Sensitivity of the Southern Ocean overturning to decadal changes in wind forcing

Alberto Naveira Garabato¹, Mike Meredith², Andy Hogg³ & Riccardo Farneti⁴

¹ National Oceanography Centre, Southampton
² British Antarctic Survey
³ Australian National University
⁴ GFDL, Princeton / ICTP, Trieste
Question

Temperature trend on isobaric surfaces since the 1970s (colour) and zonal-mean neutral density distribution (contours: 1970s - solid, 2000s - dashed) across the Southern Ocean (Böning et al., 2009).

Should we expect the Southern Ocean (upper cell) overturning to respond to decadal changes in wind stress, based on physical principles?
The Southern Ocean overturning circulation

The Southern Ocean overturning can be described as the residual arising from the incomplete cancellation between two opposing circulations…

\[ \psi^\dagger = \psi + \psi^* , \text{ where } \psi^*_z = -f^{-1} \kappa q_y \]

\( f = \text{Coriolis parameter}, \kappa = \text{isopycnal eddy diffusivity}, q = \text{Ertel PV} \)

(Speer et al., 2000)
How eddies stir tracers across the ACC... (1)

Naveira Garabato, Ferrari and Polzin (2011)

Mixing length theory \[ \kappa \propto L_e U_e \]
where \( L_e \) is an eddy mixing length and \( U_e \) an eddy velocity scale (\( = EKE^{1/2} \))

Mean potential temperature (colour) and pressure (contours) along SR3 section south of Tasmania.

Eddy mixing length along the same section, estimated from observations of (CTD) thermohaline finestructure.

Geostrophic speed along the same section.

Patches of small eddy mixing length (and therefore isopycnal diffusivity \( \kappa \)) are aligned with ACC jets - except in one case...
How eddies stir tracers across the ACC... (2)

From the barotropic QG PV equation for nonlinear eddy perturbations in a large-scale, slowly-evolving, zonal mean jet of speed $U_m$, it may be shown that

$$\kappa = \frac{EKE\gamma^{-1}}{1 + \gamma^{-2}k^2(U_m - c)^2}$$

where $EKE$ is eddy kinetic energy, $\gamma$ is an eddy damping rate, $k$ is the zonal eddy wavenumber, and $c$ is the eddy phase speed (Ferrari and Nikurashin, 2010; Naveira Garabato, Ferrari and Polzin, 2011).

The theory predicts that:

- For eddies propagating at the same speed as the jet ($c = U_m$), $\kappa$ is proportional to $EKE$ and the eddy decorrelation time scale $\gamma^{-1}$ (as in Taylor, 1921).

- However, when $c \neq U_m$, $L_e$ and $\kappa$ are suppressed by the presence of the jet, as eddy filamentation is arrested on a time scale $k^{-1}(U_m - c)^{-1}$. This is a kinematic effect.

Thus, $L_e$ and $\kappa$ suppression is predicted at the upper-ocean core of ACC jets.
How eddies stir tracers across the ACC... (3)

Relationship between $L_e$ (or $\kappa$) and the mean flow: observations vs. theory.

The theory does a good job of predicting the characteristic relationship between $L_e$ (or $\kappa$) and the mean flow, but...

Circles show average $L_e$ values in $U_m$ bins, with bars indicating standard deviation of $L_e$ within each bin. Colour shading shows mean $U_e$ ($= EKE^{1/2}$) in each bin. Dashed line denotes theoretical prediction.
How eddies stir tracers across the ACC... (3)

Relationship between $L_e$ (or $\kappa$) and the mean flow: observations vs. theory.

![Graph](image)

Naveira Garabato, Ferrari and Polzin (2011)

The theory does a good job of predicting the characteristic relationship between $L_e$ (or $\kappa$) and the mean flow, but...

... in a few occasions (narrow and twisted ACC jets close to topography), the relationship breaks down. Is this significant?

Circles show average $L_e$ values in $U_m$ bins, with bars indicating standard deviation of $L_e$ within each bin. Colour shading shows mean $U_e$ (= $EKE^{1/2}$) in each bin. Dashed line denotes theoretical prediction.
Should we expect the Southern Ocean (upper cell) overturning to respond to decadal changes in wind stress, based on physical principles?

Temperature trend on isobaric surfaces since the 1970s (colour) and zonal-mean neutral density distribution (contours: 1970s - solid, 2000s - dashed) across the Southern Ocean (Böning et al., 2009).
What we already know: the ACC is in an eddy-saturated state (over decadal time scales)

Eddies & the ACC (QG eddy-resolving model)

Insensitivity of ACC transport to wind: **Eddy Saturation**
What we already know: the ACC is in an eddy-saturated state (over decadal time scales)

Eddies & the ACC ($\frac{1}{4}^\circ$ climate model – CM2.4)

**ACC Transport**

![ACC Transport Diagram](image)

**Eddy Saturation**

![Eddy Saturation Diagram](image)

**Eddy Kinetic Energy**

![Eddy Kinetic Energy Diagram](image)
Distinction between eddy saturation and eddy compensation

Eddies & the overturning circulation?

1. Upwelling associated with northward Ekman transport
2. Naturally, isopycnals tilt upwards toward the south
3. Eddies act to flatten isopycnals

Eddies counteract wind stress forcing: Eddy compensation

Note that isopycnal tilt is proportional to ACC transport ...
Null Hypothesis
There is a one-to-one correspondence between eddy saturation and eddy compensation.

In what remains we will:
- Assume complete eddy saturation (of the ACC);
- Use scaling theory to estimate overturning response to wind;
- Demonstrate that exact eddy compensation (of the overturning) lies outside the bounds of scaling;
- Show eddy-resolving (or -permitting) model results which lie within the scaling bounds.

Thus, the above hypothesis fails ...
Scaling Theory

**How does \( \kappa \) vary?**

Ferrari & Nikurashin (2010) and Naveira Garabato et al. (2011) argue that

\[
\kappa = \frac{\kappa_{\text{Taylor}}}{(1 + \gamma^{-2}k^2(U_m - c)^2)}
\]

where \( \gamma \) is a linear eddy damping rate and

\[
\kappa_{\text{Taylor}} = \frac{k^2}{(k^2 + l^2)} \frac{\text{EKE}}{\gamma}
\]

is Taylor’s definition of \( \kappa \) in the absence of a mean flow (Taylor 1921).

Therefore,

\[
\kappa = \frac{\text{EKE}}{\gamma(1 + \gamma^{-2}k^2U_m^2)}
\]

Ferrari & Nikurashin (2010) estimate

\[
\gamma^{-2}k^2 \approx \frac{4}{\text{EKE}}
\]

giving

\[
\kappa \propto \frac{\text{EKE}^{1/2}}{k \left(1 + \frac{4U_m^2}{\text{EKE}}\right)}
\]
Scaling Theory

\[ \kappa \propto \frac{\text{EKE}^{1/2}}{k \left( 1 + 4U_m^2/\text{EKE} \right)} \]

For large \( U_m \) or small EKE,

\[ \kappa \propto \frac{\text{EKE}^{3/2}}{4kU_m^2} \]

For small \( U_m \) or large EKE,

\[ \kappa \propto \frac{\text{EKE}^{1/2}}{k} \]

Overturning sensitivity lies in shaded area.
Consider limiting cases:

1. No compensation
2. Complete compensation

If there is no compensation, then $\Psi^*$ is insensitive to wind stress
Scaling Theory

Zonal & time averaged momentum equation:

\[ \frac{\bar{f}v'\bar{h}}{f \bar{h}} = \frac{\bar{h}v'q'}{\bar{f}} - \frac{\tau}{(f \rho_0 \bar{h})} \]

Assume eddy closure:

\[ v'q' \propto \kappa \left( -\frac{\beta}{\bar{h}} + \frac{f \bar{h} y}{\bar{h}^2} \right), \]

\[-\delta \left( \frac{f v'\bar{h}}{\bar{f}} \right) = \delta \kappa \left( -\frac{\beta \bar{h}}{f} + \bar{h} \right) + \kappa \delta \left( -\frac{\beta \bar{h}}{f} + \bar{h} y \right) - \frac{\delta(\tau)}{f \rho_0} \]

Assume \( \Psi_{res} \) is invariable

\[ \delta \left( \frac{f v'\bar{h}}{f} \right) \approx 0 \]

Assume constant stratification

\[ \delta \left( -\beta \bar{h}/f + \bar{h} y \right) \approx 0 \]

Then

\[ \frac{\delta \kappa}{\kappa} \approx \frac{\tau}{\kappa \rho_0 ( -\beta \bar{h} + f \bar{h} y )} \frac{\delta(\tau)}{\tau} \]

For standard values

\[ \frac{\tau}{\kappa \rho_0 ( -\beta \bar{h} + f \bar{h} y )} \sim 8 \]
Exact compensation therefore implies

$$\frac{\delta \kappa}{\kappa} \sim 8 \frac{\delta \tau}{\tau}$$

Our hypothesis fails!
Results
Note PV and PV gradients are indeed insensitive to wind forcing in the eddy-permitting CM2.4 model...

**Fig. 4.** Zonal-mean potential vorticity (units are \( \text{m s}^{-1} \times 10^{-10} \) and the sign is reversed for clarity) and its meridional gradient (units are \( \text{m}^{-2} \text{ s}^{-1} \times 10^{-10} \)) in the GFDL/CM2.4 model. The potential vorticity is defined here as \(- (f/\rho) \partial_z \sigma_0\), where \( f \) is the Coriolis parameter, \( \rho \) *in situ* density, \( \sigma_0 \) potential density referenced to the surface, and we have neglected relative vorticity. (a) Time-mean potential vorticity (PV) in the control run (CTL); also shown are the mean isopycnals (white contours, interval 0.2 kg m\(^{-3}\)), (b) potential vorticity in the wind perturbation experiment (WIND), averaged for the 36-40 years period after the beginning of the perturbation; also shown are the mean isopycnals for the same period (solid white lines), together with the CTL isopycnals (dotted white lines). (c,d) As in (a,b) but for the meridional gradient of potential vorticity (PVG). The upper 100 m have been excluded in all plots.
Yet PV and PV gradients are sensitive to wind forcing in the coarse-resolution CM2.1 model…

Fig. 5. As Figure 4 but for the GFDL/CM2.1 model. Note the large sensitivity of the coarse-resolution model to changing winds evidenced by the steepening of isopycnals (panel b) and large modifications of meridional gradients of PV (panels c and d).
The bottom line

- Eddy saturation and eddy compensation are not the same thing, and do not necessarily go together on decadal time scales.

- Theory and eddy-permitting / eddy-resolving models suggest that eddy compensation is only partial on these time scales.

- The invariance of the ACC density field on decadal time scales implies from physical principles (*with caveats) that the upper-cell overturning rate must have increased in recent decades in response to stronger wind forcing.