Role of Oceans in Climate
A Modeler’s Perspective

Ronald J Stouffer
Geophysical Fluid Dynamics Laboratory
NOAA

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Conclusions

• The planet is warming.
• Greenhouse gases are increasing due to human activity
• Human activity very likely cause of most of the warming in last 50 years or so.
• Future climate changes are likely to be much larger than what we have experienced so far.
Oceans role in Climate

• Wet Surface
• Heat and tracer storage and transport
  – Seasonal
  – Longer time scales
• Natural variability
• Abrupt climate change
Ocean’s role
Wet Surface

• Supply water to atmosphere
  – Manabe and Wetherald Swamp Model
  – No heat capacity, wet surface only
Ocean’s Role
Seasonal Heat Storage

- Atmosphere Mixed Layer Ocean (Slab) Models
  - Manabe and Stouffer 1979
  - 50m deep bucket, no horizontal or vertical heat transport
  - Heat flux adjustments or QFLUXES
  - Assumes no changes in heat transports as climate changes
  - Still being used to estimate climate sensitivity and other types of studies
Ocean’s Role
Longer time scales

- Storage
  - Heat
  - Carbon
  - Other tracers

- Transport
Surface Air Temperature Response to Increasing GHG

- Cooling spots in N Atlantic and SO due to ocean processes.

Surface Warming Pattern A1B, 2090-2099 relative to 1980-1999

IPCC WGI SPM
Where is heat stored?
Latitude-Depth, zonal mean difference – 1% run
The Southern Ocean in the AR4 Climate Models
Comparison of AR4 Coupled Climate Models

Maximum westerly wind stress vs ACC strength

Russell et al., 2006
Comparison of AR4 Coupled Climate Models

ACC transport vs. difference in density between 65° S and 45° S

Russell et al., 2006

ACC transport vs. difference in density between 65° S and 45° S
Zonally-averaged wind stress (N/m²).
Observed (black), GFDL-CM2.1 (blue, circle), GFDL-CM2.0 (blue, triangle)
The Subtropical Front is defined as a Salinity of 34.9-35.0 at 100m
The southern boundary of the ACC is defined as $\sigma_0$ of 1027.6 at 200m
(After Orsi, 1999)
The Southern Ocean in a Warming World

How will the AR4 model errors impact the simulation of climate change?

Use CM2.1 and CM2.0 as examples – “good” and “bad” SO simulation
Surface Westerly Wind Change
Model Response to SRESA1B Scenario

(CO₂ increases to 700+ppm @ year 2100, steady to 2300)

...as CO₂ increases (~doubles), the S. Hemisphere’s westerly winds strengthen (max zonal wind stress + ~10%)

Russell et al., In press.
Model Response to SRESA1B Scenario

$(\text{CO}_2 \text{ increases to } 700+\text{ppm @ year 2100, steady to 2300})$

...as CO$_2$ increases, the latitude of the maximum westerlies moves south

$(\sim 1\frac{1}{2}^\circ \text{ (CM2.1) to } 2^\circ \text{ (CM2.0) closer to Drake Passage})$
Model Response to SRESA1B Scenario

(CO$_2$ increases to 700+ppm @ year 2100, steady to 2300)

...and the ACC strengthens over time, even after CO2 stabilization
(from year 2000 to 2300, CM2.0 ~100 to 137Sv, CM2.1 ~135 to 152Sv)
Model Response to SRESA1B Scenario

(CO₂ increases to 700+ppm @ year 2100, steady to 2300)

...N-S temperature and salinity gradients strengthen, leading to a stronger density gradient across the ACC (0-2500m)
As one might expect in a warming world, the area over which potential densities exceed 27.1 ($\sigma_\theta$) at 100m depth (shown in yellow) is reduced as surface waters warm, and the depths at which the $\sigma_\theta$ 27.1 surface lie become deeper.
The outcrop area decreases as the surface waters warm.

... decreases by \( \sim 8 \times 10^6 \text{ km}^2 \) (~33%) in CM2.1

... decreases by \( \sim 7 \times 10^6 \text{ km}^2 \) (~50%) in CM2.0
Yet the amount of water that has been in contact with the surface less than 50 years prior grows because of more Southern Ocean ventilation. (due to more surface divergence) …increases by ~6% in CM2.1… …less so in CM2.0
The Ocean’s Heat Inventory Grows Over Time

More so in CM2.1 (solid) than CM2.0 (dash) as time goes on & effects of deep ventilation differences become more apparent. The largest differences are in the Southern Ocean uptake and subsequent storage in the Indian and Pacific Oceans.
Time series of volume averaged ocean temperature difference (°K), the various integrations minus the control.

From Stouffer, Russell & Spelman, 2006
Surface air temperature difference, perturbation integration minus the 1860 control integration (°K).
So how might the Southern Ocean change in a warming world?

Changes that could lead to less oceanic CO2 uptake…

- Warmer, fresher, more stably stratified Southern Ocean surface waters would decrease ocean ventilation rates.
- CO2 solubility decreases as SSTs warm.

Changes contributing toward more oceanic CO2 uptake…

- S.H. westerlies strengthen and move poleward, thereby increasing divergence, exposing more water to the atmosphere.
- pCO2 difference between majority of upwelled water and atmosphere increases as tropospheric CO2 increases, driving more CO2 uptake by the ocean.

Note: we’re not including biological mechanisms and feedbacks here!
Method for inferring future solubility-related “carbon” uptake

- We estimate the inferred anthropogenic CO₂ concentration due to changes in solubility by:

  \[ C_{\text{anth}} = C_{\text{sat}} - C_{\text{eq-modern}} \]

  where \( C_{\text{sat}} \) is the saturation value of DIC calculated from the modeled temperature, salinity and atmospheric pCO₂ and where \( C_{\text{eq}} \) is the WOCE distribution of DIC from GLODAP.

- We assume 100 percent saturation with respect to the atmospheric pCO₂ over a 5 year period, an unchanging biological pump (\( C_{\text{bio}} \)) and pH distribution (ignoring the effect of buffering).
Caveats!

• We assume a constant pH distribution, ignoring the effect of buffering.

• We assume a constant biological pump, i.e. no change in surface to deep DIC distribution

  – These are clearly important effects that need to be addressed - but the appropriate tracers weren’t included in the AR4 models.
The Ocean’s Solubility-related Carbon Inventory Grows Over Time

Over the first 50 years, the dominant effect is the increasing carbon dioxide in the atmosphere driving an increase in surface ocean solubility. After 50 years, deep ocean ventilation diverges due to the poleward intensification of the Southern Hemisphere Westerly Winds.
Heat and solubility-related carbon inventory grows over time

More so in CM2.1 (solid) than CM2.0 (dash) as time goes on & effects of deep ventilation differences become more apparent.
Heat and “Carbon” Storage Difference in 2300

CM2.1 - CM2.0 (2300-2000)

(A) Heat Storage Difference (10^9 J/m^2) CM2.1 - CM2.0

(B) “Carbon” Storage Difference (mol/m^2) CM2.1 - CM2.0

Heat Storage Difference (10^9 J/m^2)  Carbon Storage Difference (mol/m^2)
Response time scales
Role of Oceans

Anthropogenic warming and sea level rise would continue for centuries, even if GHG concentrations were to be stabilized at or above today’s levels.

AR4 estimates 0.2 to 0.6m sea level rise per °C at equilibrium due only to thermal expansion of sea water.
Oceans: Role in Natural Variability

• ENSO
  – What sets time scale?
    • Atmosphere/Ocean/both?
  – What impacts ENSO?
    • Atmosphere convection scheme, ocean color, ocean mixing

• NAO/AO/AMO/MOC
  – Multi-decadal variability
    • Predictable?
  – Hurricanes

• Century or longer oscillations in SO
  – In some models, in real world?

• Eddies – feedback on larger scale surface climate?
Predictability of Atlantic Meridional Overturning Circulation (AMOC) in GFDL CM2.1 Climate Model
Oceans: Role in Abrupt Climate Change

- MOC
  - Unforced
  - Forced
    - Idealized (Hosing)
    - GHG increase
- Other processes?
Transient
An Anomalous Event (Unforced)
Surface variables/THC

time series of SST, SSS, SAT at 65°N, 24.5°W
(N. Atlantic max. meridional streamfunction is also shown)
Summary of Physical Mechanism
Idealized Forced THC Response

• Additional 1SV for 100 years
  – Hosing in N Atlantic
  – Hosing around Antarctica

• After 100 years, additional flux set to 0SV
Surface Air Temperature
Response

Response remarkably symmetrical (first 100 yrs)
Magnitude very similar
Precipitation Response

Response very symmetric
Magnitude very similar
ITCZ shifts toward warmer hemisphere
Hosing Experiment Summary

• Symmetrical Atmospheric Response
• Much less symmetry in ocean
• Why?
  – Strong Circum-Antarctica winds
  – Northward flowing surface waters
  – Freshwater “escapes” into other basins
    • Far a field impacts
    • Less local impacts
AR4 WG1 Assessment:
- MOC very likely to weaken
- MOC shutdown very unlikely
Warming greatest over land and at most high northern latitudes and least over Southern Ocean and parts of the North Atlantic Ocean.

- Weakening of MOC contributes to minimum in cooling in N Atlantic => smaller climate change => a positive impact?

Surface Warming Pattern
A1B, 2090-2099 relative to 1980-1999

IPCC WGI SPM
Summary
Ocean’s Role in Climate

• Wet surface
• Heat and tracer storage
  – Climate change
  – Variability
• Heat, water, tracer transport
• Abrupt climate change
Questions

• Is weakening of MOC a positive or negative impact?

• What is impact of MOC shutdown?
  – How large are changes?

• What is role of oceanic eddies in climate change?

• Do we have enough measurements to evaluate heat and other tracer storage terms and transports as climate changes?
  – XBTs – good enough?
  – ARGO
  – Initialization of decadal prediction experiments
Thank you
AR4 ensemble mean error
Temperature

Figure 8.9. Time-mean observed potential temperature (°C), zonally averaged over all ocean basins (labelled contours) and multi-model mean error in this field, simulated minus observed (colour-filled contour). The observations are from the 2004 World Ocean Atlas compiled by Levitus et al. (2005) for the period 1957 to 1990, and the model results are for the same period in the 20th-century simulations in the MINC at POMI. Results for individual models can be seen in the Supplementary Material, Figure S8.12.
AR4 ensemble mean error

Salinity

IPCC WGI Chapter 8 Suppl. Material
Impact of Current Position on Temperature Error (0:200m)
Time scales of Response
Implications of Heat Storage

• Human and natural systems
• Physical climate system
  – Greenhouse gas lifetimes in atmosphere
  – Ocean
  – Ice sheets
Special Report on Emission Scenarios (SRES, 2000) and Post-SRES scenarios

- SRES emission scenarios used to make projections of 21st century changes.
- There is high agreement and much evidence that with current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades.
Response time scales

- Note response in 2020’s very similar in spite of very different emissions.
- Note response in 2090’s much more scenario dependent.
- Actions taken today only have large impacts in climate response in the future.
Response time scales
Role of Oceans

Graph showing temperature changes over time, comparing Atmospheric GCM & Mixed Layer Ocean (near equilibrium) and Fully Coupled Atmosphere–Ocean GCM (transient response).
Experimental Design
Manabe Climate Model “MCM”

• R30 AOGCM coupled model
• Idealized Water hosing
  – 1 Sv for 100 years
  – After 100 years, stop hosing - allow recovery
• Case 1: Hosing 50N to 70N in Atlantic
• Case 2: Hosing south of 60S in Southern Ocean
• Compare to long control integration
Maximum Negative Anomaly
Maximum Positive Anomaly
Surface Air Temperature
Decadal Mean Difference

SAT anomaly (°C) averaged over years 3100–3105

SAT anomaly (above) except normalized by the standard deviation of decadal mean SAT.
SAT Difference map
SH hosing

Years 51-100 hosing minus 1-200 control
SH THC Response

SH Hosing –

SH THC weakens.

SH THC does not shut down
Atlantic THC Response

Atlantic THC does not respond in a seesaw-like manner

NH Hosing – NH THC shuts down
Differences in Sea Surface Salinity (PSU)
Southern Freshwater Escape

25 years
Hosing minus Control

100 years
Surface Salinity Response

NH SSS anomaly – Intense and confined

SH SSS anomaly – Weaker and spreads
Response more symmetrical than SSS
Magnitude also becoming more similar