Mesoscale Oceanic Eddies and the Southern Ocean Response to Climate Change

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GFDL / Climate Change Variability and Prediction

– High Resolution Ocean Climate Modelling –

An example of how finer oceanic resolution can help improve parameterizations, test theories and improve future climate change projections

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Motivation

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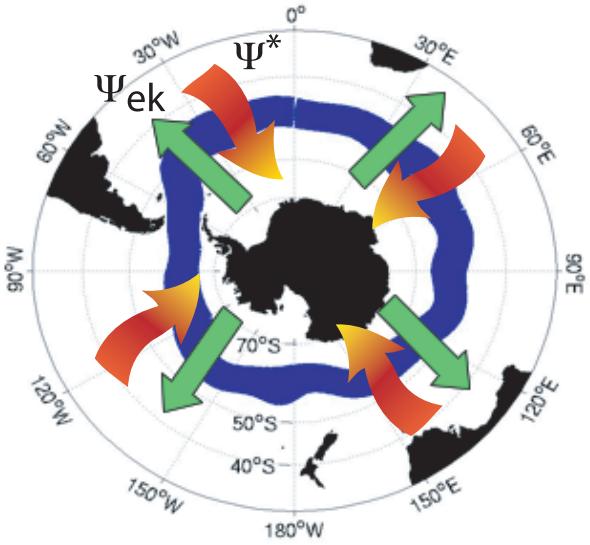
2. Eddy fluxes must be parameterized in coarse-resolution climate models. Usually with the Gent and McWilliams (1990, hereafter GM90) approach.
3. Recent observational evidence *(Böning et al., 2008)* and high-resolution ocean modelling studies *(Hallberg and Gnanadesikan, 2006; Meredith and Hogg, 2006)* have suggested **EDDY SATURATION**: increase in northward Ekman transport caused by stronger westerly winds is compensated by southward eddy fluxes, resulting in little change in Southern Ocean transport and overturning.

Southern Ocean - Balance between Circulations: Eulerian Mean and Eddy-induced



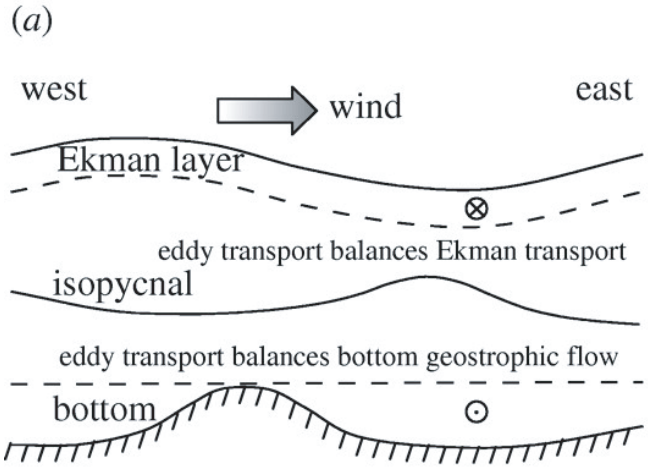
$$\Psi_{res} = \overline{\Psi} + \Psi^*$$

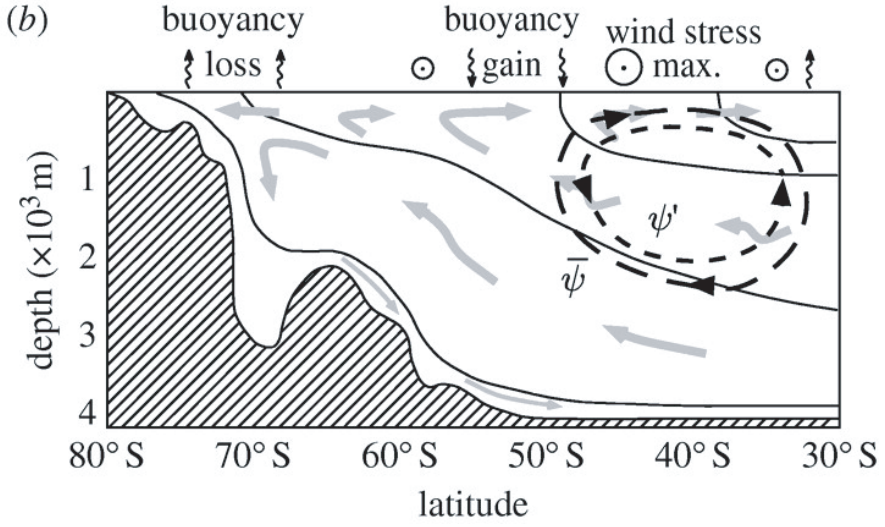
$$\overline{\Psi} = -\tau/(\rho_0 f)$$

$$\Psi^* = K S_\rho$$

$$\Psi_{gm}{}^* = k_{gm} S_\rho$$

K = Eddy transfer Coefficient
k_{gm} = GM90 Diffusion Coefficient

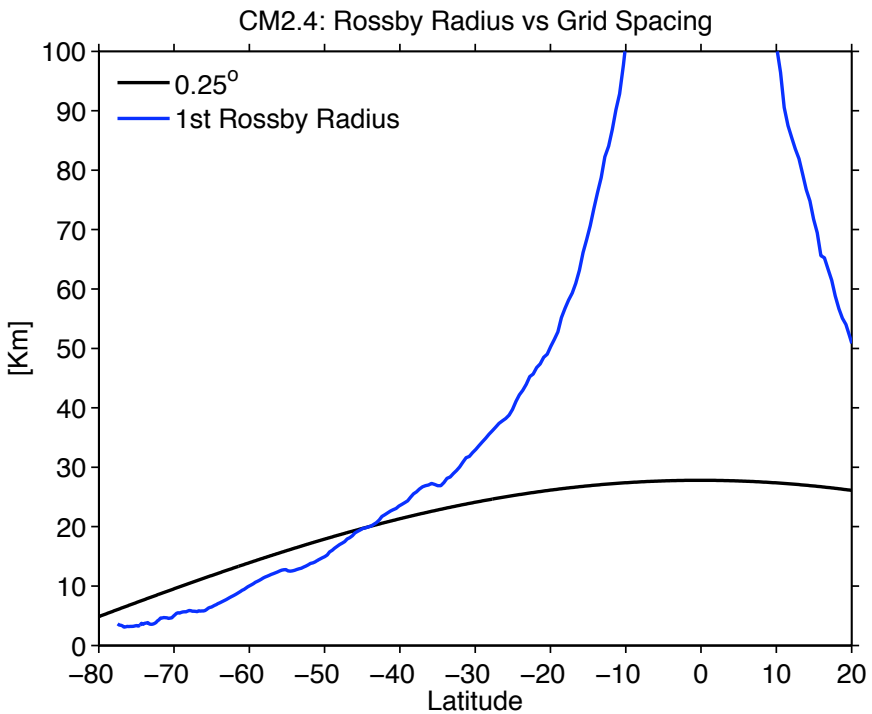




[Adapted from Olbers et al. (2004) and Speer et al. (2000)]

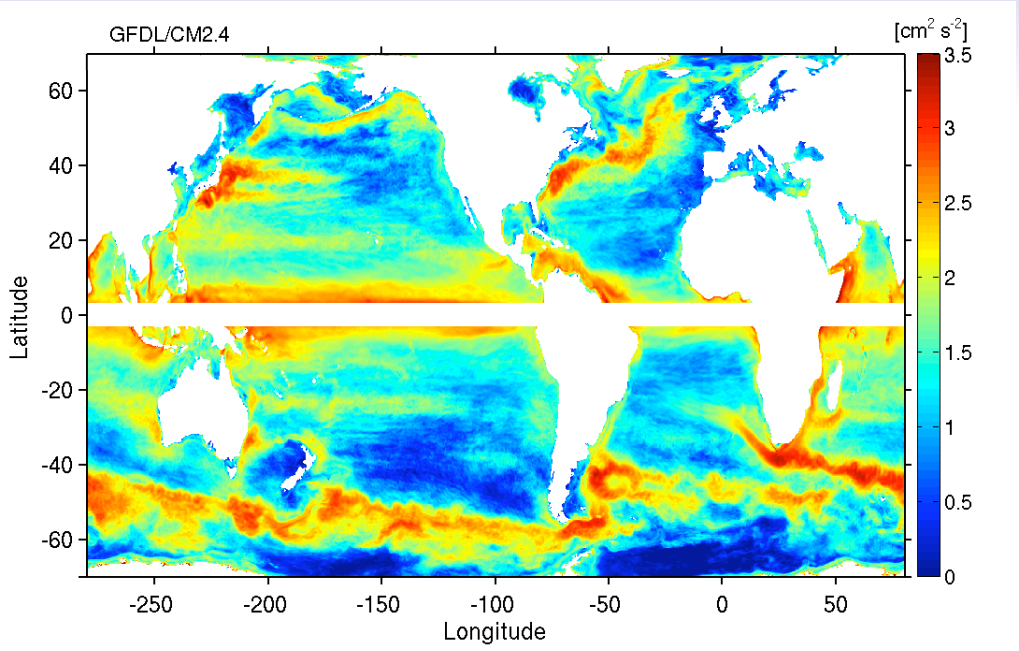
The Coupled Climate Models

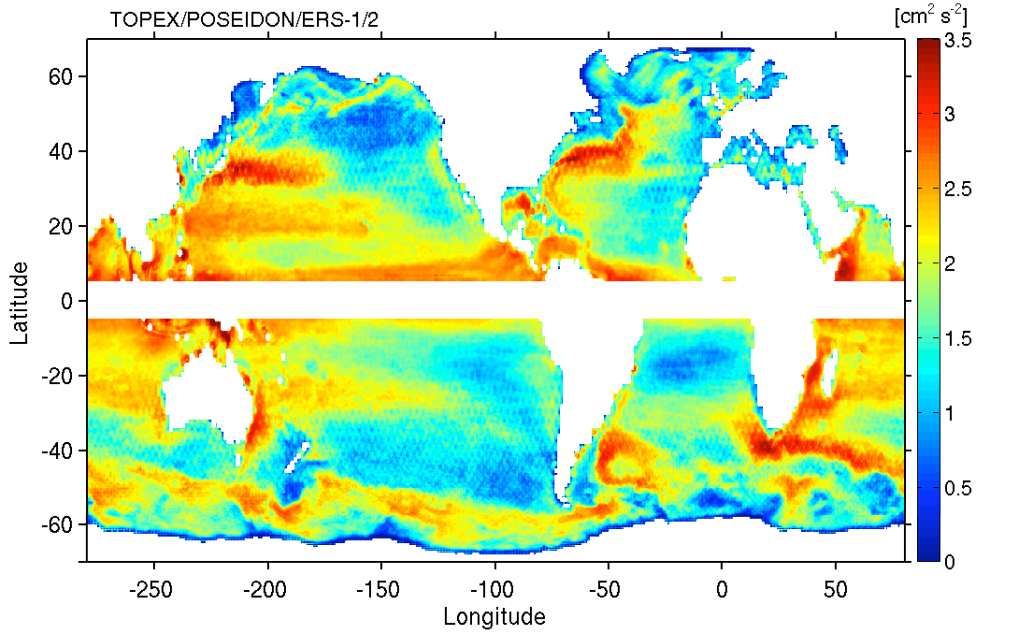
We use two GFDL Coupled Models:



1. CM2.1: Well known model $1\times1^\circ$ Ocean; $2.5\times2^\circ$ Atm.
   - Includes GM90. Very good Coupled Model and very good Southern Ocean climate *(Saenko, 2007; Sloyan and Kamenkovich, 2007)*.

2. CM2.4: New Coupled Model $1/4^\circ$ Ocean; $1\times1^\circ$ Atm.
   - No parameterization of mesoscale eddy mixing.



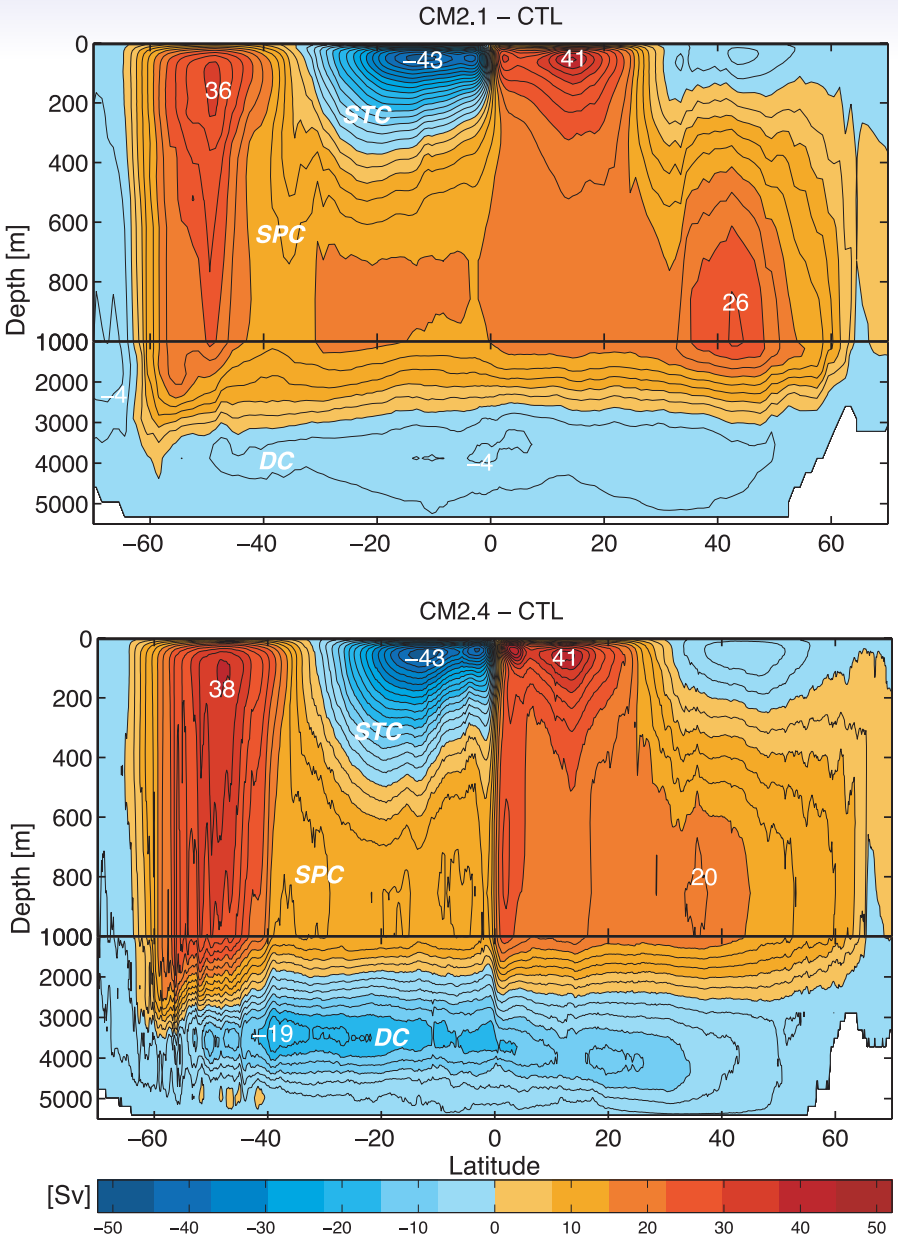


⇐ CM2.4

Eddy Kinetic Energy (EKE, in cm^2 s^{-2}) of the surface geostrophic flow for CM2.4 and the altimetric observational data set.

(log scale in all plots).

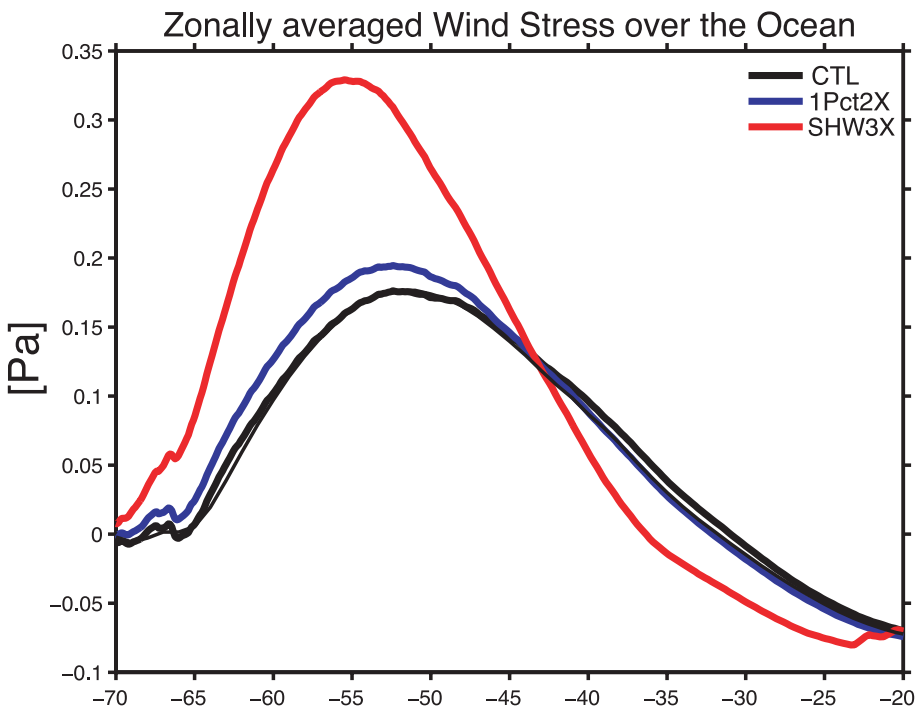
⇐ Satellite Obs



- The broad features of the global MOC are maintained when moving towards finer resolutions.
- Three main cells characterise the overturning streamfunction in the SH: the subtropical (**STC**), the subpolar (**SPC**) and the deep cell (**DC**).
- The subtropical cell unchanged across the two models (mostly wind-driven). The subpolar and in particular the deep cell strengthens in CM2.4.

The Experiments

For both Coupled Models we conducted the following experiments:



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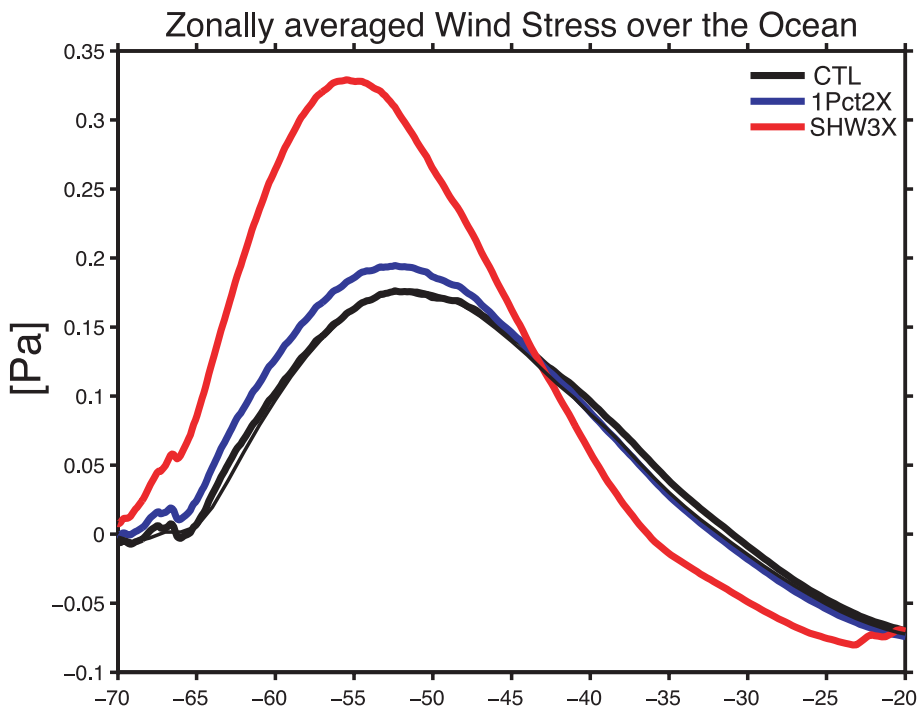

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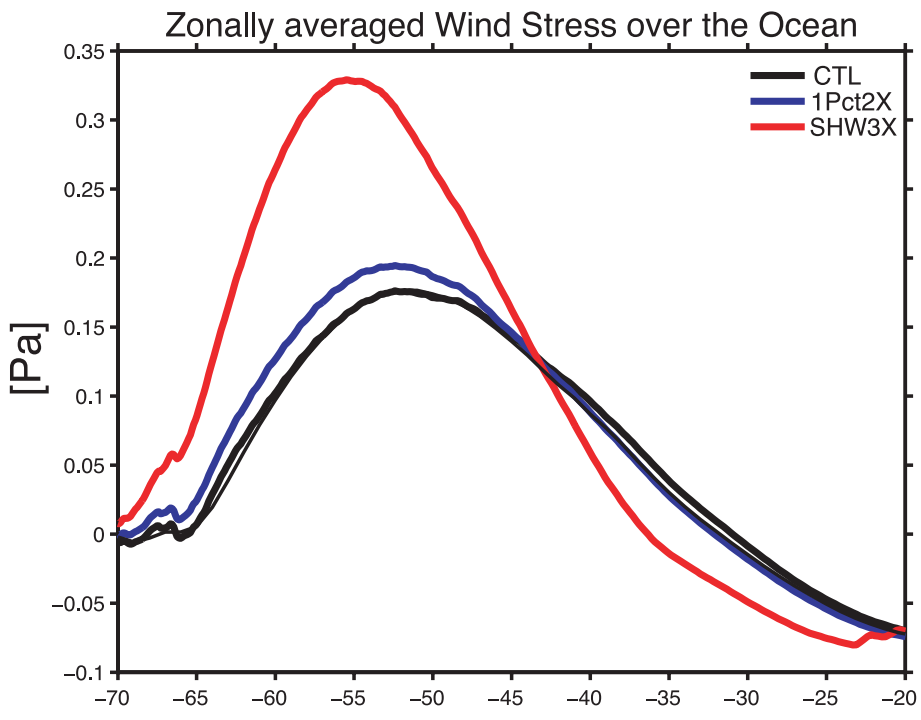

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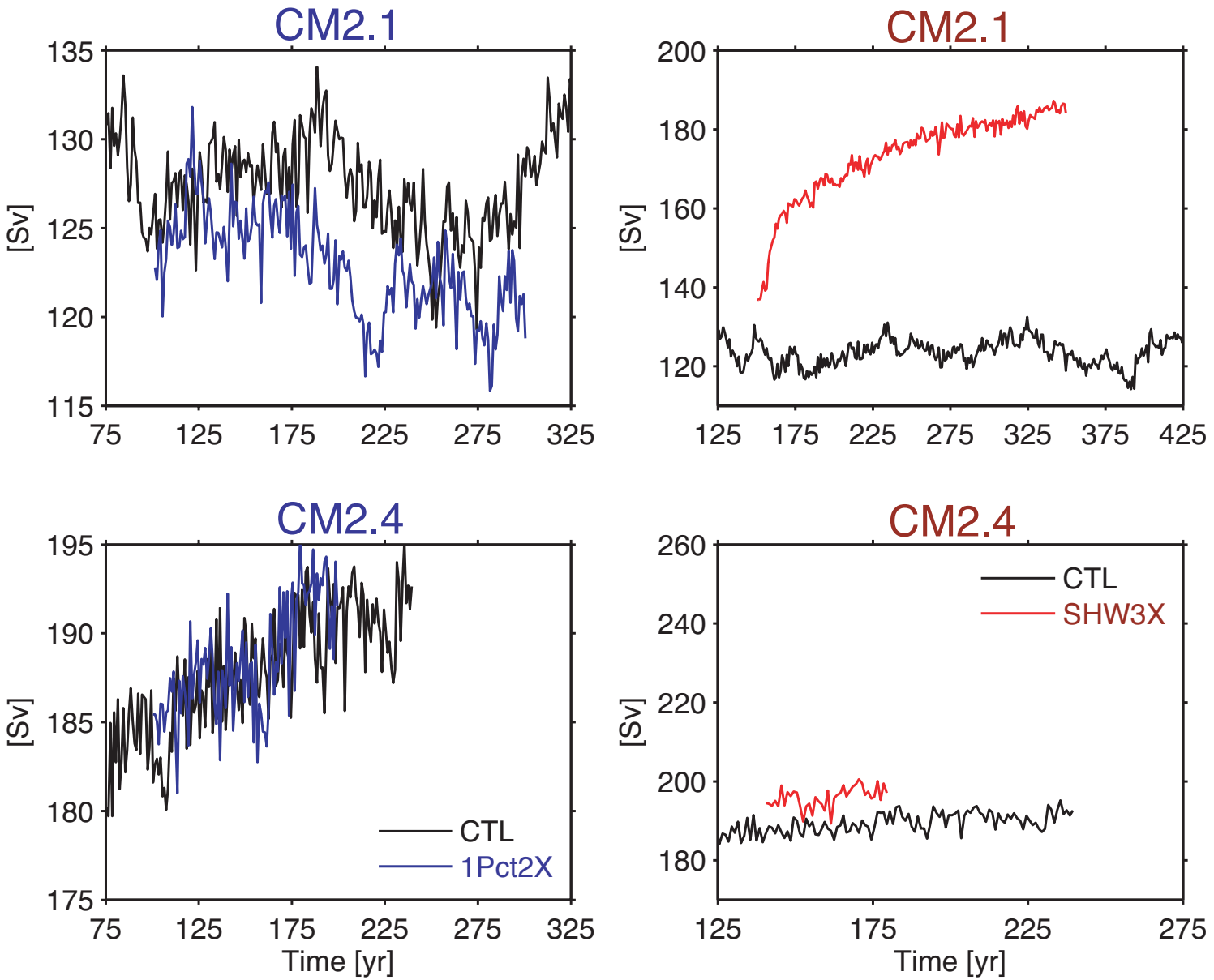
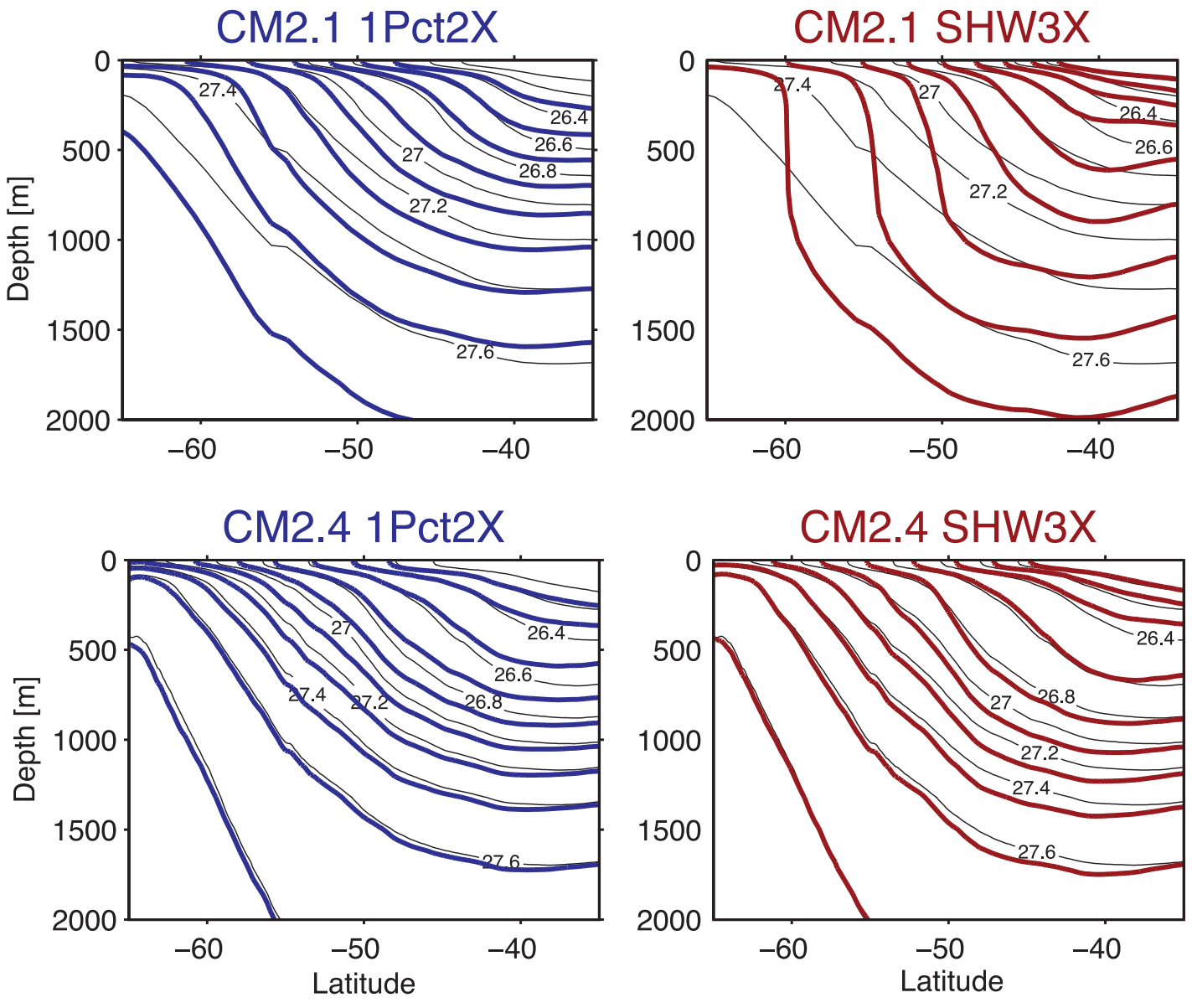
2. 1Pct2X: CO_2 concentrations are increased by 1% per year until doubling.
3. SHW3X: SH momentum flux perturbation experiment, consisting of an ensemble of 3 members. Anomalous wind stress pattern is added to the wind stress felt by the ocean between 20° S – 75° S.

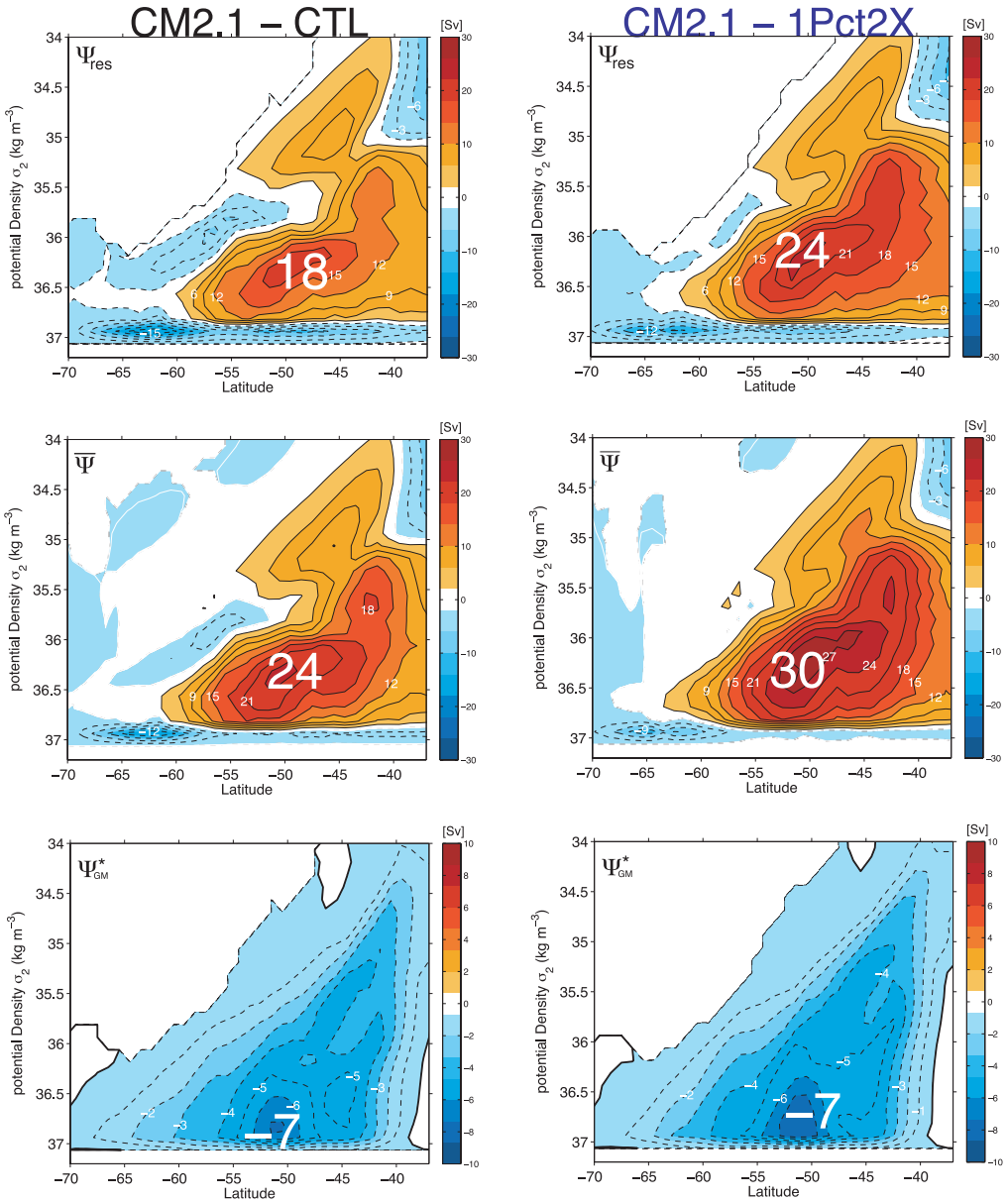
Drake Passage volume transport



Zonally averaged isopycnal surfaces of σ



MOC in σ-space



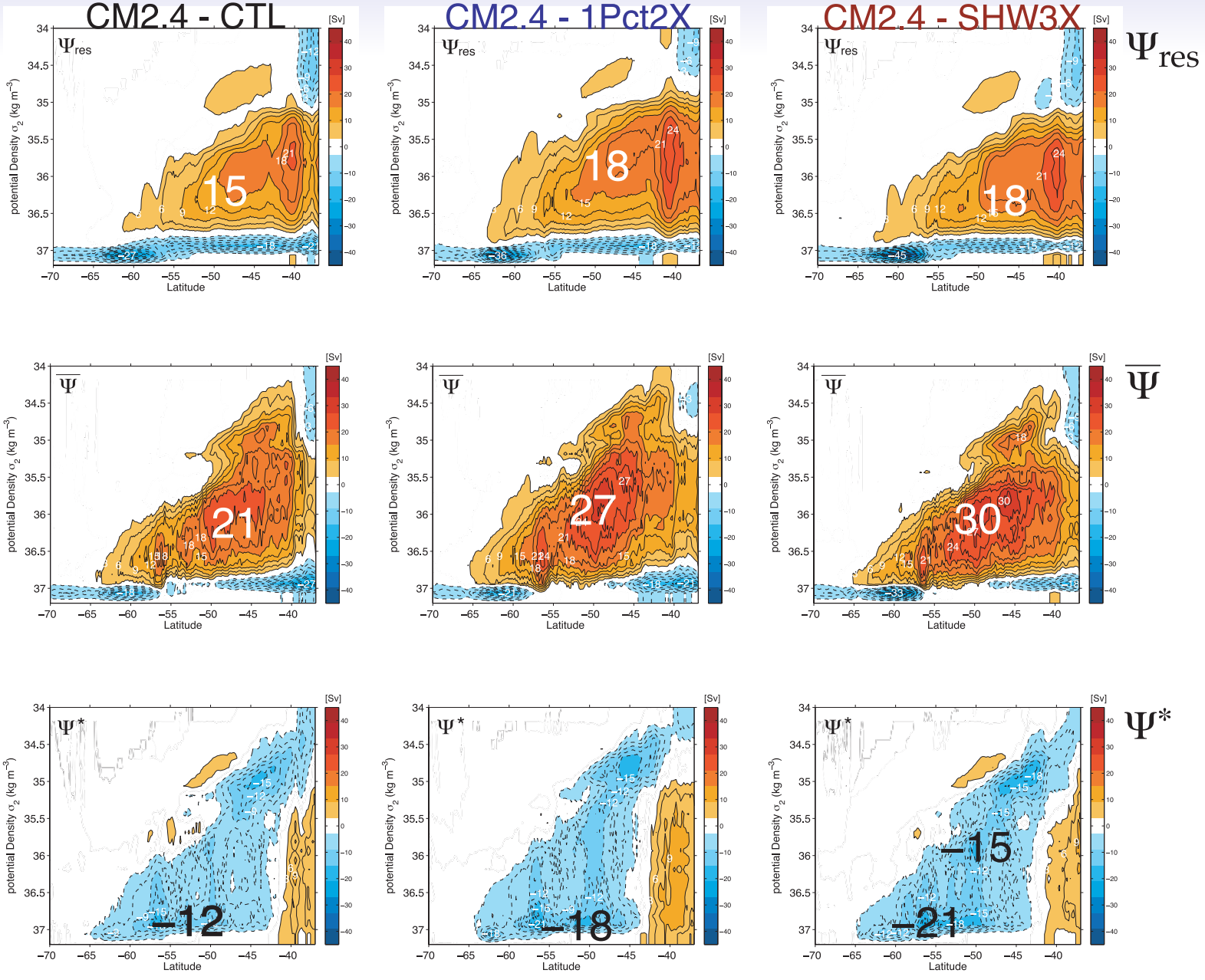
$\Rightarrow$ Ψ_{res} strongly modified in CM2.1, because

For 1Pct2X:

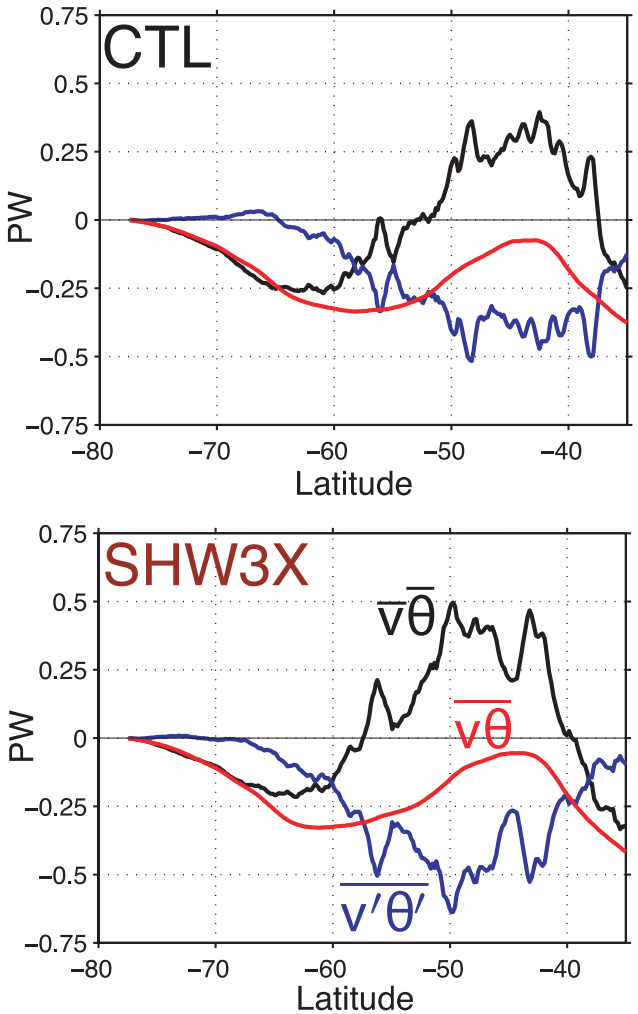
- $\overline{\Psi}$ increases by 6 Sv
- Ψ^*_{GM} does not change

For SHW3X:

- $\overline{\Psi}$ increases by $\sim$15 Sv
- Ψ^*_{GM} does not change much ($\sim$1 Sv)


CM2.4 - CTL
CM2.4 - 1Pct2X
CM2.4 - SHW3X
Ψ_{res}
$\overline{\Psi}$
Ψ^*
15
18
18
21
27
30
−12
−18
−21
potential Density σ_2 (kg m^{-3})
Latitude
[Sv]

Oceanic Heat Transport



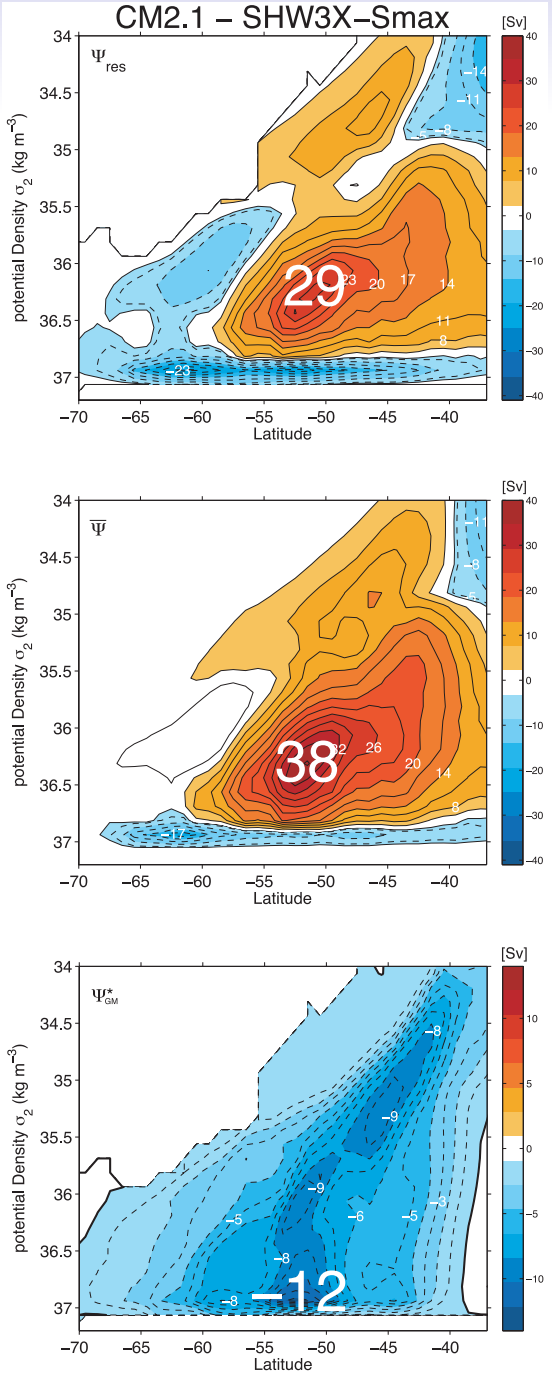
- The eddy component is negative and stronger than the transport accomplished by the mean flow, thus the total flux is directed poleward.
- If perturbed: The transport of heat by the mean flow ($\overline{v}\overline{\theta}$; black lines) increases, most notably in the ACC belt ($\sim$ 45°- 65° S). The enhanced eddy activity, though, is responsible for a stronger transfer by baroclinic eddies ($\overline{v'\theta'}$; blue lines), which helps balancing the response of the residual circulation ($\overline{v\theta}$; red lines).

Why is GM90 failing to respond in CM2.1? The S_{max} hypothesis

- GM90 relates the eddy streamfunction Ψ^*_{GM} to a coefficient κ_{gm} and local isopycnal slope $\mathbf{S}$, giving rise to an eddy-induced advective transport

$$\Psi^*_{\mathrm{GM}} = \kappa_{gm}\,\mathbf{S} \tag{1}$$

- MOM uses a slope tapering technique in order to linearly taper off Ψ^*_{GM}. Where isopycnals become 'too' steep, $\mathbf{S}$ is capped by a maximum slope $\mathbf{S}_{max}$, thereby defining a maximum eddy-induced volume flux $\kappa_{gm}\,\mathbf{S}_{max}$.
  In CM2.1 $\mathbf{S}_{max}$ is set to $1/500$.



- We performed a test setting $S_{max} = 1/100$ *(see also Gnanadesikan et al., 2007)*

- Eddy circulation responds more readily to stronger winds. However, eddy fluxes from GM90 are still responsible for a much weaker compensation than seen in the CM2.4. Meanwhile, the climatology gets worse.

Ongoing and Future Work

1. GFDL CM2.1 uses a very small value of S_{max}, 1/500, while others allow for a bigger slope (e.g., NCAR model uses 3/10).
   $\longrightarrow$ Do these results apply to other Ocean Climate Models?

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2. A new scheme has been implemented in CM2M, the eddy streamfunction approach by *Ferrari et al. (2009)*, which does not include an S_{max}, key for eddy saturation.
   - Will this new formulation give a more realistic response?
   - We will test *Ferrari et al. (2009)* with CM2M and idealized coupled simulation.

Conclusions

1. Eddy compensation mechanisms are taking place in the GFDL coupled model CM2.4, buffering the ocean to atmospheric changes.
   Consistent with Obs *(Böning et al., 2008)* and ocean-only *(Hallberg and Gnanadesikan, 2006)* results.

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Both finer-resolution eddy-resolving coupled models *and* better eddy parameterizations are needed

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