The Response of the Southern Ocean to Changing Atmospheric Winds

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Why Study the Southern Ocean?

- Unique geometry
  - no longitudinal barriers
  - physically connects all three ocean basins
  - hosts the Antarctic Circumpolar Current (ACC)

- Important area for ocean-atmosphere interactions (e.g. carbon uptake) and water mass formation
Why Study the Southern Ocean?

**Westerly Wind Stress**

**Southern Ocean Response**

Jasmine S. Bartlett, Oregon State University

Rintoul et al. (2001)
Why Study the Southern Ocean?

- The **ACC** is associated with steep **isopycnals** that outcrop at high latitudes.

- At these outcrops, the deep ocean can exchange heat and carbon with the atmosphere.

- The Southern Ocean makes up about 1/3 of the oceanic carbon sink.
Southern Ocean Dynamics

- **Wind-driven Ekman flow** tends to *steepen* isopycnals
  - Can be described by the Eulerian mean circulation ($\psi_m$)

- **Mesoscale eddies** tend to *flatten* isopycnals
  - Can be described by the Eddy-induced circulation ($\psi^*$)

\[
\psi_{\text{residual}} = \psi_m + \psi^*
\]

Adapted from Marshall & Radko (2003)
What About the Rest of the Ocean?

- Each $T$ represents a volume flux of water, with units $[T] = m^3/s$.
- Each flux $T$ depends on the global pycnocline depth $D$, which is itself set by the balance of these three fluxes.
- The Southern Ocean interacts with the rest of the ocean through these fluxes!
Observational Motivation

Anomalies from climatological mean

Changes in vertical density structure

- There is a clear trend in wind stress, but there is very little change in isopycnal tilt.

- Our central question: Why didn’t the vertical density structure respond much to the observed change in wind stress?
Why Didn’t the Isopycnals Respond?

- What mechanisms might play a role in the ocean’s response (or lack thereof) to increased wind stress?
  - Increased wind stress leads to stronger Ekman transport ($\delta \psi_m$).
  - **Hypothesis**: Enhanced eddy activity ($\delta \psi^*$) canceled out the effect of increased Ekman transport.

  Böning et. al. (2008)

\[ \delta \psi_{\text{residual}} = \delta \psi_m + \delta \psi^* \approx 0 \]
Our Approach: Hierarchical Modeling

Sophisticated numerical models
- Realistic topography and forcing
- Often much harder to interpret

Idealized numerical models
- Simplified topography and forcing
- Often harder to interpret

Simple conceptual models
- Small number of analytical expressions
- Behavior relatively easy to interpret

“... we typically gain some understanding of a complex system by relating its behavior to that of other, especially simpler, systems...we need a model hierarchy on which to base our understanding, describing how the dynamics change as key sources of complexity are added or subtracted.”

\[
A \frac{dD}{dt} = T_U + T_S - T_N
\]

or

\[
\frac{dD}{dt} = \frac{K_v}{D} + \left( \frac{\tau L_x}{A \rho f} - \frac{A_I L_x}{A \beta L_y \rho} D \right) - \frac{C g'}{A \beta L_y} D^2
\]

Upwelling

Ekman transport

Eddy-induced transport

Northern sinking
Conceptual Model

• Alternatively, we could allow the eddies to have a nonlinear dependence on pycnocline depth.

\[ T_{eddy} = \frac{L_X}{L_Y} \frac{K_{ref}}{D_{ref}^{n-1}} D^n \quad n=1,2,3... \]

• \( n=1 \) corresponds to a constant background eddy diffusivity (Gent and McWilliams 1990.)

• \( n=2 \) roughly corresponds to a parameterization based on baroclinic instability theory (Visbeck 1997.)
Conceptual Model

• To find the \textit{equilibrium pycnocline depth}, set \(dD/dt=0\) and solve,

\[
T_U + T_S - T_N = 0
\]

\[
D_0^{n+1} + aD_0^3 - bD_0 - c = 0.
\]

• To get the \textit{adjustment timescale}, linearize the time-dependent equation about equilibrium,

\[
D = D_0 + D', \quad |D_0| >> |D'|
\]

\[
D'(t) = D_0 e^{-t/\tilde{T}}, \quad \tilde{T} = \frac{AD_0}{T_U + 2T_N + nT_{Eddy}}
\]
Conceptual Model Results

- The pycnocline **deepens** in response to increased wind stress.
- The e-folding adjustment timescale is of **multi-decadal** order.

**Hypothesis:** We haven’t observed a change in pycnocline depth with wind stress because adjustment is a **very slow process**.
Idealized Sector Model

Geometry

Wind Stress Forcing

Used two different resolutions:
- Coarse (1°x1°)
- Eddy-permitting (1/6°x1/6°)
Idealized Sector Model
Equilibrium Pycnocline Depth Experiment

- **Experiment**
  - Model allowed to spin up for 500 years with several different (constant) wind stress profiles.

- **Results**
  - **Global pycnocline depth increases** with increasing Southern Ocean wind stress.
  - This is consistent with our conceptual model (lines.)
Idealized Sector Model
“Step Response” Experiment

- Experiment
  - Allow the sector model to spin up for 500 years with a constant Southern Ocean wind stress parameter $\tau=0.13$ Pa.
  
  - Run two configurations for an additional 500 yr,
    - control (no change in wind stress,)
    - doubled wind case (a.k.a. perturbed case, $\tau=0.26$ Pa.)
Idealized Sector Model
“Step Response” Experiment

- The **global pycnocline** takes *centuries* to fully adjust!
- If you decrease the basin area,
  - the response is stronger
  - the response timescale remains multi-decadal
Step Response

- Shown: stream functions of the residual (perturbed minus control run)
  - 10 years after the perturbation is applied, stronger mean, eddy, and residual circulation
  - no changes in the northern hemisphere
- Eddies did not totally cancel out wind-driven transport

10 years after perturbation
Step Response

- Shown: stream functions of the residual (perturbed minus control run)
  - 100 years after the perturbation is applied,
    - stronger mean, eddy, and residual circulation
    - wind’s influence has finally reached the Northern Hemisphere
  - Slow communication through the main pycnocline

100 years after perturbation
Step Response

- Shown: sea surface height (perturbed – control run)
- 10 years after the perturbation is applied, we observe
  - a stronger subtropical gyre
  - lower heights near topographic features

10 years after perturbation
Step Response

• Shown: sea surface height (perturbed – control run)

• 100 years after the perturbation is applied, we observe
  – stronger ACC transport (+40 Sv)
  – a small northward geostrophic current

100 years after perturbation
• Low-resolution
• Anomaly = (Perturbed – control)
• 100 years after wind stress is doubled
- High-resolution (eddy permitting)
- Anomaly = (Perturbed – control)
- 100 years after wind stress is doubled
Idealized Sector Model

- High-latitude warming consistent with Gille (2008)
- Mid-latitude subsurface warming consistent with Roemmich (2007)
Conclusion

• Our central question: Why doesn’t the Southern Ocean density structure respond much to changes in wind stress?

• Our results suggest that
  – Increased eddy activity works against increased Ekman transport, but the compensation is not complete.
  – The small residual will connect with the rest of the ocean on decadal to centennial timescales.
  – As such, the global pycnocline may take many decades to centuries to fully adjust to changes in wind stress.