7 x 10^{22} joules. Heat penetrated deepest in the Atlantic, and warming began later in the Indian Ocean than in the other basins.[258]

However, some doubt concerning these expressed certainties is in order because of the strong spatial structure in the pattern of warming at depths between 50 and 1000m: the global signal is very far from simple. A recent study of almost 8 million oceanographic profiles, partitioned among larger grid boxes than in the Levitus analysis in order to increase homogeneity in the analysis, confirms that in most of the ocean the observations do not express 50-year trends, either of cooling of warming, at a 90% confidence level. The authors of this result suggest that interpolation from the

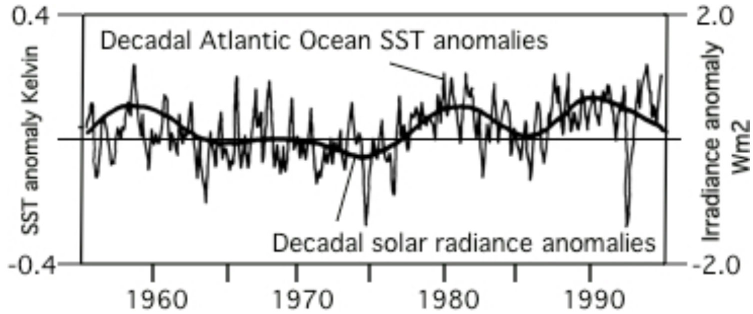
[256] *Lyman, J.M. et al. (2010) Nature, 465, 332-336*
[257] *Roemmich, D et al. (2012) Nature Climate Change DOI: 10.1038/NCLIMATE1461*
[258] *Levitus, S. et al. (2012) Science, 287, 2225-2229*

unsatisfactory distribution of observations over large regions of the ocean may have "*substantial effects on trend results*".[259]

We are on more secure ground in studies of change in ocean heat content that use only data from Argo floats, modern XBTs and precision satellite sea-surface elevation, although this restricts analysis to the very recent past. It is clear that the heat content anomaly did increase after 1993 at rates that appear to be compatible with expected effects of Niño events, but have not increased further since 2004, when the global pattern of autonomous Argo floats became fully operational and provided satisfactory coverage of the Southern Ocean, although it seems that the Southern Ocean did not participate in this flattening of the OHCA curve.

I have seen no satisfactory formal explanation of the variable warming pattern although, despite the title of his 2001 paper *"Anthropogenic warming of the global climate system"*, Levitus did comment (more prudently than some others) that it is not possible to partition the observed warming of the ocean between anthropogenic and natural variability components: *"modelling studies are required even to be able to attempt such a partition"* he wrote in an early paper in this series. One such model-based study suggested that natural internal variance in temperatures profiles should be significantly lower than observed variability over the last 40 years and suggested that an anthropogenic effect must be implicated; but, although changes in volcanic shading, variability in global cloud cover was not considered - which would seem to invalidate the stated conclusion.[260]

An interesting series of studies from Scripps will illustrate the problems of reaching certainty concerning how heat has accumulated in the upper ocean since mid-20th century. The first of these suggested a direct cause-and-effect relationship between cyclical solar irradiance and surface and sub-surface temperature in Atlantic, Pacific and Indian Oceans and investigated the consequences of solar cycles having periods of >100 years, of 18-25 years and of 9-13 years, in each of the major ocean basins; the data from simple, mechanical BTs allowed the penetration of heat down to the main pycnocline to be followed during this long period.[261] I have chosen to show the response of the Atlantic Ocean to changes in (smoothed, global) solar luminosity in this diagram, because this ocean – together with the linked Arctic Basin – is peculiarly reactive to external forcing (pp. NN) and Atlantic data are probably the most comprehensive.



However, this study also showed that there was a simple relationship in all ocean basins during the entire 20th century between the solar irradiance anomaly at the surface and SST anomalies, both having a positive trend, which was briefly reversed

[259] *Carson, M. and D.E. Harrison (2008) J. Climate 21, 2260-2268*
[260] *Barnett, T. et al. (2005) Science 305, 284.*
[261] *White, W.B. (1997) J. Geophys. Res. 102, 3255-3266. (the image is redrawn)*

after 1960 before resuming a steeper warming trend. Over shorter periods, correlations were established between the solar signal and temperature down to 80-120m, a depth that approximates the mean depth of the main pycnocline in the open ocean: this is the depth that would be predicted by simple physical principles. The modelled heat budget derived from these data suggested that responses at the sea surface to observed changes in irradiance should have been close to those observed so, the authors conclude, "*we can infer that anomalous heat from changing solar irradiance is stored in the upper layer of the ocean*".

Further, since longwave radiation back to the sky from the sea surface can equilibrate the upper ocean temperature only after a period of 1-3 years, application of the climate sensitivity of the ocean to the trend in solar irradiance at the top of the atmosphere yields an SST response of 0.2-0.3^{o}K, which is close to that observed (0.4^{o}K) suggesting, according to the authors, that "*global warming...over the past century was significantly influenced by the corresponding increase in solar irradiance*".

But the following year, almost the same group of authors published a companion paper[262], in which the heat budget of the upper ocean was investigated by means of depth-weighted, gridded estimates of heat content having different periodicities. Heating follows solar radiation with a small lag, but the study concludes (i) that the temperature change was too large to be explained by solar effects alone and requires the computed 0.5W.m^{-2} anthropogenic radiative forcing and (ii) that natural modes of Earth's variability are phase-locked to the solar irradiance cycle. Then, in 2003, another paper (same senior author, same journal) suggested on the basis of reanalysis studies of the troposphere and of upper ocean temperatures that the observed tropical diabetic heat storage observed in the BT data cannot have been driven directly by the radiative forcing approximately 0.1Wm^{-2} changes that occur during the 11-year solar cycle.[263] Rather, the warming tendency of 03-0.9 W.m-2 is driven by anomalies in the heat fluxes at the surface of the tropical ocean that are balanced by a decrease in the net poleward Ekman heat advection poleward - the process being the opposite of the mechanism of global tropical warming during El Niño episodes. The final conclusion of this set of studies, then, is that although the heating signal is phase-locked to the 11-year solar cycle the heat content of the upper ocean and lower atmosphere is not a direct consequence of variable solar radiation.

This conclusion is comforted by observations made after the completion of the array of Argo profiling floats in the new century that have reduced uncertainties in the balance between solar radiation at the top of the atmosphere and ocean heating rate. But the short observation period allows no more than a confirmation that the two rates are consistent, and to confirm that the Earth has progressively accumulated solar heat during at least this short period. These data also confirm that the response of the ocean to changes in solar intensity is modified by volcanic dust veils, and that the Earth preferentially accumulates heat during La Niña periods, when extensive regions of cool surface water occur in the tropical ocean as a result of upwelling induced by the strong trade winds characteristic of these periods.[264]

But others offer us a variety of alternative interpretations: for example, a heat content anomaly (0-700m) series from NOAA Seattle extends the corrected Lyman data

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[262] White, W.B. et al. (1998) J. Geophy. Res. 103, C10, 21355-21366.
[263] White W.B. (2003) J. Geophys. Res. 108, doi:10.1029/2002JC001396
[264] Loeb, N.G. et al. (2012) Nature. Geosc., doi10.1038/NGEO1375; see also Section 4.4

(p. NN) from the mid-1990s to the present day. Although this confirms that the heating rate differs very strongly across latitudes, between oceans and with depth, just as oceanographers would expect it to do, it also suggests a warming trajectory that differs from that of the latest analysis from the Levitus group by removing the flattening of the rate of increase after 2003. However, it has been pointed out that this study quotes results that imply that the change in temperature anomaly (-0.040^{o} to +0.045^{o}C) is known – or can be calculated - with a precision that is unattainable.[265]

It also rather carefully avoids direct comment on the mechanism of the late 20th century warming, but notes indirectly: "*The fact that relative extremes of OHC are a function of latitude and in some cases are at different latitudes in each major ocean basin indicates that different ocean, or ocean-atmosphere responses to the common forcing of the observed increase in greenhouse gases in earth's atmosphere occurred. Although carbon dioxide is well-mixed in the atmosphere, the response of earth's climate system to increasing atmospheric greenhouse gases is not simple*". This uncertainty is not very helpful, but matches the opinion of the AR5 of the IPCC.

Obviously, all this confusion confirms that the interior of the ocean has not been monitored over sufficiently long periods, and with sufficiently homogeneous methods, to give us any confidence at all in reported long-term trends – even when 'long-term' means just a few decades. There have been several attempts to plug the gap, of which the latest at the time of writing emphasizes the effects of poor sampling in the Southern Hemisphere and, using *"a large suite of climate models"*, concludes that "*the observed estimates of 0-700 dbar ocean warming since 1970 are likely biased low*" so that "*we adjust the poorly constrained estimates…so that hemispheric ratios are consistent*" with models.[266]

All this leaves us in the uncomfortable position of having two competing mechanisms before us, and a choice to make: (i) the observed heat gains are attributable to anthropogenic heat that has entered the oceans or (ii) changes in solar radiation received at the sea surface have been sufficient to cause the warming.

The IPCC asks no such questions, and rejects outright anything other than an anthropogenic effect. Thus AR5 remarks that "*The very high levels of confidence and the increased understanding of the contributions from both natural and anthropogenic sources across the many studies mean that it is extremely certain (that is greater than 95% probability) that the increase in global ocean heat content observed in the upper 700 m in the latter half of the 20th century can be attributed to anthropogenic forcing*". This is not a new conclusion, but the confidence expressed in it has changed from "*Very likely*" to "*Extremely certain*" since the previous Assessment Report.

Some may find this an unsatisfactory statement in the absence of any discussion of the surface processes responsible for the insertion of anthropogenic heat from the radiative effect of CO_2 into the upper ocean; the thermodynamics of the skin layer of the ocean are not discussed either here or in any of the other relevant chapters of AR5. The problem is, quite simply, ignored although, given the vastly different heat capacities of air and seawater, a suggestion would have been in order to explain how the amount of heat represented by the measured increase in ocean temperature could possibly have

[265] *Levitus, S. et al. (2012) Geophys. Res. Lett. 39, L10603, doi:10.1029/2012GL051106*
[266] *Durack, P.J. et al. (2014) Nat. Clim. Change 4, 999-1005*

originated in the atmosphere. Change in the radiation balance at the top of the atmosphere, and across the sea surface are a radically more satisfying solution.

For this reason, I have greater confidence in the near-surface heat budgeting approach discussed above (p. ---) that suggests that "*we can infer that anomalous heat from changing solar irradiance is stored in the upper layer of the ocean*". Whether an anthropogenic signal can be detected or not, I cannot judge.

5.3 - Cloud cover - a difficult-to-measure variable aperture

I take it as a given – from classical oceanography, expressed in analyses such as that of Woods and Barkman of mixed layer formation[267] – that the most direct way to inject heat into the ocean is to increase the flux of sunlight and UV radiation at the sea surface, and that the principal constraint on this flux is marine cloudiness. This foundation-stone of climatology is too often forgotten, but was recently re-stated with conviction: "*Earth's climate is dominated by the oceans. Clouds play important roles in climate, affecting both radiation and latent heat fluxes, but the different types of cloud affect marine climate in different ways*". [268]

More generally, the importance of clouds in the radiative balance of Earth is easily demonstrated: a doubling of the present concentration of CO_2 in the atmosphere would result in an additional forcing of about 2% of the current radiative effect of CO_2 molecules, while an increase of only 15-20% in low-level cloud cover would have equivalent radiative consequences.[269] Unfortunately, even though cloud cover is the most important single moderator of heat flux in Earth's radiation budget, there is great uncertainty concerning long-term change in cloudiness at global scale, to the extent that some studies have suggested that we cannot be absolutely certain whether cloud cover has increased or decreased during the last several decades.[270] However, these studies have been dominated by the use of satellite data that are tricky to use, and are restricted to several very short periods since 1980.

Accumulated observations of cloud cover are located in four principal archives:

<u>Extended Edited Cloud Report Archive</u> (EECRA) of synoptic weather data obtained by observers afloat (1952-2008) and ashore from a group of 5400 meteorological stations on all continents (1971-2009). [271] The marine component of this archive is based on the ship and island-based observer data held in ICOADS.

<u>Earth Radiation Budget Experiment</u> (ERBE) data were obtained with the NASA ERBE and two NOAA satellites (1984-2005) although the original objective was to produce a global radiation budget over a shorter period.[272]

<u>International Satellite Cloud Climatology Project</u> (ISCCP) associated with the World Climate Research Programme that has archived data from weather satellites

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[267] *Woods, J.D. and W. Barkmann (1986) QJMS 112, 1-27*
[268] *Eastman, R. et al. (2011) J. Climate 24, 5914-5934.*
[269] *Slingo, A. (1990) Nature, 343, 49-51.*
[270] *Norris, J.L. and A. Slingo (2009) In – Heitzenburg & Chalson (2009) "Clouds in perturbed Climate System" MIT Press.*
[271] *https://climatedataguide.ucar.edu/climate-data*
[272] *http://www.nasa.gov/centers/langley/news/factsheets/ERBE.html*

operated by member nations since 1982. Data are archived at NASA Goddard and are currently available for the period 1984-2009.[273]

NOAA High Resolution Infrared Radiation Sounder (HIRES) these instruments are flown aboard NOAA polar-orbiting satellites (1979-present)[274]

The direct measurement of cloud cover is not easy: both satellite sensors and human observers on the ground have the same basic problem because it is only directly overhead, or directly below the sensor, that the percentage of cloud cover can be estimated with accuracy. But both satellite sensors and observers see not only the top (or bottom) but also the sides of individual clouds, and so both tend to exaggerate the percentage of total cover. Observers on the ground are required to estimate how much of the sky (in octets) is obscured by cloud at all levels, a measure that represents at best only the relative shading of the surface by cloud, not absolute amounts of cloud cover. Furthermore, the relative skills and sense of responsibility of observers at sea and ashore are unlikely to be equivalent; at sea, a junior navigating officer is the responsible person while, ashore, it is a trained technician who is responsible at a meteorological observatory. And, finally, the relative distribution of observations at sea and on land is very different, because observatories tend to have been located where they would be useful, while at sea observations have been taken where ships have gone for commercial or military reasons - very large areas of ocean have therefore provided no data.

Much of the recent literature on changing cloud cover and its potential effects has been based on satellite data with rather uncertain results. However, a recent contribution, based on a comparison of patterns in the ISCCP archive of satellite observations, the HadCRUT4 surface temperature archive and the ENSO index, concluded confidently (i) that a strong relationship existed between surface temperatures and the ENSO index and (ii) that divergence between land and sea surface temperatures, and trends in these, were coincident with significant changes in cloud cover that included a sustained decrease in low cloud cover.[275] This would have been a strong support for the concept of a simple relationship between strength of solar radiation, controlled by changing low cloud cover over the oceans, and ocean heat content except for the fact that - as shall be discussed later - it has now been shown conclusively that the data used to describe changing cloud cover deliver "*spurious*" results at global scale (p. NN).

But other studies of global cloud cover, also based on the satellite data archives listed above, have reached far more nuanced conclusions: the authors of a critical study of the viewing characteristics of the ISCCP satellites proposed that "*the long-term global trends in cloudiness...are influenced by artefacts associated with satellite viewing geometry*".[276] The field-of-view of these satellites changes with time as satellite orbits degrade and also because the spatial pattern of local trends becomes strongly biased near the edges of the field of view of geostationary satellites to the extent that this corrupts gridded data. To make it worse, the number of operational satellites changed during the acquisition of data with the consequence that optically thin clouds that were detected originally were lost later on, so that total cloud cover appeared to decrease during a 5-year period. "*Despite the multiple layers of calibration and adjustment in*

[273] *http://isccp.giss.nasa.gov*
[274] *Shi, L. and J.J. Bates (2011) J. Geophys. Res. 116 doi.10.1029/2010D01487, 2011*
[275] *McLean, J. (2014) Atmos. Climat. Sci. 4, 727-742.*
[276] *Evan, A et al. (2007) Geophys. Res. Lett. 34 L04701*

ISCCP, this trend and other variations in global mean cloud cover appear to be entirely spurious", concluded this study from Scripps, referring to the evolution of global cloud cover indicated by the ISCCP archive.[277]

In fact, observations of cloud cover from national meteorological services ashore, and from ships of observing nations at sea, offer a more comprehensive and reliable source of information on the progress of cloud cover globally. The cloud observations over the ocean (1954-2008) and from meteorological stations ashore (1971-2009) are both archived in the EECRA. and have been used in a pair of studies that appear to offer the most useful and comprehensive analysis of the evolution of cloud cover.[278] Prior to use of the data, it was necessary to identify changes of protocols in some land observations, and the effect of progressive changes in the nationality of ships at sea and, once this was done it, it became clear that the observer data give a much more satisfactory description of evolving cloud cover than satellites.

The observer data show clearly that clouds over land and sea differ significantly because of the existence of high relief on land and of the evaporative environment over the oceans, in which water vapour is continually released into the lower atmosphere in the transfer of latent heat from the sea surface. The oceans are therefore significantly cloudier than the continents (3% clear sky compared with 22% over the continents) with more than double the amount of low stratus, strato-cumulus and cumulus, while only high cirrus is more frequent over land. Low cloud types tend to be negatively correlated with SST, and therefore more typical of higher latitudes, while high clouds are most abundant over tropical seas.

The evolution of observed cloud cover over the ocean is the resultant of a progressive evolution of the composition of low cloud, so that although change in low clouds dominates the whole pattern, low stratiform cloud cover has progressively increased throughout the period of observation at the expense of strato-cumulus. However, since cloud cover reacts directly to trade wind failure during Niño events in the equatorial Pacific, the consequences of the associated pauses in equatorial upwelling of cold water dominate any discussion of cloud climatology over the ocean. In such conditions, even MODIS and the ISCCP instruments show that cloud cover is regionally increased and any changing pattern of heat exchange at the sea surface will be a direct consequence of changing wind stress, while the change in cloud cover is secondary. [279]

One would expect similarly good matches between SST and total cloudiness in other regions where strong wind-induced upwelling of cold water to the surface occurs - such as along the coast of Somalia in the NW Indian Ocean, and perhaps even in the less-intense upwelling regions in the eastern boundary currents off the African and American continents. But elsewhere, it is changes in the extent of marine stratocumulus cloud cover that we would expect to have the greatest effect on the transfer of solar heat into the ocean, and this is confirmed in the fact that the equatorial Pacific is the only major ocean region where cloud cover correlates positively with SST, and where SST is forced simply by upwelling wind stress ate the sea surface.

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[277] *Norris, J.R. and A. Slingo (2009) in "Clouds in the perturbed climate system" MIT Press, ISBN 978-0-262-01287-4*

[278] *Eastman, R. et al (2011) J. Clim. . 24, 5914-5934., and (2013) J. Clim. 26, 1286-130; this section owes much to these papers.*

[279] *Pallé, E. and B. A. Laken (2013) Am. Inst. Physics 1531, 664 doi: 10.1063/1.4804857*

The gradual decrease in cloud cover observed in those regions where marine stratocumulus is the typical cloud type is usually attributed to a positive cloud feedback to a warming sea surface, thus ignoring the opposite possibility that a reduction in cloud cover by some other agency may have permitted more solar radiation to reach the sea surface. It is not simple to choose between these possibilities given that we have no data concerning air temperature in the lower troposphere over the oceans: recall that SST data are used to substitute for marine air temperatures in the HadCRUT and GISS archives. Nevertheless, such a conclusion conforms to the assumption discussed at the start of this chapter that the "missing heat" after the late 1990s had gone to heating the ocean, rather than the atmosphere.

5.4 - Does cloud cover respond to solar and galactic forcing?

The possibility that variable cloud cover should act as a variable aperture to control the strength of direct solar radiation at the sea surface cannot be ignored, but inevitably returns us to the much-vilified suggestion of Spencer and Braswell of a direct link between the behaviour of the Sun and changes in the global weather patterns and cloud cover; this suggestion then leads to the unavoidable confirmation of a role for the solar irradiance cycle in determining global weather patterns.

However, it also leads us to an even more direct mechanism by which the Sun might control cloud cover, although this mechanism is far from being accepted by the community, has been rejected by both AR4 and AR5, and lacks any association with indices of global weather patterns discussed above. This mechanism is based on the effects on cloud formation induced by the variable flux of elementary particles (or ‘cosmic rays’) that reach Earth from beyond the galaxy, the intensity of the flux being controlled by the strength of the solar wind at the heliosphere. This is a potential mechanism that has been so warmly debated that it requires special attention here because, if verified, it has fundamental conclusions for climate science.

The plasma that streams out in all directions from the surface of the Sun forms the heliosphere, within which lie all the planets. This 'solar wind is balanced at the heliopause by the opposing flux of elementary particles from space, with the result that these do not freely penetrate within the heliosphere; Earth is thus offered partial protection against the flux of particles. However, when the solar wind weakens (as it does at the minimum of each 11-year solar cycle) the flux of cosmic rays to the planets is enhanced. On Earth, at sea level, the variation of this flux during each solar cycle is approximately 2%.

The flow of cosmic particles that do reach Earth is also intermittently, but strongly, disrupted by the occurrence of solar flares; these are the Forbush events that have caused much dissension recently – as will be discussed below.

The collision of cosmic particles, especially protons, with the molecules of the upper atmosphere results in a shower of rapidly-decaying particles of which the muons or heavy electrons are the slowest to decay and so reach deep into the lower atmosphere where they are largely responsible for ionisation, the strength of the atmospheric electric field and the occurrence of thunder storms. There is evidence that the level of ionisation also controls the coagulation of molecules into condensation nuclei for water vapour and hence for cloud formation – and this process, which is obviously important for global climate conditions, should then follow cyclical changes in the strength of the solar wind, itself associated with cyclical solar brightness.

On this process is based the much-criticised reiteration of an old idea by Svensmark and Friis-Christensen, that "*the observed variation of 3-4% of the global cloud cover during the recent solar cycle is strongly correlated with the cosmic ray flux…larger at high latitudes in agreement with the shielding effect of Earth's magnetic field on high-energy charged particles*".[280] Since cosmic particles can act as cloud condensation nuclei in this way, the solar cycle may thus be associated with changing global cloudiness[281] – and this suggest another potential mechanism to modify the amount of shortwave radiation reaching the surface of the earth.

But, a decade-and-a-half later, the debate continues in the peer-reviewed literature, and the IPCC has not been supportive of the concept in their Assessment Reports. In 2007, their discussion of the issue was rather confused, while in their 2013 Assessment the IPCC tries to take no clear position - although their language leaves the reader in no doubt of their opinion.

The verification of the Svenmark mechanism itself has been approached by cloud chamber experiments and by observations of sudden drops in cosmic rate flux rate, the Forbush events that follow a sudden surge in the strength of the solar wind. Observation of cloud water content following a Forbush event reveals a drop in liquid water content in low clouds of as much as 7% about a week after each event.[282] With about the same delay, a decrease in daily temperature range (anti-correlated with cloudiness) has also been noted after these events.[283] This effect was verified by observations of low cloudiness at the Lerwick Observatory in the Shetlands at 69°N, at sufficiently high latitude that the effect is enhanced. Here, to quote the authors, "*Meteorological measurements…are compared with short-term changes in…neutron counter cosmic ray measurements. For transient…reductions of 10-12%, broken cloud becomes at least 10% more frequent on the neutron minimum day…*" Weaker events do not produce the effect and stronger events are too infrequent to provide a statistically meaningful correlation.[284]

There is also a quite different set of observations that clearly link the intensity of cosmic particle flux with clouds, and with Forbush events: at times of rapid decrease in total solar irradiance and increase in sunspot number, the Earth receives high speed streams of solar wind particles that originate in the regions of the spots. These events are associated with a statistically significant increase in the rate of satellite observations of lightning strikes, although this may simply be the effect of an increase in the intensity of each strike – so increasing the likelihood of it being recorded; but the fact that increase in strength of the solar wind of particles is expected to enhance ionisation within clouds supports the initial suggestion. But during these episodic increases in solar wind, cosmic ray flux is reduced so as to produce the largest of the Forbush events discussed above.[285]

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[280] *Svensmark, H. and E. Friis-Christensen (1997) J. Atmosph. Solar-Terr. Physics 59, 1225-1232.*
[281] *Svensmark, H., et al. (2006) Proc. Roy. Soc. Ser. A, 386-396.*
[282] *Svensmark, H. et al. (2009) Geophys. Res. Lett. 36, L15101*
[283] *Drajic, A. et al. (2011) Astrophys. Space Sci. Trans. 7, 315-318.*
[284] *Harrison, R.G. and M.H.P Ambaum (2010) J. Atmosph. Solar-Terrestrial Sci. doi:10.1016*
[285] *Scott, C.J. (2014) Envir. Res. Lett. 9, 055004*

The most cogent contrary argument is that cloud formation is not limited by the abundance of condensation nuclei, because they are present in sufficient numbers everywhere. The CLOUD experiment at CERN was intended to resolve the problem and repeated, with more precise instrumentation, earlier cloud chamber experiments done by Svensmark. The results, reported by Kirby and others[286], are not simple but do confirm that natural cosmic rays induce the formation of clusters of molecules ("particles") that in the real atmosphere might grow and form clouds. This process is shown to require H_2SO_4 and (probably) the presence of trace organic molecules. It has been suggested that the relative absence of these in the cloud chamber, compared with the atmosphere, may have restrained the rate of particle formation. It was also pointed out that the nanometre-sized particles so far obtained in the CERN cloud chamber were an order of magnitude too small to act as cloud nuclei. Further experiments are planned to explore more realistic *in situ* conditions in the chamber and other groups have independently demonstrated aerosol nucleation experimentally in a high-energy particle beam *"under conditions that resemble Earth's atmosphere"*.[287]

Lockwood examines evidence from more than 50 studies, each of which argue either for or against the relationship. Almost all assume that the verification of the suggested effect, which cannot be other than subtle, and depends on establishing correlation with effects produced on global cloud cover by changing flux rates of cosmic particles; unfortunately, such evaluations are commonly expressed in inappropriate terms: thus, "*…there is no solid GCR-cloud relationship*" wrote Sun and Bradley, perhaps ignoring the difficulty of establishing this trend with any precision.[288]

Perhaps because I have spent my life in observational science, rather than in trying to simulate nature, I have no problem at all with the mechanism itself: the simple observations made directly overhead, in real time, at Shetland, are sufficient to convince me that the effect is real, although the consequences are extremely difficult to quantify, because the rate of the particle flux co-varies with changes in solar irradiance so that it is not easy to separate the effects, and also because of the difficulty of quantifying global cloud cover. It is also clear that many authors have attempted to locate the thermal effect of cloud cover changes caused by variable cosmic ray flux in inappropriate data sets: as discussed in Chapter 4, the SAT data are so heavily contaminated by other effects as to be misleading and the correct data to be evaluated are those for heat content of the oceans. These are uncontaminated by anything other than methodological changes – the lower troposphere over the oceans being relatively particle-free compared with much of the continental surface - and should most directly record the consequences of changing cloud cover because of the direct penetration of short wavelength and UV from the Sun into the ocean..

This being the case, it should be possible to use the evolution of ocean heat content as a calorimeter to measure historical heat flux and thus obtain a proxy for heat input at the sea surface and this has been formally proposed by Shaviv in a paper that has been much criticised, since it supports Svensmark's challenge to the standard model of climate change: it suggests that one consequence of the variable flux of cosmic rays should be to modulate cloud cover over the ocean and thus its heat content, using the

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[286] *Kirby, J. et al. (2011) Nature 476, 2429-433.*
[287] *Enghoff, M.B. et al. (2011) Geophys. Res. Lett. 38, L09805, doi:10.1029/2011GL0470*
[288] *Sun, B. and R.S. Bradley (2004) J. Geophys. Res. 109, D14206*

simple and reasonable assumption discussed above that it is primarily solar short-wave radiation that controls the heat content of the upper ocean.[289]

Shaviv uses a simple 1D ocean diffusion model to compute the radiative forcing variations that are associated with the solar cycle at the sea surface using (i) observed changes in ocean heat content (ii) sea surface temperature, and (iii) sea level change - although it was necessary to confirm the relationship between the two indirect (and relatively noisy) estimates of heat content and the direct measurement of ocean heat content on which the study was primarily based. This enabled the amount of heating at the surface required to produce the observed changes to be compared with observed changes in total solar irradiation.

Correlations are both seductive and dangerous, but the correspondence between these four variables is very close and quite seductive: evolution of the neutron monitor data and TSI very nicely match global and North Atlantic mean heat flux, sea level rise and surface temperatures. The heat input apparently required to produce the observed changes in the ocean is computed as 5-7 times greater than is associated with changes in total solar irradiance "*thus implying the existence of an amplifying mechanism, without pointing to which one*", although the changes in irradiance and SST are remarkably well correlated.

Where, then, does this heat come from if not directly from variable solar irradiance, asks the author? It can only result by the intervention of a 'valve' in the atmosphere capable of modifying incoming solar radiation before it encounters the sea surface: in this case, solar flux is high at the sea surface when the valve opens and low when it closes. Always providing that these computations are verified, it seems inescapable that some mechanism magnifies the globally averaged irradiance variation during each solar cycle by almost an order of magnitude. The cloud cover data discussed above are compatible with this suggestion, with indications of decreasing cloudiness – or the opening of the valve – since the mid-1990s, associated with the accumulation of heat in the upper ocean. This observation is consistent with the conclusion that this warming is associated with the level of solar irradiance at the top of the atmosphere, and also with the discussion concerning the mechanisms that control heat flux across the surface of the ocean.

I leave the matter there, but suggest that this is not a process that should be ignored – or swept under the table, which is how it was dealt with in the current 5th Assessment Report of the IPCC: "*There is medium evidence and high agreement that the cosmic ray–ionisation mechanism is too weak to influence global concentrations of cloud condensation nuclei or their change over the last century or during a solar cycle in any climatically-significant way*". The authors appear not to have noticed the study by Shaviv, and the significance it has to confirm Svensmark's proposals concerning the flux of cosmic particles. It would have been nice if the global cloud data discussed in the previous section had been sufficiently reliable to support or reject Shaviv's interesting model with confidence; unfortunately it does not, but I think that that is not the end of the matter.

[289] *Shaviv, N.J. (2008) J. Geophys. Res. 113, A11101*

Chapter 6

REGIONAL PATTERN OF TEMPERATURE CHANGE OVER LAND SURFACES

"I'm truly sorry Man's dominion
has broken Nature's social union"

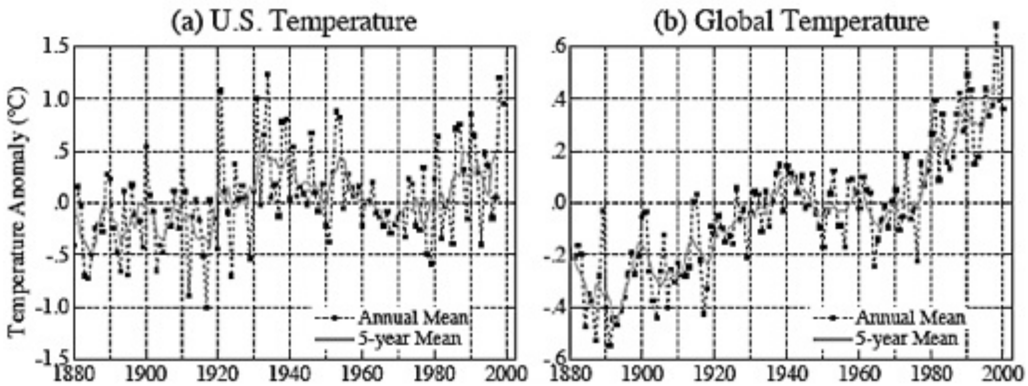
Robert Burns, 1785

The establishment of a single value to represent a global surface temperature over all land surfaces is not only difficult to achieve, as discussed in the previous chapter, but this value also hides both the regional diversity of climate and the temporal variability that occurs at all scales from between-year differences to millennial change.

These issues are the subject of this chapter that also emphasises the extent to which human activities during the Holocene have modified the natural surface of the planet - and hence its regional climates - to a degree that would have been unimaginable to Robert Burns, poet and ploughman of the 18th century – deep thinker though he was.

6.1 - Regional anomalies in the evolution of SAT during the 20th century

A press release issued by NASA GISS in 2006 suggested that: "*it must now be recognised that the USA is the sole region that did not warm progressively during the 20th century* " and it was illustrated by this pair of images.



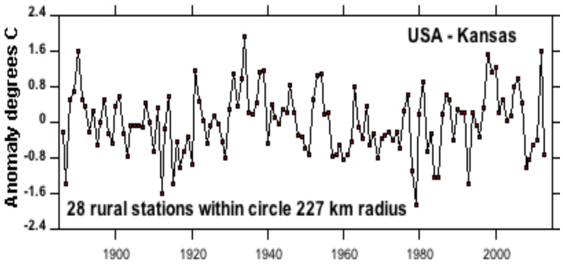
If we are convinced of the dominance of radiative warming in controlling global air temperatures, then these images, which were based on the GISTEMP data then current, appear to face us with the choice of supposing either (i) that the United States is somehow more-or-less immune to that effect, or (ii) that the USA is the sole region where a reasonable correction can be made for urban and land-use change effects on SAT. Given the extraordinary imbalance in the distribution of observations, which are dominated numerically by those made in the United States, then the choice is not hard to make.

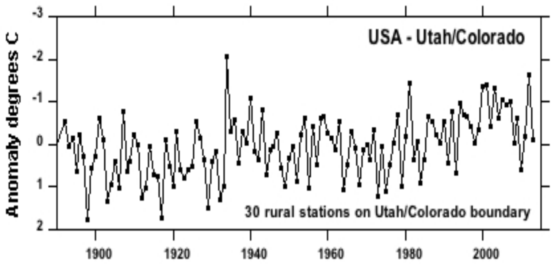
Unfortunately, we are not rich in regional analyses with which to explore this problem, even though the AR5 of IPCC remarks that "*Regional analyses of LSAT have not been limited to the United States*" and lists 13 relevant studies that "*are in general agreement*" with the global pattern. But this is an exaggerated claim – two of these discuss calibration of 18th century glass thermometers at individual stations, three discuss new national data archives, four describe SAT evolution in small regions (central Europe, Finland, India, Kenya), and close analysis of trends is offered only for China and the Peru-Chile region (four papers). Of those that discuss data, at least two discuss only urban data, some from large cities, a fact that was emphasised by one of the authors. Worse, one of the reported studies, concerning E. Africa, is a careful demonstration of the effect of urban heating on regional SAT and another discusses regional cooling induced by ocean processes in the South Pacific. AR5 is incorrect in claiming that these studies are "*generally in agreement with the global products*". What is required is regional analysis based solely on rural data, since correction of for urban heat generation - even if it has been done - has unknown effectiveness.

Regional analysis with rural data alone is easily done in the conterminous USA which is unique in the high proportion of rural compared with urban locations: at a randomly-chosen position in Kansas, within a radius of 255 km there are 22 rural stations (with data mostly starting around 1905-1910 and continuing to the present), 5 small towns and one city of 550,000 inhabitants. Elsewhere, data for many regions include very few rural stations indeed: within 350 kms of Lyons in eastern France there are 3 cities of a million or more, and only 11 rural sites, of which 6 are at high altitude (Pic du Midi, and so on) while the other 4 are in Switzerland or on the north Italian plain. One 'rural' site is the little town in which the international airport of Milan is sited, directly adjacent to an aggregation of 1.3 million people! Data from these two groups of stations would probably match the difference between US and global data patterns quite closely.

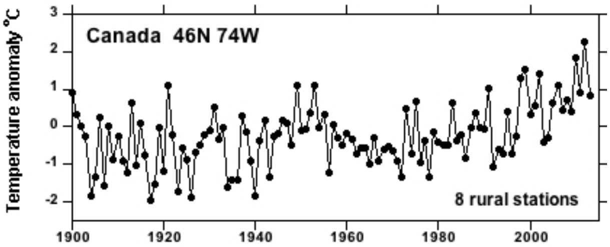
Despite such problems, I have assembled several regional groups of rural stations which show that there was no unique global pattern of temperature change during the 20th century over all land surfaces: rather, there are characteristic regional patterns that may be tentatively associated with characteristics of regional circulation patterns in the atmosphere and ocean; these patterns are not seen in the standard regional archives that are dominated by observations made in urban sites, or in regions where farming practices have changed during the 20th century, and where the natural vegetation has been progressively destroyed.

The evolution of SAT in the conterminous USA during the 20th century will be a useful starting point in reviewing the diversity of regional patterns, because this is the sole region where observations made at rural stations dominate the whole. The temperature pattern for all stations in the USA discussed by Hansen is reproduced in almost any grouping of rural stations, as in these two examples located respectively in eastern Kansas and in Colorado,





Progressively towards the northeastern USA, this symmetrical pattern changes so that stronger warming occurs at the end of the century, and this dominates rural data from regions north and northeast of the Great Lakes, as seen (below) in Canadian rural stations from the Quebec-Ontario borders.

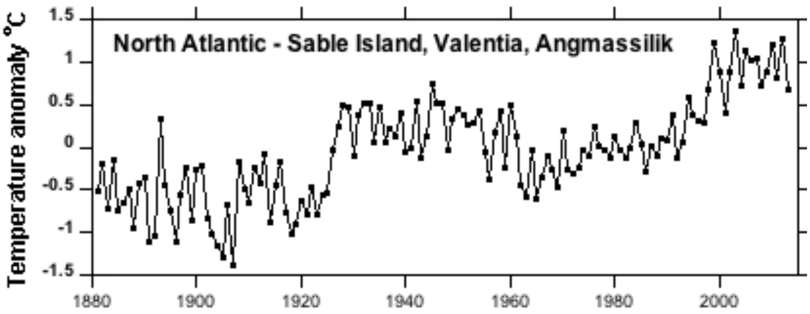


This pattern, with stronger warming in the final decades of the 20th century than rural stations in the western and southern USA, is "*very largely attributable to unforced natural causes*", according to a recent study.[290] This conclusion is based on analyses that suggest that this pattern is closely associated with strong negative trend exhibited by the NAO during the last 30 years or so. Experiments using CMIP[291] techniques with prescribed anthropogenic forcing alone fail to reproduce the circulation changes associated with NAO, nor yet the associated tropospheric warming.

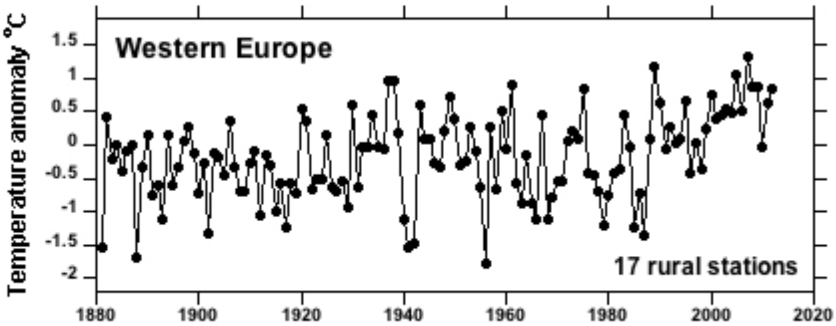
Observations show that annual mean geopotential heights in the upper troposphere have increased in the arctic zone since about 1980, especially in the NE Canada-Greenland sector, an increase unlikely to be due to changes in surface temperature, but perhaps rather associated with negative values of the NAO, itself associated with the PDO signature in the North Pacific and with the wave-train pattern that links this region with positive trends in Canada and Greenland and also with circulation anomalies over the North Atlantic. This mechanism, it is suggested, accounts for half of the recent warming in this region – but, it should be noted, the 'recent warming' referred to here is what is indicated by instrumental data that have not been filtered for the urban effect.

The regional pattern that is characteristic of eastern Canada shown in the previous plot may usefully be termed the North Atlantic pattern, since it matches the pattern of the NAO and also is characteristic of stations around the coasts of that ocean; it also matches the pattern of the Atlantic Meridional Oscillation (AMO) that codes the relative temperatures of the North and the South Atlantic Ocean basins (p. NN). The following plot shows three such stations: on a small island off Nova Scotia, on the Valentia peninsula of Northern Ireland and on the eastern coast of Greenland.

[290] *Ding, Q. et al. (2014) Nature, Lond. 509, 209-212.*
[291] *Taylor, K.E. et al. (2012) Bull. Am. Met. Soc. 93, 485-498.*

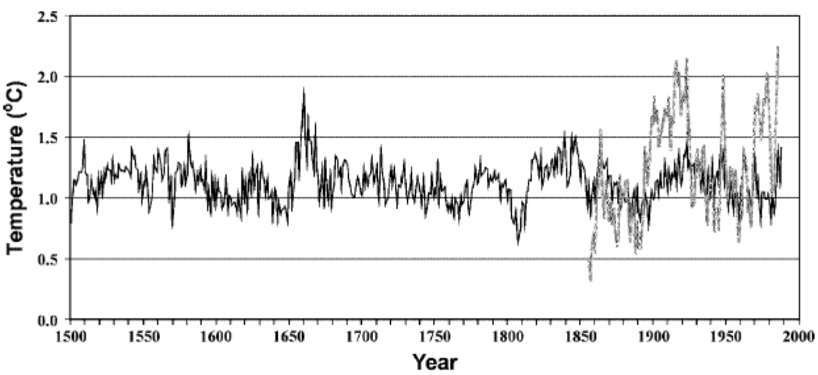


The North Atlantic pattern extends through those parts of the European region that are significantly influenced by Atlantic weather systems, although the paucity of rural GHCN stations in this region make it more difficult to observe than on the North American continent.



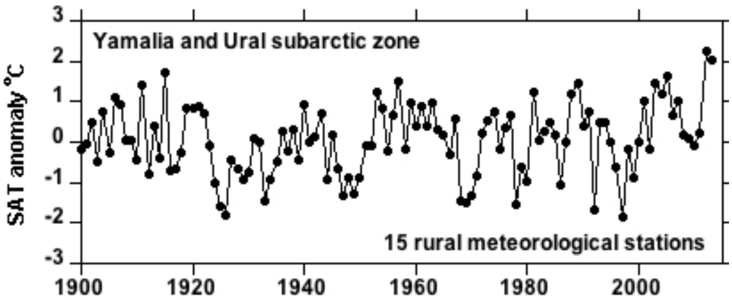
It is also exhibited by the few rural data that exist for Iberia, Britain and Scandinavia and as far to the east as northwest Russia, but does not extend to Central Europe, and it is also characteristic of North Africa, though weakening eastwards. The North Atlantic pattern is not repeated in the Labrador Sea region to the west of Greenland, just as you would anticipate from the pattern of ocean circulation in the NW Atlantic.

This result, and its lack of support for the standard model of warming in the 20th century, is supported by a recent study of the long-term temperature history of central Poland in rural, wooded regions. This temperature sequence is based on tree-ring proxies from Scots pines, and on a series of 13 temperature logs from boreholes; historical archives from city records were used to confirm the reality of anomalous years or periods observed in the tree-ring data.



The heavy line represents the proxy temperatures, and the fine line in the 20th century is the borehole data from the region of Warsaw, Bydgoszcz and Gdansk.[292] There is very little progressive temperature trend during these 400 years, but the details of the evolution of temperature during the 20th century, both from proxies and boreholes, matches rather closely the pattern of SAT from rural stations in Western Europe discussed above, just as it should.

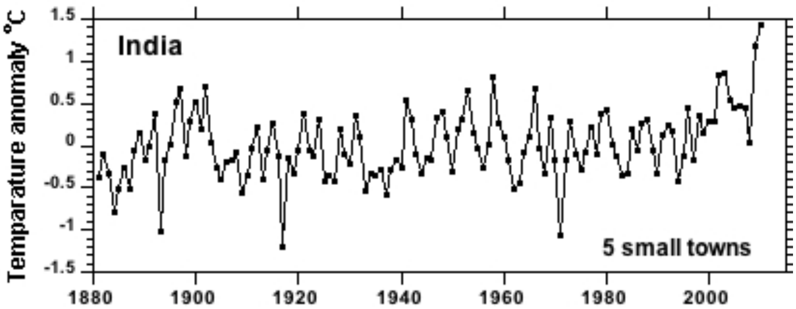
Rural stations (below) in northern Siberia beyond the Atlantic influence take a pattern that closely matches the reconstructed temperature obtained from the Yamal larch dendrochronology discussed in Chapter 6.2. Contrary to the usual assumptions concerning Arctic warming, the lack of trend in these data is characteristic of coastal sites around the shores of the Arctic Ocean where the Atlantic influence does not penetrate, and where end-of-the-century warming is difficult to demonstrate in the original, ungridded station data (Chapter 10).[293]



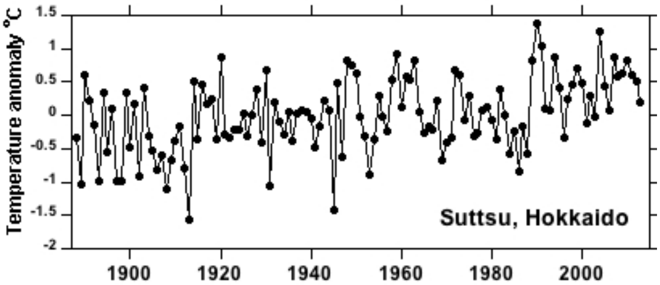
Africa is not well represented in the GHCN but does offer one of the most critical local studies done anywhere, in this case for a 5^0 grid-box including parts of Kenya and Tanzania, which was based on the original regional meteorological archives.[294] The data have very little long-term trend, although T_{max} was sensitive (from +0.059 to -0.096°C over the 20th century) to values chosen for break-point identification in the data. Over the full century, the trend of T_{max} was of order +0.015°C per decade but after 1979 this increased to 0.07°C. The most significant finding was that progressively the secular trend in T_{min} (<0.15°C per decade after 1980) greatly exceeded that of T_{max}. This result both confirms the day/night differences in the dynamics of the boundary layer in response to land use change (and perhaps to anthropogenic aerosols, due to the massive use of wood as domestic fuel in the Kenya highlands) while the low values of overall temperature trends at all time scales is noteworthy.

For India, we are fortunate in having numerous full 20th century records in the data made available at NASA Goddard in 2011, from which data from five small towns have been selected (right above); these are remarkably complete, lacking only few years in one data set early in the century. Further, the individual data are very coherent though offset by a degree or two depending on local conditions, the very warm climate of the final two years being recorded in four of the five stations; data for subsequent years suggest that SAT returned to normal for the region.

[292] *Przvylak, R. et al. (2005) Int. J. Climatology 25, 773-791*
[293] *see Chapter 8 for a wider discussion of this in the context of arctic temperature trends*
[294] *Christy, J.R. et al. (2009) J. Clim. 22, 3342-3356.*

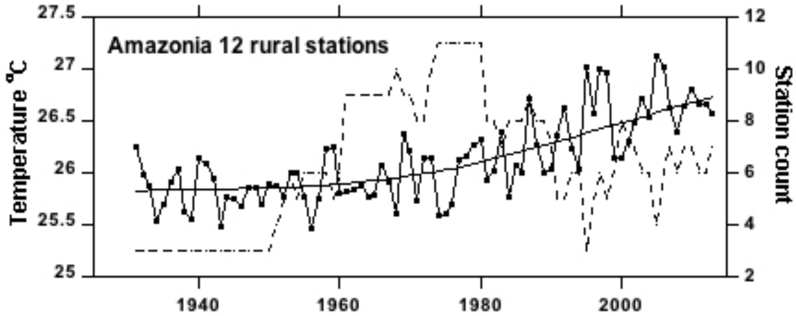


For the Far East, it is not easy to locate suitable data, with the exception of Japan, where many long sets are available from the end of the 19th century. The very long and unbroken record from a rural station in Hokkaido shown below shows a prominent and abrupt warming episode of almost a 1.0°C in 1988-89, which is probably a natural event, for the same feature occurs in many stations from all over Japan, though it is less pronounced at the southern end of the main island, as it is in South Korean data. To the north, it is not evident in data stations I have examined from Kamcha



For China, there are very few rural station data, and the majority of the reporting stations terminated in 1990, leaving only the larger cities.

In South America there are clearly several major distinct climate regimes and consequent patterns of SAT change during the 20th century. In the tropical regions of Amazonia and the Matto Grosso the available rural data is mostly from small towns in the newly-cut forest regions that are now used for soy production and other industrial crops, and here the trend since the mid-20th century has been of progressive and sustained warming.

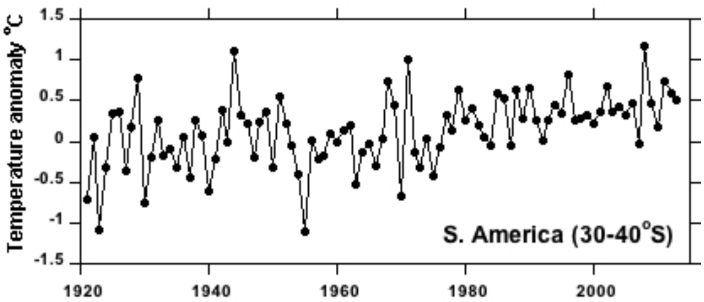


In the temperature regions, and south to Patagonia, there are rather few suitable stations that provide long-term data, although here again, changes in overall trends have been caused by the adjustment of data since 2011; for Salta, on the reverse slope of the Andes, the 2011 GHCN data indicated a cooling trend of about 1°C during the 20th century, but this is now adjusted to a warming trend of about 1.5°C.

The Pacific coastal strip of South America, west of the Andes, is a special climatic region whose conditions are dominated by the presence of the ocean; here, climate responds to changes in pressure systems over the Pacific (p. --) and to the changes in sea surface temperature and wind direction that occurred after the 1976-77 climate shift.[295] Here, regional cooling in SAT (-0.2^{o}C/decade) along the coastal plain from 1990 to about 2005, can be securely attributed to the dynamic oceanography of the southeast Pacific Ocean caused by an intensification of the South Pacific Anticyclone, creating La Niña-like conditions that may have extended to as much as 500m deep, and were clearly recorded at Juan Fernandez, about 600 km offshore, in SAT and atmospheric pressure.

The authors of this study note that these ocean conditions are a predicted consequence of increasing CO_2 concentrations, the observations nevertheless are a very strong indication of the potential link between global circulation pattern in the atmosphere and regional SATs on neighboring land surfaces. The dynamics of this trend are complex, with T_{max} decreasing more strongly than T_{min} near the coast because of the influence of the daily regime of the weakened offshore breeze at night, and the strengthened onshore daytime winds during this period; this is the opposite of the pattern established during the 1976-1977 climate shift, when minimum temperatures increased very strongly.[296]

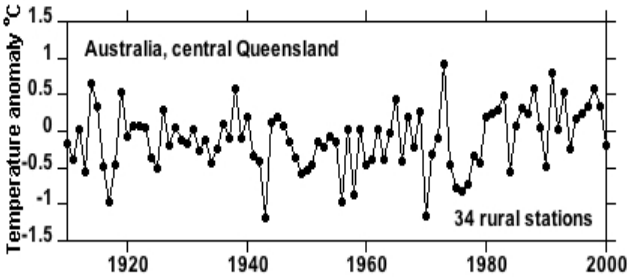
In southern South America as a whole, dominated by data from east of the Andes, there has been little sustained trend in SAT during the 20th century but with some major brief excursions and some indications of shifts between different climate regimes. Here, there is no dominant pattern comparable to the North Atlantic pattern that is so widely distributed at comparable north latitudes.



For southern Africa, proxy data from stalagmites in the Cold Air Cave (Transvaal) and from massve corals at Iftar on the coast of Madagscar (see p. NN) offer evidence of regional SAT patterns that closely match the longest SAT archives available for South Africa but carry the record back to before the Maunder Minimum.

Finally, in Australia, the network of rural stations offers a coverage second only to that of the USA, although stations have been progressively abandoned since the 1990s. A group of 34 rural stations was chosen in an inland region having very uniform conditions, and the data truncated to the period 1910-2000 to avoid bias that might be introduced by recruitment and loss of stations.

[295] *Falvey, M & R.. Garreaud (2009) J. Geophys. Res. 114, D04102 (on which this section is based)*
[296] *Villaroel, C. et al. (2006) 8th Int. Conf. S. Hem. Met. Oceanogr., Am. Met. Soc.*



These data represent a region in which very slight land-use change has occurred, the principal activity being related to local mineral resources and the data were obtained in small settlements that often comprise just a small cluster of houses at the end of a long unpaved road across uniformly flat, desert terrain with scattered bushes and small trees; they are very far from any oceanic influences. The data used are the adjusted GISSTEMP numbers of 2014, and the mean trend is too small to be the result of the same process that is represented by the iconic global warming curve. The continental climate is sufficiently strong that it dominates temperature changes even in a town as large as Alice Springs, located centrally on the land mass; the data record the same cool extreme for 1976 as recorded at the Queensland sites and also the cooling trend in the first part of the century.

But a comprehensive study of Australian climate from 1911-2010, based on four different gridded and homogenised temperature archives, each of which includes the numerous coastal stations but excludes the few major cities, suggests a rather different climate evolution in which there is some oceanic influence.[297] A mean quadratic increase of around 0.94°C is indicated for the entire period in three of these data sets, with much great change at night than during daytime (c.1.16°C cf. 0.75°C); the fourth set indicates the same pattern, with lower absolute values. There is some indication in first decade of a cooling trend from earlier warmth, as in the Alice data shown above. This study also notes the similarities of the continental warming trend and that of SST over an appropriate oceanic region: quadratic temperature changes for the period 1922-2010 are +0.94°C (SAT) and +0.83°C (SST). Independently, the study from the Australian Bureau of Meteorology discussed earlier (p. NN) that is based on 224 mostly rural stations, almost all located within 250 kms of the ocean showed the same effect: sustained warming trends after 1950 equivalent to about 0.5-1.0°C/100yr. Maritime and continental climates differ in Australia, as elsewhere, so that it must be recognised that changes in SAT ashore may be influenced as much by changes in ocean circulation and vertical motion as by direct and local radiative forcing.

Clearly, the regional pattern of warming at rural locations during the 20th century is complex and it is not easy to discern a single global pattern for this change. Of course, a single model is not what one should expect, given the shifting but repetitive pattern of atmospheric pressure systems (and hence of wind direction and the transport of heat) at global scale. But this informal survey does suggest that the mid-century warming, and the subsequent period of cooling, was prominent across much of the northern hemisphere from North America, east of the Sierra, to western Russia. It also suggests that the prime influence on climate pattern of this region is centered in the Atlantic Ocean - as you would expect to be the case from the pattern of ocean currents in the North Atlantic. Alternation between the two extreme states of the NAO, with a

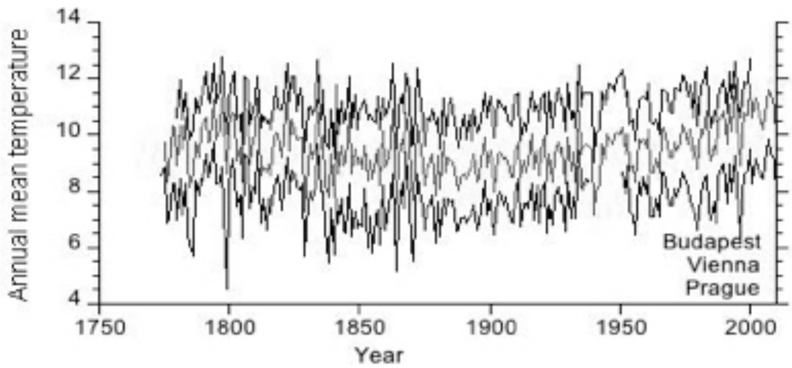
[297] *Fawcett, R.J.B. (2012) CAWCR Tech. Rep. 050; Trewin, B. (2012) Int. J. Climat. 33, 1510-1529*

characteristic frequency that matches the solar 60-80 year cycle, appears to control climate modes over his vast region.

It is also clear from these plots that the iconic temperature curve for the entire globe discussed at the beginning of this chapter conceals the existence of regional differences that are very significant. It should also be noted that the progression of warming in the surface temperature data in the GHCN departs significantly from the change in the troposphere, obtained from satellite MSU sensors and discussed in Chapter 4. Even though these data for the troposphere are available only since the 1970s, they must be the best indicator of the real radiative effect of CO_2 in the atmosphere but, despite this, they are seldom discussed in analyses of changing global temperatures.

Despite the regional patterns discussed above, we have to deal with the fact that some version of the global plot of SAT data, with or without the inclusion of SST data for the oceans, has become the iconic pattern that defines anthropogenic global warming, and has been widely disseminated in simplified form; this has the very serious consequence that this is now the pattern to which modelling results must conform if they are intended to simulate the radiative effects of carbon dioxide in the atmosphere.

Lacking confidence in this iconic and widely-distributed plot, I thought that a final reality check might be in order by examining a group of the longest extant instrumental data sets, those for several large European cities whose cityscapes have changed relatively little compared with many other places and where one might hope that proper care had been taken to obtain standard data. I have extracted the data for Vienna and for two other cities in central Europe where SAT measurement has a very long history; these data have a very interesting (and quite unexpected) common pattern, because each follows a similar trajectory over the entire 225-year period, although offset by a degree or two: this long record demonstrates that the progressive increase in temperature during the 20th century in central Europe was no more than a return to conditions that existed 200 years previously, after an intervening cooler period.



Throughout, each station responded similarly to major changes in rate of warming or cooling – including the mid-20th century warm period - although, as might be expected from the geographical position, temperature changes at Prague and were closer to each other than either was to Budapest, located in different habitat on the Hungarian plain. Remarkably, data from the several other 200-year cities in Europe today available have a rather similar overall pattern: only St. Petersberg is today significantly warmer than it was 200 years ago.

This brief and informal survey of rural station data appears to demonstrate conclusively that the global plot of SAT offered by Hansen and shown above cannot be considered as representative of the reaction of the lower atmosphere globally to the release of anthropogenic CO2 - although that is how it is presented. This is a critical issue, because it is implausible that somehow the USA should be exempt from anthropogenic global warming; the only reasonable interpretation of the plots is that the difference is driven rather by the quality of the data than by the state of the planet: it will not be forgotten that the USA has far and away the best coverage of station data, predominantly from rural stations, and that it is better processed and curated than in most of the remainder of the globe.

6.2 - The use of proxies to understand the recent past: do the trees speak clearly?

The climate history of the Holocene, and especially of the most recent millennium, is now rather well known from historical and proxy data, of which there is an abundance. One of the most widely-used proxies is derived from analysis of the annual growth rings in trees but there has been some concern that in recent decades the trees have had a different pattern of growth from that expected from regional temperature data.

The use of proxies to examine the recent past has not been without controversy and during the early years of this century many researchers insisted that the Mediaeval warmth was no more than a regional effect around the North Atlantic; there was an editorial crisis at *'Climate Research'* after the publication of a paper that concluded, on the basis of a review of 142 studies of proxy data, that the Little Ice Age and Mediaeval Warm Periods had occurred rather widely as warm climate anomalies and that the 20th century climate was probably no warmer than mediaeval times[298]. We are now thankfully done with this unseemly debate, although echoes of this argument still surround the reconstructions of past climates, illustrated by what came to be called 'hockey-stick' plots.

The second of these was based on what was then probably the largest cornucopia of proxy data mustered for a single study and it as quoted with approval in the 2013 IPCC Assessment Review.[299] A product of the PAGES 2K Consortium, associated with the IGBP Climate Programme, it was based on individual analyses of Asia, Europe, North and South America, Australasia, Arctic and Antarctic regions and, while it notes regional differences, it does confirms a millennial cooling trend.[300] Long-term cooling occurred after a warm period that occurred from 830-1100 AD in the northern hemisphere, but from 1160-1370 in South America and Australasia. This study (for which 78 contributors are listed) made no attempt to represent the consequences of the uneven data distribution even though the Southern Hemisphere is represented by just three proxies that extend back to the interval 1000-1250 yrs BP: one in the altiplano of Chile, one in Tasmania and one in New Zealand.

Some may prefer the more scholarly approach to the problem presented by a single author in two recent papers.[301] These offer a systematic and comprehensive

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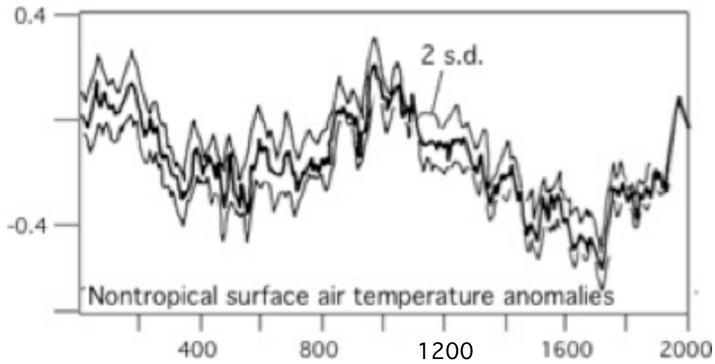
[298] *Soon, W. and S. Balliunas (2003) Clim. Res. 23, 89-110*
[299] *Mann, M.E. et al (2008) PNAS 105 (36) 13252-13257. See also* Nature ***463**, 284-287 (2010) for this criticism.*
[300] *PAGES 2K (2013) Nat. Geosc. 6, 339-346.*
[301] *Ljungvist, F.C. (2009) Geogr. Ann. 91 A(1): 11-29 and 92 A(3): 339-351*

survey of 71 proxy records, each extending back at least over two millennia, but of which only 7 are located in the Southern Hemisphere. Critical information is provided on each proxy: borehole, chemical, documentary, isotopic, freshwater fossils/sediments, fossil pollen, marine sediments, speleotherm isotopes, tree-ring width and latewood density, thickness of varved sediments. Individual plots are shown for each, with an evaluation of temporal resolution, and all on the same scale temporal scale so as to demonstrate graphically the diversity of the proxies.

Part of this data set is then used to present the evolution of climate conditions during the last two millennia in the extra-tropical northern hemisphere, with appropriate selection of data, expressed as mean SAT. The distribution of stations is adequate to represent this area, even if biased towards high elevations, although a few more proxies placed centrally in Asia and North America would have been welcome; the inclusion of some records that did not extend back to the start of the period increase the standard deviation in the first millennium, though not significantly over the more recent calibration period. The result is striking, even if (as the author comments) it is conventional and similar to the pattern already discussed by H.H. Lamb.



This is an excellent demonstration of millennial-scale periodicity, with the return of major warm periods after approximately similar intervals, suggesting that long-term change in temperature is not random, but periodic. Of course, this is supported by historical evidence of the warm climate of the Roman, Mediaeval and Modern periods, and the colder periods between when conditions were not so conducive to human comfort and expansion; Lamb described all this in his masterly history of man and climate - to which I see too few references in the recent climate literature.

There are now many studies that confirm the reality of this periodicity, although they are mostly from the northern hemisphere. Proxies (foraminifera and mineral grains) from Northwest Atlantic sediment cores confirm that the advance and retreat of northern hemisphere glaciers during the Holocene have a mean pacing of 1374 years, and demonstrate that the North Atlantic circulation exists in two distinct and alternating patterns: either extensive ice-rafting from the Arctic Ocean, or else extensive penetration of warm Atlantic Current water into Arctic through the Nordic seas.[302] The pacing of these changes can be traced back though the last glaciation, suggesting that North Atlantic periodicity is independent of climate state – a suggestion examined further in Chapter 7.

The pattern of temperature change from this and other proxy records is supported by very rare sets of numerical observations that mostly concern the dates of

[302] *Bond, G. et al. (1997) Science 278, 1257-1267.*

freezing and spring break-up of ice on rivers and lakes, of which the longest goes back to 1443 and records the dates of the freezing of Lake Suwa in Japan; long anomalies, both warm and cool, are evident in the data. Freeze-up occurred progressively earlier, with a trend of -4.5d/100y over the entire period but with indications of exceptionally cold years, and major reversals of the trend, in the years 1500-1520, 1700-1710 and 1850-1890. Seven long numerical records of freezing and break-up data of northern hemisphere rivers from the mid-19th century confirm the trend, and show that changes in freezing and thawing dates are not always symmetrical. The data also demonstrate reversals in both trends in some of the data in the cold period 1872 to 1897 and some of the series appear to be sensitive to the mid-20th century warm period. But, as always in such bundles of climate data, there are exceptions: the Angara River in Siberia froze progressively later, but there was no clear trend in the date of breakup – which might, of course, not depend on local conditions but on conditions upstream of where the observations were made.[303]

Observations at high-latitude ports that are closed with ice in the winter also provide reliable information on long term changes, because of the economic importance of the dates of the shipping season; mean winter temperature series for Tallinn, in the inner Baltic, inferred from spring break-up dates, show the same pattern as surface temperatures since 1500 that have been inferred from proxy temperature data.[304] Further, the rates of change in the modern period do not appear to exceed those recorded (for instance) for Lake Suwa since the middle of the 15th century – although it must be remembered that in time series which exhibit some form of cyclical behaviour it is the state of the cycle on the starting and ending points of the series (or of a chosen segment) that largely determines the trend.[305]

Because dendrochronology, based on measurement of annular growth rings and late-wood density in very old living trees or in assemblages of sub-fossil trees in the taiga, is one of the more profitable sources of information about past climates, it will be useful to dwell on it briefly. Growth marks in corals, and in the shells of molluscs, may be used in a similar manner and analysis of sediment cores, both in lakes and the ocean, is also capable of quantifying centennial and millennial changes in the nature of the planktonic ecosystem in the waters above, and so the long-term evolution of an ambient seasonal temperature range.

Dendrochronology is most satisfactory at high latitudes or altitudes where cores from very long-lived individual trees may be used, so minimising breaks in the record; bristle-cone pines in the Sierra Nevada and junipers in the Karakorum and other Himalayan regions have been much used although, for each study, care is required to ensure that the limiting environmental factor is correctly specified. The most often-quoted problem of this kind is whether the growth rate of a stand of trees is limited by temperature or by available moisture; this uncertainty has been raised concerning the high-altitude bristlecone pine data used in the original 'hockey stick' paper.

The sensitivity of dendrochronology is obscured when a bundle of proxies is used, but there is no doubt as to the ability of dendrochronogy to quantify not only the sequence of recurrent warmer and cooler conditions at millennial scale but also to indicate coherent pattern – rather than incoherence - at shorter periods, as seen in the

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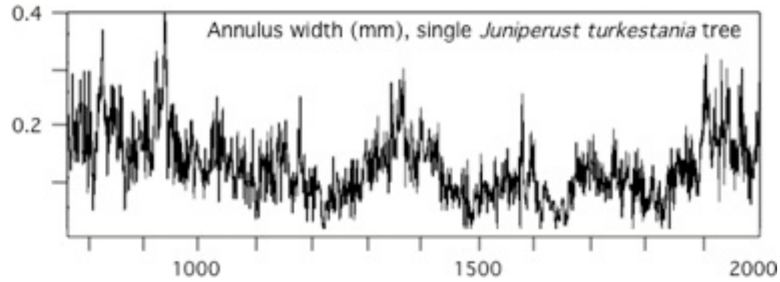
303 Magnuson, J.J. et al. (2000)Science, 289, 1743-1746
304 Tarand, A. & P.O. Nordli (2001) in: 'The Iceberg in the Mist', Kluwer Academic
305 Benson, B.J. et al. (2011) Climatic Change DOI 10.1007/s10584-0111-0212-8

tree-ring data from the Karakorum mountains shown below showing annulus width (A.D. 786-1993) of a single *Juniperus turkestania* tree, with centennial trends.[306] This gives greater precision in the description of local conditions than multi-proxy studies of longer periods such as that discussed above (p. NN): the high mountainous regions of southern Asia exhibit conditions not repeated over the entire extratropical northern hemisphere, as in that case.



However, any assumption of a direct and simple correlation between tree-growth and air temperature is too simplistic and ignores the multi-factorial character of the control of growth; it is also fallacious to generalise from such studies, because almost all have been performed on trees growing in extreme habitats and have demonstrated complex growth responses to change in the seasonal schedule of sunshine, air temperature and rainfall, or in the depth of the previous winters snow-pack.

One of the recurrent discussions to emerge from dendrochronology recently is why – after previously following the local surface air temperature very closely - the growth of trees selected for analysis should have seemed to slow, relative to instrumental temperature, after about 1970. Divergence between the growth rate of trees and the measured SAT data captured much attention after the publication of the seminal paper by Briffa and his co-authors: "*Trees tell of past climate: but are they speaking less clearly today?*".[307]

Later, Briffa reviewed this effect over all high-latitude surface temperature grid-boxes north of 50°N against all tree-ring density temperature reconstructions from the same zone; the result was striking, with divergence firmly established from 1960 and attaining about 1.5°C by the end of the century. This divergence is all the more significant after the very close relationship of the previous millennium and the demonstration of the sensitivity of summer growth to brief cooling associated with volcanic dust veils. It is this sensitivity that – as Briffa points out – that "*prevents us from claiming unprecedented hemispheric warming during recent decades on the basis of these tree-ring densities alone*". But some may think that the message of these tree-rings is rather that this is one more reason – beyond those discussed in Chapter 4 - why we should examine the instrumental temperature data even more critically.

But this seems not to have been done and the general assumption is now that the instrumental data are correct and that tree-growth has not responded appropriately since the 1960s. One author goes so far as to assert that "*No current tree-ring reconstruction of extratropical Northern Hemisphere temperatures…captures the full range of the late 20th century warming observed in the instrumental record*"[308] Such absolute statements are dangerous to any scientific enterprise, and this one ignores

[306] *Esper, J. et al. (2002) The Holocene, 12.3, 267-277.*
[307] *Briffa, K.R. et al. (1998) Phil. Trans. Roy. Soc. Lond. B 353, 65-73.*
[308] *Wilson, R. et al. (2007) JGR 112, D17103, doi:10.1029/2006JD008318*

some critical observations – for instance, that the northern tree-line is a dynamic ecotone that is strongly sensitive to temperature and is responding to the relative warmth of the 20th century by enhanced conifer recruitment, but has not yet moved as far north as during the mediaeval warm period.[309] Consequently, the divergence of annular width and late-wood density has been attributed to a wide range of potential effects, none of which have been demonstrated: the consequences of increased atmospheric ozone, of drought stress, of delayed snow melt, of reduced solar radiation at the surface – and so on. All this is discussed, as it should be, in the AR5 of IPCC which does note that divergence has not always been found when looked for, and that it may be avoided by careful site selection; the next step, of suggesting that available SAT data may not be appropriate to conditions at the experimental sites, is not taken.

But one essential characteristic of the growth of a tree is not debatable, but seems not to have been raised in this discussion: growth rate of a tree does not react to gridded regional temperature, but to the temperature regime of its intimate environment, just where it stands with its roots in the ground. Yet, rather often, ring-growth data – often from remote sites, far from any meteorological stations - are compared to surface temperature recorded at standard sites or, as in the case of one study of northern Siberia, to CRUTEM3 gridded data contained in thirty-five 5° x 5° boxes from 55-65°N!

Of course, some authors have invoked local data: the study of junipers in the Karakorum discussed earlier (p. NN) is unusual in presenting local data from selected regional meteorological stations for comparison with the proxies. In this case, data from nine high-altitude dendrochonologies were compared with instrumental data from six local stations: the correspondence is as good as one could wish for, except in the earliest decades when instrumental data were not yet fully established in this remote region. The overall pattern of SAT and thermal response in the trees is apparently cyclical at a frequency that recalls the 60-70 year Gleisberg cycles that occur in so many global ecological and weather indices during the 20th century (see Chapter 3). This result suggests that appropriately-chosen local temperature data sets, rather than global or regional data archives, should perhaps be used more widely in proxy studies, although I have found none that use this method to address the divergence problem directly.

One of the regions where this might be done is in western Siberia, where there is a good spread of apparently well-tended meteorological stations in rural areas and small towns and where sub-fossil larch trees found in eroding river banks in the Yamal region have figured prominently in investigations of ancient temperatures which suggest that the climate of the 20th century to 1996 was not outstanding in this region, compared with the conditions during the previous four millennia.[310] This is a very significant observation, because northern Asia is one region for which hind-cast modelling suggests that 20th century warming has been the strong (p. NN).

This region, and these sub-fossil larches, have been extensively used also by Briffa and his colleagues in long-term temperature reconstructions that were compared with temperature data for the 20th century period obtained from a single regional meteorological station at Salehand. The result seemed to indicate that the tree-growth matched the temperature data from a single, local meteorological stations rather well.

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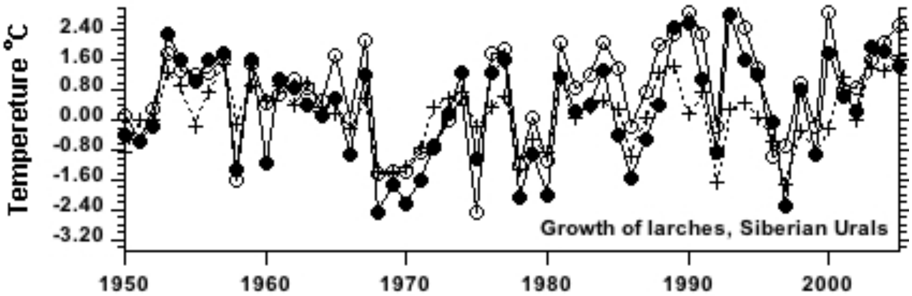
[309] *MacDonald, G.M.(2007)Phil. Trans. Roy. Soc. B 363, 2285-2299; D'Arrigo, R. et al. (2008) Global Plan. Change 60, 289-305*

[310] *Hantemirov, RR.M. and S.G. Shiyatov (2002) The Holocene 12, 10.1191/0959683602hl585rp*

To verify this result in greater detail for the recent period, and to test how appropriate was the choice of meteorological data, I located 15 individual stations having long SAT records within the climate region of the Siberian Urals in which the proxy larches had grown along the banks of river, in the southern part of the Yamal peninsula.[311]

The following plot shows that the temperature data (open symbols) from these stations and from Salehand (+ symbols) are similar and both very closely match the reconstructed temperatures obtained from the larches (solid symbols), year-by-year and decade-by-decade; unfortunately, they do not go sufficiently far back to verify the existence here of a warmer period in the 1930s and 40s, seen in the Karelia data discussed below (Chapter 8.2).



These results are interesting from two points of view – first, they would seem to close the door on the tree-ring divergence problem, which is surely caused by the use of instrumental data that record processes other than those representative of the natural environment in which the sampled trees had grown.

They also suggest that the rapid acceleration of warming after 1970, common to all the major SAT archives discussed in the previous chapter, is the product of a process that has not affected the growth of those trees that have been used for growth ring studies. These have been, almost by definition, situated in regions remote from human activity – as are the corals, speleotherms, glaciers and ice-caps also used in proxy studies.

And that should give all of us food for thought concerning what inferences may be drawn from the instrumental temperature record.

6.3 - The thermal footprint of changes in land use and vegetation cover

By far the largest part of the surface of the continents (57%) is uninhabited or supports an extremely light human footprint, about 40% is used in some form of agriculture, while just 3% of the surface is urbanised. Yet the great majority of archived

[311] *I am grateful to Keith Briffa for tree-ring data, very generously sent in accessible format.*

measurements of SAT have been made in, or near, the urbanised regions and almost none in uninhabited regions; this is not surprising, since uninhabited regions do not require daily weather forecasts. Consequently, it is difficult – or even impossible – to obtain a satisfactory understanding of the human impact on global climate from the GHCN data. In fact, it is reasonable to conclude that the global SAT archives are contaminated by local anthropogenic contamination of the original instrumental observations, where 'contamination' is used in the sense that the principal role for the surface data in climate change science today is to record the effects of increasing CO_2 concentration in the atmosphere.

That farming and land clearance modify regional climate is a concept deeply embedded in rural culture as expressed, for instance, in this 1848 text: "*But the nature of the surface is not to be disregarded. The heat increases as the soil becomes cultivated. Thus, for the last thousand years, Germany has been growing gradually warmer by the destruction of forests, the draining of lakes, the drying up of bogs and marshes. A similar sequence appears to be happening in the cultivated parts of North America, particularly in the Atlantic states....Barren soils admit of much more intense heat than loam. Meadow lands are not so warm in summer as the bare ground.*"[312]

The IPCC has come only slowly to an acknowledgement that some human activities other than CO_2 propagation contribute to warming the lower atmosphere and may have significant consequences for regional trends. In 1995, the text of AR3 of the IPCC treated these problems very cursorily in a short discussion of the possible consequences of urbanisation on the diurnal temperature range in SAT data during the 20th century, although it was noted that SAT was increasing more rapidly than lower troposphere temperature, perhaps indicating contamination of the SAT data by urbanisation effects. This Assessment was issued at a time when the existence of urban heat islands (UHI) was still contested by some, and the studies that were discussed by the IPCC suggested to them that the UHI effect, if real, could not have exceeded 0.5°C during the 20th century.[313]

Small potential effects of deforestation were also noted in AR3 but, in 2007, the 4th Assessment Report offered a more interesting, though still brief, discussion of albedo and radiation effects of changes in forest cover, and of land use change on croplands and pastures; some consequences of geographic and spatial variability of human activities were noted, based on satellite-based mapping of the global distribution of ground-cover types. No change from the assumption by AR3 for the radiative forcing (-0.20 $W.m^{-2}$ since 1750) caused by land use changes was suggested, nor was any new statement on the effects of urbanisation made by this Assessment.

The recently-issued AR5 proves to be much more forthcoming on land-use change generally and on UHI effects in particular, perhaps reflecting the more critical approach to these issues taken in the peer-reviewed literature in recent years; the introduction of techniques to adjust station data for the UHI effect is also recognised, as are the problems of data bias by poor instrument siting or non-standard observation procedures.

Previous studies on the consequences of the UHI effect have been discussed realistically by AR5 which noted that "*It is indisputable that UHI and land use change are*

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312 The Rural Cyclopedia (ed. Rev. J.M. Wilson) Edinburgh, 1848. Vol 1, p. 816
313 IPCC, AR3, Chapter 2.2.2.1

confounding influences on raw temperature measurements" and that *"Based primarily upon the substantial number of independent urban minus rural comparisons and the degree of agreement with a broad range of reanalysis products it is concluded that it is likely that residual biases arising from Urban Heat Islands and Land-Use and Land-Cover changes account for no more than 10% of the land surface air temperature warming trend globally and 25% regionally in rapidly developing regions."*[314] But these numbers are not supported by any calculation or citation and, consequently, are presented as representing the opinion of the authors of Chapter 2 of this Assessment Report. But it is very useful that the IPCC has now acknowledged that, at some level, anthropogenic effects other than CO_2 release must be considered when interpreting the surface temperature record, and opinion appears to be evolving fast: in 2015 Nature editorialised on "*How cities beat the heat*", comparing urban to rural albedo effects.

It is now no longer possible to insist that changes in global SAT must be caused by changing carbon dioxide concentration alone. It is clear that when instrumental data are accumulated in regional archives they not only record the radiative effects of CO_2 in the lower atmosphere, but also a wide range of other anthropogenic forcings: urbanisation, the production of heat by combustion of fossil fuels, and – perhaps equally importantly for their effect on the temperature record - the radiative consequences of land use changes due to the plough, to drainage, to irrigation and to the chain-saw, a process evoked by Robert Burns already in the 18th century.

It has only been through progressive modification of the natural vegetation cover of the continents that the human population has been able to grow to its current size, and the changes we have made have been massive, and cannot be without consequences for the climate. These changes go back to beginnings of agriculture, to irrigation of low-lying terrain, to forest clearance for timber and for farming, and to the ploughing of grasslands; they continue today and, especially in the tropical regions, the pace of change is accelerating with consequences for regional climates that are major and complex: surface albedo, air temperature, particulates and- perhaps above all - rainfall must all be considered in studies of the evolution of regional climate during the Holocene.

That local climate is a dominant influence on the nature of local natural vegetation is self-evident, but is not so widely appreciated that a change in vegetation cover will induce a modification of local climate that may be complex and not easily understood. Reviews of this topic often suggest that the effects are much simpler, and easier to generalise, than they are in reality; a recent student text on climate change science remarks that "*Forest clearance causes a net increase in albedo as darker forests are replaced by brighter croplands and pastures…on a global average basis, the net effect of land clearance has been a small cooling of the planet*".[315] But a very short excursion into the literature will reveal to any student that at least the first of these generalisations is incorrect; it may also reveal that there is a difference of opinion between the results of model-based investigations and those based empirically on observational data. In the file of studies that I have consulted, model-based studies tend to suggest a cooling effect of land-use change, while observations tend to suggest the opposite effect. In the special case of urban areas, there is no longer any reason to doubt the existence of a close

[314] IPCC, AR5 Chapter 2, p. 34

[315] Ruddiman, W.F. (2008) "Earth's Climate" W.H. Freeman, NY., pp. 335

relationship between increasing population size, urban extent and warming of ambient temperature, especially at night.

Some simple generalisations may be made concerning local control of SAT by the major vegetation natural types.[316] Trees have a lower albedo than grass or croplands although the surface warming induced by the low albedo of forests and plantations may be offset by the cooling effect of their higher rate of evapotranspiration and the induction of more cloud cover than over croplands. Seasonal effects differ with forest type: dark boreal forests have significantly higher albedo during winter when the open ground between the trees is snow covered, while broadleaf forests have higher evapo-transpiration than coniferous woodlands - but only during the summer.

Tropical broadleaf forest has the greatest evapo-transpiration effect of all major vegetation types, so the dominant effect of clear-cutting rain forest is expected to be a regional warming due both to the reduction of surface evaporation and the consequent reduction of tropical cloud cover, so important a feature of the regions of monsoon climate.[317] This process is the first step towards regional desertification, and appears to be proceeding at a rate of 11 million hectares or 0.6% each year. However, an early modelling study, using the albedo parameters of the Amazon basin, concluded that total tropical deforestation and replacement by crop or grassland coverage, would have effects on regional temperature that "*would be negligible*" because the effect of reduced cloud cover would counteract the effect of increased albedo.[318] But this model can be shown to be incorrect by recourse to observations; a group of eight meteorological stations has been used to generate a historical record of Amazon basin temperatures that shows the initiation of a warming phase in the 1970s that is coincident with the start of major regional land-use changes. Until that time, climate in the Amazon basin had been more stable than the whole of northern South America that exhibits a century-long warming trend suggesting much earlier and progressive land modification than has occurred in Amazonia.[319]

This is a very good example of the danger of model-based approaches to issues as complex as these. I much prefer the good common-sense of a person familiar with both problem and region: "*Each large tree pumps 1000 litres of water each day into the atmosphere…the Amazon basin emits more water…in this way than the Amazon river puts into the ocean…*".[320] The regional drought of 2005 was the worst in the 20th century and that of 2010 even worse: that of 2014, as I write, may be drier than either - yet clear-cutting in the Amazon basin is again increasing: 5843 km^2 were cut in one year, 2012-2013, under a new and more relaxed federal Forest Code, that has replaced that of 1965, considered as one of the strictest anywhere.

It is an irony that this deforestation is very largely a result of the public and political concern over future atmospheric warming which has led to rapidly increasingly large areas to be planted with crops to be used in the production of biofuels; this that has already had major regional climatic consequences in tropical regions where it frequently involves the clear-cutting of forest and other natural vegetation.

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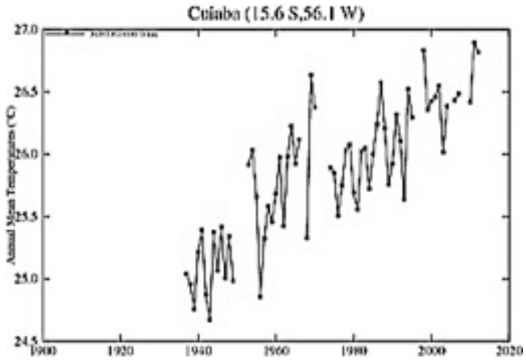
[316] *see, for example, Bonan, G.B. (2008) Science, 320, 1444-1449*
[317] *Zhang, H. et al. (2001) Clim. Change 49, 309-338*
[318] *Henderson-Sellers, A and V. Gornitz (1984) Clim. Change 6, 231-257*
[319] *Victoria, R.L. et al. (1998) J. Climate 11, 1105-1110*
[320] *Antonio Nobre, agronomist, Le Monde 26 November 2014*

It is clearly unsustainable to take two or even three crops a year, of which the most valuable is the shallow-rooted soya, from cleared cerrado forest in the Amazon basin; after only a few years, the hydrologic cycle is disrupted for lack of transpiration from deep-rooted trees, regional rainfall is severely reduced, soil erosion by both water and wind fills river beds with sand. Consequently, regional SAT has rapidly increased over a large region and remedial measures are not effective: soya production has been banned in cleared land in the rainforest belt of Amazonia, but not in the cerrado of the Matto Grosso – perhaps because a former Governor of that State is in the business, and is himself a major exporter of soy beans.[321]

So it is not surprising to find that SAT at small towns such as Cuiaba (15.6^{o}S 56.1^{o}W) in the Matto Grosso exhibits a warming trend of more than a full degree Celsius since mid-20th century, along with the other stations from thi region discussed in Section 6.1.[322]



It also goes without saying that grass or croplands are more sensitive to annual, seasonal variation in rainfall than the forests that they have replaced.[323] Observations from very diverse areas are legion - ranging from Amazonia[324] to the savannah country of East Africa – and all confirm this generality. Croplands, often irrigated, have lower albedo than scrubby or sandy desert terrain, so irrigation, that now covers a very much larger area than at the start of the 20th century, is an important modifier of local SAT. Large-scale irrigation for crops such as rice of formerly natural landscape in tropical regions has been observed to lead to regional cooling, in this case perhaps due to the effect of high humidity on the formation of a cold nocturnal boundary layer at ground level.

For all these reasons, it is no surprise that observations of several hundred plots of Amazonian forest, from the coast to the mountains, but mostly situated near main branches of the river, consistently show signs of stress with long-term decreasing trends of carbon accumulation and increase in tree mortality and stock of dead organic material[325]. This has been reported in the context of a reduction in the global sink for anthropogenic carbon due to global warming effects, but there seems to be no logic to looking further than the regional effects of forestry, mining and intensive single-crop agriculture discussed above.

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[321] *Mahr, D.E. (2011) thesis, Brown University, Center for Env. Studies.*
[322] *Data from NASA Station Selector site*
[323] *Wilson, K.B. et al. (2002) Water Resources Research 38 (12) 1294 doi:10.1029/2001*
[324] *Gash, J.H.C. and C.A. Nobre (1997) Bull. Am. Met. Soc. 78, 823-830.*
[325] *Brennen, R.J.W. (1015) Nature 519, 344-348.*

Similar effects may arise in already cultivated regions in higher latitudes, from no more than an increase in the intensity of cultivation without any major change in land usage; this has had significant effects on regional climate across the North China plain where, in some regions, two crops are now being taken annually, so as to increase total yields. Observed SAT is now 0.4°C higher during the summer where two crops are taken compared with single-cropping regions, and the daily maximum temperature is as much a 1.0°C higher. These effects are due to reduced evapo-transpiration and have consequences for regional rainfall that is associated with the East Asian monsoon over the entire plain.[326] Yet it is not reasonable to consider only the present-day environment of China, although it is very difficult to go far back with reliable SAT data; but this country has suffered a greater impact from deforestation and land-use change than perhaps anywhere else: the original vegetation comprised a mosaic of temperate and tropical forests in the southeastern highlands, boreal forests along the northern borders while the North China Plain with much intrusion of loess soil and dust from the west was probably originally mostly dry heath country. Irrigation has permitted massive growth of the population of peasant farmers and induced the repetitive killing droughts that occurred throughout the 19th century: as someone wrote, there was no California to flee to in China.

Then, the Great Leap Forward - of grain production for export - of the late 1950s added to these already disastrous conditions by encouraging even more rapid deforestation in the south and collectivisation of peasant farms on the northern plains, to which end deep ploughing replaced superficial peasant agriculture. These land use-changes were such as to encourage drought, warming surface temperature and, aided by inept management of food supplies, the resulting famine of 1958-1962 killed somewhere between 28 and 43 million country people.[327] To these effects came to be added those of the rapid growth of the industrial economy of China after the fine particle pollution of the lower atmosphere.

Leaving aside controversies surrounding early support by the IPCC for suggestions that the UHI effect was negligible, that were partly based on rural/urban comparisons of China data, an early, well-argued but largely neglected study suggested that although Chinese "*rural stations are not really rural*", already having some UHI effect, the overall effect of urbanisation on SAT was computed at 0.23°C over China as whole, and was much greater on the northern plains; there, in the three consecutive decades 1954-1983 the UHI effect was 0.62, 0.57 and 0.70°C/decade.[328] This period was only the very beginning of the massive and widespread industrialisation that followed and continues today, with the growth of villages to towns, and of towns to cities. Overall, for the entire country a UHI effect of 0.23/decade was computed which is consistent with a recent study that suggested that urbanisation is responsible for about 24% of recent warming of SAT in China.[329]

But, despite all this evidence, I have found no targeted investigation of the sum effect of anthropogenic pressure – urban albedo, heat of combustion, radiative atmospheric particles, land-use change from agriculture, and all the rest - on the lower atmosphere and how this is recorded in instrumental SAT data. In some regions, as on

[326] *Jeong, S-J, et al. (2014) Nature Clim. Change 4, 615-619.*

[327] *Yang Jisheng "Tombstone: the great Chinese famine 1958-1962" New York, 2012 pp. 628*

[328] *Wang, W-C et al. (1990) Geophys. Res. Lett. 17, 2377-2380.*

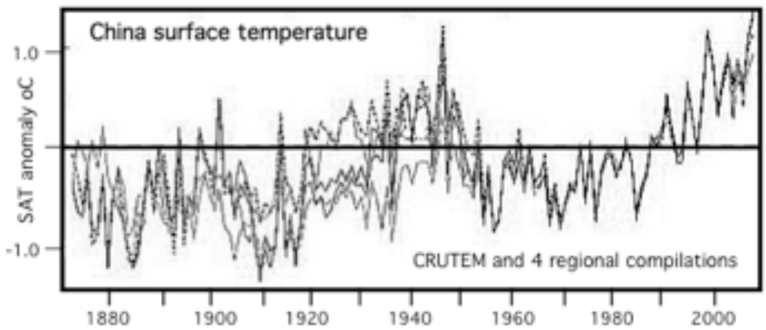
[329] *Nature (2011) 476, 129 (and also see p. NN)*

the northern plain, it must be very large, while on the southern coast or in the mountains of Tibet, it may be negligible: this, of course, is the case everywhere.

Obviously, China is a special case that merits special attention: in the first place, the interpretation of the SAT data is complicated by the fact that there was a more extreme drop-out of stations reporting to the GHCN here than probably anywhere else, as is evident in the GISS data available on the NOAA Station Selector site as I write, in late 2014; however, the CRUTEM data appear to include a remake of the China data by the inclusion of a homogenised historical SAT dataset for 1951-2004 based on data from the 731 national meteorological stations in China; the data have been homogenised and corrected in the manner discussed in Chapter 3.[330] These data would appear to be the basis for studies on China SATs after that date.

It is in China, if anywhere in the world, that the local effects of urbanisation might be expected to dominate the SAT record and to render the radiative effect of CO_2 hard to detect with confidence (p. --}; more recent studies of regional SAT than that discussed above are far from agreement on how this has evolved. Qian and Qin, writing prior to the homogenisation of the national data, presented a nuanced analysis of causes of observed SAT change. They derived 9 regional patterns for the years 1960-1990 and each of these show cooling to about 1980, then warming to the end of the century of about 0.2-0.3^{o}C/10yr in northern China, and rather less in the hilly southern regions.[331] Changes of rate of change and even changes of climate state are attributed to the known sensitivity of Chinese conditions to the change in the state of the Siberian high pressure cell, the strength and position of which in 1980 introduced the period of rapidly-rising winter temperatures, especially in northern China. This, they suggest, will have augmented the effects of urbanisation and industrial aerosols.

A very different story is told by Tang and his co-authors who used an amalgam of 5 data sets in a single regional synthesis to describe the regional evolution of SAT for the whole of China, with its very diverse regions, back to the end of the 19th century: this is not at all exceptional in comparison with other regional series discussed here.[332] Perhaps the most-easily criticised aspect of this presentation is the fact that regional weighting is uneven – prior to the 1930s, only the eastern part of China is represented.



Even so, this redrawn plot offers food for thought, especially in the light of another study performed in the same year, but using the new homogenised data base discussed above. In this, analysis was presented of uncertainties by correlation between

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[330] *Li, Q. et al. (2009) Bull. Am. Met. Soc.* *DOI:10.1175/2009BAMS2736.1*

[331] *Qian, W. and A. Qin (2005) Metorol. Atmos. Phys. DOI 10.1007/s00703-005-0163-6*

[332] *Tang, G. et al. (2010) Adv. Clim. Res. I, 11-19. This regional paper was not noticed by AR5 in their list of regional studies.*

annual station anomalies and the distance between stations – of course, correlation degraded with increasing distance. Here, warming was confirmed to be greatest on the northern China plain and in winter, and the annual rates were comparable with those noted above: the authors judged urban effects to be negligible, though they offer no reason for this.[333]

The effects on SAT of land-use change have probably not yet been studied directly by observation in China, but they have been studied in this way elsewhere. In California, the regional climatic consequences of the agricultural transformation of the San Joaquin valley after irrigation was introduced: there, data from 41 meteorological stations (1895-2005) showed that striking changes in the valley occurred through changes in the surface temperature balance. Diel temperature range progressively decreased through reduced night-time cooling, while nearby non-irrigated desert areas showed no change during the same period.[334]

At larger scale, we have the consequences of the European invasion of the American continent and the rapid transformation of landscape as a model for understanding the consequences of settlement and agriculture in the more distant past. In North America, these land use changes have accelerated during the 20th century and have transformed albedo and evapotranspiration very profoundly: some studies have suggested that the consequences may be at least as important for regional climate as the consequence of radiatively-active gases in the atmosphere.[335] This suggestion is also supported by a study which demonstrated that 20th century temperature change in western North America from the NW Canada to Texas can be causally associated with changes in ground cover: this paper is of great interest because it offers massive documentation on the consequences of landscape modification.[336]

Trends in the relevant North American SAT data and in ground surface temperature (GST) profiles from almost 100 borehole profiles in western Canadian prairies east of the Cordillera, confirm that the areas of greatest warming during the 20th century of both air and ground temperatures are those in which forest clearance and the conversion of prairie grassland to cropland have been most intense; *"calculated flux changes* (say the authors) *associated with land-cover change are comparable in magnitude with greenhouse gas radiative forcing. It therefore appears that through a step change in GST, land-cover changes have contributed to a portion of the observed SAT warming in this region"*.[337] The surface temperature trend reported from these borehole data matches the indications of phenological studies in almost the same region of the western prairies where it was found that the heading – or flowering – date of the winter wheat cultivar Kharkof showed a consistent trend to earlier dates of 0.8-1.8 days per decade across a period of 70 years.[338]

However, these conclusions, based on observation, are not supported by two influential modelling studies of the effects of land-use change on North American surface air temperature. Diffenburgh uses a high-resolution, nested modelling system to test the

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[333] *Li, Q.X. et al (2010) Chin. Sci. Bull. 55, 1974-1982.*
[334] *Christy, J.R. and W.B. Norris (2010). 16th Conf Clim. Var. & Change*
[335] *Bonan, G. et al. (1992) Nature, 359, 716-718.*
[336] *Diffenbaugh, N.S. (2009) Clim. Dyn. DOI 10.1007/s00382-009-0566-z*
[337] *Skinner, W.R. and J.A. Majorowicz (1999) Clim. Res. 12, 39-52*
[338] *Hu, Q. et al. (2006) Agric. Forest. Meteorolog. 135, 284-290*

sensitivity of regional and local climate response to changes in land use.[339] The dominant response is suggested to be a cooling on the Great Plains and in areas of the Midwest where short-grass prairie and interrupted forest, respectively, has been replaced with mixed farming and the planting of crops. In the western regions, and especially in North Dakota, Montana and Alberta, this simulation suggests that cooling would be introduced – just where the observations discussed above show the opposite trend. Of course, whether cooling or warming is induced, the ploughing of prairies anywhere is not a very good idea in the long term: in the natural state, the prairie grass forms a dense mat of dry material during winter that protects the soil from frost and from wind erosion. The dust storms that reached as far as the eastern seaboard in the 1930s – and recurred in the dry, hot summer of 2012 – are a direct consequence of ploughing. Another modelling study of the clearance of the interrupted forest lands of the Midwest had the somewhat misleading title of '*Frost followed the plough*'; in fact, the regional cooling was rather the consequence of cutting the forests – so a better title would have evoked an axe.[340]

It is abundantly clear that the effects of the ongoing transformation of natural vegetation and of farmed lands must be considered in any analysis of the evolution of global SAT over the continents. Because land use change has strong regional characteristics that reflect the pattern of human intervention and population growth, direct extrapolation to global scale either from the studies of North American land surfaces or from the Amazon basin would be inappropriate. Despite such diversity of response to land use change, it is essential that the scale and complexity of the transformation should be admitted so that the essential studies may proceed quietly and without prejudice.

But other environmental factors intervene in determining the occurrence of extreme conditions of rainfall or drought. For North America, the mechanism is driven by variable sea surface temperatures over the North and Tropical Pacific Ocean, as the rate of the upwelling of cold water along the equator responds to the changing intensity of the easterly Trade winds. Episodic weakening of the mid-latitude westerlies associated with El Niño events reduces the flux of moisture from the North Pacific onto the North American continent and brings drought conditions to northeastern Mexico, the southern Great Plains and the Gulf coast; further to the north, the association between rainfall and Pacific SSTs is less clear.[341] In suitable tree-ring proxies, drought conditions therefore have a periodicity that is characteristic of the Southern Oscillation index and these suggest that severe drought conditions obtained during the mediaeval period, and a recent study suggests that conditions will be even more severe in the coming century; however, the bundle of models deployed are unable to reproduce the major changes in the soil moisture index data with any fidelity, although it is claimed that they are indistinguishable statistically over the brief period 1931-1990.[342]

Others may disagree, but I find this kind of prediction of future conditions very unsatisfactory and in this case my confidence is not increased by the comments of the authors that "*Quantitatively comparing 21st century drought projections from general circulation models (GCMs) to the paleo-record is nevertheless a significant technical*

339 Diffenburgh, N.S. (2009) Clim. Dyn. 33, 945-948
340 Bonan, G.B. (1999) Ecol. Applic. 9, 1305-1315
341 Seager, R. and M. Hoerling (2013) J. Clim. 27, 4581–4606.
342 Cook, B.J. et al. (2015) Sci. Adv. 1;e1400082

challenge. Most GCMs provide soil moisture diagnostics, but their land surface models often vary widely in terms of parameterizations and complexity (for example, soil layering and vegetation)". As I shall comment later, if we did not have models to suggest otherwise, the present observations would not give us any cause for alarm.

Much, here as elsewhere in climate change science, rides on climate simulation of open systems that cannot be completely specified, and for which we are unable to specify all perturbing factors The complexity of the processes in ocean and atmosphere that eventually control SST in the NE Pacific - and hence drought in the SW USA - are sufficiently great as to suggest caution in believing the probity of their simulation by GCMs.

6.4 - The thermal consequences of urban development

This phenomenon has been understood for almost two hundred years. Meteorologist Luke Howard (quoted by H.H. Lamb) wrote in 1833 concerning his studies of temperature at the Royal Society building in central London and also at Tottenham and Plaistow, then some distance beyond the town: "*But the temperature of the **city** is not to be considered as that of the **climate**; it partakes too much of an artificial warmth, induced by its structure, by a crowded population, and the consumption of great quantities of fuel in fires: as will appear by what follows….we find London always warmer than the country, the average excess of its temperature being 1.579°F (1.5-1.8)….a considerable portion of heated air is continually poured into the common mass from the chimnies; to which we have to add the heat diffused in all directions, from founderies, breweries, steam engines, and other manufacturing and culinary fire..*"

So the concept is not new, and modern city administrators have no doubt about the reality of UHI and the effects of combustion of fossil fuels: in 2013, the then Mayor Delanoe of Paris contracted a study of ways to reduce the "*dome thermique*" of his city, to reduce the unacceptable warmth in the city centre on still summer nights, said to be almost 5°C higher than in the outer suburbs.[343]

But the existence and significance to regional and global SAT measurement has been strongly resisted by many in the climate research community, and in the early years of the present century the presence or absence of urban heat islands was found to be very hard to demonstrate with formal statistical methodology; the central problem is the difficulty of assembling a set of data that can be considered be competent to support a demonstration of the effect because of the eradication of inhomogeneities in the original data prior to incorporation into the analysis. Ideally, appropriate adjustments must be made for all changes in the local environment at each site, for differences in time-of-reading of the instruments, for displacements of the instrument screens, for the interpolation of missing data[344], for the effects of difference in altitude, or of distance from the sea or a lake - both in the case of pairwise comparisons or of integrated comparisons between large rural and urban data sets. This problem was examined by the US National Climatic Data Center using data from 26 previous studies of the UHI effect; the suitability of almost all the available data sets was criticised with comments such as *"in situ data homogeneity was not addressed at all*" or "*There was no discussion*

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[343] *Le Monde, 26.10.12*

[344] *Interpolation was not done in the preparation of the HADCRUT archive.*

concerning potential homogeneity issues such as instrumentation". The review then went on to document their own study, entitled "*Assessment of urban versus rural in situ temperatures in the contiguous United States: no difference found*".[345] This was done with 289 very carefully selected stations, both urban and rural, in 40 clusters across the United States; inhomogeneities in their data were "*rigorously evaluated and thoroughly documented*" and population effects quantified with satellite night-light observations. No differences were found in the data that could be attributed to local population size, although it was suggested that the actual local effects at instrument sites in cities might be locally anomalous: on the whole, it was thought, instrument towers are not placed in the densest parts of large cities.

Strangely, the authors of this study did not point out that their conclusion contradicts the results of much relatively simple field-work, published in peer-reviewed journals, that convincingly demonstrates a positive UHI effect in urbanisations both large and small. It was merely noted that such studies would not be addressed. The authors also ignored the fact that the urban landscape and its climate was been extensively discussed since the 1960s as a component of the developing concept of landscape ecology, especially in Europe but not especially in the frame of concern for anthropogenic climate warming.[346]

Such studies demonstrate that urban landscapes are unique in many significant ways: they are less humid than the countryside because of rapid drainage of rainwater, because less heat is used in evapotranspiration of plants, because they have a high proportion of hard or cement surfaces, some sloping, that absorb heat more effectively from an oblique sun than rural, vegetated surfaces – and release it at night; the high atmospheric particle count both reflects solar heat and assists in the retention of local heat of combustion which, in Amsterdam in 1970, was computed at 65×10^{15} kj annually and is a major factor in urban heat islands everywhere.

Many modern field studies have now unambiguously quantified the 19th century observations of the existence of anomalous warmth in towns and cities: the most direct demonstration of the UHI effect that I have seen was made by means of automobile traverses of 10 urbanisations in the St. Lawrence lowlands in Canada, selected to eliminate all non-urban climatic influences, by which it was shown that *"the heat island intensity under cloudless skies is related to the inverse of the regional wind speed, and the logarithm of the population"*. This result was modelled globally to show that at least with low winds and clear sky the result may be generalised.[347]

An elegant demonstration of the fine detail of the UHI effect has been based on the flowering dates of cherry trees in the city of Kobe; in 1989 the date varied by as much as 12 days between the city centre and the suburbs, with a small city park adjacent to the warmest central area of the city forming a cool anomaly within the urban region; such variability is to be expected and will have confounding effects on the extent to which any site for the measurement of SAT can be considered representative of the grid square to which its data contribute.[348]

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[345] *Peterson, T.C. (2003) J. Climate 16, 2941-2959.*

[346] *See, for example, Vink, A.P.A. (1980) Landscape Ecology and Land Use (Longman, Harlow)*

[347] *Oke, T.R. (1973) Atmospheric Environment **7**: 769-779.*

[348] *Primack, R. and H. Hihuchi. Arnoldia 65/2*

Finally, in a situation where one would imagine that the effect must be negligible, a demonstration of the UHI effect was nevertheless made in the little Alaskan community of Barrow, on the coast of the Chukchi Sea: this demonstration used a network of 54 thermal data-loggers placed at 1.8 m elevation (to match that of a Stevenson screen) all over the town, and in the surrounding areas. This network showed a UHI effect of up to 2^0C in the winter, the effect being greater on still than on windy nights.[349]

After this demonstration in a community of <10,000 inhabitants, no further debate on the real existence of the UHI effect can be entertained so it is no surprise that a sample of 1200 sets of station data in the US Historical Climate Network archives should show small, but clear, differences between rural and urban stations - both when averaged over the entire 20th century and also when progressive changes in the difference during the same period were investigated. This study found (as you would expect) that differences were greater for night-time temperatures, and for the diel range of temperature, than for daytime temperatures. The authors pointed out that greater reliability could be placed in the long-term average differences than in the progressive changes because of uncertainties concerning progressive changes in instrumentation, placement and in the immediate environment of the instruments themselves.[350] The evidence for contamination of station data by local human activity is now generally accepted, and the AR5 of 2114 commented that: this appears to reflect the opinion of the climate science community some of whom continue to affirm that UHI and land-use change effects in the global data are small, against all logic.[351],[352]

The urban effect has important local consequences for the day and night thermal patterns of the lower atmosphere, to understand which it is necessary to consider the vertical structure of the atmosphere a kilometre or two above the ground. Air is transparent to visible sunlight, which heats the surface of land or sea and is retransmitted vertically as long-wavelength heat and this is partly absorbed by, and heats, the atmosphere during daytime – always depending, of course, on relative cloud cover. In the ideal state, a warm surface layer, some hundreds of metres deep, is thus formed during daytime in the convective layer of the lower atmosphere: importantly in the context of urbanisation, particulate pollution is very largely confined to the convective boundary layer. At night, heat loss from the ground ceases and a cool night boundary layer perhaps 250m deep is formed below a thermal inversion in the atmosphere in which the concentration of particulates is high.[353]

This process has been observed in the field under conditions ideally suited to demonstrate the effect of urbanisation, that reduces the day/night thermal difference a meter or so above the ground where the instruments are exposed. Clearly, any changes to the environment at ground level that tend to restrict the formation of a nocturnal cool boundary layer will increase temperature minima and hence the diel temperature change. The evolution of the day/night effect has been observed during the rampant growth of four major cities in SE China during the second half of the 20th century; in each city, the overall warming of SAT was dominated by retention of heat at night and so a

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[349] *Hinkel, K.M. (2003) Int. J. Climatology 23, 1889-1905.*
[350] *Karl, T.R. et al. (1988) J. Climate 1, 1099-1123*
[351] *Jones, PD et al. (1990) Nature, 347, 169-172.*
[352] *Jones, P.D. et al. (2008) J. Geophys. Res. 113, D16122*
[353] *Dartmouth College, Thayer School text on environmental fluid dynamics, Chapter 12*

reduction of the midday/midnight temperature difference, and also by reduced overall cooling during the winter.[354] On the north China Plain, mean summer SAT (June-August) has increased by 0.82°C since the 1950s, accompanied by massive drought conditions. This warming has largely been forced by massive urbanisation, according to the authors of the study.[355]

Globally, the progressive spread of urbanisation during the 20th century can be followed by changes in the day-night temperature difference at meteorological stations and, since the NOAA and Hadley archives of SAT data are numerically dominated by urban stations, this effect heavily contaminates the global archive - with the single exception of the conterminous USA where proportion of truly rural stations is exceptional. Consequently, the observed daily temperature range obtained at all northern hemisphere stations in the GHCN exhibits a progressive trend to lower values (indicating progressively warmer nights) during the entire second half of the 20th century; this certainly represents the effect of creeping urbanisation rather than any natural phenomenon.[356]

Because the original data are provided by national agencies as daily or monthly means, surface air temperature data are very rarely shown so as to distinguish maximum and minimum temperature trends, even though the difference is very significant at both global and regional level and has important implications for understanding temperature trends. In a study that analysed daytime maxima and night-time minimal temperatures at 2000 stations in North America, Russia and parts of Africa, the effect was very clear and suggested that the overall warming trend that is observed in the mean daily data is simply the effect of failure of the nocturnal cold boundary layer to be formed, perhaps largely through local landscape modfication.

This effect introduces a change in the trend observed in the data in the early 1970s. which demonstrates without any reasonable doubt that the long-term reduction in day/night temperature differences caused by the UHI effect has been to introduce an anthropogenic trend into the global SAT data that cannot be attributed to the radiative effects of CO_2. An independent demonstration of this effect has been based on a comparison between observed surface temperatures in the United States and the corresponding trends in a reconstruction of surface temperature obtained from a reanalysis of global weather over a 50-year period. Because the reanalysis is insensitive to surface observations, this comparison showed that at least half of the decrease in diurnal temperature range must have been caused by the effects urban and rural land-use change. The resultant extent of anthropogenic surface warming at global scale - not due to the radiative effects of CO2 in the troposphere - was therefore of order 0.3°C during the last half of the 20th century.[357]

But, it must be emphasised that it is not simply the existence of the effect of land-use change or the UHI effect itself that is important, because "*A fixed, unchanging bias does not matter in detecting climate trends, but a changing bias…does matter, since it introduces a trend not linked to climate*" – as Ian Strangeways wrote recently.[358]

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[354] Tian, L. et al. (2013) Landscape and Urban Planning 115, 18-29.
[355] Sun, Y. et al. (2014) Nature Clim. Change 4, 1082-1085.
[356] Wild, M. (2009) J. Geophys. Res. 114, D00D16 doi:10.129/2008JD1470
[357] Kalnay, E. and M. Cai (2003) Nature 423, 528-531
[358] Strangeways, I. "Measuring global temperatures" (CUP, 2010, p. 62)

It is now certain that a trend in SAT "*not linked to climate*" (or to the effects of CO_2) but to changes in city landscapes is (i) now present in all SAT data sets, (ii) has clearly modified their trend since at least the 1970s, and (iii) is predicted by those global agencies that are concerned with human welfare to continue, and perhaps to steepen, at least until mid-21st century.

The 2011 revision of the UN "*World Urbanisation Prospects*" report makes it very clear that during the last 50 years there has been a massive movement of population to cities and towards the urbanisation of previously rural areas. The facts speak for themselves: more than 50% of all people now live in urban areas and the change in regions such as Africa may be extrapolated to suggest that this ratio will be reached in just a few decades from the present. The phenomenon is equally applicable to cities in the developed and developing regions; in the USA, the city of St. Louis experienced a 355% growth in built land from 1950-1990, Kansas City experienced 110%, Denver 66% and the Chesapeake Bay region 180%. In Europe, it is expected that another 20-28% increase in built-up areas over the 2000 percentage will be reached by 2020. In Bangalore and Mysore, a 194% increase in built-up area occurred between 1972 and 1998 and similar increases were found for regions in Assam where rural populations are flooding the cities and towns.

The massive increase in the number and size of urban areas globally that has occurred since the mid-20th century and the long-term movement of people to urban economies from rural regions has major consequences for the measurement of SAT globally. *These measurements were not initiated with climate change in mind, but rather to serve local issues such as weather forecasting, and therefore have been made preferentially in or near centres of population*; as has often been pointed out, it is only in the USA that a satisfactory coverage of rural areas has been achieved.

As discussed in the previous chapter, to obtain a global value for SAT, it is necessary to infill each sparsely inhabited grid-cell with data from the nearest point at which data have been taken – rural or urban - but almost always from an inhabited area. This is not a problem that can be solved by technological advances in observing global surface temperatures, because it is for the critical 20th century that we lack observations. It is also a problem that is very largely ignored, although it will not go away.

6.5 - The regional effects of anthropogenic heat of combustion

Discussion of the effects of urbanisation on near surface air temperatures are habitually focused on the radiative effects of buildings, ground cover and the consequent low albedo of cities, but there is another aspect of urbanisation that may be more important: the consequences of the generation there of massive amounts of heat of combustion which may produce effects far from the source of heat in an urban region.

The energy budget of the agglomeration of Toulouse in southern France has been analysed in some detail: here, anthropogenic heat release is of order 100 Wm^2 in winter and 25 W m^{-2} in summer in the city core, and somewhat less in the residential suburbs; observations of resulting evolution of surface air temperatures in central Toulouse are compatible with the anticipated effect of the inventory of all heat sources seasonally. Below the urban canopy layer, a budget for heat production and loss through advection into surrounding rural areas can be computed and it is found that this transport is important under some wind conditions. In this and many other urbanisations, there is an important seasonal component heat release by road traffic that forms a major component of the heating budget, since national highway systems commonly pass close to major centres of population.[359]

There is also observational evidence of a rather extensive effect of heat of combustion in Japan, whose national meteorological agency warned in 2006 that their regional climate trends even for rural regions may not be free of this effect, because they show significant and anomalous warming.[360] Measurements in the core of the city of Tokyo during the 1990s indicated a seasonal heat flux range of 400-1600 W.m^{-2} and the entire Tokyo coastal plain appears to be contaminated by urban heat generated within the city, especially under certain meteorological conditions in summer and in the presence of an extended sea breeze[361]. Under these conditions, warming extends to 1 km altitude and is thus much higher than the simple nocturnal heat island over large cities.[362] In the region around Kobe and Osaka it has been found that excess urban heat not only propagates upwards into the atmosphere but also downwards into the ground. Data from six boreholes around Osaka show anomalies of 2-3^{o}C in ground surface temperatures, so that surface air temperature measurements, taken at 1.5m above the surface, are seriously contaminated by anthropogenic ground heat.[363] That borehole temperatures are, in fact, generally contaminated by cultural influences is shown by a study in Australia, and by the extraordinary observations that show that boreholes around Bangkok are contaminated by urban heat as far away as 80 kms from the city centre! [364]

The 4th Assessment Report quotes a study that places the significance of heat of combustion in a global context, suggesting that the overall effect must be quite trivial with a global heat flux of merely 0.03 W m^{-2}. There seems to be no reason to reject this simple computation based on the consumption of fossil fuels, but the quotation by the IPCC suggests that the problem has been misunderstood. Ignored is the very simple fact that SAT measurements are made only in locations and regions where heat of combustion is released and virtually none are made in uninhabited regions. It is the effect of heat of combustion on the instrumental temperature record that should have been presented, not the trivial effect on global surface temperature overall. It is now clear that heat of combustion is a significant contributor to the anomalous warming of urban regions that is recorded in the global surface temperature archives.

Further, the export of the heat of combustion from major urbanisations has been generalised in a recent study by Zhang from Scripps and his co-authors.[365] Globally, energy from heat of combustion is equivalent to only a tiny fraction of the energy transported in the atmosphere yet it does appear to be capable of disrupting natural circulation patterns sufficiently to induce distant as well as local effects on the global SAT pattern derived from observations. Release of this heat into the lower atmosphere is concentrated in three relatively small mid-latitude regions – eastern North America,

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[359] *Pigeon, G. et al. (2007) Int. J. Climat. 27, 1969-1981*
[360] *Das, L. (2011) Atmos. Sc. Lett. (Roy. Met. Soc., unpaginated)*
[361] *Ichinose, T.K et al. (1999)Atmosph. Envir. 33, 3897-3909*
[362] *Fujibe, F. (2009) 7th Int. Conf. Urban Clim., Yokohama.*
[363] *Huang, S. et. al. (2006) Sc. Tot. Envir.407, 3142-3152.*
[364] *Taniguchi, M. (2006) Clim. Past. Discuss. 2, 831-846.*
[365] *Zhang, G.J. et al. (2013) Nature Climate Change doi: 10.1038/nclimate1803*

western Europe and eastern Asia - but the inclusion of this regional injection of heat (as a steady input at 86 model points where it exceeds 0.4W m^2) in the NCAR Community Atmospheric model CAM3 has important but distant regional effects, especially in winter. Comparison of the control and perturbation runs of this model showed significant regional effects from the release of heat from these three regions at 86 grid points at which observations of fossil fuel use suggest that it exceeds 0.4 Wm^{-2}: specifically, in winter at high northern latitudes, very significant temperature changes are induced: according to the authors, *"there is strong warming up to 1 K in Russia/northern Asia…. the north-eastern US and southern Canada have significant warming, up to 0.8 K in the Canadian Prairies*". Especially in northern North America, where the instrumental record is good, this effect is readily observed.

These are also the regions and seasons for which another GCM simulation that was based entirely on the consequences of radiative gases had failed to simulate warming as strongly as required by observations. The authors of that study noted that one possible reason for their failure might be "*errors or omissions in the specified forcing agents*" – although they suggested that these omissions might consist of incorrect specification of aerosols.[366] It is remarkable that the addition of such apparently trivial changes in the initial assumptions of one of the standard climate models should have such critical consequences for assumptions concerning the mechanism of anthropogenic forcing of change in global climate patterns. In this model, radiative forcing from CO_2 and CH_4 alone does not produce a pattern of SAT that matches observations.

One of the most interesting recent papers on the problem of urban heat contamination of SAT is a recent statistical analysis of temperature in grid cells and associated population and GDP that concluded that the global average temperature trend reported by NASA for the period 1980-2002 should be reduced by about half, if it was to represent only the radiative effects of CO_2. Using a new data base for all available land grid cells a test was made of the null hypothesis that the spatial pattern of temperature trends is independent of socio-economic effects: the hypothesis was strongly rejected ($P = 7.1 \times 10^{-14}$). "*The economic imprints are present in both rich and poor countries but are strongest in countries experiencing real income growth. The effects are significant at the global level and likely add a sizable upward bias to trends in the global mean temperature anomaly. Our results suggest that as much as half of measured post-1980 land-based global warming may be attributable to contamination of the basic data*". This finding strikes at the heart of climate change science by questioning the basis of model verification against real data[367]. It also confirms the findings of an earlier paper based on a matrix of climatic variables and socioeconomic factors for 93 countries that demonstrated similarly significant effects.[368]

As we would expect today, this conclusion was quickly challenged by a paper from NASA Goddard, which suggested that the data used were unrepresentative because weighted to the northern hemisphere, that other effects (such as aerosols) had not been considered, and that the results are supported by statistical methods that lacked rigour; it was proposed, therefore, that reference should rather be made to the dozens of simulations available within the CLIMAP3 files.[369] This is an interesting response,

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[366] *Knutson, .R. et al. (2006) J. Climate 19, 1624-1651*

[367]*McKitrick, RR and PJ Michaels (2007) J. Geophys. Res. 112, D24S09 .*

[368] *McKitrick, R.R. and P. J. Michaels (2004) Clim. Res. 26(2) 159-173 & 27(3) 265—268.*

[369] *Schmidt, GA. (2009) Int. J. Climat. 29, 2014-2048.*

coming from Goddard, because it requires that Hansen's 2001 correction of temperatures at urban stations in the USA, based on satellite night light observations, must now be rejected. In any case, a reading of the original paper suggests a very logical selection of data, their very careful analysis, and a conclusion that really does no more than confirm the results of many previous studies.

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On the basis of the studies discussed in this chapter we may reasonable conclude that at least a large fraction of the difference between Hansen's US and global temperature plots with which the chapter opened is due to the effect of land use change, of urban development, of urban heat production and its regional dispersal - and not to the effects of the progressive increase in atmospheric CO_2 levels. This is a direct consequence of the very different proportions of rural and peri-urban data sets in the USA and the rest of the world.

But beyond that, it is very easy to forget that the SAT data discussed in this chapter represent changes in surface temperature only over the continents, or 30% of the surface of the planet, where it is reasonable to suppose that, in the absence of land-use and urbanisation effects, SAT would respond directly to changes of radiative molecules in the atmosphere. But over the remaining 70% covered by the ocean, where sea surface temperature is used as a proxy for near-surface air temperature, major changes <u>in this value</u> occur as a result of quite different processes (see Chapter 4). The strong warm anomaly of 1998 that has dominated the global SAT record for the last 20 years represented no more than the cessation, for a short period, of near-surface vertical motion over large regions of the tropical Pacific Ocean. Yet the data that record this event are incorporated into the global SAT data – whose characteristics are discussed daily as if they represent the consequences of the radiative effects of CO_2 in the atmosphere, yet it is clear that the 1998 peak (any more than the developing 2015 peak) in the SAT record has nothing directly to do with CO_2.

This presents a fundamental challenge to the iconic anthropogenic warming model: that what we observe today, with so much concern for our future welfare and a sense of guilt that we have brought future disaster on children, may reflect a quite different reality. Our careful 20th and 21st century observations may be recording no more than those parts we can measure of a complex ballet in the circulation of atmosphere and oceans, induced by the imprecise but reliable changes in external forcing from the Sun. Much is made today of the influence of anthropogenic radiatively-active gases in the atmosphere on the frequency and strength of changes codified in the principal climate indices – NAO, PDO, ENSO and so on – and the influence of external forcing is very largely decried because Earth is treated very much as a closed system. I suggest that perhaps the most important aspect of long-term proxy data sets, such as the Karakorum junipers discussed above, is the extent to which they reveal cyclicity in conditions and the consequences of recurrent change in external forcing that were discussed in Chapter 3.

Chapter 7

THE NORTH ATLANTIC: ARBITER OF CLIMATE STATE

"There is a river in the ocean. In the severest droughts it never fails, and in the mightiest floods it never overflows…the Gulf of Mexico is its fountain and its mouth is in the Arctic Seas. It is the Gulf Stream…."[370]

Although the Gulf Stream, and the other western boundary currents, are often cited as the principal agents of heat transport from tropics to high latitudes, this is not correct; at around 35^0 latitude, where poleward heat transport is maximal, 78% of the heat is carried by the winds in the Northern hemisphere, and 92% in the Southern.[371] Long ago, Maury understood that this was the case and compared the Gulf Stream to the hot-water heating system that warmed the air in the old Naval Observatory in Washington: "*Such an immense volume of heated water can not fail to carry with it beyond the seas a mild and moist atmosphere. And it is this which so much softens climate there*" he wrote in 1863. What Maury specifically did not suggest was that the transport of heat in the ocean – at least in the case of the North Atlantic - was critical in setting the state of the climate of some neighbouring regions.

The reference to heat transfer to the atmosphere rather than transport in the ocean is especially appropriate to the Atlantic which differs from the Pacific in its windiness and therefore its stronger surface evaporation and subsequently stronger rainfall to the east of the ocean. The consequence is that the North Atlantic surface water has higher salinity than either the Pacific or the Arctic Ocean, which is the least saline of all ocean basins. But the North Atlantic and the Arctic Oceans form a continuum, the one receiving strongly saline ocean water, the other exporting very large quantities of water that has been freshened by Siberian and Canadian rivers and perhaps passed through several freeze/melt several cycles.

Another unique feature of the North Atlantic is that part of the flow of its subtropical gyre – of which the Gulf Stream forms the western limb - passes as the North Atlantic Current directly into the Arctic Ocean through the open passages of the Nordic and Barents Seas. These two ocean basins are thus sufficiently intimately connected that strong interaction occurs between them which drives an alternation between two Arctic climate states – increasing and decreasing ice cover. This alternation is associated with two states of North Atlantic circulation – strong flow through the Nordic Seas, or weak.

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[370] *Maury, M.F. (1855) "The Physical Geography of the Sea", p. 25*
[371] *Trenberth, K. and J.M. Caron (2001) J. Climate 14, 3422-3445*

These relationships have been, to some extent, lost sight of in the emphasis that climate science placed in recent years on the potential climate consequences of the other unique feature of the North Atlantic – the density-driven, mid-winter sinking of cold, salty surface water in the area of the sub-polar gyre at one of the origins of the global density-driven deep circulation: this process is itself strongly dependent on the strength and pattern of freshened surface water in the subarctic gyre, exported from the Arctic Ocean.

Unfortunately, the Atlantic and Arctic basins, and the processes of polar ice formation and sub-arctic deep convection are usually discussed separately in climate change studies, but this is an error; they are so intimately connected that processes in one cannot be understood without reference to the other. A good case can be made that the critical factor in determining the extent of Arctic ice cover lies rather in Atlantic circulation patterns than in air temperatures above the ice.

7.1 - Consequences of regional wind patterns over the North Atlantic

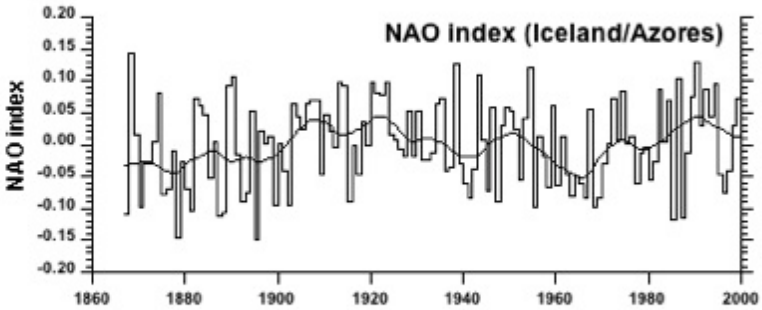
That the presence of the Gulf Stream brings moderate winters to Europe compared with regions at the same latitude on the American east coast hardly needs saying, but the North Atlantic has a much wider influence than that because an alternation between two patterns of flow in the North Atlantic initiates changes of climate state at global scale. Although the North Pacific also alternates between two stable states, the consequences for regional climate are not so significant; this difference is a direct consequence of the very different basin-form of the two oceans. Although there is a minor, shelf-depth connection to the Arctic Ocean at the Bering Straits, the North Pacific basin is closed compared with that of the North Atlantic which exchanges flow with the Mediterranean through the Straits of Gibraltar and with the Arctic Ocean through the Labrador Sea and also – most importantly - through the deep Nordic Sea between Greenland and Norway. The North Atlantic also exports a large fraction of the Gulf Stream flow to the atmosphere because regional winds are stronger than over the Pacific and so evaporate, and carry away, relatively more water than over the Kuroshio. Consequently, North Atlantic surface water becomes sufficiently saline and dense as to sink in convection cells in the sub-polar gyre to form one of the deep water masses of the global thermohaline circulation; this volume is approximately balanced by an inflow of warm South Atlantic water in the Brazil Current into the Caribbean.

Although the Gulf Stream and the Kuroshio transport approximately equivalent quantities of heat poleward around their subtropical gyres, their subpolar gyres are strikingly different. That of the North Pacific is a large, closed anticyclonic feature that lies between Canada and northern Japan which, in the west, brings cold water from the Aleutians as far south as central Japan in the Oyashio stream.

But the subpolar gyre of the North Atlantic is relatively very small and forms a circulation cell between Iceland and Newfoundland. because a major part of the Gulf Stream flow leaves the subtropical gyre and passes into the Arctic Ocean as the North Atlantic Current through the deep Nordic seas. This flow is rather variable and has major climatic consequences, so that changes of state in the Arctic cannot be understood without reference to the state of the Atlantic. The strength of this flow is strongly variable and is largely determined by the changing degree of cyclonicity of the Rossby waves that form on the jet stream along the Polar front forming a series of (usually) five equatorward cold troughs and poleward warm ridges, which tend to remain in preferred positions in response to the location of high terrain, or of very cold regions. The individual weather systems in their eastward movement around the northern hemisphere conform to the position of these troughs and ridges.

This pattern in the jet stream is particularly prominent over eastern North America, where winter weather is strongly influenced by a cold trough on the Polar front that brings arctic air southwards across the prairie States; the return flow along the eastern side of the trough brings blizzard conditions on the east coast from New York to Newfoundland. The quasi-permanence of this trough on the Polar Front is due to the existence of the western mountain chains of North America; passage of weather systems across these creates a semi-permanent trough on the Polar Front over the lower terrain to the east that may extend south of the Great Lakes. Between this and the next trough (or southward excursion of the jet stream) lies the preferred position of the Icelandic low pressure cell, which is one of the two key regions used to quantify the value of the North Atlantic Oscillation discussed in previous chapters. Although the consequences of shifts in the value of the NAO are habitually assumed to concern only the North Atlantic, the circulation pattern of pressure at the surface changes state over the Arctic Ocean between negative and positive states of the NAO.[372]

Change in the strength of the westerly winds of mid-latitudes are diagnostic of the positive and negative phases of the NAO forced by changes in the strength of the Icelandic low pressure cell. During the 20th century, there have been two periods of increasing westerly wind stress over the North Atlantic and each have been associated with major changes in the state of the ocean; the following plot of the evolution of the NAO shows that during two periods of the 20th century (1910-1925 and 1970-1990) there was a sustained increase in westerly wind-stress over the North Atlantic.[373]



The pattern of change in the NAO corresponds (as it must) to the pattern of northward flux of Atlantic water into the Nordic Seas, for which a deterministic mechanism is proposed that involves changes of hemispheric sea-level pressure associated with amplification in the North Pacific: the resultant wind field controls ice export through Fram Strait – and hence also the fresh water balance of both North Atlantic and Arctic Oceans.[374] This is expressed as a close correspondence between sustained wind direction anomalies over the NW Atlantic region and the principal component of ice cover in the Nordic and Barents Seas in the second half of the 20th century – all of which is discussed more fully in Chapter 10.[375].

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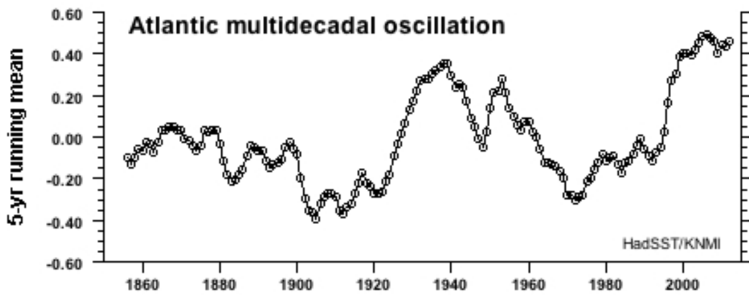
[372] *from Dickson, R.R. et al. (2000) J. Climate, 13, 2671-2696*
[373] *see also Lamb, H.H. (op. cit. p. 53) on change in the westerly winds over Britain.*
[374] *Dima, M. and G. Lohman (2007) J. Climate 30, 2706-2719*
[375] *Deser, C. et al. (2000) J. Climate 13, 617-633*

During both of the 20th century periods during which the NAO took positive values, there is evidence of major increase of transport in the northern limb of the Gulf Stream, and in the North Atlantic Current through the Nordic Seas and on into the Arctic Ocean. Tree-ring and speleotherm proxies sensitive to the two dipoles of the oscillation suggest that this was a persistent feature of the Mediaeval Climate Anomaly of the period 800-1300 AD - although this interpretation has been challenged by a wider bundle of proxies that suggest that a positive NAO was dominant only during the 13th and 14th centuries.[376] But no matter, both sets of proxies serve to show that the NAO pattern is influential in setting climate state in regions distant from the northeast Atlantic. The satellite image used as the cover for this text was selected to emphasise the open nature of the connection between North Atlantic and Arctic Oceans and the direct transport of water, warmed in its passage around the southern limb of the gyral circulation, into the Arctic Ocean – corresponding to those regions where summer melt is strongest. It is salutary to consider what this image would have looked like had it been obtained in 1970, or 1930 or in the 1860s.

The expansion and contraction of the area of warm surface water northwards that is associated with change in the NAO index is codified in the values of the Atlantic Multidecadal Oscillation (AMO) index, of which the original definition referred simply to the mean surface temperature of 11 regions of the North Atlantic and its bounding continents in relation to the South Atlantic region.[377] The AMO has proved to be a useful code for a hemispheric pattern of climate variability that is associated with rainfall pattern in regions as distant as India, and it has also been identified in a new tree-ring reconstruction for northeastern Asia over the entire period 1568-2007.[378] As discussed in Chapter 3, the pattern is reflected in secular-scale SAT data for northeastern North America and for western Europe.

The AMO is now usually specified as the detrended pattern of North Atlantic SST after removal of ENSO influences, and it has exhibited a 60-80 year variability during the instrumental period. It should be noted that this is a measure only of surface temperature and not of the heat content of the North Atlantic, as seems to have been assumed by some authors who associate the AMO with the strength and timing of the deep convection of surface water into the thermohaline circulation (the Atlantic Meridional Overturning Circulation, discussed in the next section). A simpler, and therefore perhaps better, interpretation is that the AMO is largely determined by the areal extent of warm Gulf Stream and Atlantic Current water.



[376] *Trouet, V. et al. (2009) Science, 324, 78; Ortega, P. et al. (2015) Nature 523 71-74.*
[377] *Schlesinger, M.E. and N. Ramakutty (1994) Nature 367, 723-726.*
[378] *Wang, X. et al. (2011) PloS ONE 6, doi10.1372/journal.pone.0022740*

This interpretation is consistent with the onset of rapid increase in the value of the AMO during the 1920s when warm water of the North Atlantic Current penetrated generously into the Europeans seas, and even into the Norwegian and Barents seas and beyond (p. NN); such events demonstrate a strong correlation between the AMO and ice cover in the Arctic Ocean, as will be discussed in the next chapter.[379]

Because marine biology was already well developed in Europe the advective shift of the 1920s was almost immediately noted by the disappearance of cold-water forms of zooplankton in the routine observations already being made off Plymouth. By the 1930s, a massive replacement of northern marine biota by southern was observed around Britain and southern Scandinavia that involved species from phytoplankton to reptiles: medusae, siphonophores, molluscs, tunicates, barnacles, echinoderms, fish and turtles were among those recorded; fisheries were also affected strongly. In some cases, it can be shown that this occurred due to physical movement of the stocks rather than an increase in relative dominance of previously rare southern species; thus some individual cod taken off Jan Mayen in the 1930s had Icelandic hooks embedded in their jaws and, further south, the spawning cod present at Iceland during the 1930s had appeared there as mature fish at the beginning of the warm period. The monographic review of these events by Cushing and Dickson is required reading for an understanding of the scope of this shift of the water mass of the North Atlantic Current, together with its associated biota, towards the northwest.[380] This anomalous flow has been described as a "*huge warming that...lasted for almost two decades…one of the most spectacular climate events of the 20th century*".[381] This event forced itself directly upon everybody's attention in the Arctic and Nordic regions, because one of its consequences was a massive reduction in the area of arctic sea-ice cover and an extension of the open-water season for the export of coal from mines on Svalbard from 3 to 7 months between 1920 and 1930.

The effects on North Atlantic fish distribution were major and well recorded: boreal species (cod, capelin and herring) rapidly shifted towards the north to be replaced around Britain by southern species (bluefin tuna, saury, mackerel, sardine). These shifts have been analysed statistically in relation to the preferred environmental conditions of 42 species with results that are consistent with observations.[382] Strictly demersal species, such as Greenland halibut, tied to a particular bottom type, did not move but instead their abundance was modified.

All this was sufficiently surprising that ICES held an '*Enquiry into the problem of climatic and ecological problems in northern waters*' in 1948. The meeting noted that the northward population shifts on the western European shelf of cold-water herring (*Clupea harengus*) and of warm-water pilchard (*Sardina pilchardus*) resembled earlier northward shifts of the herring fisheries, from 1820-1850 and 1870-80 – to which, using historical fishery information concerning pilchard fisheries as a proxy, we can add earlier periods for northward population shifts of herring and pilchard in these seas: 1590-1630 and 1700-1740.[383] Similar evidence can be drawn from the records of the cod fishery in Icelandic waters and on the west coast of Greenland.

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379 Chylek, P. et al. (2009) Geophy. Res. Lett. 36, L14801, doi:10.1029/2009GL038777,
380 Cushing, D and R. Dickson (1976) Adv, Mar. Biol. 14, 1-122
381 Bengtssen,L. et al. (2004) J. Climate 17, 4045-4057.
382 Rose, G.A. (2005) J. Mar. Sci. 62, 1360-1374.
383 Longhurst, A.R. (2010) Mismanagement of Marine Fisheries, p. 92 et seq. (CUP, Cambridge)

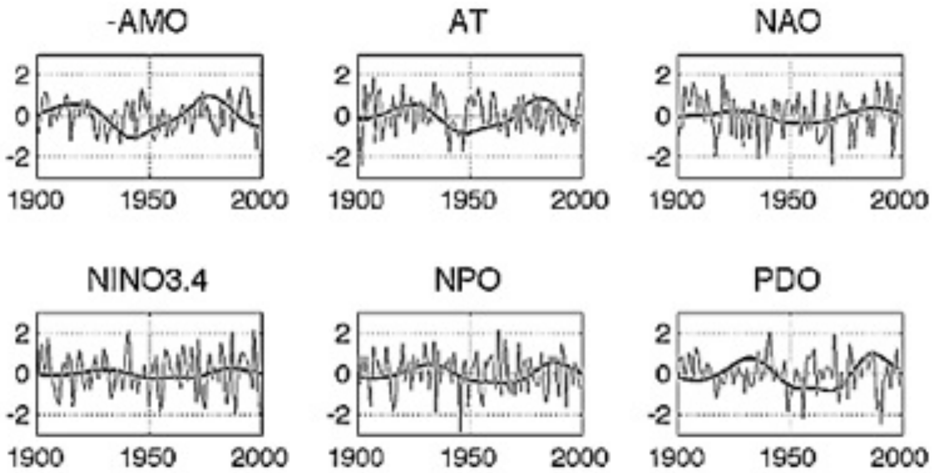
These shifts of species of marine organisms towards higher latitudes were sustained until the mid-1950s after which the NAO took negative values, indicating low cyclonicity on the Polar Front and weaker westerly winds towards Europe; consequently, the distribution of marine organisms returned to conditions typical of the beginning of the century and the so-called the Russell cycle was completed.[384]

But, once again, around 1970, a return to the 1920s pattern of stronger cyclonicity and positive NAO values was initiated, and a renewal of warming of the North Atlantic surface temperatures was indicated by the rising value of the AMO. A new poleward shift of fish and marine invertebrates once again indicated strong penetration of warm Atlantic water northwards towards the Norwegian Sea. This new incursion of the North Atlantic Current into the Norwegian Sea culminated in two pulses of warm water into the Arctic Ocean, in 1997-98 and in 2002-03, and there seems no reason to suppose that these were different in nature from those that occurred, but were less well monitored, earlier in the 20th century. But it was suggested, on the basis of the northward penetration of a southern diatom, recorded in sediment cores, that this was an event of a different calibre and therefore to be associated with anthropogenic climate change - although this proposition seems not to be supported by the evidence offered.

Simulation studies suggest that North Atlantic variability has responded to solar forcing over the last 600 years, modulated by volcanic events that play an important role through their direct influence on sea surface temperatures: in this simulation, the emergence of a positive NAO state occurs two years after major volcanic events.[385] Further, based on ^{10}Be isotope proxies in cores of the Greenland Ice Core Project, it seems probable that the role of solar forcing on North Atlantic variability has been underestimated in the past so that – given the excellent match between solar data and historical evidence of ocean variability – solar control of the basic variability of regional SST cannot be ignored, even if such suggestions are repeatedly challenged (as was this one) in favour of the essentially sunless standard climate model.[386]

A group of recent studies, based on observations made during the 20th century, has suggested that the North Atlantic is a key region for understanding the cyclical evolution of regional climate states; the pattern of AMO departures from the mean is echoed through a suite of other northern hemisphere climate indices. With suitable lags, the normalised and reconstructed components of these indices are synchronised, though with non-zero lags, so that the AMO signal propagates sequentially through the other indices, culminating in an opposite-sign AMO after about 30 years: a partial listing of this sequence is: negative AMO→AT→NAO→NINO3.4→NPO→PDO→positiveAMO. Below is the evolution of six of the more important indices during the 20th century, from observations.[387]

[384] *Drinkwater, K (2006) Progr. Oceanogr. 28, 134-151.*
[385] *Ottera, O. et al. (2010) Nature Geosc. 3, 688-694, Ortega, P. et al. (2015) Nature 523 71-74*
[386] *Shapiro, A.I. et al. (2011) Astron. Astrophys. 529, A67 (but cf. Nature Geosc. 7, 104–108)*
[387] *from Wyatt, M.G. et al. (2011) Clim. Dyn. DOI 10.1027/00382-011-1071-8 with permission*



This progression has been likened to the propagation of a 'stadium wave' through a suite of atmospheric and oceanic indices that code the status of regional climates. [388] It will be discussed more fully in Chapter 10.

Although it has become habitual to consider the ENSO signal to be a prime moderator of global surface temperatures, Nino events in the eastern Pacific do not exert a primary control on global surface temperature: instead, they impose intermittent spikes of warm vaues, as in the case of the 1998 event whose effects are so prominent in the recent record of global SAT. Rather, it appears to be the instability of ice conditions in the Arctic Ocean that forms the primary control mechanism. The recent decline in ice cover has been simplistically interpreted as a novel feature of the region, and as caused by a simple anthropogenic increase in surface air temperature; in fact, ice coverage appears to be cyclical in nature, responding to a sequence of changes induced by basin-form, circulation within the basin, periodic incursions of warm, salty Atlantic water and, finally, periodic peak flow of fresh water from Canadian and Siberian rivers see Chapter 8).

Although the stadium wave thesis awaits resolution and confirmation by other studies, but this early attempt at a synthesis of the way in which regional climate states change and interact (at scales consistent with a dominant mode of solar variability at 60-80 years) is not to be neglected and it certainly strengthens opinions that solar variability is both the engine and control mechanism for changes in regional climate conditions - and, through them, exercises significant control of the instrumental global temperature (p. NN). The analysis also adds weight to less formal conclusions concerning the key role that changes in North Atlantic conditions exercises in northern hemisphere climatology - with some global consequences, too. This should be no surprise, considering the unique feature of this ocean - the direct transport, deep and fast, of very large volumes of warm sub-tropical water towards the north. Depending how the calculations are made, poleward mass transport at mid-latitudes in the Atlantic may be as much as 10 times greater than in the western Pacific.

Unfortunately, these simple observations and deductions are ignored by some writers: a recent paper entitled "*Climate-driven regime shifts in marine benthos*" describes increasing temperatures and decreasing ice-cover during the 30 years since 1970 at eastern Svalbard, associated with benthic regime shifts and a 5-fold increase in macroalgal cover in two fjords. The opening words are "*Climate change can trigger*

[388] *Wyatt, M.C. et al. (2011) Clim. Dynam. DOI:10.1007/s00382:1071.8*

abrupt ecosystem changes in the Arctic" – although it is clear from the content that anthropogenic climate change is intended - and the paper closes with a suggestion that the Arctic may be ice-free by 2050. There is no mention of any previous warm periods in the Nordic seas discussed in the next chapter, nor of the biological regime shift that so surprised European marine biologists in the 1920s.

7.2 - The density-driven circulation of the oceans

It was understood from the earliest days of oceanographic science that the dominant wind-driven circulation in the upper kilometre of the ocean must be accompanied by a density-driven (or thermohaline) circulation, because the distribution of sunshine, evaporation and precipitation at the sea surface must result in surface water being denser at high than at low latitudes, so that a global vertical circulation of some kind must also exist. This hypothesis goes back at least to von Humboldt and Maury, who attributed the presence of cold water at depth in the tropical oceans to this cause.[389] But it was not until the surge in oceanographic studies during the second half of the 20th century that the existence of a thermohaline flow could be directly investigated at sea.

One of the curiosities of climate science writing in the last 20 years has been the new emphasis on the global thermohaline circulation (THC) which is now curiously referred to as the Atlantic Meridional Overturning Circulation, or AMOC and the rate of publication of studies dedicated to it has been increasing by almost an order of magnitude each decade since the turn of the century.

Consequently, the community view of ocean circulation appears to have been modified, at least as expressed in communications concerned with climate change. In the past, it was the wind-driven general circulation of the oceans, in which horizontal and some vertical motion is imparted by exchange of momentum between atmosphere and ocean, that dominated our collective vision of water motion. We would have been very surprised then by the statement that *"The ocean is not a still body of water. There is constant motion in the ocean in the form of a global ocean conveyor belt".* This suggestion is to be found on the NOAA web-site "Ocean Facts", which makes no mention of any form of ocean circulation other than that of the density-driven thermohaline circulation; this model of global flow is now widely discussed and is expressed in cartoons like this. The popularisation of the concept has generated some curious statements by people who really do know better. [390]

The flurry of cartoons that now infest the literature are supposed to portray some version of the internal circulation of the oceans, but usually suggest no more than a selection of possible routes for the return of water from the deep convection cells: they may be quite misleading because, for instance, there is no reason to specify that westward flow through the Bass Strait should be considered as anything other than a component of the wind-driven circulation, yet it was described recently as a novel component of the thermohaline circulation. The same could be said for the errant Agulhas eddies in the South Atlantic, which will continue to develop as long as the wind-

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[389] *Dietrich, G et al. (1980) General Oceanography (2nd ed), Wiley-interscience.*

[390] *At http://www.giss.nasa.gov/research/news/20011119/ you may still find "…the North Atlantic Deep Water circulation system that drives the Gulf Stream…" which has survived uncorrected since it was posted at Goddard 14 years ago!*

driven circulation continues to be wind-driven: some eddies do not retroflect back ito the Indian Ocan at the Cape because mass must be replaced in the Atlantic basin to replace mass exported into the deep circulation from the northern Gulf Stream regions, but because of instability when the Agulhas Current runs out of a western land boundary and is forced to turn eastwards back into the Indian Ocean: most eddies retroflect, some dont.[391]

The critical process in the thermohaline circulation occurs at high latitudes, where winter winds cool and evaporate the surface water mass so that it may become sufficiently dense to sink until it reaches density equilibrium at depth. This convection occurs only in a few locations in the Norwegian Sea, on the Barents Sea continental shelf and in the SW Labrador Sea. Deep convection of surface water also occurs in coastal regions of the Southern Ocean to the east of the Antarctic Peninsula and, on a very small scale and during very brief events, in the northwest Mediterranean and in the Red Sea. A weaker, but similar, process occurs more widely in the eastern sub-tropical North Atlantic below the dry easterlies that blow over the ocean from North Africa: high-salinity, dense water is formed that passes westwards within the gyral circulation at 100-150m depth.[392]

Although the transformation and sinking of surface water by deep convection is often presented as being a relatively simple process, it is really quite complex.[393] In the Labrador Sea, it occurs only near the centres of mesoscale cyclonic circulation features in which the isopycnals dome upwards towards the centre, so that only a small volume of water has to be cooled before sinking is initiated; the water within the vortex is denser and cooler, and the mixed layer deeper, than the surrounding water mass.[394] Subsurface cores ('blobs' one author calls them) of warmer, very dense water from the Mediterranean outflow may occur in the cyclonic flow of the Labrador gyre and the presence of these appears to facilitate the process. But the most essential factor is very cold, very dry north-westerly wind coming off the high Labrador plateau that accelerates surface evaporation, and forces the necessary increase in density: it requires unusual dedication and equipment to investigate this transformation in these regions in mid-winter.

There are several main flows of NADW from sources (i) in the Labrador Sea, (ii) through the Denmark Straits from the Nordic Seas, and directly from the northeast and the Norwegian Sea. The subsequent movement of this water mass is complex and cannot be generalised, even if it is well-characterised by its high salinity, low nutrient and high $^{14}C/^{12}C$ characteristics, because transport is constrained by the individual sill depths that stand between source sites and the deep western boundary current that will eventually carry the NADW southwards below the Gulf Stream.

Because the subduction of cold, dense water from the surface is controlled in large part by regional surface wind stress, its variability responds to the distribution of atmospheric pressure, indicated by the state of the North Atlantic Oscillation (NAO, see p.). Variability in the strength of deep convection has been observed to be a consequence of differences in dominant wind direction during the critical winter period. It is not surprising, therefore, that changes in strength of convection are not

[391] *Durgadoo, J.V. et al. (2013) J. Phys. Oceanog. 43, 2113-2131.*

[392] *O'Connor, et al. (2005) Oceanography 28(1):106–113*

[393] *Toggweiler, JR and RM Key (2001) Encyclop. Ocean Sci. 4, 2941-2947.*

[394] *Clarke, R.A. (1982) Bedford Institute of Oceanography Review, 5-8*

simultaneous over the whole North Atlantic region: during the decade of the 1970s, Greenland Sea deep water became progressively warmer and more saline, while Labrador deep water became colder and fresher.[395] It is often assumed that subsequent lateral motion of the cold, deep water masses into adjacent ocean basins is entirely density-driven but, in fact, external energy is required to lift these water masses across deep stratification and across deep sills. The only sources for this are wind-stress on surface water masses and deep tidal motion: so, "*the ocean's mass flux*", Wuntsch notes, "*is sustained primarily by the wind and secondarily by tidal forcing*".[396]

Present-day interest in the deep convection process originated in a suggestion concerning a millennial cold interval during the recovery from the last glacial period, apparently associated with anomalous levels of atmospheric CO_2. This was the most recent of a series of such 'Dansgard-Oeschger' events during recovery from glaciations and had very strong effects in Scandinavia and northern Europe but was also recorded globally. The proposed mechanism required a discharge of fresh water from glacial Lake Agassis in eastern Canada to flood through the St. Lawrence estuary, and to interrupt the deep convection process in the Labrador and Norwegian Seas, so that the "*turning on and off of the Atlantic Ocean's conveyor circulation was responsible for the large and abrupt temperature changes*".[397] This mechanism involves an assumption that only a reduced flow of warm water northwards across the equator would have been required to maintain balance in the North Atlantic, so total heat transport into the North Atlantic would have been reduced accordingly.

Unfortunately for this proposition, it was quite soon discovered that the CO_2 data were incorrect and that there was therefore no reason to use this event as a model for a high-CO_2 world; currently, proposed mechanisms for Dansgard-Oeschger events are more catholic and now simply involve a suggested lag between general stadial cooling over North America and of ice-rafted debris appearing in the North Atlantic.[398]

But even so, the proposal that deep convection in the North Atlantic was responsible for much of Europe's warmth has been so influential that it requires closer examination: "*The benefit provided by the conveyor is the heat that it releases to the atmosphere over the North Atlantic…amount released is given by the product of the conveyor's flux and temperature change required to convert upper-limb to lower-limb water (i.e. to create NADW)…this totals 4 x 10^{21} calories each year…an amount of heat equal to 35% of that received from the sun by the Atlantic north of 40^o latitude*".[399]

But the strongest heat flux to the atmosphere from the surface of the warm ocean occurs in the subtropical gyre south of Nova Scotia[400] and by the time this water mass has reached the restricted sites of deep convection far to the north in Nordic and Labrador Seas it has lost the greatest part of the heat acquired in low latitudes as is illustrated in this diagram of heat loss.[401]

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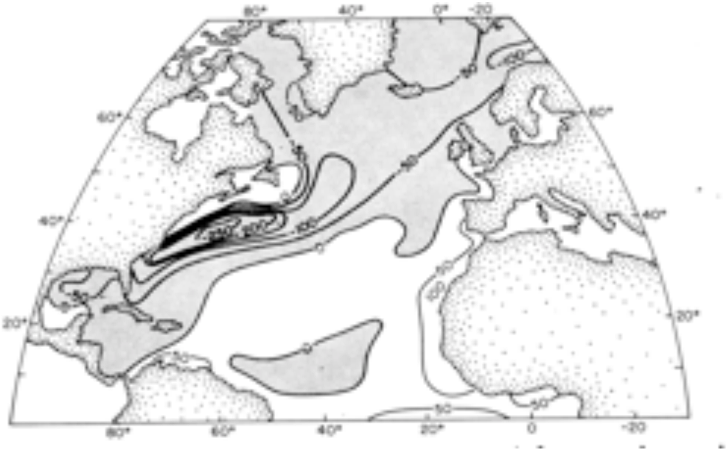
[395] *Dickson, R. et al. (1996) Progr. Oceanogr. 38, 241-295.*
[396] *Wunsch, C. (2002) Science 298, 1179-1180 and (2003) Quatern. Sci. Rev.22, 371-385*
[397] *Broecker, W. (2013) Chem. Perspectives 1(2), 279-284*
[398] *Barker, S. et al. (2015) Nature, 520, 333-336*
[399] *Broecker, W.S. (1991) Oceanography 4, 79-89*
[400] *Image from Ross Hendry, BIO Review '84, , 13*
[401] *courtesy of Bedford Institute of Oceanography*



This computation of heat flux during the convective process assumes that the mean temperature of upper-limb water is 10^{o}C and that of NADW after deep convection is 3^{o}C; these are regional averages over unstated regions and so are not relevant to heat fluxes due to the deep convective process itself. In fact, each parcel of warm upper limb water that is transported by the Gulf Stream from the southern part of the North Atlantic circulation, potentially to be converted into NADW, has already released to the atmosphere most of its original heat content long before reaching the sites of deep convection – where it may sink or pass on, depending on the density of surface water each year. When convection does occur, the water that sinks is from the Labrador Sea, the East Greenland Current or the southern Norwegian Sea – these being bodies of frigid water that have little more to lose in the deep convective process.

But the idea of tipping-points associated with shut-downs of the AMOC adds even greater confusion to the frequent erroneous conflation of the Gulf Stream with the AMOC. In reply to a Nature paper that reported that simulation studies had probed a Gulf Stream model for early warnings of system failure, and perhaps found them, it is not surprising that Wuntsch wrote: "*European readers should be reassured that the Gulf Stream's existence is a consequence of the large-scale wind system over the North Atlantic Ocean, and of the nature of fluid motion on a rotating planet. The only way to produce an ocean circulation without a Gulf Stream is either to turn off the wind system, or to stop the Earth's rotation, or both.*"[402] While it is perfectly possible to envisage control of the deep convection mechanism by, for example, the surface salinity anomalies that pass across the regions of deep convection, it is not possible to envisage comparable changes in the flow rate around the North Atlantic gyral circulation and, hence, its heat transport.

Nor is it often noted today that Stommel pointed out long ago that, in theory, the global thermohaline circulation should exist in two stable modes, an argument he based on the consequences of a thought-experiment in which flow would be regulated between two connected containers by changes in salinity and temperature in one of them.[403] The same concept was introduced later to demonstrate that the ocean could, theoretically, exist in two stable states that would correspond to those of today (Mode A) and of glacial periods (Mode B).[404] The former has an active deep-convection mechanism in the North Atlantic, which is absent or weak in Mode B and the present-day pattern is maintained by a flux of fresh-water from Atlantic to Pacific in the

[402] *Wuntsch, C. (2004) Nature, 428, 601.*
[403] *Stommel, H. (1961) Tellus 13, 224-230*
[404] *Stocker, T.F. and D. Wright (1991) Nature, 351, 729-732.*

atmosphere. If this flux is reduced below a critical value, Mode B is induced, deep convection ceases and the Atlantic circulation comes to resemble that of the Pacific. Increase of the flux above a critical level will once again flip the system back to Mode A.

A similar pattern has been found in the modern sea surface temperature data sets (ERSST and HadSST) in which two modes of variability are recognised by EOF analysis, each having different spatial and temporal properties.[405] In the first case, a slow adjustment of the thermohaline circulation and, in the second, relatively fast adjustment of the North Atlantic overturning cell occurs, swinging between two states. A shift of state in the THC appears to have occurred around 1970, against a background a steady weakening of the thermohaline circulation since the 1930s; as in the case of the previous study, the two states correspond in the most general terms to situation of the glacial and modern periods.

The IPCC of course commented on this general issue: "*Has the Meridional Overturning Circulation in the Atlantic changed?*", they ask, and go on to say that "*The North Atlantic MOC is characterised by an inflow of warm saline upper-ocean waters from the south that gradually increase in density as they move northwards through the subtropical and subpolar gyres*." They discuss the observations and consequences of changing conditions in the Labrador Sea and conclude that no coherent trends in MOC strength have been observed despite the consequences of large-scale, multi-year salinity anomalies in the Nordic and Labrador Seas.

But the results of a series of transatlantic oceanographic sections from Morocco to Florida had shown a significant decrease in the southward transport in the eastern Atlantic from 1998-2004; consequently, a 'slowdown of the AMOC' was reported in the journal *Nature* just prior to an international post-Kyoto meeting.[406] Such an attribution of the term AMOC to the Gulf Stream at mid-North Atlantic latitudes has now become almost habitual, even in scientific writings. However, this paper was rapidly challenged by a comment in the journal Science entitled "*The Atlantic Conveyor may have slowed, but dont panic yet!*"[407] It was pointed out that the reported trend was hardly greater than the uncertainty in the calculations shown by the original authors, and that climate models shown by IPCC AR4 do not project a slowdown of deep convection until well into the 21st century. Except for a single outlier, these models do predict a progressive weakening of the AMOC, but none suggest any increase in response to increasing greenhouse gases, although – in the case of one model – part of the weakening is due to natural cycling of the value of Atlantic Meridional Oscillation during the next few decades.

The text of the AR4 on this subject notes: *"None of these models show a permanent shut-down of the MOC, but this cannot be excluded"* - if certain thresholds are exceeded: once again, one has to ask, why should flow rates at the latitude of Florida be thought to have anything to do with the varying rate of deep convection in, say, the Labrador Sea in the dead of winter? Now that we know that the Dansgaard-Oeschger cold events were not caused by low salinity anomalies flooding across the high North Atlantic, one might begin to hope that the bogey of an AMOC slow-down will disappear – but I am not confident because even today it continues to be raised; an "AMOC Index" has been proposed very recently that is based on evolution of the temperature anomaly (SST) in

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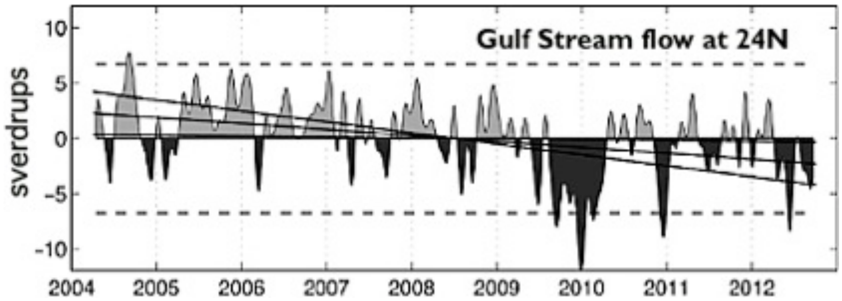
[405] *Dima, M. and G. Lohman (2010) J. Climate 23, 1-15*
[406] *Bryden, H.L. et al. (2005) Nature, 438, 655-657.*
[407] *Kerr, R. (2005) Science 310, 1403-1404.*

the central North Atlantic at 40-60°N compared with the entire northern hemisphere (SST and SAT). A cooler period from 1970-1990 is caused by a "*slowdown in the AMOC*", by which is meant a change in the "*cross-equatorial heat transport of the AMOC*". The authors seem not to have examined maps of North Atlantic geostrophic flows: this flux of heat is an order of magnitude smaller than the flux up the western limb of the North Atlantic gyre and ignores the fact that most of the heat transported in the Gulf Stream has been acquired within the circulation of the North Atlantic gyral system at low latitudes.[408] A decreased flow in the Gulf Stream has been observed in recent years and this is expected to be associated with reduced flux of warm Atlantic water into the Arctic Ocean in coming years (section 8.3).



In any case, what direct evidence has been presented for the suggested change in strength of shallow, wind-driven flows at mid-North Atlantic latitudes? The transatlantic sections mentioned above showed that while the northward transport in the western ocean off Florida had remained constant over these 50 years at about 32 SV, the return transport within the main thermocline into the Canary Current had increased progressively from 13 to 23 SV between 1998 and 2004. That certainly implies that a smaller volume was involved in transport from the Gulf Stream into the North Atlantic Current (NAC) and the authors suggest that this implies a deficit in NADW formation in the Norwegian Sea of about 8 SV. In so doing, they appear to assume that all NAC water is fated to enter the lower limb of the AMOC by being transformed into NADW.[409]

Simple on-line introductions to the bones of physical oceanography exist and should perhaps be read more widely. One of them comments that *"Some of the stories being told about the ocean are so fantastical that they stick in the public consciousness as "truth", and begin to influence public policy makers. Thus it is important that anyone studying climate should be able to distinguish science from science fiction"*.[410] In reading about flow in the Gulf Stream, one enters cloud-cuckoo-land, and encounters statements concerning 'stalling' of this flow for very short periods of just a few days: that such a flow could briefly slow down as if it was the water in the pipes leading to the faucet in your bathroom is a ridiculous notion, though suggested by data obtained by induction in a cable under the Florida Straits. What is observed, of course, is the effect of the changing arrangement of meso-scale eddies within the broad flow directly above the cable. Nevertheless, the NOAA oceanographers who maintain this facility describe flow-rates that change by as much as 10 Sv within a 7-day period – an excellent source for yet more alarmist press stories about the Gulf Stream shutting down.

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[408] *Rahmstorf, S. et al. (2015) Nature Climate Change DOI:10:1038/NCLIMATE2534*
[409] *Boulton, C.A. et al. (2014) Nature, DOI10.1038/ncomms6752*
[410] *http://ocean.mit.edu/~cwunsch/papersonline/oceanandclimatelectures.pdf*

Chapter 8

THE TOP AND BOTTOM OF THE WORLD: TWO SPECIAL CASES

"In the midst of this danger, they had sighted open water and now they saw it plainly. There was no wind stirring and its face was perfectly smooth…Hans could scarcely believe it. But for the birds that were seen in great numbers, Morton says he would not have believed it himself."[411]

If our planet had been designed with comparative high-latitude studies in mind, its present configuration couldn't have been better arranged than it is. In the south, the line of 70º latitude encompasses an entire continent while, in the north, it passes around the coasts of a small ocean, that is open to both Atlantic and Pacific. So the northern polar climate is moderated by a variable flow of heat carried by the warm water of the North Atlantic Current that passes deep into the eastern Arctic Ocean while a small flow of Bering Sea water carries some Pacific heat into the Chukchi Sea. Comparable fluxes of heat do not perturb the frigid climate of the Antarctic continent, which is set in the great circumpolar Southern Ocean.

For these reasons, we should not be surprised that comparative studies reveal that the Arctic climate varies strongly at decadal and secular scales, while the Antarctic climate has changed little during the shorter period we have been able to observe it closely. So the public is not much concerned about climate change in the Antarctic, while the progressive reduction in the area of summer ice in the Arctic Ocean since the mid-1990s has captured wide attention, as has the fear that an increasingly rapid movement of some coastal glaciers of Greenland may prelude a major change in sea level. Unfortunately, it is easy to forget to what extent the Arctic was an invisible ocean until recently: if we had secular-scale satellite imagery of arctic ice cover, instead of only for very recent decades, then perhaps we would be less alarmed by the extent of regression of sea ice in summer.

Changes in the polar regions cannot be understood without reference to the entire cryosphere, in which regression since the 1970s has been general but is not universal: the Hubbard glacier of the Yukon has been steadily advancing for at least a full century, and within 20 years will become the largest glacier anywhere that flows directly into the ocean.[412] This results from a long-term positive balance between snow accretion on the high massif on the Yukon-Alaska border and melting of ice at the glacier mouths on the Pacific coast. The glaciers at the other extremity of North America, on Bylot Island, were recently found to be at their terminal moraines. Elsewhere, glaciers also advance and retreat in response not to temperature, but to winter precipitation.

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[411] *E.K.Kane (1856) "Arctic Explorations", Nelson & Sons., London (p. 170).*
[412] *US Corps of Engineers, Yakatat Watershed study, 2015 (fide CBC 13.6.15)*

During 20th century, the outlet glacier at Briskdalbreen, on the Norwegian coast, has advanced during periods of positive NAO values because of the high winter snowfall that accompanies this state.[413]

The general regression of the cryosphere during 19th and 20th centuries is almost always attributed to rising air temperatures alone, and the chapter on detection and attribution in the IPCC AR5 report concurs with this opinion, although with some reference to the role of SST in the break-up of Southern Ocean ice-shelves. But the intended readers of the Assessment Reports are told little or nothing about the evolution of the cryosphere in the near past, while the global advance of glaciers that so alarmed us in mid-20th century has now been forgotten.

8.1 - Arctic Ocean ice cover during previous centuries

A rather common assumption of recent studies of arctic sea ice cover is that what has been observed in recent decades is a unique event, unlike any previous conditions, although the quotation at the head of this chapter describes open water in June 1854 at 80-81°N, to the north of the Kane Basin, along the Kennedy Channel that leads north to the Lincoln Sea; a sledding party, searching for traces of Franklin's expedition, found open water as far up the channel as they could see from hilltops. But, in summer 1980, our ice-strengthened CSS HUDSON could not penetrate even into the northern bight of Kane Basin, which remained ice-covered in mid-August.

Obviously, one can't read much into a single observation, except to note that it doesn't match our expectations concerning ice conditions at the end of the Little Ice Age. But a 1949 ICES investigation on arctic climate change reported that the decade 1840-1850 was a period of anomalously warm conditions at high northern latitudes in the Atlantic region. Iceland was ice-free for several years around 1850, and cod fisheries developed off eastern Greenland. In the same period, strong warming and melting of tundra permafrost occurred in northern Siberia in some years. In 1846, the River Lena was hard to locate in a vast flooded landscape and could be followed only by the "*rushing of the stream*" which "*rolled trees, moss and large masses of pea*t" against a Russian survey ship, which secured from the flood "*an elephant's head*". [414]

Today, exposure of sub-fossil remains of mammoths is almost automatically hailed by the press as the result of 'climate change' - an anthropogenic effect being understood - *"Climate change led to the discovery of this 40,000 year old mammoth by melting vast swaths of Siberian and Arctic permafrost",* said NBC *Science News* in 2011, concerning one recent find. The reporter probably didn't know that mammoth ivory had entered trade as early as the end of the 16th century, soon after a Russian Tsar completed the conquest of Siberia. The subsequent volume of the trade was driven by demand, rather than supply, and became substantial only in the early 19th century, destined for mass-production of piano keys and billiard balls among other novelties: I have seen estimates of some 50,000 mammoths having been uncovered during the last 250 years.

During glaciations, both the tundra on what is now the continental shelf of the Laptev Sea and of regions that are still dry land became frozen to great depths and the

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[413] *Nesje, A. and S.O. Dahl (2003) The Holocene 13.1, 139-145.*
[414] *See Lamb H.H. p. 252 et seq.*

shelf remains frozen to this day even though it is now inundated by the sea. But it would be very surprising indeed if the mass of frozen soil along the coasts was not being eroded, with or without any intervention on our part; in fact, after each glaciation, something like the situation now being observed must have occurred. IPCC AR4 quotes coastal erosion rates from 1.0-3.0 m/year - with maximum rates of up to 17 m/year having been observed. On a 60 km segment of the Beaufort Sea coast, erosion has increased from about 7 to about 14 metres annually since the mid-20th century.[415]

Such melting of frozen Arctic tundra has been pronounced one of the dangers inherent in climate warming, anthropogenic or otherwise, because it is assumed that a massive release of methane will ensue – this 'methane bomb' adding significantly to the GHG fraction of the atmosphere. This effect is frequently proposed to be one of the catastrophic consequences of global warming, but this prediction, apparently quite obviously correct, proves to be otherwise on closer inspection: contemporary studies on the warming Alaskan tundra in the last few years reveal that, instead, exactly the reverse process may occur. Instead, the tundra vegetation 'wakes up', as the authors of one study put it, so that plant biomass (including a fraction of woody vegetation) actually increases as soil structure is re-homogenised, and decomposer activity is suppressed. This process also increases net ecosystem carbon storage in the tundra, especially at the mineral horizon.[416]

Nevertheless, observations at sea have suggested that the permafrost of the Laptev Sea shelf is currently releasing a larger flux of methane than elsewhere in the oceans and that super-saturation of shelf water with methane is now occurring. This flux, one study suggested, could become massive, because of geological fault lines across the shelf, and could cause catastrophic global warming.[417] But less alarming is the judgment of two more recent papers that demonstrate that although recent warming of the shelf water has occurred, this has not extended below 20-30m depth. Current methane releases "*are the result of the permafrost still adjusting to its new aquatic conditions, even after 8000 years*" and the current rate of melting is about 10 metres per century.[418] So, because most of the methane now stored within the shelf of the Laptev Sea lies at depths of 200m below the sea floor, it is largely capped and massive release is thought to be unlikely although, on the east Siberian shelf, kilometre-scale seeping areas have been found in recent years.[419]

So, I shall take this particular problem no further, but will note one other regional concern that is widely ignored these days, perhaps because there is no solution: that of radioactive debris and contamination on Novaya Zemblya, the result of 138 Soviet bomb tests (including the 50 megaton *Tsar Bomba,* the largest ever tested), and half-a-dozen reactors from submarines and icebreakers (plus two submarines complete with their reactors), 20,000 containers of radioactive waste and, finally, two US reactors from their arctic military bases.[420]

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415 Jones, B.M. et al.(2009) Geophys. Res. Lett. 36, DOI: 10.1029/2008GL036205
416 Sistia, S.A. (2013) Nature, doi:10.1038/nature12129
417 Shakalova, N, et al. (2008) Geophys. Res. Abstr. 10, EGU2008-A-01526.
418 Schultz, C. (2011) J. Geophys. Res. doi: 10.1029/2011JC007218. & Dmitrenko, I.A. et al (2011) Eos, Trans. AGU, 92 (49) 464.
419 Semiletov, AGU, San Fransisco, 2012
420 Le Monde, 23.11.12

Modern analyses and simulations of ice-cover generally concur that the late 20th century ice-loss is caused by the radiative effect of anthropogenic GHGs on surface air temperature. Yet, during the Holocene, the extent of Arctic ice cover has generally followed the pattern of solar radiation; multi-proxy evidence from the Arctic region confirms that there was a steady increase from very low to rather high summer ice-coverage that peaked between 2000 and 4000 years ago. At intervals during the Holocene, there was sufficient open water in summer in the Canadian archipelago for Pacific and Atlantic bowhead whales to mingle, but whether these open-water periods were a response to solar radiation levels, to changing patterns of ocean and atmospheric circulation, or to another cause is moot. Yet the evidence for the occurrence of low ice conditions during the Holocene is unambiguous: on the north coast of Iceland there are isostatically-raised, wave-formed beaches along some hundreds of kilometres of shoreline as high as 83^{o}N.[421]

The extent of arctic sea ice in the past has been quantified by several independent studies of proxy data and these give generally consistent results: analysis of reference horizons and annual-layer analysis of oxygen and hydrogen stable isotopes in the Severna Zemlya ice core reveals a long term cooling to an absolute minimum around 1800 that is associated with a decline in summer insolation and to the growth of the ice cap from which the core was obtained; a matching decrease in sodium concentration was also indicated.[422] During this long period there were several abrupt warming and cooling events *"partly accompanied by corresponding changes in sodium concentration*". The decline was interrupted by the modern double-peaked warming episode that was initiated around 1800.

A multi-proxy study, based on Scandinavian tree rings and Svalbard ice cores, of sea ice extent since the mediaeval period around in the western Nordic seas indicates strong variability until a rather sustained decline in summer ice cover was initiated after the extremely cold period of the 1860s; during the 1930-50s warm period, coverage was reduced from 0.90 to 0.45 x 10^{-6} km^2 in just a few years in the eastern Arctic, before recovering again in the subsequent decades,; ice cover began to decline once again after 1975. The reconstructed sea ice extent is dominated by decadal changes associated with the NAO/AO oscillation, and also lower frequency changes on about 50-120 year intervals. [423] The authors offer support for their assumption that the proxies do, in fact, track surface air temperature in the arctic region by comparison of the 20th century proxy oxygen isotope data with SAT data from some high-quality stations and a regional mean.[424]

A wider bundle of proxies, both terrestrial and from ocean cores, and extending back two millennia, has been widely quoted in recent studies because it proposes that the present rate of ice-loss is unique during this entire period and suggests that the 20th century record terminates in an upside-down hockey-stick, so rapid is ice loss.[425] This result requires more analysis than I can offer, and the data used include no direct proxies of ice-cover (such as diatoms in sediment cores) but many that offer only general information concerning regional climate: they comprise >50 regional ice-cores,

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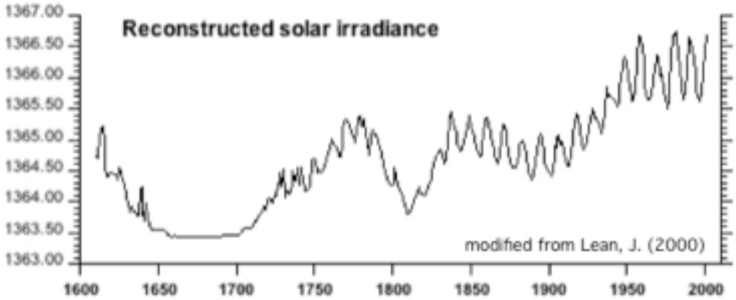
[421] *Polyak, L. et al. (2010) Quatern. Sci. Rev. 29, 1757-1778.*
[422] *Opel, T. et al. (2013) Clim. Past 9, 2379-2389.*
[423] *Fauria, M.M . et al. (2010) Clim. Dyn. 34, 781-795 (see also p. NNN)*
[424] *The latter from Polyakov et al. (2003) J. Climate 16, 2007*
[425] *Kinnard, C. et al. (2011) Nature, 479, 509-512*

4 lake cores and 11 tree-ring sites. No direct explanation is offered concerning the relevance of these to the areal extent of ice cover, and such proxies could at best indicate only general climate conditions in the Arctic; I think this anomalous result has to be left to future judgement and, as will be discussed below, ice cover responds to the salinity of the surface water mass of the Arctic Ocean as well as to air temperature. Ice cover does not respond directly to solar irradiance levels, although there may a threshold at around 1365 W/m2 above which anomalous seasonal ice-loss does occur: recent revues of solar irradiance suggest that such a threshold has been exceeded in recent decades[426].



It is clear from these and other proxy studies that Arctic sea ice extent is rather variable, and this is reflected in the older scientific publications: it was reported in 1922 that *"The Arctic Ocean is warming up. Reports all point to a radical change in climate conditions and hitherto unheard-of temperatures in the Arctic zone".*[427] This was a response to significant ongoing economic change - the open season for shipping coal from Spitzbergen was to lengthen from 3 to 7 months by the late 1930s.[428] The area of mid-summer pack-ice in the Nordic Seas declined by 10-20% and an oceanographic ship from Norway found ice-free water to above 81°N, noting that "*warm Gulf Stream*" water was encountered in the profiles they examined as far north as Spitzbergen: they suggested that this should ensure ice-free conditions there "*for some time to come*". According to these oceanographers, mean summer ocean surface temperatures at Spitzbergen had been about 3°C for 50 years prior to 1917, but by 1922 had risen to 5°C with major consequences for the distribution of marine mammals and arctic fish.[429]

"*The Arctic…is not recognisable as the same region from 1868 to 1917*" said Captain Ingebrigsteen, who had sailed these seas during the previous 54 years. His observation is confirmed by studies of the distribution of benthic invertebrates having specific Atlantic and Arctic affinities along the west coast of Spitzbergen during two periods (1898-1931 and 1949-1959) showed a strong movement to the north of Atlantic species between these two periods: in the earlier period, Arctic species dominated except in the extreme south, but these were present only in shallow shelf water during the later period, while Atlantic species dominated the deeper benthos.[430]

Thereafter, cooling again intervened in the Arctic "*in the very regions which experienced the greatest warming in the earlier decades of the century*", so that by the 1950s the situation once again resembled that of the early 20th century, with very extensive ice developing around Iceland, creating havoc with agriculture on the island –

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[426] *see e.g. Lean, J (2000) Geophys. Res. Lett. 27, 2425-2428*
[427] *Monthly Weather Review, November 1922*
[428] *See Lamb, H.H. p. 260*
[429] *I have searched for, but cannot locate, the original report in Norwegian archives.*
[430] *Blacker, R.W. (1957) ICNAF Spec Publ. 6, 791-794.*

all of which has been put at the door of very greatly increased southward flow of cold arctic water in the East Greenland Current. At Franz Josef Land the mean surface air temperature declined during the 1960s by 3-4°C and the winter minima declined by as much as 6-10°C. This cooling caused the habitual results on farming in Iceland, where the essential hay crops essentially failed and grain crops were abandoned. Fishing off both Iceland and west Greenland faltered as cod stocks declined or, perhaps, migrated. This cold period in the Nordic and Arctic seas was only reversed during the late 1970s, when warming was once more observed and we heard once again the same remarks concerning loss of ice cover and of glacier retreat that had been made in the 1920s-30s[431].

So, it is abundantly clear that any synthesis of the evolution of the 20th century Arctic climate, and any attribution of the present loss of ice cover to anthropogenic forcing, must integrate also the periods of warming and cooling that have occurred in the past. The very earliest, and subsequently abandoned, satellite imagery has recently been recovered so that we now have observations of ice cover for September, 1964, a month when near minimal seasonal ice coverage is expected; the mosaic made from individual monochrome images shows that ice-cover in that month is near the average for 1979-2000, suggesting that it was only after 1979 that a decreasing trend in summer ice cover was established; there has been some recovery since the maximum summer melt recorded in 2012.[432] This is what would be expected, since 1964 was at the start of the cold interval in the NE Atlantic-Arctic Ocean region, that occurred between the 1920-1950 and the 1980-2000 warm periods discussed earlier.

Unfortunately, the analysis of arctic climate change offered by both IPCC AR4 and AR5 is very restricted in scope. The chapters on observations and attribution ignore the unique oceanographic situation of the Arctic Ocean and the climatic role of periodic influxes of warm, salty Atlantic water. The latest (AR5 of 2014) assessment attributes decreasing ice cover almost exclusively to increasing SAT, particularly as associated with 'Arctic intensification' that shall be discussed below; I suggest this is a particularly myopic view of this highly variable polar environment but, unfortunately, analysis of the situation in the Arctic is dominated by data from the satellite period and other modern instrumental data. The IPCC AR4 discussion of changing conditions in the Arctic was almost exclusively based on data obtained since global images of snow-cover were first routinely got in 1978 and, because emphasis is placed on passive microwave satellite data that was available only after 1980, trends of ice cover and related phenomena that are reported by IPCC4 are firmly negative. It would be easy to read such material without understanding the limited extent of our knowledge on the variable conditions at the top of the world during the previous century.

A bundle of model simulations is also offered by IPCC and because these cover a much longer period than the satellite data, they better conform to what is suggested by historical data of ice volume anomalies during the second half of the 20th century. More recent presentations of ice anomalies habitually refer to changes in ice extent which occur preferentially in the regions where warm, salty Atlantic and Bering Sea water penetrate the Arctic Ocean deeply. Data on ice draft, or thickness, come from the larger area of permanent ice but follow the same pattern.

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431 Kelly, P.M. et al. (1983) Month. Weath. Rev. 110, 71-83. This section owes much to H.H. Lamb.
432 Meier, W.N. (2013) The Cryosphere 7, 699-705

IPCC does not discuss the historical record of the periodic changes in ice conditions forced by repetitive atmospheric circulation patterns during the 20th century, only remarking in AR4 that the "*Arctic climate is characterised by a distinctive complexity due to numerous nonlinear interactions between and within the atmosphere, cryosphere, ocean, land and ecosystems*" and that observations "*can no longer be associated solely with the dominant climate variability patterns such as the Arctic Oscillation or Pacific North American pattern*". So the progressive reduction in the extent of arctic sea-ice during summer is widely attributed (not only by the IPCC) simply to 'global warming', and to the increase in surface air temperature. But the historical changes in ice cover and in the dynamics of the seasonal freezing/melting cycle must be forced by a far more complex mechanism than that, involving interactions between rivers, oceans and atmosphere - the "*nonlinear interactions"* of AR5. I am surprised that the basic oceanography of the Arctic Ocean (on which floats the ice that we are all so concerned about) is largely absent in discussion of arctic temperatures today: it will be reviewed later in this chapter.

Recent studies have attributed polynya formation (which is the initial phase of open water development) to two distinct mechanisms: (i) when latent heat occasioned by ice formation is removed by wind, so that re-freezing occurs during periods of calm and (ii) when sensible-heat polynyas are formed by vertical heat flux caused by vertical motion of warmer, deeper water either by mixing or by the induction of upwelling. Heat flux at the ice-seawater interface is complex and involves both solar heating of the subjacent water through the transparent ice, and cooling of the same water by physical contact.

The complexities of ice dynamics are invisible in the simple repetitive annual curves of changing annual ice cover of the Arctic Ocean which is an ocean with complex surface circulation and includes regions that receive warm, salty water from the Atlantic. The ice over the open Arctic Ocean flows differentially towards the main ice-export region to the east of Greenland, while the relative rate of ice loss in recent decades responds directly to the input of Atlantic water through the Nordic Seas discussed in the previous chapter. Despite such facts, changes in Arctic sea ice cover continue to be attributed simply to radiative warming by atmospheric CO_2, and thus presumably to the effect of sensible heat in the atmosphere, so perhaps we should ask whether the lower atmosphere over the Arctic Ocean is really getting warmer, or not?.

8.2 - Is surface air temperature really increasing strongly over the Arctic Ocean?

Everyone who writes on sea ice cover assumes that it is, but evidence to support this opinion is very weak: thus, a recent paper suggests that all that is required to explain observations is a simple mechanism in which variable warming of SAT by CO_2, volcanic dust and solar irradiance is melting the ice pack and greening the tundra.[433] One might well ask why the same atmospheric processes don't also warm the Antarctic? And where are the ocean processes in this model? Finally, can one ignore the unique

[433] *Overland, J.E. et al. (2004) J. Climate 17, 3263-3282/*

and variable flow of warm water from the Atlantic into the Arctic? Obviously not, but before examining that proposition further, perhaps we should be sure that arctic air temperatures really have significantly increased in recent decades.

To place the modern observations in context, and before looking at the recent evidence in detail, perhaps we should first examine what is known of the millennial-scale history of SAT in the Arctic. It is now well understood that a sustained cooling and climate deterioration that began in the 12th century disrupted the Inuit and Thule people who had long before settled at the head of the Labrador Sea, and also the Danes in southern Greenland who had arrived rather later. Here, about 500 families lived, built decent stone farm-houses and churches, and raised families in places where today this would be quite impossible. Their farms were progressively abandoned as their owners failed to raise children, living on a progressively less adequate diet: the last people died in the middle of the 16th century. It is now clear that these Norse settlements were doomed from the time they were established – a long climatic decline lay ahead of the hopeful colonists who, at the time of their greatest prosperity, enjoyed a relatively brief period of warm summers. They had settled in habitat that only Inuit and Thule peoples understood.

This sustained cooling can now be followed with the use of millennial-scale proxy data from (for example) oxygen isotope analysis of ice-cores from two locations on Svalbard (Vardo and Longyearbyen) whose chronology can be constrained by radionuclide and oxygen isotope analysis and by sulphate and volcanic dust layers of known date: remarkably, even the 1950-1970 cooling is recorded by the proxy data. [434]

Evidence of intermittent decoupling of summer and winter temperatures is indicated by variation in the annual cycle of $\delta^{18}O$ in the ice cores obtained at Lomonosovfonna, also on Svalbard, although the climate record obtained from these is dominated by a long winter cooling trend of SAT of about 0.3-0.9°C/century from around the year 800, that reached its nadir during the 1800s at the end of the Little Ice Age : once again, the data indicate that today's arctic climate is no warmer than the climate of the mediaeval period. The particular interest of this record for the Arctic Ocean is the location of Svalbard, near the major flux of warm Atlantic water into the arctic basin.[435]

A similar millennial cooling trend is indicated in a 23-proxy analysis of SAT in the Arctic based on lake sediments, tree-rings and ice-cores taken poleward of 60°N, although some of these were rather far from the Arctic Ocean – including two proxies located on the southern, Pacific coast of Alaska, and three in Europe to the south of the Baltic. The authors note that a progressive cooling from a Holocene thermal maximum may also be observed in retreating tree-lines on high terrain and advancing glaciers.[436] This long-term cooling trend in arctic climate is attributed to a progressive reduction of summer insolation since the Holocene thermal optimum, responding to a June-August insolation decrease at 60°N during the period covered by these multi-proxy data. However, the annual proxy temperatures do not, as the authors suggest, closely match the evolution of relevant CRUTEM3 temperatures during the 20th century, when summer warmth is suggested as the cause of the disappearance of cold-adapted lake

[434] *D.M. Divine, et al. (2011) Polar Res. 30, 7379 - DOI:10.3402/polar.v30i0.7379*
[435] *Fauria, M.M. et al. (2010) Clim. Dyn. 34, 781-795*
[436] *Kaufman, D.S., et al. (2009) Science 325, 1236-1239*

plankton: the annual data in 2000 take the same value as in 1930 and it is only the fitted curve that suggests sustained warming from 1890 to 2000.

One of the foundations of climate change science is that northern polar regions have warmed several degrees beyond warming elsewhere and extraordinary SAT anomalies over the Arctic Ocean are reported that reach as much as 2.5-3.5°C compared with a global mean anomaly of only 0.44°C for the same period. But this result is based on gridded SAT data from all available land stations, together with surface air temperature data where these exist over the oceans, a practice that may be especially problematic for the Arctic because such extrapolation is dominated by data from stations that represent more than the coast of the Arctic Ocean. It is unfortunate that this is also a region for which there has been much station drop-out since the 1990s.

The concept of arctic intensification of global warming – whether anthropogenic or natural – is impeccable: the effects of a small rise in ambient air temperature will decrease surface albedo of both dry land and open water as snow and ice coverage is reduced so that reflectance of solar heat at the surface is decreased. But the evidence that air temperatures have really increased significantly since, say, the early 20th century is very weak: the most commonly quoted evidence is that of Bekraev and his colleagues,[437] who integrated data from large numbers of long-term SAT observations down to 60°N, of which a very small proportion were made on the coasts of the Arctic Ocean; there are significantly larger numbers of stations in the centre of the Siberian and North American land-masses where, as already noted, summer temperatures may reach as much as 20°C. A non-negligible number of data used in this study, especially in Scandinavia, are from urban environments, the consequences of which are explored in Chapter 5.

Yet the most significant finding of this compilation is that the warming rate poleward of 60°N (at 1.36°C per century) is about twice the overall mean rate of 0.38°C of the northern hemisphere, from which is derived support for the concept of polar intensification. But the authors do not comment on the fact that, around the Arctic coastline itself (65-75°N), there is only a very small temperature difference between the 1940s warm period and the end of the century.

Obviously, this data set is an unreasonable compilation on which to base conclusions concerning temperature evolution over the Arctic Ocean, even if it is representative of observations made over the wider area – many of which are from stations in urban regions. To define the evolution of temperature above the Arctic Ocean, it is very easy to do better, more simply and more directly: for instance, a Russian study of surface temperatures at 19 stations in Karelia finds no long-term progressive warming, but simply records the expected occurrence of warmer periods of the 1930s and the end of the century.[438]

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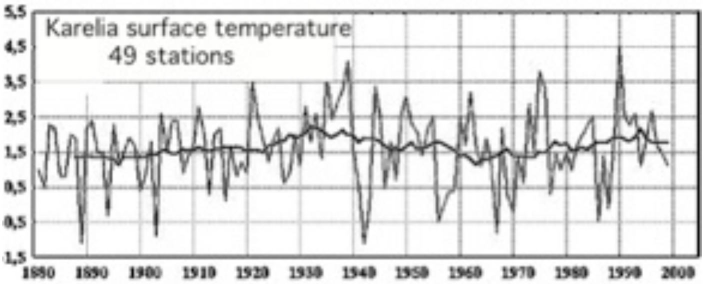
[437] *Bekryaev, R.V. (2010) J. Climate 23, 3888-3906*
[438] *http://nwpi.krc.karelia.ru/e/climas/Climatology/climdata.htm*



These thermometric data correspond very well with the evolution of surface temperatures further to the east in Yamalia, at the mouth of the Ob, that was derived from the growth pattern of larches (Chapter 6.2).

An earlier approach, by Polyakov and colleagues, was based on meteorological stations carefully selected for their proximity to the Arctic coastline and for the reliability of their observations.[439] Because of the strong spatial correlation between Arctic regions,[440] these may be taken represent the whole area very adequately, and over longer periods than some of the data sets of the wider study. Hudson Bay is not included, for instance, because it is considered to have a climatic regime distinct from that of the Arctic Ocean.[441] Although I would have preferred the elimination of four stations in Scandinavia and Scotland, this study did obtain a simple pattern of SAT evolution within the Arctic basin since the 1880s that corresponds very well with the pattern obtained from the ice-core proxies from Svalbard discussed earlier; their reconstruction is dominated by a low-frequency oscillation of 50-80 years in both temperature and pressure data. These authors also report that ice extent and fast ice thickness in Siberian seas respond to the value, positive or negative, of this atmospheric oscillation. But the critical finding from this study is the confirmation that, around the shores of the Arctic Ocean and Nordic seas, SAT at the end of the century had not reached values equal to those of the 1930-40s.[442]

Another compilation took 64°N as the limit of the Arctic region, within which 59 stations were identified, and the data have been used to analyse the pattern of regional co-variability of SAT anomalies based on PCA techniques.[443] This confirms the Polyakov study in suggesting that SAT over the Arctic Ocean did not increase progressively during the last century in response to the consequences of increasing GHGs in the atmosphere; instead it responded to the changing values of the NAO, although it suggests that the end-of-the-century warming episode was associated more directly with extreme values of the AO than with the NAO.

These compilations of station data gives an overall pattern of warming and cooling that is illustrated by the following cartoon that represents the mean SAT anomalies for each study; it would be easy to draw a simple trend line through the combined data to suggest a secular-length period of warming in the arctic region that has, in fact occurred.

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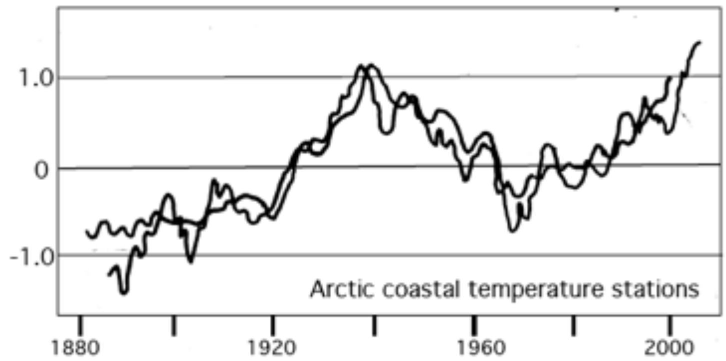
439 *Polyakov, I.V. (2003) J. Climate 16, 2067-2077*

440 *Przybylak, R. (2003) Int. J. Climatol. 20, 587-614.*

441 *Gagnon, A.S. and W.A. Gough (2005) Arctic 58, 270-282.*

442 *Chylek, P. (2009) Geophys. Res. Lett. 36, L14801, doi.10.1029GL038777*

443 *Overland, J.E.. et al. (2003) J. Climate pp-pp*



But that is not done (and shouldn't be done) for two reasons: first, that if the data had extended back only a few more decades then this plot would, have included a third warm period – that of the 1850s, during which a Russian survey ship picked a mammoth's head out of the flooded country around the Lena River (see section 8.1), prior to the very cold epoch of 1860-1880. Versions of this graphic (or of others telling the same story) are consistently given a trend line on which the 'warming of the Arctic' concept largely rests..

Perhaps the most important result of this study was obtained by power-spectrum analysis of proxy data covering the last millennium that demonstrated quasi-periodicity in ice cover in the Svalbard region (or the northern Nordic Seas) of about 50-80 years: at least eight previous periods of relatively low ice cover can be identified back to about 1200. This low-frequency oscillation is ubiquitous in many modern time-series of biological data from the ocean and appears to be confirmed by the few scattered observations that we possess, such as that of Lt. Kane's expedition to find Franklin's ship that was discussed at the start of this chapter. In the context of cyclical or periodic phenomena such as this, a solar cycle influence on surface air temperature is frequently proposed and as promptly rejected: a very recent contribution to this debate shows that "*a linear relation exists in the temperature series from Svalbard between the length of each solar cycle and the average temperature in the next solar cycle…the yearly averages and the winter temperatures can be modelled as a function of the length of the previous solar cycle, with highly significant negative trend*".[444]

These results are consistent with observations made at the Russian North Pole drift stations over a 20-year period at the end of the 20th century and during the period of critical acceleration of ice loss found by the proxy studies discussed above. There was no trend in the dates of the onset of freezing and thawing of sea ice during this period, indicative of a lack of trend in surface air temperatures above the ice. The data obtained at the drifting Russian ice-camps in the vicinity of the Pole do record a progressive reduction in depth of snow cover above the ice in the late 20th century, they do not record any progressive change in SAT; annual mean SATs were in the range -17.0 to -20.0^{o}C throughout the observing period.[445]

The studies of arctic SAT based on the properly selected data sets discussed above are, of course, in direct contradiction to the results of simulation models (associated with the Coupled Model Intercomparison Project version 3 of IPCC4) that have been used to affirm that that increased summer ice melt observed today is forced almost directly by surface air temperatures over the ocean. Others concur with the

[444] *Solheim, J-E et al (2012) Adv. Metorol. (Special Issue On Svalbard Meteorology).*
[445] *Radionov, V.E. et al. (1997) Tech. Rep. APL-UW TR9701, U. Washington, Seattle.*

modellers that "*the current reduction in Arctic ice started in late 19th century consistent with the rapidly warming climate and became very pronounced over the last three decades, unmatched...last few thousand years and unexplainable by any of the known natural variabilities.*" [446]

The sea-floor sediment proxies discussed above show that this statement must be incorrect, because extent of ice cover during the 20th century followed a very similar pattern to that of the previous millennium and, at the end of the long data series in 1995, coverage was not anomalous. These facts cannot be explained by a simple, progressive anthropogenic radiative forcing in the atmosphere following the pattern of the Keeling curve and its projection back in time: a quasi-periodic oscillation of conditions imposes itself on any interpretation of these data.

There is, therefore, very little support for the implications of the widely-disseminated and quoted NOAA analysis and graphic used to introduce this section; the 1.5-3.5^{0}C warm anomaly for Arctic regions that it suggests is most probably a result of gridding, and of adjustment and homogenisation of station data.

8.3 - Why is the Arctic climate and ice cover so strongly variable?

The conclusions discussed in the previous section are inconvenient for standard assumptions concerning of ice loss, such as those outlined in the '*Detection and Attribution*' chapters of IPCC Assessments, which consistently attribute ice loss to increasing air temperatures. Although it is surely common knowledge that salty water freezes only at lower temperatures than fresh water, the rather variable salinity of the surface layers of the Arctic Ocean is absent from the IPCC discussion of causal mechanisms which considers only air temperature and the effect of the different albedos of ice surfaces and of open water. Consequences of the influx of warm Atlantic water to the Arctic Ocean merits only the brief comment in AR5 that "*Ocean circulation delivers warm water to ice sheets. Variations in wind pattern associated with the NAO….probable drivers of increasing melt at some ice margins*". The authors apparently chose to ignore much recent work concerning this dominant feature of the global environment, which quantifies a principal forcing of the dynamics of Arctic Ocean sea ice - and so of the variability of the area and thickness of seasonal ice cover. It is now clear that variability in the past has been dominated by oscillations that are *"frequently associated with decadal components of the NAO/AO and multi-decadal lower frequency oscillations operating at 50-100 year. Sea ice and NAO showed a non-stationary relationship during the observational period"* as one study proposed recently. [447] Models suggest that increased cyclonicity, or high values of the NAO, favours lighter ice conditions in the Eurasian Basin, as in fact occurred during the 1940s and early 1950s - and again at the end of the century.[448]

A recent compilation of the Arctic heat budget uses the ERA-40 reanalysis of ocean and atmosphere data (see p. NN for a note on the use of reanalyses in studies of this kind) for an Arctic domain defined by the 70^{o}N parallel.[449] Seasonal cycles of

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[446] Polyak, L. et al. (2010) Quat. Sci. Rev. 29, 1757-1778. (note the contrary opinions of Polyak and Polyakov expressed in the regional literature)
[447] Fauria, M.M. et al. (2010) Clim. Dyn. 34, 781-795
[448] Polyakov, I.V. and M.A. Johnson (2000) Geophys. Res. Lett. 27 (24) 4097-4100

vertically-integrated heat storage and of the convergence of energy transport show that the net surface flux is the primary driver of seasonal heat change in the Arctic Ocean: horizontal transport of heat convergence from the ocean (Bering Straits and Barents Sea) and of sea ice to the ocean (Fram Straits) are relatively very small terms.[450] This study emphasises the atmospheric balance in July between incoming SW radiation and outgoing LW radiation (each about 230-240 Wm^{-2}) in the atmosphere, and also a lateral atmospheric transport of 91 Wm^{2}; about 120 Wm^{-2} of the SW radiation enters the ocean which loses 10 Wm^{-2} of LW radiation back to the atmosphere; this budget assumes that no LW radiation enters the ocean, although a diagram in another paper by the same principal author does suggest such a flux, though it is unquantified. A net July flux of 101 Wm^{-2} is, therefore, proposed from the atmosphere into the ocean, associated with the effects of ice-melt and sensible heat gain; this flux is presented as the principal cause of seasonal changes in heat storage in the Arctic Ocean, dominating the 6 Wm^{-2} accumulated from heat exchange divergence (sea/ice) and from sensible heat flux associated with Atlantic and Pacific water passing into the Arctic. This model suggests that it is atmospheric processes that dominate the heat budget.

These calculations comfort those of the AR4 of the IPCC and describe the energy balance of the domain in a very elegant way, but they dont answer the question before us: why is the Arctic so variable? The model uses oceanic and atmospheric data only for the period 1979-2001, and this may be a sufficiently short period that the data representing the alternation of episodes of weak and strong Atlantic water influx to the Barents Sea were not available to the model.

Observations, unlike models, suggest that variability in oceanographic conditions in the Arctic is very largely driven by the consequences of the flows through open passages to both Atlantic and Pacific Oceans, which themselves respond to the different and characteristic variability of the circulation patterns of each ocean: each inflow is not only variable in volume of water transported but also in the temperature of the water imported. Of the two passages, the wide-open Arctic Ocean-Nordic Seas connection is the most important and the oceanography of this region has long been a focus of research and review so, that the dominant processes are now rather well understood and quantified.[451] This flow of Atlantic water is facilitated by the low sea level of the Arctic Ocean – itself a consequence of baroclinic overflow southwards through Fram Strait and the Canadian archipelago.[452]

Of the 8.5 Sv of warm, salty Atlantic water that passes north across the Greenland-Scotland Ridge annually, about 4.0 ±2.5 Sv passes into the Barents Sea either directly to the north of Norway as a barotropic flow, or along the western coast of Spitzbergen as a baroclinic flow. These fluxes of warm water (6-8^{o}C) carry almost 100 TW of Atlantic heat into the eastern Arctic Ocean annually, while another 10-20 TW passes into the western Arctic basin through the Bering Strait in a flow of about 0.8 ±0.2 Sv of Pacific Ocean water.[453] The high-salinity water Atlantic water fills the Arctic basin between the low-salinity surface water and the Arctic bottom water while the small flow of Pacific shelf water passes to the east along the Alaskan-Canadian shelf.

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[450] *Serreze, M.C. et al. (2007) J. Geophys. Res. 112 D11122 doi. 10.1029/2006JD008230*
[451] *Meincke, J. et al. (1997) ICES J. Mar. Sci. 54, 283-299*
[452] *e.g. McLelland, J.W. et al. (2010) Est. Coasts. DOI 10.1007/s12237-010-9357-3*
[453] *Beszcynska-Moller, A. et al. (2011) Oceanogr. 24 (3) 82-99*

Although the Arctic Ocean comprises only 3.7% of the surface of the global ocean, it receives an input of freshwater from Asia and North America that is equivalent to 11% of the flow of all rivers, whose flow across the northern continents and into the arctic seas is at least as variable as it is in other regions.[454] This fresh water, together with melt-water from the melting ice-pack in summer forms a permanent superficial layer (usually about 200m deep) of low salinity over the entire Arctic Ocean, without which much less seasonal ice would form. The flow of freshwater from the northern continents represents an export to the world ocean that goes almost entirely into the Atlantic, about 5.1 Sv passing as relatively low salinity water through the passages between Greenland and Ellesmere Island into the Labrador Sea, a flow of low salinity water that can subsequently be traced around the subpolar gyre.[455] Balance is also maintained by flow from the Arctic Ocean through the western part of Fram Strait to enter the East Greenland Current. The strength of both of these annual fluxes during summer will have consequences for the salinity of the surface water mass of the Arctic Ocean and hence on the strength of the freezing cycle during the following winter.

Because the incoming and the outgoing flows, warm and cold respectively, lie side-by-side between Greenland and Scandinavia, an asymmetry is induced in the distribution of ice-cover on the Arctic Ocean; this is generally dense to the west of Fram Strait while, to the east of Spitzbergen, much of the Barents Sea – at similar latitudes – remains ice-free even in winter due the eastward flow of warm Atlantic water. The satellite image used on the cover demonstrates graphically to what extent the Atlantic and Arctic Oceans form a unified ocean region and to what extent the region of Atlantic influence coincides with the regions of maximum loss of summer pack-ice during recent decades. One sees perfectly clearly from water colour in the flow around the North Atlanic gyre how heat is gained in the passage through low latitudes and lost at moderate to high latitudes on the western side of the ocean. Cloud pattern invokes (and probably describes) warm winds above the flow towards the Norwegian Sea and how this coincides with the regions lacking ice cover in the eastern Arctic Ocean.

The outgoing flow through Fram Strait carries with it large volumes of fresh water as fragmented pack ice, a flow that is strongly episodic at decadal scale and is associated with the series of so-called Great Salinity Anomalies observed within the circulation of the subarctic gyre and in the Nordic seas that were discussed in the previous chapter.

But it has been suggested that *"the early-21st century temperatures of Atlantic water entering the Arctic Ocean are unprecedented over the past 2000 years and are presumably linked to the Arctic amplification of global warming"*. This suggestion has been very influential in moulding opinion concerning the effects of anthropogenic global warming in the Arctic, and was based on examination of annual varves in cores taken in the West Spitzbergen Channel. These show that the number of sub-polar species of fossil foraminifera currently being deposited exceeds the number of polar species for the first time in the last two millennia, and that by about double.[456] These data have been used to suggest that the ongoing range-shift of warm-water species of fish and

[454] *Polyakov, L. et al. (2010) Quart. Sci. Rev. 29, 1757-1778*
[455] *Belkin, I.M. et al. (1998) Progr. Oceanogr. 41, 1-68*
[456] *Spielhagen, R.F. et al. (2010) Science 331, 450-453.*

zooplankton is not a replay of the Russell cycle, but a different phenomenon associated with anthropogenic global warming.[457]

Perhaps so, but a careful examination of the data shows that the anomalously warm Atlantic temperatures at depth that was inferred from the increasingly high fraction of subpolar foraminifera in the core samples is the result of a trend imposed on the sequence as early as the 17th century; in fact, unprecedented levels of warm-water species occurred as early as the beginning of the 20th century and those who choose to categorise the climate of the early 20th century as the (hopefully) near-final stages of recovery from the Little Ice Age whose last expression was the very cold period of the 1860-70s may point to these data for support.

So there is really no reason to suggest, as some have done, that the current northward translocation of species ranges in the North and Norwegian Seas is a novel phenomenon. The post-1970 warm period is discussed in a paper from the Faeroese fishery laboratory that demonstrates a bottom-up physical link between ocean circulation (the strength of the sub-polar gyre is critical) and successive trophic levels in the food chain.[458] This places the late 20th century event firmly in the context of similar events over at least the three previous centuries that you will find in any history of European fisheries, especially those for herring and cod, which have brought feast and famine to North Sea fisherfolk, and which were mentioned in the previous chapter.

In the Barents Sea, a '*Code for the long-term fluctuations of Norwegian spring-spawning herring*' has been proposed which is based on the effects of the 18.6 year lunar tidal node that influences the inflow of Atlantic water to the Barents Sea and controls temperature conditions within that sea.[459] During the 20th century, the archived Russian ocean temperatures (0-200m) in this region closely follow the 18.6, the 18.6/3 = 6.2 and the 18.6 x 3 = 55.8 year harmonics of the nutation (or wobbles) in Earth's axis of rotation as it passes around the cone of precession.[460] Earlier, Yndestad (*op. cit.*) had pointed out that the third harmonic cycle of 55.8 years should reach a new maximum in the year 2000, a prediction that seems to have been fulfilled in the 0-100m temperature record for the sea areas around the Kola section of the Barents Sea from 1900 to 2006. This pattern is consistent with the end-of-the-century northwards shift of marine species distributions into the eastern Arctic. Yndestad also noted the worldwide correlations that have been reported between the 18.6 yr nutation rate and rainfall, tree-rings, harvest dates, and landings of cod in northern Norway.[461]

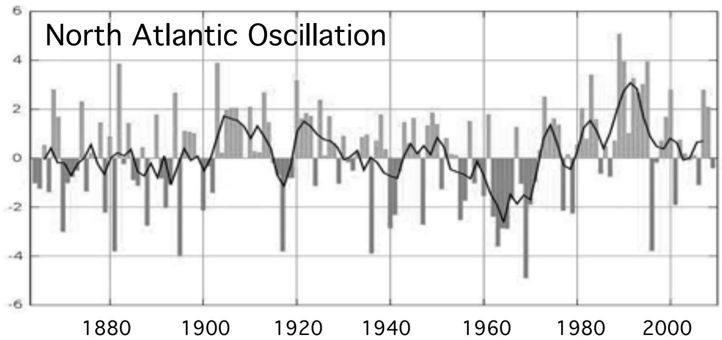
The significance of these events continues to be revealed: a new synthesis of circulation in the Arctic basin has been made from almost 3000 oceanographic profiles obtained in the central Arctic Ocean since the 1890s, which were not previously accessible.[462] This makes it clear to what extent the variability in the inflow of '*warm and salty*' North Atlantic water at times of positive values of the NAO dominates the temperature of the Atlantic water mass by importing '*vast quantities of heat*' into the Arctic Ocean to induce core temperatures in the intermediate layer in Nansen Basin that are much warmer than in the Canadian Basin, far downstream. This warm intermediate

[457] *Beaugrand, G and P.C. Reid (2003) Glob. Change Biol. 9, 801-817.*
[458] *Hátún, H. et al. (2009) Progr. Oceanogr. 80, 149-162.*
[459] *Indestad, H. (2002) ICES Ann. Sci. Cnf. CM 2002/Q:02*
[460] *Yndestad, H. (1999) ICES Journal of Marine Science, 56: 381–387.*
[461] *Levitus, S et al. (2009) Geophys. Res. Lett. 36, L19604, doi:10.1029/2009GL039847*
[462] *Polyakov, I.V. et al. (2004) J. Climate 17, 4485-4497.*

layer has the potential for significant control of the annual cycle of formation and melting of arctic ice.

On the other hand, during the negative phase of the AO, water motion in the Arctic Ocean is anticyclonic and the Beaufort gyre is strengthened, so that ice is retained and thickened both in the Canada Basin and along the Siberian coastline, where it may survive summer melting. Similarly, records of fast ice thickness and extent in four Arctic marginal seas (Kara, Laptev, East Siberian, and Chukchi) indicate that long-term trends are small and generally statistically insignificant, although correlation degrades eastwards- as you might expect it to do - and is absent in the Chukchi Sea. That a simple warming trend throughout the 20th century does not characterise arctic conditions is also confirmed by records of ice-cover in the four seas that lie north of Siberia (Kara, Laptev, East Siberian and Chukchi); these show clearly that ice variability in these seas is dominated by a low-frequency oscillation of frequency 60-80 years that - in the authors words - "*places a strong limitation on our ability to resolve long-term trends*".[463] This low frequency signal is strongest in the Kara Sea (where very strong ice minima occurred in 1940 and at 2000 the end of the data series studied) and decays eastward so that in the Chukchi Sea ice cover is dominated by decadal fluctuations. Only in the Kara Sea is ice cover dominated by thermodynamic factors, while ice cover in the other basins is dominated by the effects of wind and currents. [464]

Transport of warm water on this scale may be expected to be directly related to the pattern of low and high pressure cells in the atmosphere. A stubborn, positive state of the NAO characterised the final decades of the 20th century, and was associated with transport of Atlantic water into the Arctic Basin that significantly reduced ice coverage.



Since 2002, this process has accelerated due to very thin spring ice and to the "*memory of the system to the positive winter AO state that characterised the mid-1980s and 1990s*" as Stroeve et al. put it.[465] As well, these authors note that the character of sea ice has also progressively changed after so long a period of positive NAO values, particularly in the progressive loss of multi-year ice. The single, strongly-negative NAO index during the winter of 2009/2010 was not sufficient to reverse the process.

The first evidence that a warm pulse had entered the Arctic Ocean in 1990 was the occurrence of anomalies of order 1°C in the Atlantic water mass of the Nansen Basin. These were transported in the anticyclonic gyral circulation along the Asian continental slope through the Makarov Basin to reach the Canadian Basin 7 or 8 years later as a warm anomaly of about 0.5°C. A second set of warm pulses was detected at Fram Strait

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[463] *Polyakov, I.V. et al. (2003) Journ. Climate 16, 2078-2085.*
[464] *Polyakov, I.V. et al. (2010) J. Clim. 16, 2078-2085.*
[465] *Stroeve, J.C. et al. (2010) Geophys. Res. Lett. 38, L02502*

in 2004 were a little warmer, but followed the same trajectory as in 1990 so that peak warming in the Eurasian Basin occurred in about 2007. [466]

Warm anomalies such as these, transported within the Atlantic sub-surface water mass, are not in direct contact with the pack ice that is insulated across a steep pycnocline from the warmer water by a <50m layer of cold surface layer of low salinity. The heat lost by each warm anomaly as it passes eastwards must in part be lost into the bulk of the Atlantic water mass below, but there is good evidence also of significant upward heat flux during transit along the slope: despite microstructure observations that suggest that mixing is very weak across the Arctic halocline, heat budget estimates nevertheless yield significant vertical fluxes. These in turn suggest that decreases in ice thickness of <30 cm may be attributable to this flux, rather than to the supposed consequence of a warming atmosphere over the Arctic Ocean by the studies of arctic SAT data that were discussed above.

The pulses of warm Pacific water that pass north through the Bering Straits are rather variable, and the occurrence of a major irruption was confirmed by observations of Pacific diatoms (*Neodenticulata seminae*) in Labrador Current water in the late 1990s[467]. Following the gyral circulation of the Arctic Ocean, it is presumed that these must have passed eastwards through the Chukchi Sea and along the Canadian coasts. Sea surface temperatures at the source of these fluxes in the Bering Sea have followed the now-familiar pattern of a *fin de siècle* repetition of the mid-20th century warming and thus closely matches the evolution of the value of the PDO.[468] The significance of this observation is that it confirms that the inflow of Pacific summer water (PSW) in the late 1990s through wind forcing of near-surface transport was both unusually warm and unusually strong – as it must have been to transport Pacific organisms unusually far eastwards along the Canadian coastline and then south into the Labrador Sea. The area of this interflow in the southern Canadian basin and the Chukchi Sea corresponds with the area of summer ice reduction during the late 1990s. However, increasing Bering Sea temperatures at the end of the 20th century cannot be formally correlated with relative ice loss in the Arctic Ocean, and an alternative mechanism has been proposed: that the warm pulse of PSW retards winter ice formation and so ensures a more efficient transfer of momentum from wind to the coastal water mass which "*in turn causes an imbalance between ice growth and ice melt*". This feedback mechanism, leading to an abrupt change in coupling efficiency, is unique to ice-covered seas and may possibly dominate processes in the Arctic Ocean. [469]

Variability in summer ice-cover in the Chukchi Sea, as in the Barents Sea, has been correlated – at least over some periods - with the values of the AO and the NAO, and hence with the frequency of cyclonic depressions over the Arctic Ocean. During the years 1979-2009 there was an increasing frequency and strength of extreme wind events on the north coast of Alaska during late summer and autumn: mean extreme winds evolved from 7.0 to 10.5 m.sec^{-1} during this period. Some very high wind events have been recorded in recent years – the August 2000 cyclone that wrecked the little town of Barrow on the north coast of Alaska included gusts that were reported at about

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[466] *Polyakov, I.V. et al. (2011) Bull. Amer. Met. Soc. 561-566.*
[467] *Nature Reports Climate Change; 18 October 2007 | doi:10.1038/climate.2007.61*
[468] *Levitus, S. et al (2009) Geophy. Res. Lett. 36, Li9604*
[469] *Shimada, K. (2006) Geophy. Res. Lett. 33, L08605, doi:1029/2005GL025624.*

120 km.hr^{-1}.[470] Such conditions will not only hasten melting of ice formed the previous winter but, independently of that process, will also increase the apparent area of open water by rafting and compacting small, isolated ice floes.

Unfortunately, no contemporary discussion of recent arctic conditions can ignore the furore occasioned in September 2012 as the press reacted to the news that the area of open sea in the western Arctic Ocean was larger than has been observed before, having exceeded the previous minimum observed a few years earlier. Perhaps this modern record for open water may have been partly the immediate effect of the passage of an exceedingly deep (970 mb) and rapidly-moving Pacific depression across the Arctic Front into the western Arctic in early August whose heavy winds fractured and dislodged the ice-pack: but the late director of the Scott Polar Research Institute described the situation thus: "*By 2015, at this rate, summer melting will outstrip the accumulation of new ice in winter, and the entire ice cover will collapse. Once summer ice goes away entirely, the physics of latent heat will make it very difficult, if not impossible, to get it back. We will have entered…the Arctic death spiral*". He also rather rashly suggested that the first ice-free arctic summer could occur by 2019 – or about 80 years ahead of the IPCC4's central projection! He described this as a global disaster and called for urgent reconsideration of geo-engineering to reduce global temperatures: reflecting sunlight back into space by whitening clouds, and so on.[471] I judge that simplistic interventions like this, though typical of the genre, are not very helpful in the present situation.

To summarise the arguments presented so far concerning ice-loss in the arctic basin, at least four mechanisms must be recognised: (i) a momentum-induced slowing of winter-ice formation, (ii) upward heat-flux from anomalously warm Atlantic water through the surface low-salinity layer below the ice, (iii) wind patterns that cause the export of anomalous amounts of drift ice through the Fram Straits and disperse pack-ice in the western basin and (iv) the anomalous flux of warm Bering Sea water into the eastern Arctic of the mid-1990s.

These and other observations can be integrated into a model with feedbacks and having two unstable end-points that is consistent both with classical studies of past climate states, and also with recent analysis of ice dynamics in the Arctic basin by Zhakarov, whose oscillatory model identifies feedback mechanisms in atmosphere and ocean, both positive and negative, that interact in such a manner as to prevent long-term trends in either ice-loss or ice-gain on the Arctic Ocean to proceed to an ultimate state.[472]

The key to this model lies in the distribution of precipitation on Earth, with maxima in the tropics and in high latitudes, so that the Arctic receives an excess of precipitation over evaporation of about one third, which is associated with the permanent presence of the low salinity surface water mass of the Arctic Ocean, separated by a halocline from the saltier Atlantic water below. The presence of this low salinity surface water mass would enable ice cover to fully recover in winter, even in the extreme case in which it was totally absent by the end of summer; studies of the Bear

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[470] Segall, S.T. and J. Zhang (2012) J. Climat. 25, 8075-8089 and Lynch, A.H. et al (2003) Mon. Weath. Rev. 131, 719-732.

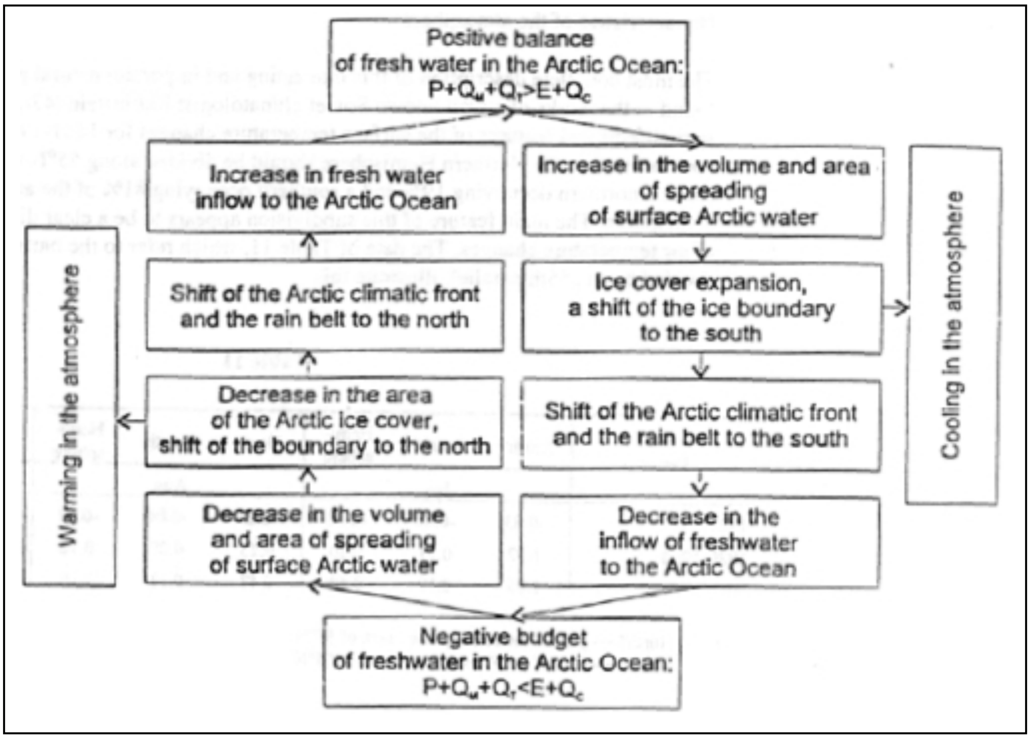
[471] The Guardian, 17 September 2012

[472] Zakharov, V.F. (2013) U. Colorado NSIDC Spec. Rep. 16, 1-71

Island region, where complete ice melt occurs in summer, confirm this suggestion. Only the draft of the sea ice would be lower in such periods than during cold epochs when summer melt rate is low.

Clearly the dynamics of the Arctic Ocean and the northwest Atlantic are integrated, and are critical to the orderly progression of climate changes that have been observed at 60-80 year intervals in many regions - the apparent effects of a Gleisberg cycle, often attributed to solar dynamics – having been discussed on pp. N-N. The model also provides a key to understanding the causes of the natural oscillation of the Arctic climate between two states of relative ice cover, depending on the balance of the relative volume of freshwater in the Arctic basin. Zhakarov's model is conceptually simple: during periods of high precipitation when winter ice forms readily, summer ice cover increases, the atmosphere cools, the arctic front together with its associated rain belt shifts south so that freshwater input to the Arctic Ocean decreases, and winter ice cover is thicker, has a deeper draft, and so survives better in summer.

This, in turn, shifts the Arctic front poleward again, warms the atmosphere and so completes the cycle by reinforcing the influence of the halocline of the Arctic Ocean.



All this has been available to arctic science since the 1990s, but has been widely neglected perhaps because it suggests that when we are predicting change in arctic conditions we should look to the ocean for the major forcing, rather than to local atmospheric temperature. It emphasises that there is a strong internal relationship between the formation, stability and extent of sea-ice and the structure of the upper layer of the Arctic ocean: it is the relative area and depth of low-salinity arctic water above the halocline that are paramount to ice formation and its summer survival.

A similar oscillatory mechanism for the control of arctic summer ice cover – based on the changing freshwater balance of the upper layer of the Arctic Ocean - has been invoked as initiating the low-frequency climate signal that *"propagates through a network of synchronised climate indices"* with the same 60-80 year frequency that was discussed in the last chapter.[473] The Arctic Oscillation, which codes the relative penetration of Arctic air down to mid-latitudes, is included for this purpose in the bundle of indices of climate state: a high value of the AO is associated with less active penetration southwards. This signal propagates through four stages of progressively-evolving global climate states that are expressed regionally, each in a characteristic pattern, and recorded in proxies. It is also expressed in records of secular change in Earth's rotation rate, in Carioca Basin cores, Palmyra Island corals, records of population strength of Japanese sardines and Oyashio intrusions, temperature proxies for large-scale winds, and the Atlantic SST dipole.

The sequence during the 20th century was of a warming regime initiated around 1918 by a transition of the AMO from cooling to warming. In the early 1920s this was followed by the same switch in the AT and then, in about 1930 by the PDO and finally, at the end of the 1930s, a switch to a cooling regime in the ArctT introduced a new northern hemisphere which was terminated in about 1975 by a return to a warming regime that was once again initiated by the AMO. This sequence implies that the circulation of the North Atlantic and its unique direct connection between subtropical and polar regions through the Barents Sea is a critical region that controls global climate states at scales that interest us today, supporting the argument made in the last chapter. The consequences of the changes implied are significant and far-reaching geographically and also intellectually: we can no longer treat change in the arctic regions as a simple response to changing atmospheric temperature in accordance with the standard model of anthropogenic climate change.

Whether Arctic ice coverage, like the other phenomena that appear to demonstrate a 60-80 year Gleisberg cycle, responds as a resonance to solar dynamics has not, I think, been directly addressed; the most probable candidate for a mechanism for this response would seem to be the simple AMO oscillation of heat content, north and south, in the Atlantic. I note that this is both the initiator of the repetitive cycle of arctic phenomena and is also associated with weather phenomena over rather wide regions of the adjacent continents.

It is very strange that that the strong variability of conditions in the North Atlantic-Arctic Ocean region at shorter than secular scale appears to be of no interest to at least some scientists now working in that region on climate change problems. A recent report on climate research on Svalbard and in Norway described interviews with some working at Longyearbyen who talk of the recent period of sea-ice loss and glacier retreat as if it were a unique and novel event – no mention is made of the conditions that so impressed Captain Ingebrigsteen almost a century previously (p. NN).[474] Such a myopic view of environmental change is today unfortunately only too common.

8.4 - Is the loss of the Greenland ice cap imminent?

Dominating the geography of the Arctic, Greenland has become one of the paradigms of climate change. The theoretical loss of the Greenland ice cap is described in apocalyptic terms: an "*irreversible meltdown*" was invoked by a *Nature* journalist in 2012 in an article entitled "*Climate change: losing Greenland*". The title of this essay was

473 Wyatt, M.C. and J.A. Curry (2013) Climate Dyn., 42, 2763–2782.
474 Le Monde, Les Vigies du climat, 22.7.15.

drafted as a statement, not a question, even if the text was less alarming than the title, but this is typical of science journalism today.

Because some science journalists have played on public fears of rapidly rising sea-level, and of Manhattan drowning, it should be emphasised that, in the context of the Greenland icecap, 'fast' is a very relative term: the authors of a recent study commented that "*Averaged over the past several years, Greenland is losing about 100 cubic kilometres of ice annually out of a total volume of 2.85 million cubic kilometres and this contributes about 0.25-0.5 mm annually to sea level rise globally*". If this is correct, we risk *"losing Greenland*" (to use *Nature*'s expression) no sooner than in about 15,000 years.

The ice-streams of the Greenland ice cap conform to the general behaviour of glaciers: snow is deposited at high levels and is progressively buried and compacted into ice that then flows by deformation downhill to the glacier termination – in the case of Greenland, at the coastline, which is strongly dissected by ice-cut fjords. The existence of melt-holes (*moulins*) on the surface of the ice-cap, into which summer melt-water pours in impressive volume, suggests fragility of the mass of ice and models have been used to propose that sudden increases in this flow caused by the draining of a surface lake may create pools below the ice and enhance downhill movement; however, the steady flow is well accommodated and has little lubricating effect.[475]

A temperature reconstruction for surface air above Greenland over the last millennium derived from argon and nitrogen bubbles in ice cores taken at the GISP site in central Greenland shows a long decline in temperatures since the mediaeval period and relatively rapid recovery since the early 19th century, a trend which differs from what is seen in the data for the dates of the freezing period for northern hemisphere lakes and rivers. The entire record – in which 20th century temperature are rather similar to those of the Mediaeval Warm Period - is marked by multi-decadal oscillations over 2-3^{o}C so that, consequently, the observed recent changes are not unusual either in scale or duration: the ice-core record of temperature thus confirms historical evidence. [476] Nor does this reconstruction, in the last half-century, in any way match the pattern of the global surface temperature changes indicated by the global surface temperature data used by the IPCC - although it is likely that the record of the period immediately prior to the termination in 2000 may be unreliable. It seems not improbable that a peak similar to the mid-century warm period may be concealed in the noise., and that seems to be the conclusion of at least one study of historical melt rates at Greenland because at longer time-scales such data show that a very large range of temperatures were experienced in the geologically-recent past, and which should be kept in mind when discussing Greenland's future because, in the past, Greenland has conformed to the general pattern of glacier evolution elsewhere

The history of the relict volume of ice on Greenland has also been explored recently by reference to changes in the depositional surface elevation at GRIP and at Camp Century on the central and northern parts of the ice sheet respectively. This result is based on analysis of the air content of ice progressively down very long ice cores from which a proxy can be obtained for the actual elevation of the surface when the ice was formed. These data demonstrate a long decline in altitude, and hence ice depth, during the last 1000 years with the northern region showing different rates of loss of ice before and after about 5000 BP; prior to this date, air temperatures are calculated to have been

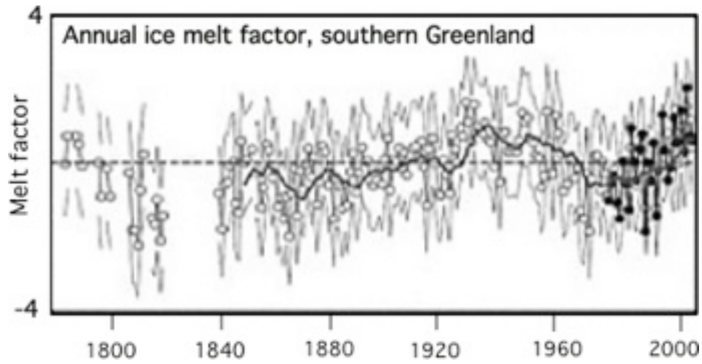
[475] *Schoof, C. Nature. (2010) 468: 803-806.*
[476] *Kobashi, T. et al. (2010) Clim. Change 100, 733-756*

1.5^{0}C warmer than the present day. Progressive loss of ice after the Mediaeval Warm Period is quite clear in these data, which also show that - at least up to 1995 - the present air temperature in this region is no warmer than it was a millennium ago.[477]

Most recently-published studies on the evolution of the ice cap are done in response to the perceived consequences for society of global warming, and I find myself more sympathetic to studies, like those of Chylek *et al.*[478], which approach Greenland as a phenomenon to be understood rather than as a problem to be solved. These authors observe that temperatures at the Greenland coast follow those of the Arctic Ocean, and hence the pattern of the changes of sign of the AO/NAO, with which they are highly anti-correlated. The rapid warming of the 1920s is recorded in all coastal Greenland temperature data, as is the more recent warming in the final decades of the 20th century. It is also pointed out that ice-core data from five locations on the ice cap show strong periodicity of conditions during the past 500 years that is consistent with the signature of the Atlantic Meridional Oscillation – which, as noted above, is associated with the NAO/AO periodicity, itself exhibited in a wide variety of marine and terrestrial observations. These authors also point out that the 5-year melt-day-average on the western part of the ice cap was greater in the period 1920-1940 (when it already attracted significant attention) than it has been in recent years.

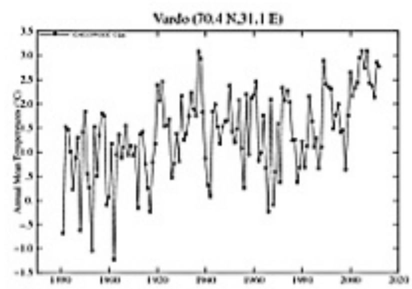
Although there is good evidence, discussed above, for stability of sea-level air temperatures in the Arctic in recent decades and for the rejection of the concept of 'polar amplification' of global warming, Chylek *et al*. do find an anthropogenic signature in the ice-core data for recent decades. I suggest that this is yet one more paradox that will be satisfactorily resolved in the future if everybody keeps an open mind on the subject.

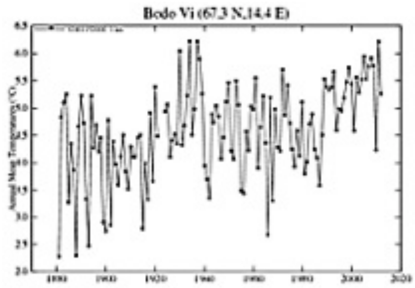
At shorter time-scales, a "*pretty decent*" relationship has been established between annual ice-melt and a combination of summer SAT in southern Greenland with winter atmospheric circulation, indexed by the NAO. This has permitted a reconstruction of melt-rate back to the beginning of the 19th century which suggests that, while this has been quite rapid in some recent years, some earlier periods in the 20th century must have experienced equally fast ice-loss as observed at present: in the following figure, black dots are observations, white dots are reconstructed values.[479]



This pattern very closely matches that of SAT at rural stations in northern Scandinavia, just as we would expect it to do (see also p. NN):

477 Vinther, B.M. et al. (2009) Nature, 461, 385-388.
478Chylek, P. et al (2006) Geoph. Res. Lett. 13, L11707, (2004) Clim. Change 63, 201-221, (2011) Geophys. Res. Lett. 38, L17304,
479 Frauenfeld, OW (2011) J. Geophys. Res. ***116****, D08104*





But, even more significantly, we now have some direct evidence of the reaction of the ice cap to the warm Nordic Seas episode of the 1920s-30s that was discussed above in relation to conditions in the Arctic Ocean. As would be anticipated, this was also a period of loss of ice mass and glacier retreat on Greenland; a survey was made of the eastern coast of Greenland by Danish authorities in the early 1930s and the many oblique aerial photographs taken have recently been rediscovered in secure storage in a citadel at Copenhagen. These photographic data have been used to locate the terminations of 132 glaciers and demonstrate their retraction during the warming period of the 1930s. To these have been added some similar photographic data obtained by the US Air Force in the 1940s and more recent satellite and observational data to complete the series. These images collectively show that many land-terminating glaciers retreated more rapidly in the warm 1930s than they are doing at present, although sea-terminating glaciers retreated more slowly. After mid-century, a general growth of glaciers was observed along this coast until the 1970s.

In the most recent decades, much has been made of a significant increase in the flow rate of at least some of the glacier tongues along coastal fjords to the sea although it appears that the history of this ice cap and its peripheral glaciers is not very different from the general history of advance and retreat of glaciers worldwide. As was noted in the Preface, after about 1850, there was a general retreat of glaciers which, with some temporary reversals (as in the 1930s-40s) continues to the present time: the overall pattern of global climate change during the last millennium should not be ignored when trying to understand changes, such as those we are concerned with here, at decadal scale today – but, unfortunately, they are often dismissed from the debate.

It is characteristic of the seaward movement of glaciers on Greenland that at least some exhibit very strong variability, changing their flow rate by a factor of two within a 10-year period. Once again, recent increases of flow-rate have been reported with alarm although the most recent study that I have seen suggests that the rate of freshwater flowing from a series of the largest glaciers in recent decades does represent rather a series of bursts than a steady acceleration; in this case, the contribution of Greenland to sea-level rise in this century will be well below previously-modelled upper bounds.[480] Increased flow rate at the terminations has previously been reported for southeast and northwest glaciers and it has now been found that the northeast Greenland ice stream (which covers 16% of the total ice cap and extends 600 km into the interior) has accelerated in recent years after 25 years of relative stasis.[481] All these observations are consistent with the recent changes in the flow of warm North Atlantic water into the Arctic Ocean.

[480] *Nick, F.M. et al. (2013) Nature 497, 235-238.*
[481] *Khan, S.A. etal. (2014) Nature Clim. Change. 4, 292-299.*

But the present glacier retreat is not a uniform phenomenon, as it is usually portrayed. On Bylot Island, across Baffin Bay from the Greenland coast at about 73°N, a party of Canadian geologists in summer 2009 found that almost all of the glaciers were at their terminal moraines, implying a regional lack of glacier retreat.[482] Nevertheless, it is widely believed that Greenland has participated in the global pattern of glacier retreat, and because images of some of the faster-moving glaciers are easy to obtain, they have been used to suggest to the general public that a rapid disintegration of the ice-cap is in progress; a favourite site to obtain such images is the Ilulissat glacier which calves abundant icebergs into Disko Bay and did so throughout the last century – the *Titanic* iceberg is thought to have come from here in 1912. Even more impressive, but more difficult of access, are the fjords in the extreme southeast of Greenland, with melting glacier terminations and many bergy bits in the fjords. Of course, those glaciers that calve bergy bits into the sea are also at their normal terminations, like those on Bylot Island.

Although commonly attributed to global warming (and by inference to increasing SAT), in fact both the recent increase in glacier thinning, retreat and the high rate of iceberg discharge better coincides with periods of relatively strong influence of Atlantic water, with warm summers and with the negative phase of the NAO; a recent study, using sand-grain deposit rates in Sermilik Fjord as a proxy for calving of icebergs, also demonstrates that this rate responds to short-term (3-10 years) fluctuations in large-scale atmospheric and ocean conditions.[483]

A parallel conclusion has been reached for the retreat of the Jacobshaven outlet glacier in Disko Bay facing the Labrador Sea, which is the strongest exporter of ice of the entire Greenland ice-cap during the late 1990s, because this was triggered by the arrival along the west coast of a pulse of warm subsurface water of Atlantic origin which – at such times – spills over the sill into Disko Bay. In this case, the glacier terminates in a floating tongue which is known to exhibit non-linear melting in response to seawater temperatures. Here again is yet another example of the influence of changes in the circulation pattern of the warm North Atlantic Current and its variable transport of heat into the Arctic regions.[484]

But these are phenomena that must exist wherever an ice-cap meets an ocean with summer temperature above freezing and, in themselves, imply nothing about the mass balance between snowfall and ice formation on the higher elevations of the ice-cap and peripheral melting rates. Such a balance has, of course, been struck - but with rather disparate results. I find two quite different approaches to the problem: the first is an explicit response to environmental concern for the effects of global warming on the ice cap and so on consequent global sea level, while for second group of studies this is of secondary importance. The first group discusses only processes in the last few years, using satellite altimetry, interferometry and gravimetric data , while the second group places the problem in a wider context with reference to past climatic oscillations recorded in ice-cores.

Thus, a recent study in the first group uses data from satellite altimetry, interferometry and gravimetry to estimate mass balance of polar ice, north and south; it concludes that Greenland has been losing 142 ± 49 gigatonnes annually during the

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[482] *Annual Review, Bedford Institute of Oceanography, 2009.*
[483] *Andresen, C. et al. (2012) Nat. Geoscience 5, 37-41.*
[484] *Holland, D.M. et al. (2008) Natute Geosci. 1, 1-6.*

satellite period, in this case 1992-2011.[485] This, and other papers in this group make little or no mention of periodicity in the Arctic Ocean environment either at Greenland or more widely: recurrence of similar conditions appears not to be of concern for these authors. These and other calculations available to us in no way suggest that the ice cap is close to reaching a tipping point, or that a catastrophic rise in sea level is in any way imminent. Although the published estimates of total ice volume and its loss rate have varied very widely, a consensus is emerging of a mass of around 2.5-3.0 km^3 and a loss rate of around 200 x 10^6 m^3 – which, as I have already suggested, indicates a date for the last ice on Greenland about 15,000 years from now.

Recent authors are about equally divided between those who compute gain and those who compute loss of mass during recent years, although all who have considered the question seem agreed that the ice-cap is gaining mass centrally and losing it at the coasts. It is, of course, mass rather than area which is important: the satellite images routinely offered by NASA showing changing areas over which the surface of the ice cap may seasonally exceed 0^{o}C are not the same as a volumetric approach, although they show what would be expected considering the present period of Atlantic water intrusion. But it is very easy to forget that we are inundated today with information and images unimaginable only 20-30 years ago. I have little doubt that conditions similar to those revealed by the NASA images have recurred many times in the past: they are most unlikely to be unique and are too easily read as indicating a novel, anthropogenic process.

It is also fascinating to discover that – as happened in summer 2012 – an unusual arrangement of the atmospheric circulation pattern at higher latitudes can bring a heat wave to Europe and a brief 2-3 day overall surface melt over the entire ice-cap; this was caused by a very unusual low altitude mass of cloud having high water content that blanketed the entire ice cap for several days. Although I have not seen it suggested formally, I cannot help observing that surface melt, even at the top of the icecap (which has a mean altitude of over 2000m) may be enhanced by deposition of black carbon particles on the surface of the ice. Photographic images of the sides of the moulins, and of pooled melt water within them suggest that the melt water flowing over the surface of the ice in periods of thaw aggregates such particles into a nasty-looking black brew that gathers at, and within, the sink holes. I have seen no comments on the consequences of this process, but images abound, and the recent observations of darkening of the surface of the ice-cap by a Danish scientific party with carbon-rich dust suggests that this may originate in forest fires across North America.[486]

Current discourse concerning the fate of the Greenland ice cap, and more generally concerning glacier retreat elsewhere in the context of climate change, is characteristically constrained by recourse to data that represent only the very recent past; hidden from view is the store of geological data that have been obtained from study of 'fossil' moraines in mountainous regions - many of which can be dated by radiocarbon analysis of vegetation associated with each moraine, and which therefore record the changing extension of a glacier in its valley over the course of millennia.

A recent study of the glacier length changes (GLC) of seven alpine glaciers in Europe shows conclusively that these responded during the last 1400 years to changes in external forcing that include sulphate aerosols from tropical volcanic eruptions,

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[485] *Shepherd, A et al. (2012) Science, 338, 1183-1189.*
[486] *Science Nordic 7/11/14*

precipitation, temperature, solar radiation and – during the last 50 years or so, to surface darkening from industrial black carbon.[487] Observations of the rapid retreat of terminal positions after 1865 can be explained by response to solar radiation mediated by volcanic stratospheric shading, by regional reconstructed SAT and also by precipitation - although this is not a required factor.

There is good evidence that links the long-term evolution not of only these European glaciers but also those of Greenland with the value of the dominant climate variable for these regions, expressed as the North Atlantic Oscillation (p.) because this codes the strength of the westerlies over Europe and, hence, the temperature and rainfall pattern. Strong coincidence between the NAO (as an anticorrelation with the AMO) and the integrated growth and retreat of 30 European glaciers, expressed as their volume anomaly, occurred during the 20th century.[488]

Remarkable confirmation that glacier length responds to changes in regional climate state comes from the glaciers of Norway and New Zealand - because both dance to the same tune: these glaciers lie in high latitude regions and both are exposed to humid westerly winds across major oceans and both respond similarly to the relative strength of these winds. Glaciers in both regions showed no pronounced retreat in the early decades of the 20th century, while during the middle part of the century they exhibited a spectacular retreat; then, from the early 1980s to the year 2000 the glaciers in each region advanced more rapidly than in any period since the Little Ice Age. These advances were associated in each region with an increase in the westerly winds from the ocean, and with increased precipitation; in Norway, this process matched strong positive values of the North Atlantic Oscillation (as noted above) and in New Zealand with a change in the Interdecadal Pacific Oscillation and increased numbers and strength of El Niño events. Here, glacial advance and retreat is clearly associated not with changes in global surface air temperatures, as is often assumed to be the general case, but with changes in global atmospheric circulation patterns and thus, most probably, in response to changes in solar insolation.[489]

Study of terminal moraines in the Andes of Peru show that these tropical glaciers advanced and retreated during the late Holocene in a pattern that matches that of the alpine glaciers of Europe, demonstrating that the process was forced similarly at global scale, which is not surprising in the light of the coincidence of effects coded by the main set of global climate indices.[490] A study of the terminal moraines and proxy data on 57 glaciers from Peru to southern Argentina showed that during the last century or so, these have experienced progressive ice-loss and retrea.[491]

Despite these observations, models continue to be presented to demonstrate that the loss of glacier mass during the 20th century has been dominated by anthropogenic processes; the latest that I have seen suggests that although *"only 25 ± 35% of the global glacier mass loss during the period from 1851 to 2010 is attributable to anthropogenic causes…. during 1991 to 2010…the anthropogenic fraction of global glacier mass loss during that period has increased to 69 ± 24%*".

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[487] *Luthi, M.P. (2014) The Cryosphere 8, 639-650.*
[488] *Huss, M. et al. (2010) Geophys. Res. Lett. 37, L10501, doi:10.1029/2010GL042616, 2010*
[489] *Chinn, T. (2005) Geografiska Ann. 8, 141-157.*
[490] *Jomelli, V. et al. (2009) Palaeo. Palaeo. Palaeo. 281, 269-282*
[491] *Masiokas, M. H. et al. (2009) Paleo. Paleo. Paleo. 281, 242-268.*

However that may be, once again we are faced with a difficult confrontation between observations and models that introduces unseemly friction into debate.[492] But we can be sure, at least, that the 'eternal snows' of Mount Kilimanjaro – or of any other mountain – are not, and never were, eternal and that their generally relative rapid retreat at the present time is due to many factors, some our fault and some not, other than a simple increase in surface air temperatures caused by greenhouse gases.

8.5 - The bottom of the world

The Antarctic is, in many ways, the antithesis of the Arctic, because the polar region is occupied by a high continent that has almost the same dimensions as the Arctic Ocean. The South Pole lies at 2800m altitude and the highest part of the ice cap reaches almost 5000m, on which snow continues to accumulate even as regional SAT on the plateau cools. The continent is surrounded by an annular ocean that is warming, although the winter coverage of sea-ice paradoxically appears to be increasing in area.

It has been difficult for some people to accept evidence for cooling SATs over parts of continental Antarctica, yet this is one of the consequences of anthropogenic perturbations of the stratosphere. Indeed, the Antarctic climate literature is refreshing, for there is little reluctance to admit that climate change forced by other factors than CO_2 must take its proper place in the literature. Here, there are no local interest groups to insist on the primacy of anthropogenic forcing, while firm evidence is readily available in ice cores and cores of marine sediments for natural regional climate change at both short and long scales. Science has a higher profile here than almost anywhere else.

For this discussion, it will be appropriate to use the subpolar front that circles the continent in mid-ocean as the limit of the Antarctic, although a wider region - south of the 60th parallel and including the Patagonian peninsula - is used in the political definition and also in many polar studies.

The westward flow of the Antarctic Circumpolar Current lies poleward of the subpolar front, and this cold water mass partially isolates the southern continent from intrusions of warm maritime air-masses from lower latitudes. There is, nevertheless, some maritime effect on the climate of the continent, so that those regions where major changes have been recorded during the 20th century are mostly coastal and mostly on the Antarctic peninsula. Here, and on the adjoining western Antarctica (comprising low-lying terrain equatorward of the trans-Antarctic mountain chain) changes in conditions have been most significant while there is negligible maritime influence over the much higher ice plateau of eastern Antarctica that reaches almost 5000m in elevation. Surface air temperatures at the coast and on the peninsula resemble those in the central Arctic Ocean, with winter minima close to those of the Russian ice-camp data, around -18°C. On the central plateau, as at Halley, -18C is close to the summer maximum SAT while, in winter, temperature plunges to around -80°C.

As in the Arctic, long-term climate history of the region has been satisfactorily reconstructed from proxy data which are perhaps more easily interpreted here than elsewhere, since the small polar continent has simple relief and form, and is influenced by continuous eastward movement of weather systems over the Southern Ocean. These

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[492] *Marzeion, B. et al. (2014) Science, doi:10.1126/science.1254702*

proxies rather clearly record the continuous but episodic global cooling from the greenhouse world of 40 MA BP to today's climate; proxies for solar output ($\Delta^{14}C$ residuals) are associated with changes in atmospheric circulation during the Holocene.

These reveal '*both the responsiveness of the ice sheet to changes in orbitally induced insolation patterns and the close association between atmospheric greenhouse gases and temperature*', according to a recent SCAR Review which goes on to say that *"Increased solar irradiance is associated with increased zonal wind strength near the edge of the Antarctic polar vortex, and the winds decrease with decreasing irradiance. The association is particularly strong in the Indian and Pacific oceans and may contribute to understanding the role of natural climate forcing on drought in Australia and other Southern Hemisphere climate events".* For this reason, an 11-year cycle is observed in zonal wind strength and in associated climatic events over the Southern Ocean.

During the 20th century, *"the most prominent and robust"* feature (as it has been called) of climate change in the Southern hemisphere has been associated with an increase in the sea level pressure gradient between mid- and high-latitudes, coded as an increase in the value of the atmospheric Southern Annular Mode (SAM) index. Changes in this index are associated with a meridional shift of the westerlies and hence of the mean latitude of the subpolar front in the Southern Ocean. The recent increase in this index is associated with in an increase in pressure difference across southern latitudes, and so with a strengthening of the westerlies, especially in late summer.

Dispute concerning the reason for this shift is a feature of recent Antarctic studies, and both leading arguments are for anthropogenic effects: was it due to the effects of increasing radiative gases in the atmosphere or to the effect of the Antarctic ozone hole on processes lower in the atmosphere? The destruction of the stratospheric ozone layer came to everybody's attention during the 1970s and reached maximal destruction over Antarctica quite rapidly and (perhaps thanks to the Montreal Protocol) seems to be slowly recovering at about 1% per year.

The stratosphere above Antarctica is several degrees colder than over the Arctic at comparable altitudes and is still cooling due to the springtime destruction of ozone and the production of stratospheric clouds within the polar vortex annually by halogens such CFCs, halons and freon, while above the Arctic the ozone layer remains relatively pristine. The difference between mid-winter stratospheric temperatures over the poles in the two hemisphere is not insignificant: around -80°C in the Arctic and about -92°C in the Antarctic.

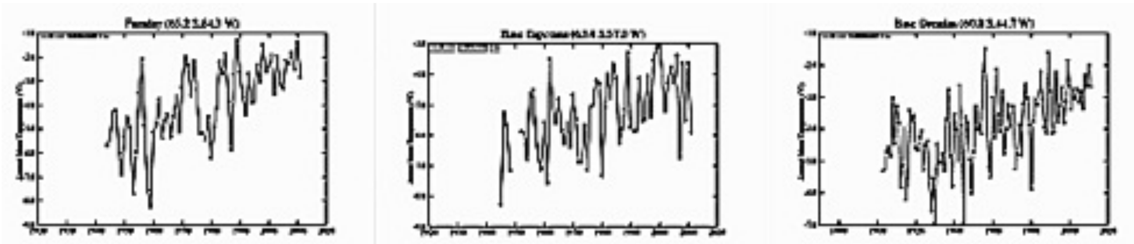
Model-based interpretations of the cause of the end-of-the-century poleward shift of the mid-latitude jet and its associated weather systems, and the cooling of the lower stratospheric polar cap with a time lag of about two months, suggest that the depletion of stratospheric ozone over the pole "*is the likely dominant cause of SH circulation changes in the 20th century, overwhelming by a factor of 2-3 the changes induced by increasing greenhouse gases over the period 1960-2000*". These studies emphasised the differences between the two polar regions so that "*circulation changes in the NH can be directly be related to SST changes, while SH circulation changes are only weakly affected by SST and are controlled, rather, by direct atmospheric radiative forcings*". [493]

[493] *Polvani, L.M. et al. (2011) J. Climate 24, 795-812.*

This conclusion echoes that of Thompson and others[494] who emphasise the geographic extent of the climate control by polar ozone destruction, suggesting that the influence may be traced in summer climate conditions across the southern land masses of New Zealand, Australia and South Africa as well as the near-by Patagonia. It is not surprising, therefore, that the surface air temperature over Australia from selected rural stations record a pattern that is different from similar analyses of northern hemisphere rural regions (p. NN).

Curiously, however, there is one relatively minor point on which these suggestions and simulations disagree with observations because most predict that a consequence of the polar ozone hole will be a decrease in sea-ice extent in the Southern Ocean and one study that I have encountered conclude that the polar ozone depletion could not cause any increase of sea ice area, although without suggesting any direct causation.[495] Unfortunately for these suggestions, observations of sea ice extent around Antarctica reveal small increases in recent decades. This contradiction, as I shall discuss below, appears to be related to the effects of local winds that are perhaps not integrated in large-scale models.

It should be no surprise that the most significant temperature changes now being observed are restricted to the area of the Antarctic Peninsula, whose climate is directly influenced by the ocean. Although the change in mass balance in the continental ice shelves[496] and sea ice[497] is slightly positive – opposite trends were observed by satellite sensing (1979-2002) in the eastern and western ice shelves - the peninsula ice sheets and glaciers are in rapid retreat, along with glaciers in New Zealand and South America. The air temperature at three stations at the tip of the Antarctic peninsula, and one on the South Orkneys is said to have shown a remarkable warming, especially in winter, amounting to 5°C in the last 50 years. But a reality check at GISS suggested that, on an annual basis, the warming is really less impressive: here are the NOAA surface air temperatures for the three principal stations on the peninsula:



This peninsula warming would appear to be a seasonal, Southern Ocean-dominated phenomenon, rather than being associated with the climate of the Antarctic continent where SAT has remained remarkably stable since measurements were first made: indeed, until very recently, it was thought that the principal signal in central Antarctica has been sustained weak cooling. Since the 1970s, the Antarctic Oscillation (or Southern Annular Mode) has been in its positive state in summer, associated with strong pressure gradient between middle and high latitudes and consequently with the contraction southwards of the belt of strong westerly winds around the continent, a process that must warm the peninsula - and cool the eastern Antarctic coast.

[494] *Thompson, D.W.J et al. (2011) Nature Geoscience doi 10.1038/NGEO1026*
[495] *Sigmund, M. and J.C. Fyfe (2010) Geophys. Res. Lett. 37, L18502, doi 10.1029/2010GL044301.*
[496] *Liu, J., J.A. Curry and D.G. Martinson Geophys. Res. Lett. 31, L02205.*
[497] *Jhang, J (2006) J. Climate 20, 2515-2529*

Unfortunately, the evolution of SAT in Antarctica cannot be left without discussing one sour note; in 2009, *Nature* published a paper which suggested that the Antarctic need no longer to be considered an uncomfortable anomaly to general global warming; it was claimed that surface air over the entire continent had been warming for some time, and more strongly over West Antarctica than over the peninsula. Without going into detail, I found that the paper was being heavily criticised informally for improper use of an unusual algorithm for spatial infilling of data, and for lack of care in selection and quality control of data sets.

A formal criticism, offering an improved method of using the same algorithm, was subsequently published - but only after what the authors described as an '*abusive peer review*' that ran to a file of 88 pages! This rebuttal was based on re-computation, using a critically edited sub-set of the original data: it reconfirmed that strong warming is restricted to the peninsula with some slighter warming on the continent, especially in adjacent western Antarctica. In coastal regions of eastern Antarctica, slight cooling is currently experienced.[498] Independently, it has now been re-affirmed that strong warming is restricted to the peninsula and in regions congruent with sea-ice loss and, more generally, that *"trends in near surface winds and geopotential heights over the high-latitude South Pacific are consistent with a role for atmospheric forcing of the sea ice and air temperature anomalies"*.[499]

None of this satisfactorily explains one of the much-remarked differences between climate evolution here compared with the Arctic: why should the seasonal extent of sea-ice remain unchanged or even increase? The three ice-sheets that cover the Antarctic continent each extend out to sea in the form of ice shelves that are many time thicker than seasonal pack-ice, standing 25-50m above sea level; these shelves fracture and lose ice in the form of the giant tabular bergs that infest the Southern Ocean and were noted by the earliest navigators of these seas, so the break-up of ice shelves is not a phenomenon restricted to modern times.

There is a significant difference between the three ice sheets that carry ice from the high continent towards the coast, which have the characteristics of flowing glaciers, and the ice shelves that carry some of their flow out over the ocean; these shelves are floating in the ocean, though attached to the continental ice sheets, so if they become detached and large fragments move out over the ocean, no rise in sea level will result from their eventual melting.

On the other hand, there has been much recent and quite proper concern over the fact that the West Antarctic ice sheet (which is not floating) appears to be unstable, and has a rather uncertain base on the sea floor. It was this ice-sheet that attracted the attention of Revelle, who computed a 70 cm rise in sea level if it were to disintegrate and melt; this concern is reflected in the sensitivity of commentators on the issue of sea level rise and in the frequency of press reports when some ice loss occurs from the this sheet. In fact, we now know that geothermal heat below some of the glaciers that flow onto the shelf causes intermittent changes in their flow rates, so we cannot expect the West Antarctic Ice Sheet to be an entirely stable entity. We hear much less about seasonal sea-ice cover in the Southern Ocean than in the Arctic perhaps because (apart from the fact that here there are neither polar bears nor a potential new passage for shipping) there is a major growth of sea ice cover during the polar winter which almost entirely

[498] *O'Donnell, Lewis, McIntyre and Condon (2010) J. Climate, **24**, 2099–2115.*
[499] *Schneider, D.P., C. Deser & Y. Okumura (2011) Clim. Dyn. DOI 10.1007/s00382-010-0985-x*

melts in summer back to the margins of the ice shelves and seems to be progressively increasing its coverage in recent years.

Winter ice cover does not extend over the entire ocean south of the subpolar front, as you might expect it to do, but its surface is not negligible, being approximately equivalent to the area of the entire southern continent. Paradoxically, as noted above, even as SST south of the front has warmed by almost 1ºC in recent years, the extent of winter ice cover has increased. This paradox has caught the attention of several research groups although they are not unanimous in the explanations they offer. Some suggest that the observations require a thermodynamic mechanism based on surface heating while others offer a simpler explanation based on regional wind-drift of pack ice.

Those in favour of a thermodynamic explanation of the observations use a rather complex model based on the concept that increases in ice volume (and hence in salt rejection) occur in response to increases in SAT and in downwelling longwave radiation so that, through enhanced density stratification, upward heat fluxes are reduced. Thus, it is suggested that '*The ice melting from ocean heat flux decreases faster than ice growth does in the weakly stratified Southern Ocean, leading to an increase in ice production and mass*".[500]

However, this model is contrary to other evidence that it is simple dynamics and thermodynamics that '*initiate and therefore dominate in the production of ice-edge anomalies*'. This conclusion was based on observations of the dominant effect of synoptic variability in meridional wind speed in determining ice-edge retreat and advance in the region of the West Antarctic Peninsula, rather than thermal effects on the freeze-thaw cycle. Between-year comparisons of seasonal ice-extent were consistent with seasonal values of the semi-annual oscillation and the ENSO cycle.[501] This also echoes an earlier suggestion that pointed out the existence of co-variability between ice extent and the ENSO and AMO indices, although it was thought at that time that the potential effect of the changes in wind patterns was probably too weak to explain the observations.[502]

But a much simpler mechanism has been proposed recently, apparently independently in two studies, which requires only wind-drift of floating pack ice to explain the observed changes in sea-ice extent. It is pointed out that the Ross and Weddell Seas carry the largest areas of pack-ice globally and are, coincidentally, the regions where drift and variability of sea ice are maximal. Spatial patterns of ice drift and of southerly winds, blowing permanently from the continent and out over the ice shelves are coincident and persistent year-round. The flow pattern of very cold winds both exports pack ice constantly towards the open ocean but also encourages rapid formation of new sea ice. The author concludes: "*The long-term variations in outflow correlate well with variations of the sea ice cover and meridional sea ice transport in the Ross and western Weddell Seas. Further, the results suggest that the positive trend of sea ice cover in western Ross Sea and the negative trend in the western Weddell Sea are related to a respective seasonal increase and decrease of cold air outflow.*"[503] This suggestion is supported by a more recent study which is based on a 19-year archive of

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[500] *Zhang, J. (2007) J. Climate 20, 2515-2529*
[501] *Stammerjohn, S.A. et al. (2003) J. Geophys Res.108, NO. C10, 3329, doi:10.1029/2002JC001543*
[502] *Liu, J. et al. (2004) Geophys. Res. Lett. 31, L02205.*
[503] *Haumann, A. (2011) Dynamical interaction between atmosphere and sea ice in Antarctica. (U. Utrecht, M.Sc. thesis.*

satellite-observed ice-movement and which confirms that the overall increase in ice coverage is the result of opposite regional trend in the Weddell and Ross Seas.[504]

[504] Holland, P.R and R. Kwok (2012) Nat. Geoscience doi:10.1038/ngeo1627

Chapter 9

INTENSIFICATION OF EXTREME WEATHER EVENTS

"*1690 11 Jan. This night there was a most extraordinary storme of wind…did great damage in many places, blowing down houses…being a kind of hurricane, which mariners observe have begun in late yeares to come Northward."*[505]

Had such a storm occurred today, and created the same havoc, it would probably have been reported in the press as a consequence of global warming, but in the 17th century no reasons were looked for to explain big storms although the one recorded by Evelyn occurred, he wrote, during an exceptionally mild winter. Storms were just one of the natural hazards of life, like the exceptional hail in September 1658 which "*being four to five inches about, brake all the glass about London*", or the exceptional wind storms in 1658, 1662, 1687, 1689 and 1690, one of which required the diarist to "*return home to repair my house, miserably shattered by the late tempest*" that '*did greate harme...killing many people*' in southern England. This storm lasted only three hours in London, so it must have been the passage of a single extratropical low-pressure cell that threw down thousands of trees in southern England.

Similar extreme events, though involving tropical cyclonic storms, were being recorded on the other side of the Atlantic in the same years: the great 1609 hurricane that scattered a convoy of ships carrying settlers to New England was immortalised by William Shakespeare in '*The Tempest*'. In 1667 a hurricane destroyed 80% of the New England tobacco crop and thousands of homes, while in 1780 many thousands of lives were lost to a hurricane in the Caribbean islands. Climate historians have commented on the exceptional weather conditions during the 17th century in Europe when the northeast Atlantic and the Nordic seas were exceptionally cold; such conditions are associated with a strong atmospheric pressure gradient across northeast Europe, so it is not surprising that storms such as those noted by Evelyn have been found in records from 1634 to 1703 – when the Eddystone light off Plymouth was destroyed.[506] I especially relish the fact that the wind observations that were found in the logs of the ships of the Spanish armada of July 1588 have been used to demonstrate the tight cyclonic nature of the storm that saved England: "*He blew with his winds and they were scattered*".

Although the historical record is biased by progressively comprehensive data acquisition, it is clear that neither tropical nor extra-tropical storms that flood coastal lands, destroy property and take people's lives are anything new. But the shifting baseline of observations must be quantified before any conclusions can be drawn

[505] Evelyn's Diary (Chandos Classics, p. 537). That 17th century mariners were not averse to the idea that climate might change is interesting.
[506] Lamb, H.H. op. cit., pp. 191-219

concerning either (i) the progressively changing intensity, frequency, and location of extreme weather events or (ii) the role of anthropogenic effects in inducing the observed changes. It goes without saying that the immediate interest is the role that CO_2 and other radiatively-active gases may have played in warming sea surface temperatures above critical temperatures for the induction of cyclonic storms in the humid tropical troposphere. Although this suggestion is based on sound understanding of the mechanism of cyclonic storm formation, it is worth noting at once that *"global modelling results for doubled CO_2 ... show a lack of consistency in projecting an increase or decrease in the total number of hurricanes"* although all agree on an increase in their intensity.[507] Yet hurricane formation requires not only that SST be above a critical temperature for a vortex to form but also that conditions in the troposphere must be sufficiently humid and unstable as to permit its further development, constraining hurricane formation to the western part of each tropical ocean.

9.1 - The variability of cyclonic storms: reality or artefact of the records?

It is characteristic of studies of the potential consequences of anthropogenic climate warming that a short base-line of useful observations must be used to comment on change over the longer periods that are of interest to society; this is, to some extent, inevitable but the results of using such data may not be very useful – because would seem to require an initial assumption that climate is stable unless disturbed by us. Both AR4 and AR5, in discussing variability of extreme events, laid emphasis on the record of the 20th century and, even more prominently, on the last 20-30 years. While AR4 provides a solid discussion of the problem of understanding changes in the frequency of storms, AR5 prefers to note many individual studies, most of which have short baselines: thunderstorms during the last 50 years over the Rockies, increasing hail frequency in Ontario from 1979-2002, or in Germany from 1974-2003, and China from 1961-2005, an increase in tropical Atlantic cyclonic activity since 1970, and of extratropical cyclones in the Atlantic and in the North Pacific since 1950 – and so on. Reports of 'killer' storms, such as the one which devastated Vanuatu in March, 2015, are routinely ascribed in the press to anthropogenic effects: thus, of this one it was noted that "t*hese ravages have occurred even as the UN reminds us of the urgent action required to counter the consequences of climate change*".[508]

Some of the other cases discussed by AR5 do have secular-scale trends, which is the minimum duration that would appear essential for any sort of understanding of the significance of trend. Base line studies of severe storms and windiness over Europe suggest that periods of decreasing trends outnumber periods of increasing trends, and data for land-falling cyclones in eastern Australia and in the USA are introduced. These show rather noisy but coherent decreasing trends during almost 150 years but, curiously, the AR5 authors chose not to mention the key finding of the quoted studies: "*Land-falls occurred more frequently during La Nina years, primarily because multiple land-falls occurred only during these years*", that "*Land-fall frequency can be predicted to a moderate degree with the pre-season values of the SOI*" and finally that "*Decadal variability in ENSO drives some of the variability in land-fall numbers*". In other words, the characteristics of cyclonic activity in the SW Pacific are thought to be natural and to respond to whatever forces the variability in the strength of the monsoon wind

[507] *Webster, P.J. et al. (2005) Science, 309, 1844-1847*
[508] *Le Monde, 17 March 2015*

circulation. Why AR5 chose not to show even the key images from this study is hard to understand unless it is that there is no support in them for any anthropogenic effect; in fact, the authors themselves noted that the decline to low numbers of landfalls in recent years coincides with a record high level of El Niño dominance which "*seems part of a broader climate shift…(so)…it would be imprudent to conclude that the very low land-falling rates in recent years will continue. Planning should therefore reflect the possibility of a rapid return to much higher land-fall rates*." There seems little doubt that variability in phenomena such a cyclonic storms or regional rainfall at secular scale is primarily a direct response to the pattern of circulation within the troposphere, coded by indices of climate state (principally ENSO, PDO, NAO), even if anthropogenic influences may be postulated to account for long-term trends. Nevertheless, a global index of tropical cyclone activity that was constructed for the five principal ocean basins shows no comprehensive global response to either the quasi-biennial or the ENSO oscillations, although both of these have been shown to be associated statistically with cyclonicity in the North Atlantic, the Northwest Pacific and the South Pacific. A good association with the North Atlantic Oscillation has now been demonstrated, indicating a stronger influence from high latitudes on tropical cyclonicity than had been previously suspected: linear regression of the global index of tropical cyclone activity shows clear correlation with the NAO but not, for instance, with the ENSO index.[509]

Although model predictions of future climate states generally emphasise fewer but more intense tropical cyclones, the probability is high that the strength of cyclonic storms has in fact increased in recent decades, since any increase in sea surface temperature must enhance the probability that one of the large population of small atmospheric depressions that occur everywhere will be strengthened by the vertical entrainment of warm, moist air, leading to the formation of a major cyclone or hurricane. This is consistent with observations that land-falling hurricanes on the American southeast coast were associated with an upward trend in rainfall during the 20th century, a trend projected to continue.[510]

Although we do not have comparable information on conditions during the earlier part of the 20th century for the satellite era, there does exist a historic record of tropical storm frequency and strength. Even if we can judge that a hurricane which crossed the Florida coast and struck Miami in 1926 was at least as strong as Katrina that devastated New Orleans in 2005, the overall record of the occurrence of such storms – even in the well-observed North Atlantic – leaves very much to be desired: nevertheless, these data are all we have and must be used. An interesting example of their use was a response by Holland and Webster to a formal statement released by NOAA after the 2005 hurricane season which had suggested "*unequivocally, with no reference to peer-reviewed literature, that the current high level of activity was entirely due to natural variations*".[511]

This response was based on analysis of HURDAT, the North Atlantic tropical storm database, and the authors discussed the evolution of observing methods, particularly the advent of aerial meteorological reconnaissance flights in 1945 (prior to which they considered the data very unreliable) and the availability of satellite data since 1970. The analysis suggested that a good relationship exists between SST in the

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[509] *Elsner, J.B. and B. Kocher (2000) Geophy. Res. Lett. 25, 129-132*
[510] *see discussion by Trenberth, K. (2005) Science 308, 1753-54*
[511] *Holland, G.J. and P.J. Webster (2007) Phil. Trans. Roy. Soc. A doi:10.1098.2007.2083*

area of cyclogenesis in the eastern tropical Atlantic and numbers of recorded hurricanes in the western Atlantic. Four climatic periods were distinguished in the data, each thought to be associated with characteristic SST regimes in the eastern tropical Atlantic, although evidence for this is not shown; in the first period, from 1855-1900, 7-9 hurricanes were recorded annually, a number that dropped by 30% until 1930, after which a 'stable regime of around 10 per year continued to 1994, after which year there was an increase in variability (6-14 per year). Relatively sharp transitions between the regimes are suggested, and with these is associated a shift in the SST anomalies in the eastern ocean, which explains 60% of the tropical cyclone variance: the increase in occurrences post-1994 is emphasised. It is implicit in this study that the relationship between the systematic increase in cyclone numbers and increasing SST in the eastern tropical Atlantic is the consequence of anthropogenic forcing of higher SAT in the same region {even though this is not such a simple process as it might appear to be and is discussed in some depth in Chapter 9}. Despite this, the authors wrote "*It is concluded that the overall trend in SSTs and tropical cyclone numbers and intensity is substantially influenced by greenhouse warming*".

This would be a very interesting result, were it not for the very high probability that the recorded increase in the frequency of storms of short duration is no more than the result of increasingly competent gathering of observations as the century progressed. Using a previously-tested method, based on an analysis of the distribution of ship observations during the 20th century, the probable numbers of missed small storms was calculated and this suggested that there was a progressive improvement during the entire period, interrupted during the two world wars when observations were obviously constrained. After the introduction of weather satellite observations, all storms are recorded.

The authors of the study commented that "*while it is possible that the recorded increase in short duration tropical cyclones represents a real climate signal... it is more plausible that the increase arises primarily from improvements in the quantity and quality of observations*"; they go on to suggest that we should expect to have "*severe difficulties in constructing reliable century-long records of these phenomena".*[512] Parenthetically, it may be useful to note that exactly the same argument has been made for the frequency of tornadoes in the USA: the reported frequency of small tornadoes has increased progressively since 1950, while the frequency of major incidents remained stable, or even slightly decreased during the same period.[513] There is, therefore, no good evidence that this eminently 'extreme event' has increased in frequency.

The adjusted frequency of tropical cyclones of medium and long duration in the western tropical Atlantic indicated by the revised HURDAT data supports the original statement from NOAA quoted above, and the present situation no longer appears anomalous in the long-term record. This frequency also closely matches an index of accumulated cyclonic energy (ACE) computed by NOAA for the second half of the 20th century, is also compatible with the reported evolution of thermal anomalies in the tropical eastern Atlantic, excluding the Caribbean west of 80°W (below), this being the principal region of cyclogenesis in the Atlantic Ocean.[514]

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[512] Landsea, C.W. et al. (2010) J. Clim. 23, 2508-2519
[513] Foucault, A. (2009) Climatologie et Palaeoclimatologie (Dunod, Paris), p. 74
[514] Trenberth, K. (2005) Science 3081753-1754.

Further north in the same basin, documentary evidence from the local press in the Azores has been used to analyse the occurrence of major and minor storms since 1836 to show that while there have been four periods (1836-70, 1870-1920, 1920-40 and 1940-98) of contrasting storm frequency, nevertheless the frequency of storms at the end of the 20th century was unexceptional and resembled (or was a little weaker than) that of a century earlier; furthermore, no overall trend in the data could be observed but association of tbe NAO index with storm frequency shows a relationship that suggests that this climate mode is partially responsible for the pattern of storminess in the Azores region.[515] This is not surprising, given the results of a review of extratropical cyclones on the eastern seaboard of North America that found that the principal factor in determining frequency of landfalls was the displacement of the storm track zonally, towards or away from the coastal lands.[516]

A global index of tropical cyclone activity (GTCA) has been constructed for the five major principal ocean basins for the period 1965-1998, from which an analysis may be made of the degree to which cyclonic activity is in phase at global scale and to what extent activity in each matches the NAO and ENSO indices over the same period: this suggests that cyclonic activity in the North Atlantic is out of phase with the other four basins, while providing a multi-basin index of tropical cyclone activity for the latter part of the 20th century that is consistent with the pattern discussed above for Atlantic tropical cyclones. Correlation between the indications of cyclonic activity in the GCTA, the ENSO and NAO indices suggests a much greater influence of high latitude processes on tropical cyclonicity than might have been expected even if, as the authors of this study emphasise, the NAO represents a significant climate fluctuation associated with the position and orientation of the mid-latitude jet-stream.[517]

Challenges to studies such as these, and to analyses of the centennial evolution numbers of cyclonic storms (whether by simple counts or by reference to seasonally accumulated cyclonic energy) very often fail to convince, because of their short baseline. Similarly, assertions that the origin of any trend observed in cyclogenesis must be anthropogenic (by reference to outputs from bundles of models) are unsatisfactory because no mechanism is prescribed for the passage of anthropogenic heat into the ocean. Such is the case for the output of 22 climate models whose has been used to determine the cause of observed changes in cyclonic activity, using probabilistic estimates of individual contributions to observed SST changes, and hence of relative cyclonicity. Based on the finding that there is "*an 84% chance that external forcing explains at least 67% of the observed SST increases*", this study concluded "*human-caused changes in greenhouse gas concentrations are the main driver of 20th century SST increases in both tropical cyclogenesis regions*".[518] The assumed relationship between SST and greenhouse gas concentration is far from proven, and the mechanism lacks formal description.

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[515] Andrade, C. et al. (2008) The Holocene 18.5, 745-754.
[516] Hayden, B.P. (1981) Monthly Weath. Rev. 109, 159-166.
[517] Elsner, J.B. and B. Kocher (2000) Geophys. Res. Lett. 27, 129-132.
[518] Santer, B.D. et al. (2006) PNAS 103, 13905-13910.

9.2 - Droughts, floods and the 'expansion of the tropics'

It is generally assumed that the effect of global warming must be not only to increase surface dryness (due to increased evaporation) but also to increases in rainfall and snow (due to increased water vapour in the atmosphere) with the consequence that droughts and desertification in some regions and, elsewhere, heavy rains and flooding would become characteristic of the new global climate regime.[519]

Consequently, prediction of increasing frequency and consequence of droughts and floods in the future figures prominently in the public media and in speeches by 'decision makers', as in President Obama's remarks in the UC Riverside commencement address in 2014: *"...weather-related disasters like droughts, fires, storms and floods are going to get harsher and costlier..."*.[520]

Such new and difficult conditions are usually thought to be a direct result of increased temperatures in the lower troposphere, but it may be useful to recall that, in fact, such events are likely to result from a rather complex set of factors; the disastrous 'dust-bowl' droughts of the southwestern USA in the 1930s being a useful example of this complexity. Rainfall in this region is heavily dependent on sea surface temperature in the eastern sub-tropical and tropical Pacific Ocean which is, itself, forced by the relative strength of the easterly Trade winds; when these are in their normal condition, in which condition upwelling of cold water from below is induced by a variety of processes along the western coastline of the continent: here, longshore, equatorward winds induce divergence and vertical motion at the coast, while curl of the wind-stress induces weaker upwelling offshore. Along the equator and out to mid-Pacific longitudes, cool water is upwelled to the surface by divergence that is partly Coriolis-driven. Under these conditions, rainfall in California and Oregon is relatively small and water conservation is a permanent preoccupation.

When the Trades fail, as they do intermittently, these processes cease and the entire surface of eastern Pacific Ocean warms, creating what have come to be called El Nino conditions, when low pressure over the North Pacific permits the moist westerlies to flow directly inland across California and Mexico, bringing good rainfall to those regions, instead of being diverted northwards by a blocking high pressure over the North Pacific - thus leaving California, the prairies and northern Mexico dry.

However, it has been found that if the conditions of the ocean and atmosphere known to have existed in the 1930s (after an unusually long period without a major Niño episode) are used to force models of precipitation over the continent, the observed drought conditions are not reproduced because weaker-than-observed rainfall anomalies occur too far to the south. However, when reasonable assumptions (and some observations) of dust levels in the lower atmosphere in the regions of strongest winds are integrated into the models, the observed drought conditions are reproduced: so, it was "*unprecedented atmospheric loading over the continental US*" that "*exacerbated the Dust Bowl drought*" on the prairies from Arkansas to Texas.[521] If these conclusions are robust, then the plight of the farmers on the prairies resulted from a combination of

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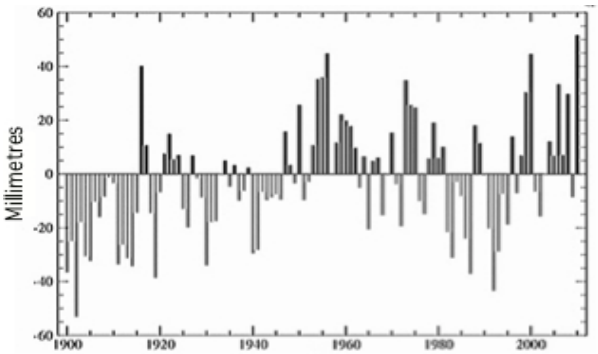
[519] *Trenberth, K.E. (2011) Clim. Res. 47, 123-138 is a much-quoted contribution to the debate.*
[520] *Sacramento Bee, 15 June 2014.*
[521] *Cook, B.J. et al. (2008) Geophys. Res. Lett. 35, doi:10.1029/2008GL033486, 2008.*

their own ploughing of virgin grasslands together with the consequences of sea surface temperature conditions across the Pacific Ocean.

The oceanic processes that are involved in the control of rainfall in the southern USA also have consequences that extend eastwards to northern Africa. The evolution of drought in the Sahel region of Africa during the 20th century is controlled by the variable strength of the West African monsoon as this responds to oceanic forcing that occurs simultaneously in the ENSO region and also in the tropical Atlantic.[522] The long-term rainfall data that are obtained at meteorological stations together with the surface temperature data are essential in putting such relationships in perspective. These data suggest that the overall rainfall pattern since the start of the 20th century rather closely resembles the most probable pattern of global temperature change that is indicated by the SAT data: mid-century and end-of-century peak values are imposed on a generally increasing trend of global rainfall that probably extends back into the mid-19th century.[523]



There are good reasons to expect that such a match would occur between the pattern in the evolution of SAT and rainfall, because the intensity and location of rainfall is, like the SAT data, sensitive to urbanisation and land-use change. Both the increase in vertical motion in the lower troposphere induced by urban heat, and also the increased numbers of particles or cloud condensation nuclei in the urbanised atmosphere will enhance regional cloud cover and rainfall; rain-gauge data, like the SAT data, are obtained preferentially in urbanised regions everywhere except in the USA. With the general increase in SAT – whether natural or human-induced – is associated a generalised increase in specific humidity, especially over the oceans, thus facilitating the formation of storms, clouds and precipitation and lengthening the duration of rainy periods.[524]

Globally, rainfall is maximal in two zonal bands, where rising air masses carry water vapour up into the troposphere, causing cloud formation, and is minimal where descending air completes the three cells within the global zonal wind circulation. The strongest rainfall maximum occurs below the ascending air of the equatorial Hadley cells of the global atmospheric circulation, while minima occur generally in the polar zones and also in the descending air between the Hadley and Ferrell cells, and thus below the subtropical jet-stream; the zones of characteristically high precipitation rates

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[522] Giannini, A.R. et al. (2003) Science 302, 1027-1030; Longhurst, A.R. (1993) Deep-Sea Res. 40, 2145-2165.
[523] NOAA image
[524] Trenberth, K.E. (2011) Clim. Res. 47, 123-118 is a useful reference for this topic

do not run east-west at fixed latitudes but are forced to conform to the asymmetry of the continental masses and their mountain chains.[525]

On a symmetric Earth, lacking mountain chains, the location of each climate zone would respond rapidly to any changes in overall global temperature through control of the global rates of evaporation and precipitation; nevertheless, even when the locations of the subtropical and polar jets are constrained by high terrain, some response of their location is anticipated – and will be accompanied by changing characteristic precipitation, resulting in unusual droughts and floods. For this reason, attention has been drawn to the anticipated poleward displacement of the subtropical jet and, in consequence, of what has come to be called 'tropical widening'.

Observations and models suggest that this has, indeed, occurred in recent decades. A shift of the mid-latitude storm tracks has brought drier conditions, characteristic of the subtropical regions between the Ferrel and Hadley circulations, to areas previously characterised by reliable rainfall. The mechanism is complex, and may involves several mechanisms, each of which can potentially create the effect alone; unfortunately, the numerous studies of the effect have two common attributes – all are restricted to the period since around 1980, when relevant satellite information became available, and all tend to discuss a single mechanism and impute a single causation. Thus, based on the behaviour of the height of the tropopause, which is normally higher in the tropical (>15 km) than in the subtropical (<13 km) zone, it has been suggested that an expansion of the tropical zone by 5-8^{o} latitude between 1998 and 2005 is indicated by radiosonde measurements, and that this "*reveals that the widening trend can be attributed entirely to direct radiative forcing, in particular those related to greenhouse gases and stratospheric ozone depletion*".[526]

However, as always, it is not as simple as any single study might suggest, nor is there any reason to suppose that similar widening has not occurred naturally in the past – especially if the evidence presented represents only the last few decades. There is a clear relationship between the width of the Hadley cell and the relative strength of the monsoon winds, quantified as the El Nino-Southern Oscillation index. During El Niño conditions, with the failure of the Trades, contraction of the Hadley cell occurs as equatorward movement of the maximal residual vertical velocity in the upper troposphere. Modelling studies suggest that the meridional extent of thermal forcing controls this movement – narrow forcing along the equator induces contraction, while wider forcing induces expansion.[527] This tension between different approaches to a very complex natural phenomenon is not unusual in climate studies and this problem has very recently (and usefully) been reviewed in this case by a wide-ranging Australian study.[528]

This study once again reminds us of two generalisations concerning the climate change literature: (i) baselines for observations that are often too short to capture natural cycles and (ii) assumptions concerning causes that are often too restrictive. It points out that the use of the height of the tropopause is not the only method that has been used to quantify change in the location of the edges of the Hadley cells: there are

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[525] *NOAA image*

[526] *Seidel, D.J. and W.J. Randel (2007) J. Geophys. Res. 112, doi:10.1029/2007DJ008861*

[527] *Tandon, N.F. et al. (2013) J. Clim. 26, 4304-4310.*

[528] *Lucas, C., B. Timball and H. Nguyen (2013) Clim. Change 2013 doi: 10.1002/wcc.251*

also (i) stream function methods based on vertical integration of meridional winds, (ii) methods based on observation of changing jet stream position, (iii) surface-based methods based on observations of shifts of the subtropical precipitation minimum, and (iv) by observation of changing intensity of the Hadley cells and the zonal circulations. changing intensity of the Hadley cells and the zonal circulations.

The same review also points out that several different mechanisms have been suggested for the forcing of tropical widening, starting with apparently natural variability associated with the phase of the ENSO index and hence the strength of the trade winds: when these falter, during El Nino episodes, the Hadley cell narrows and strengthens and the opposite occurs during conditions of normal trades. Other mechanisms that have been invoked include stratospheric ozone depletion and the complex effects of black aerosols effect on humidity and cloud formation, and of natural, reflective aerosols in the opposite sense. It is very difficult to synthesise the effects of these factors and the modelled and range of estimates of tropical widening since 1980 are very wide and range from stasis to almost 2^{o} per decade.

9.3 - Concerning storminess to come

The two recent assessments of the IPCC suggest that there has been some evolution of opinion in that body over the last ten years or so concerning this issue. The AR4 explored the relevant literature in some depth, concluding that cyclonic storms had increased in intensity and frequency since mid-20th century, as had other extreme events including droughts, floods and anomalously warm nights. It was suggested that "*Single extreme events cannot be simply and directly attributed to anthropogenic climate change, as there is always a finite chance the event in question might have occurred naturally*." The text goes on to suggest, however, that if the conditions persist they may be classified as an extreme climate event and that "*It may be possible to say that the occurrence of recent events is consistent with physically-based expectations arising from climate change*".[529] The Summary for Policymakers that was derived from AR4 studies suggested that "*discernable human influence*" could be detected in changes in wind patterns, affecting storm tracks, in changes in the frequency of extremely hot nights, of cold nights and of cold days, and had increased the probability of heat waves, droughts and flood. *"Impacts"* it was suggested *"are very likely to increase due to increased frequencies and intensities of some extreme weather events. Recent events have demonstrated the vulnerability of some sectors and regions, including in developed countries, to heat waves and tropical cyclones, flood and drought, providing stronger reasons for concern as compared to the findings of the TAR."*

But the consensus of the IPCC appears to be have changed and the AR5 of 2014 has expressed rather fundamentally different opinions concerning – for example - extreme wind events: "*Recent re-assessments of tropical cyclone data do not support the AR4 conclusions of an increase in the most intense tropical cyclones or an upward trend in the potential destructiveness of all storms since the 1970s. There is low confidence that any reported long-term changes are robust, after accounting for past changes in observing capabilities. However over the satellite era, increases in the intensity of the strongest*

[529] *IPCC AR4 (2007) Chap. 3, p. 310.*

storms in the Atlantic appear robust."[530] Once again, one has to note here the use of inappropriately short baseline in this comment.

AR5 also seems to have been significantly less certain concerning the effect of human activities on humidity patterns and is relatively restrained in its predictions: *"While the AR4 concluded that it is more likely than not that anthropogenic influence has contributed to an increase in the droughts observed in the second half of the 20th century, an updated assessment of the observational evidence indicates that the AR4 conclusions regarding global increasing trends in hydrological droughts since the 1970s are no longer supported. Owing to the low confidence in observed large-scale trends in dryness combined with difficulties in distinguishing decadal-scale variability in drought from long-term climate change we now conclude there is low confidence in the attribution of changes in drought over global land since the mid-20th century to human influence".*[531]

"There have been statistically significant trends in the number of heavy precipitation events in some regions. It is likely that the number of heavy precipitation events has increased in more regions than it has decreased since 1950. There is low confidence in observed large-scale trends in drought, due to lack of direct observations, dependencies of inferred trends on the index choice, and geographical inconsistencies in the trends"[532]

The measurement of change in extreme events and their attribution is quite clearly not a problem that has any easy answer. And it is necessary to suggest, once again, that those who seek that answer are not looking in the right place: it is not to be found by examining only present conditions and the very recent past. To list a series of major droughts and floods that have occurred since the previous Assessment Report, as did AR4, is not useful: what is needed is a careful examination of climate history over periods as long as possible to locate proxies for the present time, so it is strange that no references are made to the classical literature which appears no longer to be of significant interest to climate scientists.

So it is very hard to understand why so little reference is made to what we do know about the occurrence of extreme events in the past, either by the IPCC or those climatologists who are active in analysis of this aspect of the 20th century climate. The first director of the Climate Research Unit at the University of East Anglia recorded the numbers of severe coastal flooding events per century around the North Sea over the last two millennia.[533] This makes it clear that that policy-makers ought be told that extreme events on the European coasts are not novel, and not necessarily associated with anthropogenic warming: a much higher frequency was recorded during some periods in the distant past than during the 20th century….

It is clearly unreasonable to suggest that a change in frequency of extreme weather events observed within a few recent decades – if, indeed, their frequency has increased - can be confidently attributed to a single anthropogenic cause. But that is commonly done today.

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[530] IPCC AR5 Chapter 2
[531] IPCC AR5 (2013) Tech. Summ. p. 32.
[532] IPCC AR5 (2013) Summ. Policy Makers p. 26
[533] from H.H. Lamb (1995) Climate history & the modern world (2nd ed.)

Chapter 10

THE OCEAN: SEA LEVEL RISE AND pH

"*Do not build your houses closer to the sea than this place*"[534]

This chapter addresses two potential effects of anthropogenic warming of the lower atmosphere, each of which has been widely discussed in the press in terms that can only be described as alarmist. The consequences of rising sea levels – and the mechanisms that cause a rise to occur in some regions – are well-known and predictable, but the consequences of changing acidity of seawater by solution of atmospheric CO_2 are far more subtle, and much less-well understood or predictable.

A good sense of the complexity of these problems, and of the uncertainties involved, is given by these texts, extracted from AR5 of the IPCC. In the original, each value is quoted with wide uncertainty limits.

"Proxy and instrumental sea level data indicate a transition in the late 19th century to the early 20th century from relatively low mean rates of rise over the previous two millennia to higher rates of rise…It is likely that the rate of global mean sea level rise has continued to increase since the early 20th century, with estimates that range from 0.000 mm yr–2 to 0.013 mm yr^{-2}. It is very likely that the global mean rate was 1.7 mm yr^{-1} between 1901 and 2010 for a total sea level rise of 0.19 m. Between 1993 and 2010, the rate was very likely higher at 3.2 mm yr–1; similarly high rates likely occurred between 1920 and 1950".

"The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification….The pH of ocean surface water has decreased by 0.1 since the beginning of the industrial era (high confidence), corresponding to a 26% increase in hydrogen ion concentration…The consequences of changes in pH…and the saturation state of $CaCO_3$ minerals for marine organisms and ecosystems are just beginning to be understood."

Such are the issues discussed in this chapter.

10.1 - Rising sea levels

The UN has already been seized with the problem of re-locating populations whose homes are predicted to become uninhabitable in the not-so-distant future., and much has been made of the predicted consequences for places like Manhattan, whose streets are built very close to the high-water level of extreme tides.

[534] *On a hillside not far from Fukushima, this advice is engraved upon a stone.*

These are real concerns in the context of modelled projections of warmer air temperatures, and of a warmer ocean, caused by the radiative effects of increasing concentrations of CO_2 in the atmosphere. But even without these effects, real concerns for changing sea level would still be in order, although not with the same urgency as now. This chapter examines the proposition that although sea coasts are, and always have been, a critical habitat for the development of human activities, they are unstable and not suitable for large permanent settlements and industrial activity.

Most of the changes discussed in this section have a common characteristic – they operate at very long time scales, but they and their consequences are studied today on time-scales of human lifetimes, and so we perhaps misunderstand their significance. We are very concerned by small and difficult-to-measure changes in global sea level or in the pH of surface seawater, but what is predicted for each of these is relatively trivial compared with changes that have occurred naturally in the past at rates greatly exceeding what are measured today.

We have never fully understood the consequences of building our cities beside an inconstant ocean and many people have already paid a heavy price for their temerity: even as late as the 20th century, new city growth was initiated it totally unsuitable places. Consider the situation of Lagos, the capital city of Nigeria, built on what were mangrove areas at the entrance to a coastal lagoon system, bounded by a long sandy ocean beach with strong coastwise sand transport. The population was less than one million when I worked there in the 1960s, but is now over 21 million and those people who cannot find building plots on dry land have instead constructed extensive suburbs of houses and planked streets, all supported on piles and stilts out across the main lagoon. Lagos today may be more vulnerable to the whims of the ocean than any other city.

When the climate warms and glaciers melt, the mean sea level must rise and cover previously dry land, and this process is reversed in periods of cooling climate. During the 20,000 years of the Holocene, since the end of the last glaciation, sea level has risen a total of about 120m initially at a rate many times faster than observed anywhere today - and it is against this background that we now to try measure the sea level consequences of anthropogenic CO_2 in the atmosphere.

Since it is probable that the end-of-the-Holocene effect has not completely worked itself out of the system, this is a difficult exercise and, in this context, it is salutary to remember that during the recovery from the last glaciation, when the rate averaged about 10 mm a year, there were major (but poorly-dated} pulses of melt-water that increased the rate of rise very dramatically, because each was equivalent to the melting of a couple of Greenland ice sheets in a matter of several centuries.[535]

Many studies have estimated the present rate - and changes in that rate - from a variety of sources, both globally and regionally: these are based on data from tide gauges, mass balance computation, satellite altimetry and so on. Computations are being presented which integrate up to nine budget items with unrealistically narrow error terms: a computation of a total rise in sea level between 1993-2008 of 2.54 ± 0.46 mm/yr is accounted for by a budget that requires 15 items, each with a different value for two different periods. Tiny residuals of 0.05 ±0.40 and 0.08 ±0.72 mm/yr are

[535] *Alley, R.B. et al. (2005) Science 310, 456-460*

claimed for the two periods that increase spectacularly if surface air temperature is included.[536]

As you might expect from such complex and multi-variate computations, results of different studies are rather diverse. One study of global tide gauge data using neural network analysis concluded that the rate was about 1.6 mm y^{-1} and that there had been no significant acceleration from 1900 to 2006 but that long periodicity at about 25 and at 50-75 years could be identified[537]. This pattern is familiar in the climate history of the 20th century and has figured in several earlier chapters and demonstrates once again the futility of studies of the form "*Is it today rising faster/more slowly than prior to (say) 1993*?" - as was asked by a recent Nature author, who concluded that after this date the ocean expanded (at about 3mm/year) faster than the mean trend from 1901-1990.[538] This study contradicted another Nature author who had, 12 months previously, suggested a similar rate since the early 1990s but found that the rate had apparently slowed by 30% after the turn of the century, as had the surface air temperature, although this change disappears when corrected for natural variability caused by the Southern Oscillation effect; in this case, it is supposed that ENSO effects modify the atmospheric water cycle sufficiently to withdraw - or return - significant volumes of water from the ocean through changes in the strength of monsoon rainfall.[539],

When thinking about all this, I suggest that it would be salutary to remember that only a few years ago, Walter Munk wrote on the 'enigma' of the twentieth century sea level because, in his view, there were several problems to be solved before even the sign of global sea level change could be agreed upon.[540]

Of course, changes in sign of change in sea level do occur and these are the consequences of changes in atmospheric and oceanic circulation patterns and of changing rainfall and run-off patterns associated with the Southern Oscillation Index and the strength of the trade winds. This is yet one more case where linear projections of rates observed today into the future are meaningless: what one can predict with great confidence is that the cyclical nature of change in sea level is not going to disappear into a linear future. And, once again, it should not be forgotten that the start of the 20th century was not very long after the cold anomaly of the 1860s and 1870s, so that any centennial linear trends are likely to mislead concerning conditions to come.

Historically, of course, the search for a global mean sea level (GMSL) has preoccupied hydrographers of maritime nations since the 17th century and perhaps earlier; long data sets exist, but are regionally clustered. Such measurements were originally based on assumptions that the Earth is a perfect sphere and that the mean level of the surface of the ocean, conforming to it, could be found very simply by observing the local lunar tides. This level was then used as the reference height on the local tide gauge.

Unfortunately for this very sensible enterprise:

- Earth is not a perfect sphere,
- gravity is not equal everywhere,

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[536] *Church, J.A. et al. (2011) Geophys. Res. Lett. 38, L18601.*
[537] *Wenzel, M and J Schroter (2010) J. Geophys. Res. 115, C08013 15pp.*
[538] *Hay, C.C. et al. (2015) Nat. Clim. Change517, 481-484*
[539] *Cazenave, A. et al. (2014) Nature Clim Change 4, 358-361.*
[540] *Munk, W. (2002) Proc. Nat. Acad. Sci. 99 (10) 6550-6555*

- sea surface is nowhere 'flat' but slopes, conforming to flow pattern
- coastal lands may either sink or rise in relation to the adjacent sea.

The true shape of Earth, the geoid, at the ocean surface is defined as the shape that this surface would take under gravity alone providing there was free passage through the continents. Anomalous masses of material of high density within and below the crust ensure that the geoid is not a perfect sphere although the excursion from this form is less than ± 100m. Added to these effects of gravity anomalies in the solid earth, the instantaneous sea surface also integrates both the effects of lunar tides and the influence of the underlying geostrophic current system; this can be observed most easily in the eddy field of major ocean boundary currents.

For all these reasons, it would have been very difficult to measure, map and monitor any secular changes in GMSL using only data from coastal tide gauges, even if the elevation of coastal lands did not change with time. But, unfortunately for early hydrographers, even this stability could not be counted on.

Vertical motion of coastal lands is not unusual and in high latitudes it is driven by post-glacial rebound after the removal of the mass of ice whose weight depressed the crust during the last glaciation, together with upward pressure from the plastic material in the mantle. Obviously, this is especially important on northern coasts where the burden of ice during the last glaciation was heavy; further, the region most affected by the weight of glacial ice is often surrounded by a region where the crust has risen in compensation. The consequence is that, as the central region rises again after the weight of the glacial ice has been removed, it may be surrounded by a zone of subsiding terrain, and if this includes coastal lands the consequence will be an apparently rising regional sea level.

Another process that complicates the tide-gauge record is the preferential location of tide gauges near cities and major ports because the weight of buildings and other installations tends to depress the elevation of the coastal land on which they are built while, conversely, significant extraction of ground water around a developing city may produce the opposite effect. These effects may be non-trivial: the deltaic region of the northern Gulf of Mexico is very rapidly sinking, subsidence of as much as 1.0 cm/year having been observed. Conversely, the subsidence of Adelaide is an effect of groundwater extraction in the 'greening' of that city, an effect that may occur in many places.

Some tide-gauge data that had been corrected for glacial rebound by detrending the original measurements were presented in IPCC AR3, but the data that are made available by NOAA for about 225 gauges globally are not detrended and therefore misleading. It is simple to locate stations such as Stockholm and Trieste having rather slight tidal influences: one shows post-glacial rebound of the solid earth, while the other shows rising sea level. None of this matters to the journalists for whom any damaging rise of sea level is now a consequence of climate change: *Le Monde* reported in August 2015 that trees were being killed and uprooted by rising sea level in the Assateague National Seashore on the Maryland and Virginia coastlines. A simple check at the USGS public site would have told the journalist that this is a case of sinking terrain due to compensation for post-glacial rebound further to the north: a fascinating story, but not one to excite the public.

Of course, the volume of the ocean, and so the height recorded on tide gauges, changes as water is removed by evaporation, added by rainfall and rivers, and also as the total mass of ocean water warms and cools. So, in addition to geological problems, we must also be aware of the history of incident solar irradiance at the sea surface (and hence the time-course of volcanic activity) and of cloudiness and rainfall. In most computations of past and present sea level rise, these latter are ignored. This raises yet again the assumption, commonly made in modelling studies, that there is a direct connection between small changes in ambient air temperature due to increasing CO_2 concentrations and ocean heat content. This assumption has been discussed already in Chapter 4, but must be discussed again here.

Of the many investigations of 20th century sea level, I shall choose two examples for discussion: the first is based on just 9 widely separated sites, selected for the quality of their records (which cover the entire 20th century} from the data held in the Permanent Service for Mean Sea Level (PSML).[541]

These data are compared with the 177 post-1955 stations used in an earlier study by the same first author. Expressed as rate of change of sea level, there are no sustained differences in this rate during the period: 1.41 mm/y in the second half and 1.47 in the first half of the century. Instead, strong, sustained oscillations in the rate were observed; these were coherent across great distances and represent changes in global ocean circulation in response to atmospheric pattern of wind stress. The ENSO signal is well observed. The second exemplary study took exactly the opposite approach, by the aggregation of all stations that reach back to 1850 in the PSML archives. These show that the trend in sea level rise was very far from linear, confirming previous studies, and that during the 20th century, fast rate regional rates of up to 3-5 mm/yr occurred in the period 1920-1950; the extent of regional differences in the overall rise is also emphasised. The greatest contribution to average sea level rise during the 1990s is attributed to change in the North Atlantic and Arctic regions, while in the earlier period it was contributions from the southwest Atlantic and western Pacific that dominated. This study also emphasises the significant effects of solar irradiance at the sea surface on the rate of rise; this responds to clarity of the upper atmosphere - and, though not noted by the authors of the study - rather closely matches the 1930s-50s period of enhanced solar irradiance. The fundamental oscillations in the data are coherent with oscillation observed in at least some of the climate indices, implying that eustatic sea level is a component of the global cyclical climate cycles of Earth and that these include changes in global heat content which is the dominant factor in the rate of change of sea level.

The 60-year periodicity in sea level data figured in the IPCC-AR5 was also discussed in another study of the PSMSL and other archives and it was noted that this occurs in each ocean basin with similar phase and amplitude with some exceptions in the Pacific. The signal is shifted by 10 years in the western South Pacific and is absent in parts of the North Pacific.[542] The authors of this study suggested that minor cyclical changes in ocean volume of this kind should indeed be expected, because of cyclical changes in the hydrologic cycle and consequently in the transfer of water between oceans and land.

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[541] *Holgate, S.J. (2007) Geophys. Res. Lett. 34 L01602, 1-4*
[542] *Chambers, D.P. et al (2012) Geophys. Res. Lett. 39, L18607, 6 pp.*

This suggestion is comforted by reported observations of a 60-year cycle in rainfall in Africa and the Americas that is significantly correlated with the AMO signal in North and South Atlantic SSTs; it also suggests that we should examine the consequences for sea level of a progressive change in salinity of the ocean, a possibility almost completely ignored in the literature, even though during the last half-century about 10% of the mean sea level rise has been caused by a freshening of the upper 3000m of the oceans, as fresh water from the continents has been added to the oceans. Of course, the freshening of ocean water is not similar everywhere, and it penetrates more deeply in some regions than others.[543]

The measurement of salinity changes in the ocean has been used in an independent assessment of global sea level rise. This is based on an estimate that 650 km^3 per annum of freshwater would be required to produce the observed freshening, from which is removed the contribution from sea ice, leaving an estimate of 220 km^3 per annum for continental run-off. Over the 3.6×10^{-8} km^2 of the ocean this would give a sea-level rise of 0.6 mm per annum, for a total rise of 1.1 mm from steric expansion, which is within the IPCC range of estimates.[544] However, the authors emphasise the uncertainty of this (and, I suppose, all such) estimates and the results "*do not exclude a negative eustatic rise, that is, a net movement of water onto the continents*" by storage of rainfall. Incidentally, the authors of this study note that the fate of freshwater from high latitude melting can be understood by observation of changes in the rotation rate of Earth: rapid transfer of this freshwater mass over the oceans would produce a slowing of the rate, measured by increasing length-of-day measurements: in fact the opposite is observed, indicating movement of mass poleward. Clearly, the suggestion that fresh Arctic water does not very freely enter the Atlantic is supported.

Although much reliance is now placed on satellite observations, here again we are faced with the problem of a short baseline; the record to date from Topex and Jason satellites indicates a rate of 3.2 ±0.4 mm. yr^{-1} and it is encouraging that during the short period of overlap between the PSML data discussed above and the Topex-Poseidon satellite data, a similar rate of rise was indicated by the two techniques: 2.4 ±1.0 mm and 2.6±0.7 mm respectively.[545]

The recent AR5 of 2014 has performed what I believe to be an excellent and fair-minded review of recent sea level rise - attributing the multidecadal change that has been observed to changes in the major climate indices, the AMO, ENSO and so on. Their conclusions are summarised as follows: *"It is virtually certain that global mean sea level (GMSL) has risen at a mean rate between 1.4 to 2.0 mm yr–1 over the 20th Century and between 2.7 and 3.7 mm yr–1 since 1993 (99% confidence limits). This assessment is based on high agreement between multiple studies using different methods and independent observing systems (tide gauges and altimetry) since 1993. It is likely that GMSL rose between 1930 and 1950 at a rate comparable to that observed since 1993, possibly due to a multidecadal climate oscillation, as individual tide gauges around the world and reconstructions of GMSL show increased rates of sea level rise during this period."* The relevant figure, (AR5 13.4) however suggests a more nuanced interpretation, even if a line fit to the tide gauge data does suggest higher values at the end, rather than the beginning, of the century. But only the models suggest the progressively faster rate of

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543 *Antonov, J.L. (2002) J. Geophys. Res. 107, C12.*
544 *Wadhams, P. and W. Munk (2004) Geophys. Res. Lett. 31, L11311.*
545 *Nerem, R. S., et al. (2010) Mar. Geodesy 33, 1 supp 1: 435.*

increase on which the media have fastened. Similarly, a suggestion that until 1850 the rise was slower because the effects of increased CO2 in the atmosphere from industrial activities was not yet significant, relies not on data but on modeling.[546]

The IPCC is not the only group to make such confident estimates of the present rates of sea level rise; recent projections, based on a business-as-usual assumption for CO_2 release, and on simple semi-empirical models, all of which suggest a eustatic sea level rise higher than the maximum rise offered by the IPCC.[547] Typical assumptions inherent in such calculations are (i) that gaseous radiative forcing scenarios project a sea level rise of 0.6-1.6 m by 2100, (ii) that volcanic and solar forcing can account for, at best, only 5% of this and (iii) that observed secular minima of solar radiation and maxima of stratospheric injections of SO_2 would result in negligible change to any prediction.[548]

Although it is clear that the community is not going to stop gnawing on this bone, the more reasonable approach would be to accept uncertainty rather than to overstate confidence in any single computation; in any case, as shall be discussed in the next section, the problems of coastal and island communities - which are already serious - from an invasive ocean have little or nothing to do with climate change, anthropogenic or otherwise.

10.2 - On living on islands and coasts

According to many people, some of the most serious problems that we shall face in the future are the practical consequences of a thermosteric rise in sea level due to the effects of atmospheric CO_2. This is predicted to flood coastal regions and cities, creating social conflict and economic losses of great magnitude, being one of the IPCCs more insistent messages and one of their central concerns: indeed, their AR5 goes so far as to suggest that it was through their activity that sea level change was essentially brought to the attention of the scientific community: it is suggested that *"The First IPCC Assessment...laid the groundwork for much of our current understanding of sea level change"*.[549]

That text deals largely with projections for the future, and these have been translated into economic consequences by others: a recent World Bank study computed extraordinary costs that will accrue to society as the consequence of flooding coastal cities at various intervals into the future, costs that are clearly beyond the ability of most nations to cover.[550]

Unfortunately for such worries concerning what lies ahead, the reality is that the future is already with us without any help from greenhouse warming, heat accumulation in the oceans and transfer of water from land to ocean. Many coastal regions and small islands were in danger of flooding from the time people settled there and long before any concern for sea level rise was expressed. Whether or not a global warming trend continues and whether or not sea levels respond as predicted, some shorelines will

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[546] *Jevrejeva, S. et al. (2010) Geophys. Res. Lett. 37, doi:10.1029/2010GL042947*
[547] *Rahmstorf, S. (2010) Nature Climate Change 4, 44-45*
[548] *Jevrejeva, S. et al. (2010) op.cit.*
[549] *IPCC, AR5, 13.1.1.*
[550] *Hallegatte, S. et al. (2013) Nat. Clim. Change doi:10:1038/NCLIMATE10/79*

continue to sink and erode (just as they always have), some coastal cities built just above sea level will continue to be flooded (just as they always have) and may have to be abandoned, and some inhabited islands may become uninhabitable.

All this is ensured by (i) our historical choice of site for settlements and the establishment of towns, (ii) our construction of dams on all significant rivers, (iii) our widespread removal of sand and coral rock for building and even (iv) on some simple fishing activities. Those who claim that the problems facing New Orleans, the coastal lands of Bangladesh or the island state of the Maldives are caused principally by a sea level rise of a few millimetres a year, even accumulated over long periods, cannot have read the relevant literature in geoscience and ecology.

Estuaries, beaches and coasts are dynamic features whose morphology reflects the changing balance between erosion and deposition. The presence of a cliff, large or small, above a beach, indicates that the coast is receding naturally so that anybody who builds near it should study its rate of recession beforehand. Unfortunately, this is seldom done and when modern housing projects have to be abandoned, climate change and increasing erosion rates are usually invoked as convenient scapegoats. Of course, the truth is that erosion rates of land bordered by sea cliffs are everywhere being increased by coastal works and by extraction of sand and rock from the beach below.

If deposition rates in estuaries and coastal lagoon are reduced by the sequestration of river-borne silt in the quiet water of dams upstream, then the result must inevitably be what has happened at New Orleans. This case has been well documented by the US Geological Survey and others; here, there are also annual subsidence rates of 5 mm at the city, and as much as 1 cm a year on parts of the adjacent NE Gulf coast, in relation to mean sea level. I can do no better than quote the litany of what has gone wrong, apart from rising sea level at <2 $mm.yr^{-1}$: "*Subsidence of the land surface in the New Orleans region is also attributed to the drainage and oxidation of organic soils, aquifer-system compaction related to ground-water withdrawals, natural compaction and dewatering of surficial sediments, and tectonic activity (geosynclinal down-warping and movement along growth faults). The problem is aggravated owing to flood-protection measures and disruption of natural drainage ways that reduce sediment deposition in the New Orleans area.*" Already, parts of New Orleans are well below sea level and it is projected that by 2100 these will be 2.5-4.0 metres below MSL.[551]

Similar projections have been made for Norfolk, major port and naval base, in what are known as the tidelands of Virginia; here, the situation is worsened because the crust in this region is weakened and fractured by an ancient meteor impact, recognised today as the Chesapeake Bay Crater. Despite such well-known facts, the regional and federal consensus seems to be that climate change is the cause of the problems – which are major: by 2040, it is likely that the largest US Navy base will be inaccessible by road 2-3 hours daily.

The case of Venice, one of the cities most at risk from rising sea levels, is very instructive: its builders found a site that was economically and militarily superb for the overseas trade by which they lived: an island in a coastal lagoon, separated from the sea by a narrow sand bar and not approachable by land. But its builders didn't foresee that in a few centuries Venice would be (i) sinking as its mass of stone masonry

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[551] *www.nwrc.usgs.gov/hurricane/katrina_rita/**Sea-Level-Rise**.pdf, and also see Olson, T.H. (2006) Nature, 441, 587-588*

progressively compacts the soft sediments of the coastal lagoon, on which it is built, (ii) suffering the consequences of groundwater extraction (now prohibited), (iii) affected by crustal subsidence related to the tectonic effects in this highly active zone of the collision between African and European plates and (iv) a rising sea level that has some impact as well. As if all that were not enough, Venice is gently tilting as it sinks.[552]

Wherever you look, similar situations are to be found: many city founders built in the wrong places. When parts of New York become flooded in the future, as they will be, this will be due not only to sea level rise, but also because Manhattan is sinking; the difference between sea level rise obtained from the Battery tide gauge and sea level stability observed in satellite data makes it clear that the fill on which this part of the city is built is sinking significantly.

The same problem faced by these cities must affect unbuilt coasts as well, and this appears to be happening in the Sunderbans of Bangladesh. This coastal region may be seriously flooded long before any rise in sea level becomes significant, because the mangrove forests that stabilize the delta have been heavily damaged by tree-cutting for fuel wood and farming. Further, the silt transported by the Ganges is now held up as sediment in dams in the Himalayas, instead of back-filling the delta against continual, natural erosion of the coastline as it should .[553] It is not surprising that the balance between accretion and erosion during a recent 37-year period involved a loss of 170 km^2 of coastal lands.[554] Evidently, the unfortunate Sunderbans tigers have other things to worry about than the Chinese trade in their body parts.

History tells us that we don't have to wait for anthropogenic sea level rise for major problems to visit communities that were built on low-lying coastal lands: if you want to build for posterity, you should build on the higher ground. Unfortunately, our ancestors did not have that luxury, because they had to build where the resources and economic opportunities lay: so because coastlines are naturally evolving geological features, the results were inevitable. But I have seen very little reference to the fact that the submergence of coastal lands with great loss of life is not only something we have to fear in the future, but was also a feature of life in the past. Consider the case of Holland and the evolution of the Zuider Zee that, at the start of the modern era, was a small inland brackish basin connected to the sea by a network of channels that became progressively widened by erosion over the next millennium or so. Then, in winter 1287, a major storm coincident with unusually high tides sufficiently opened the inland basin to the sea that it was subsequently referred to as a 'zee'. But a worse disaster occurred in the storm of January 1362 - the *Grote Mandrenke* (the Great Drowning of People) that killed 25,000 men, women and children and caused 60 parishes entirely to disappear - with effects that were felt as far to the east as southern Denmark. Ever since, the Dutch and Belgians have been struggling to keep the sea within the bounds they have set for it, but on 15 January 1916, the New York Times reported that "*High tide menaces all of north Holland, dikes burst and all Volendam and Marken (provinces) are under water*" and spoke of the highest tides since 1860.

The climate change community is not concerned with the consequences of seismic activity and the generation of tsunamis, but these are not something that happens only in distant lands, or only in the distant past, but – for instance – they are a

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[552] *Bock, Y. (2012) Geochem. Geophys. Geosyst. pagination?*
[553] *Jim Syvitsky, pers. comm.*
[554] *Ranman, A.F. et al. (2011) Rem. Sens. Env. DOI:10.1016/j.rse.2011.06.019*

danger endemic on almost all coasts of the seismically-active Mediterranean Sea: in France, we have received two alerts this year, one concerning activity near the Azores, the other on the North African coast.

The great Lisbon earthquake of 1755 was the result of tectonic movement between plates in the Atlantic between Europe and the Azores and was accompanied by very large tsunami waves that swept devastatingly into the town, leaving tales of people on horseback racing to high ground: many other western coastal ports were flooded and the waves were observed in the Caribbean. The 'great flood' of 1607 in the Bristol Channel of western Britain occurred on a sunny day, the water retreating before returning in a series of 'mountainous' waves 'faster than a horse could run'; Galway, on the Irish coast at the head of a long arm of the sea, was also hard hit, as it had been by the 1755 event.

This devastating flood is now thought to have been a tsunami caused by tectonic movement on the mid-Atlantic ridge to the south-west of Ireland, a tremor having been felt in Ireland on the morning of the disaster.[555] This contemporary print weirdly reflects a scene we have seen too often on our TV screens in recent years.

Given that tectonic and volcanic activity will be always with us, those who live beside the sea must accept that there may one day be a big price to pay for the economic benefits that accrue from this proximity. Should the caldera of the Cumbra Vieja volcano in the Canaries, sooner or later, collapse then western Europe will face major a devastation of its coastal regions facing the Atlantic.[556]

Some degree of political concern at the UN is associated with the fate of people living on small islands in the face of rising sea levels, perhaps because atolls and atoll islands appear to an untrained eye to be vulnerable to even a very small rise in sea level.[557] The models on which IPCC projections are based suggest that global sea level rise during the 21st century will be between 15 cm and almost one metre by the year 2200 and that this will drown many small islands and coral atolls.[558]

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[555] *Haslett and Bryant (2002) Archaeology in the Severn Estuary.*
[556] *http://phys.org/news77977989.html*
[557] *Grigg, R.W. (1982) Coral Reefs, 1, 29-34.*
[558] *IPCC 4th Report, p. 820.*

But this prediction ignores a body of knowledge that goes back to Charles Darwin's "Coral Reefs" of 1842 and which can be used to make more realistic suggestions concerning the future of atolls if sea level continues to rise. Fortunately, Darwin taught us how the growth rate of coral communities accommodates to changes in sea level so as to maintain the proper relationship of each atoll with prevailing sea level. But what Darwin did not know was that sea level itself could change, so he explained his observations only by imagining the sinking of submarine peaks on which his reefs, with the associated atolls, were rooted. Even though an obscure reference in the 4th IPCC report does acknowledge this possibility (without referring to Darwin) the Summary for Policy Makers makes no reference to it.

Atolls or coral reef islands are accretionary land-forms standing on coral platforms, built of wind- and wave-transported coral sand and debris that may or may not be accreted, the supply of which comes form the active growth of coral organisms as they maintain an optimal profile across the reef into deep water in relation to sea level as this rises and falls at millennial time scales. Even at scales appropriate to human lives, coral reefs are dynamic landforms that change in response to periodic changes in ambient patterns of wind and wave heights, so it is contrary to received wisdom that coral reef islands and atolls should be in any imminent danger of destruction by rising sea level today.

When the continental shelves were flooded by the sea at the end of the last glaciation, the sea rose much faster than it is predicted to do by the IPCC during this century – at rates of up to 5 cm a year - and because most of the coral reefs that exist today survived this higher rate, you might well conclude that atolls and reefs will easily survive the rise predicted by the IPCC. [559], [560] But, unfortunately, you would probably be wrong, because even such ordinary activities as fishing can destroy the ability of an atoll to respond to sea level rise by growth of coral colonies - the massive release of urban sewage, implicated in the bacterial destruction of reefs off Florida, is not required and nor is the mining of carbonate rock on reefs for the production of cement.

The mechanism is very simple. Fishing is an essential activity of people living off the sea in tropical regions as elsewhere, and large fish species are habitually prized above small species. But many of the large fish species are herbivores, and if they are removed the macroalgae on which they previously grazed will progressively smother the coral and prevent its continued growth. Other large reef fish are spongivores, and their removal by fishing similarly results in overgrowth of corals by sponges.[561] I find it remarkable and depressing that a recent major multi-author review of coral reef problems noted that those visiting reefs today are unlikely to see the large fish that were a character of reefs in the past, but no mention is made of the inevitable consequences for coral organisms of their absence. [562] Can it be that todays reef ecologists are ignorant of the literature on the ecological consequences of the removal of keystone species from littoral ecosystems?[563]

So, a natural balance is required between corals, algae, sponges and fish for an atoll or reef to survive and if atoll islands and their remnant corals are drowned in the

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[559] *Rohling, EJ et al. (2009) Nature Geoscience 2, 500-504*
[560] *Blanchon, P and D Blakeway (2003) Sedimentology 50, 1271-1282*
[561] *Dybas, C.N. (2013) Oceanography, 26, (4), 8.*
[562] *Global Coral Reef Monitoring Network, Status of Coral Reefs of the World, 2008.*
[563] *McManus, J.W. et al. (2000) J. Mar. Res. 57, 572-578.*

event of unusual sea level rise, it will be because islanders have ignored simple natural history by permitting tourism on their shores, and in participating in slash-and-burn fishing to supply the 'live reef food fish' trade: this bizarre practice air-lifts live, large, colourful reef fish to China where they are exhibited in aquaria for the choice of diners in restaurants. This production was estimated, at a single entry-point in Hong Kong, to be worth US$150 million annually at the turn of the century. Many of the most prized species are the essential herbivores and spongivores without which coral growth must disappear below a cover of macroalgae and sponges.[564]

Suggestions have been made that there may be two alternative steady states for atolls - either coral-dominated and macroalgal dominated- but this appears to deny the living reef any possibility of responding to changing sea levels through compensatory coral growth although this has happened continually during earth history and must be permitted to continue if atolls are to survive.[565] Some have challenged this by asserting that macroalgae grow only on already damaged corals - damaged by the invasive echinoids *Diadema*, for instance - which simply says that there are far more direct and damaging causes for coral death than the removal of herbivores. A recent study of proxy evidence on the Maldive archipelago suggests that sea level rise can initiate enhanced growth processes in an impacted reef system and so reactivate the process of reef-island accumulation, but unless this involves regrowth of herbivorous fish, it cannot function.[566] Further, despite the significant change in conditions in the open ocean recorded during the 20th century, including a rise in sea level close to predicted rates, a survey of reef islands on atolls over a large part of the SW Pacific shows no alarming changes: over periods of about 20-60 years, of 27 reef islands surveyed only 14% suffered any loss of area, while the other showed either some accretion or minor changes of outline - of which some could be attributed to aggregation of material caused by the building of piers or jetties.[567]

Of course, the ecology of coral and its habitat is very complex and perhaps not yet fully understood in relation to anthropogenic climate change predictions; much is made, for instance, of the ejection of their endosymbiotic, photosynthetic organisms when temperatures pass a critical level, in the coral bleaching phenomenon and also the fundamental control of coral distribution by environmental temperatures: 18^{o}C is often quoted as their lower tolerance limit and their upper lever of tolerance is usually quoted as that at which they eject their symbionts.

But these seem likely to be unjustified assumptions. Corals are very ancient organisms and the dominant modern group, the *Scleractinia* go back to the early Triassic and have therefore passed satisfactorily through periods when surface seawater temperatures were significantly higher than today (p. NN); this proposition also ignores the natural genetic diversity we expect now to find in natural populations of unicellular organisms, and the rapidity of the selection for those appropriate to changing environmental conditions. Only thus could ancient lineages of microbiota have survived to the present era. As recently as the mid-Pliocene, the western Pacific - the region of highest coral diversity today - experienced surface seawater temperatures about 3^{o}C

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[564] *Longhurst. A. (2008) Mismanagement of Marine Fisheries (CUP), Chapt. 8*
[565] *Knowlton, N. (1992) Am. Zool. 32, 674-682*
[566] *Edwards, R. (2002) Prog. Phys. Geog. 30 (606: 785-796.*
[567] *Webb, A.P. and P.S. Kench (2010) Glob. Plan. Change doi:10.1016/j.gloplacha.2010.05.003*

higher than during the present period, as the Pacific circulation pattern remained in a quasi-permanent El Niño state.

Under normal conditions, coral polyps can rapidly recruit a new population of symbionts from the ambient photosynthetic microplankton when temperatures are again comfortable and - one must suppose - if they remain high, as during the Pliocene, the free-living population of photosynthetic cells will evolve to favour those whose genomes are best adapted to current ambient temperatures. Corals are known to possess plasticity in their choice of the species of the symbionts that they can accommodate - so that a population of corals could adapt itself to changing thermal conditions, through their 'choice' of new species or physiological types of symbionts, to replace those whose photosynthetic activity is compromised by novel temperature conditions. Corals also contain fluorescent chemicals that block IR radiation although this ability is not uniformly distributed within populations, but it would be expected that as conditions changed, high-blocking individuals would come to dominate the population.

The bleaching phenomenon is usually presented as if it is novel to this era of global warming, but it is really a well-known process that can be initiated either by high temperatures, excessive freshwater run-off or excess nutrients from agricultural lands borne by coastal rivers (by overgrowth of symbiont populations) and also by unusually high IR irradiance. In fact, a listing of all reports of bleaching back to 1870 demonstrates – just as you would expect it to – that anomalous increases in numbers of these accompanied the explosion of global expenditure on marine science in the 1960s and the rapid development of global communications on the 1990s. The probability of a bleaching event that occurred in 1890 being recorded is very different from the probability of a similar event in 1910, or 1930, or certainly than in 1950: such is the simple consequence of creeping globalisation. I submit that we really have very few firm data on which to base an increasing trend of bleaching events related to ocean warming or to anything else.

General predictions on the future of coral reefs and descriptions of their present state are almost wholly negative and tend - I judge - to emphasise global warming compared to human activities related to mining for coral rock to use in building and cement production, fishing, pollution, the invasion of exotic species and all the other insults that this fragile habitat now receives.

Perhaps such problems are more serious in the densely populated Caribbean than elsewhere, but they are also very serious on some coral islands and atolls of the Indian Ocean of which the tectonically-raised atolls forming the main island of the Maldives are perhaps the worst case of self-destruction by the development of mass tourism - and also one of the loudest voice in the cries for assistance.

Some Pacific atolls are in no better shape; this is the southeast corner of the atoll-city of Majuro, not far from the ribbon-like International Airport of the Marshall Islands; special concern has been raised by he UNO for the future of the population of this island nation, which claims that it will be forced to abandon its homeland due to rising sea levels for which the developed world is responsible. But this argument ignores the fact that the living corals of their atoll home must remain fully functional even to compensate for natural and cyclical changes in sea level. One wonders where the carbonate rock for the cement for the runway was dredged from and where the sewage from such a large population goes to? Majuro, together with similarly urbanised coral islands, is a disaster waiting to happen - climate change or not.

Many of the atolls of the Marshalls are uninhabited and appear to be in a viable state, so far as their main features are concerned. Wake Island, also in the western Pacific, is an interesting case; intensely used as an air base by US forces in the Pacific war it is now very sparsely occupied, although the military airport remains in place: this atoll is now a wildlife sanctuary for sea birds and its coral ecosystems must be gently returning to a pristine – or at least a viable – status. The Chagos archipelago in the Indian Ocean is a similar case; the population was removed to Mauritius in 1960 by the British government of the day so that a NATO surveillance and transit base could be established on Diego Garcia. The rest of the archipelago has by now largely reverted to pristine state and is hopefully to be declared a Marine Protected Area - much against the wishes of the exiled islanders who still want to return home.

The reality is that the reef islands that are formed on living coral arcs or atolls are not a suitable long-term habitat for anything but a very light human footprint: in the not-so-distant past, limitation would have been placed on population growth by the size of the freshwater lens that may form by the accumulation of rainwater in the compacted sand behind the beach, and above sea level. If this becomes exhausted by the withdrawal of too much water for drinking or for growing vegetables, the human population must die out or migrate. In the case of Majuro, the use of the airport runway to divert rainwater into reservoirs has increased the atoll's storage capacity to 3-4 months usage, compared with the previous 2-3 weeks.

10.3 - Acidification of seawater: uncertainty levels

One of the major concerns now expressed is that increasing atmospheric CO_2 may soon come to affect those marine organisms, large and small, which incorporate carbonate into their exoskeletal structure. Although the dissolution of carbonate sediments will buffer pH changes by adding alkalinity and so restore some of the buffering/uptake capacity of the oceanic CO_2 system, it is the biological effect that has taken our attention and this has been confidently described as an inevitable disaster for marine ecosystems. The consequences of this process are only now beginning to be understood in all their complexity, and I suggest that doubt and certainty concerning the long-term future of some marine organisms may be appropriate in about equal proportions.

These potential problems came to our attention only relatively recently compared with other concerns about changing climate. Until the 2005 Royal Society report on the potential effects of ocean acidification by atmospheric carbon dioxide, no more than a handful of studies on the subject were published annually; subsequently, the floodgates opened and 'acidification of seawater' rapidly became headline news. This term, perfectly proper chemically, had been very rarely used previously in this context, and its use has undoubtedly assisted in bringing the issue to our attention.

The pH of ocean water is everywhere, and at all depths, higher than 7.0 and therefore basic, and even the most extreme anthropogenic climate change scenarios do not suggest that the pH of ocean water will fall below neutrality, since the reserves of carbonate in the ocean are far too great for that. But, because ocean surface water is naturally alkaline, atmospheric CO_2 does readily pass into solution, at rates determined by the pCO_2 gradient and by physical factors including water temperature, wind speed and surface roughness. The rate of this flux is well constrained and was estimated by the IPCC AR4 to lie between 1.9 and 2.2 $gtCy^{-1}$. Of the anthropogenic carbon dioxide that was emitted into the atmosphere during the 19th and 20th centuries, approximately 48% has been dissolved in the oceans, where it is not uniformly distributed. Regions influenced by the formation of deep and intermediate water masses in the North Atlantic dominate the column inventory, yet <10% occurs deeper than 1500 m.[568]

The first consequence of the solution of CO_2 in seawater is the formation of carbonic acid, but this immediately dissociates to form bicarbonate. Over geological time scales, this process is buffered by the terrestrial carbonate cycle so that a balance tends to be maintained between carbonate weathering ashore, sedimentation of biogenic carbonates as chalk or limestone in the ocean that has been recorded in several locations.[569]

So, to understand the reactions of marine organisms having carbonate incorporated in the skeletal material to the solution of CO_2 in ocean water, we must look not only at changing pH, but also at the ambient level of carbonate saturation of seawater. Decreasing pH may erode skeletal material, and calcite under-saturation may constrain the rate of production of skeletal material, the whole entering a delicate balance.

If the rate of change of pH is faster than the rate of equilibrium of carbonate saturation dynamics under-saturation of calcite may result with potentially stressful consequences for calcifying marine organisms; unfortunately, rates of change of pH at present are significantly faster than during periods in the distant past when atmospheric CO_2 concentrations increased much more slowly. In such periods, a different balance occurred between saturation levels of calcite and ambient seawater pH. The faster rate of change in pH in today's ocean must result in greater relative changes in calcite saturation than during CO_2 increases during geological time.[570]

This critical observation must be considered carefully when remarking, as is often done, that many extant marine organisms have passed successfully through

[568] *Sabine, C.L. et al. (2004) Science 305, 367-370.*
[569] *Hõnisch, B. et al. (2013) Science 335, 1058-1063*
[570] *Hõnisch, B. et al. (2013) Science 335, 1058-1063*

ancient episodes of high atmospheric CO_2 concentrations: it is essential that changing calcite saturation should be considered when predicting the consequences of changing pH of ocean water, otherwise conclusions drawn concerning the consequences of pH changes may not be correct.

Near the surface, we expect to find the highest pH values, with progressively lower values downwards. At the surface of the Pacific, values run from pH 8.05 in the tropics to pH 7.6 in the Gulf of Alaska while, at 1000m in high latitudes and 250m at the equator, water of around pH 7.5 occurs at mid-depths; a similar pattern occurs in the Atlantic, where near-surface water in the Arctic regions reaches pH 8.2 compared with about 7.9 in the African upwelling regions in low latitudes. Near-surface, the pCO2 difference between gas and water phases controls gas CO2 exchange across the surface, while in the interior of the ocean pCO_2 values are controlled by respiration and carbonate dissolution. Since concern was first expressed about ocean pH values, data have accumulated rapidly and several global archives established: a useful entry into these data would be the special publication on CARINA (Consistent carbon-relevant data base of the Arctic, Atlantic and Southern Oceans).[571]

The regions of interest to the CARINA data archives was investigated by the early meridional oceanographic section from Europe to Antarctica (10°N to 55°S) obtained by the *Meteor* expedition in the early 20th century, and this will serve to illustrate the general pattern of pH distribution with depth. *Meteor* obtained 312 CO_2 analyses of air above the sea surface and comprehensive pH and alkalinity profiles were obtained to the bottom - in fact, this may be the only one-off, top-to-bottom, whole-ocean section of pH values that we have; it is reproduced in Sverdrup, Johnson and Fleming and is a very useful illustration of the overall pattern. The mean atmospheric CO_2 concentration of 300 ppm measured by the *Meteor* scientists is close to what we would now expect for the period, with marginally higher values being found off Antarctica and in very low latitudes; the surface pH values are not greatly different from current values, a result concordant with the drop of 0.1 pH at the surface since the pre-industrial era.

There is clear evidence from several monitoring programmes that the pH and alkalinity of the ocean have been evolving just as they would be expected to do in a world on which the atmosphere is becoming progressively richer in CO_2. At Hawaii, the station Aloha data demonstrate that the pH of surface water fell by about 0.4 units between 1988 and 2003, all the while exhibiting a seasonal signal that matches that of atmospheric CO_2.

It is perhaps not surprising that some researchers have pursued their studies of this progression in the upwelling system off the California coast where one would anticipate strong temporal variation of pH in surface water - and where there is a large concentration of marine science laboratories. The water that lies below 140m in the California Current has pH values <7.7 (compared with oceanic surface water of pH 8.0) and has an aragonite saturation state of <1.0 so that, after each upwelling episode such values may be found on the narrow shelf and even near shore. Accordingly, the title of a Science paper evoked the upwelling of "corrosive" seawater at this coast and it was accompanied by a NOAA press release that can only be described as alarmist. Of course, in the strictest sense this term is correct, because there is evidence that seawater of pH

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[571] *Tanhua, T et al. (Eds) (2009) ESSDD - Special Issue*

as low as this may erode the carbonate shells of some molluscs and other marine invertebrates, so the word can be justified.

It was suggested that the levels of aragonite under-saturation observed on the shelf are not predicted by IPCC "*to occur in open ocean surface waters until 2050*"; this is a curious statement, since it must be perfectly clear to any oceanographer that upwelling off California - and along the equator - brings water of pH <7.4 to the surface from the oxygen minimum zones in which respiration in the planktonic ecosystem may have already reduced ambient O_2 to very low levels - or even to near zero in some areas, as off Peru. That the effect of increased CO_2 concentration in the atmosphere will have added to this effect is certain, and pH of upwelled water must be lower than in pre-industrial times - everything else being equal. Nevertheless, the upwelled water is not normally corrosive to carbonate, as has been reported in some cases, because the saturation state of carbonate remains above unity.

Post-industrial shoaling of the depths of aragonite and calcite saturation, below which these forms of $CaCO_3$ will start to dissolve, by some tens of meters have been shown for several regions; the pattern appears to have been approximately maintained for several decades with some shifts towards sedimentary carbonate dissolution; nevertheless, there are also water mass effects - dissolution rates of calcium carbonate are (at <0.31 Pg C yr^{-1}) about seven times faster in North Pacific Intermediate Water at 400-800m than they are in deeper water.[572]

Some of the alarming reports concerning corrosive sea water have been based on observations of commercial shellfish cultures in which the oysters have failed to produce normal shells; this syndrome has popularly been ascribed to changing pH of ocean water, especially on the Oregon and California coasts. But this is incorrect, because the failure to produce normal shell material is due to very low levels of calcite saturation that results in abnormal calcification of larvae and adult shells that appear to be eroded.[573] Here, it is not pH that is involved but rather calcite saturation in a usually complicated environmental situation in which river water quality is involved as well as that of coastal sea water. Yet it is likely that it is calcite undersaturation, rather than pH itself that is the principal agent of change in the ecology of small calcifying organisms.

So, a reality check is in order here. Hermatypic coral reefs in shallow water are commonly presented as one of the most obvious victims of decreasing pH of the oceans, but consider the facts: the daily range of pH experienced by near-surface reef corals should, by this logic, prevent their continued existence – we have long known, but apparently forgotten, that, where water circulation is relatively limited on the reef top of the Great Barrier Reef, "*CO_2 in the water is depleted by photosynthesis during the hours of daylight, while the O_2 content rises to as much as 250% saturation and the pH rises to 8.9. At night, photosynthesis ceases, O_2 may fall to as low as 18% saturation and the pH drops to 7.8*".[574] Revelle and his associates had made similar observations in isolated reef pools in the Atlantic and recorded pH 9.4 at noon, and pH 7.5 at night against a local background of pH 8.2 around the reef.

When these apparent dangers for the health of marine organisms were first widely discussed, after the publication of the 2005 Royal Society report, it was thought

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572 *Feely, R.A. (2002) Glob. Biogeochem. Cyc. 16 (4) 1144doi:10.1029/2002GB001866*
573 *Waldbusser, G.G. et al. (2015) Nature Clim. Change 5, 273-280*
574 *Orr, A.P. and F.W. Moorhouse (1933) Sci. Rep.Great Barrier Reef Exp. 1, 323-352.*

that the consequences would be simple and disastrous for marine ecosystems, both in the benthic coastal ecosystem and in the pelagic and oceanic realm. It was widely assumed that autotrophic, single-celled plankton such as the coccoliths that built the chalk hills of southern England, and benthic metazoans from clams to corals, would all be in danger and might even disappear from marine ecosystems. It was also assumed that there would be very little, if any, boost to marine photosynthesis from increased carbon availability because growth would be limited – as it is at present - by available inorganic nutrients and trace elements in seawater.

We now know that although all these dangers are real, and cannot be ignored, the probable outcome is more nuanced than was once thought. The relief (if you can call it that) comes from experimental evidence that shows that the reaction of organisms to low pH water is not as simple and direct as might be assumed from first principles; to some extent, this is due to the fact that populations of organisms tend not to be homogenous genetically, but to include individuals having a rather wide range of potential response to their naturally-variable environment. Epigenetic variability is likely to be strongly reduced only in those relatively unusual species that exist as small remnant populations.

Natural populations therefore can respond rapidly to changes in the characteristics of their habitat, which do not remain stable over periods appropriate to natural climate changes as, for instance the glacial cycle. The best example that comes to my mind is terrestrial, but the principle holds: consider the species of Lepidoptera that presently inhabit Europe; these tend to be distributed from Russia to Portugal in a pattern of multiple, often isolated, populations that differ slightly in their morphology, and may or may not be accorded sub-specific rank; but are all novel, because it is unreasonable to suppose that each found a unique niche in Africa during the last glaciation when Europe became uninhabitable to all but a few high-latitude species; during this period, a modern lepidopterist would not have recognised the populations he was observing, because a different pattern would have evolved to suit the terrain

The last deglaciation, just a few thousand years ago, induced a poleward movement from their glacial refuges and the returning individuals diversified, adapted and occupied the new home territories they occupy today. The genetic variability within their populations enabled the colonists to adapt progressively - but very rapidly - to the habitat characteristics they encountered during their progressive return:.

So it is with marine organisms. Each group of species has encountered in the past, and also in the recent ocean prior to anthropogenic modification of its chemistry, a range of conditions of pH, and of saturation levels of calcite and aragonite to which they became adapted by selection of genotypes. Many marine organisms are very ancient forms, yet continue to be critical (one might even say 'keystone') groups in the structure and functioning of today's marine habitats; these lineages passed through epochs when high acidity and low carbonate saturation levels were, by today's norms, rather severe.

At least some of those who have recently studied the reaction of marine organisms to elevated low pH appear not to have understood this characteristic of living organisms nor, perhaps, the wide range of conditions their progenitors encountered in the past: conditions of very high concentrations of CO_2 in the atmosphere - with all that that implies for ocean pH - were not unusual.

Scleractinian corals go back to the Triassic and survived very well on the planet when atmospheric CO_2 levels were very much higher (1500-2000 ppm) than anything predicted for our own future Anthropocene era; judging by their survivors today, corals and molluscs passed though ancient high-CO2 and low calcification events successfully and we might hope that they will survive the Anthropocene event: in reality, their future will probably be determined mostly by their degradation by tourists with snorkels, by mining for carbonate rock for cement, by local fishermen using cyanide knockdown techniques...and all the rest of that dismal story.

It is generally assumed that the principal supply of carbonate sediments in the oceans comes from the calcareous plankton of the surface layers from which it sinks in the biological pump to the deposits on the sea floor, but this simple model ignores the benthic production of carbonate by, for instance, echinoderms (asteroids, echinoids, ophiuroids, crinoids and holothurians) which occur everywhere between the intertidal zone and the abyss. This extensive depth range means that they are able to exist over the entire range of pH that occurs in the oceans, even if 80% of their carbonate production occurs above 800m, and therefore largely above the calcite saturation level. As this shoals in future scenarios, shifts in the distribution of echinoderms must be anticipated although some adjustment in the formation of their exoskeletons is also likely to occur since regional differences, related to calcite saturation conditions already occur in the ocean: some Antarctic echinoid species, for instance, have 15% thinner skeletons than comparable temperate species, probably as a consequence of different elemental composition of the different regional water masses.[575]

There have been many attempts to simulate experimentally the probable reaction of marine biota to anticipated future conditions, but I think that few have used realistic combinations of calcite saturation and pH. Unfortunately, it is not easy to find analogues in the distant past for the observed and projected Anthropocene evolution of pH and of calcite saturation balance, but some responses of marine biota to past massive increase in atmospheric CO_2 have been documented.[576] At the most recent episodes, during the Pleistocene deglaciations, with a CO_2 increase of 30% over a 5000-year period, shell weights of foraminifera and coccoliths decreased significantly.

The ocean that existed prior to the onset of the Pleistocene glaciations was characterised by temperatures approximately 3^{o}C higher than today and lay below an atmosphere containing about 30% higher concentrations of CO_2 than the pre-Industrial atmosphere: estimates from six ice-core sites suggest maximum concentrations between 365-415 ppm. The ocean then lay in a permanent El Niño state with reduced monsoon winds and coastal upwelling, yet all our familiar marine organisms passed through this era in sufficient abundance to populate today's ocean. [577]

Much earlier in Earth history, the rapid release of >1500 Gt of CO_2 and CH_4 from the sediments at the Palaeocene-Eocene boundary resulted in a 170K year thermal anomaly (the PETM) of 5-7^{o}C. Today's calcareous nannofossils passed successfully through this major event although their Sr/Ca ratios were significantly and progressively modified. But the calcite compensation depth rose to <1.5 km (compared to 4 km in the present ocean) and this was associated with important extinction rates among benthic foraminifera and invertebrate benthos, involving a major 'reef crisis'. At

575 *Lebrato, M. et al. (2010) Ecol. Monographs 80, 441-467.*
576 *Honisch, B. et al. (2012) Science 335, 1058-1063.*
577 *Pagani, M. et al. (2009) Nature Geoscience 3, 27-30.*

the same time, the nannoplankton appears to have changed community structure but without extinctions or the favouring of non-calcareous forms. Unfortunately, it is not easy to disentangle the effects of pH and calcite saturation from changes in stratification, nutrient availability and temperature during this warm episode.[578] But I think that those who now deeply worried about the observed changes in pH and calcite saturation in today's ocean might well take some comfort from a reading of the palaeontological literature, into which I have no more than dipped my toe.

10.4 - Experimental evidence for acidification effects

All this must be in mind when evaluating experiments performed today in an attempt to know the future. One of the most interesting of these concerned coccolithophores that now account for about one-third of all marine calcification and have been major producers of chalk since the mid-Mesozoic; contrary to expectation, laboratory experiments demonstrated that both calcification and net primary production of these organisms "*are significantly increased by high CO_2 partial pressure*".[579] This was, of course, challenged because it did not confirm earlier studies that demonstrated decalcification; however, it was found that the original experimenters controlled pH in the experimental containers with inappropriate acid/base manipulation techniques rather than simple CO_2 bubbling. In any case, North Atlantic box-core samples were examined to identify possible effects of the presently-increasing CO_2 content of ocean water: progressively, samples representing the last two centuries showed an increasing species-specific calcite mass per individual coccolith. But that is not the end of the story because a more recent set of experiments on *Emiliania huxleyi* suggested that this dominant coccolith is capable of progressive adaptation to increasing water temperatures near their upper tolerance levels that was independent of ambient pH.[580]

Because barnacles have calcareous exoskeletons in the form of scutes these organisms may be expected to respond negatively to altered ambient pH in the oceans; barnacles are most abundant and diverse in coastal regions, but they also occur at all depths and so, as a group, have long encountered a range of pH conditions. So, jut perhaps, it is not surprising that exposure to a range of pH values (from ambient pH 8.2 down to a value of pH 7.4 to represent extreme conditions projected for the future) during incubation from egg to adult of the littoral *Amphibalanus amphritite* produced no deleterious effects on *"larval condition, cyprid size, cyprid attachment and metamorphosis, juvenile to adult growth, or egg production"*. The only difference noted between controls and animals reared at pH 7.4 was that the latter developed more massive scutes.[581]

Of course, there is no reason to suppose that all barnacles will respond similarly, and predicted responses differ; an evaluation of future risks to a variety of barnacle groups in a warming ocean include not only forms such as *Idioibla* which has very slow growth and plates that contain apatite, whose solubility increases at low pH, and so they are likely to be outcompeted, but also *Alepas*, a pelagic form whose area of distribution will expand. In general, it may be assumed that many barnacle groups are very resilient

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[578] *Stoll, H.M. (2007) Earth Planet. Res. Lett. 258, 192-206*
[579] *Iglesias-Rodriguez, M.D. et al. (2008) Science 320, 336-340.*
[580] *Schluter, K.T. et al. (2014) Nature Clim. Change 4, 1024-1030*
[581] *McDonald, M.R. (2009) MEPS 385, 179-187.*

and will adapt to new conditions as these develop. The passage of cirripede-like organisms with carbonaceous exoskeletal structures through the fundamentally-different ocean conditions since the Palaeozoic gives at least some observers confidence in their survival through the Anthropocene ocean.[582]

A study of the consequences of decreasing pH on sea urchins *(Strongylocentrotus purpuratus)* on the California coast showed that this population uses the genetic-diversity strategy that I discussed above to cope with changing conditions; in those individuals that were subject to ambient low pH values, the genes expressed were those involved in the control of calcium transport and enable the individuals to grow normal calcium skeletons under such conditions. In the same region, a genetic survey of abalones (*Haliotis rufescens)* computed a potential one million genetic variants based on 19,000 expressed genes in individuals found in locations having a range of characteristic pH environments due to different upwelling conditions.[583]

But this epigenetic diversity had not been looked for in earlier studies of changing pH and temperature on larval development of another, Australian species of *Haliotis* which concluded flatly that development and calcification of larvae were severely affected if pH was set in experiments at levels that are reasonably sure to occur in the future in near-surface water, while a small increase in ambient temperature increased growth and metamorphosis rates at pH levels studied.[584]

Experimental data on the consequences of low pH on shallow reef corals once again show that organism response is not simple and could not easily be predicted. A recent study of calcification in the reef coral *Stylophora pistillata* showed that ambient pH determines the internal pH of calcifying cells within coral tissues but also the pH in the extracellular fluid [the subcalicoblastic medium, SCM) at the calcifying tissue/skeleton interface within which aragonite crystals are precipitated and laid down as new skeletal material. [585]

It was found that the SCM responded to ambient pH but also that the response is not linear, but lagged, so that a steep gradient is induced between pH of the extracellular fluid and seawater. Reduction in growth-rates of the coral was observed only at the lowest pH treatments (pH 7.23 ±0.08), with which was associated also a reduction in the pH of intra-cellular fluid. It seems, then, that this reef coral possesses a mechanism to mitigate the effects of reduced ambient pH levels by regulation of the pH of the many studies that suggest that corals mitigate the effect of changes in ambient seawater pH by maintaining strong pH gradients between ambient seawater and the SCM over large ranges of pH. The authors of this study warn that their experiments – like all such experiments – are simplifications of the complexity of nature and do not take into account any potential effects of the variable levels of nutrition or ambient temperature on the calcifying mechanism investigated.

The concerned reader may well be excused for being confused by recent studies concerning problems with coral decline on the Great Barrier Reef. The story starts with a study published in 2009 by De'Ath and others who suggested that calcification in massive *Porites* colonies on the Great Barrier Reef had declined by as much as 14% since

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[582] *Buckeridge, J.S. (2012) Integrative Zoology 7, 137-146.*
[583] *Nature (2013) doi:10.1038/nature.2012.11482*
[584] *Byrne, M. (2011) Proc. Roy, Soc. B 278, 2376-2383*
[585] *Venn, A.A. et al. (2013) Proc. Nat. Acad. Sci. 110, 1634-1639.*

1990, associated with a decline of about the same magnitude in linear colony growth; it was held that this was an unprecedented decline compared with rates over the last 400 years; although the cause was not established, increasing temperature stress and a declining saturation state of aragonite was suspected.[586] This report resulted in alarmism at the BBC and local media and the public were assured that "*coral growth could hit zero by 2050*". In any case, this result appeared to contradict an earlier study that had concluded that, far from declining, coral growth on the Barrier reef had increased by up to 4% in warm periods of increasing temperature during the 20th century.[587]

But even more confusing the publication of a later paper by De'Ath, who reported that the decline in growth had really been caused by a 27-year period of strong tropical cyclones (48%), by crown-of-thorns starfish predation (42%), and by bleaching (10%). Associated with this was the good news that the estimated rate of recovery of coral cover in the absence of these factors would be about 3% p.a., and also that in northern regions, where the three destructive factors had minimal effect, there was no significant decline in coral cover.[588]

In the light of the studies discussed above it would appear that a reduced rate of calcification is, at least at present, a negligible factor in whatever it is that ails Great Barrier Reef corals. It is not helpful to suggest, as some have done, that the Barrier Reef of 2050 will be no more than rubble of carbonate rock.

The entire subject of the response of the marine ecosystem to increasing levels of atmospheric CO_2 is in such an early stage of investigation that I believe it is not yet possible to achieve any level of certainty about what the future holds for the marine ecosystem, but one has to conclude that alarmism is premature. It seems clear from these few examples of recent studies that our opinion on the consequences for marine biota of increasing ocean acidification should be more nuanced than it was 10-15 years ago.

However, the subject cannot be left without noting an extraordinary growth in experimentation on the consequences of acidification on marine organisms, principally larvae, many results of which are now widely web-published, often without peer review; many of these are performed by adherents to the California Current Acidification Network - "*a collaboration of interdisciplinary scientists, resource managers, industry and others from local, state, federal and tribal levels dedicated to advancing the understanding of ocean acidification and its effects on the biological resources of the US west coast*" .

This smacks more of arousing public alarm than of disinterested investigation and is possible because the required equipment is very simple – what has come to be known as an "acidification chamber" within which pCO_2 is controlled by bubbling this gas; the experimental set-up is a series of small vessels in which larvae or other small organisms may be reared. These experiments have come to be an integral part of the curriculum of marine laboratories and many that are web-published have clearly been assigned to students as part of their course-work. While this may be seen by some people as a very commendable response to a problem, and one that sensitises the young, it does have an Achilles heel – because, for the students tasked with the experiments,

586 *DeAth, S et al. Science (2009) 32,116-119. DOI: 10.1126/science.1165283*
587 *Lough and Barnes (2000) J. Exptl. Mar. Biol. Ecol. 245, 225-243*
588 *De'Ath, G. et al. (2012) Proc Nat Acad Sci /doi/10.1073/pnas.1208909109*

there will be a single desired result: that the experimental animals react unfavourably. How then can we be sure that negative results are not simply treated as an experiment that went wrong, and consequently are not reported?

Be that as it may, I recommend a quick search on "*acidification larvae*" that will release a torrent of such studies onto your desktop; some are clearly more serious than others, but all predict negative consequences for survival or growth; I looked at studies of cod larvae in the Baltic, on *Aplysia* egg masses and on coral larvae from the Great Barrier Reef, on oyster larvae from California, on lobster larvae off Nova Scotia, and on sea urchin larvae and on the byssus-threads of blue mussels on the California coast, and so on. Most appear to be competently done although one or two were clearly performed by people with no background in the subject, simply as a class assignment.

If one were to read only these studies, one would certainly conclude that the future for marine biota was far from assured if atmospheric CO_2 levels continue to increase, as they most certainly will. But the rush to study 'acidification' has fortunately extended also to more serious work and to the biological oceanography community at large; reviews, study groups, and specialised meetings (such as the interesting BIOACID Phase 2 kick-off meeting held at GEOMAR, Kiel in 2012) devoted to the issue are now almost commonplace and are presently more likely to attract funding than more classical topics.

Studies arising from these activities present a quite different aspect from those coming out of the California Current Acidification Network mentioned above. Consider the results of an experimental treatment of a natural population of protists from the plankton community of the Derwent estuary in Australia. Using a control pH of 8.3 to represent present-day ambient conditions, two experimental chambers were kept at pH 8.0 and 7.7 and the assemblage was incubated for 14 days; during this time a major succession of species occurred, but the succession in the two experimental chambers matched the pattern in the control. It was only in an extreme chamber kept at pH 6.3 that any effects could be identified. A high pH resilience for estuarine protists is inferred although, given the very rapid turnover of these forms and the numbers of individuals tested, progressive epigenetic selection cannot be excluded from the results.[589]

A very similar result was obtained in large floating mesocosm incubations of microzooplankton in a polar environment in Kongsfjorden on Svalbard; here, the test organisms comprised a natural population of microzooplankton containing both protists and metazoans that was incubated in post-bloom natural seawater at 3 levels of pCO_2 (175-250, 340-600 and 675-1085 µatm) over a period of 27d. Almost no effects, direct or indirect through food supply, or of different levels of pCO2 were observed on either the microzooplankton composition or its diversity. During the month-long incubation a predictable evolution of the contained plankton communities occurred as calanoid copepods, enclosed as nauplii, grew towards adult form and modified the entire food chain in each mesocosm.[590]

An even more important experiment, designed to answer the interesting question "*How long does it take for a plankton species to adjust physiologically to anomalous pH values?*" has been reported recently: the answer, as far as the coccolithophore *Emiliani*

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[589] *Nielsen, L.T. (2012) Aq. Microb. Ecol. 65, 271-285*
[590] *Aberle, N. et al. (2013) Biogeoscences 10, 1471-1481.*

huxleyi is concerned, is <500 asexual generations.[591] Clonal populations were selected and maintained at a range of partial pressures of CO_2 with the result that "*Compared with populations kept at ambient CO_2 partial pressure, those selected at increased partial pressure exhibited higher growth rates, in both the single- and multiclone experiment, when tested under ocean acidification conditions. Calcification was partly restored: rates were lower under increased CO_2 conditions in all cultures, but were up to 50% higher in adapted compared with non-adapted cultures. We suggest that contemporary evolution could help to maintain the functionality of microbial processes at the base of marine food webs in the face of global change*".

Rather different is the anticipated reaction of *Thalassiosira,* an abundant diatom, a group that is a major primary producer in the planktonic food-web, which responds to increasing CO2 in the air over experimental chemostats by a differential expression of the genes that control the carbon concentrating mechanism of these organisms which are expected, therefore, to acclimate rapidly to predicted atmospheric concentrations.[592] These results give a great deal of confidence in the ability of a wide range of marine organisms to adapt to anticipated coming conditions.

The possible effects of low pH in coastal seas on teleost fish has of course given rise to alarming suggestions concerning the future of global fisheries; a recent study that generated many press reports was performed on Baltic cod larvae by the Leibnitz Institute under the title "*Severe tissue damage in Atlantic cod larvae under increasing ocean acidification*": two experimental levels of acidity were imposed on larvae over a 2.5 month period under conditions representing extreme CO_2 levels of 1800 and 4200 μatm. Internal organs were severely damaged but, as Branch et al. point out, these tests should be discounted because of the unreasonably low pH of the experimental seawater. But despite the organ damage, dry weight growth at these unreasonably high levels could not be distinguished from that of controls until day 35 of the treatment. This is perhaps not surprising, given the evidence that adult cod and similar marine teleosts are relatively unaffected by very low pH levels: physiological functions of adult fish of species such as cod seems unmodified by pH values representing even extreme levels of CO_2 even over periods as long as 12 months. This may be a general result - if the observation of healthy mussels *(Bathymodiolus sp.*) in water of only pH 5.4 near abyssal volcanic vents is any criterion.[593]

Fortunately, we now have an increasing body of experimental evidence for large marine organisms, done at realistic pH levels, that suggests two major conclusions.[594] First, as noted above, adult fish appear to be little affected by water of rather low pH although there do appear to be serious but subtle consequences for brain function and hence behaviour pattern. This has mostly been investigated in tropical reef teleosts, relatively easy to handle experimentally, among which responses to olfactory, optical and auditory stimuli have been found to become inappropriate: cues for larval settlement, for prey and for predator recognition, and for habitat landscape may be misinterpreted. These are subtle effects, in a variety of species, for which failure of a single receptor function in the brain is shown to be responsible.

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[591] *Lohbeck, K.T. et al. (2012) Nature Geoscience DOI: 10.1038/NGEO1441*

[592] *Hennon, G.W.M. et al. (2015) Nat. Clim. Change 5, 761-765.*

[593] *Tunnicliffe, V. et al. (2009) Nature Geoscience doi:10.1038/NGEO500*

[594] *Branch, T.A. et al. (2013) Trends Ecol. Evol. 28, 178-186.*

But, once again, one must recognise that these findings are all based on relatively short-term experimentation and that they deliver no prediction of the probability that species may evolve an appropriate response, by selection of genotypes from the existing range, if the pH of ambient water changes as slowly as it is doing in the ocean at the present time. In fact, there is some evidence, reported by Branch et al., to support that this suggestion; when adults of the shore fish *Amphiprion melanopus* are exposed to near-future levels of CO_2, their young show reduced size and growth rate when grown at similar levels, but this is not the case for the young of adults that have been exposed to very high CO_2 levels: epigenetic changes in gene expression would appear to be responsible for this result.

But if one thing is sure in climate science, it is that without a global economic meltdown or pandemic, atmospheric CO_2 will continue to increase and the pH of ocean water will continue to change accordingly: to count on anything else is to put too much credence on the common-sense of the human animal. And of all the topics that I have reviewed for this book, it is the consequences of the changes in ocean pH and calcite saturation that will accompany the inevitable increase in atmospheric CO_2 that are the most worrying, and the most likely to cause consequences to biota. I do not venture to suggest what these consequences will be, although I agree with the comment from a reliable source that "*we are entering an unknown territory of marine ecosystem change*".[595]

[595] *Honisch, B. et al. (2012) Science 335, 1058-1063*

Chapter 11

DETECTION AND ATTRIBUTION: NATURAL OR ANTHROPOGENIC?

The detonation of the first atomic bomb…changed the world in many ways, not least of which is the view scientists have taken towards their profession. Many have come to feel that responsibility…rests partially with them and should not reside solely with politicians...this activity has at times tainted the objectivity that is crucial in any scientific endeavour…nowhere is this more apparent than in the recent literature on 'nuclear winter' research…[596]

In this final chapter, the conclusions reached in earlier chapters will be reviewed and evaluated. But, because some of these do not support the standard model of anthropogenic climate change, it may be useful first to discuss the formal mechanism used by the IPPC to determine the level of confidence that they place on their findings.

During more than a quarter of a century, this organisation has built both internal consensus and solid support for its conclusions, which have been criticised mainly by conservative politicians and the right-wing press but have been widely accepted by the science community; sceptical scientists – and there are some – generally keep their doubts to themselves. The IPCC has provided regular and increasingly comprehensive assessments of the changes associated with CO_2 contamination of the atmosphere and the latest of these, the 5th Assessment Report of 2013, is a superbly crafted piece of advocacy. It will be very difficult for the intended readership to be other than convinced by the arguments presented. These are likely to be challenged only on behalf of the petrochemical industries and by those scientists who are, shall we say, freethinkers and who have no professional stake in the outcome. Unfortunately, the latter are often assumed to be in the pay of the former, and so may find themselves categorised as deniers, or worse. Yet, as discussed in Chapter 1, many studies that have been published in the best journals present relevant material or conclusions that do not support, or even that contradict, the standard model – often without emphasising this fact. Such papers represent a significant fraction of what is published in earth science.

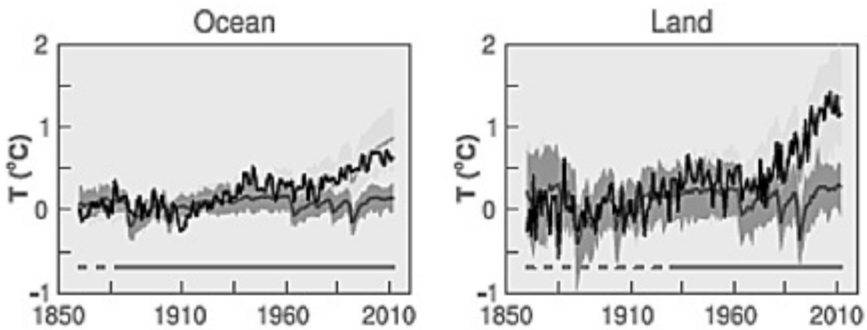
11.1 - Formal attribution of cause

The IPCC has established, and periodically revised, a strict procedure to detect changes in climate conditions that lie outside the anticipated range of natural variability, and then to attribute the cause of each to a perturbing factor, be it natural or

[596] *Emmanuel, K.A. (1986) Nature, 319, 259*

anthropogenic. Although the logic is simple, the practice is complex and is codified in a Good Practice Guidance Paper that defines the detection of change "*as the process of demonstrating that a system…has changed in some defined statistical sense, without providing a reason for that change*".[597] Attribution is more complex than detection and is the "*process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence*". Numerical simulation is used for both these processes, but especially for attribution in which models both with, and without a specific casual factor, are compared. AR5 goes so far as to suggest that formal attribution is not possible without the use of a numerical model, simple or complex, since "*we cannot observe a world in which either natural or anthropogenic forcing is absent*". This is not, of course strictly true if one allows observation to include the past – and even the deep past – that may be observed by proxy data.

If the detected change is consistent with simulations that include anthropogenic factors but is inconsistent with simulations that do not include such factors, then the case is considered closed. In that event, model simulations are used to discover what scaling factors may be applied, while remaining consistent with observations; this is illustrated in the two plots below, from AR5: the black line represents observations, the pink and blue areas are simulations with and without anthropogenic forcing, respectively.[598] The conclusion, as presented, is inescapable: surface air temperatures have responded to an anthropogenic effect, presumed to be dominated by radiative forcing by CO_2.



Although the procedures devised by the IPCC are admirable, they are only as good as the fidelity of their models to reality, and as the reliability of the observations made by others. The latter proposition requires comment because the examination of the SAT and SST data presented in Chapters 3 and 4 suggests that the instrumental observations respond to other variables than CO_2 and must be used with extreme caution, and selectively. If this proposition is correct, then the black line in the above images is misleading.

The current Assessment notes that observational uncertainty has been explored more thoroughly than previously - but, all the same, the IPCC proceeds as if it "*doesn't know that it doesn't know"* why global or regional air temperatures really evolved as they did during the 20th century. And that, as Donald Rumsfeld pointed out, is the most dangerous sort of ignorance for any complex enterprise, be it maintaining the security of

[597] *Report on IPCC Expert Meeting on Detection & Attribution, 2010 U. Bern, Switzerland*
:[598] *IPCC, AR5 (2013) p. 930.*

the USA or projecting the future global climate to which our societies may have to adapt. [599]

This is a conclusion that should be stated neither lightly, nor with any intention to deceive, but it is not possible to have spent several months examining the critical surface temperature data impartially - and in comparing the different archives presented for our use after progressive adjustment of the instrumental record - and to remain confident that the final product is apt for the principal use for which it is intended.

The direct observations of surface temperature now accumulated in global archives do not fulfill the basic requirements for use in predictive modeling: (i) that they should have been taken at spatial scales appropriate to the models, (ii) that the distribution of observations in space and time should have been uniform and (iii) that they should have uniform accuracy and precision. The original observations have, moreover, been subject to non-standard adjustment and correction during the archiving process. That they have subsequently been reassembled on a 5^o grid to match that used by GCMs is no substitute for the original inadequate and patchy distribution in both space and time.

I can find nothing in the AR5 chapter on detection and attribution, nor in the remainder of the Assessment, that discusses in any realistic and properly critical manner either the original temperature observations, or the archives that have been constructed from them. Nor does AR5 examine the other critical problem with the surface temperature data - that they do not record changes in the accumulation or loss of heat by the planet - which is the change most relevant to radiative warming of the atmosphere by CO_2. As discussed earlier, the global surface temperature index includes sea surface temperature over the oceans, so that the global temperature index may rise (as it did spectacularly in 1998) without any significant change in global heat content, merely by a reduction in wind strength over the Pacific Ocean at low latitudes so that cold water is no longer exposed at he surface (p. NN).

The lack of any serious discussion of the quality of the observations in the Assessments is all the more striking when compared to the massive documentation and discussion devoted to the simulation models. One has the impression that those involved in the modelling process have been uninterested in the observations, and have accepted that the adjusted and gridded data correctly describe the pattern of change to which model output must correspond for validation. This practice raises the problem of model validation because, although models have become a pivotal tool in all of the sciences, they do not have the same level of predictive certainty in the earth sciences as in the exact sciences. For this reason, prediction of future climate states and future climate sensitivity to doubled CO_2 levels, is often based on bundles of numerical simulations that have been drafted independently, and whose properties and behavior must be taken on trust by those who must recommend actions to be taken in remediation of projections of climate change. Yet these are highly improbable projections of climate conditions for the next 40-50 years, because it can be stated with confidence that climate does not, never has, and will not exhibit the uniform warming

[599] *US Secretary of Defense Rumsfeld on the failure to find 'weapons of mass destruction' in Irak.*

trend predicted by the mean trend of the bundle of models that is offered by the IPCC as their collective opinion.[600]

It is unlikely, for instance, that the pattern of change in North Atlantic conditions should somehow evolve linearly in the coming century and that the 60-70 year cycle of interaction with the Arctic Ocean should be broken. In this most influential region for global climate variability, the production of cold deep water, and the secular ebb and flow at of warm Atlantic water into the Arctic, and the return of cold water and sea ice southwards will surely continue (p. NN). These ebbs and flows have persisted - marching in step with solar variability - throughout the Holocene and there is no reason to suppose that they will not continue to respond in the same manner in the coming century and beyond. But both modelers and the IPCC choose to ignore such strong probabilities as these.

The evidence concerning changing conditions in the past at decadal to millennial scales assures us that even if anthropogenic effects prove to be negligible, we can have great confidence that the climate of the 21st century will not resemble those of the 19th or 20th centuries. The cycles detected in proxies of past climates conditions are real, and are a response to the natural and cyclical forcing of sun and tides, and it is certain that comparable cyclical behaviour will be imposed on the climate ahead of us. Yet none of these effects is incorporated into projections of future conditions derived from ensemble models that respond only to the consequences of the radiative balance in the atmosphere and ocean; *so it is a reasonable proposition that if we did not have the results of these simulations before us, our observations of past and present climate states would not be causing us any particular concern for the future*.

Under such circumstances, we would very comfortably accept the observations of minor temperature changes and of glacier advance and retreat during the 20th century, because the entire body of climatology, prior to the 1980s was based on the simple assumption that Earth's climate is very largely under the control of changes in solar irradiance, caused both by change within the Sun and by modulation of irradiance received at Earth due to orbital changes within the Solar System. As was noted in Chapter 5, it is remarkable that the IPCC has abandoned the entire *'theorie astronomique de climat'* in favour of a weak statement comparing the relative radiative forcings of Sun and CO_2 (p. NN).

Obviously, three different forcings will determine how the climate of the 21st century evolves, although the IPCC concerns itself seriously only with the first of these:

(i) Consequences of the presence of radiatively-active molecules and particles in the atmosphere: there will certainly be some consequences of these anthropogenic forcings, both global and regional, but these are probably not predictable in any quantitative sense and it is unproven that they will dominate the evolution of future climates or the heat budget of the Earth.

(ii) Consequences of external forcing, solar, lunar and volcanic: variable solar radiation incident at the top of the atmosphere will have consequences for surface temperatures, associated both with the changing geometry of the solar system and with cyclical change in radiation emitted by the Sun. The effects of tidal stress in the ocean in the coming century may contribute a cooling effect.[601] The

[600] *IPCC AR5 Fig. 11.3*

effects of these forcings will be modified by those of non-cyclical volcanic eruptions.

(iii) Consequences of anthropogenic modification of the environment: this effect will be greatest where human populations are most crowded or where deforestation, intensive agriculture, industrial or petrochemical activities and simple occupation of space by buildings will modify regional climates more radically than any effect of anthropogenic CO_2. It is not our motor cars that are causing rapid warming in eastern Amazonia and many other regions, but the intensive ploughing of cleared forest regions for – of all things – growing biofuel-producing plants for the same vehicles. These effects are easier to identify in the global surface air temperature data than any global effect of CO_2 to which all warming is habitually attributed.

It is also important to recall that solar irradiance is predicted to be progressively reduced during the first half of the 21st century, because of our recent passage through a solar maximum that was related to the increasing distance of the Sun from the barycentre of the Solar System, in a cycle that has near 60-year periodicity (p. 123). This will reverse the trend of increasing irradiance that was observed after the 1960s and may be expected to continue for several decades to come. It is impossible to predict what influence this will have on temperatures measured *in situ*, regionally, because regional anthropogenic effects on temperature observations may very well – when aggregated globally - mask any effect of reduced radiative warming from a weakening Sun.

11.2 - Conclusions

If the peer-reviewed scientific literature, with all the levels of uncertainty associated with individual contributions, has anything to say collectively in assessing the standard climate model, then a small number of conclusions may be drawn from the almost references to 600 peer-reviewed papers that I have quoted in the footnotes.

While I am aware that the general opinion of the relevant scientific community is that no further debate is necessary after five successive assessments by the IPCC, I suggest that this is premature because these conclusions concern topics that have not yet been properly addressed by that body, and so should be accorded status in a continuing debate concerning the influence of anthropogenic effects on regional climates:

- \- the global archives of surface air temperature measurements are unreliable estimators of the consequences of atmospheric CO_2 contamination, because they are already themselves contaminated by the effects of deforestation, land use change, urbanisation and the release of industrial particulates into the lower atmosphere *(Sections 6.3, 6.4, 6.5*).

- \- users of these data are not able to judge the consequences of the adjustments that have been made to the original observations of surface air temperature ashore, although the limited investigations now possible show that the adjustments have changed the long-term trends that had been recorded by some reputable national meteorological services (*Sections 4.1, 4.2*).

- \- sea surface temperature is not a substitute for air temperature over the oceans because it responds to changes in vertical motion in the ocean associated with coastal and open-ocean upwelling; the resultant change in surface temperature is independent of any changes in atmospheric temperature caused by CO_2, yet these changes are integrated into the GMST record which is used to estimate the effects of CO_2 (*Section 4.3*)

- \- surface air temperatures respond to cyclical changes within the Sun, and to the effect of changing orbital configurations in the solar system: the changes in the resultant strength of received irradiance (and of tidal stress in the oceans, which also has consequences for SAT) are both predictable and observable (*Sections 3.2, 3.3, and 3.4*),

- \- our description of the evolution of the global heat budget and its distribution in multiple sinks is inadequate for an understanding of the present state of the Earth's surface temperature, or to serve as the initial state for complex modelling of climate dynamics. Future states are therefore unpredictable, cannot be modelled, and will certainly surprise people living through the next century (*Sections 4.1, 4.2, 4.4, 4.5*),

- \- the planetary heat budget is poorly constrained, perhaps principally by our inability to quantify the mechanisms that control the accumulation and loss of heat in the ocean, where most solar heat accumulates; the quantification of changes in cloud cover is so insecure that we cannot confidently describe its variability - yet clouds are the most important control on the rate of heat input at the sea surface (*Sections 5.1-5.4*),

- \- the evidence for an intensification of extreme weather events and, in particular, tropical cyclones is very weak and is largely due to the progressively-increasing reliability and coverage of weather monitoring: todays frequency of cyclones and other phenomena does not appear to be anomalous when longer data sets can be examined (*Sections 9.1, 9.2*),

- \- global climate in the present configuration of the continents falls naturally into a limited number of patterns that are forced externally and patterned by internal dynamics. Some of these climate patterns will tend to conserve global heat, some will tend to permit its dissipation to space, while all move heat from one region to another. Two dominate the whole: the North Atlantic Oscillation that describes the flux of tropical heat through the North Atlantic Current into Arctic regions, and the Southern Oscillation that describes the strength of trade winds, especially in the Pacific, and thus the relative area of cold, upwelled water that is exposed to the atmosphere (*Sections 7.1, 7.2*),

- \- the recent melting of arctic ice cover over larger areas than 20 years ago in summer is not a unique event, but is a recurrence of past episodes and is the result of cyclically-variable transport of heat in warm North Atlantic water into the Arctic basin through the Norwegian Sea; the present episode will likely evolve in the same way as earlier episodes (*Sections 8.1-8.3*),

- \- sea level is indeed rising as described by the IPCC and others, but the causes - especially at regional scale - are more complex than suggested by that agency and involve many processes other than expansion due to warming. Had the human population of some very small islands remained within carrying capacity, their occupation could have been permanent, but this is not the case (*Sections 10.1, 10.2*),

- - the consequences of acidification of seawater is one of the most enigmatic questions, and may bring serious biological problems, although it seems now that (i) marine organisms are more resilient to changing pH than was originally feared, because of the genetic diversity of their populations and (ii) the history of pH of seawater during geological time suggests that resilience through selection of genomes has emerged when appropriate in the past (*Sections 10.3, 10.4*).

* * * * * * *

Unfortunately, the essential debate on these issues will not take place, at least not openly and without prejudice, because so many voices are today saying – nay, shouting - '*enough, the science is settled, it is time for remediation*'. In fact, many have been saying this for almost 20 years, even as fewer voices have been heard in the opposite sense. As discussed in Chapter 1, the science of climate change - like many other complex fields in the earth sciences - does not function so that at some point in time one can say "*now, the science is settled*": there will always be uncertainties and alternative explanations for observations of complex natural systems.

Of course, politicians and journalists, mostly from the left, have long supported the opinion that the science is settled, and the tide seems to be turning in their favour. After almost a dozen international conferences (Berlin, Kyoto, Marrakesh, Bali, Copenhagen Cancun, Durban, Doha, Lima and now Paris in 2015) on the implementation of protocols to reduce emissions, at least it is now formally agreed that every nation must take action and none may be excused, so some realistic hope is being expressed that a Convention may finally be signed in Paris. And some bilateral agreements are being made, as between the USA and China - each signing on for quite different reasons, but signing on all the same, there being both financial and political profits to be had for both from the deal: China invests in new technology and sells it globally, and the US president earns political capital he sorely needs.[602] There are also major interests in the carbon credit markets - markets that are no longer trivial - which will not permit the issue to resolve itself in any other way.

But perhaps the strongest emphasis on certainty that the science is settled comes from the scientists themselves, who have collectively worked on these issues for almost half a century and who have built lives and careers developing evidence to support the standard model of climate change – the teaching of which is now prominent in all earth sciences degree courses. This model is sufficiently embedded in the culture and practice of the earth sciences today, and in the education of several generations of young scientists, that it will survive all assaults - including this one - for several decades to come.

Perhaps the one thing that would shake the collective certainty would be if the simple, single value used to represent global surface temperature continued to languish at around the same value as it has for the last 15 years for, say, another 5 years? Of

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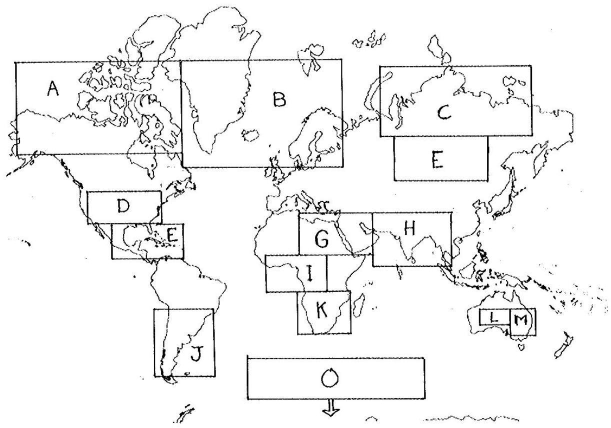
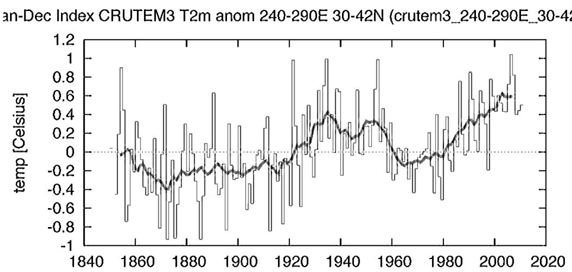
[602] *Globe and Mail, 14.3.15*

course, it may not – simply because the next Nino will quickly reduce the area of cold, upwelled water exposed at the sea surface and global SST will suddenly rise, as it did in 1998. In fact, as I write, this is occurring and the anticipated announcement has already been made NOAA that this year we have experienced the warmest July ever recorded.

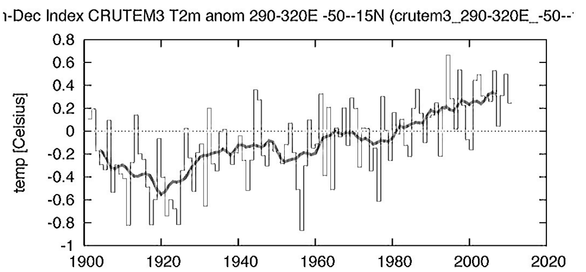
But if a new Gleissberg cycle makes itself felt when the equatorial Pacific has settled back into its 'normal' Trade Wind state, and if the new cycle overwhelms the effect on SAT measurements of urbanisation and land use change so that the GSMT index cools significantly, then the earth sciences will have a heavy bill to be paid in the arena of public support - and the more so if a Convention concerning measures agreed to be taken has already been signed into effect…

Annex 1 – Regional mean surface air temperatures (CRUTEM3) for selected global regions obtained from the KNMI Climate Explorer facility. Note that the temporal axes are not uniform, and that some entire regions have no data record until well into the 20th century. Note also that these data represent both rural and urban meteorological sites and have not been adjusted for the urban heat island effect.

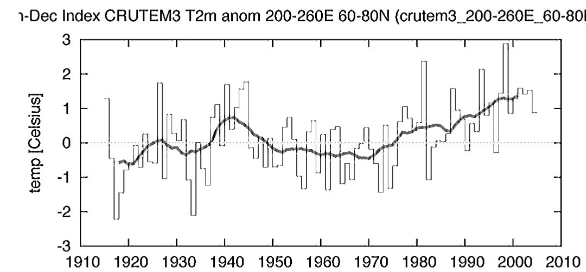




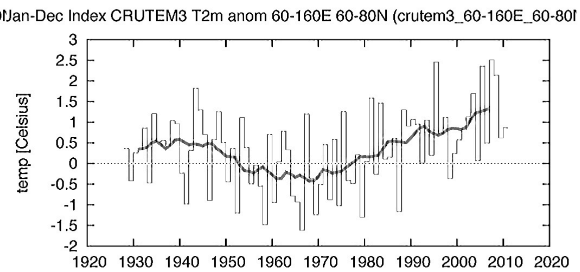
Region D – USA



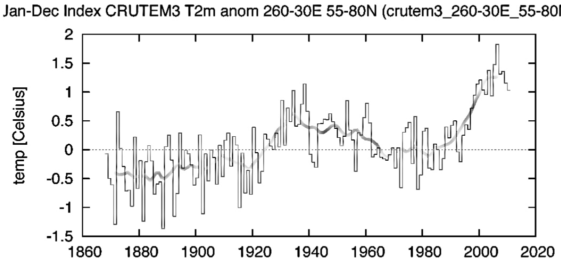
Region L – Southern S. America



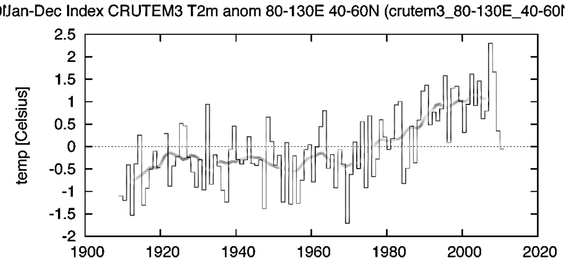
Region A – Northern Canada



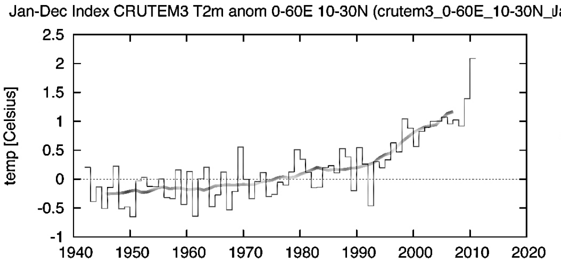
Region C – Northern Russia



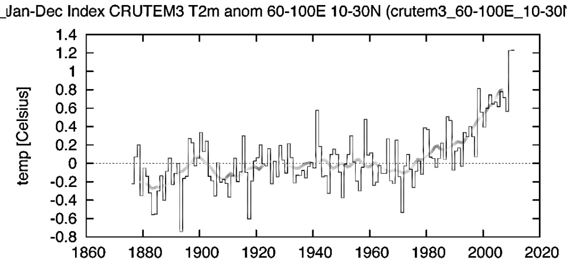
Region B – Atlanto-Nordic



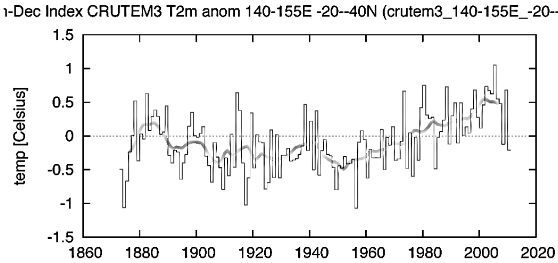
Region E – Central Asia



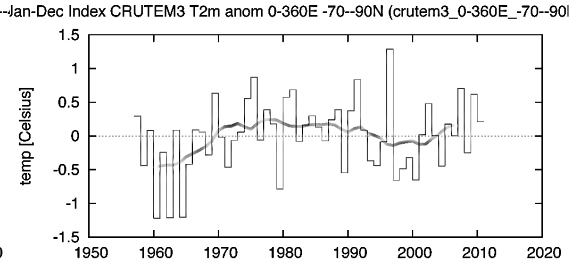
Region G – Middle East



Region H – Pakistan to Burma



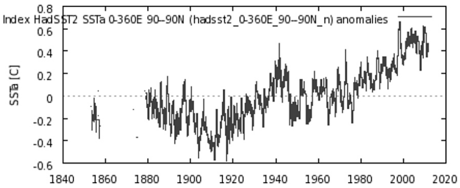
Region M – Eastern Australia



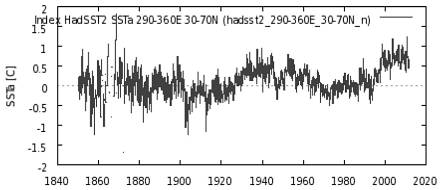
Region O – Antarctica inlandeis

Annex 2 - Global and regional ocean SST anomalies, Hadley Center SST 1850-now, 5^0, obtained through KNMI.

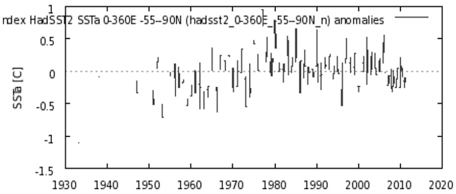
All oceans



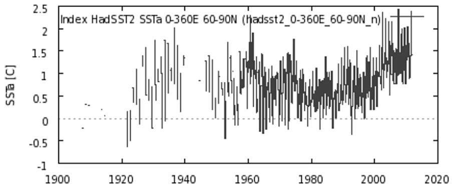
North Atlantic



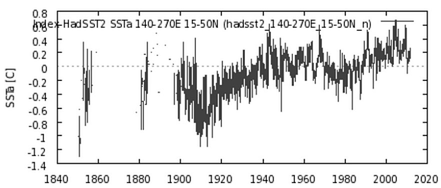
Antarctic Ocean



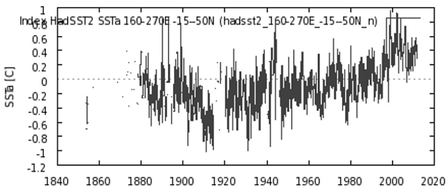
Arctic Ocean



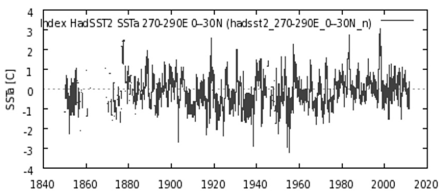
North Pacific



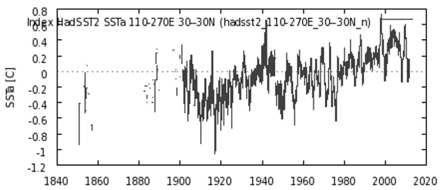
South Pacific



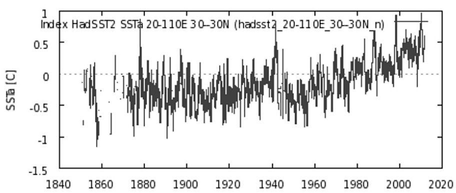
Peru Upwelling region



Tropical Pacific



Indian Ocean



Tropical Atlantic