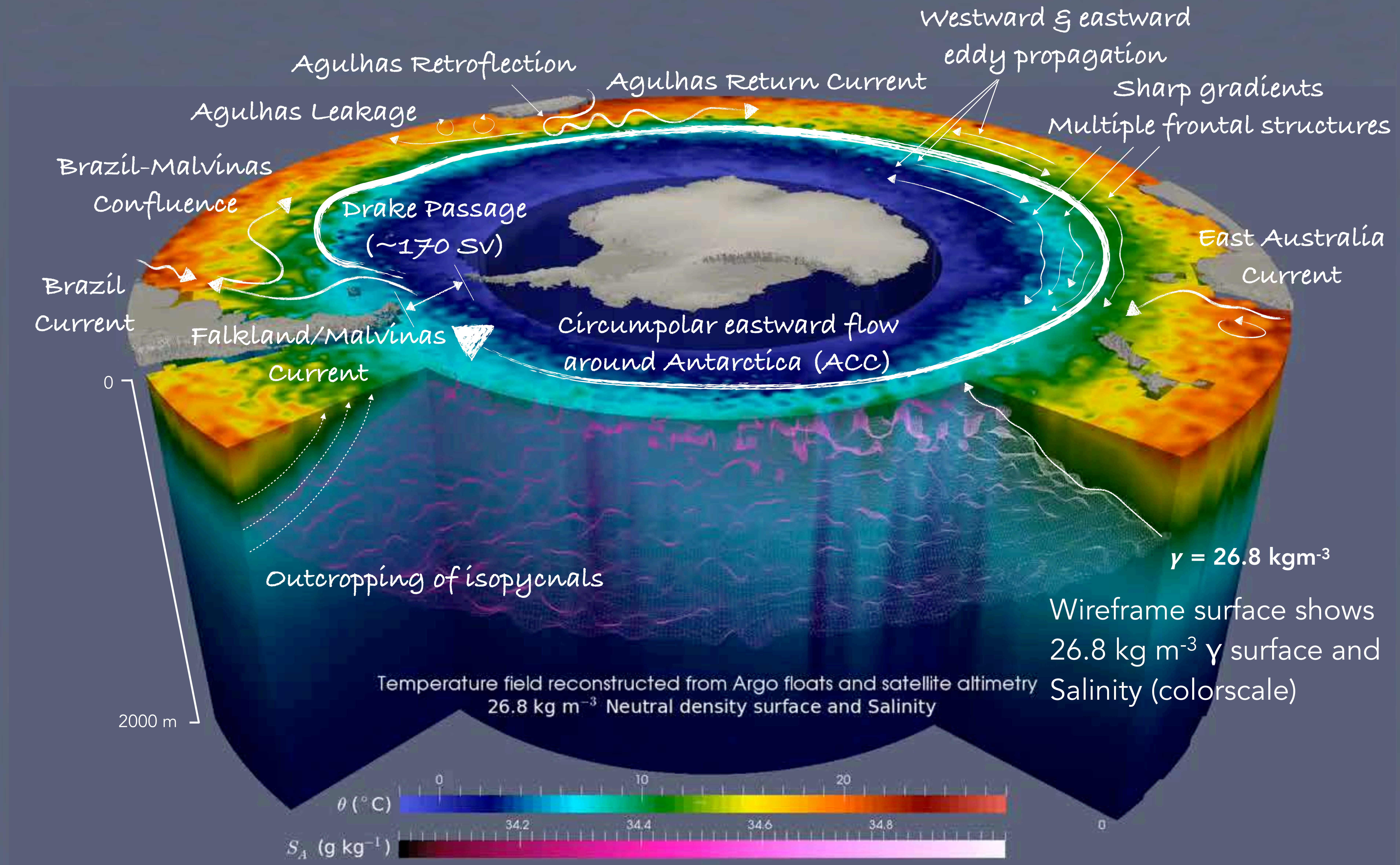
Eddy generation and propagation in the Southern Ocean diagnosed from Satellite Altimetry and an Ocean State Estimate

Uriel Zajaczkovski
Sarah T. Gille & Matthew R. Mazloff

This work was supported by NASA Headquarters under the NASA Earth and Space Science Fellowship Program Grant 'NNX11AL55H'

Motivation - The role of eddies in the Southern Ocean

Potential temperature reconstructed by combining Argo floats measurements and SSH anomalies



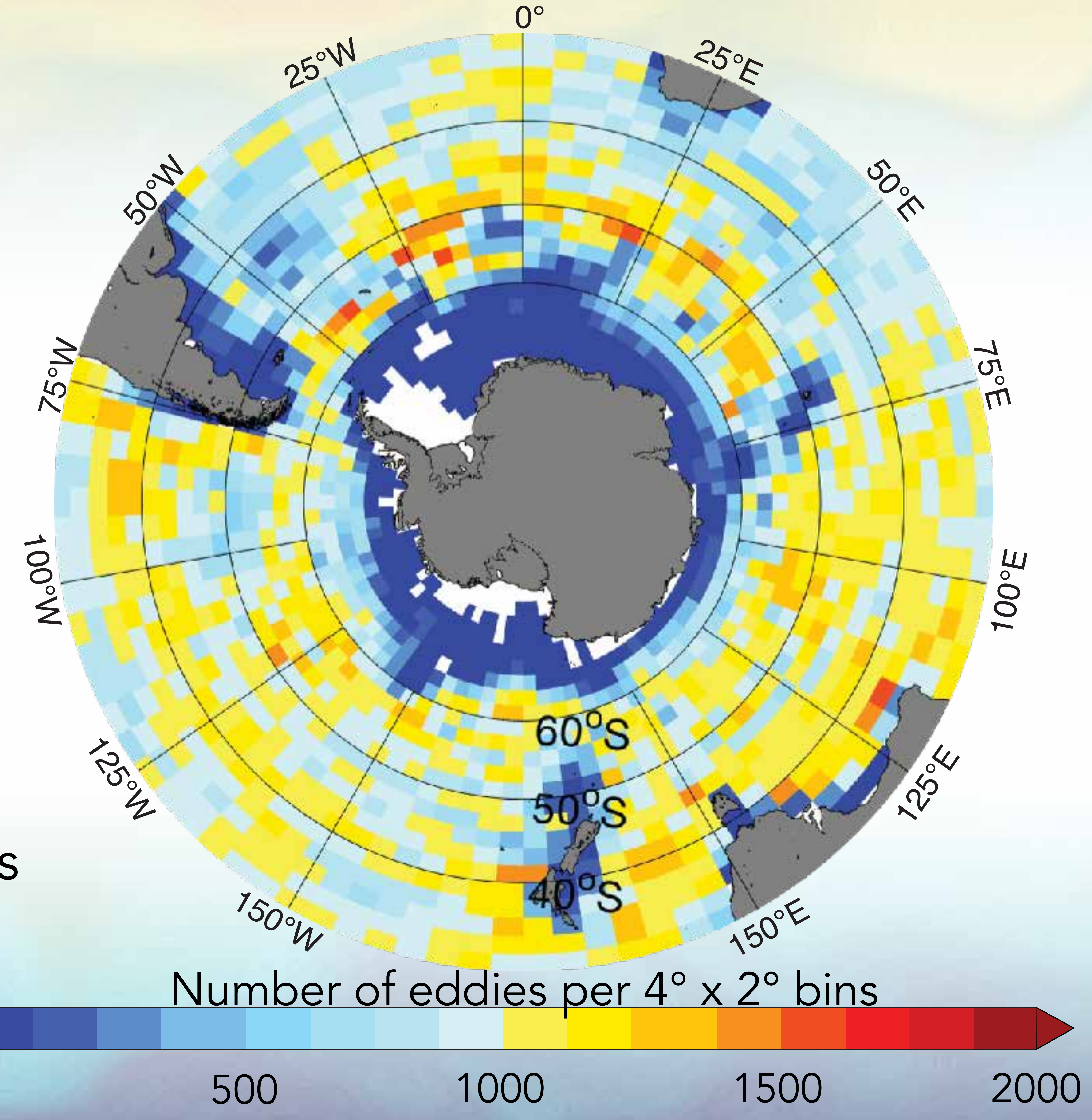
Wireframe surface shows 26.8 kg m^{-3} γ surface and Salinity (colorscale)

Eddy identification and tracking methodology

Eddies are identified as **closed geostrophic streamlines** that satisfy the following criteria:

- All SSH values are above a given threshold for anticyclonic eddies (and below for cyclonic eddies).
- There is at least one local maximum for anticyclonic eddies (and minimum for cyclonic eddies).

Total number of eddy 'events'

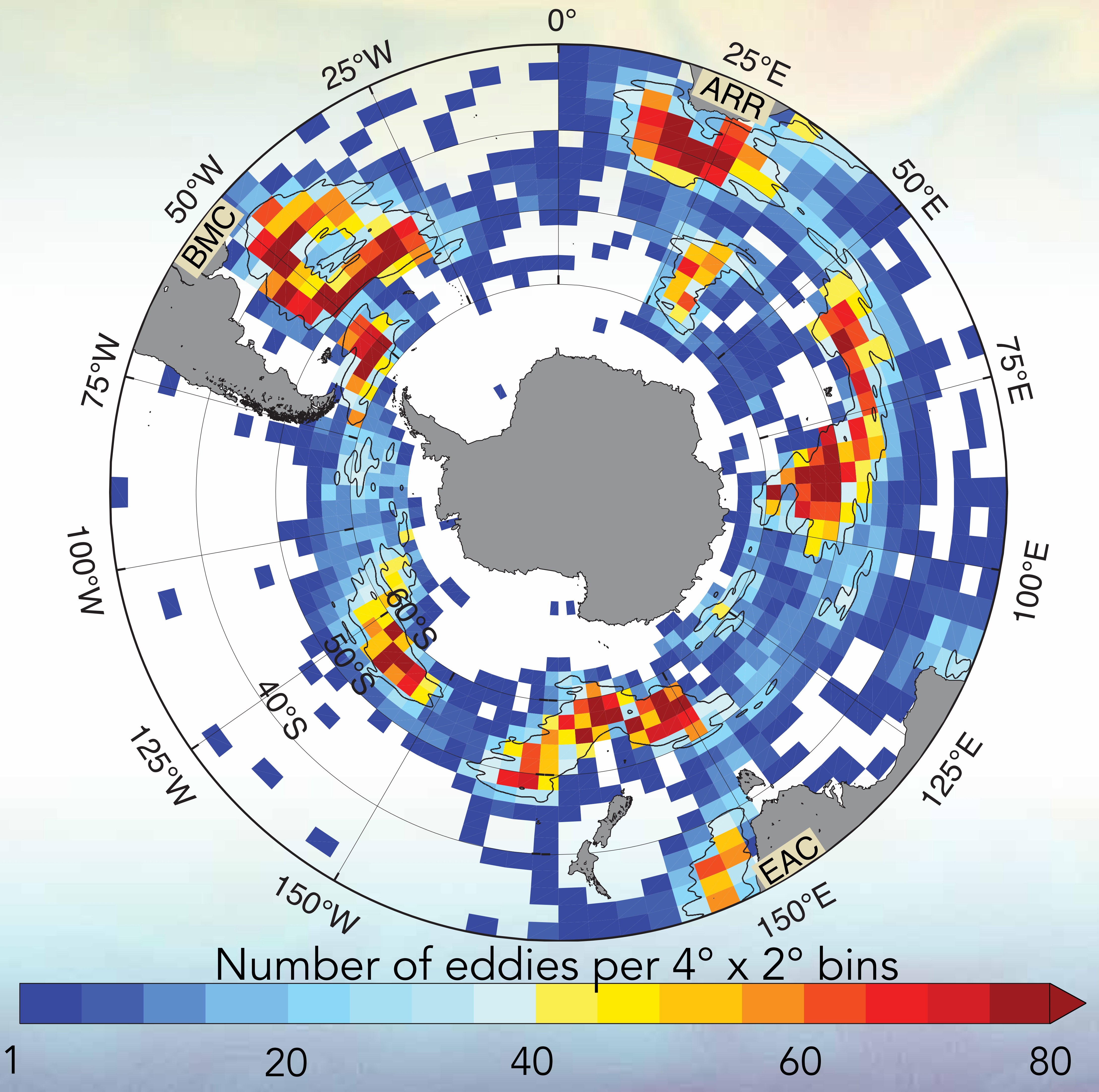


Total number of eddy 'events':
Individual eddies are counted multiple times

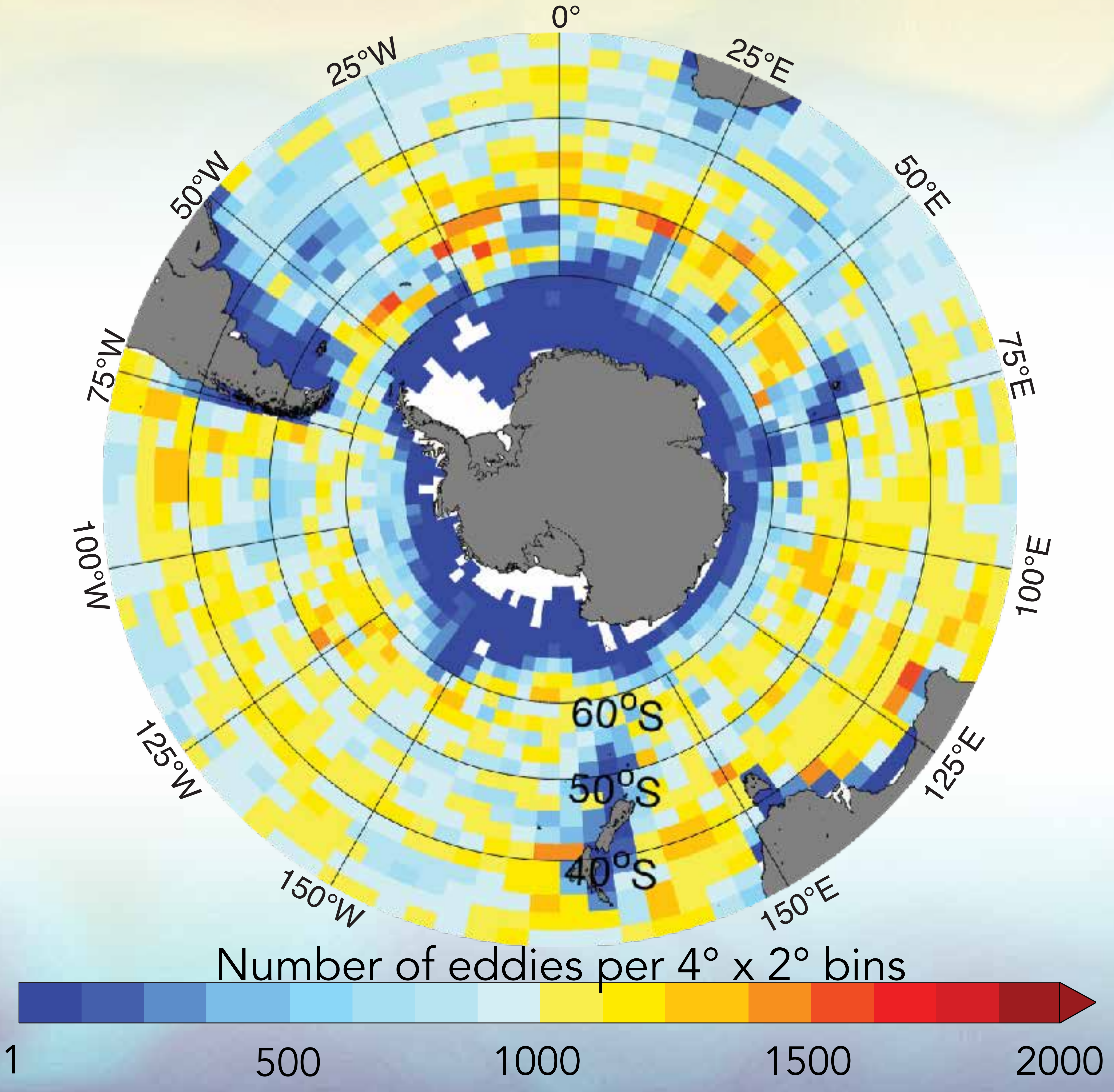
Eddy tracking methodology
Chelton et al. (2011)

Eddy identification and tracking methodology

Initial locations of eddies (amplitude > 4 cm)

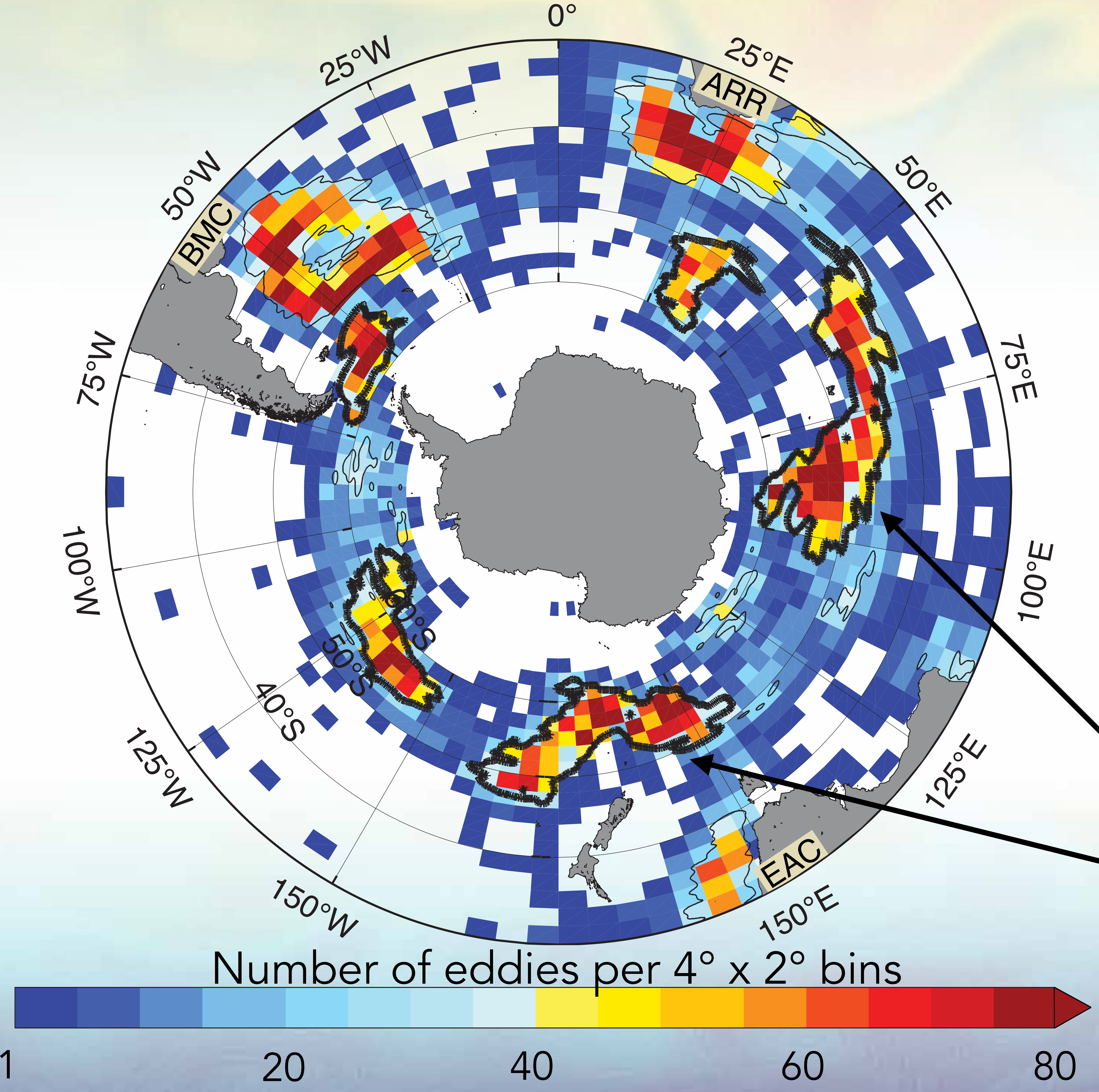


Total number of eddy 'events'



Boundaries of eddy "hotspots"

Initial locations of eddies (amplitude > 4 cm)



Kernel Density Estimate

Multi-Peak 2 dimensional Gaussian function:

$$\hat{f}_H(\mathbf{x}) = \frac{\mathbf{1}}{\mathbf{n}} \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{K_H}(\mathbf{x} - \mathbf{x_i})$$

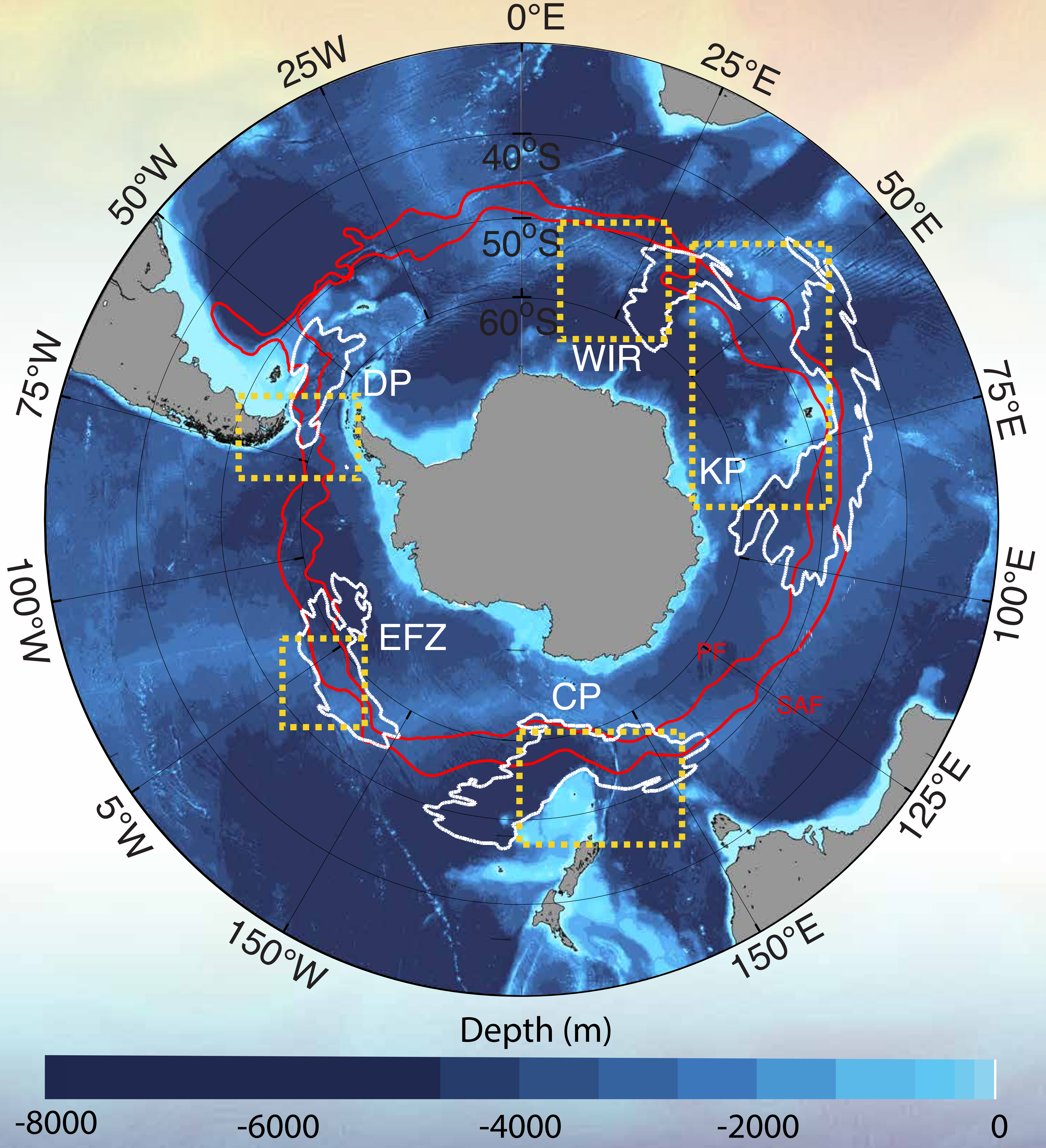
$$K_H(\mathbf{x}) = |\mathbf{H}|^{-\mathbf{1/2}} \mathbf{K}(\mathbf{H}^{-\mathbf{1/2}} \mathbf{x})$$

K_H Kernel function

$\mathbf{H}$ Bandwidth matrix

Black contours denote equal-probability of eddy generation occurrence

Eddy hotspots and topographic features



High probability of eddy generation downstream of topographic features:

Drake Passage (**DP**)

Western Indian Ridge (**WIR**)

Kerguelen Plateau & Eastern Indian Ridge (**KP**)

Campbell Plateau & Macquarie Ridge (**CP**)

Eltanin Fracture Zone (**EFZ**)

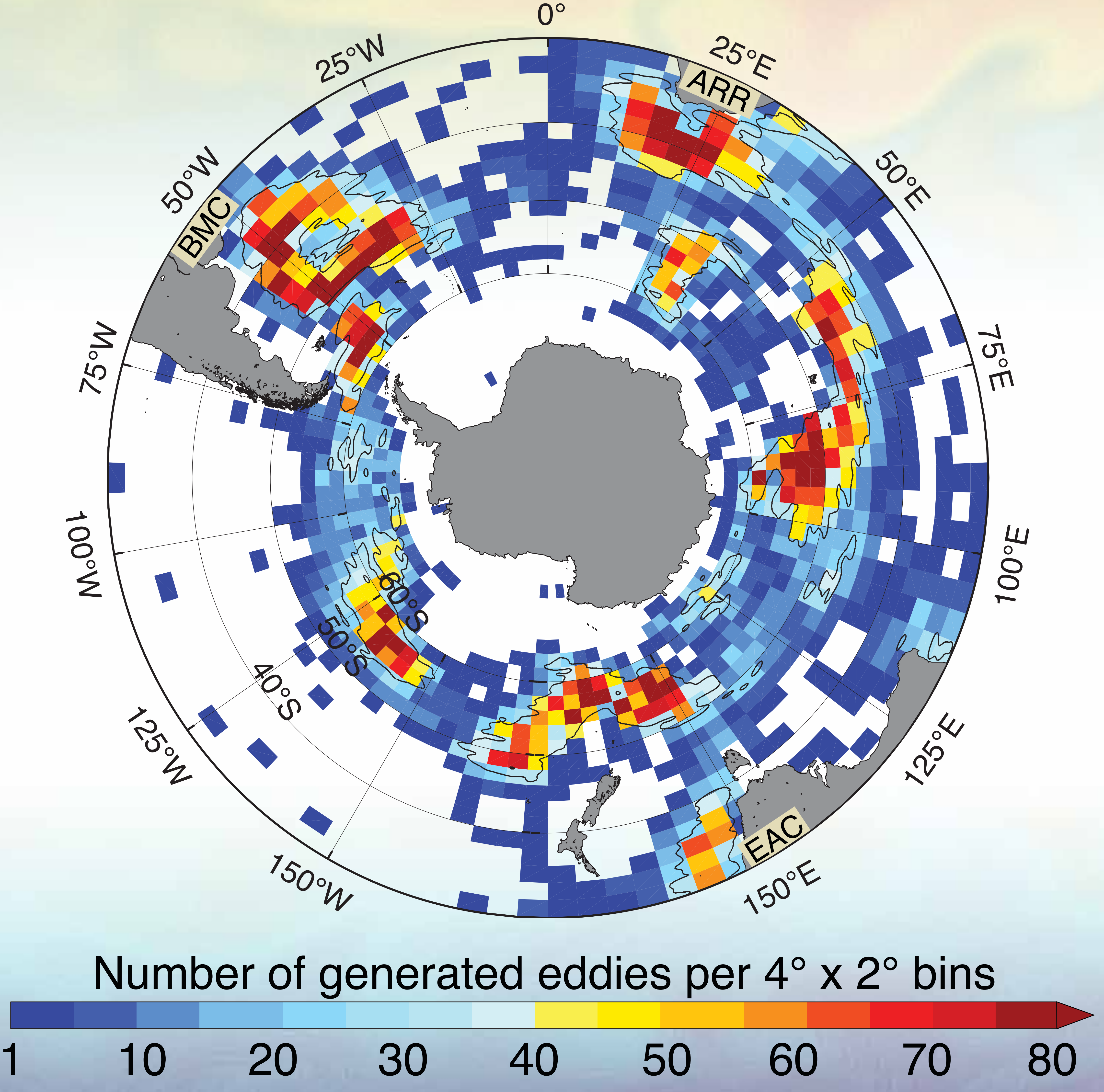
Contours of KDE of initial location of eddies (white) and climatological positions of fronts (red)

Climatological fronts (Orsi et al. 1995)

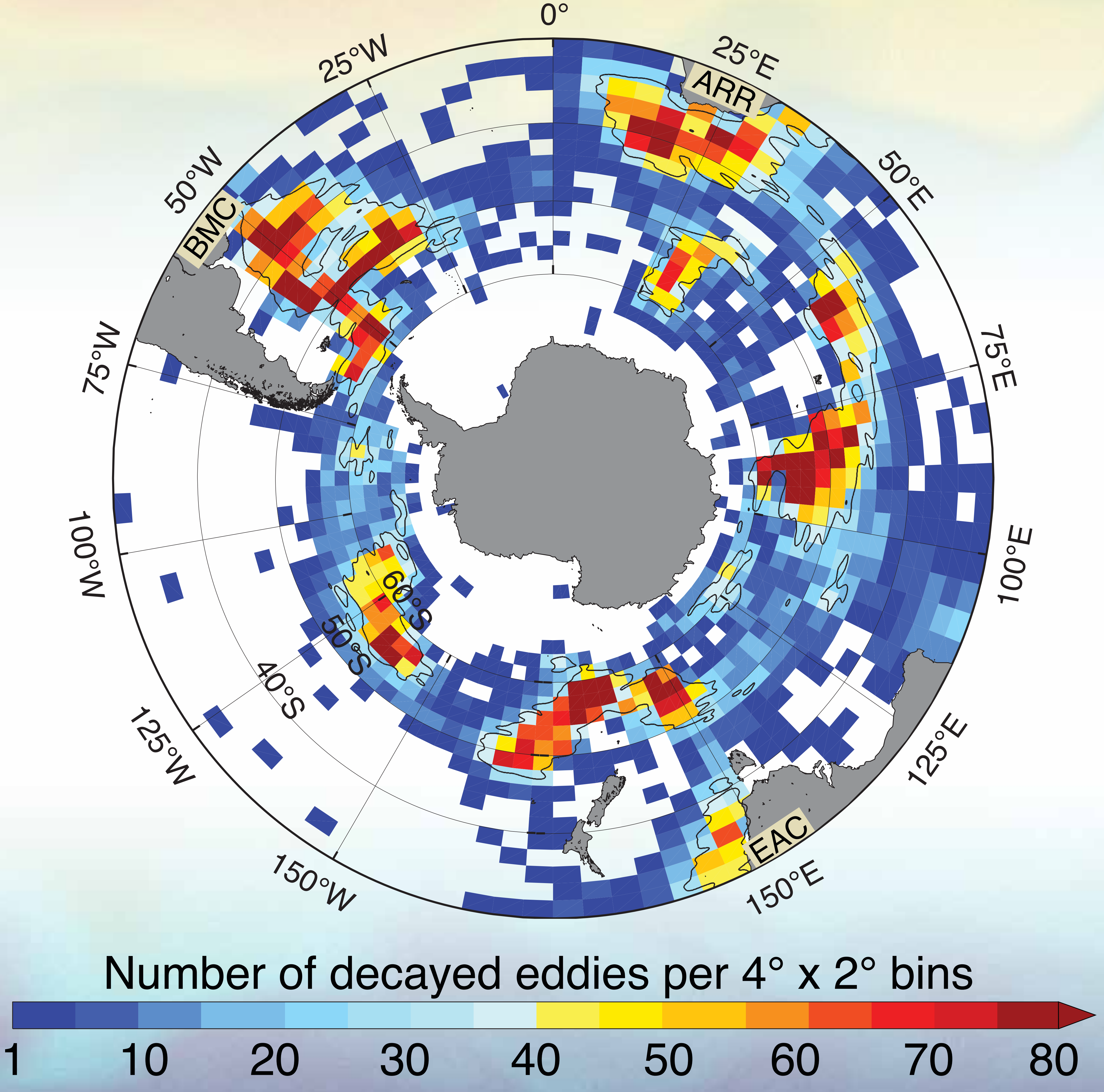
Topography (Smith & Sandwell, 1997)

Comparison of generation and decay locations

Generation: Initial location of eddies

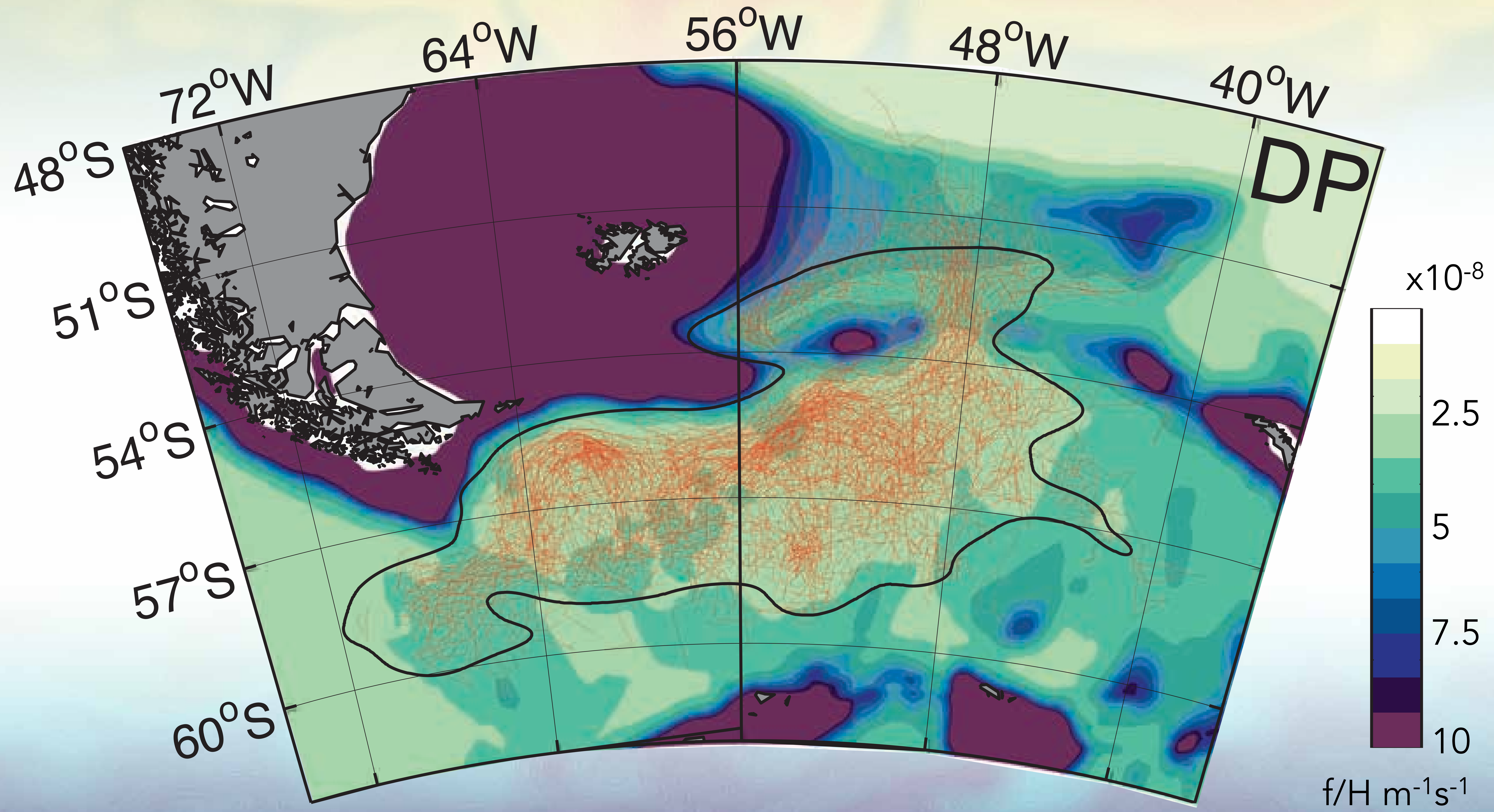


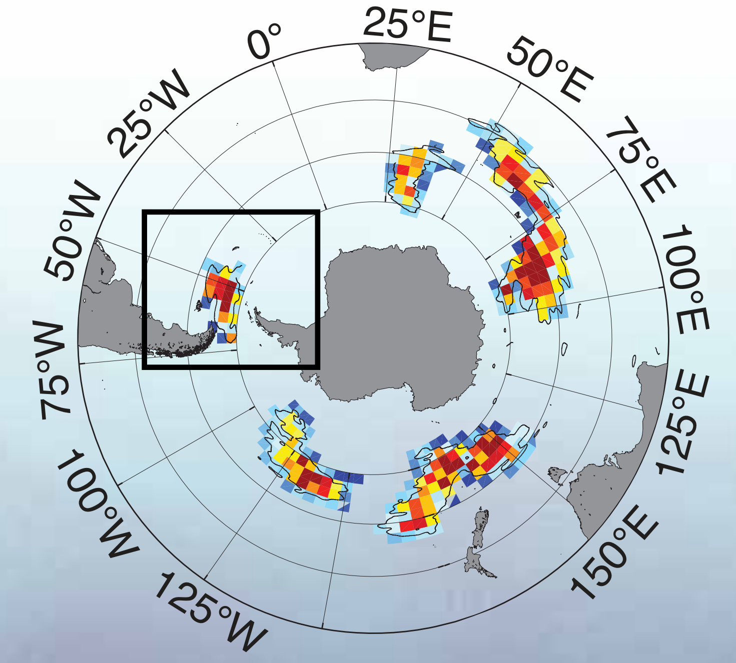
Decay: Final location of eddies



Eddy tracks inside Drake Passage hotspot

Eddy trajectories (red), Drake Passage Hotspot boundary (black) and f/H field $m^{-1}s^{-1}$ (colorscale)



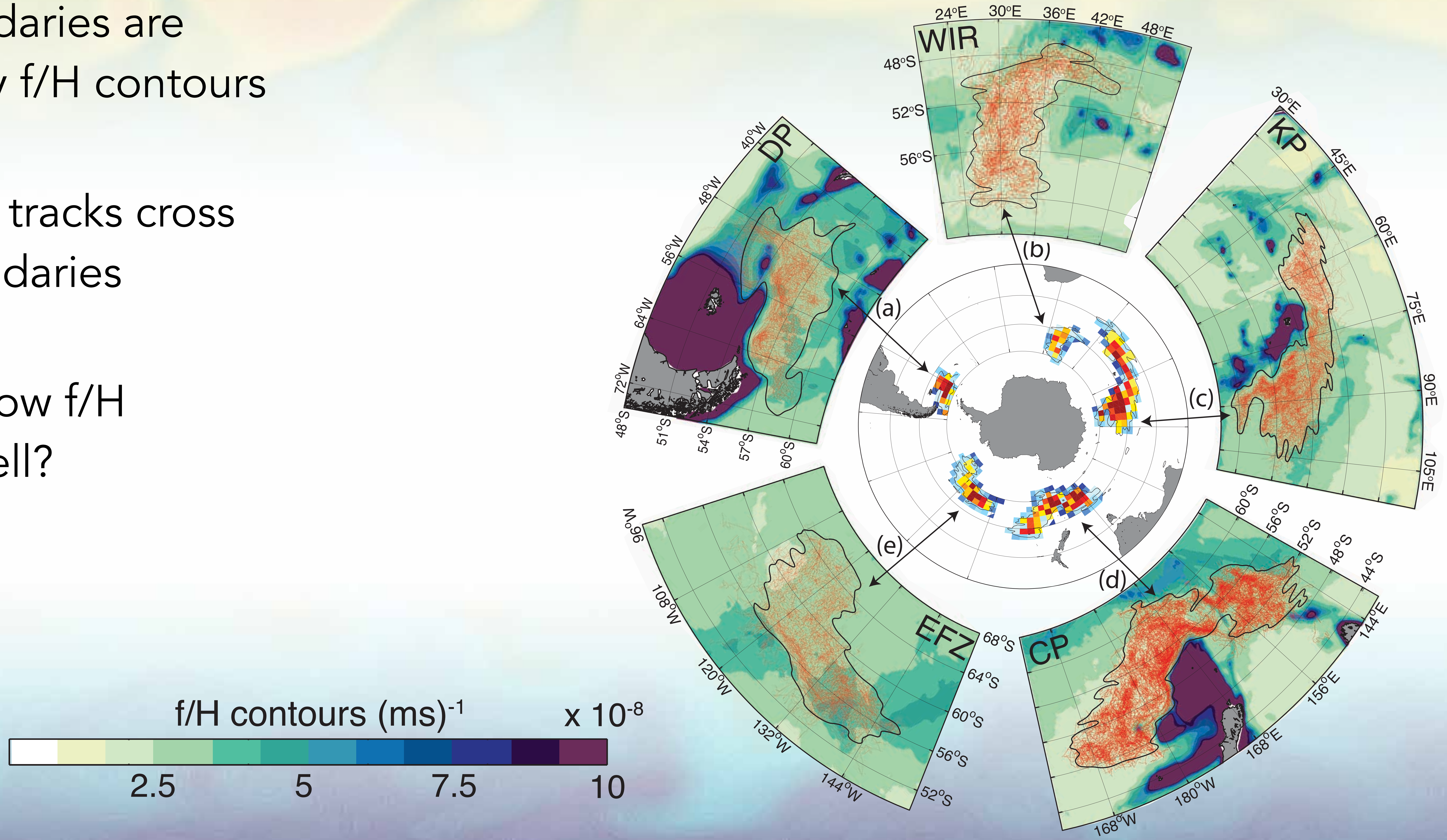


Eddy tracks inside all hotspots

Hotspot boundaries are constrained by f/H contours

Very few eddy tracks cross hotspots boundaries

Do eddies follow f/H contours as well?



Eddy energy budget: estimation of energy exchange

Momentum equation: $$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\alpha \frac{\partial p}{\partial x_i} - g\delta_{i3} + \nu \frac{\partial u_i^2}{\partial x_j^2},$$

Reynolds decomposition (mean + fluctuations): $u_i = \bar{u}_i + u', \quad p = \bar{p} + p', \quad \alpha = \bar{\alpha} + \alpha'$

Eddy energy equation:

$$\frac{D}{Dt}\overline{\left(\frac{1}{2}u_i'^2\right)} = \underbrace{-\frac{\partial}{\partial x_j}\left(\frac{1}{\rho_0}\overline{pu_j'} + \frac{1}{2}\overline{u_i'^2 u_j'} - 2\nu\overline{u_i' e_{ij}}\right)}_{\text{transport}} \underbrace{-\overline{u_i'u_j'}\frac{\partial \bar{u}_i}{\partial x_j}}_{\text{shear production}} + \underbrace{\frac{g\overline{u_3'\rho'}}{\bar{\rho}}}_{\text{buoyancy production}} - \overbrace{2\nu\overline{e_{ij}'e_{ij}'}}^{\text{viscous dissipation}}$$

Shear Production: Conversion of **mean KE** to **eddy KE** (associated with **barotropic instabilities**)

Buoyancy Production: Conversion of **mean PE** to **eddy KE** (associated with **baroclinic instabilities**)

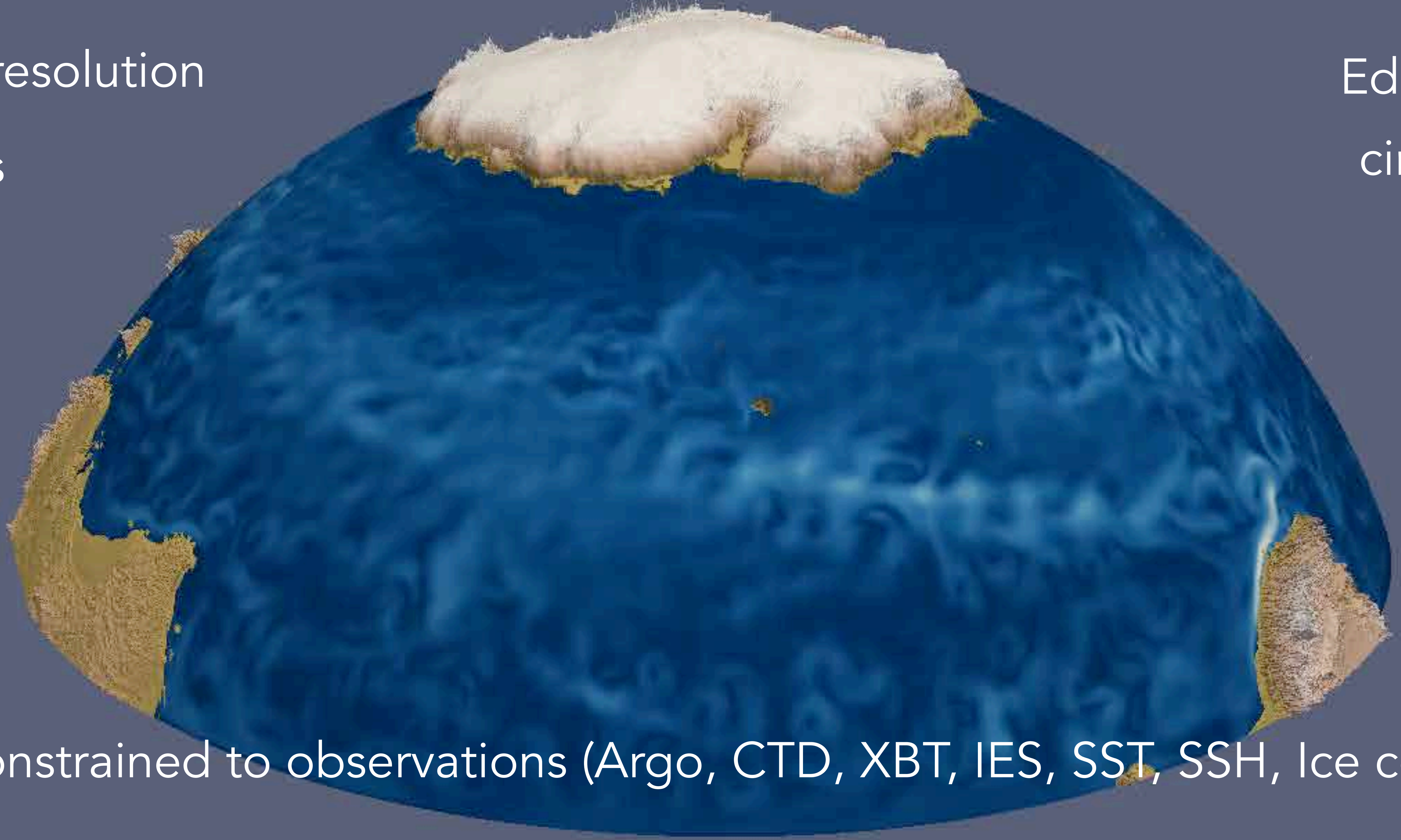
Eddy energy budget: estimation of energy exchange

$$\frac{D}{Dt}\overline{\left(\frac{1}{2}u_i'^2\right)} = -\underbrace{\frac{\partial}{\partial x_j}\left(\frac{1}{\rho_0}\overline{p u_j'} + \frac{1}{2}\overline{u_i'^2 u_j'} - 2\nu\overline{u_i' e_{ij}}\right)}_{\text{transport}} \underbrace{- \overline{u_i' u_j'}\frac{\partial \bar{u}_i}{\partial x_j}}_{\text{shear production}} + \underbrace{\frac{g\overline{u_3'\rho'}}{\bar{\rho}}}_{\text{buoyancy production}} - \overbrace{2\nu\overline{e_{ij}' e_{ij}'}}^{\text{viscous dissipation}}$$

Southern Ocean State Estimate (SOSE)

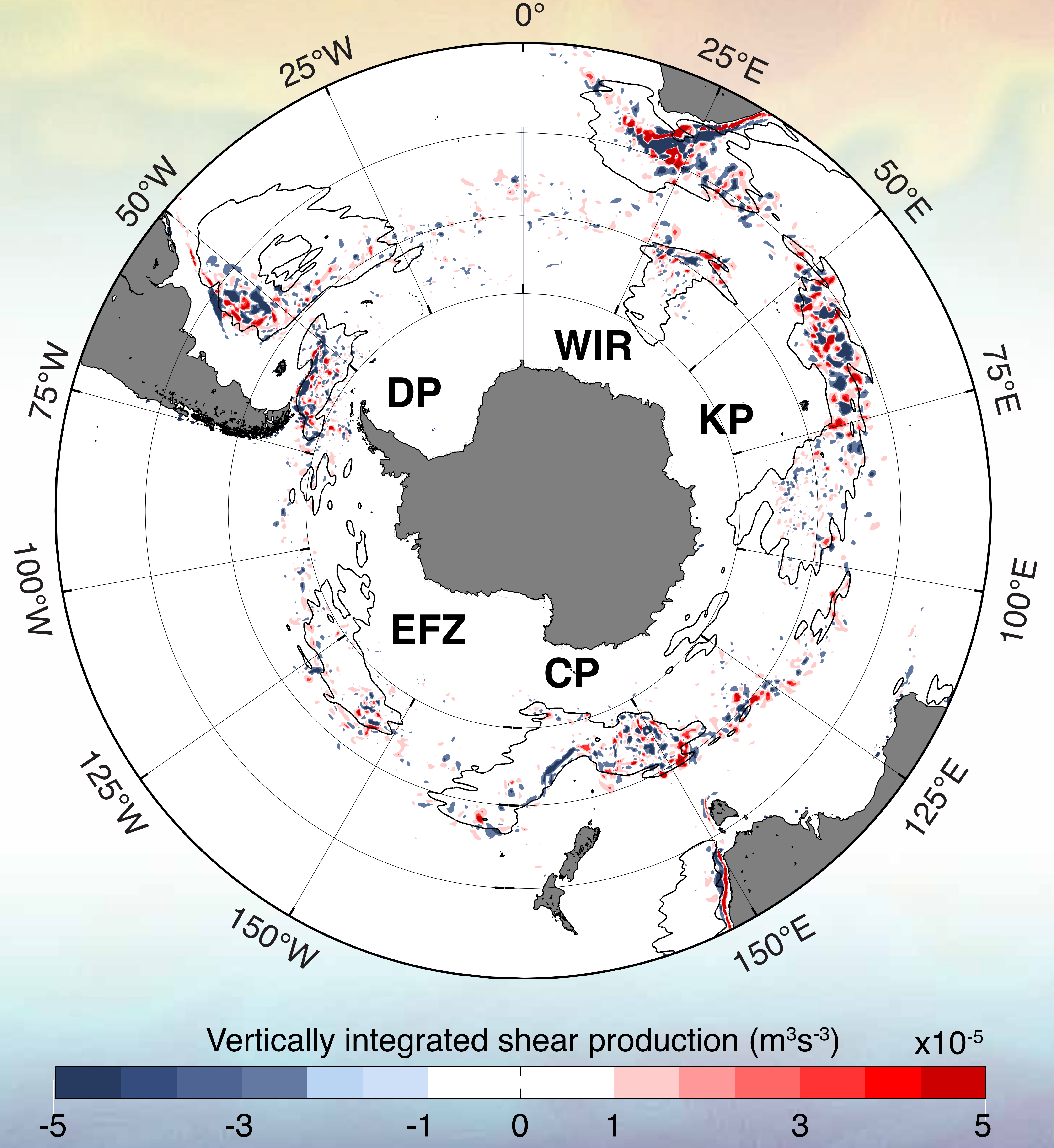
- 1/6° Horizontal resolution
- 42 vertical levels
- 2005-2010

Eddy-permitting general circulation model of the Southern Ocean



Constrained to observations (Argo, CTD, XBT, IES, SST, SSH, Ice cover...)

Shear Production: the role of barotropic instabilities

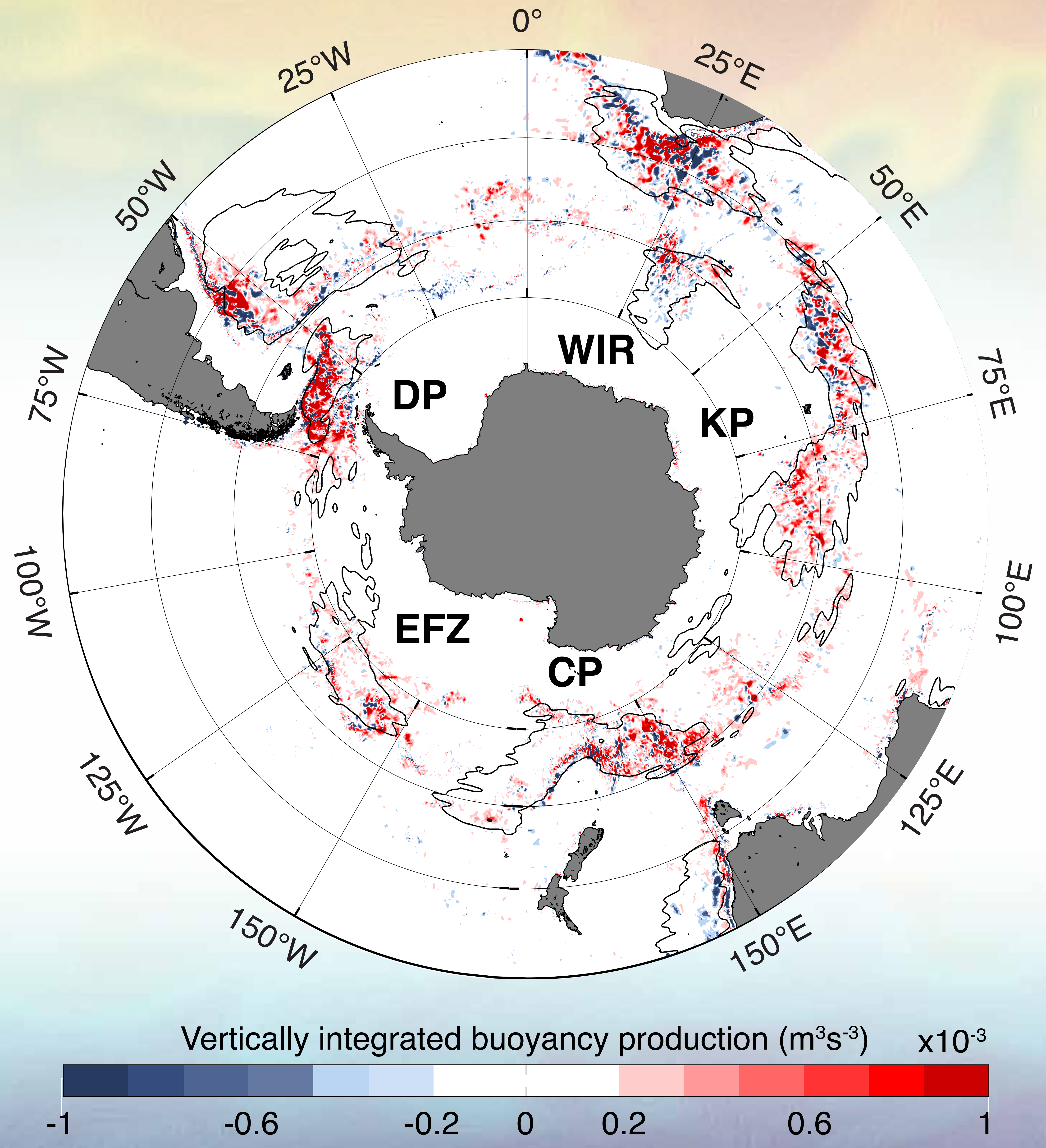


Vertically integrated time averaged (2009) shear production from SOSE:

$$\int_{-H}^{Z} \langle u_i' u_j' \rangle \frac{\partial U_i}{\partial x_j} \, dz$$

Site	Shear prod. (std error)
DP	**7.7 ×10−7** (± 1.9 ×10−7)
WIR	**2.6 ×10−6** (± 4.0 ×10−7)
KP	**2.2 ×10−6** (± 1.7 ×10−7)
CP	**-2.4 ×10−6** (± 4.5 ×10−7)
EFZ	**5.6 ×10−7** (± 1.2 ×10−7)

Buoyancy Production: the role of baroclinic instabilities

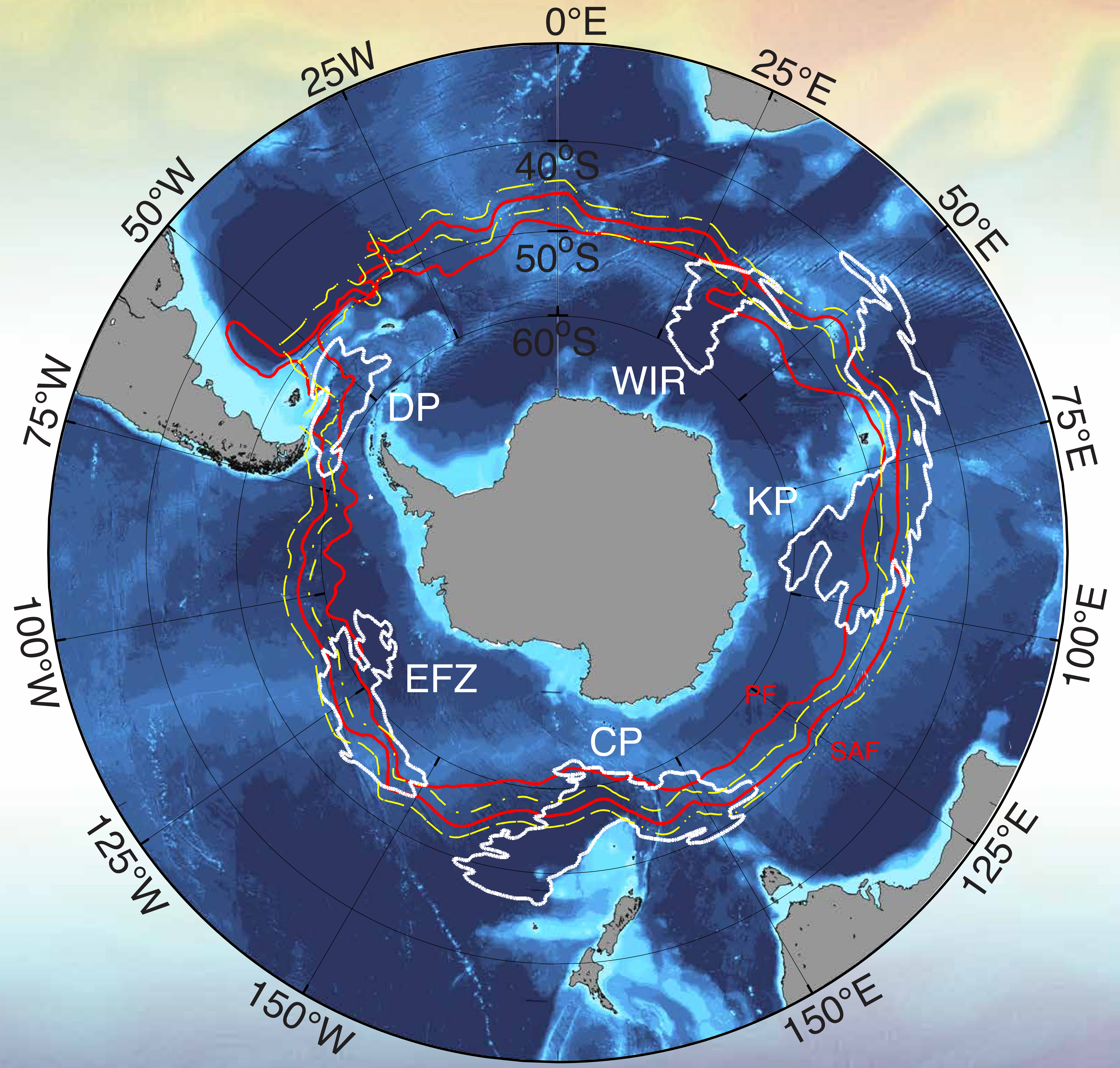


Vertically integrated time averaged (2009) buoyancy production from SOSE:

$$\int_{-H}^{Z} \langle b'w' \rangle \, dz$$

Site	<b'w'> (std error)
DP	**3.1 ×10−4** (± 1.4 ×10−5)
WIR	**3.6 ×10−5** (± 7.0 ×10−6)
KP	**6.9 ×10−5** (± 3.6 ×10−6)
CP	**9.0 ×10−5** (± 3.4 ×10−6)
EFZ	**6.6 ×10−5** (± 3.8 ×10−6)

Average properties along a circumpolar path

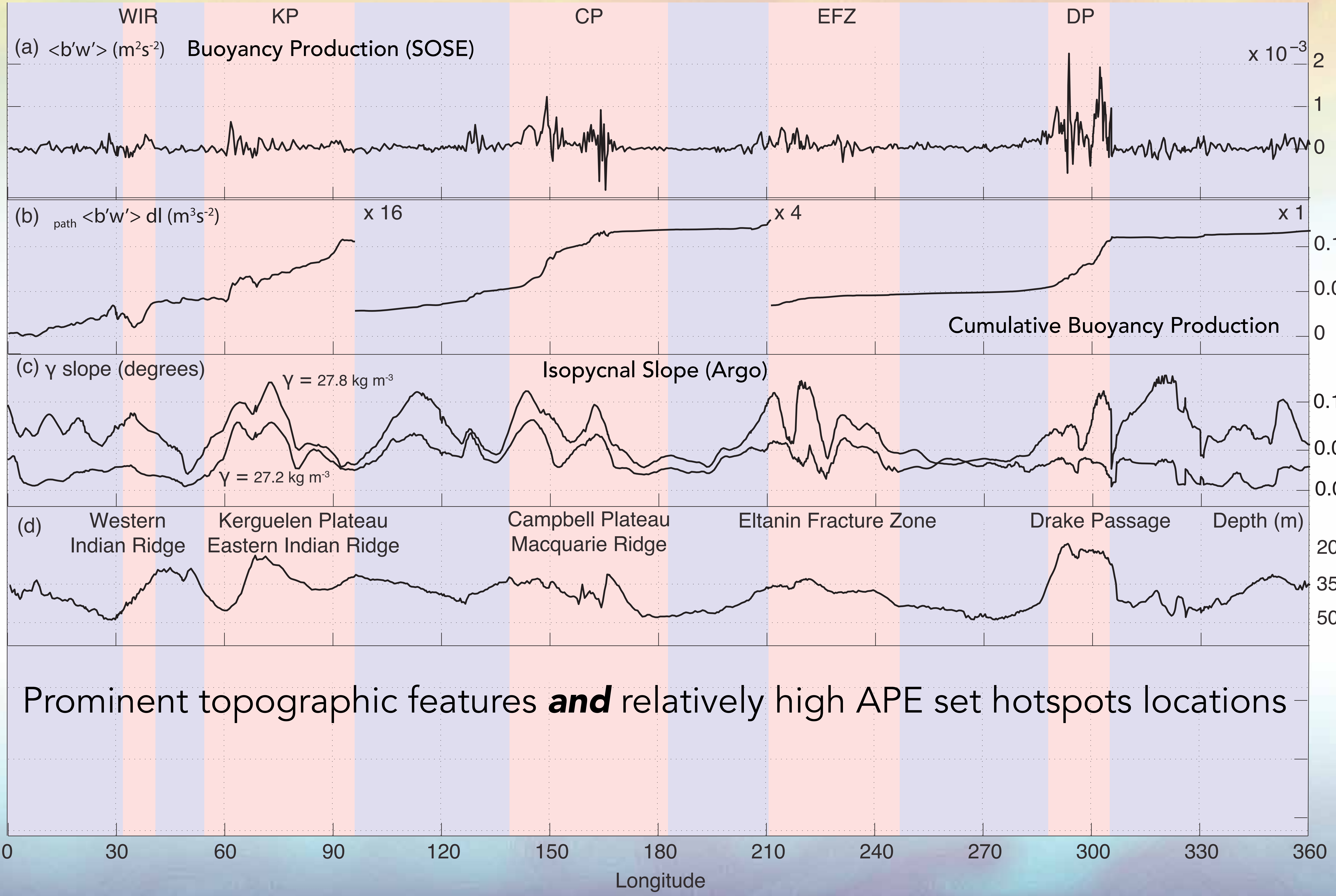


Boundaries of circumpolar path (yellow), contours of eddy generation sites (white) and climatological fronts (red).

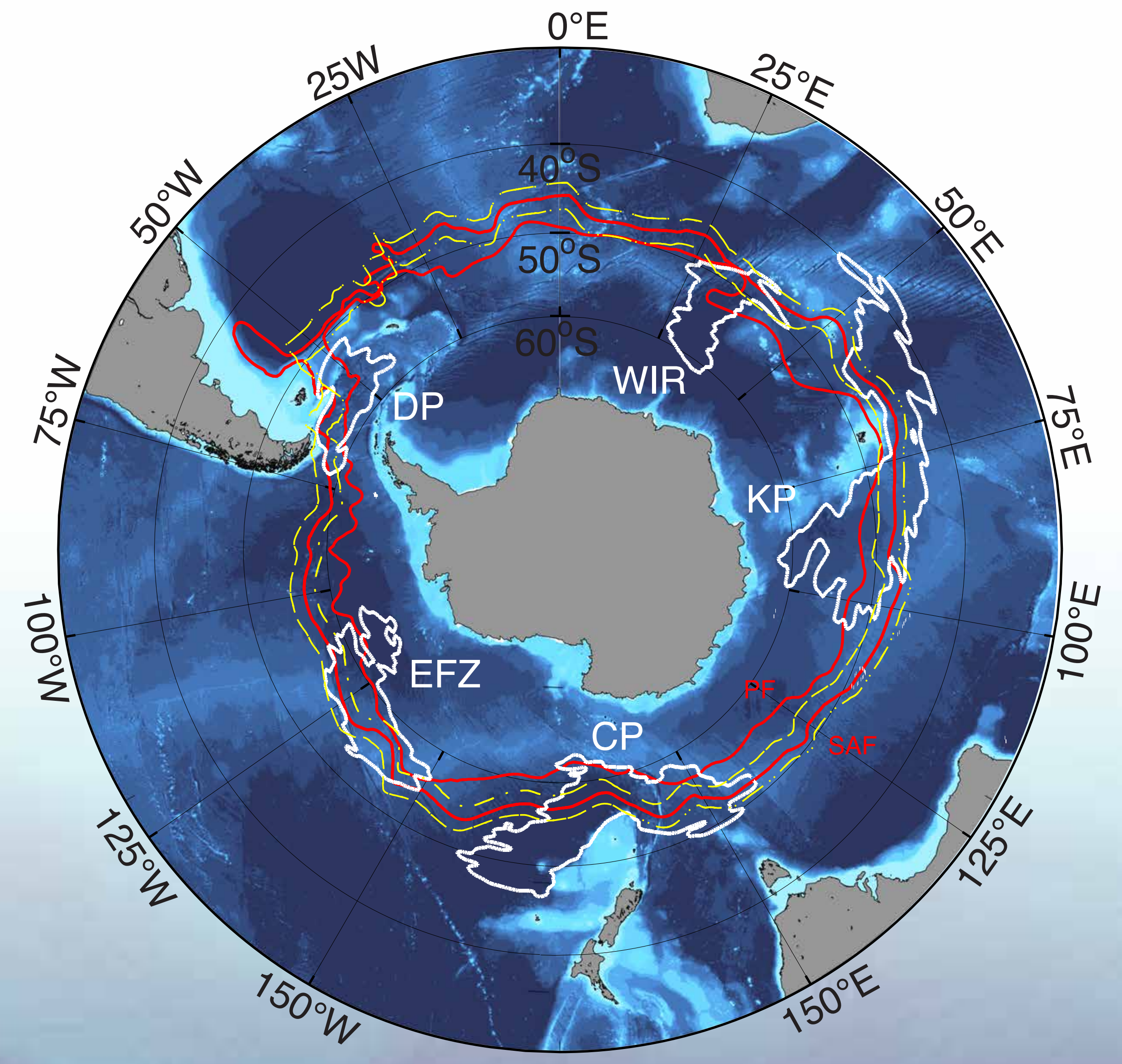
Climatological fronts (Orsi et al. 1995)

Topography (Smith & Sandwell, 1997)

Average properties along a circumpolar path

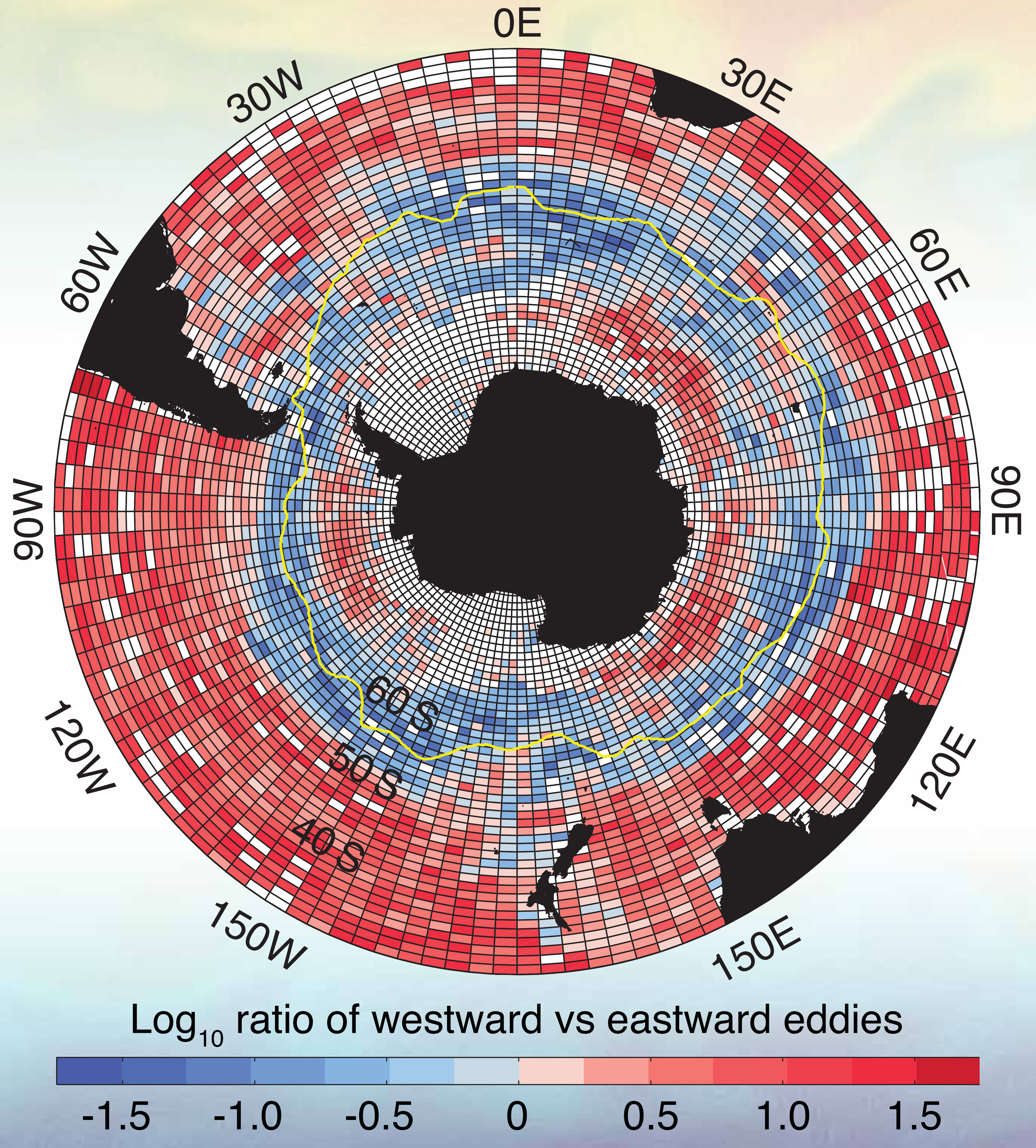


Blue shaded/**Red shaded** areas: Circumpolar path is **outside**/**inside** regions of high probability of eddy generation



Eddy Propagation in the Southern Ocean

Zonal displacement

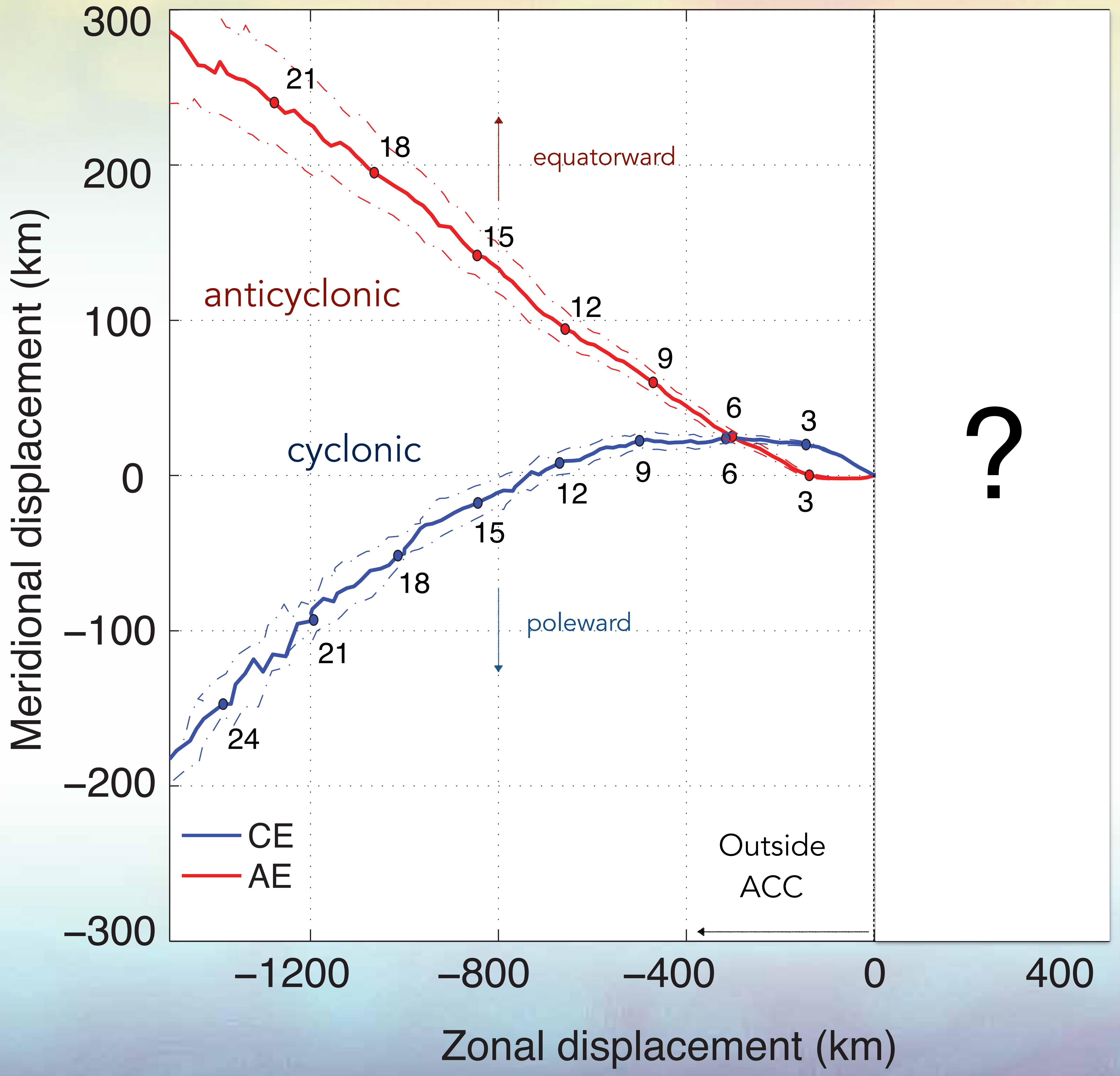


Ratio of initial locations of altimetry tracked eddies with a net displacement **due west** vs eddies with a net displacement **due east**.

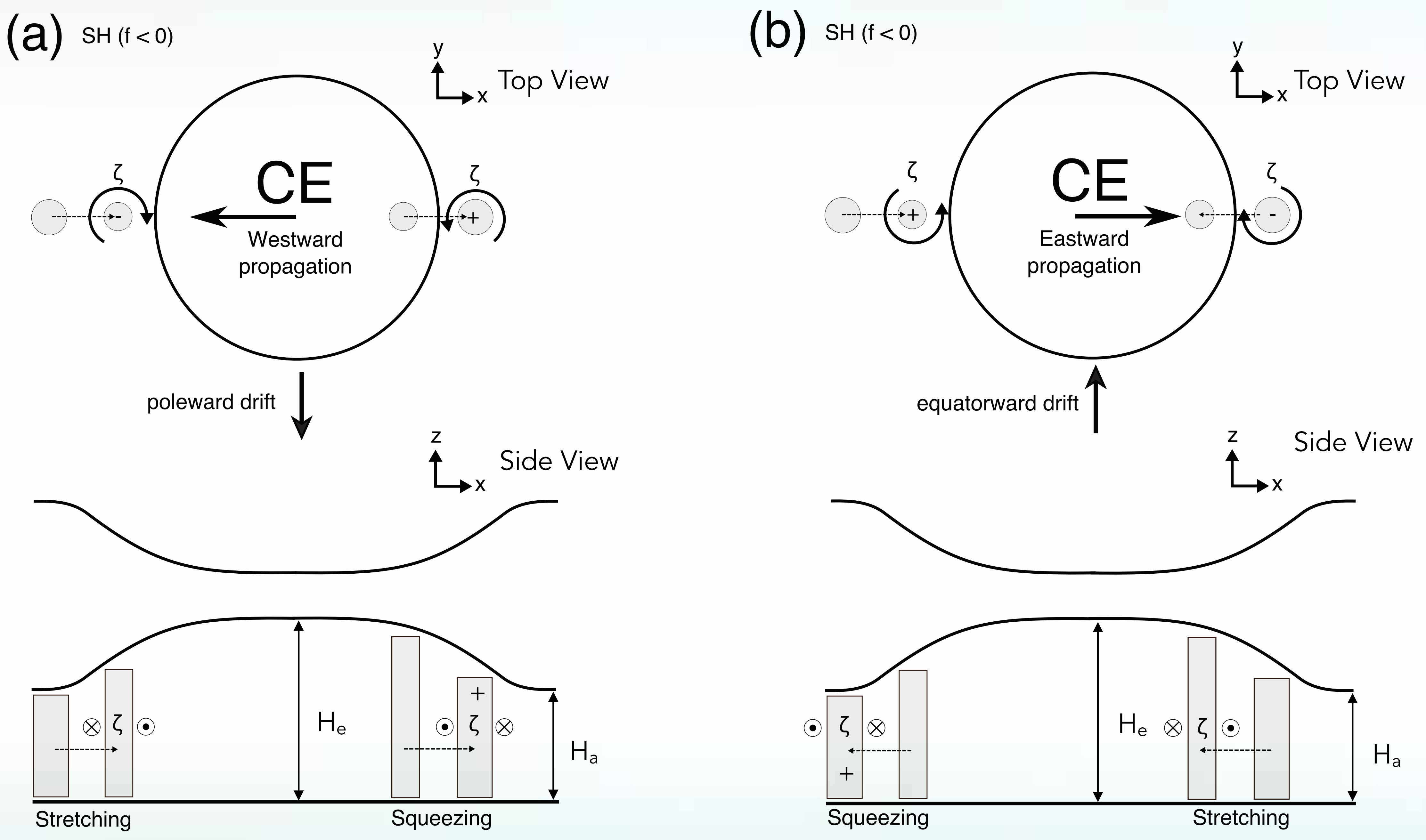
Dark **blue**/**red** cells implies that more than 95% of eddies generated in those cells have a net **eastward**/**westward** displacement.

Eddy Propagation in the Southern Ocean

Meridional displacement



Average relative displacement of **anticyclonic eddies** and **cyclonic eddies**. Dots and numbers denote the time evolution in months.



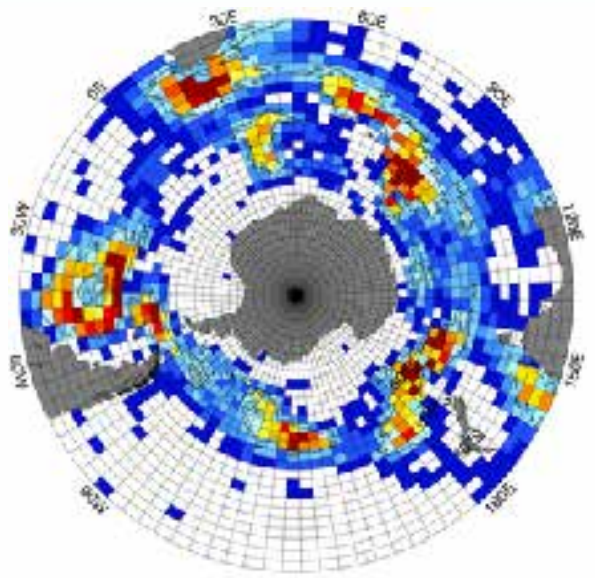
Westward propagating CE (AE) drift poleward (equatorward) in both hemispheres

Eastward propagating CE (AE) drift equatorward (poleward) in both hemispheres

Summary I

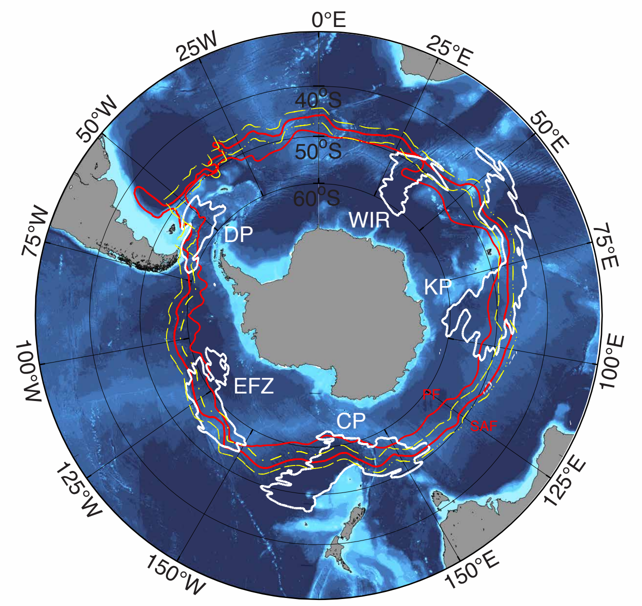
- ***Eddy generation and decay sites***

  Large eddies (> 4 cm) are not a ubiquitous feature of the Southern Ocean. This eddies don't propagate long distances and they decay near the formation regions.



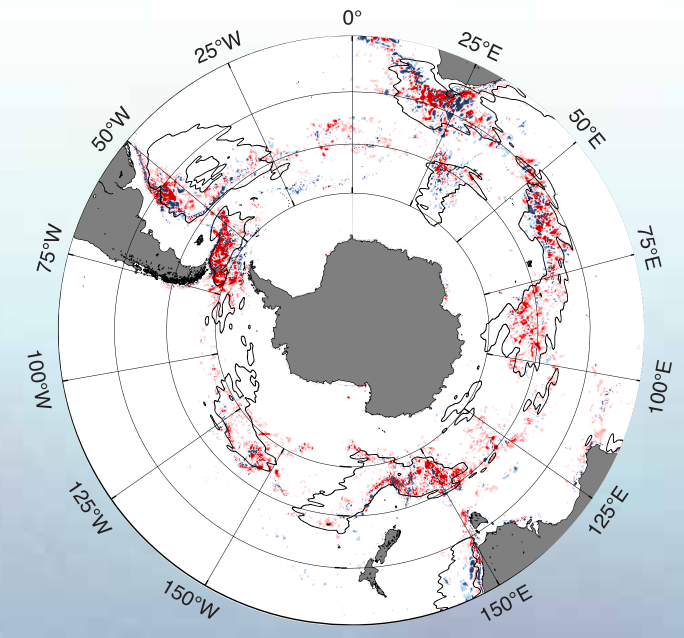
- ***Topographic impact***

  Formation sites are downstream and on top of big topographic features. Eddy hotspot boundaries and tracks are constrained by contours of $f \times h^{-1}$



- ***Eddy energy sources***

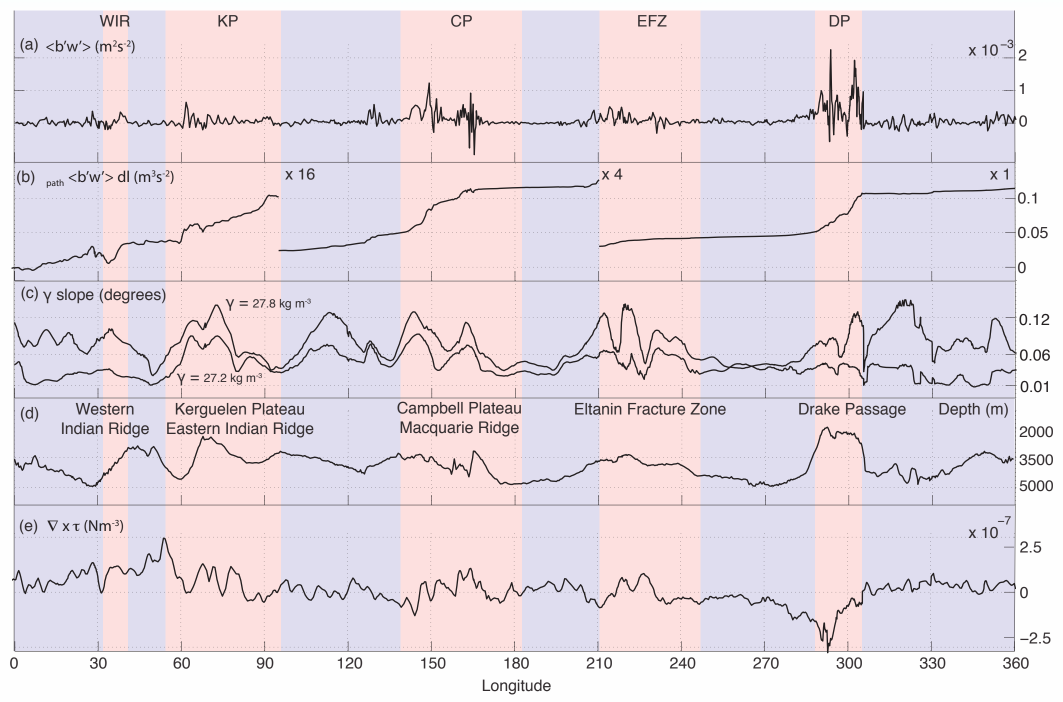
  Observations support baroclinic instability as the main mechanism. There is relatively small net energy derived from the mean KE of the flow.



Summary II

- *Enhanced baroclinic instability*

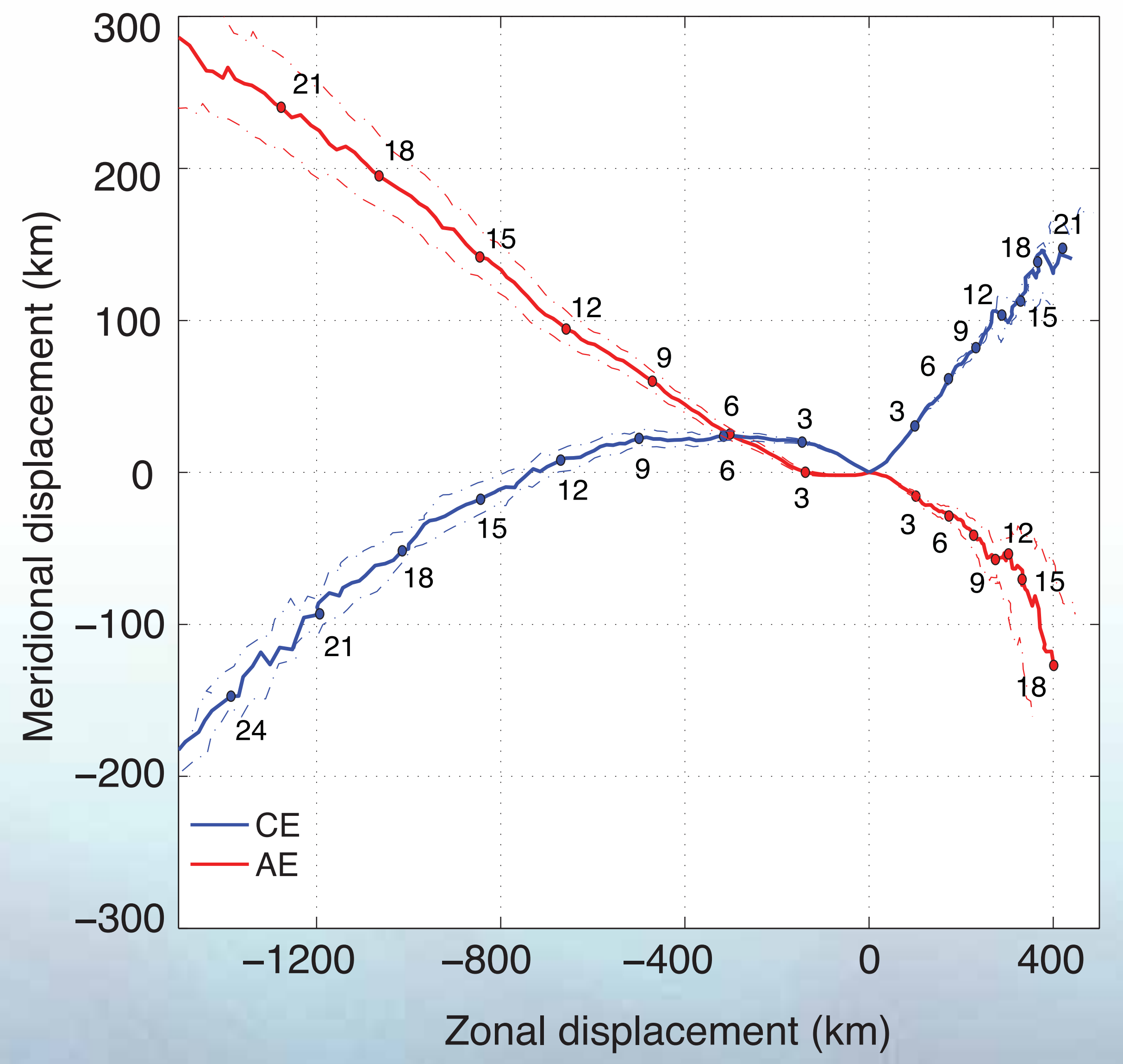
  Locations of high probability of eddy generation are a combination of high levels of APE and topographic features where standing meanders form.



- *Eddy propagation*

  Southern Ocean eddies have two regimes of propagation:

  - North and south of the ACC eddies propagate westward with a meridional drift in accordance with was found in other regions of the world ocean.
  - Within the boundaries of the ACC eddies propagate eastward and have a “reversed” meridional drift.



Thanks!

Questions?