Southern Ocean Response to Wind Shifts

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Summary of results from eddy-resolving ocean alone and eddy-permitting coupled models

Hallberg & Gnanadesikan JPO (2006)
E-R isopycnal ocean model

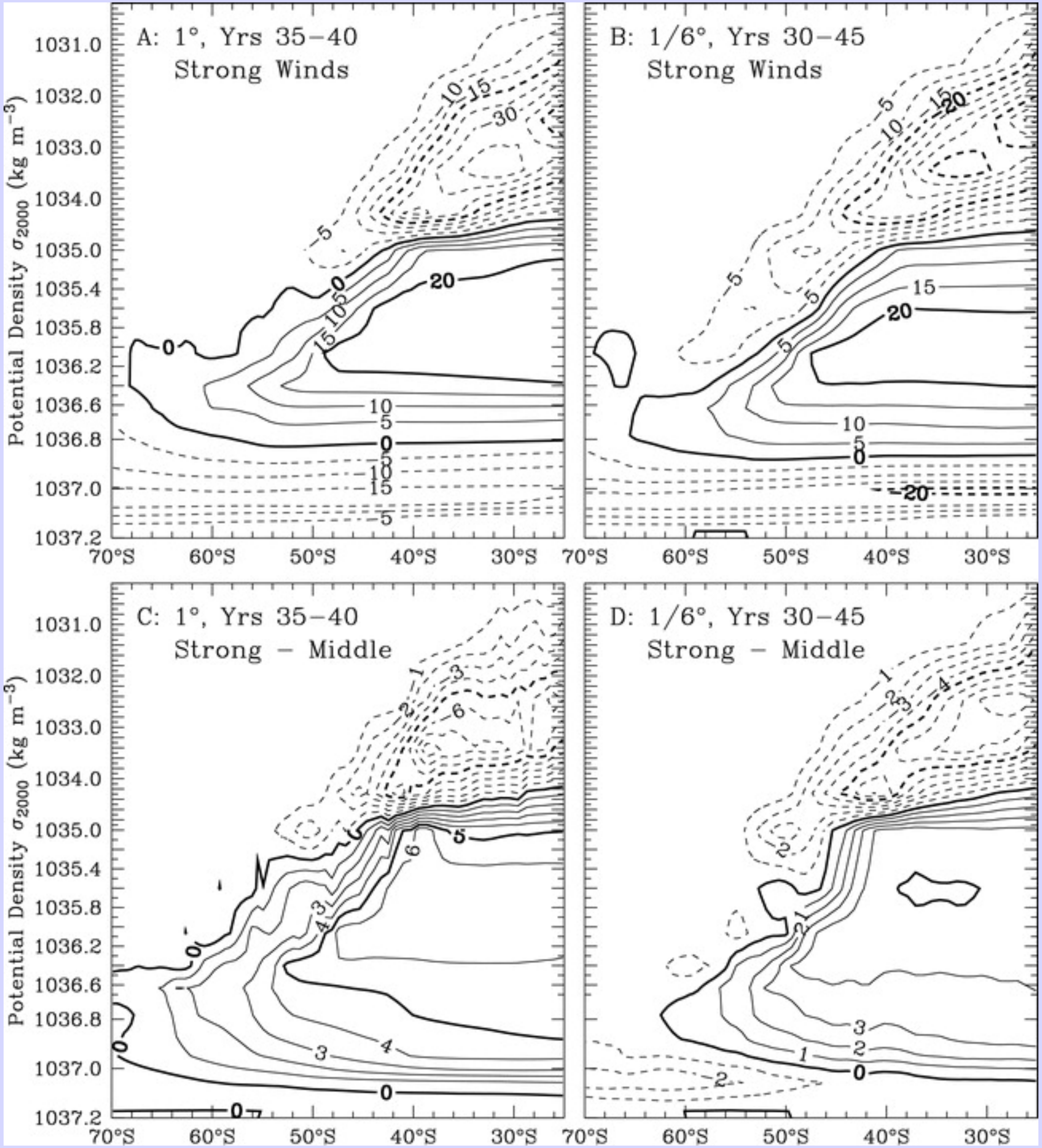
Meredith and Hogg GRL (2006)
& Hogg et al. J Climate (2008)
E-R 3-layer QG ocean model

Screen et al. J Climate (2009)
E-R OCCAM ocean model

Spence et al. JPO (2009), J Climate (2010)
E-P U-Vic climate model

Farneti et al. JPO (2010)
E-P GFDL CM2.4 climate model

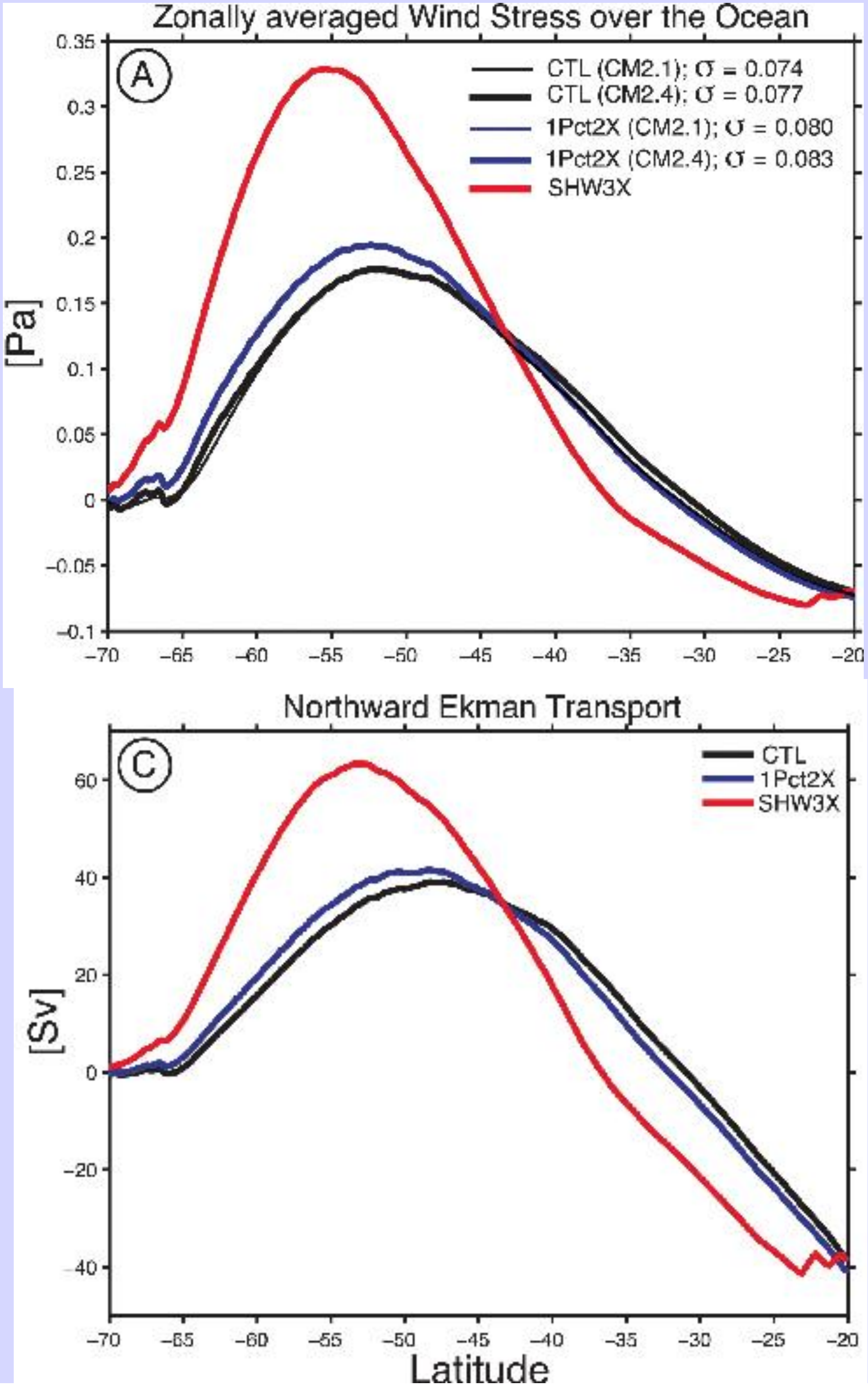
- The ACC is in an "eddy saturated state": originally Straub (1993) => increased zonal wind stress causes increased eddy activity to produce increased MOC that almost balances the increased mean flow MOC.
- This means there is not much change in the distribution of isopycnals (Boning et al. Nature Geoscience 2008), and therefore only a small increase in the ACC transport through Drake Passage.
- There is an approximately 2-3 year delay in eddy MOC spinup.
- In ocean model runs using observed winds, the maximum zonal wind stress moves 3^o to the south in addition to becoming stronger. Then the ACC maximum and entire ocean circulation moves a bit to the south.
- This causes warming throughout the upper ocean (1 km or deeper) to about 60^{o}S (Gille Science 2002 & J Climate 2008), helped by increased southward eddy heat transport balancing increased northward mean heat transport to the north of ACC.
- In U-Vic model, the Antarctic sea ice volume decreases mostly due to an increased northward wind-driven transport of sea ice into warmer ocean SSTs. This also increases the strength of the polar MOC cell.



SH MOC in density space in strong wind run: 1° and 1/6° resolutions.

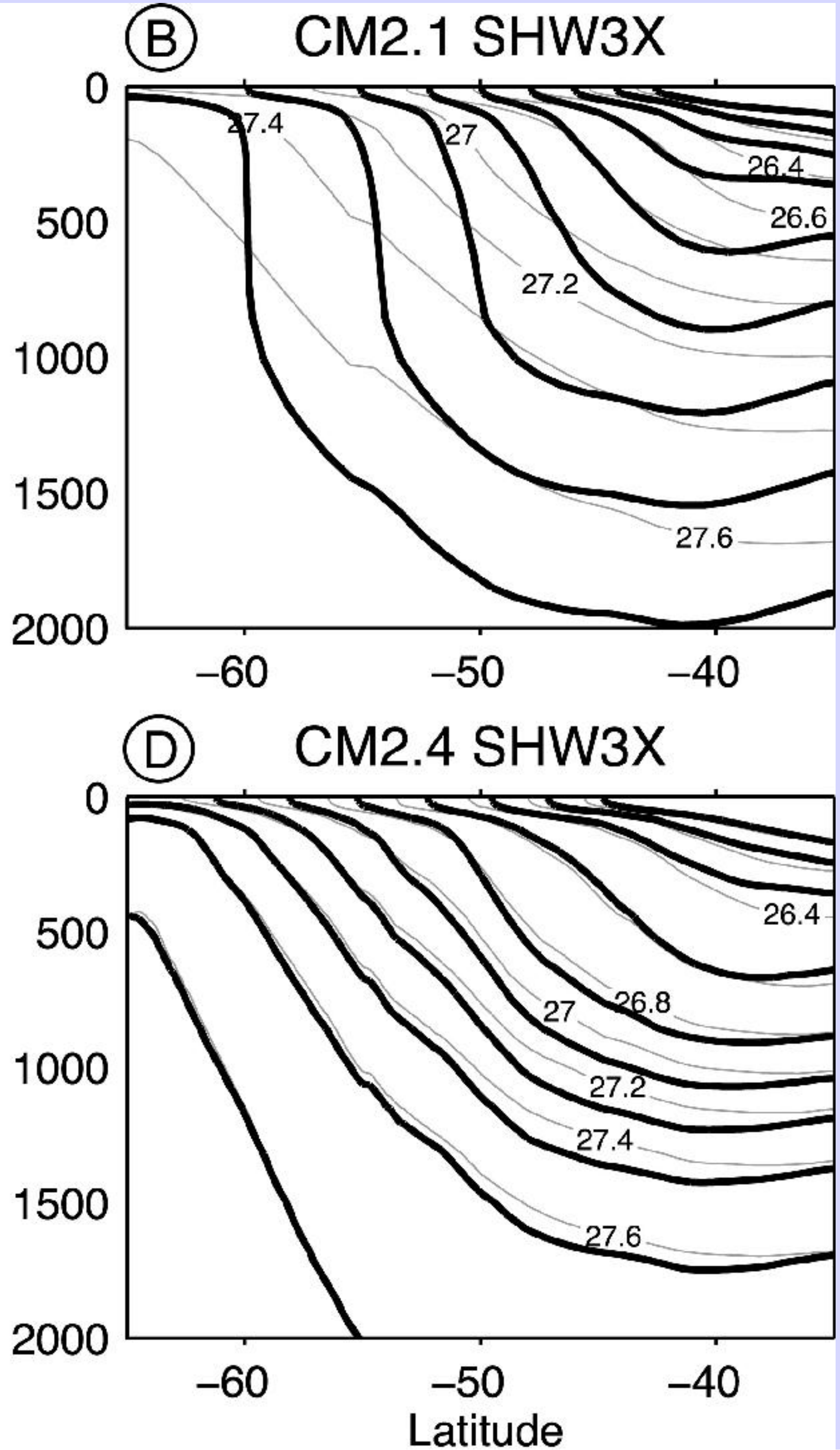
Change in MOC between strong and middle wind runs: smaller in 1/6° resolution.

Hallberg and Gnanadesikan, JPO (2006).



GFDL group ran two cases using coupled models, CM2.1 (ocean 1^o resolution) and CM2.4 (ocean 1/4^o E-P resolution), where the maximum zonal wind stress over the ACC is about doubled and moved 3^o to the south: (red line compared to control run black line)

Farneti et al. JPO (2010).



CM2.1 with GM shows a change in the structure of the density surfaces across the ACC.

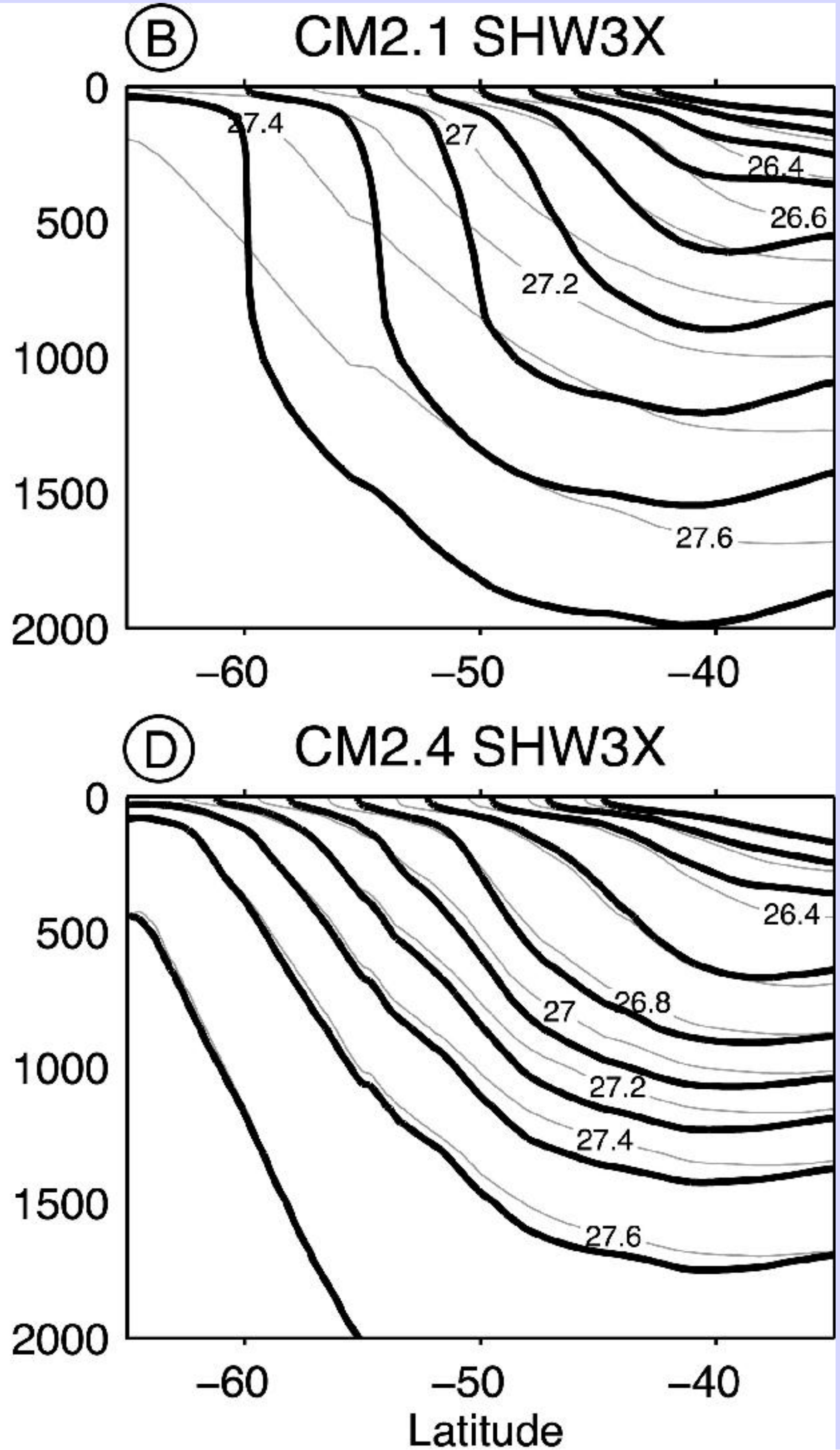
CM2.4 with partially resolved eddies shows little change in density structure.

The GM Parameterization

$$\frac{\partial T}{\partial t} + (\underline{u} + \underline{u}^*).\underline{\nabla} T = \underline{\nabla}_\rho.(\kappa \underline{\nabla}_\rho T)$$

$$w^* = -\underline{\nabla}.(\kappa \underline{\nabla} \rho / \rho_z), \underline{\nabla}.\underline{u}^* = 0.$$

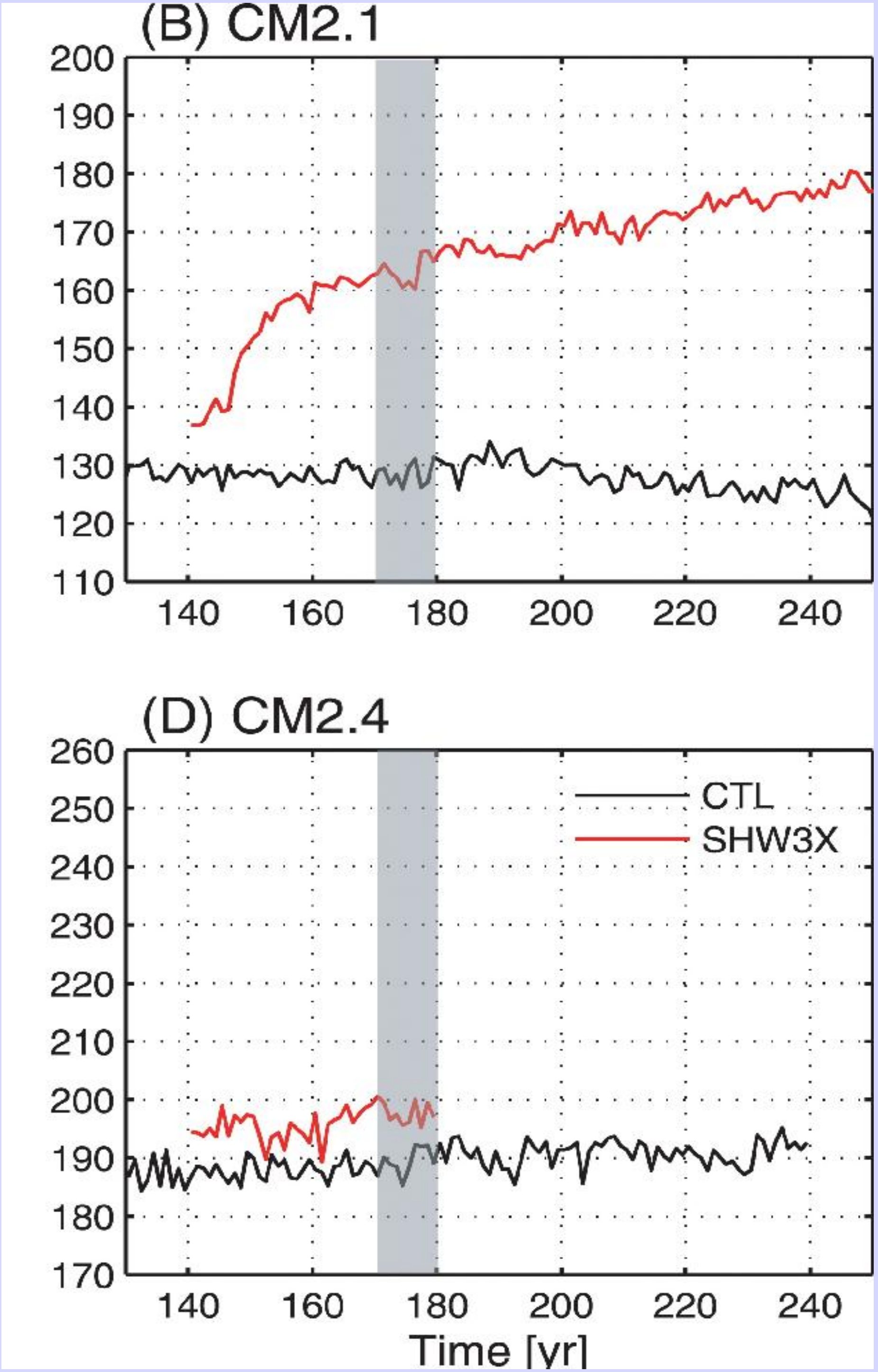
Temp and salinity have an eddy advection and diffusion along isopycnal surfaces. The GM form of eddy advection was chosen because it ensures a global sink of potential energy.



CM2.1 with GM shows a change in the structure of the density surfaces across the ACC.

GM kappa is capped at 600 m^2/s, clipped at slope of 1/500.

CM2.4 with partially resolved eddies shows little change in density structure.



Correspondingly, there is a change in the Drake Passage transport in CM2.1 with GM

Not much change in Drake Passage transport in CM2.4 with partially resolved eddies.

Four of the papers show results from a variety of ocean model resolutions. They show that the low resolution results do not agree with the E-R/P results, because the eddy MOC does not increase; so does not compensate the larger mean flow MOC. The change in eddy heat transport also not captured correctly.

Hallberg and Gnanadesikan JPO (2006)

"Transient eddies play an important role in Southern Ocean water mass transformation – a role that is not well described by at least one common diffusive eddy parameterization (Gent and McWilliams 1990)."

Screen et al. J Climate (2009)

"The parameterization scheme is unable to mimic the effects of changes in the eddy field on Southern Ocean temperatures." "This questions the ability of coarse-resolution climate models to accurately capture the impact of strengthening and poleward shifting winds on the Southern Ocean."

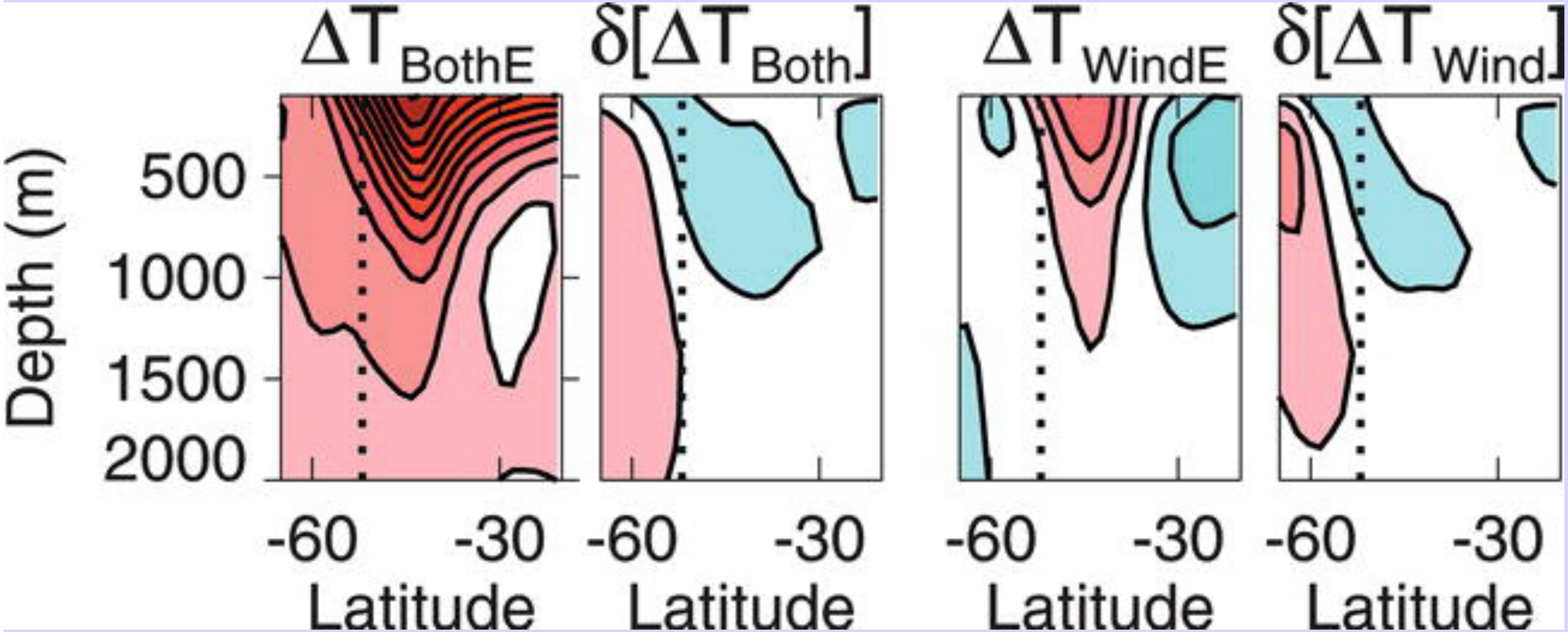
However, all the papers that use GM in non-eddy-resolving resolution versions use a constant coefficient, kappa. If these models are to represent the effects of different levels of eddy activity, then kappa needs to have a variable definition.

Fyfe et al. J Climate (2007)

In a 1850-2100 run of U-Vic climate model, they made kappa increase from 800 m^2/s to 1100 m^2/s as the strength of the imposed SH zonal wind stress increased. They found that the response was much more like that from E-R ocean version.

Farneti et al. JPO (2010)

Even though the CM2.1 ocean component uses a variable kappa formulation, the value is capped at 600 m^2/s. This is fine for the present day zonal wind stress, but not for the doubled wind stress run. This is why CM2.1 results do not match E-P CM2.4.



Linear trend in zonal-mean temperature over 1950 to 2000.

a) Forced by CO_2 increase and stronger wind stress

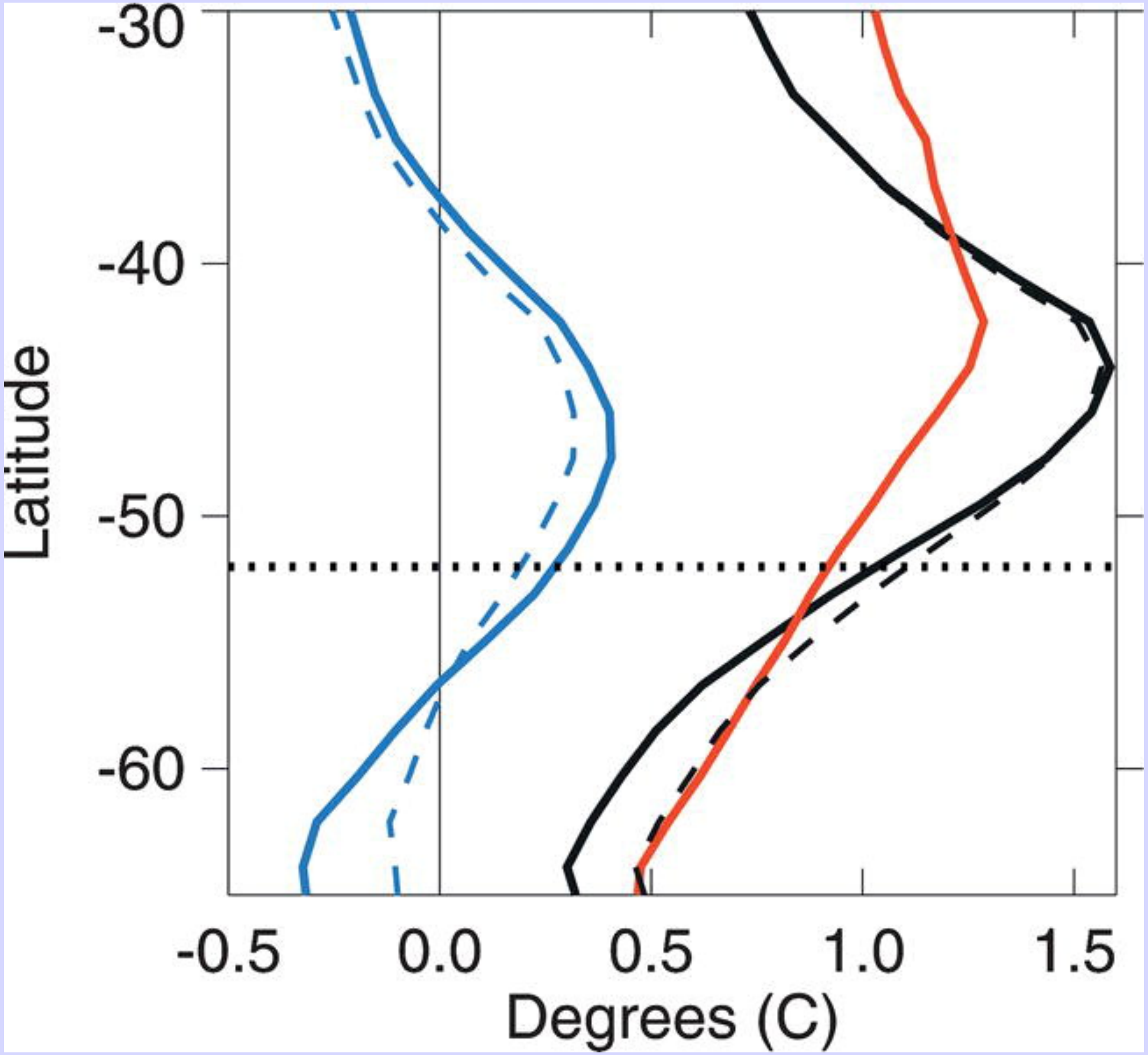
b) Difference between increasing and constant kappa

c) Forced by poleward intensifying winds only

d) Difference between increasing and constant kappa

Fyfe et al. J. Climate (2007)

Temperature change between 1850 and 2000



Black; forced by both CO_2 and stronger winds:

Red; CO_2 only:

Blue; winds only:

Solid; constant GM kappa:

Dashed; kappa increased:

Fyfe et al. J. Climate (2007)

Hofmann and Morales Maqueda GRL (2010)

Non-E-R ocean model with variable GM kappa. Response to increased SH winds is much better than constant kappa. "Eddy formulation does not lead to levels of compensation as high as suggested by observations or E-R models."

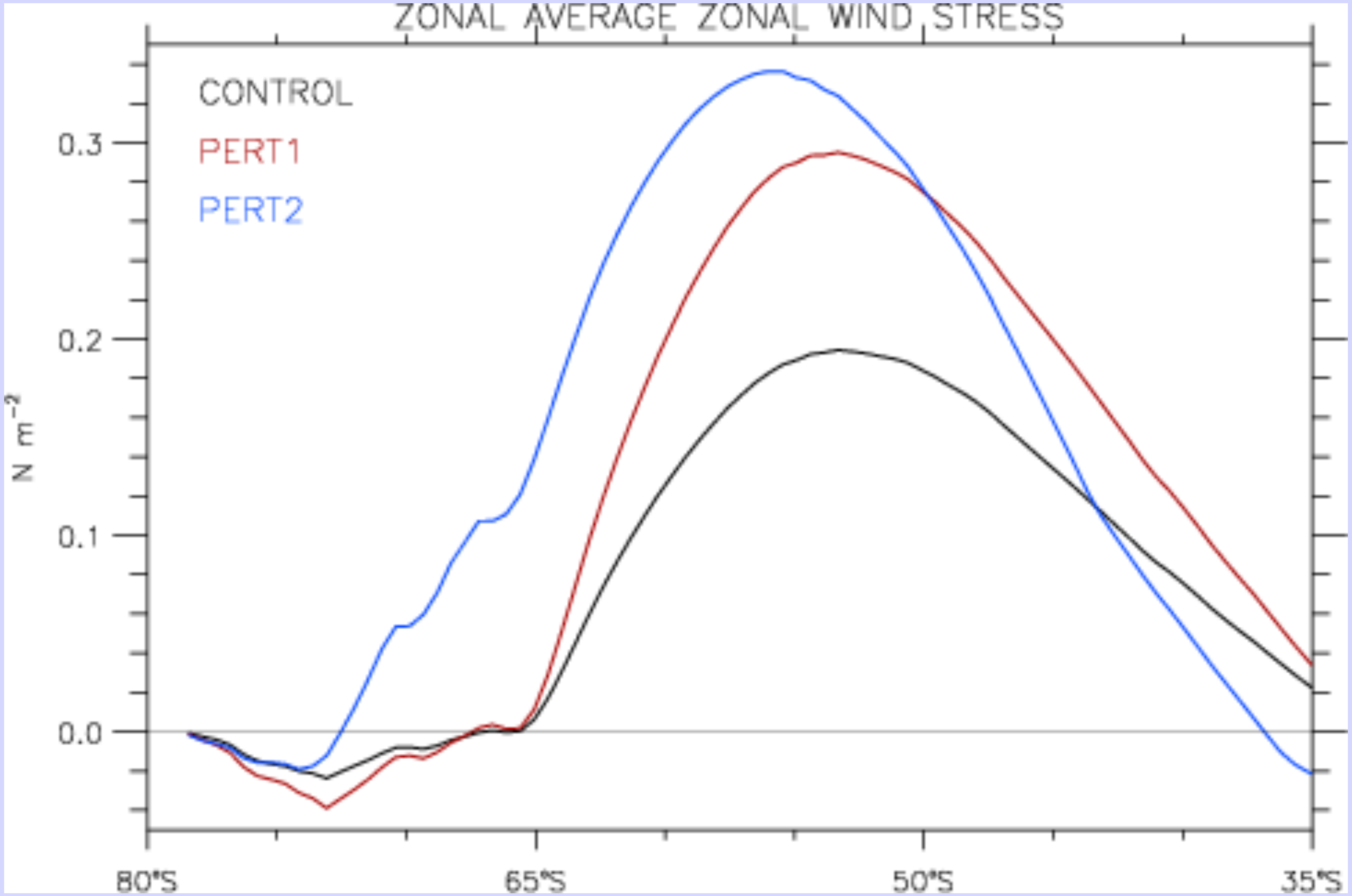
Farneti and Gent Ocean Modelling (2011)

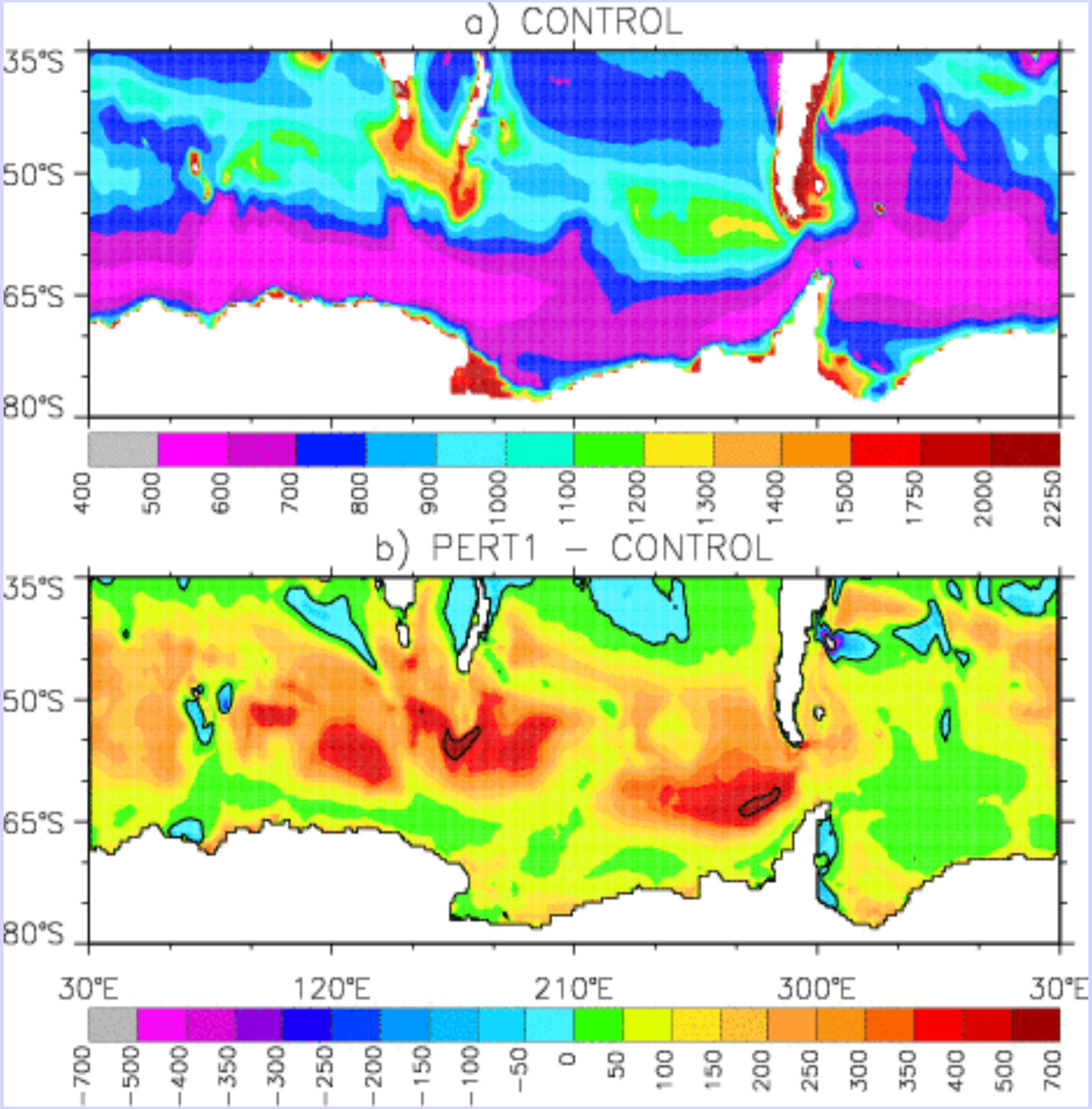
Use a modified CM2.1 where the cap on kappa is doubled to 1200 m^2/s. The control simulation degrades in several aspects (which is why it was capped), but the response to increased SH winds is much more like that in the E-P CM2.4 model.

Gent & Danabasoglu J Climate (2011)

Use the latest CCSM4 model that has another different variable kappa definition. Again, the response to increasing SH zonal winds is much more like in E-R ocean and E-P climate models.

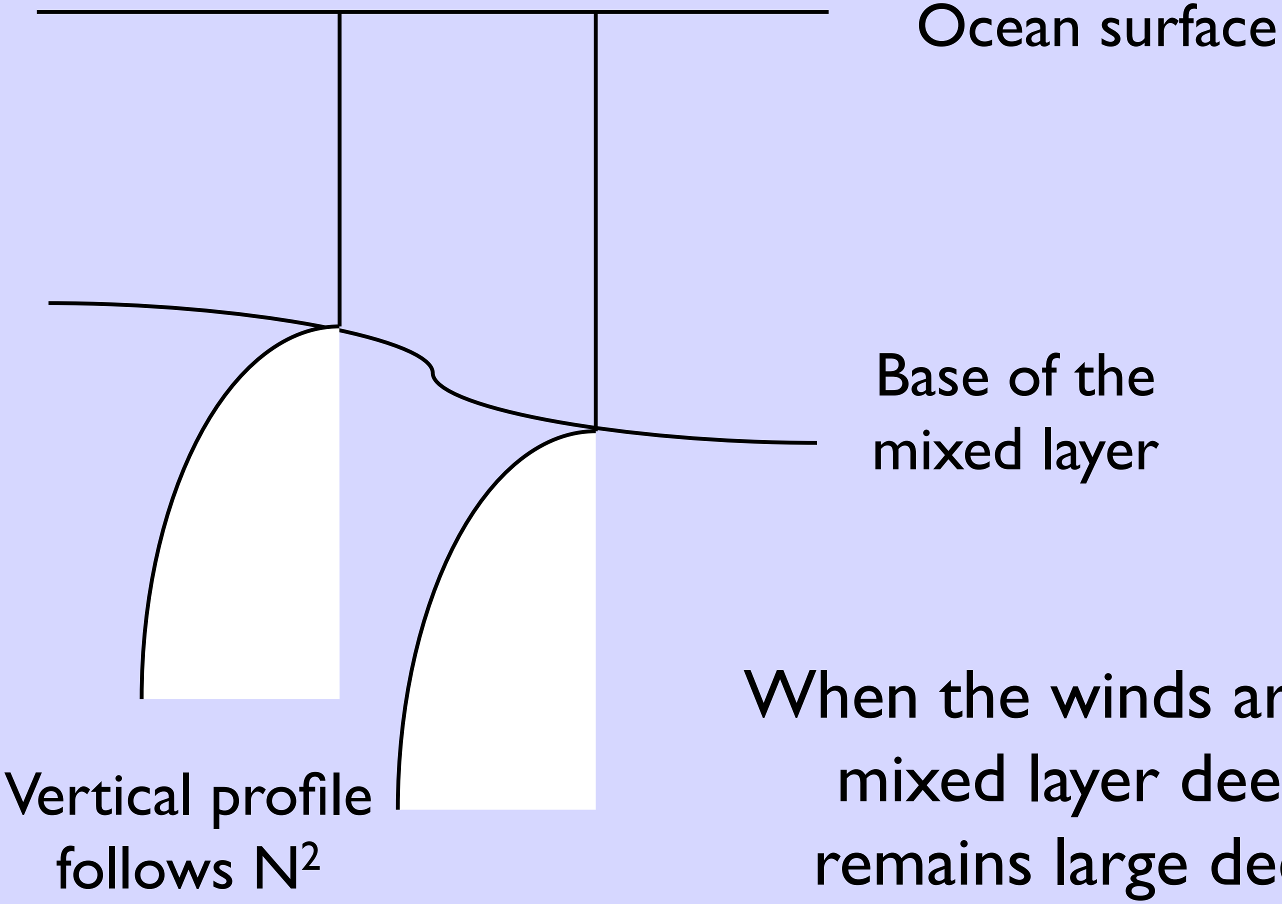
CCSM4 1°: PERT1 (red) increases zonal wind stress by 50% south of 30° S.
PERT2 (blue) adds same zonal stress as in CM2.1, which moves maximum 3° to south.



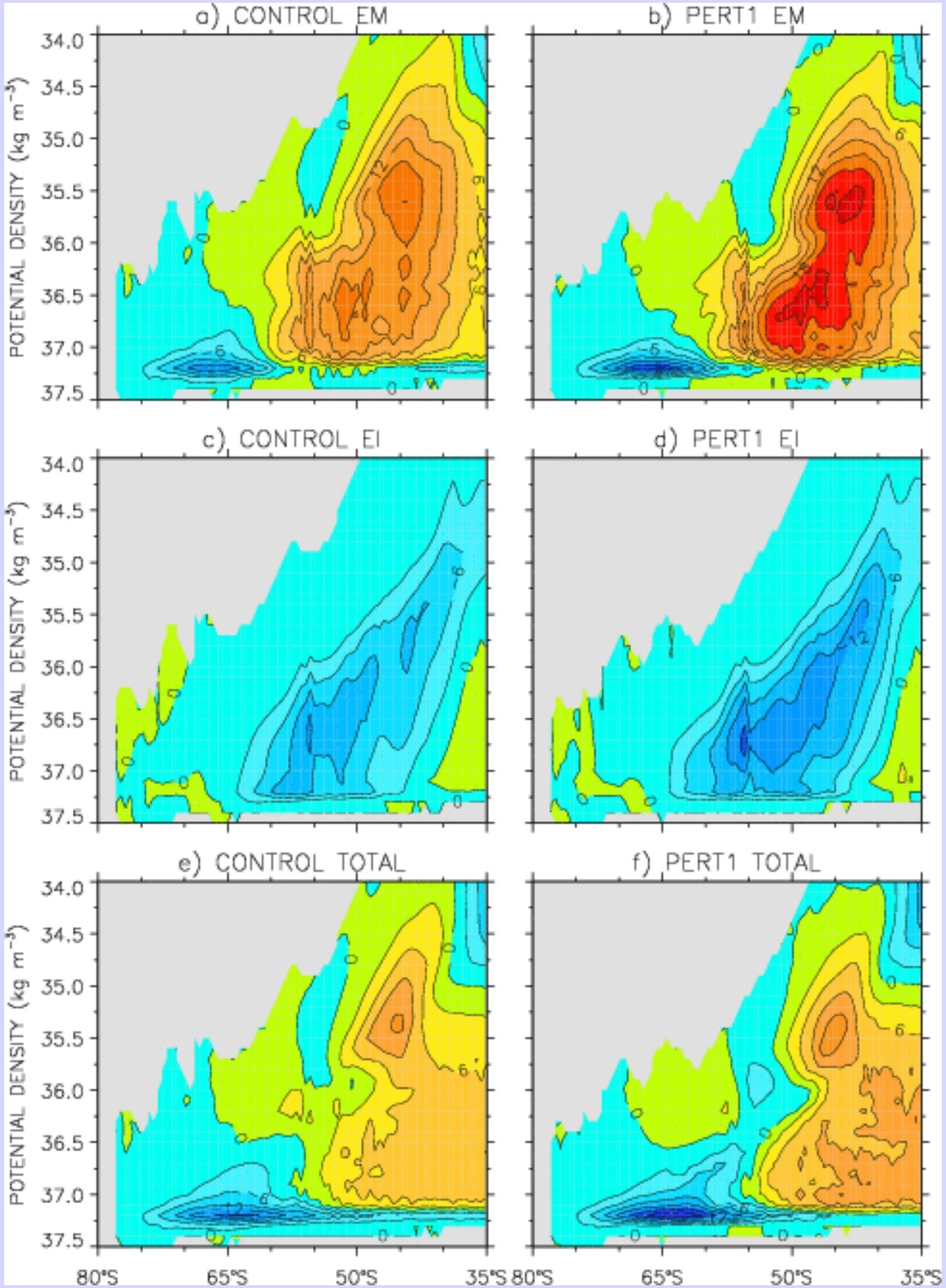


GM coefficient averaged over upper km in 1° CCSM4 control, and GM coefficient increase in PERT1 (50% increase in zonal stress).

GM coefficient: kappa in CCSM4



When the winds are stronger, the mixed layer deepens, kappa remains large deeper, and N^2 decay occurs deeper, so vertical average is larger.



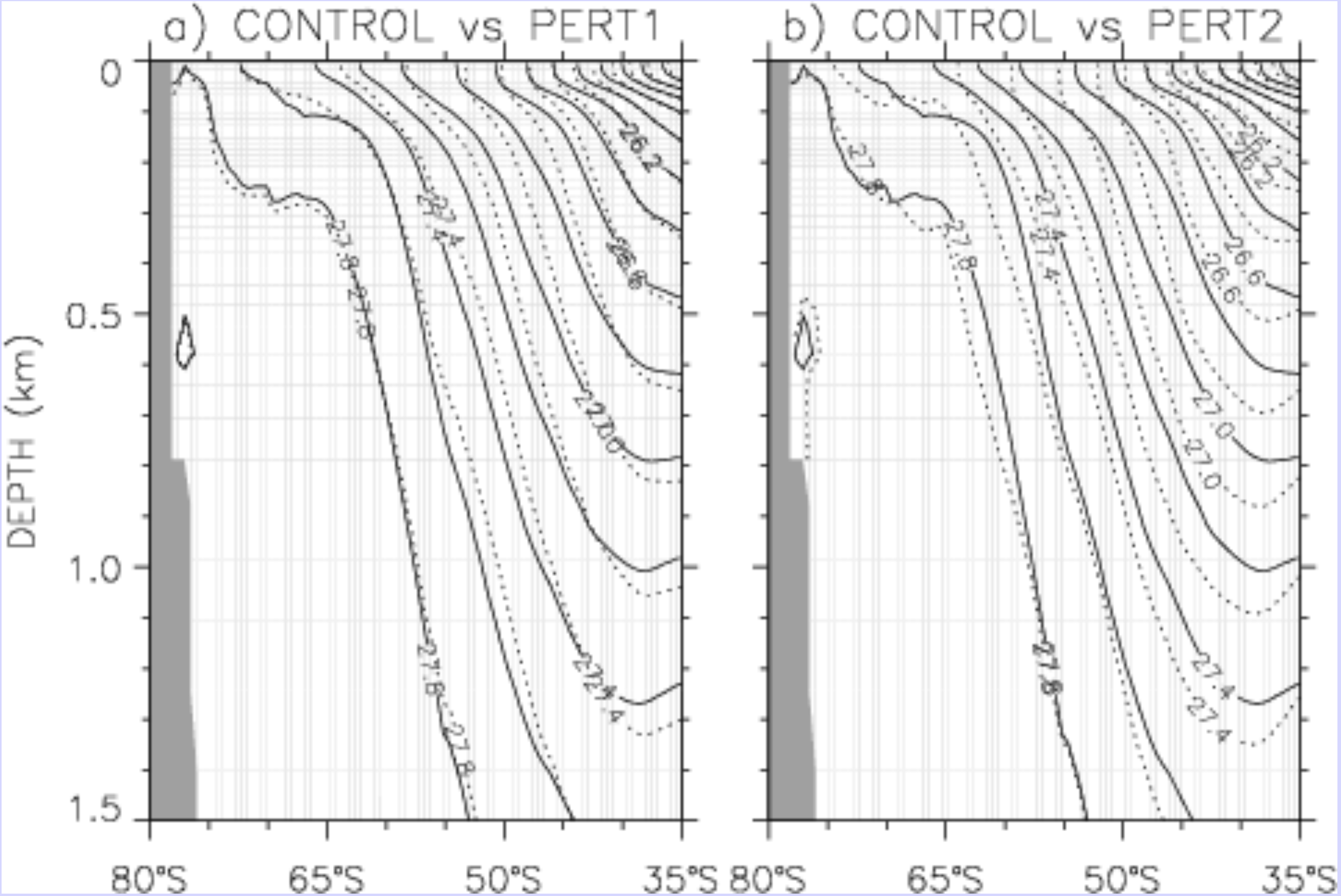
MOC plotted against potential density referenced to 2km for CCSM 1° control and PERT1 experiment.

Eulerian-mean (17.3 Sv : 21.6 Sv),

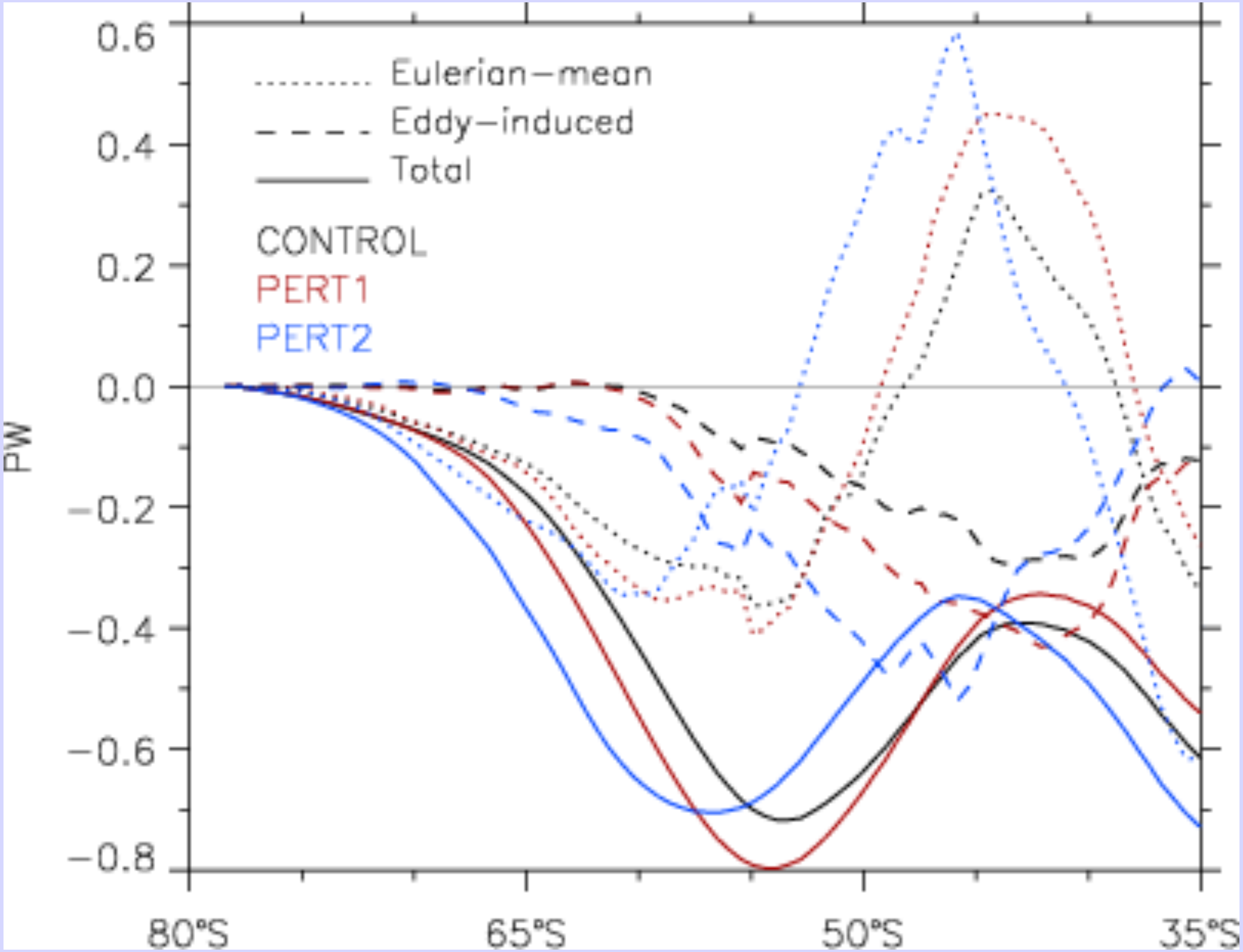
Eddy-induced (12.7 Sv : 16.0 Sv),

Residual (Total) (6.5 Sv : 8.3 Sv).

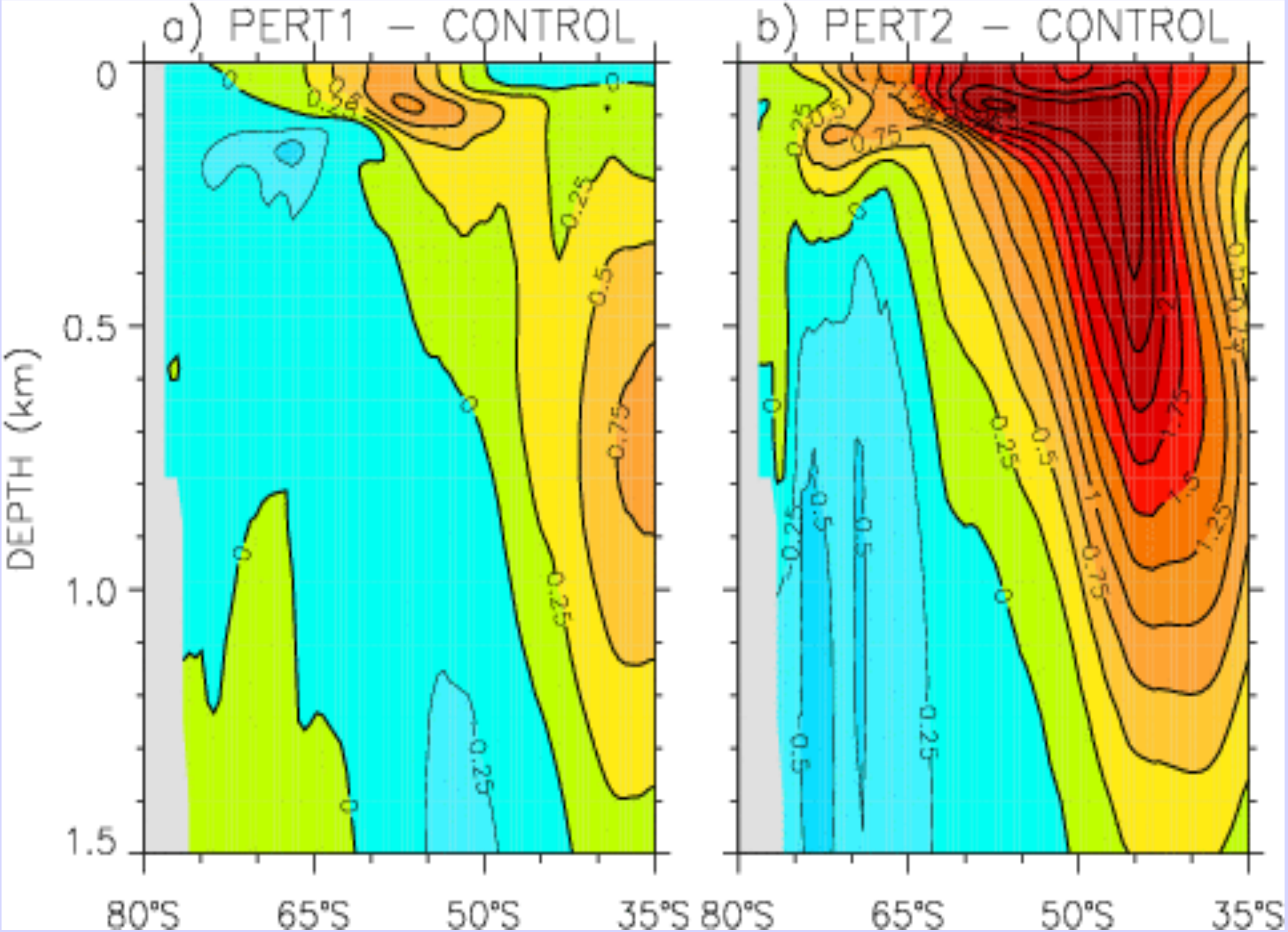
Potential Density from the CCSM4 1° control (solid) and the two perturbation runs (dotted).



Northward heat transport by mean, eddy and total (which includes transport by isopycnal diffusion).



Zonally-averaged potential temperature changes (°C) from PERT1 and PERT2



CONCLUSIONS

- E-R/P models show ACC is in eddy saturated state => change in eddy MOC balances mean flow MOC.
- Southward eddy heat transport is important to get the correct temperature and sea ice distributions.
- Climate models with constant GM kappa do not get correct response to SH wind shifts; a good variable definition of kappa is required. The eddy response appears to be a little too small in current models.
- A southward shift in the SH zonal wind maximum causes a much larger change in the temperature distribution than an in-situ zonal wind increase.