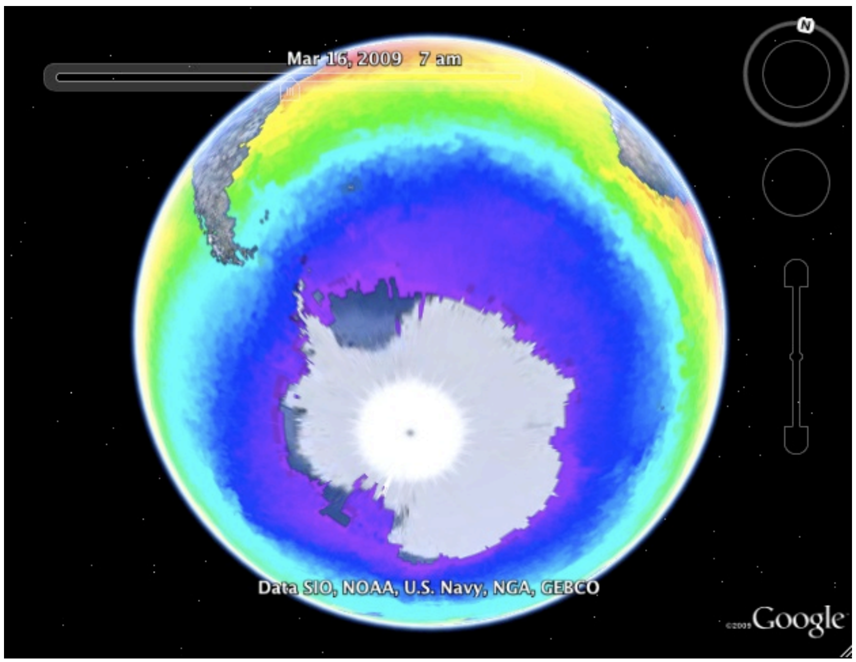
The Response of the Southern Ocean to Changing Atmospheric Winds

Daniel Jones[1], Takamitsu Ito[1], and Nicole Lovenduski[2,3]

[1]Department of Atmospheric Science, Colorado State University
[2]Department of Atmospheric and Oceanic Sciences, University of Colorado
[3]Institute of Arctic and Alpine Research, University of Colorado

Why Study the Southern Ocean?

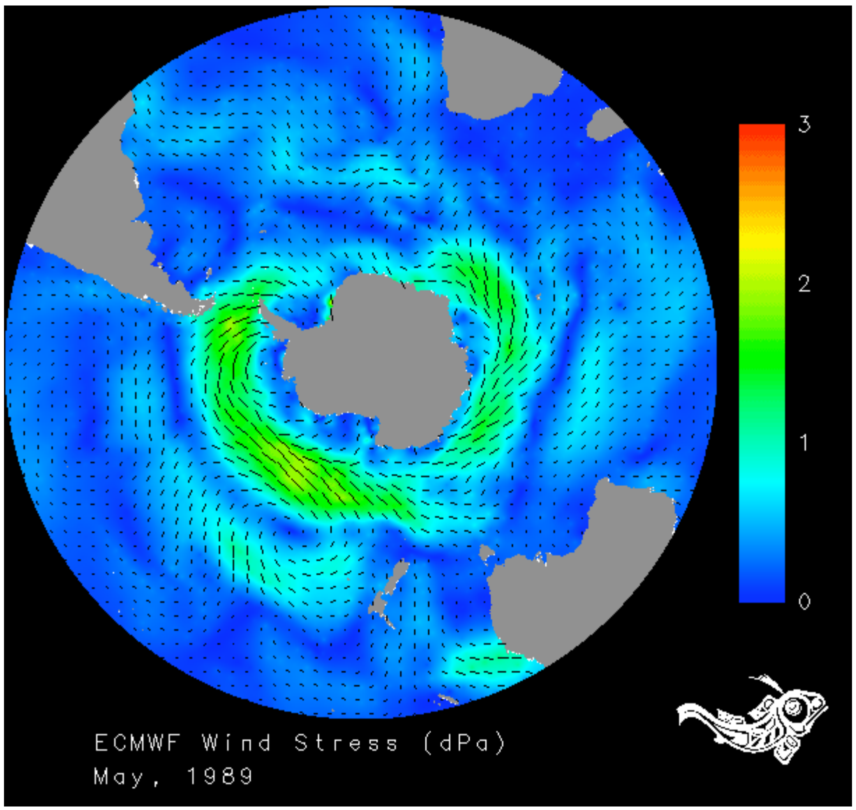


- Unique geometry
  - no longitudinal barriers
  - physically connects all three ocean basins
  - hosts the Antarctic Circumpolar Current (ACC)

- Important area for ocean-atmosphere interactions (e.g. carbon uptake) and water mass formation

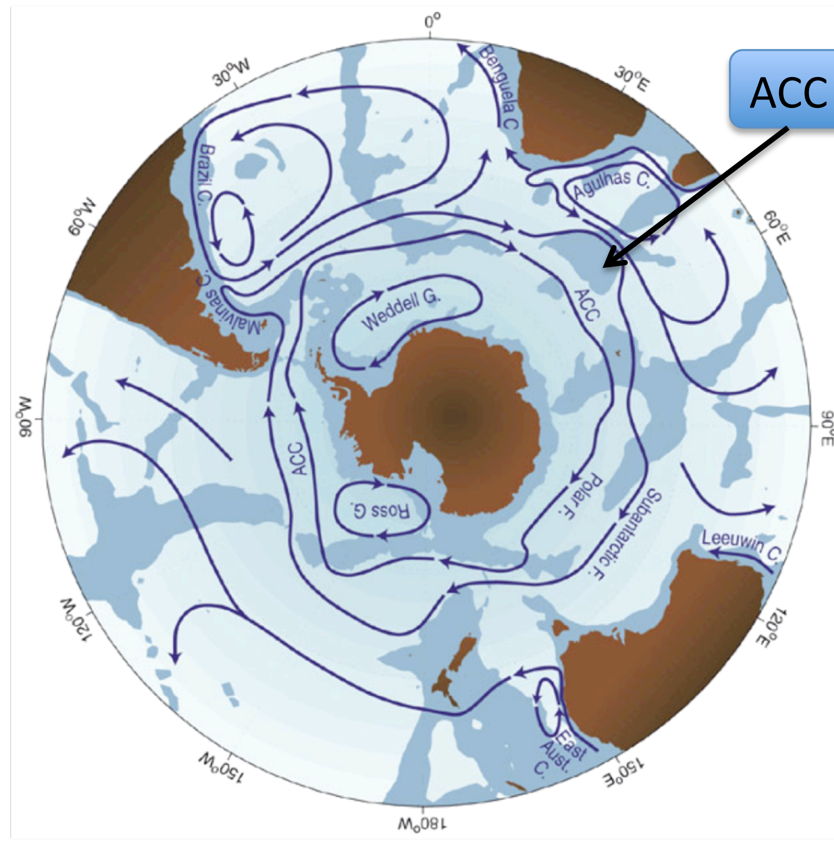
Why Study the Southern Ocean?

Westerly Wind Stress



Jasmine S. Bartlett, Oregon State University

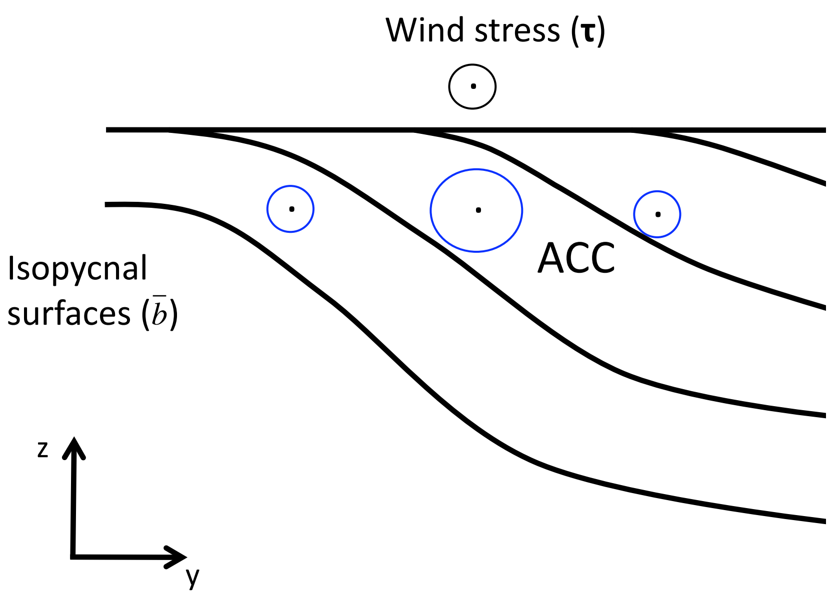
Southern Ocean Response



Rintoul et. al. (2001)

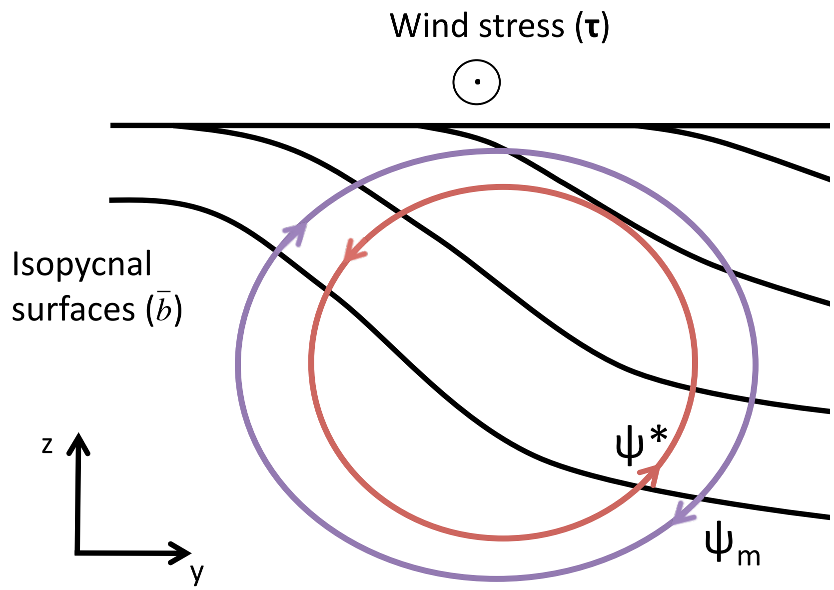
Why Study the Southern Ocean?

- 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

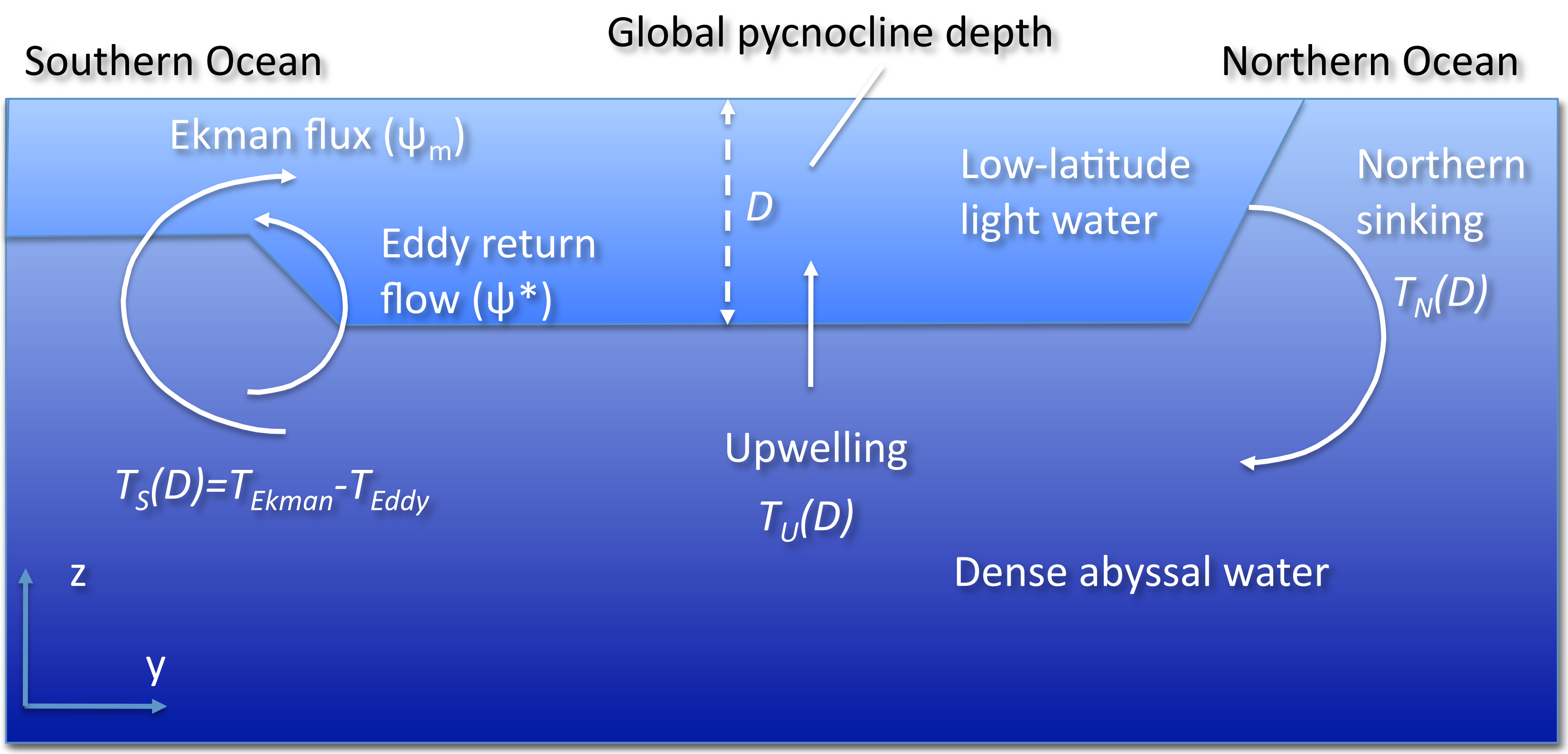
- Wind-driven Ekman flow tends to *steepen* isopycnals
  - Can be described by the Eulerian mean circulation (ψ_m)
- Mesoscale eddies tend to *flatten* isopycnals
  - Can be described by the Eddy-induced circulation (ψ^*)



Adapted from Marshall & Radko (2003)

$$\psi_{residual} = \psi_m + \psi^*$$

What About the Rest of the Ocean?

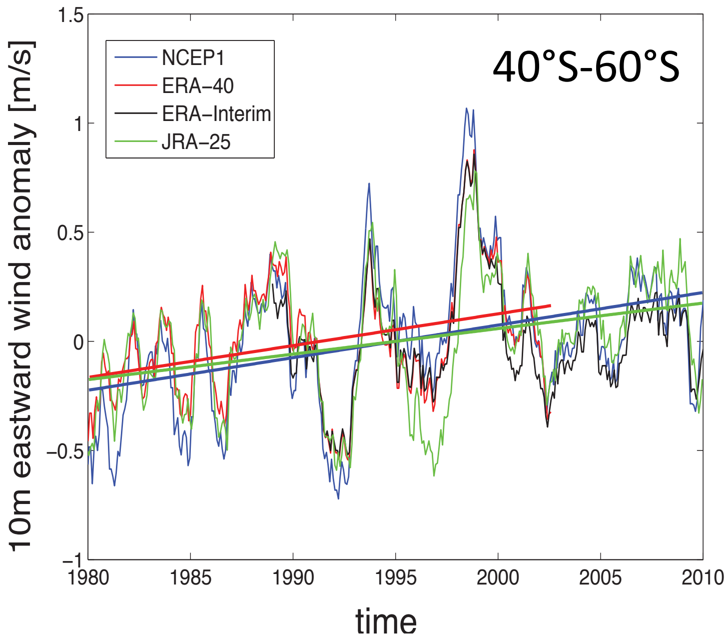


Gnanadesikan (1999)

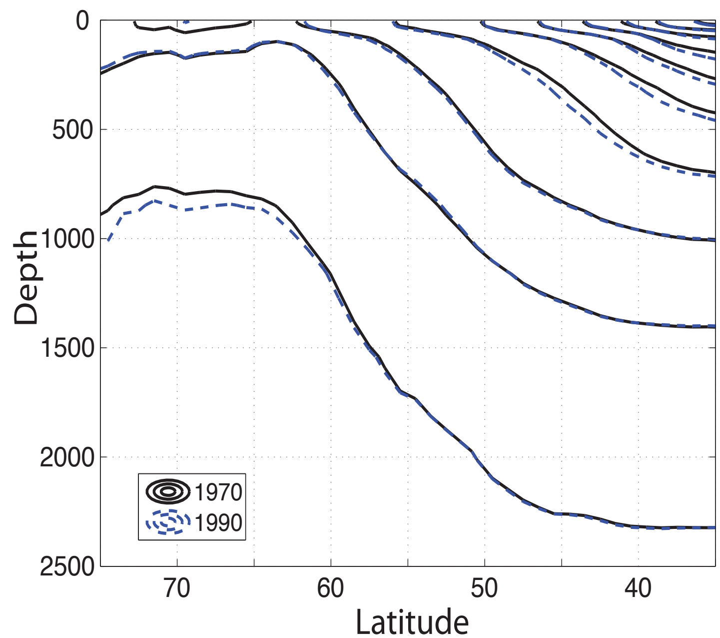
- Each T represents a *volume flux* of water, with units $[T] = m^3/s$.
- Each flux T depends on the global pycnocline depth D, which is itself set by the balance of these three fluxes.
- The Southern Ocean interacts with the rest of the ocean through these fluxes!

Observational Motivation

Anomalies from climatological mean



Changes in vertical density structure

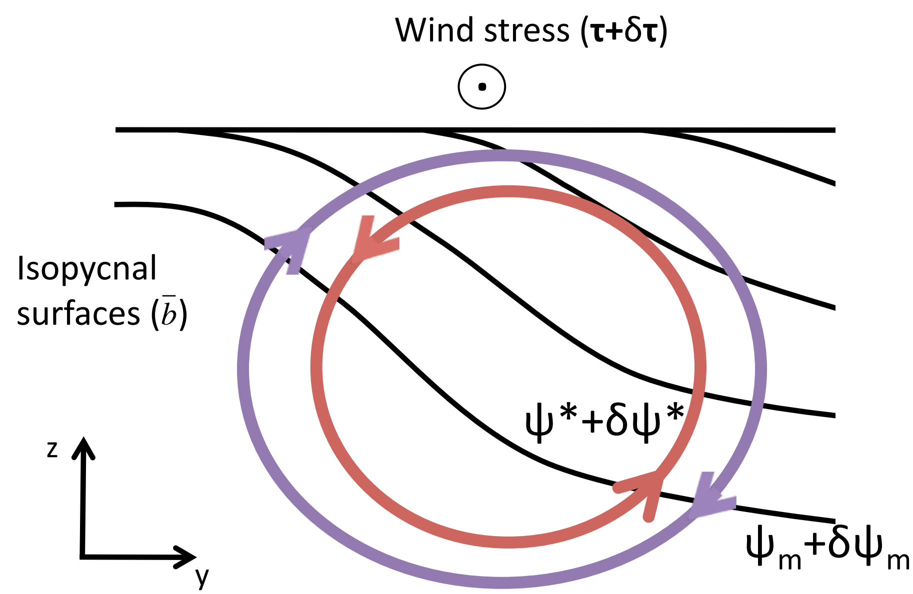


- There is a clear trend in wind stress, but there is very little change in isopycnal tilt.
- Our central question: Why didn't the vertical density structure respond much to the observed change in wind stress?

Why Didn't the Isopycnals Respond?

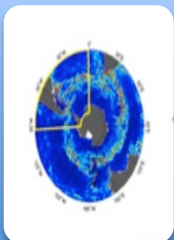
- What mechanisms might play a role in the ocean's response (or lack thereof) to increased wind stress?
  - Increased wind stress leads to stronger Ekman transport ($\delta\psi_m$).
  - Hypothesis: *Enhanced eddy activity* ($\delta\psi^*$) canceled out the effect of increased Ekman transport.

Böning et. al. (2008)



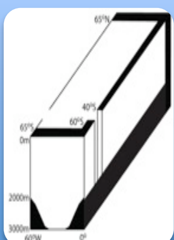
$$\delta\psi_{residual} = \delta\psi_m + \delta\psi^* \overset{?}{\approx} 0$$

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

$$\frac{dD}{dt} = -b_2 D^2 -$$

$$\tilde{T} = \frac{AD_0}{T_{Eddy} + 2T}$$

Simple conceptual models

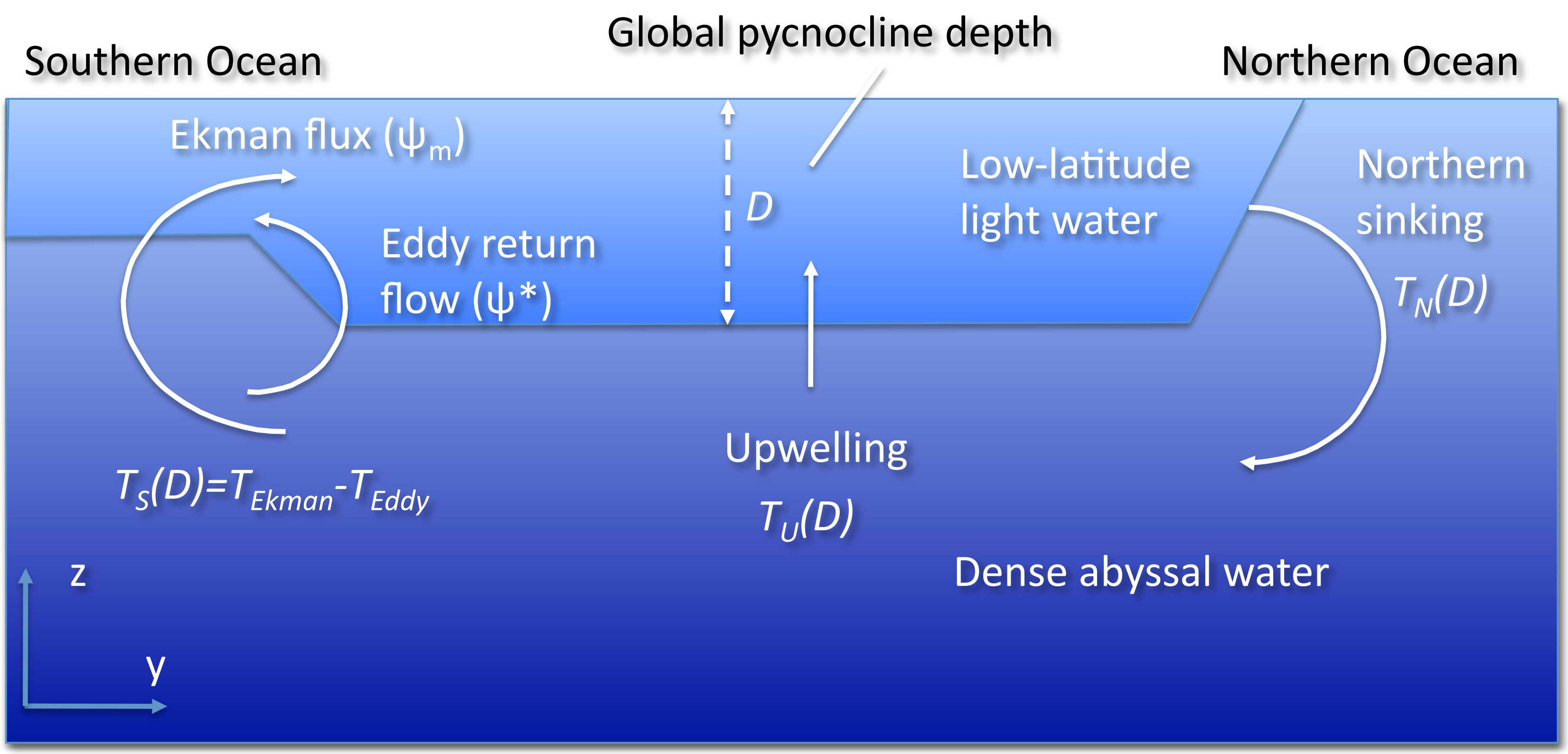
- Small number of analytical expressions
- Behavior relatively easy to interpret

Observational motivation

"… 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."

– I.M. Held, BAMS (2005).

Conceptual Model



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

or

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

Upwelling

Ekman transport

Eddy-induced transport

Northern sinking

Conceptual Model

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

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

- *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 equilibrium pycnocline depth, set dD/dt=0 and solve,

$$T_U + T_S - T_N = 0$$

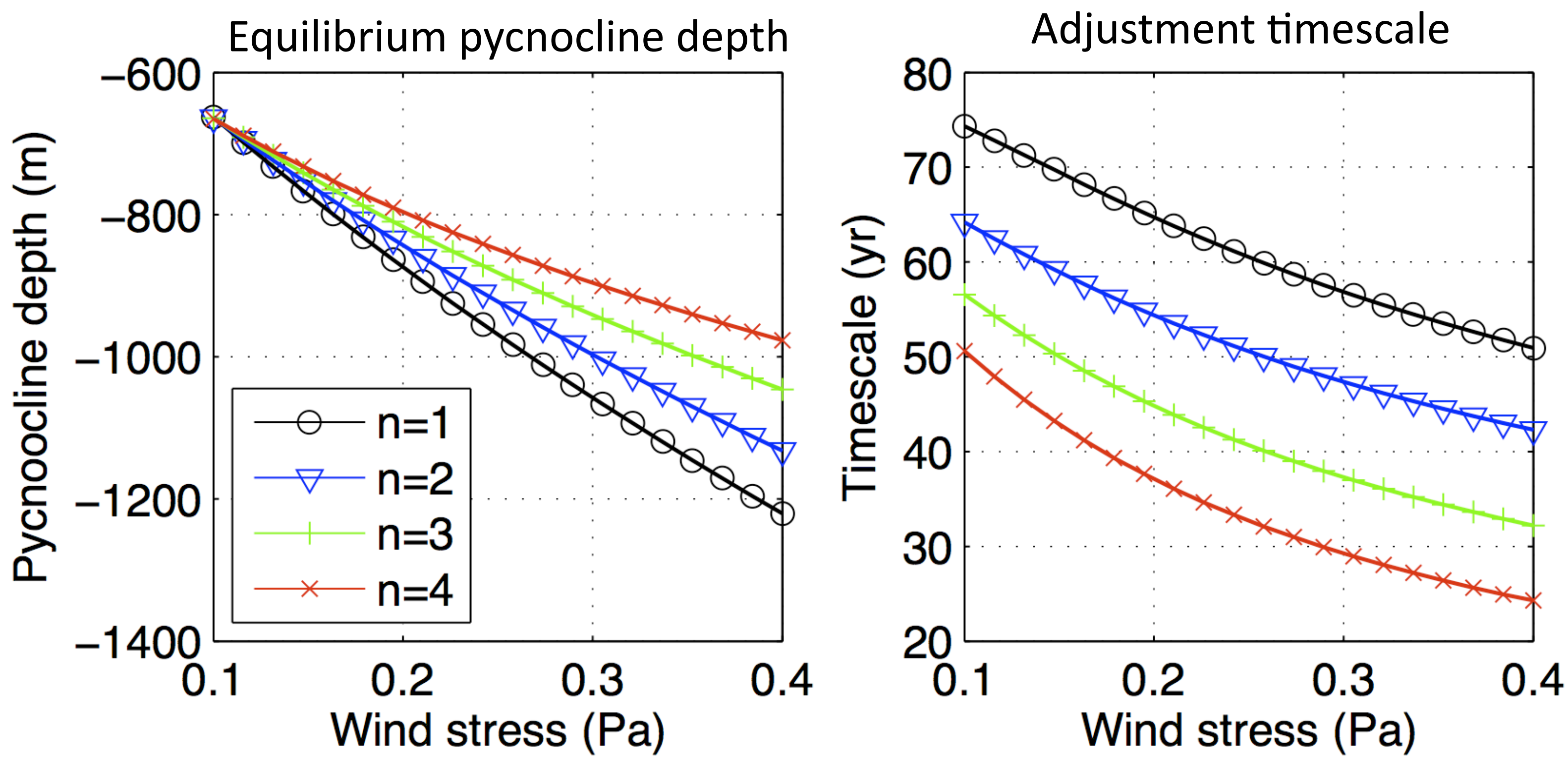
$$D_0^{n+1} + aD_0^3 - bD_0 - c = 0.$$

- To get the adjustment timescale, linearize the time-dependent equation about equilibrium,

$$D = D_0 + D', \quad |D_0| >> |D'|$$

$$D'(t) = D_0 e^{-t/\tilde{T}}, \qquad \tilde{T} = \frac{AD_0}{T_U + 2T_N + nT_{Eddy}}$$

Conceptual Model Results

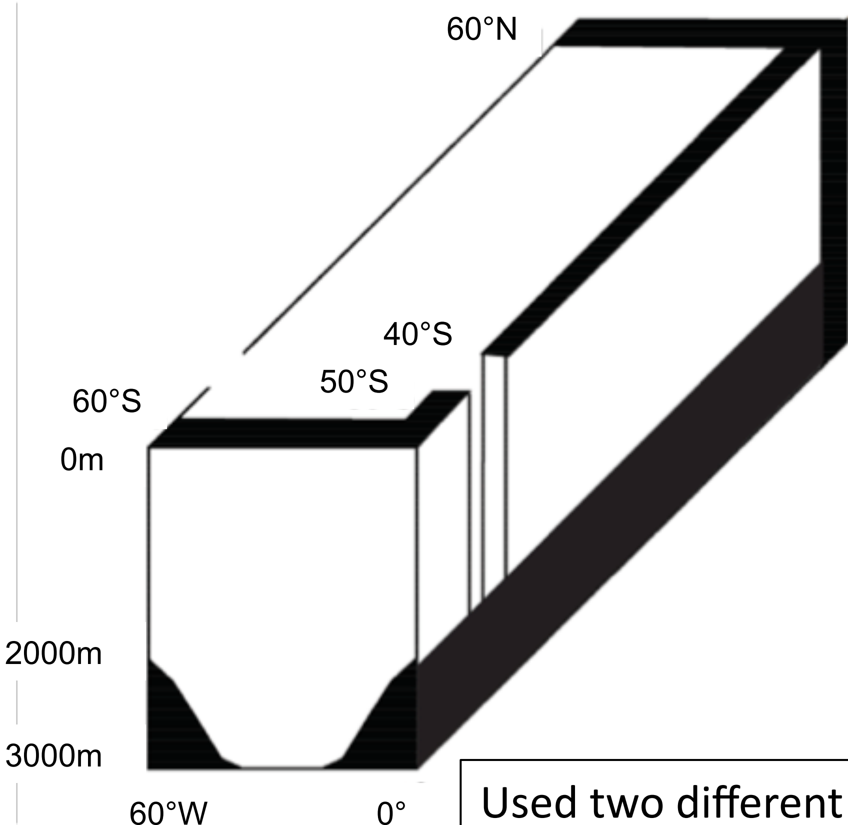


- The pycnocline *deepens* in response to increased wind stress.
- The e-folding adjustment timescale is of multi-decadal order.

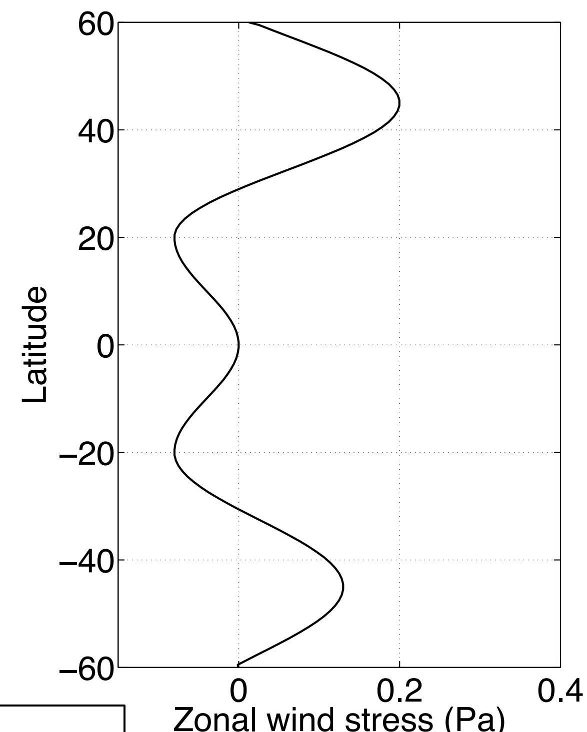
- Hypothesis: We haven't observed a change in pycnocline depth with wind stress because adjustment is a *very slow process.*

Idealized Sector Model

Geometry



Wind Stress Forcing

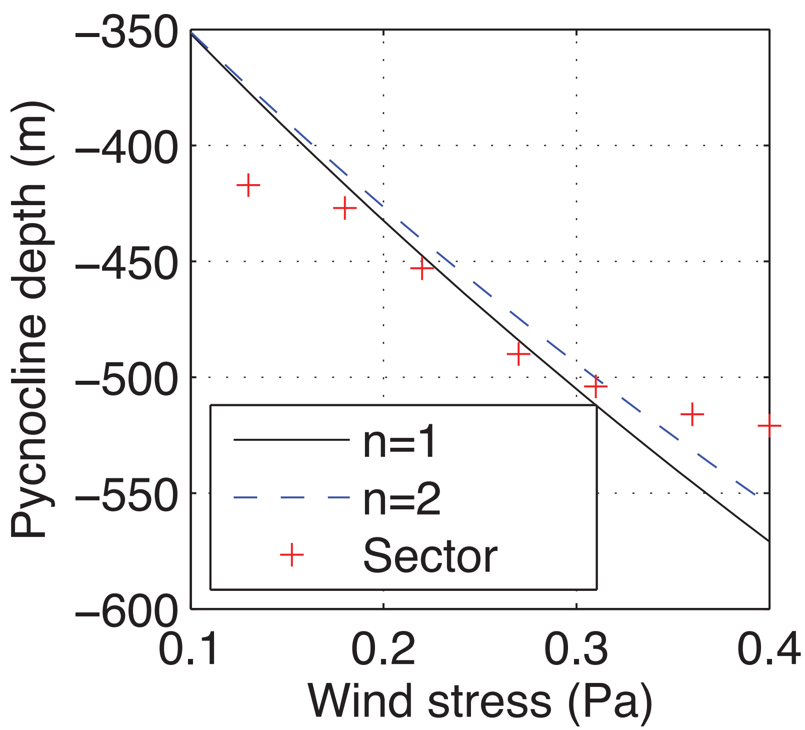


Used two different resolutions:

- Coarse (1°x1°)
- Eddy-permitting (⅙°x⅙°)

Idealized Sector Model

Equilibrium Pycnocline Depth Experiment

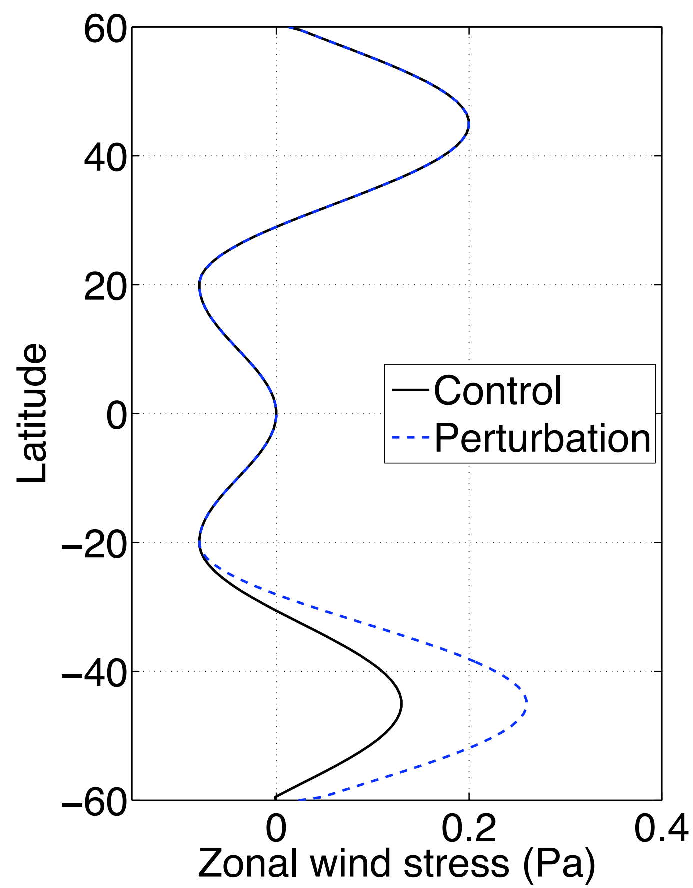


- Experiment
  - Model allowed to spin up for 500 years with several different (constant) wind stress profiles.
- Results
  - Global pycnocline depth *increases* with increasing Southern Ocean wind stress.
  - This is consistent with our conceptual model (lines.)

Idealized Sector Model

"Step Response" Experiment

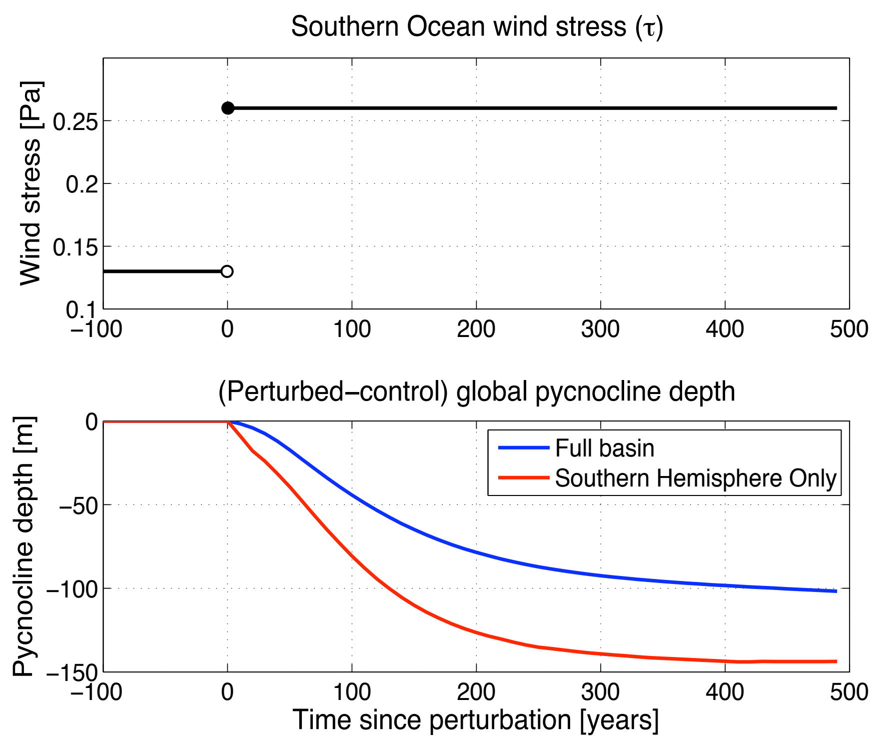
- Experiment
  - Allow the sector model to spin up for 500 years with a constant Southern Ocean wind stress parameter τ=0.13 Pa.
  - Run two configurations for an additional 500 yr,
    - control (no change in wind stress,)
    - doubled wind case (a.k.a. perturbed case, τ=0.26 Pa.)



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

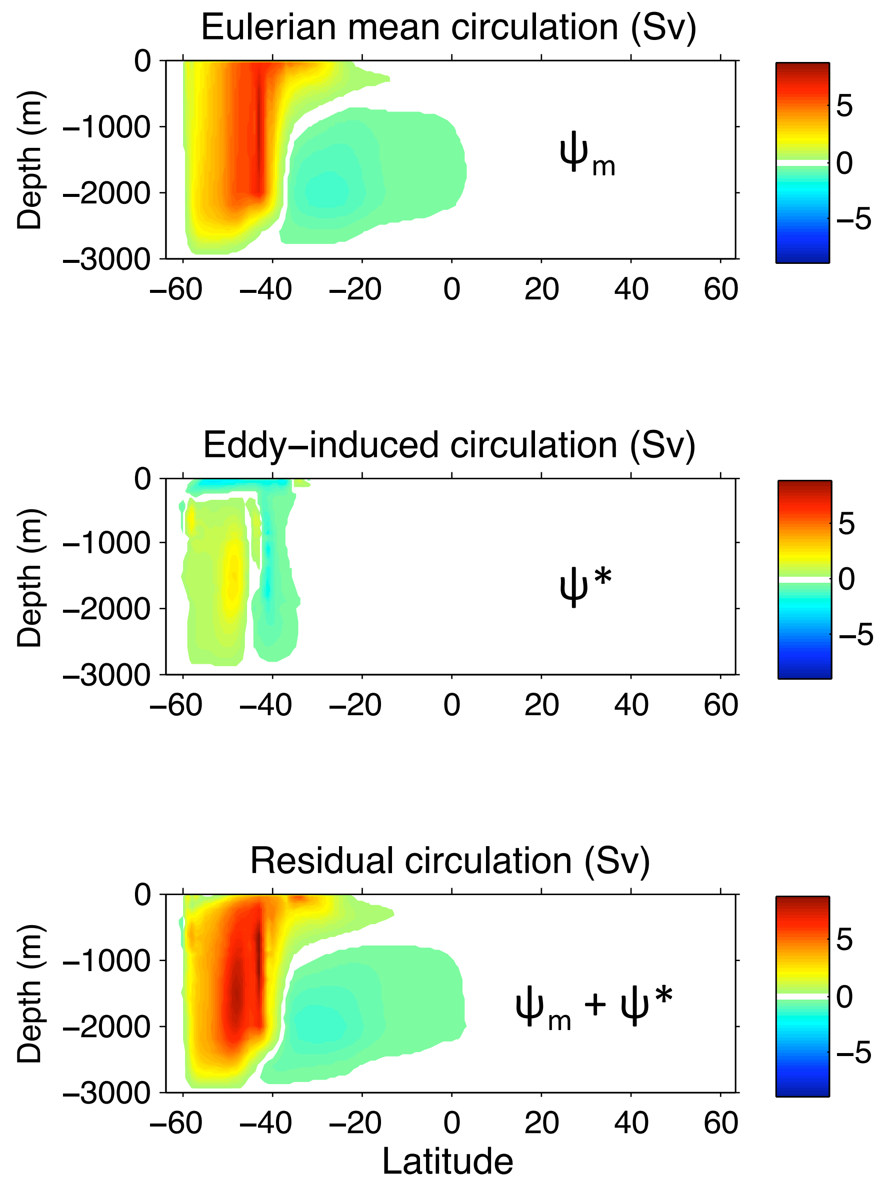


Step Response

- 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

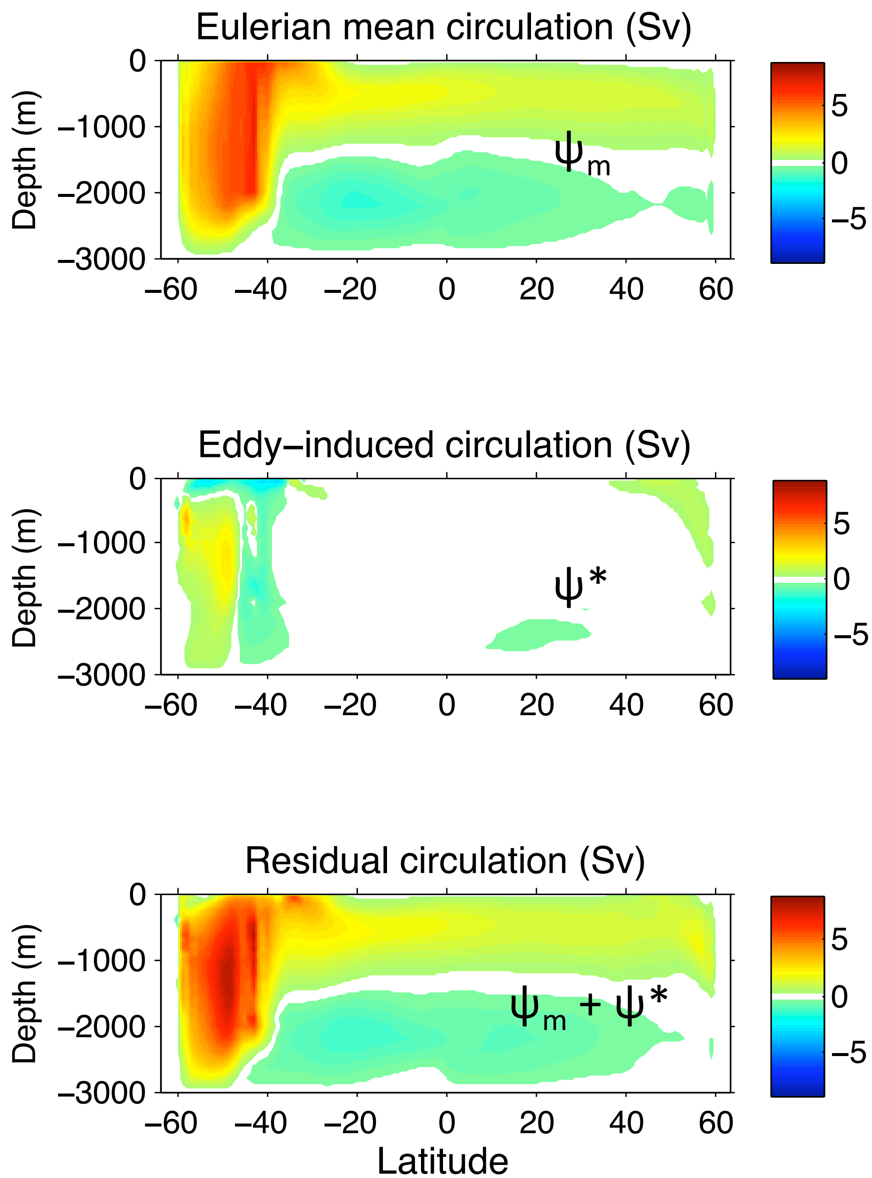
- Eddies did not totally cancel out wind-driven transport



10 years after perturbation

Step Response

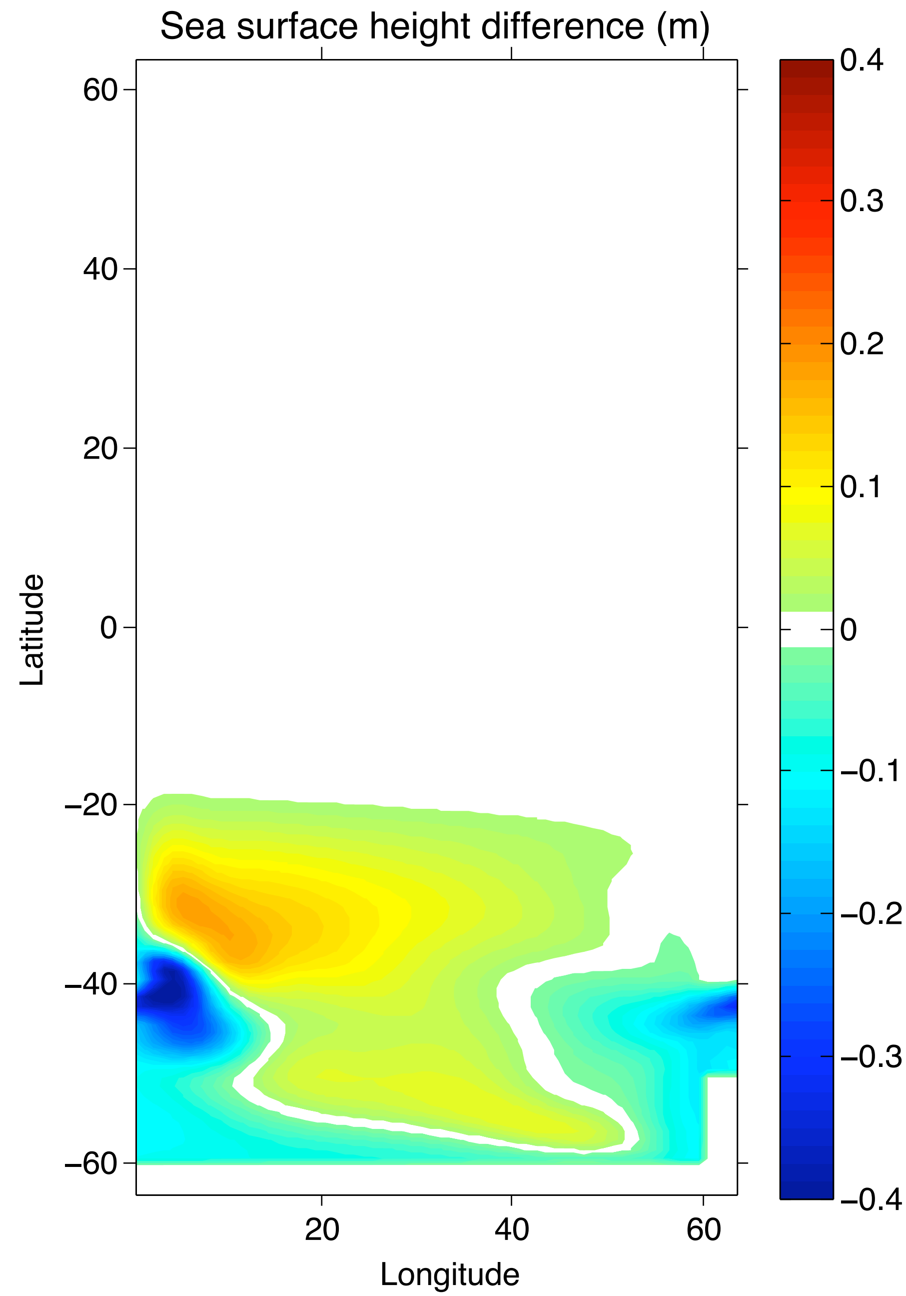
- Shown: stream functions of the residual (perturbed minus control run)
- 100 years after the perturbation is applied,
  - stronger mean, eddy, and residual circulation
  - wind's influence has finally reached the Northern Hemisphere
- Slow communication through the main pycnocline



100 years after perturbation

Step Response

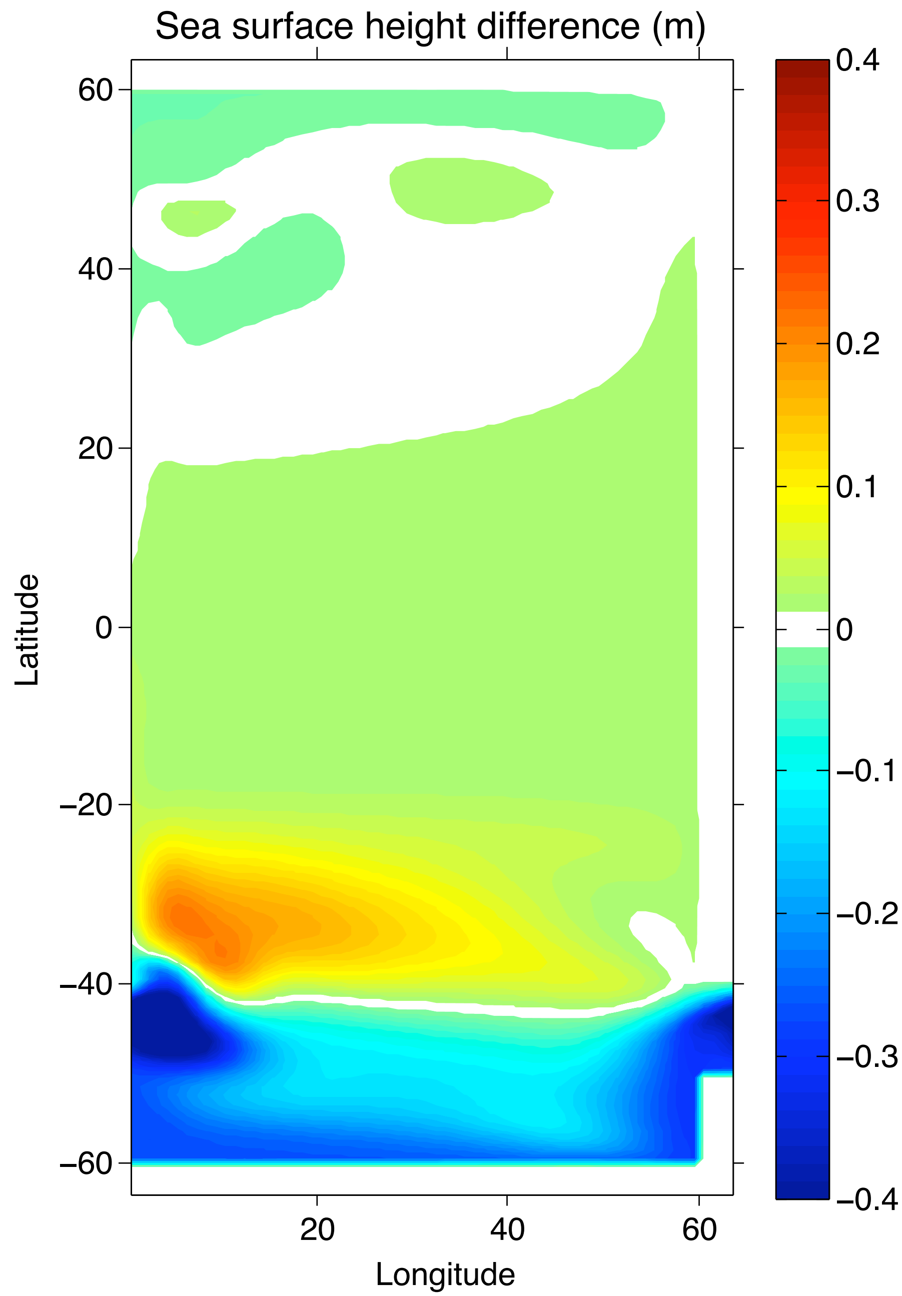
- Shown: sea surface height (perturbed – control run)
- 10 years after the perturbation is applied, we observe
  - a stronger subtropical gyre
  - lower heights near topographic features



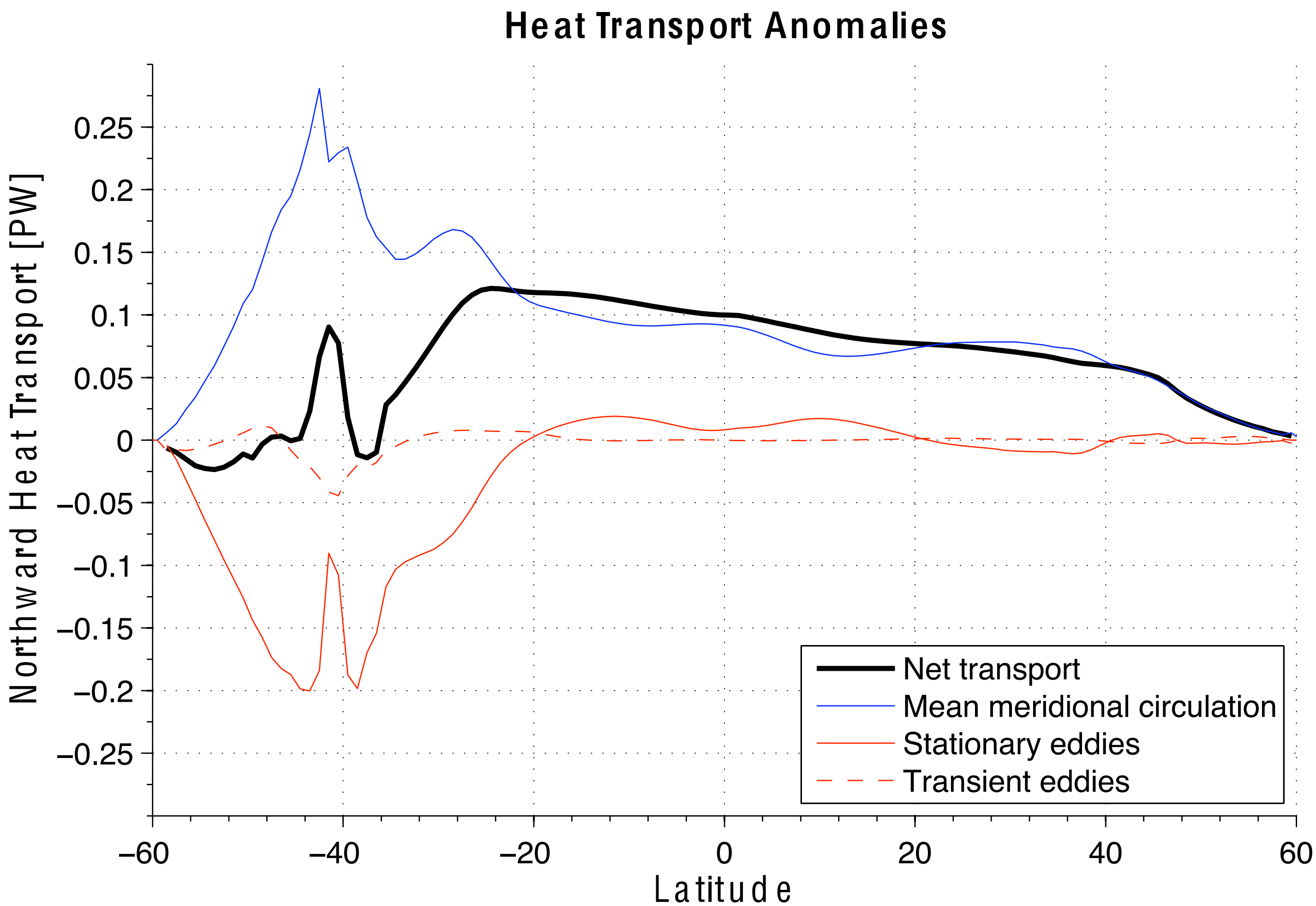
10 years after perturbation

Step Response

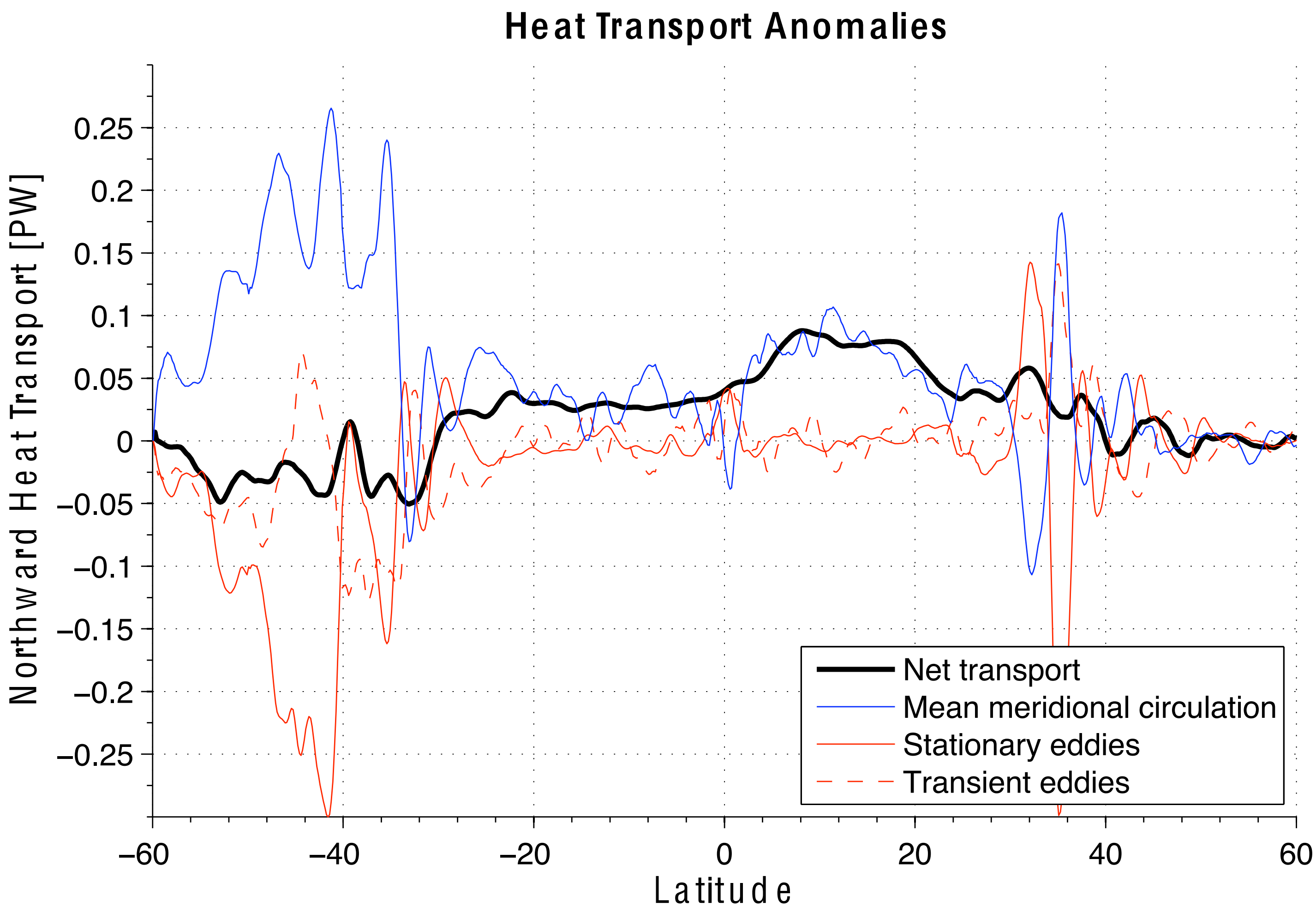
- Shown: sea surface height (perturbed – control run)
- 100 years after the perturbation is applied, we observe
  - stronger ACC transport (+40 Sv)
  - a small northward geostrophic current



100 years after perturbation

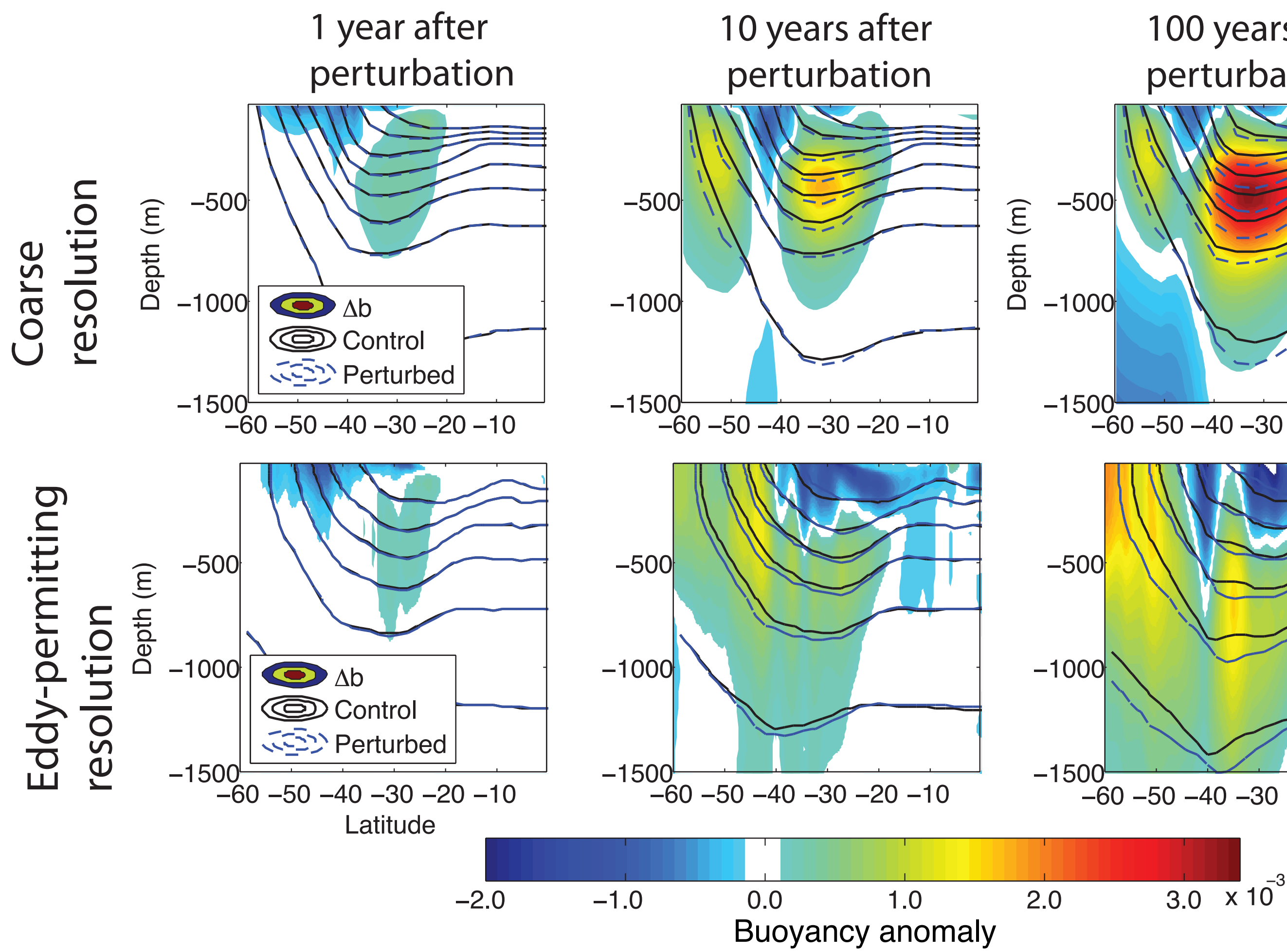


- Low-resolution
- Anomaly = (Perturbed – control)
- 100 years after wind stress is doubled



- 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.