Interannual to multi-decadal forcing of mesoscale eddy kinetic energy in the subtropical southern Indian Ocean

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Image: Time-mean surface eddy kinetic energy, from SSALTO/DUACS altimetry product

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Why study eddies in the subtropical southern Indian Ocean (SSIO)?

SSIO eddies are not as energetic as eddies in some other areas, however they…

- Are located at the intersection of numerous currents, including an unusual poleward-flowing eastern boundary current (Leeuwin Current)

- Are important for heat transport of the IO shallow overturning circulation (Lee and Marotzke 1998, Schott et al. 2002, Lee 2004), and may interact with the atmospheric boundary layer

- Have significant impacts on chlorophyll anomalies in the region (Gaube et al. 2013, Gaube et al. 2014)
SSIO sea surface height (SSH) and eddy kinetic energy (EKE) variability

Motivation and research focus
Eddy relationship to SSH
Climate & internal ocean forcing
Global context

Why are SSH and EKE anomalies correlated in the eastern SSIO (Leeuwin Current region)?
Research questions

• Which mechanism(s) explain the close relationship between SSH and EKE on interannual/decadal timescales in parts of the SSIO?

  ...with possible implications for multi-decadal trends in EKE and SSH

• Which climate and/or interior ocean forcings control the interannual and decadal variability of EKE in the SSIO?

  ...with implications for heat/tracer transport variability/predictability, and ecosystem behavior
In order to focus on dynamics at mesoscales (tens of km to ~200 km)

- Low-pass filter SSH (or SLA, i.e., SSH anomaly) in both longitude and latitude
- Use 6° wavelengths (~670 km) as the cutoff threshold, based on eddy scales in Chelton et al. (2011)

The low-passed field represents larger-scale motions
Residual represents mesoscale motions (such as eddies)

EKE can be computed from each individual field, e.g.,

$$EKE_{meso} = \frac{1}{2} \left\| \mathbf{k} \times \frac{g}{f} \nabla (SLA_{meso}) \right\|^2$$
Correlation between SSH and EKE at interannual/decadal timescales

Zero-lag ID correlation of unfiltered SSH and

Large-scale EKE ($EKE_{lp}$) – mostly Rossby waves

Mesoscale EKE ($EKE_{meso}$) – mostly eddies

- Robust positive correlation between SSH and EKE associated with both large scales and mesoscales
- SSH relationship with mesoscale EKE gets more robust at higher latitudes, where eddies also account for much more energy than planetary waves
Why care about the relationship between SSH and EKE?

- Large-scale changes in sea level indicate shifts in ocean currents and/or planetary waves that may drive changes in conditions for eddy generation

  Sea level \rightarrow \text{dynamics} \rightarrow \text{eddies}

- On the other hand, mesoscale patterns in sea level variability and/or trend imply that mesoscale phenomena (eddies) are influencing sea level

  \text{Eddies} \rightarrow \text{sea level}

Lee and McPhaden (2008)

Mesoscale features in SSH trend

SSH trend (cm yr\(^{-1}\), 1993-2016
**Scale-dependence of SSH-EKE relationship**

- In the subtropical eddy band, the SSH-EKE relationship is associated almost entirely with large-scale SSH variability.

  ![Large-scale SSH corr. with EKE\textsubscript{meso}](image1)

  ![Mesoscale SSH corr. with EKE\textsubscript{meso}](image2)

  **Higher sea level associated with more mesoscale EKE**

  **Higher eddy activity associated with lower sea level**

- This contrasts with the Agulhas Return Current/ACC region to the south, where eddies contribute to sea level variability.

  Sea level $\rightarrow$ dynamics $\rightarrow$ eddies

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**Scale-dependence of SSH-EKE relationship**

**Sea level \(\rightarrow\) dynamics \(\rightarrow\) eddies**

Why?

Higher sea level associated with more mesoscale EKE
Hypothesis: Pacific variability forces both SSH and mesoscale EKE variations in eastern SSIO

- Correlation implies that Pacific dynamics are an important influence on SSIO eddy activity
- Any connection with the tropical Pacific also implies a connection with ENSO…
Here we carry out an “optimum correlation” analysis…correlate the Niño3.4 index with the time variation in mesoscale EKE around the region at varying lags

- Plot the maximum magnitude correlation coefficient at any lag in a 0–2 year range

La Niña (negative Niño3.4) produces higher sea level in W tropical Pacific → stronger Leeuwin Current → more eddy activity
Decadal variability (PDO) and mesoscale EKE in the SSIO

- If ENSO has such a robust influence on eddy activity west of Australia, does the dominant mode of decadal variability in the Pacific (PDO) have a similar effect?

- Pacific forcing has a more robust and far-reaching effect on mesoscale EKE at decadal timescales than interannual timescales!
- Though this still doesn’t explain mesoscale EKE variability in the central and western SSIO
Decadal variability (PDO) and mesoscale EKE in the SSIO

- The decadal part of the SSH and mesoscale EKE variations in the eastern SSIO are very well explained by variations in the PDO index.
What drives eddy variability away from the Leeuwin Current (central & western SSIO), in the absence of large-scale climate forcing?

Using eddy trajectory dataset (developed by Chelton et al., now distributed by AVISO), quantify \( EKE_{\text{meso}} \) associated with eddy tracks passing through the central/western SSIO.

- **Anticyclonic** \( EKE_{\text{meso}} \) (\( \text{cm}^2 \text{s}^{-2} \))
- **Cyclonic** \( EKE_{\text{meso}} \) (\( \text{cm}^2 \text{s}^{-2} \))

Elevated \( EKE_{\text{meso}} \) originates in SE SSIO.
The impact of density and potential vorticity gradients

- Available potential energy (APE) is a function of the local density variance at a given depth, related to the lateral density gradient $\nabla_H \rho$, as well as vertical shear of horizontal velocity $\partial u/\partial z$, $\partial v/\partial z$
- We use the Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2) state estimate to examine these gradients

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- But just because APE is present doesn’t mean baroclinic instability follows
  - Nor do APE variations necessarily drive EKE variations
Charney and Stern (1962) considered baroclinic instability (in the atmosphere) from the perspective of potential vorticity (PV) gradients along isopycnals. Zero crossing in the PV gradient along a sloping isopycnal implies the potential for parcels at different depths but similar PV to be exchanged → potential release of APE and growth of baroclinic instability.

\[ PV = (f + \zeta) \left( -\frac{\partial \rho}{\partial z} \right) \]

Negligible in SSIO

Steeply stratified, very negative PV
Weakly stratified, slightly negative PV

\[ \frac{\partial PV}{\partial y} = 0 \]
The impact of density and potential vorticity gradients

- **Lateral density gradients** help explain the existence of the SSIO eddy band...do they help explain its temporal variability?

Slight differences between composites of high vs. low eddy activity are generally **not statistically significant**
The impact of density and potential vorticity gradients

- What about potential vorticity, whose variability is driven by changes in stratification/thickness?

\[ PV = (f + \frac{\partial \rho}{\partial z}) \]

- There is a significant difference in PV between high and low eddy states
  - i.e., higher PV in the southern part of the eddy band (50-150 m depth) → more eddy activity
The impact of density and potential vorticity gradients

- Now consider the along-isopycnal meridional (AIM) gradient of potential vorticity

\[ PV = (f + \zeta)(-\frac{\partial \rho}{\partial z}) \]

- Negative AIM gradient anomalies associated with higher eddy activity
  - Likely driven by the positive PV anomaly on the southern side of the eddy band
If the PV anomaly influences mesoscale EKE levels, how is it forced?

- Hence we have one mechanism for forcing of eddy activity in the west central SSIO
  - Downwelling (upwelling) wind stress curl enhances (inhibits) eddy activity by forcing PV anomalies
Global implications: the relationship between sea level and EKE

- The temporal variability of EKE is associated with sea level in a number of regions.
- Some of these areas have energetic currents and very high levels of eddy activity.
Global implications: the relationship between sea level and EKE

- The sea level-EKE relationship at interannual/decadal timescales may also have implications for multi-decadal trends

+ SSH-EKE corr. & + EKE trend $\rightarrow$ increased SSH trend?
  N & S Pacific, S Indian
+ SSH-EKE corr. & - EKE trend $\rightarrow$ decreased SSH trend?
  N Atlantic
- SSH-EKE corr. & + EKE trend $\rightarrow$ decreased SSH trend?
  S Pacific (just north of the Polar Front)
Global implications: the relationship between sea level and EKE

- Using a two-layer model, Qiu et al. (2015) found that eddy momentum fluxes can force multi-decadal sea level trends.
Conclusions, and remaining questions

- Tropical Pacific sea level drives variations in mesoscale EKE in the eastern SSIO near Australia
  - Is responsible for the co-variability of sea level and EKE in this region

- Forcing from the Pacific is more robust on decadal than interannual timescales, and is likely driven by the Pacific Decadal Oscillation

- West of the Pacific-driven region in the interior SSIO, eddy activity is forced (at least in part) by variations in wind stress curl that change along-isopycnal PV gradients

- Mesoscale eddy activity may contribute to sea level variability and trends, by exhibiting a preference for anticyclonic or cyclonic eddies, or by forcing sea level changes through eddy momentum fluxes

For more info, keep an eye out for:

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EKE time mean

EKE time mean, computed from data 1993-2015

Eddy kinetic energy (cm² s⁻²)

0 200 400 600 800
ID correlation of regional $EKE_{meso}$ leading $EKE_{meso}$ in the central/western SSIO

- Objective: look to see if temporal variability of mesoscale eddy energy propagates from another region, via an oceanic pathway

Leading box-averaged central/western SSIO $EKE_{meso}$ by

- 24 months
- 18 months
- 12 months
- 6 months

95% significance contour
Effect of the Pacific Decadal Oscillation (PDO) on EKE is similar to the effect of ENSO… but more focused on the interior of the ocean.
Forcing of EKE interannual variability globally

IOD-EKE interannual/decadal correlation

0 lag: Optimum values: IOD leads EKE by 0-2 years
Forcing of EKE interannual variability globally

SAM-EKE interannual/decadal correlation

0 lag

Optimum values: SAM leads EKE by 0-2 years
Distribution of EKE associated with large scales and mesoscales

Low-passed $EKE_{lp}$ time mean ($cm^2 s^{-2}$)  
Mesoscale $EKE_{meso}$ time mean ($cm^2 s^{-2}$)

Difference in color scale (by factor of 4)

<50% of total EKE  
~90% of total EKE
Hypothesis 1: The interannual/decadal variability of EKE in the SSIO is driven by variations in the number of anticyclonic (warm-core) eddies → More AC eddies → EKE increases → SSH increases also

- Highly positive “tracks” in long-term SSH trend look like eddy propagation pathways
Mesoscale eddies and EKE – the eddy counting approach

- Isern-Fontanet et al. (2003; 2006), Morrow et al. (2004), and Chelton et al. (2007; 2011) have used algorithms to identify individual mesoscale eddies.

- The Chelton et al. (2011) method identifies eddies as closed, compact contours of spatially high-passed sea level anomaly (SSH minus its time mean).

Spatially HP sea level anomaly, 28 Aug. 1996

30%-60% of total EKE explained by individual eddies (lifetime ≥4 weeks)

Chelton et al. (2011)
Do anticyclonic eddy variations explain SSH and EKE variability?

Histograms of cyclonic and anticyclonic eddies identified using the Chelton et al. (2011) method, during low and high EKE periods

Low EKE
185 cyc
147 anti

High EKE
177 cyc
128 anti

Hypothesis 1:
More AC eddies \( \Rightarrow \) EKE increases \( \Rightarrow \) SSH increases also

- There are fewer anticyclonic than cyclonic eddies
- Number of AC eddies does not increase during high EKE & SSH periods