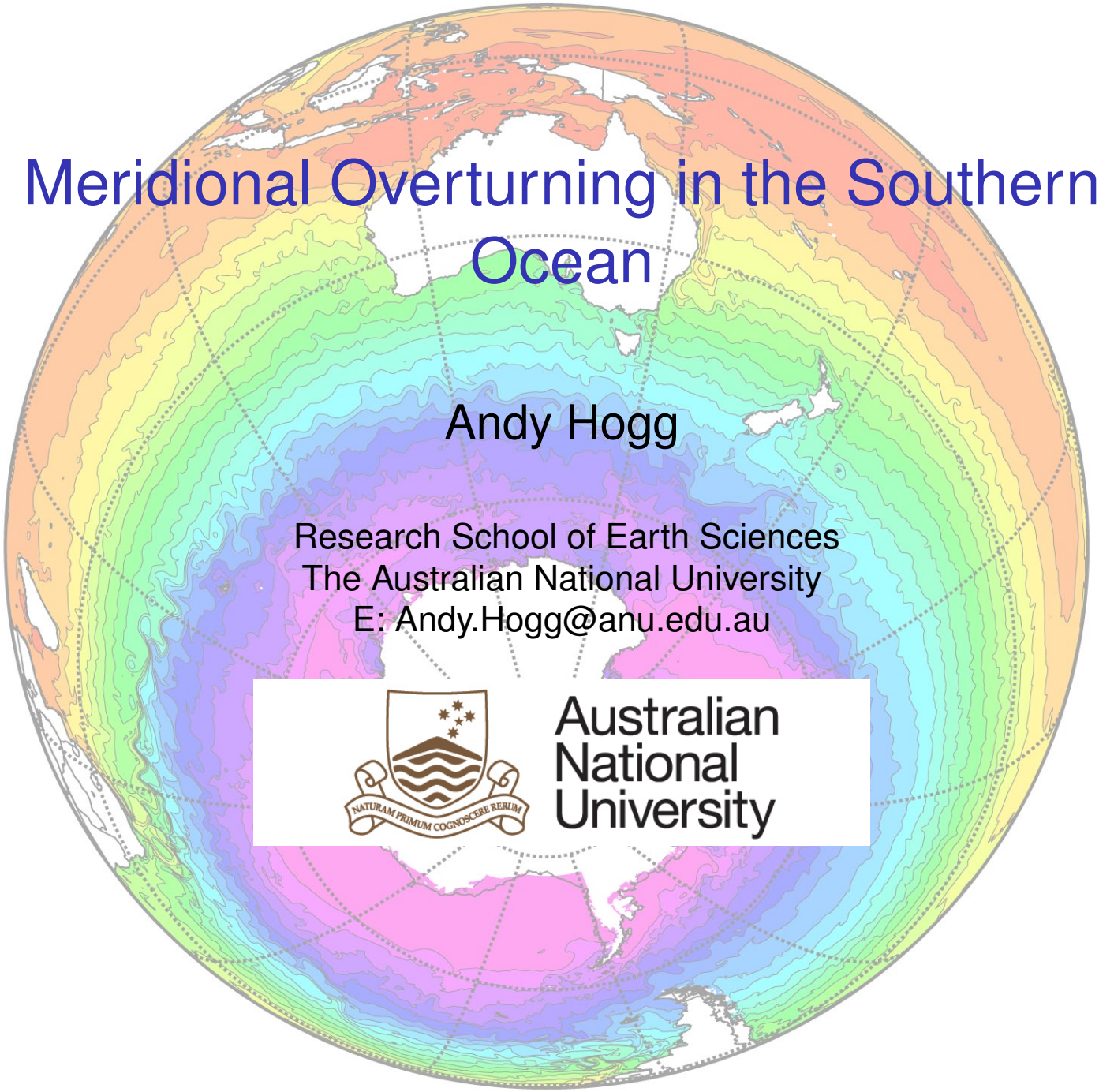

Meridional Overturning in the Southern Ocean

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The Southern Ocean

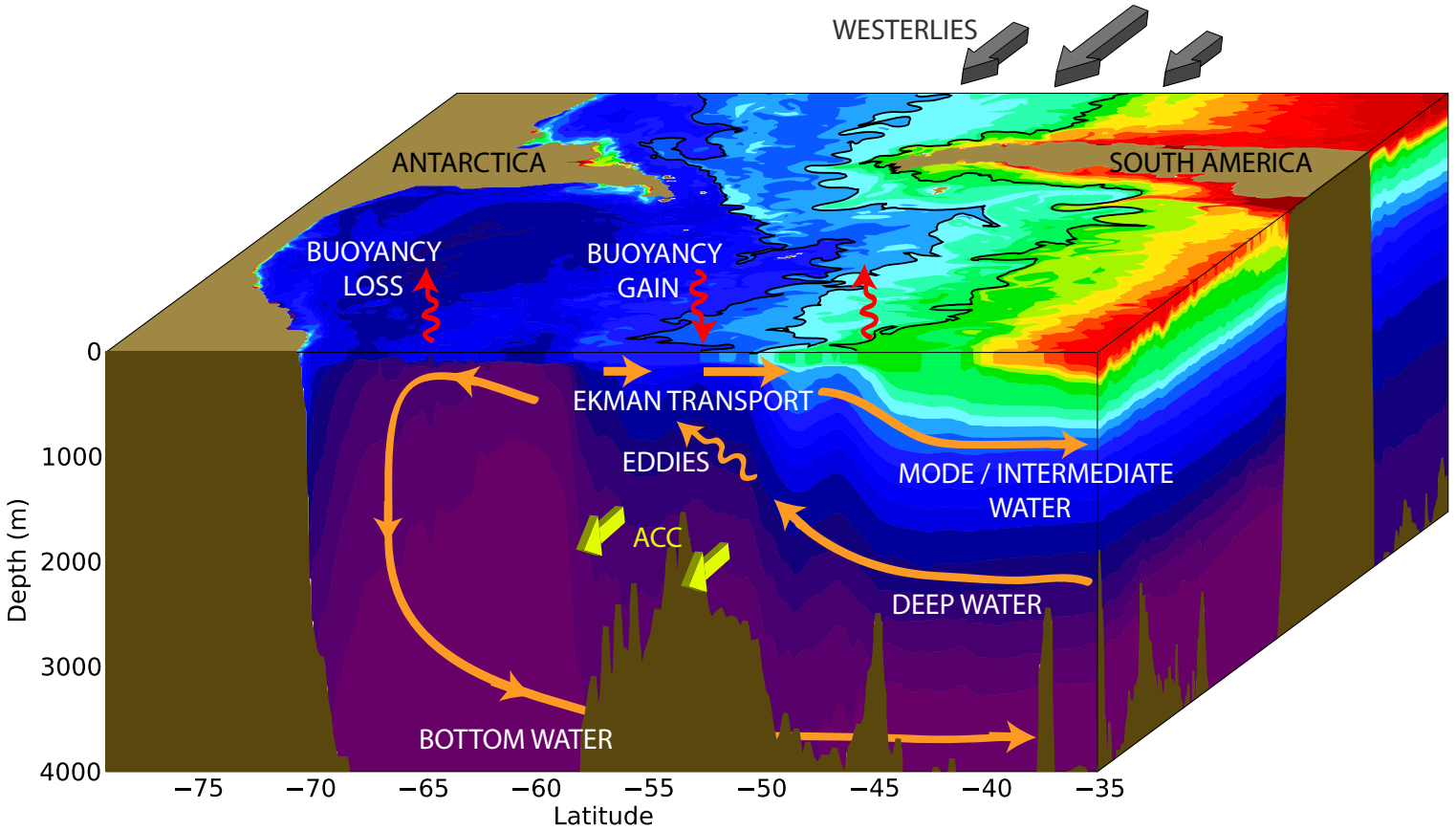


Image from Morrison et al., 2015: "Upwelling in the Southern Ocean." Phys. Today.

- "Wind-driven" Antarctic Circumpolar Current (ACC)
- Upper & lower overturning cells
- Buoyancy fluxes also drive circulation

Southern connections to global overturning

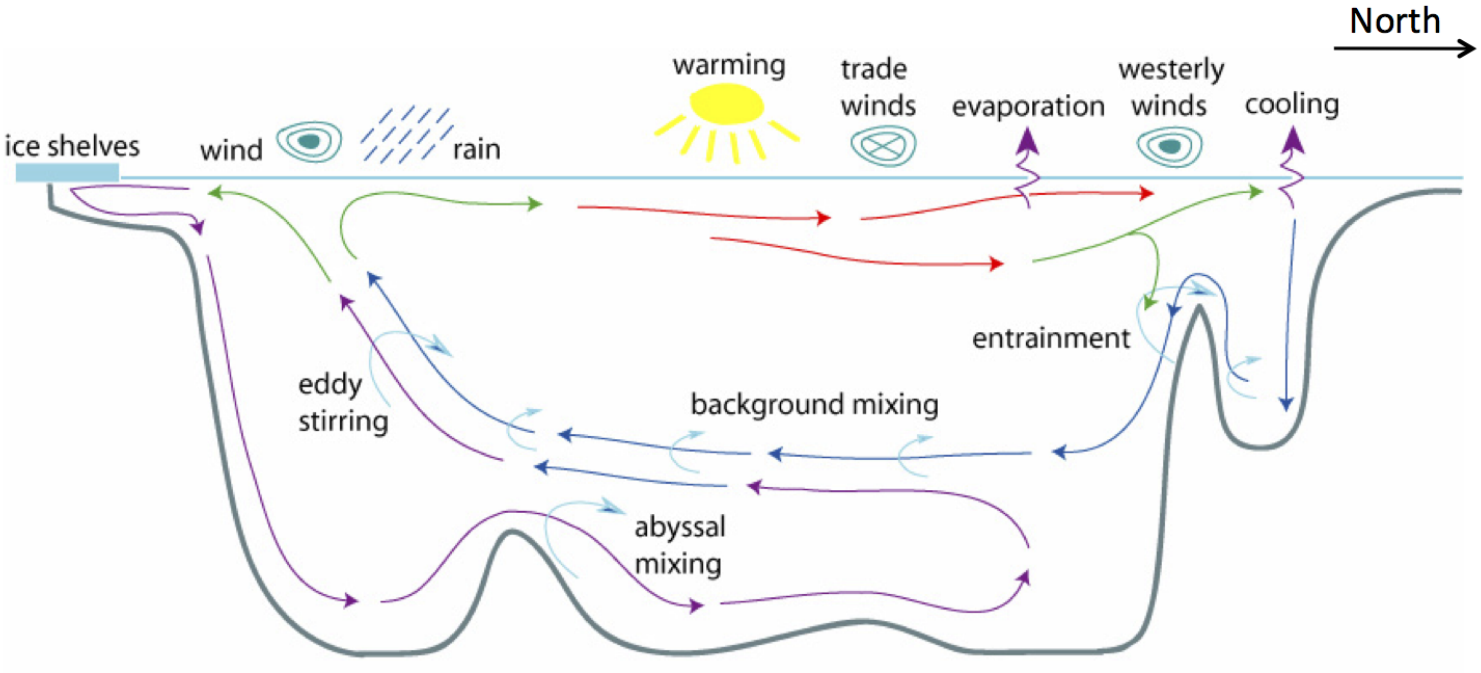
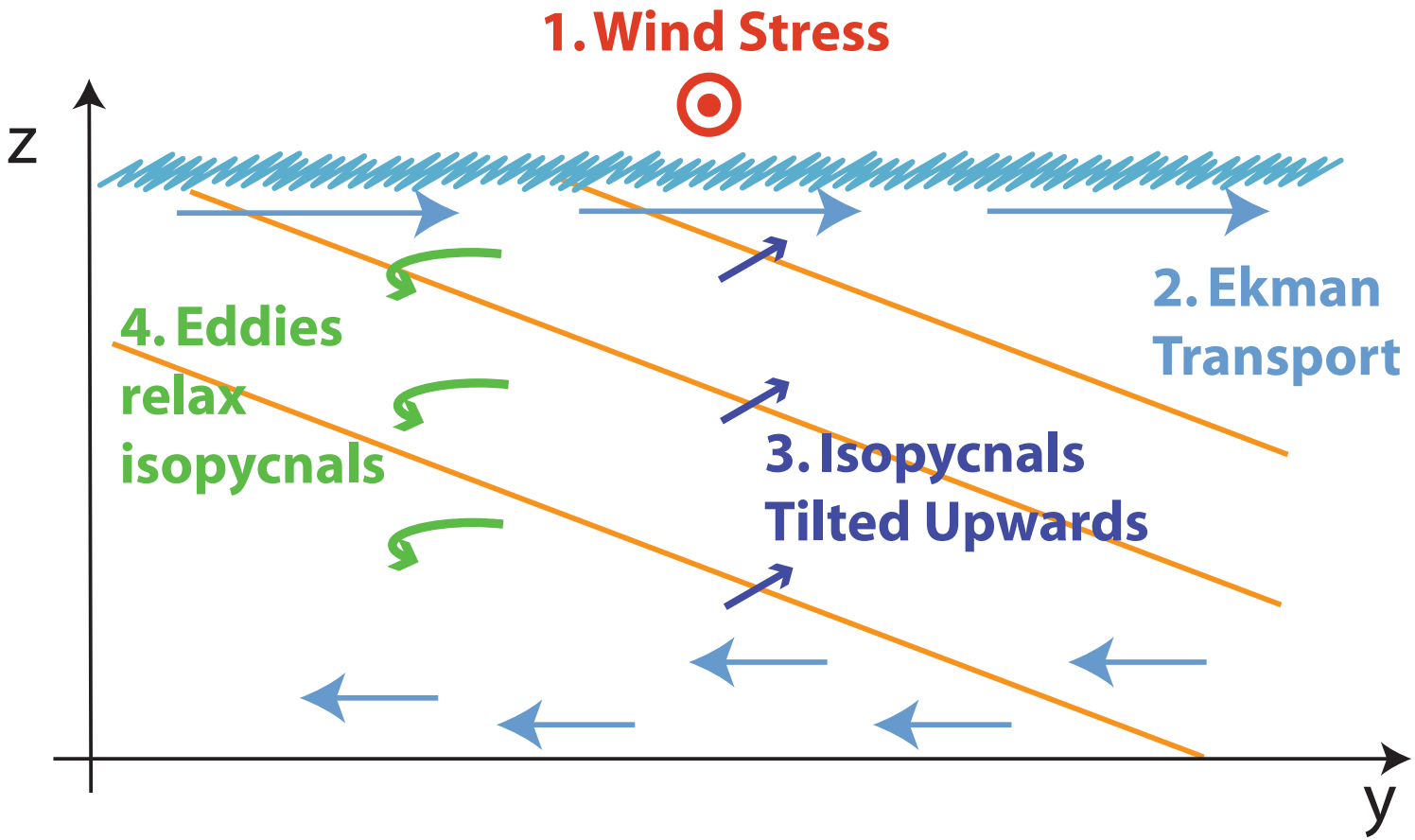


Image thanks to R. Marsh, NOC.

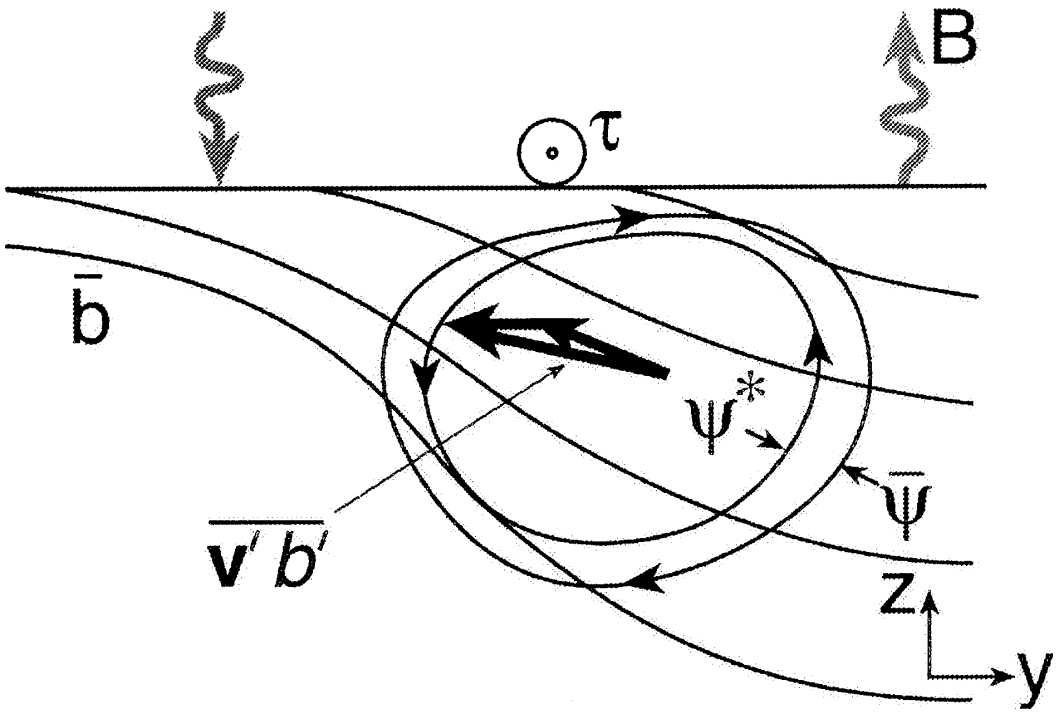
- Upper (NADW) cell – partly wind-driven?
- Lower (AABW) cell – balance between interior mixing and southern buoyancy fluxes

Today's talk: Review how (and why) the upper & lower cells are likely to change with variations in forcing – both wind stress and surface buoyancy flux.

The Upper Cell: The Basics



(i) Theory: Residual Mean



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

Marshall & Radko, JPO (2003)

- Can divide flow into a mean, eddy and residual overturning.
- Eddy overturning "opposes" the mean

Insensitivity of upper MOC cell to wind stress forcing:

- **Eddy compensation**

Insensitivity of ACC to wind stress forcing:

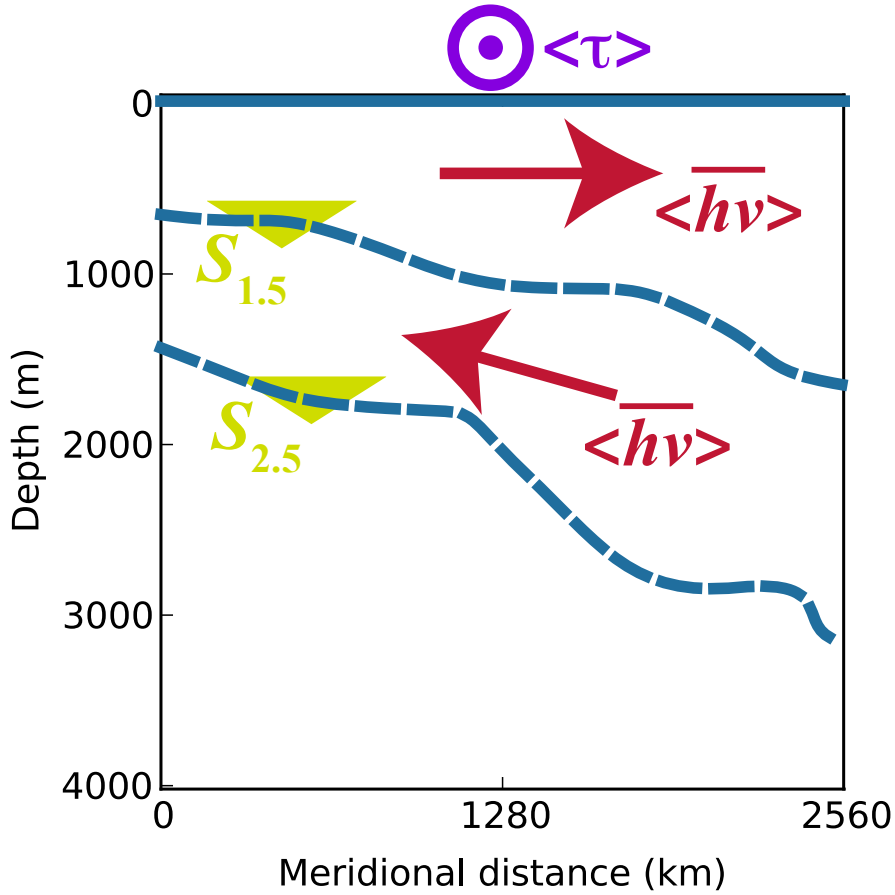
- **Eddy saturation**

A “simple” model to explore MOC dynamics

Zonally averaged, layer averaged zonal transport:

$$T = \int_0^{L_y} hu\, dy \equiv \langle hu \rangle$$

$$T_t \approx f\langle \overline{hv} \rangle - \langle \overline{hM_x} \rangle + \langle \tau \rangle$$



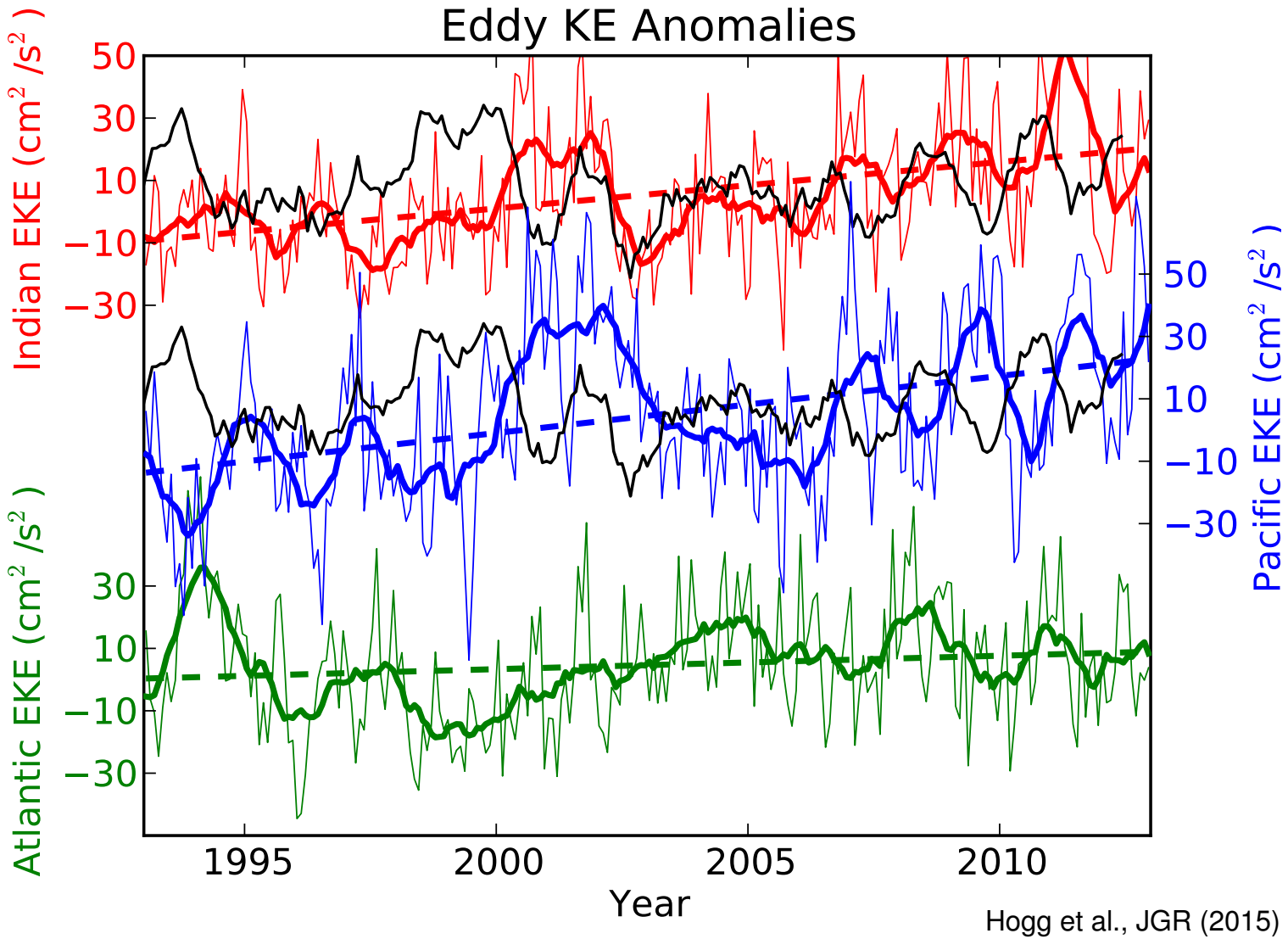
$$\boxed{T_{kt} \approx \mathsf{C}_k + (\mathsf{S}_{k-\frac{1}{2}} - \mathsf{S}_{k+\frac{1}{2}}) + \tau_k}$$

Eddies modify both the meridional transport and the form stress terms.

If you want to follow the maths, read Killworth & Nanneh, JPO (1994). See also Howard et al., JPO (2014)

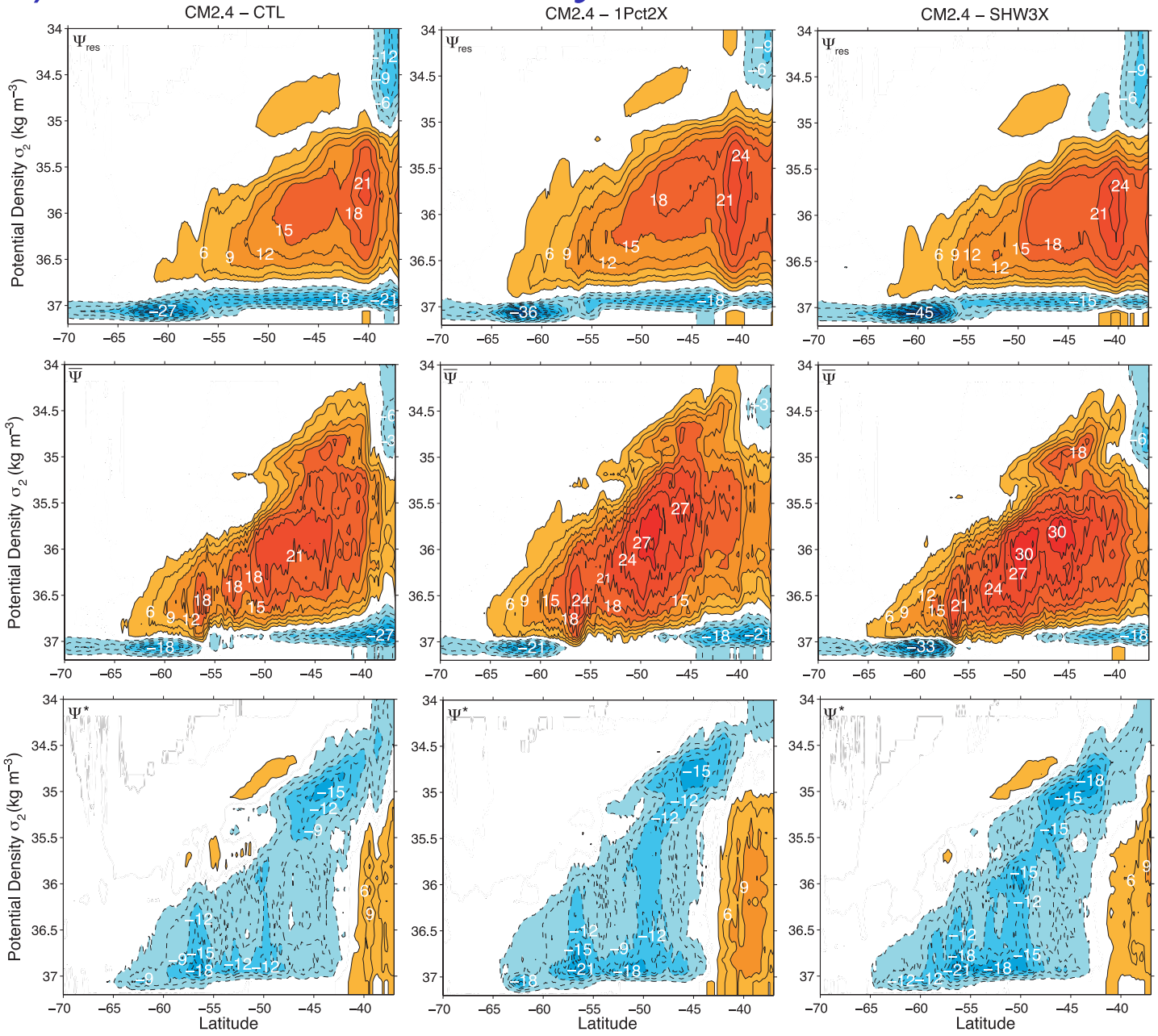
(ii) Observations: Sensitivity of Eddies

Satellite observations now confirm that eddy KE has increasing with the wind.



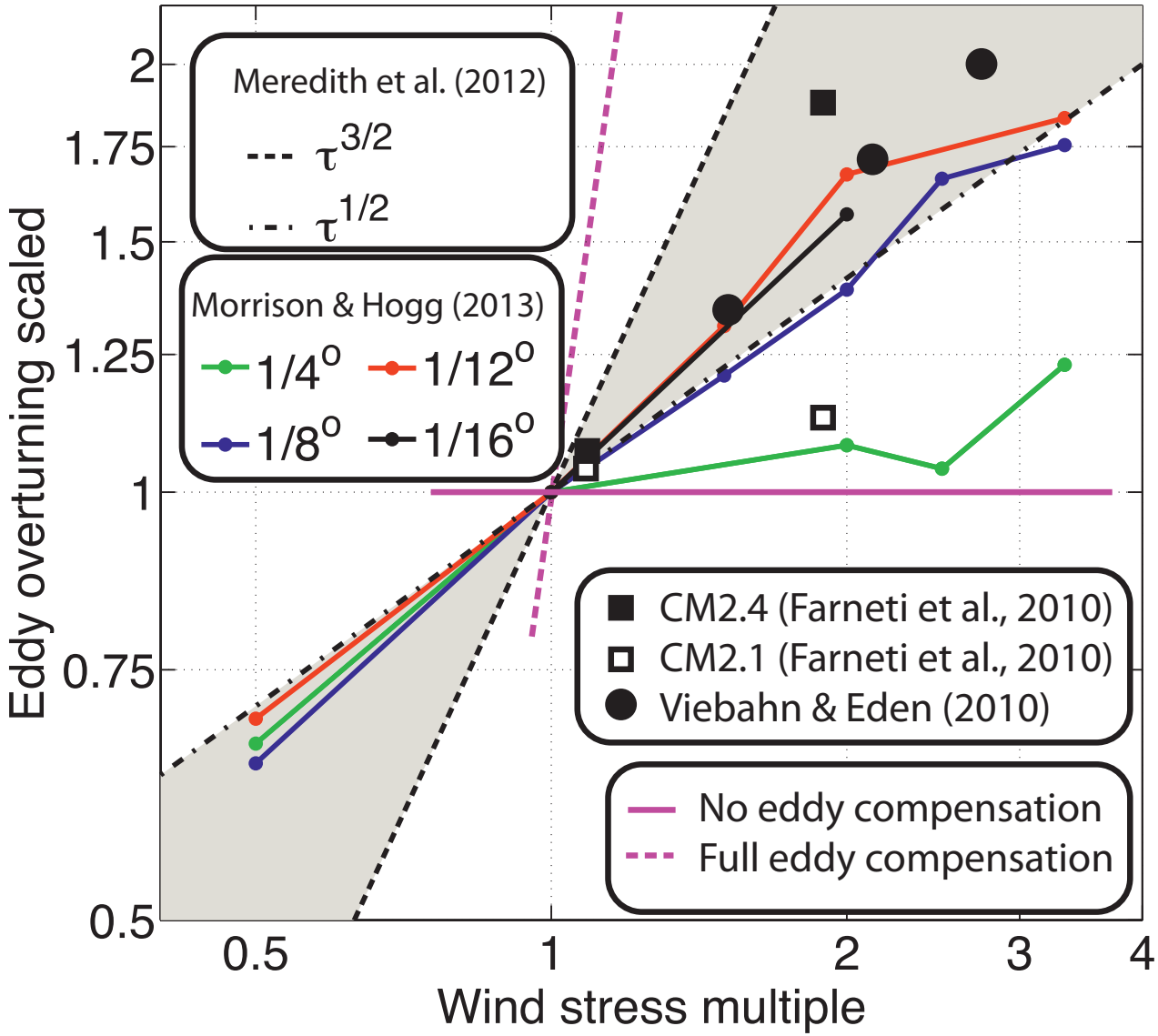
Hogg et al., JGR (2015)

(iii) Models: Sensitivity of MOC to Eddies



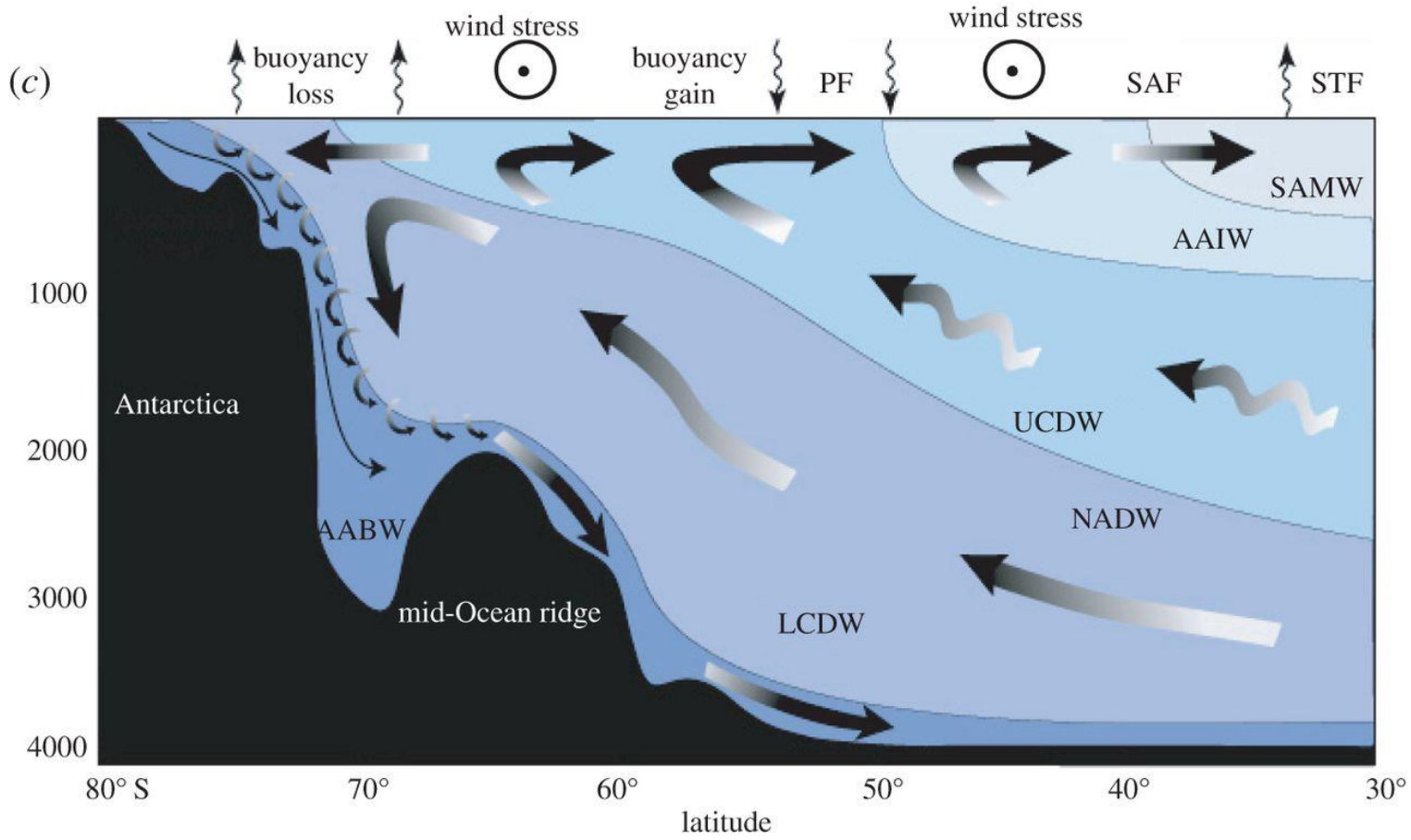
Farneti et al., JPO (2010)

(iii) Models: Sensitivity of MOC to Eddies



Coarse-resolution models have weak compensation, unless GM coefficient is variable (e.g. Gent & Danabasoglu, J. Climate, 2011)

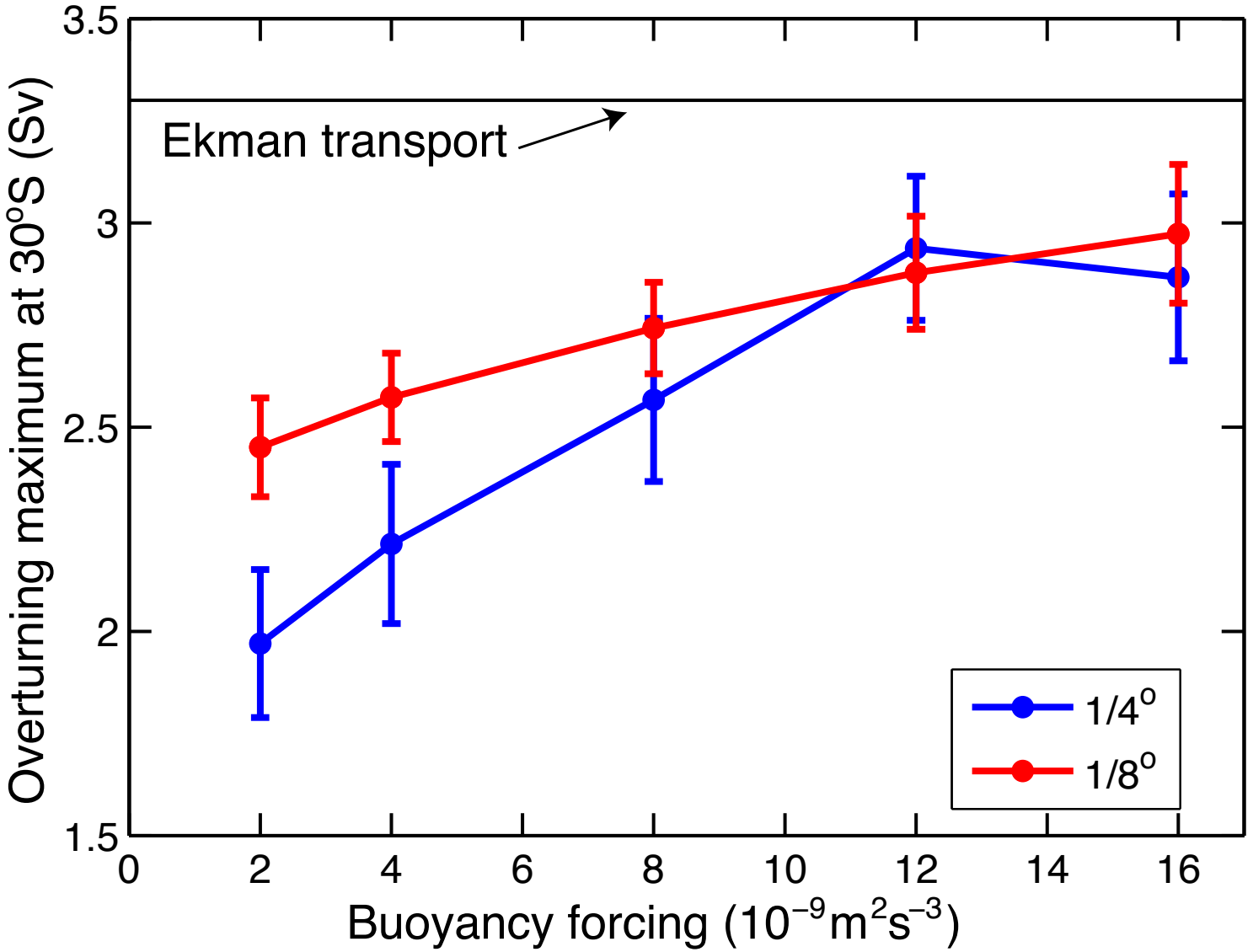
(iv) Complications: Sensitivity to Buoyancy



e.g. Speer et al., JPO (2000)

We have known for sometime that buoyancy gain is an important aspect of the Southern overturning . . . in fact, overturning can be diagnosed from buoyancy fluxes (Badin et al., JPO, 2013)

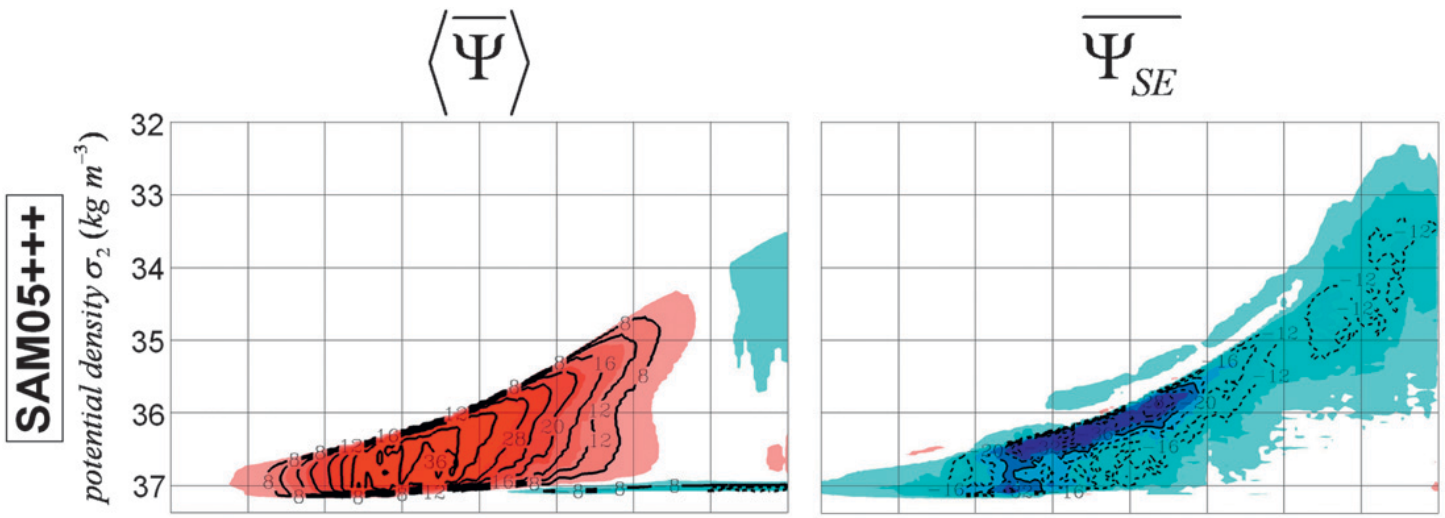
(iv) Complications: Sensitivity to Buoyancy



Morrison et al., GRL (2011)

[Equivalently, the overturning response to wind depends upon surface BC (Abernathey et al., JPO, 2011)]

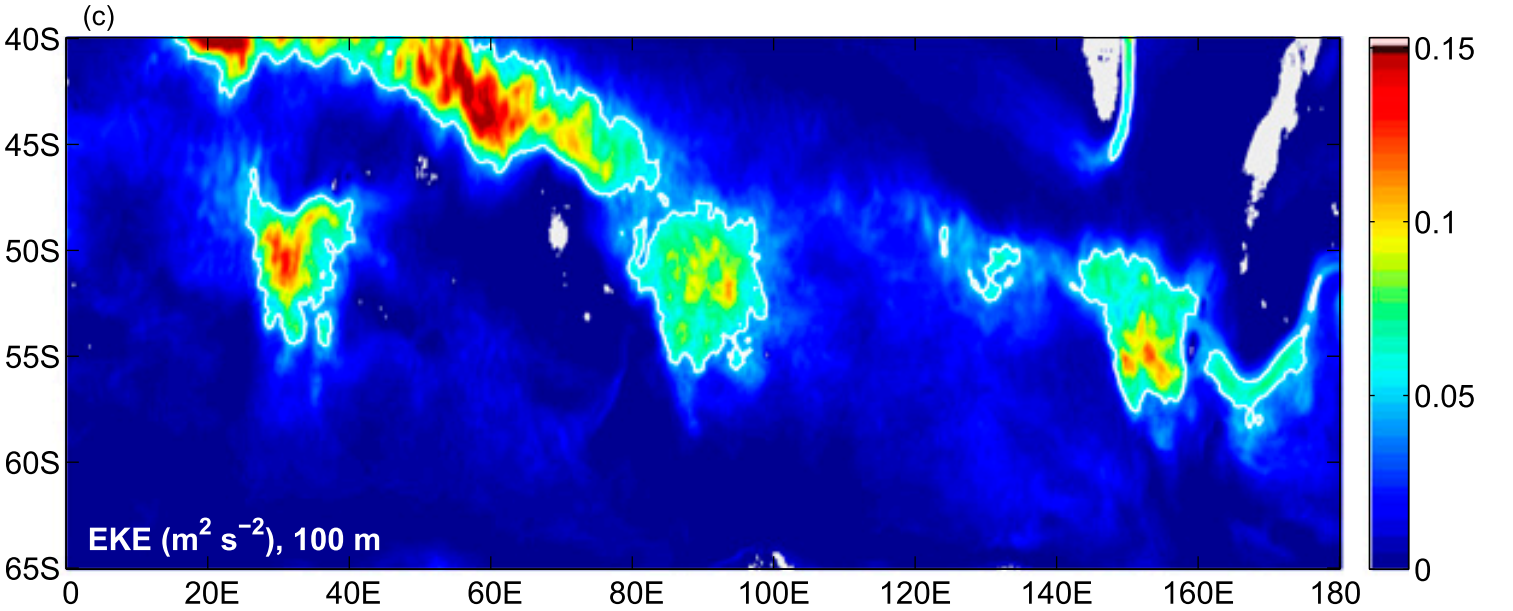
(iv) Complications: What is an eddy?



Dufour et al., J. Climate (2012)

- **Standing eddies** can actually explain a significant component of the overturning circulation.
- Standing eddies may also control the location of heat fluxes (Abernathey & Cessi, JPO, 2014)
- Standing meander response to forcing is also important (Thompson & Naveira Garabato, JPO, 2014)

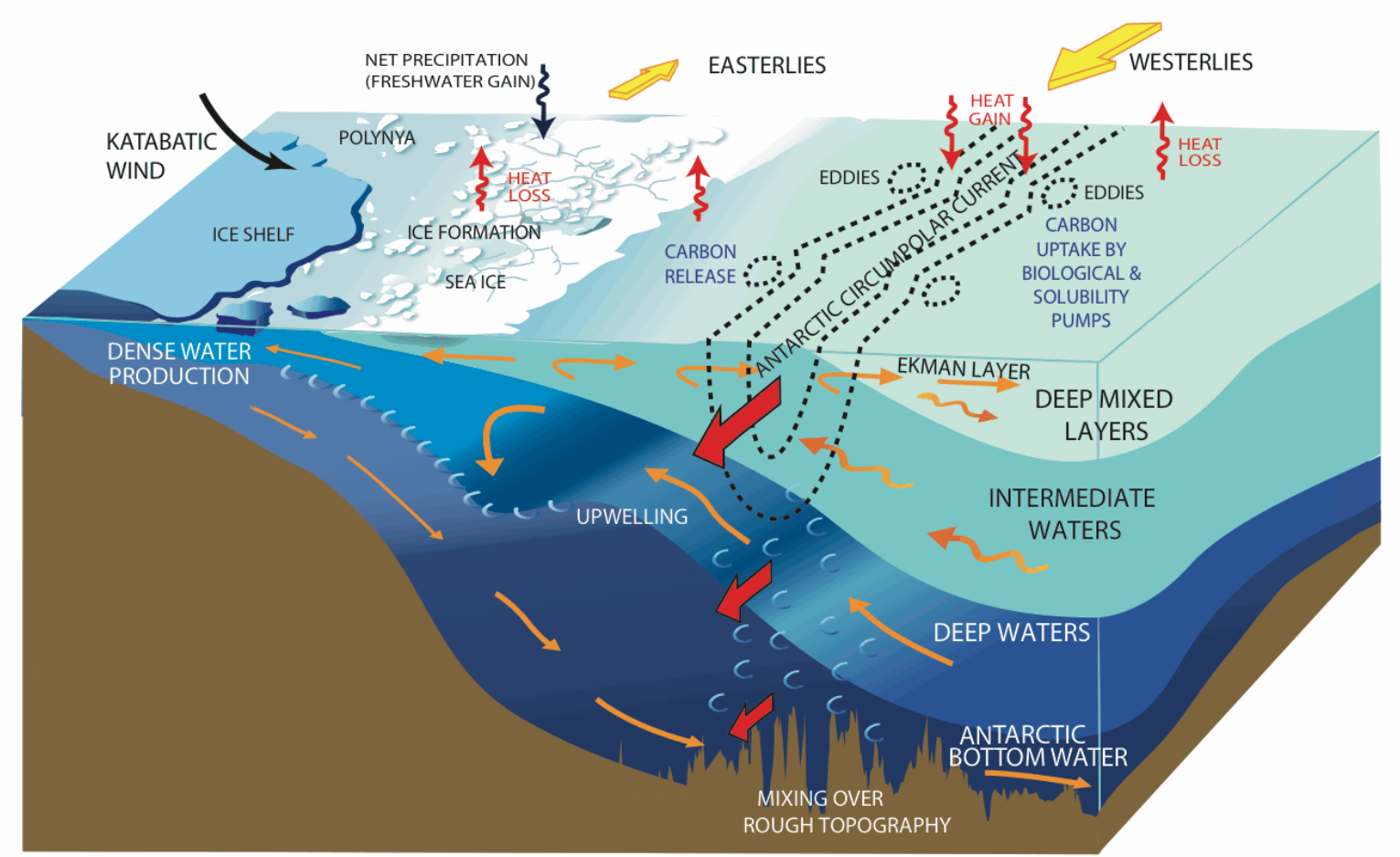
(iv) Complications: Three-dimensionality



Thompson & Naveira Garabato, JPO (2014)

- ACC is non-zonal
- No guarantee that a 2D representation of overturning is relevant to transport of tracers!

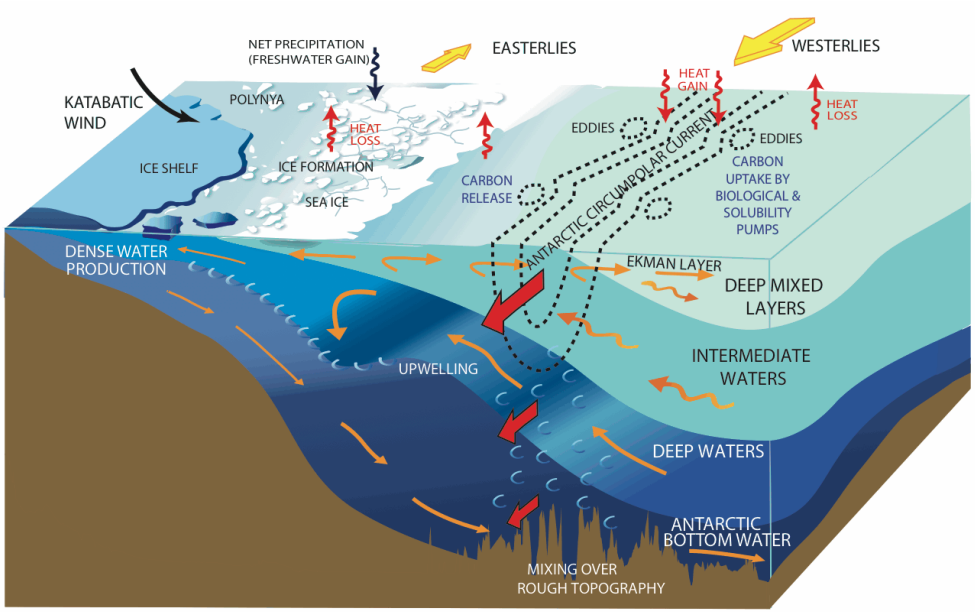
Lower Cell



From Talley (adapted from NRC, 2011)

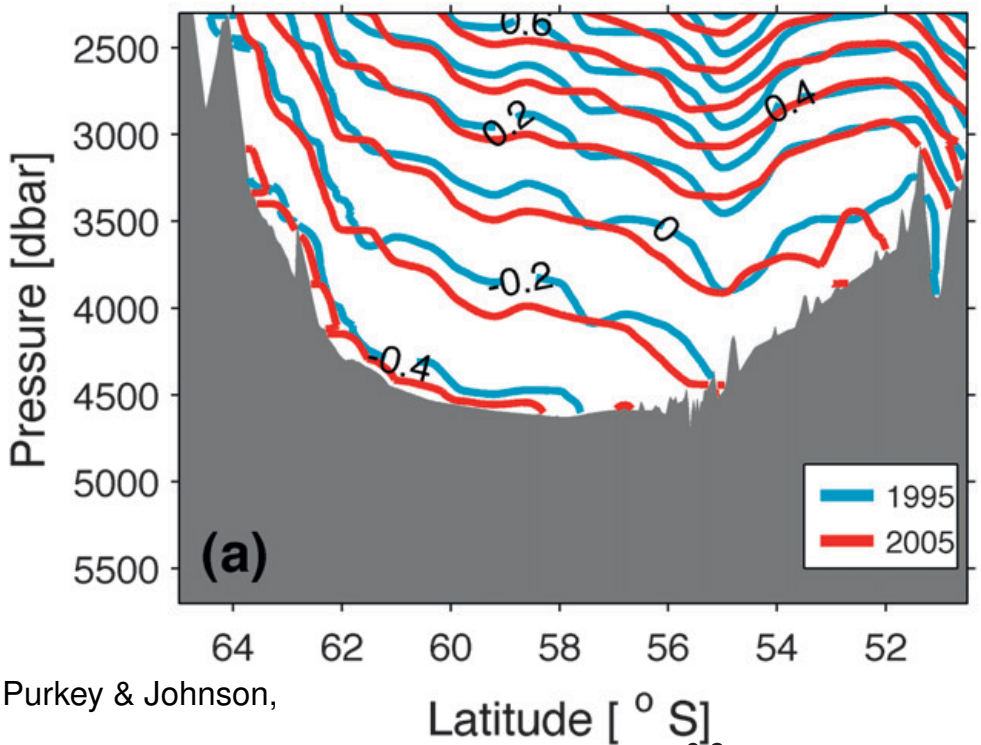
What sets the strength of the lower cell?

- Available Potential Energy input from surface buoyancy fluxes (Hughes et al., JPO, 2006)
- Entrainment of the descending plume (Hughes & Griffiths, Ocean Mod., 2006)
- Interior mixing . . . (Nikurashin & Ferrari, GRL, 2013)
- . . . as well as lateral eddy fluxes (Ito & Marshall, JPO, 2008)
- All of the above?



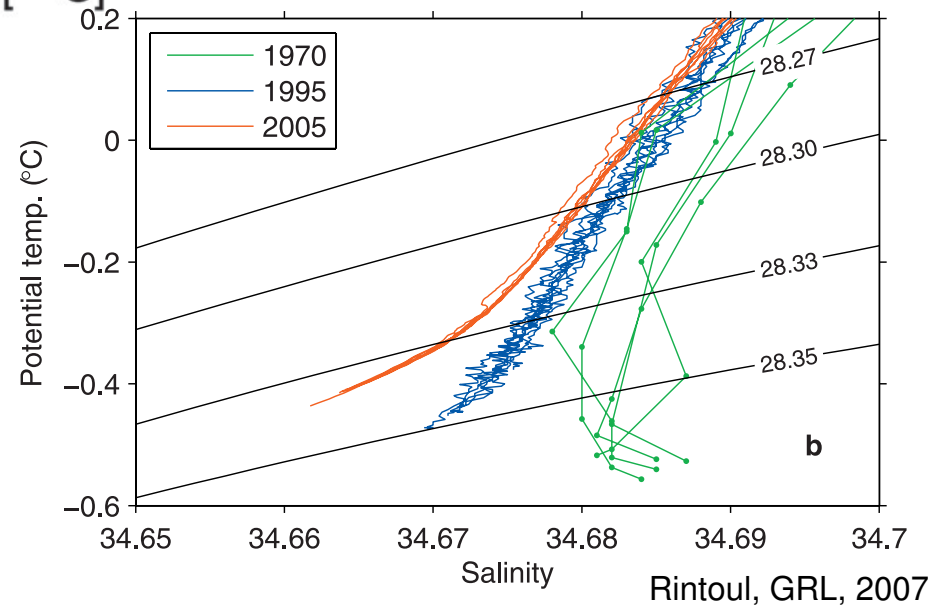
From Talley (adapted from NRC, 2011)

(ii) Observations: Warming & Freshening



Purkey & Johnson,

J. Climate, 2012

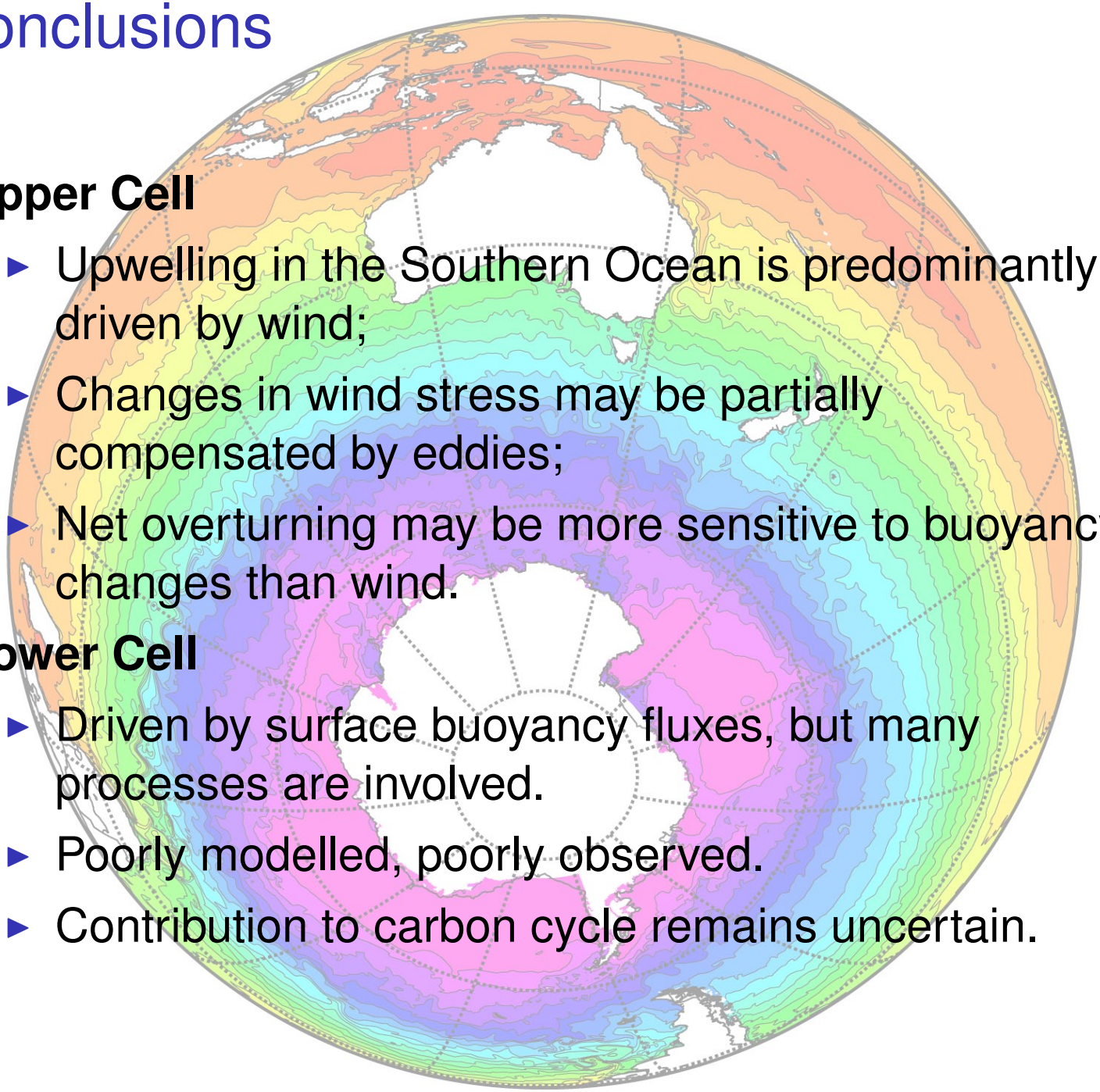


Rintoul, GRL, 2007

(iv) Complications

- It is very likely that surface freshening/warming will reduce AABW formation, but is it also sensitive to changes in wind stress?
- Can or should changes in lower cell be offset by changes in the upper cell?
- Can we estimate current buoyancy fluxes close to the Antarctic coast? (see Tamura et al., GRL 2008)
- The lower cell is potentially more important to the carbon cycle than the upper cell, but can we even estimate the carbon uptake in these regions?
- How can we model all the processes involved in bottom water formation?

Conclusions



Upper Cell

- Upwelling in the Southern Ocean is predominantly driven by wind;
- Changes in wind stress may be partially compensated by eddies;
- Net overturning may be more sensitive to buoyancy changes than wind.

Lower Cell

- Driven by surface buoyancy fluxes, but many processes are involved.
- Poorly modelled, poorly observed.
- Contribution to carbon cycle remains uncertain.