The South Atlantic and the Atlantic Meridional Overturning Circulation

This presentation borrows heavily from the paper by the same name by Silvia L. Garzoli and Ricardo Matano published in Deep-Sea Research II 58 (2011) 1837–1847

Introductory Video on Ocean Circulation

Please view video at this link

https://www.youtube.com/shorts/G6zcWjBwIB4

Disclaimer

- Discussions this paper (written in 2010 based on data previous to that) were highly influenced by climate alarmism which was becoming popular at the time
  - They are wrong in my opinion
  - This is especially true of human caused Climate change
- In fact this paper because of it's wide scope of naturally occurring climate drivers often makes the case for solar cycles and nature as the driver
- As a wide ranging discussion of complicated ocean currents the paper isn't generally too bad

Disclaimer

Continues

- And I have found more recent papers that cover the subject in smaller parts than this one, but we cannot forget that:
  - It is more than 15 years out of date
  - ARGO and other ocean monitoring systems have given us a clearer view of this complicated dynamic ocean system that is fundamental to weather and climate activity
  - Even those alarmist “climate scientists” who say humans and CO_2 are the main drivers of climate change admit that CO_2 warming is only in the few W/m^2 realm
  - At the solar furnace in the 1980s I observed variations in solar activity in the 100s of W/m^2 with H_20 humidity and clouds being some of the most basic moderators of those large inputs of energy
  - Another non-human moderator of ocean activity is wind
    - Sea surface temperature (SST) is fundamental in producing wind variations at sea
- The paper at least shows some of the great natural complexity of these basic oceanic phenomena

Aside on Two Types of Ocean Circulation

- Wind driven
  - Forced by wind stress on the sea surface, inducing a momentum exchange
- Thermohaline circulation
  - Driven by the variations in water density imposed at the sea surface by exchange of ocean heat and water with the atmosphere
  - Induces buoyancy exchange

Wind Driven Circulation

- More vigorous of the two
- Configured as gyres that dominate an ocean region
  - Subtropical gyres extend from the equatorial current system to the maximum westerlies in a wind field near 50° latitude
  - Subpolar gyres extend poleward of the maximum westerlies
- Strongest in the surface layer
- Similar for each ocean
- In stratified tropical regions, typically extend to < 1000 m depth
- In less stratified regions, can extend to the sea floor

90°N
60°N
30°N
0°
30°S
60°S
90°S
45°E
90°E
135°E
180°
135°W
90°W
45°W
0°
Speich 2009 adapted from Lumpkin 2007

Thermohaline Circulation

- More sluggish
- Typical speed of 1 cm/s
- But extends to the seafloor
- Forms circulation patterns that envelop the global ocean

Wind Driven Circulation

More information

- Equatorial currents
  - North equatorial current
  - South equatorial current
  - Equatorial countercurrent
- Subtropical gyres
  - Anticyclonic
  - Complex structure as seen in the Gulf Stream
- Subpolar gyres
  - Cyclonic
  - Ekman transport within these features forces upwelling and surface water divergence
- Antarctic circumpolar current
  - Extends to sea floor and so highly influenced by sea floor topography

Introduction

- Before 2007, discussion of greenhouse warming and collapse of the global Meridional Overturning Circulation (MOC) were largely restricted to the academic circles
- Owing to climate activism and media hype, these topics have become fodder for public debate
- Mounting evidence suggests that climate is indeed undergoing **significant variability and change**
- Data sets generally show increases in global temperature and sea level rise during the last century
- Predictions based upon models often are **keen to show consequences** that such changes might have on societies
- Paleo-climate investigations suggest that past shutdowns of the MOC may have **triggered ice ages** with dramatic decreases of the temperatures in western Europe and beyond

Perceived Fragility of the Climate System Has Prompted a Flurry of Studies (2010 Time Frame)

Conclusions are, <u>if not alarming, at least worrisome</u>

- Hansen et al. (2001) reported a 20% reduction in the overflow of deep waters through the Greenland–Scotland Ridge that feeds the densest portion of the MOC cell

- Häkkinen and Rhines (2004) showed that the subpolar gyre of the North Atlantic has slowed appreciably during the last decade and suggested that a weakening of the MOC is underway.

- Bryden et al. (2005) argued that the strength of the MOC has decreased by more than 30% over the last five decades

- **None of these studies is conclusive:**
  Different models show different results

Policy Implications

- Bryden findings are based on just five hydrographic snapshots; nevertheless some say the robustness of the conclusions deserves the attention of the scientific community

- Policymakers face the dilemma that the changes suggested by the above studies could be the response of the oceans to global warming, **but they could just as well be a natural mode of oceanic variability**

- To separate anthropogenic from natural effects we need to substantially improve the existing observational system and foster development of models that more accurately capture the complexity of the climate system

It is not always easy to separate fact from fiction

- The paleo-climate record indeed suggests that past shutdowns of the MOC triggered ice ages with dramatic decreases of the temperatures in western Europe and beyond. Almost all the statements on the previous slides (especially those about human caused climate change are mostly false).
- **But**
  - It is clear that natural cycles are the driver of climate change - especially cycles that are sun based
  - CO_2 does have a small warming effect and humans have introduced relatively small additional amounts into the atmosphere over the past 100 years
  - Water vapor and clouds (H_2O) have a much larger effect (several orders of magnitude) on atmospheric warming and cooling

State of the Measurements

- Currently(in 2010), there is only one quasi-comprehensive monitoring system of the AMOC in the northern North Atlantic: the RAPID/MOCHA array in conjunction with the observations of the warm, shallow limb in the Florida Current/Gulf Stream and of the Deep Western Boundary Current (DWBC)
  - Started in the early 1980s off Florida
  - Provided the basin-wide integrated strength and vertical structure of the Atlantic Meridional Overturning Circulation (AMOC) at 26.5° N
- Other systems (next several slides-post 2010) have been designed to observe some of the important components of the AMOC that can be used to verify and be assimilated into models, including
  - Attempts to monitor the same components are located in other parts of the North Atlantic, e.g., the Denmark Straits overflow
  - A small pilot effort recently started in the South Atlantic (as of 2020)
- Given the complexity and worldwide impact of the AMOC, even if these systems succeed in warning of potentially important changes of the AMOC, they are insufficient to determine causality and are unable to predict further evolution of such changes

Information Needs

A more comprehensive view must take into account the changes in the other basins is needed

- To interpret the climate-related changes occurring in the North Atlantic, e.g., we need to understand the variability of its contiguous basin, the South Atlantic, because
  - Its heat and salt fluxes are essential for the formation of the North Atlantic deep waters
  - It has a natural link with all the other major oceans.
- In the current study, the South Atlantic is defined as the region between the tip of the Palmer Peninsula (60° S) and the northern limit of the subtropical gyre (15° S) to encompass the subpolar and subtropical regions
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Information Needs continues

- Contribution of the South Atlantic to the AMOC was implicit in early observations conducted from the German research vessel Meteor (1935)
    - Show a mean South Atlantic meridional circulation that exports heat in the “wrong” direction (e.g., from the south pole to the equator)
- There remains great uncertainty on the magnitude of the South Atlantic inter-ocean fluxes
- Uncertainties are compounded by the fact that South Atlantic is not just a passive conduit for transit of remotely formed water masses, but actively influences them through air–sea interactions, mixing, and subduction and advection
    - E.g. it is insufficient to know the inflows at the Drake Passage and the Cape of Good Hope to determine the South Atlantic export of thermocline water to the North Atlantic.
    - It can be argued that, since the South Atlantic circulation depends on the inter-oceanic fluxes and those in turn depend on the South Atlantic circulation any attempt to determine one independently of the other leads to an ill-posed problem.

New Information Is Becoming Available

- Some short-term measurements seemed to show that the AMOC was slowing down
- Writing in The Daily Sceptic, Chris Morrison reports on a 20-year study of the AMOC.
    - “For 20 years the RAPID-MOCHA-WBTS Array has measured the movements along the Atlantic Ocean at 26°N. A number of submerged stations have collected large amounts of data on the currents that bring warm waters from the Gulf up to the Arctic and return them cooled, heavier and saltier back to the south. Alarmists and Net Zero fantasists have long argued that humans interfere with this process. In unison they wail (perhaps next year!) that a ‘tipping point’ could be reached where the currents reverse and bring ice age weather to countries in the northern hemisphere.”

New Information (as of 2026)

Continues

- Computer models that have produced countless *The Day After Tomorrow* headlines that are being rendered increasingly worthless by the actual RAPID data
- In fact, there has been a largely unannounced pause in any weakening of the Gulf Stream—which is part of the Atlantic Meridional Overturning Circulation (AMOC)—since the early 2010s
- Before that and going right back to the start of measurements in 2004, the strength was generally relatively high, but there was a substantial weakening between 2009-2010
    - The scale of this temporary weakening skewed the 20-year record to show a 6% decadal decline
    - RAPID has shown that sharp changes on a daily to inter-decadal period are the norm rather than exceptional
    - All of this is likely to be due to natural variation, what is often referred to as ‘noise,’ rather than any human cause.

New Information
Continues

- Many of the fluctuations appear to be driven by changing air currents rather than deeper water formulations alone
- These findings are fundamentally changing the way scientists understand the operation of the AMOC
    - Single or short-period snapshots are inadequate in measuring long-term strength
- Needless to say, computer models are simply not up to the task of separating out any noise arising from the natural variability

New Information

Continues

- Scale of natural variation can be truly astonishing
  - RAPID observations from 2004- 25 show a weakening of 1 Sv per decade in the AMOC.
    - The Sverdrup (Sv) is a unit used in oceanography equal to 10^6 m^3/s of water flow
  - AMOC has an average strength of 16-18 Sv, so the 20-year 6% average decadal decline is measurable but not necessarily significant especially in light of the enormous outlier recorded around 2010
  - RAPID has shown that the AMOC can vary by several Sverdrups over months to years
  - The decline in 2009-2010 saw a 30% weakening
    - Since that time, flow has been returned to normal
  - Enormous scale of changes can be seen by comparing the 2009 value 14.6 Sv with the 2018 value of 18 Sv
    - One “possible” cause of this huge change that we can confidently rule out is humans using hydrocarbons
- Natural variation is not a long-term trend from increasing CO_2


Sea Surface Temperature (L4, MUR)
Multi-mission / GHRSST
v4.1 STD
< 0.00 °C
≥ 32.00 °C

New Information

Continues

Goal of the study was to demonstrate that, in addition to the existing observations in the North Atlantic, monitoring the South Atlantic for inter-basin exchanges and the choke points that connect the basin with the Pacific and Indian oceans will improve our understanding of these phenomena, facilitate the search for predictors, and lead to improved climate prediction models

Background Information

- Mean meridional structure of the South Atlantic circulation involves a deep southward flow of cold and salty North Atlantic Deep Water (NADW) along the eastern coast of South America, and compensating northward flows of surface, central, and intermediate waters

- South Atlantic connects with the Pacific and Indian Oceans providing the gateway by which the AMOC connects with the rest of the globe. As such, a significant exchange of water masses imported from the adjacent basins is to be expected

- The warm and salty water that spreads in the North Atlantic is cooled primarily by evaporation, which sinks to the deep ocean and forms the North Atlantic Deep Water (NADW)

- Export of NADW to other ocean basins is compensated for by a net northward flow through the South Atlantic and across the equator of surface, intermediate, and bottom water layers

- The compensating northward flow is a mixture of warm and salty surface and central waters, and cooler fresher Atlantic Intermediate Water (AAIW) (Fig. 1).


90°N
60°N
30°N
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90°E
135°E
180°
135°W
90°W
45°W
0°
Speich 2009 adapted from Lumpkin 2007

Background Information

Atlantic Surface, Mid and Deep Water Currents

- The surface water is characterized by high salinity and is formed in the tropics/subtropics transition region by subduction between 12°N and 15°S
- Central water is commonly subducted into the thermocline, and its formation in the South Atlantic occurs at the confluenceof the Brazil and Malvinas currents in the southwestern Atlantic with characteristics of Subtropical Mode Water at 16–18° C
- In the Southwestern Atlantic, the AAIW originates from a surface region of the circumpolar layer, in particular north of the Drake Passage and in the Malvinas Current, a loop of the circumpolar current entering the South Atlantic
- In the eastern side of the basin, AAIW from the Indian Ocean enters the South Atlantic via the Agulhas leakage
- This South Atlantic circulation pattern, in which warm waters flow towards the equator and cold waters flow towards the pole, results in an equatorward heat flux
- This net northward flow of properties is expected to be sensitive to the relative contributions of the components of the returning flows originating in each one of the connecting oceans

Background Information

Atlantic Heat Transport

- The South Atlantic is the only basin extending to high latitudes in which the heat transport is equatorward.
- Although this distinct heat flux was recognized by the middle of the last century, the sources for the upper waters are still in dispute.
- A portion of the South Atlantic upper waters is produced locally but most of the South Atlantic upper waters are thought to originate in the Pacific and Indian oceans.
- At issue are not only the relative importance of these sources but also the mechanisms of entrainment.

Background Information

Theories of current paths

- Gordon (1986) proposed the warm path hypothesis, which postulates that the South Atlantic receives most of its upper waters from the Indian Ocean as eddies and filaments released at the retroflection of the Agulhas Current and driven to the northwest by the Benguela and the Benguela Current extension.

- Rintoul(1991) proposed an alternative source, the cold path, by which AAIW injected from the Pacific through the Drake Passage is converted to surface water through air–sea interactions to become the main supply of South Atlantic upper waters.

- To reconcile the differences between these theories, Gordon et al. (1992) proposed a modification of the original warm path route by which the AAIW carried eastward by the South Atlantic Current is entrained into the Indian Ocean and recirculated by the Agulhas Current (Fig. 1)

Background Information

Very little change in path theories

- It has been over three decades since the publication of Gordon's and Rintoul's influential articles, but there is still no consensus on the origins of the South Atlantic northward mass outflow

- Some of the studies that followed supported the coldpath theory while others supported the warm-path theory

Background Information

More “Path” Discussion

- Donners and Drijfhout, 2004; Speich et al., 2002), and others postulated that both paths are important (Matano and Philander, 1993; Macdonald and Wunsch, 1996; Poole and Tomczak, 1999)
- Donners and Drijfhout (2004) contested the studies supporting the cold-path hypothesis on the ground that their conclusions were biased by the method of analysis. Using the results of a global, eddy permitting model, they argued that the results of inverse calculations are hindered by a lack of spatial resolution
- They showed that if the model results are analyzed within an Eulerian framework they also seem to suggest the dominance of the cold-path over the warm-path theories
- However, if the model results are analyzed with a Lagrangian technique, which follows the trajectories of specific water masses, they show the dominance of the warm path over the cold path.

Background Information

South Atlantic Circulation

- Although these arguments are far from being conclusive, they clearly illustrate that the weakest link of existing estimates of the South Atlantic water mass balance is our lack of knowledge of the South Atlantic circulation itself
- The uncertainty about the South Atlantic circulation also manifests itself in the estimates of the meridional heat transport, which vary from negative to positive values(e.g., Macdonald et al., 2001)
- This broad spread in the estimates reflects deficiencies in both the data available and in the methodology used for the calculation
- Since climate change studies assess the variability of the different components of the Earth system, it seems particularly worrisome that the gaps in our understanding of the South Atlantic variability are much larger than those of its mean circulation.

Background Information

Continues

- There are numerous studies on the mesoscale variability of the South Atlantic most energetic regions such as the Brazil/Malvinas Confluence and the Agulhas retroflection, but very few on the low-frequency variability of the large-scale circulation.
- Venegas et al. (1997,1998) and Palastanga et al. (2002) investigated the low-frequency variability of the South Atlantic's sea surface temperature (SST) from approximately 40 years of climatological data
- They identified three low-frequency modes of variability with periods of about 14, 6, and 4 years that, according to their analyses, are associated with variations of sea-level pressure
- Sterl and Hazeleger (2003) and Haarsma et al. (2005) added that these modes are generated by anomalous winds through turbulent heat fluxes, Ekman transport, and wind-induced mixing
- Although these studies are valuable contributions to the understanding of the climate variability over South America and Africa, it has been argued that SST anomalies do not necessarily reflect the variability of the oceanic circulation below the mixed layer

Background Information
Continues

- Witter and Gordon (1999) published an observational study of the low-frequency variability of the South Atlantic's thermocline circulation
- Using 4 years of altimeter data they identified two dominant modes of sea surface height (SSH) variability
- The first mode has a maximum in the eastern portion of the basin and indicated that the anti-cyclonic circulation in the subtropical gyre weakened from 1994 to 1996 and strengthened thereafter
- They also observed a similar temporal signature in the zonal winds, suggesting a coupling between the oceanic and the atmospheric variability
- The second mode was associated with inter-annual variations in the Brazil/Malvinas Confluence

Background Information

South Atlantic subtropical gyre

- A recent study analyzed the variability of the South Atlantic subtropical gyre using satellite derived SSH and SST anomalies and concluded that the interior of the gyre has expanded by 40% of its total area.
- They also found that the mean dynamic height of the gyre had increased 3 cm per decade and hypothesized that this increase may be due to increased heat storage of the upper layer
- Lumpkin and Garzoli (2011), through the analysis of a combination of surface drifters and altimetry, found a southward shift of $0.86\pm.06^{\circ}$ per decade in the confluence latitude of the Brazil and Malvinas Currents
- A comparable trend is found in the latitude of the maximum wind stress curl averaged across the South Atlantic basin
- This variation appears to be inversely related to long-term variations in SST anomaly in the Agulhas–Benguela pathway of the eastern South Atlantic subtropical basin

Background Information

NADW relative to South Atlantic Basin

- The time series of the bifurcation of the South Equatorial Current shows a trend of $0.23 \pm .06^{\circ}$ per decade with an asymmetric growth of the subtropical gyre

- In summary, the South Atlantic is the main pathway of the compensating flows needed to maintain mass balance due to the export of NADW

- This compensation is accompanied by a distinct northward heat transport

- The strategic location of the South Atlantic raises the question of whether this basin is just a passive conduit for the passage of remotely formed water masses or whether its internal dynamics influences the AMOC

Let’s End Today’s Discussion with this Global Simulation of Ocean Circulation from NASA

https://svs.gsfc.nasa.gov/vis/a000000/a005400/a005425/perpetual_ocean2_beauty_hw5x3_810p30_5.mp4