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

Drake Passage (~170 Sv)

Brazil-Malvinas Confluence

Falkland/Malvinas Current

Agulhas Leakage

Agulhas Return Current

Agulhas Retroflection

Circumpolar eastward flow around Antarctica (ACC)

East Australia Current

Wireframe surface shows 26.8 kg m⁻³ γ surface and Salinity (colorscale)

Temperature field reconstructed from Argo floats and satellite altimetry

26.8 kg m⁻³ Neutral density surface and Salinity

Westward eddy propagation

Sharp gradients

Multiple frontal structures

Motivation - The role of eddies in the Southern Ocean

Potential temperature reconstructed by combining Argo floats measurements and SSH anomalies

Drake Passage (~170 Sv)

Brazil-Malvinas Confluence

Falkland/Malvinas Current

Agulhas Leakage

Agulhas Return Current

Agulhas Retroflection

Circumpolar eastward flow around Antarctica (ACC)

East Australia Current

Wireframe surface shows 26.8 kg m⁻³ γ surface and Salinity (colorscale)

Temperature field reconstructed from Argo floats and satellite altimetry

26.8 kg m⁻³ Neutral density surface and Salinity

Westward eddy propagation

Sharp gradients

Multiple frontal structures
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’:
Individual eddies are counted multiple times
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:

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

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

\(K_H\) Kernel function
\(H\) 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

Number of generated eddies per 4° x 2° bins

Number of decayed eddies per 4° x 2° bins
Eddy tracks inside Drake Passage hotspot

Eddy trajectories (red), Drake Passage Hotspot boundary (black) and f/H field m⁻¹s⁻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: \[
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\alpha \frac{\partial p}{\partial x_i} - g\delta_{i3} + \nu \frac{\partial u_i^2}{\partial x_j},
\]

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

Eddy energy equation:
\[
\frac{D}{Dt} \left( \frac{1}{2} u_i'^2 \right) = -\frac{\partial}{\partial x_j} \left( \frac{1}{\rho_0} \bar{pu}_j' + \frac{1}{2} u_i'^2 u_j' - 2\nu u_i'e_{ij} \right) - u_i'u_j' \frac{\partial \bar{u}_i}{\partial x_j} + \frac{gu_i'^3p'}{\bar{\rho}} - 2\nu e_{ij}e_{ij}.
\]

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

\[
\frac{D}{Dt} \left( \frac{1}{2} u_i'^2 \right) = -\frac{\partial}{\partial x_j} \left( \frac{1}{\rho_0} \frac{\partial u_i'}{\partial x_j} + \frac{1}{2} u_i'^2 u_i' - 2\nu u_i' e_{ij} \right) - \frac{g u_i' \rho'}{\rho} - 2\nu e_{ij} e_{ij}
\]

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:

\[
\int_{-H}^{Z} \langle u'_i u'_j \rangle \frac{\partial U_i}{\partial x_j} \, dz
\]

<table>
<thead>
<tr>
<th>Site</th>
<th>Shear prod. (std error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>$7.7 \times 10^{-7}$ (± $1.9 \times 10^{-7}$)</td>
</tr>
<tr>
<td>WIR</td>
<td>$2.6 \times 10^{-6}$ (± $4.0 \times 10^{-7}$)</td>
</tr>
<tr>
<td>KP</td>
<td>$2.2 \times 10^{-6}$ (± $1.7 \times 10^{-7}$)</td>
</tr>
<tr>
<td>CP</td>
<td>$-2.4 \times 10^{-6}$ (± $4.5 \times 10^{-7}$)</td>
</tr>
<tr>
<td>EFZ</td>
<td>$5.6 \times 10^{-7}$ (± $1.2 \times 10^{-7}$)</td>
</tr>
</tbody>
</table>
Buoyancy Production: the role of baroclinic instabilities

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

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

<table>
<thead>
<tr>
<th>Site</th>
<th>( \langle b'w' \rangle ) (std error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>3.1 \times 10^{-4} (\pm 1.4 \times 10^{-5})</td>
</tr>
<tr>
<td>WIR</td>
<td>3.6 \times 10^{-5} (\pm 7.0 \times 10^{-6})</td>
</tr>
<tr>
<td>KP</td>
<td>6.9 \times 10^{-5} (\pm 3.6 \times 10^{-6})</td>
</tr>
<tr>
<td>CP</td>
<td>9.0 \times 10^{-5} (\pm 3.4 \times 10^{-6})</td>
</tr>
<tr>
<td>EFZ</td>
<td>6.6 \times 10^{-5} (\pm 3.8 \times 10^{-6})</td>
</tr>
</tbody>
</table>
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

Prominent topographic features and relatively high APE set hotspots locations
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.

(a) SH (f < 0)

(b) SH (f < 0)

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.