Sea Level, Subsurface Gradients, and the Temporal Variability of Mesoscale Eddies

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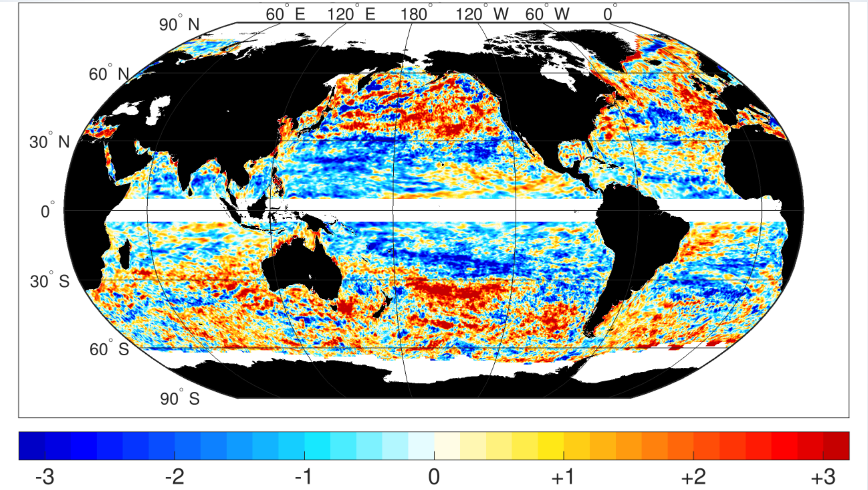

Eddy kinetic energy (EKE) trend (% yr^{-1}) from altimetry, 1993-2016

Jet Propulsion Laboratory
California Institute of Technology

Sources and Sinks of Ocean Mesoscale Eddy Energy workshop – Tallahassee, FL

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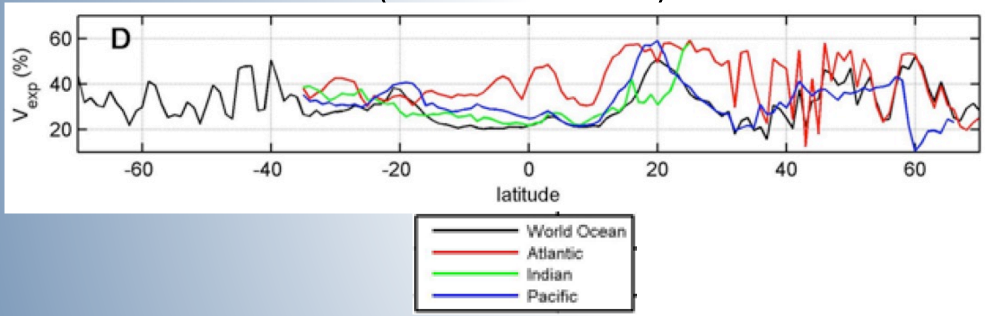
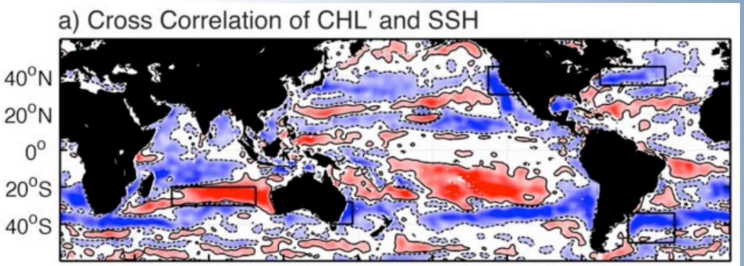
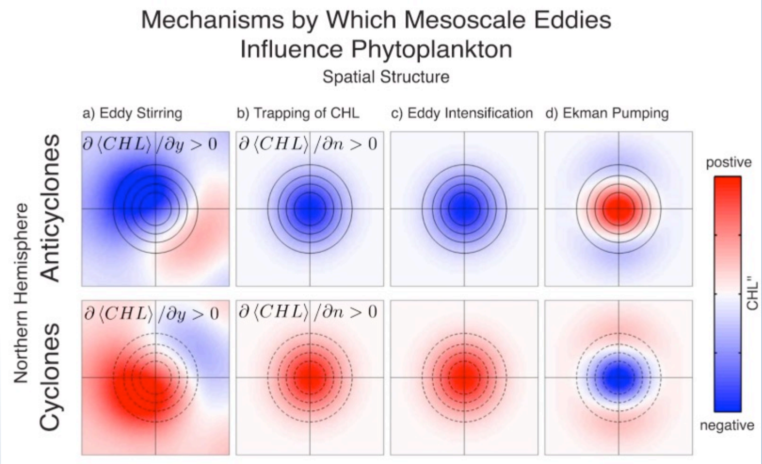
Key motivation: Oceanic mesoscale dynamics play a pivotal role in the climate system, and in marine ecosystems

Eddy meridional heat transport variance, as % of total (Volkov et al. 2008)



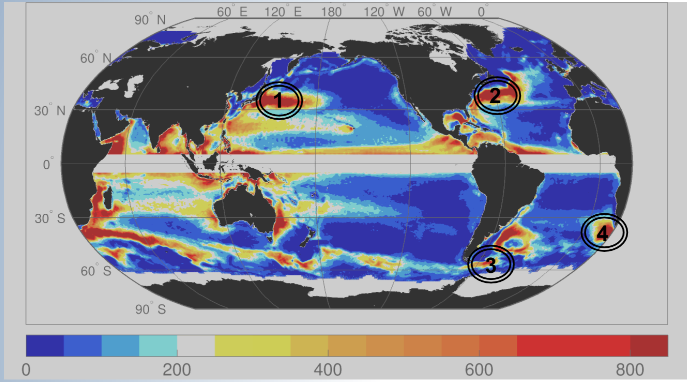
Relationship between chlorophyll anomalies, SSH, and eddies (Gaube et al. 2014)



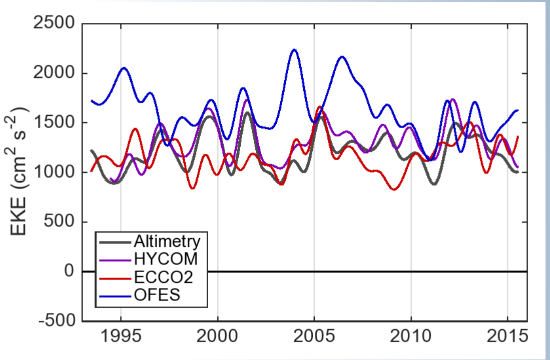


Key motivation: The temporal variability of eddy kinetic energy (EKE) at interannual/decadal timescales is generally not well represented in ocean models

EKE time mean ($cm^2\ s^{-2}$), from gridded altimetry (CLS/CNES)



Kuroshio Extension EKE, low-pass filtered for periods > 14 months

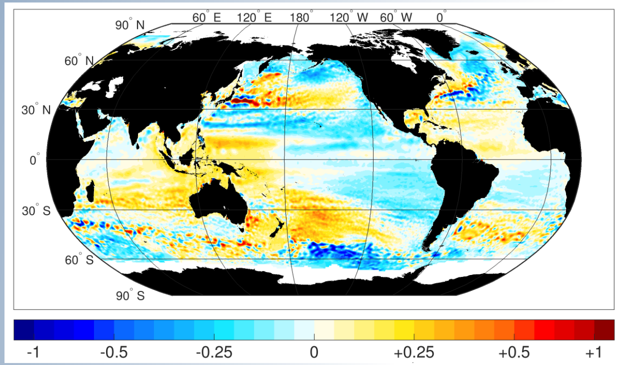


Surface EKE correlations between altimetry and models, with 14-month low pass filter

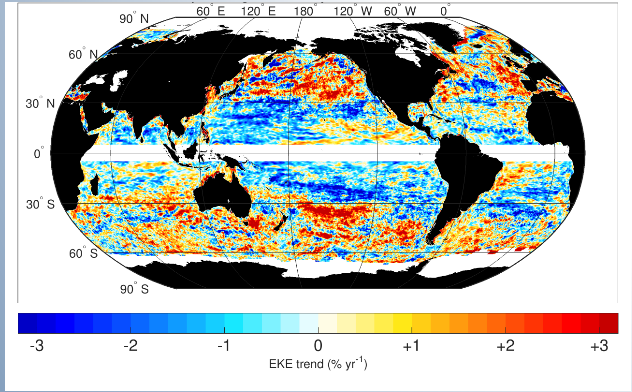
Altimetry correlation with	HYCOM GOFS 3.1 Rean	ECCO2	OFES 0.1° NCEP
Kuroshio Extension (1)	**0.89**	0.22	0.03
Gulf Stream Extension (2)	**0.76**	-0.03	0.10
Drake Passage outflow (3)	0.25	0.09	0.17
Agulhas rings (4)	**0.49**	-0.14	0.09

Key motivation: The oceanic mesoscale may influence regional rates of sea level change

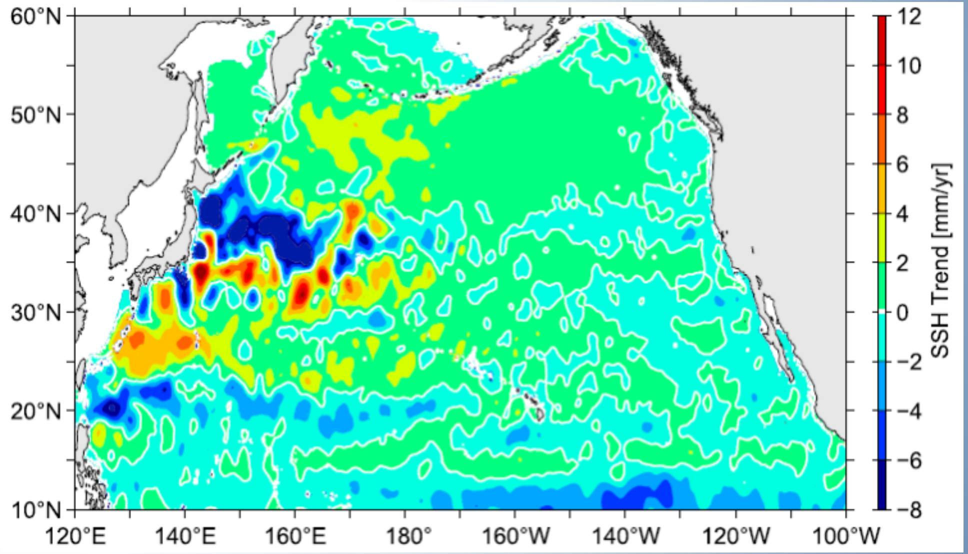
Sea level trend minus global mean (cm yr^{-1}), 1993-2016



Eddy kinetic energy (EKE) trend (% yr^{-1}), 1993-2016



Difference in sea level trend (1992-2013) forced by wind stress & eddy momentum fluxes, vs. wind stress alone (Qiu et al. 2015)



Research focus

- **Where are interannual and decadal changes in eddy kinetic energy (EKE) associated with changes in local sea surface height (SSH)?**

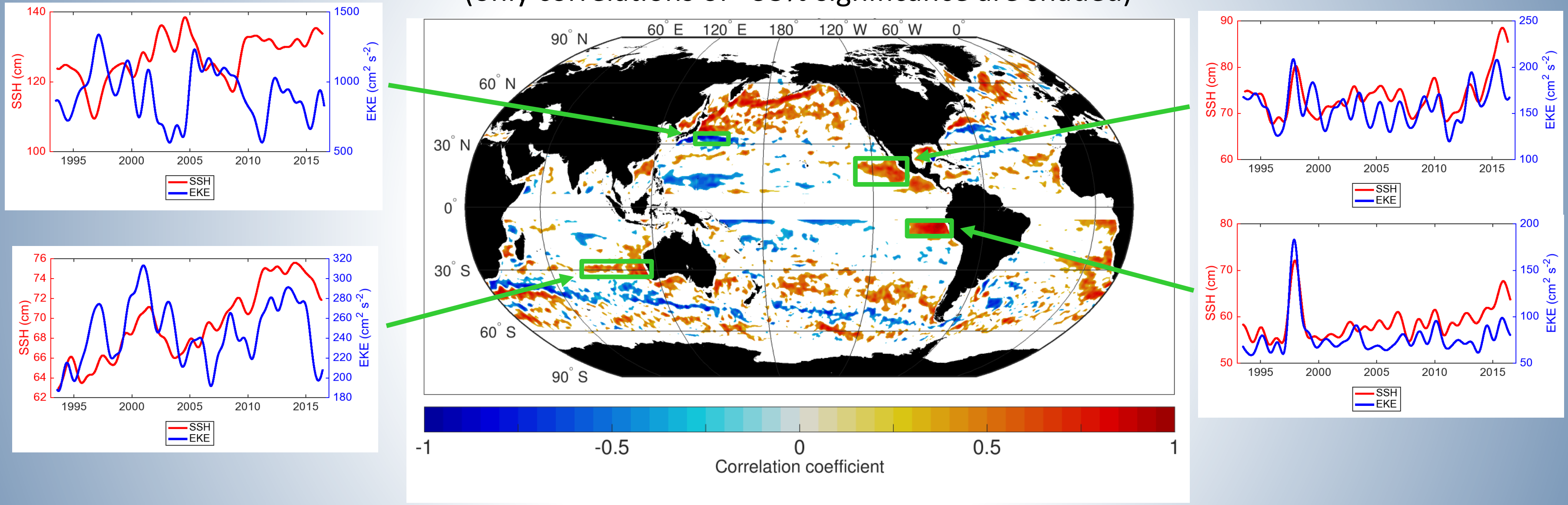
- **What does this imply about the relationship between mesoscale energy (represented by EKE) and large-scale circulation (represented by SSH) on these timescales?**

    - Do mesoscale eddies influence interannual/decadal changes in sea level?

    - Are sea level variations a useful indicator of areas where large-scale atmospheric or oceanic forcing influences the variability of mesoscale eddy activity?

Sea level and EKE co-variations

Local correlation of SSH and EKE, at interannual/decadal timescales
(only correlations of >95% significance are shaded)



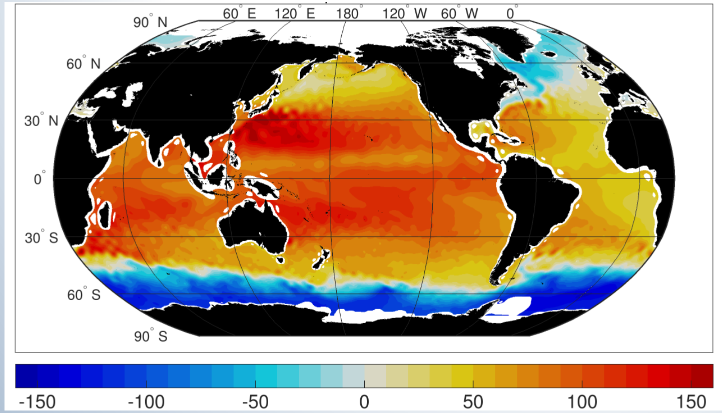
- Change in sign of SSH-EKE correlation occurs across many strong currents
- SSH-EKE correlations are robustly positive in more places then they are negative
  - Higher sea level tends to be associated with higher eddy activity…why?

Anticyclonic/cyclonic bias

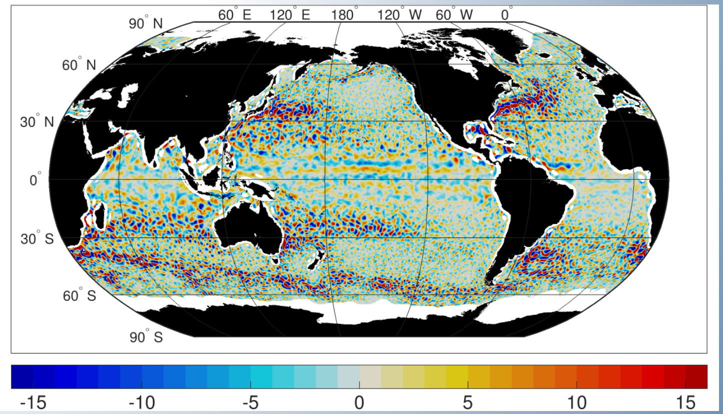
- Some of the co-variability of sea level and EKE may be attributed to a tendency for anticyclonic or cyclonic eddies to form in a given location

- We consider the relative contribution of anticyclonic vs. cyclonic mesoscale phenomena to EKE, as follows:
    - Low-pass spatial filter SSH in two dimensions, with the cutoff wavelength varying by latitude
    - The residual is the **mesoscale SSH or SSH_{meso}**
    - $SSH_{meso} > 0$: anticyclonic eddies (and other mesoscale phenomena)
    - $SSH_{meso} < 0$: cyclonic eddies/other mesoscale phenomena

Snapshots of SSH components on 1998 Jan 01



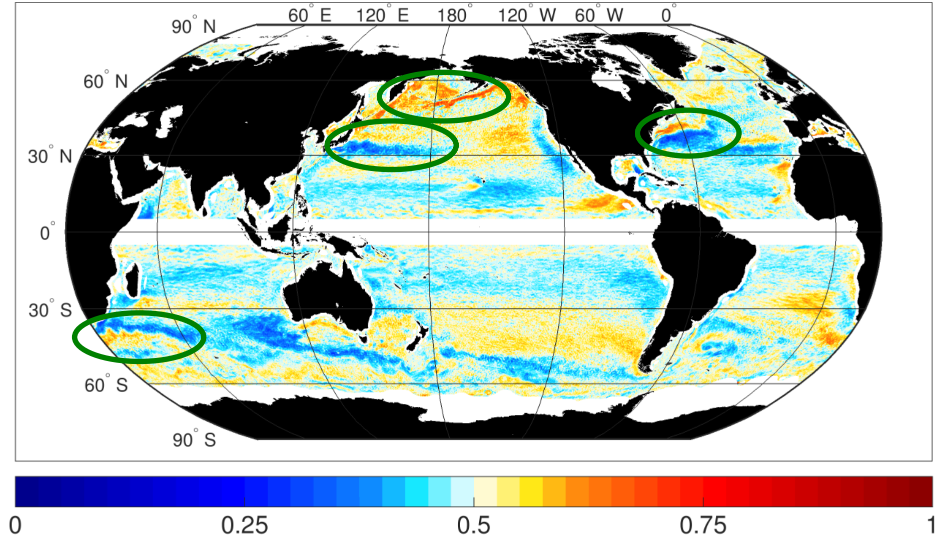
Low-passed SSH_{lp} (cm)



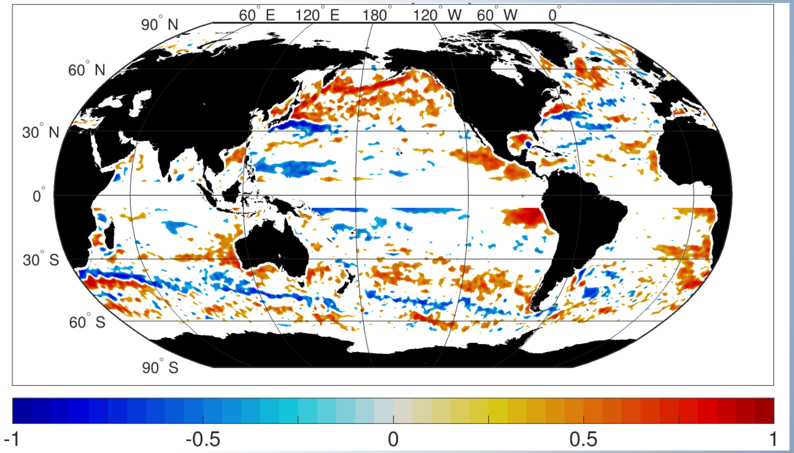
Mesoscale SSH_{meso} (cm)

Anticyclonic/cyclonic bias

- An anticyclonic or cyclonic bias at mesoscales appears to be responsible for the SSH-EKE relationship in many areas, including near strong currents.
  - More anticyclonic (cyclonic) eddies → higher (lower) sea level locally



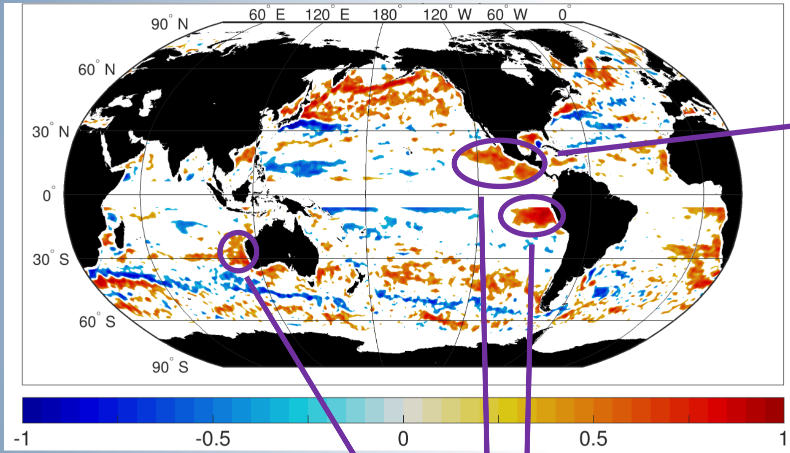
Fraction of EKE associated with positive SLA_{meso}



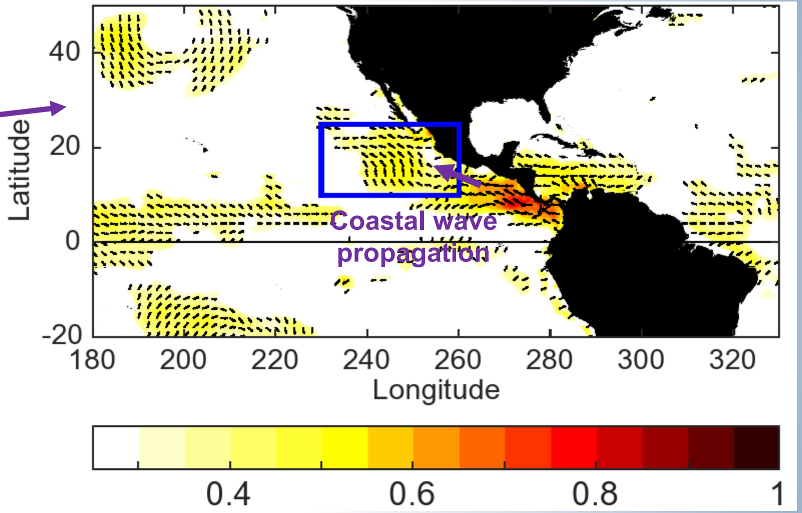
Local SSH-EKE correlation coefficient

Atmospheric forcing

- Surface winds (and planetary waves generated by them) may drive interannual/decadal variations in eddy generation, particularly near eastern boundaries



Local SSH-EKE correlation coefficient

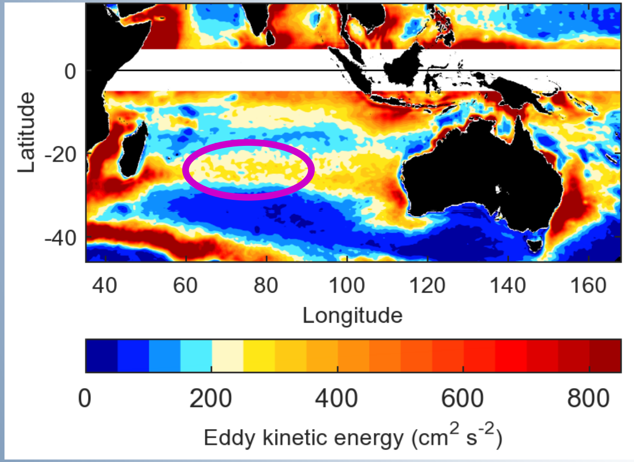


Box-averaged EKE correlated with CCMP 10 m wind: Wind leads EKE by 6 months

- EKE variability in the lower-latitude Pacific and Indian Oceans is forced largely by wind and planetary waves associated with ENSO

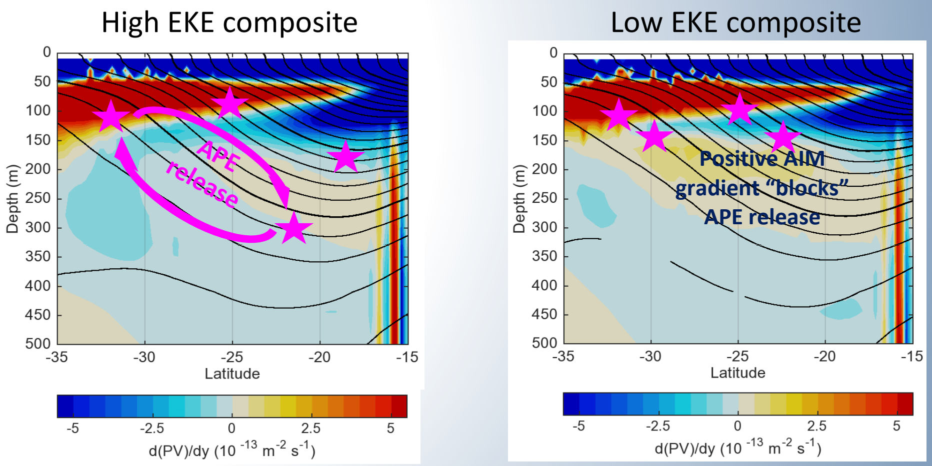
Influence of subsurface gradients on interannual/decadal EKE variability

- In the central Indian Ocean between 30°-20°S, we found that the time-mean EKE maximum was coincident with the **lateral density gradient**
- The EKE time variability appears to be explained in part by changes in the **along-isopycnal potential vorticity (PV) gradient** (Delman et al. 2018)



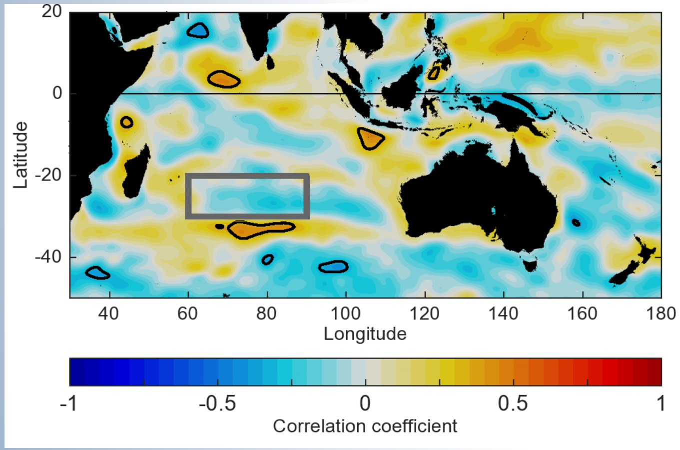
Time mean surface EKE from altimetry

Meridional, along-isopycnal PV gradient from ECCO2

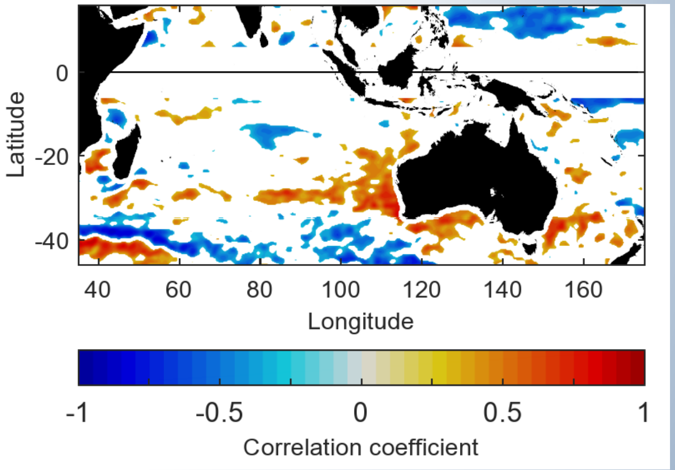


Subsurface gradients, interannual/decadal EKE (and SSH?) variability

- **Higher EKE** in this region is associated with a subsurface positive PV anomaly near 30°S, in turn likely induced by **anticyclonic wind stress curl** anomalies
- These anticyclonic wind stress curl anomalies might also force a positive SSH anomaly, explaining the **positive SSH-EKE correlation** in the region



Correlation of wind stress curl, leading mesoscale EKE in **gray box** by 6 months, ID timescales



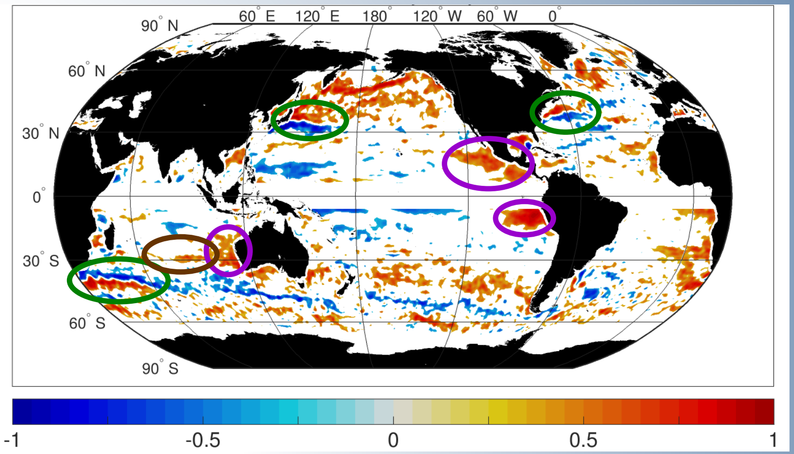
Zero-lag correlation of SSH and EKE anomalies, ID timescales

Conclusions

- In many regions of the ocean, EKE co-varies with sea level (SSH) on interannual/decadal timescales

- There appear to be several types of mechanisms for this co-variation (that may also explain EKE interannual/decadal variations generally):

    - **Preferential shedding of eddies of a certain sign:** occurs commonly (but not exclusively) near strong currents
    - **Surface winds forcing planetary waves:** most common near equator and eastern boundaries
    - **Subsurface density and PV gradients:** may influence eddy generation, and share common forcing with sea level anomalies



Local SSH-EKE correlation coefficient, at interannual/decadal timescales

- A regional study considering these mechanisms in the subtropical Indian Ocean was recently published:
  Delman, A. S., Lee, T., & Qiu, B. (2018). Interannual to multidecadal forcing of mesoscale eddy kinetic energy in the subtropical southern Indian Ocean. *J. Geophys. Res. Oceans*, 123. https://doi.org/10.1029/2018JC013945.

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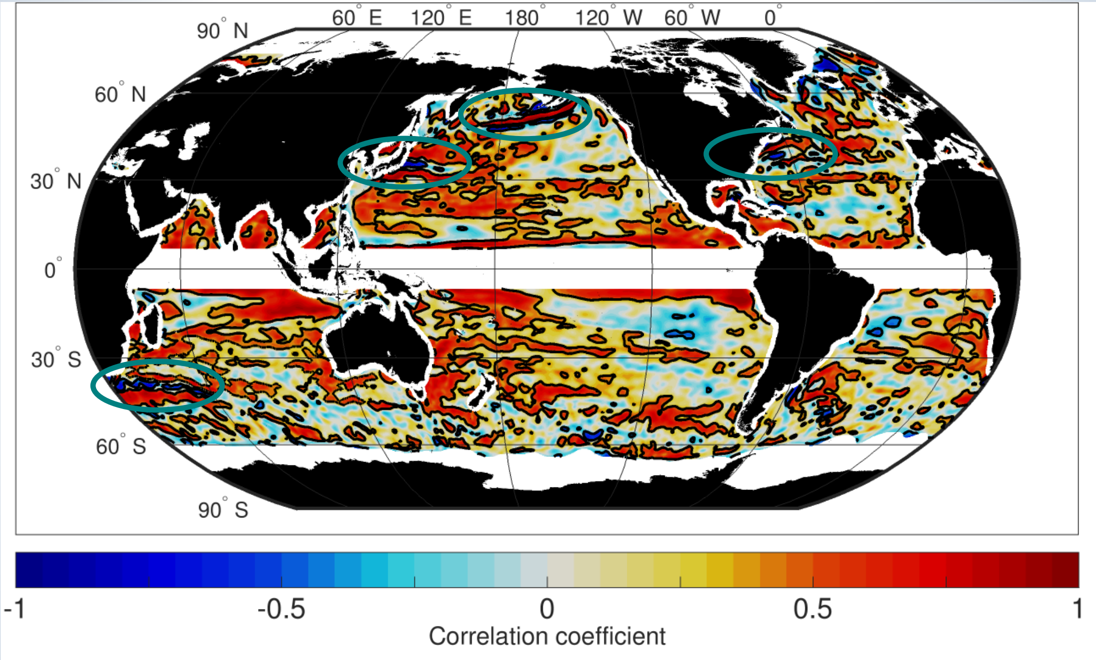
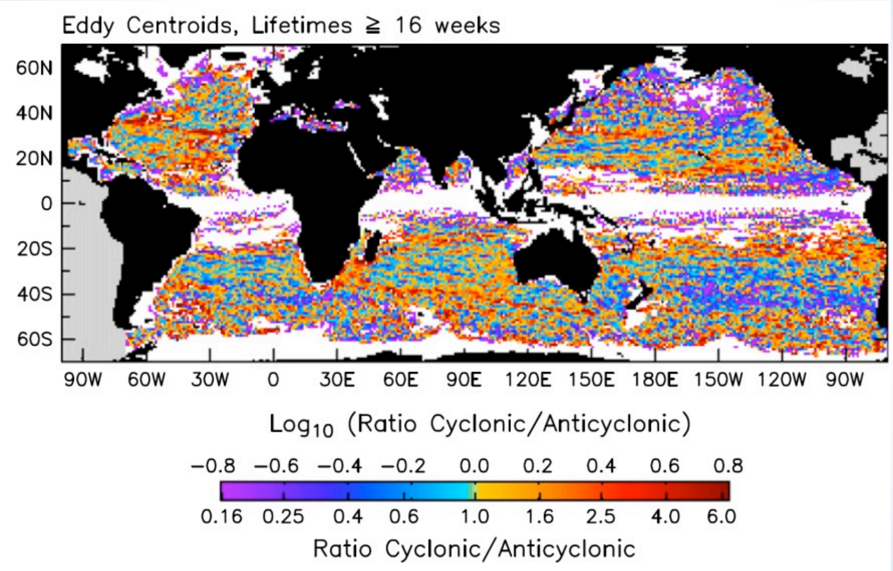
SSH gradient and EKE co-variations

- At the surface $\mathrm{EKE} \propto |\nabla SSH|^2$, so we expect that the $|\nabla SSH|$-EKE correlation will be positive by definition
  - It is in most places, but if the correlation is computed with most mesoscale variations removed, the correlation turns negative along strong currents



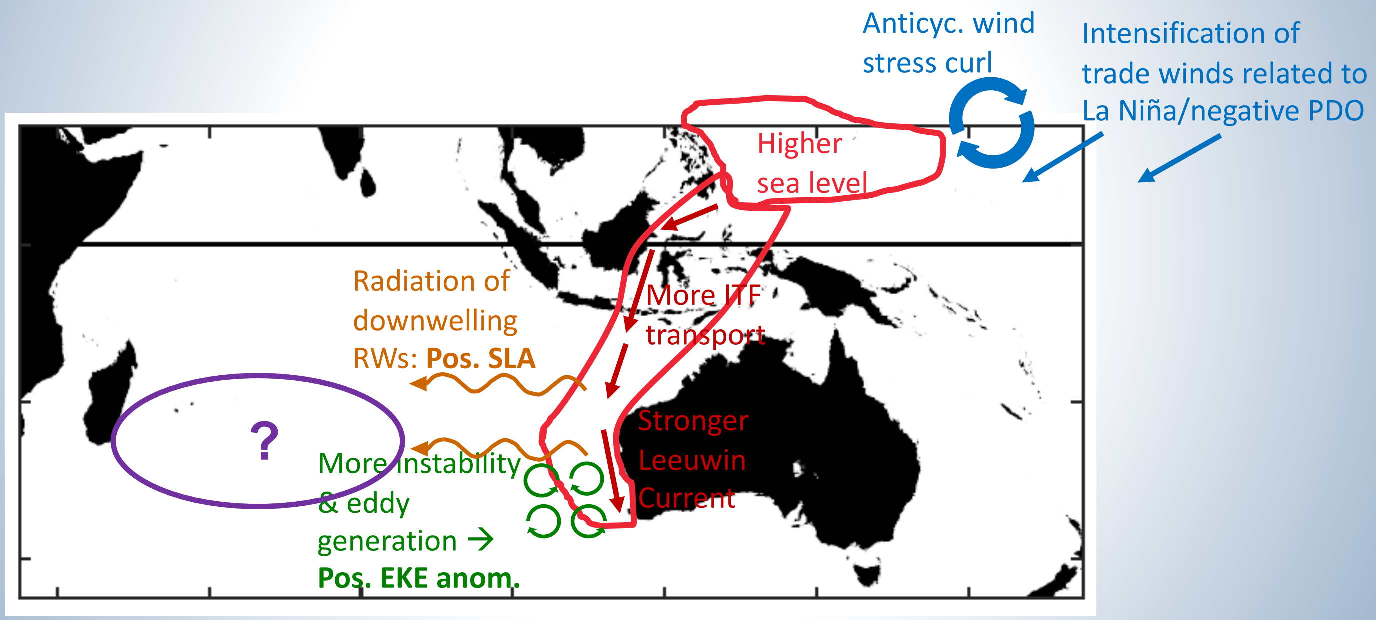
Local correlation of SSH gradient and EKE, smoothed with Gaussian filter (2° e-folding radius) (contours indicate 95% significance level)

Eddy ratio (Chelton et al. 2011)



Pacific influences eddy activity in the eastern SSIO

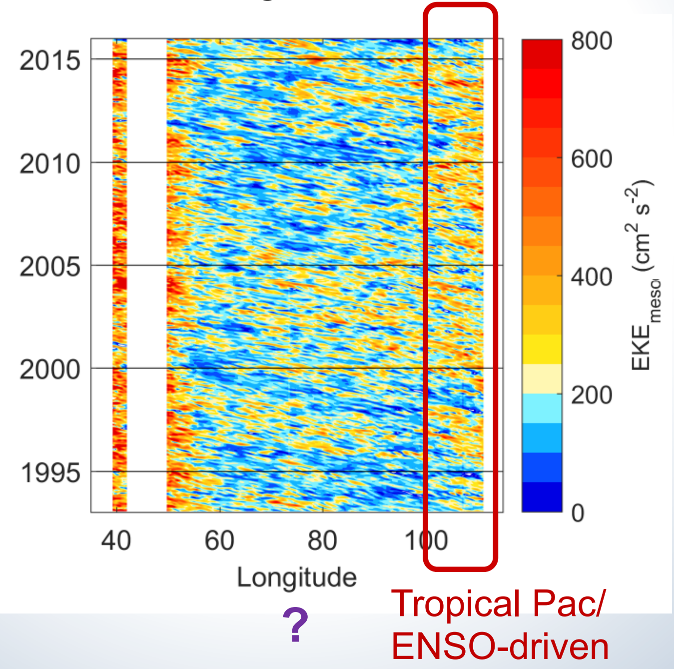
- In short, we have a robust (if somewhat complicated) explanation for the influence of Pacific sea level and climate forcing on eddy activity in the **eastern SSIO**



- However, Pacific forcing does not explain mesoscale EKE variability in the **central and western SSIO**

- What drives eddy variability away from the Leeuwin Current (central & western SSIO), in the absence of forcing from the Pacific?

Hovmöller diagram of mesoscale EKE, averaged 25°-20° S



The impact of density and potential vorticity gradients

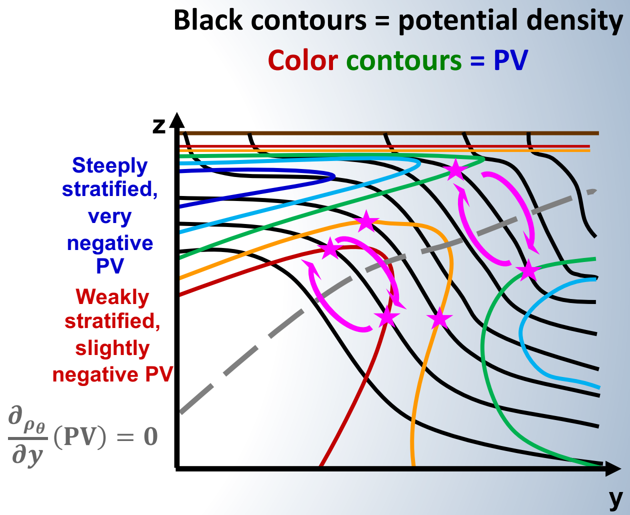
- Charney and Stern (1962) considered baroclinic instability (in the atmosphere) from the perspective of potential vorticity (PV) gradients along isopycnals

negligible in SSIO

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

$(f + \zeta)$: Pos. in NH, Neg. in SH (ζ negligible in SSIO)

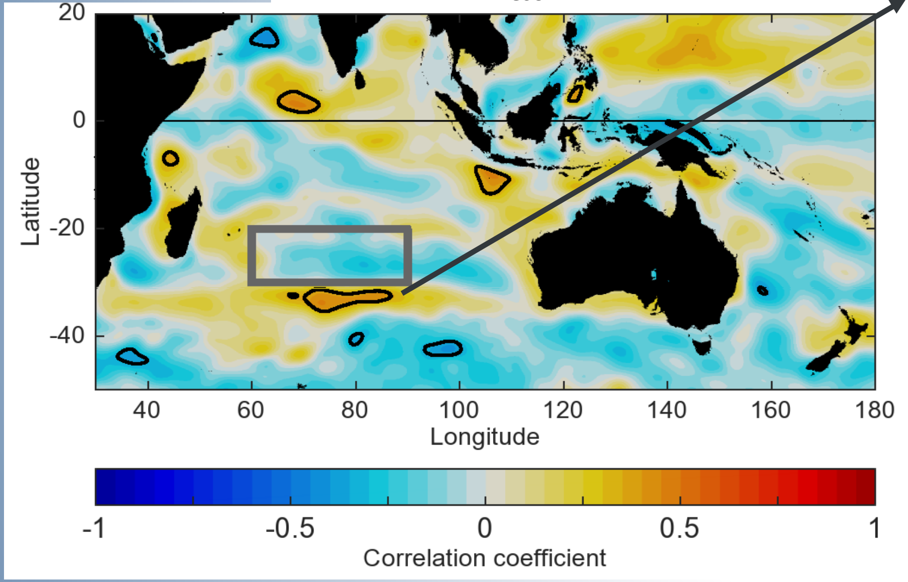
$\left(-\frac{\partial \rho}{\partial z}\right)$: Positive



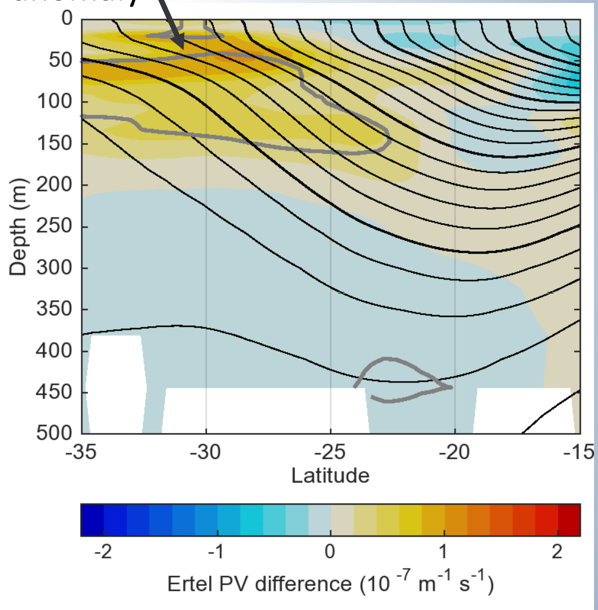
- Zero crossing in the PV gradient along a sloping isopycnal implies the potential for parcels at different depths but similar PV to be exchanged
→ potential release of APE and growth of baroclinic instability

If the PV anomaly influences mesoscale EKE levels, how is it forced?

Correlation of wind stress curl (from CCMP), leading box-averaged EKE_{meso} by 6 months

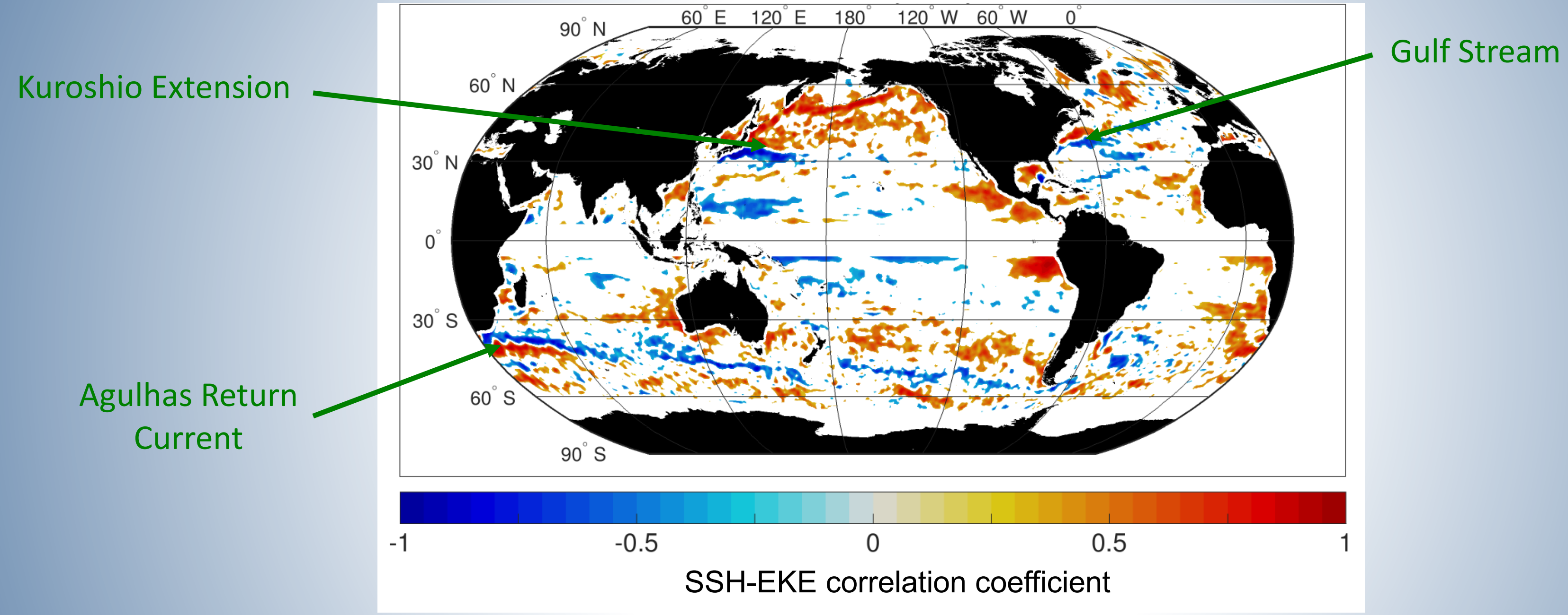


Wind stress curl forces PV anomaly



- 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
  - Often there is a preference for cyclonic (anticyclonic) eddies on the equatorward (poleward) side of strong currents → sea level impact

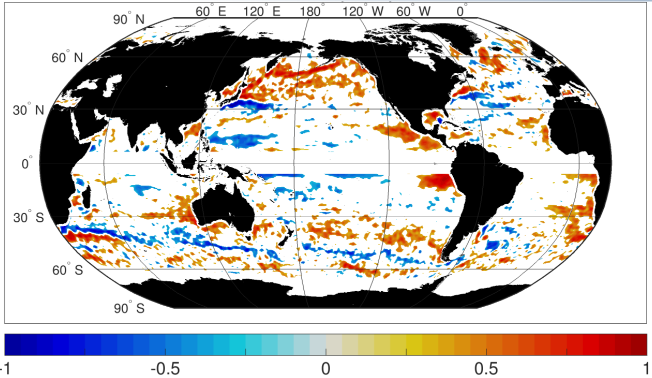
Global implications: the relationship between sea level and EKE

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

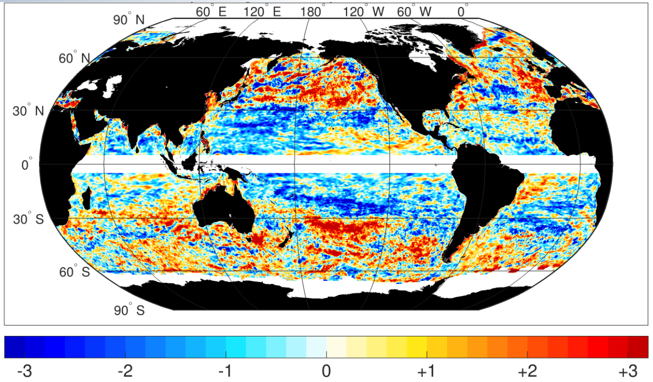
+ SSH-EKE corr. & + EKE trend → increased SSH trend?
N & S Pacific, S Indian

+ SSH-EKE corr. & - EKE trend → decreased SSH trend?
N Atlantic

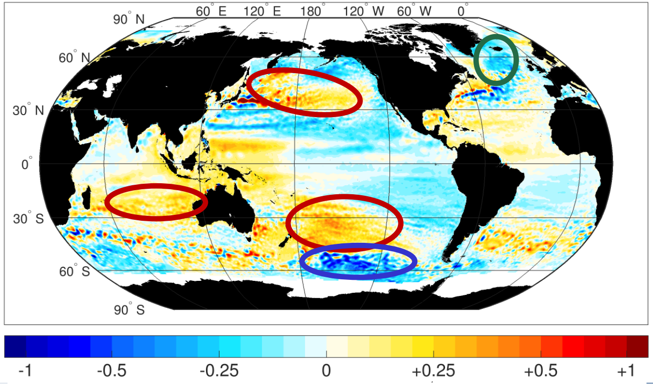
- SSH-EKE corr. & + EKE trend → decreased SSH trend?
S Pacific (just north of the Polar Front)



SSH-EKE correlation coefficient

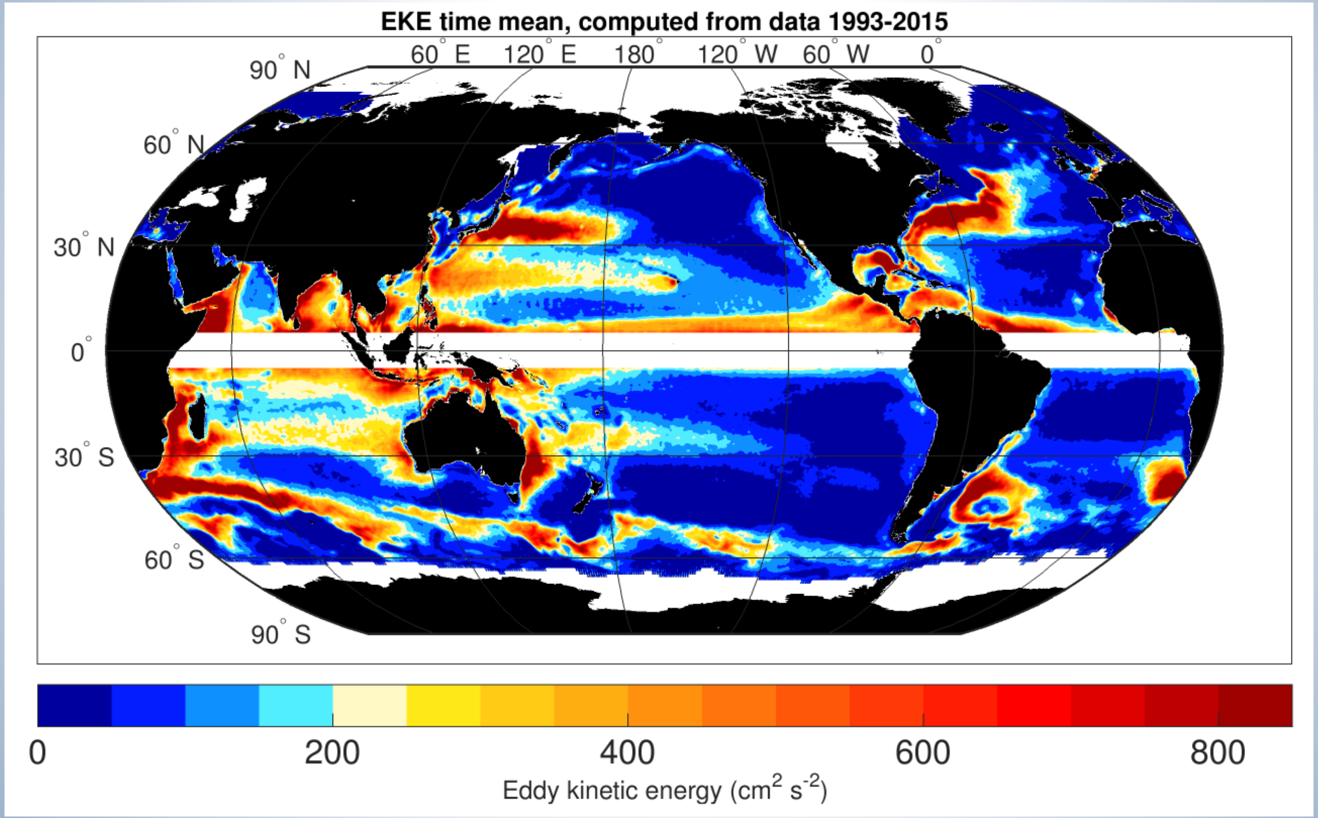


EKE trend (% yr^{-1}), 1993-2016



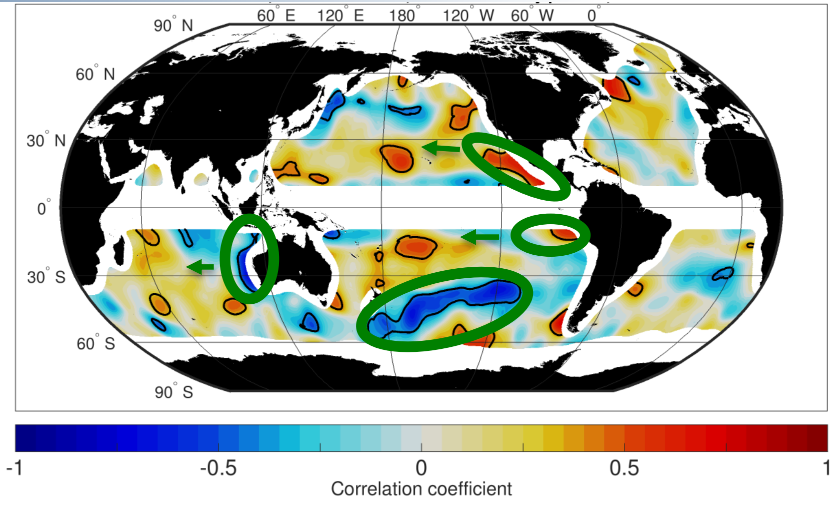
SSH trend minus global mean (cm yr^{-1}), 1993-2016

EKE time mean

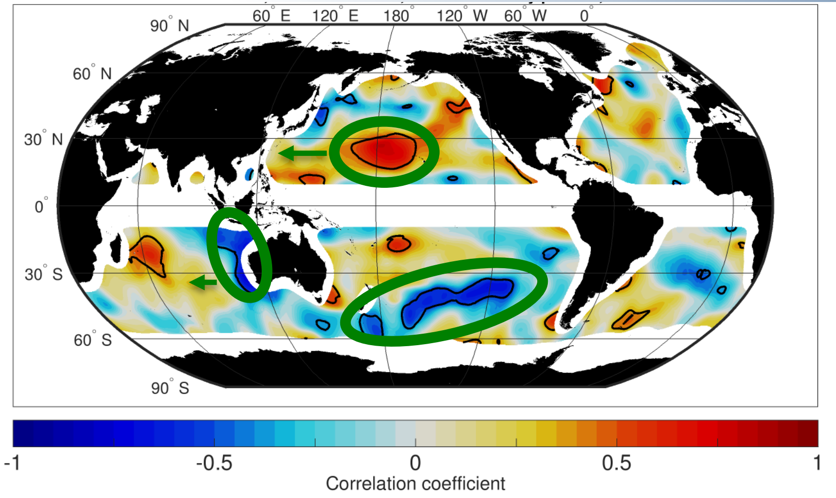


Forcing of EKE interannual/decadal variability globally

Niño3.4-EKE correlation
0 lag



PDO-EKE correlation
0 lag



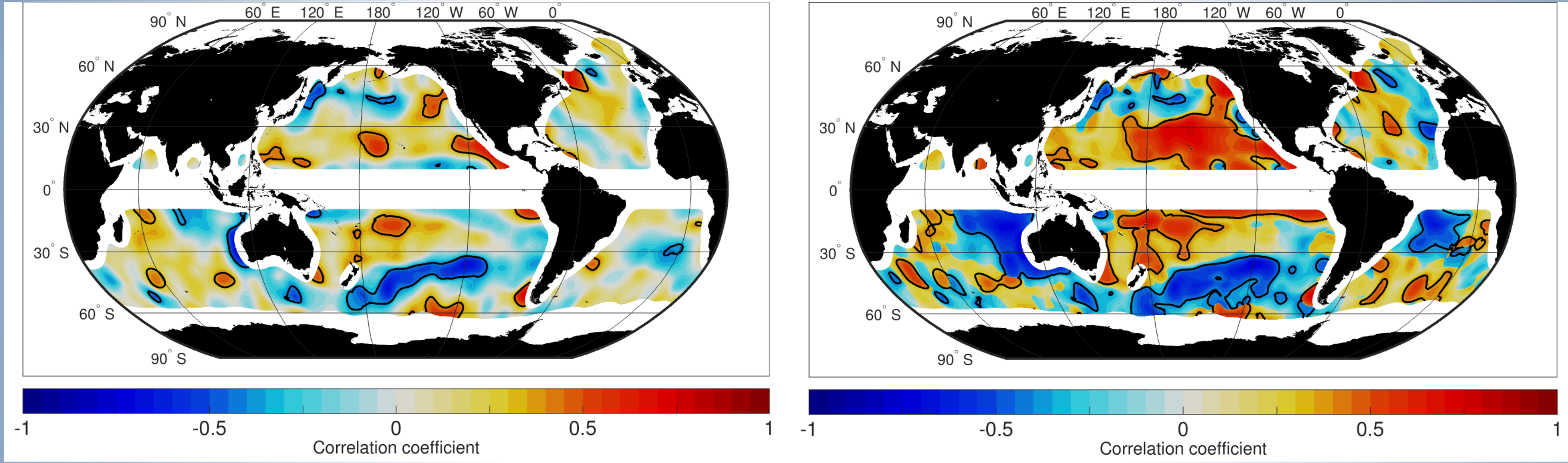
- Effect of the Pacific Decadal Oscillation (PDO) on EKE is similar to the effect of ENSO… but more focused on the interior of the ocean

Forcing of EKE interannual variability globally

Niño3.4-EKE interannual/decadal correlation

0 lag

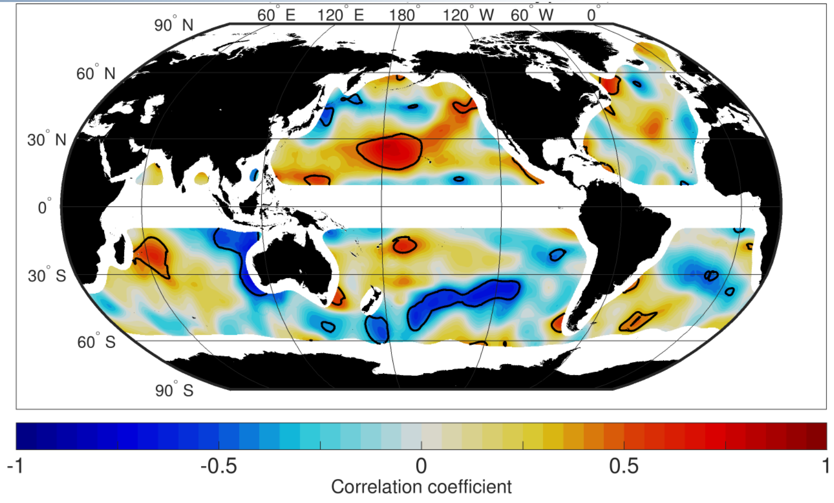
Optimum values: ENSO leads EKE by 0-2 years



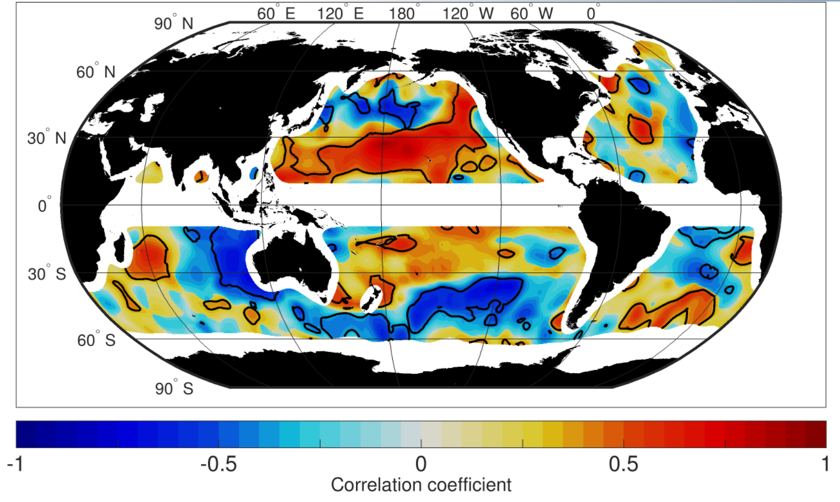
Forcing of EKE interannual variability globally

PDO-EKE interannual/decadal correlation

0 lag



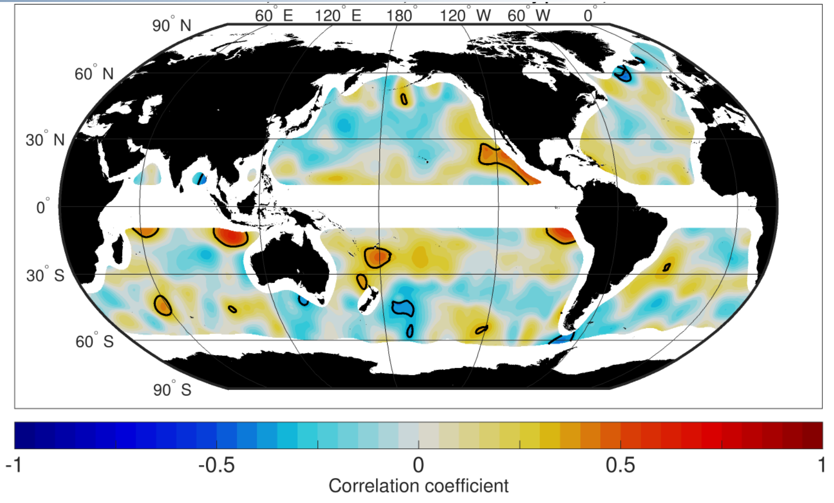
Optimum values: PDO leads EKE by 0-2 years



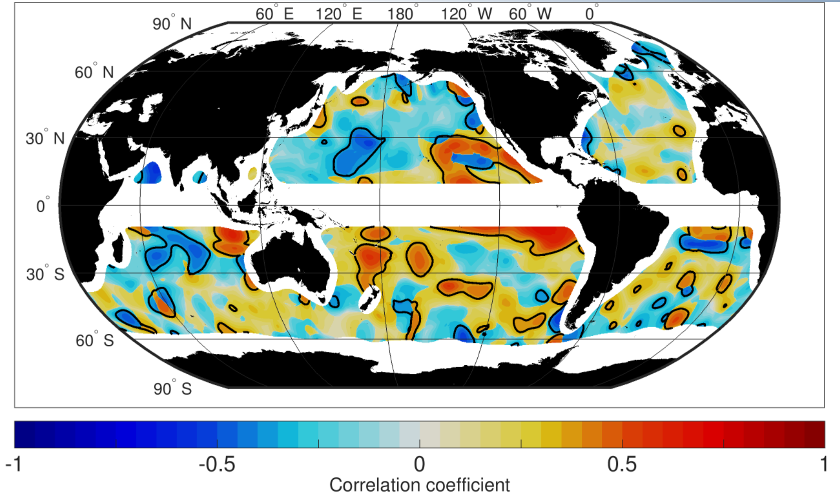
Forcing of EKE interannual variability globally

IOD-EKE interannual/decadal correlation

0 lag



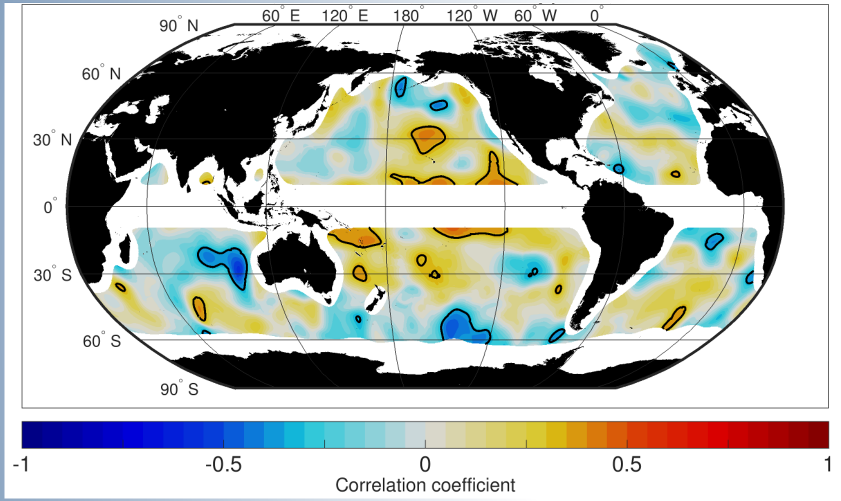
Optimum values: IOD leads EKE by 0-2 years



Forcing of EKE interannual variability globally

SAM-EKE interannual/decadal correlation

0 lag



Optimum values: SAM leads EKE by 0-2 years