# Surface ocean eddy kinetic energy trend from 3-decade satellite altimetry missions: Observations & causes

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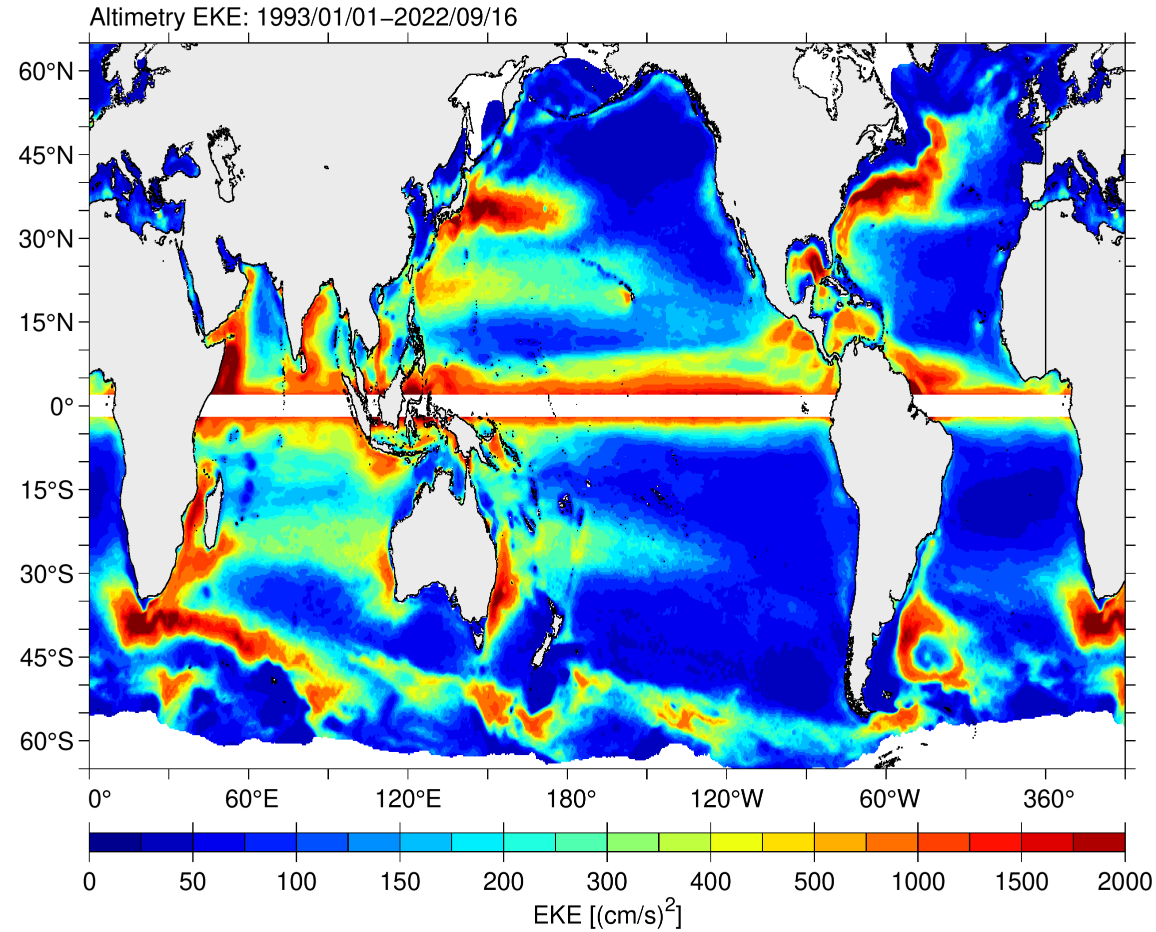
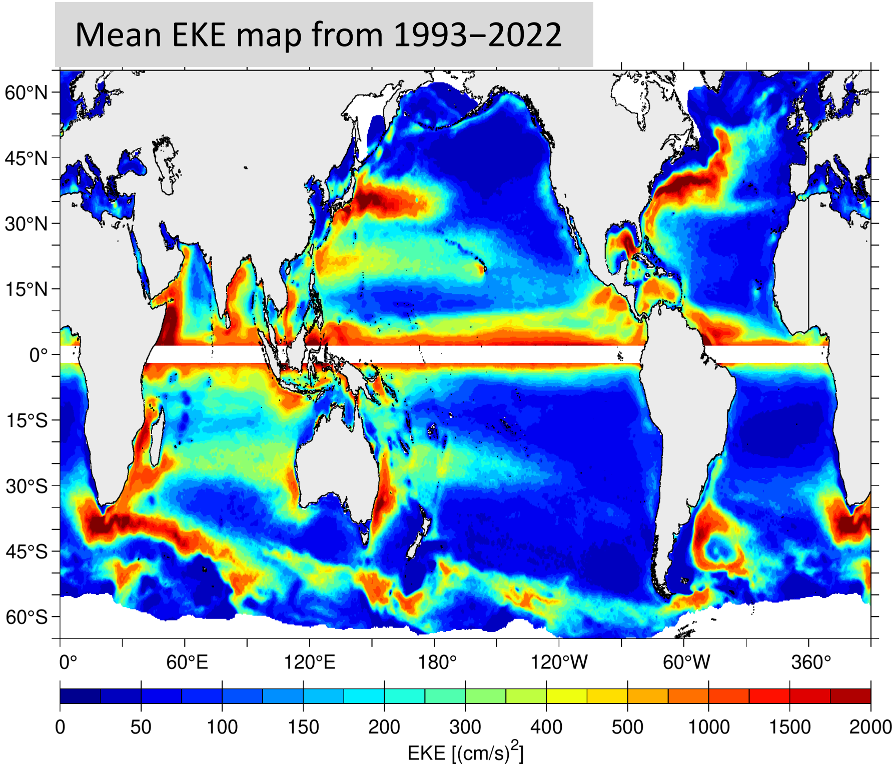
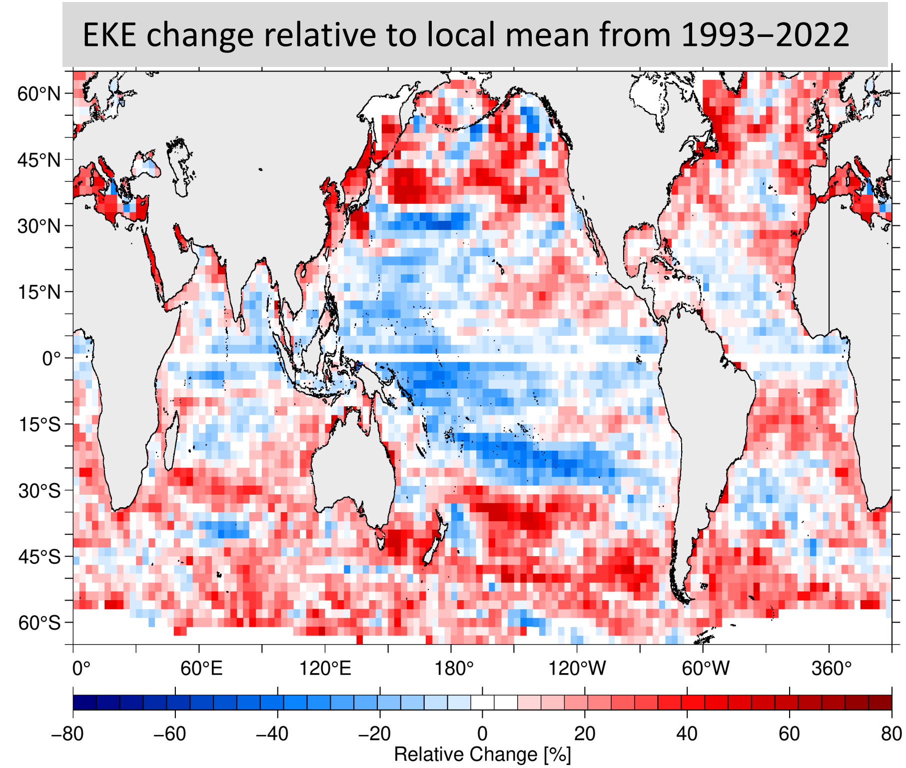


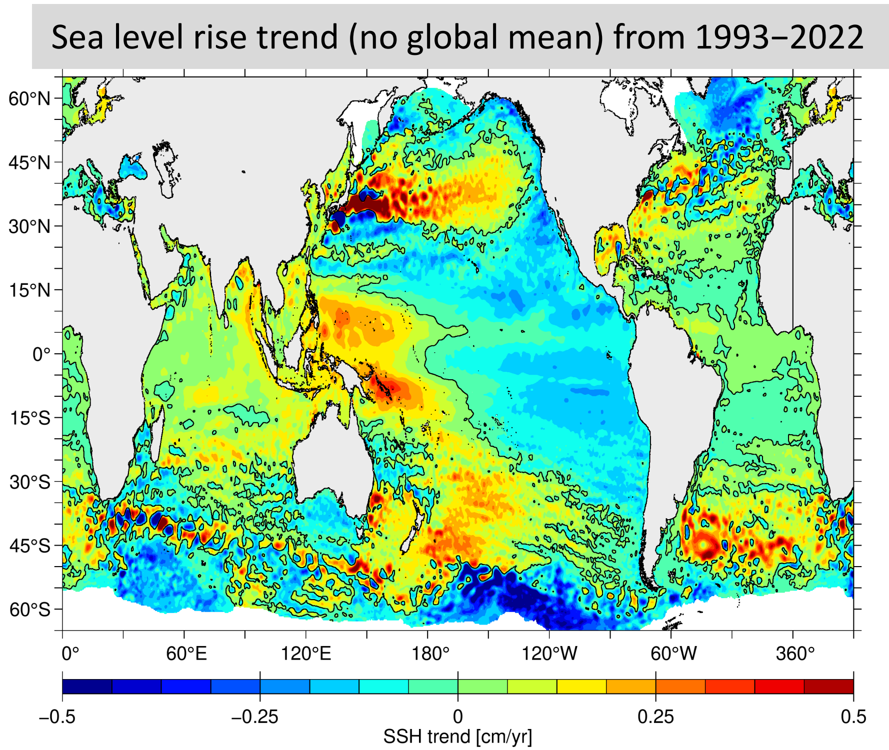

Altimeter-derived EKE map in global ocean from 1993–2022

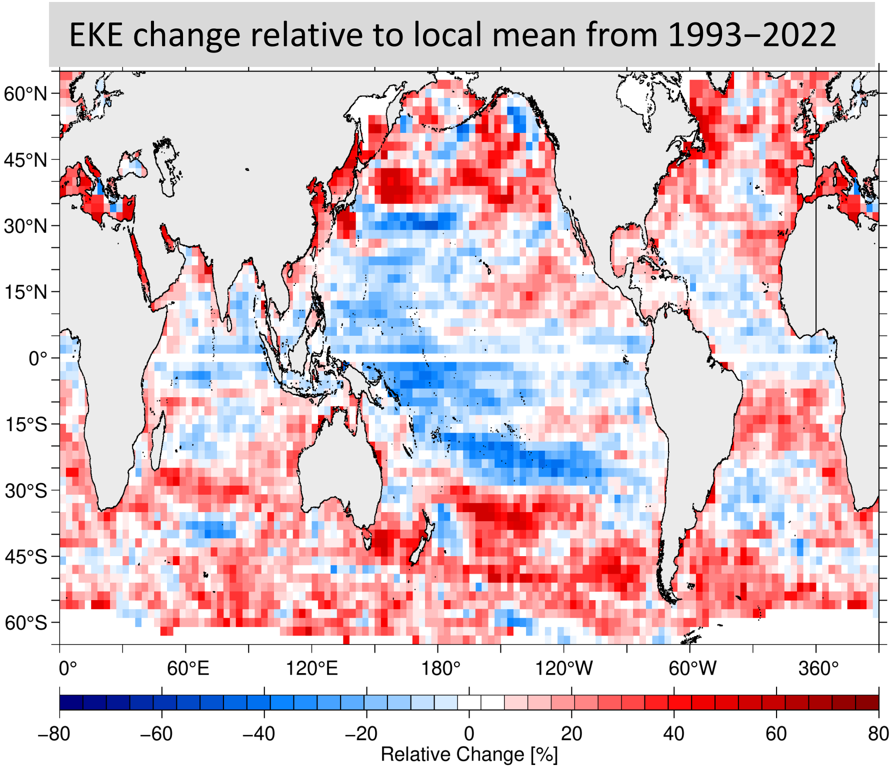
**OSTST PI Meeting, Venice, 3 November 2022**




- Surface ocean EKE distribution has been established since beginning of the satellite altimetry era
- 3-decade accumulation of altimetry data allows us now to examine EKE linear trends; right map shows relative EKE change over the past 30-year period
- Increasing trends are seen in most of the interior quiescent world oceans
- Decreasing trends appear in equatorial & western basins of tropical/subtropical gyres

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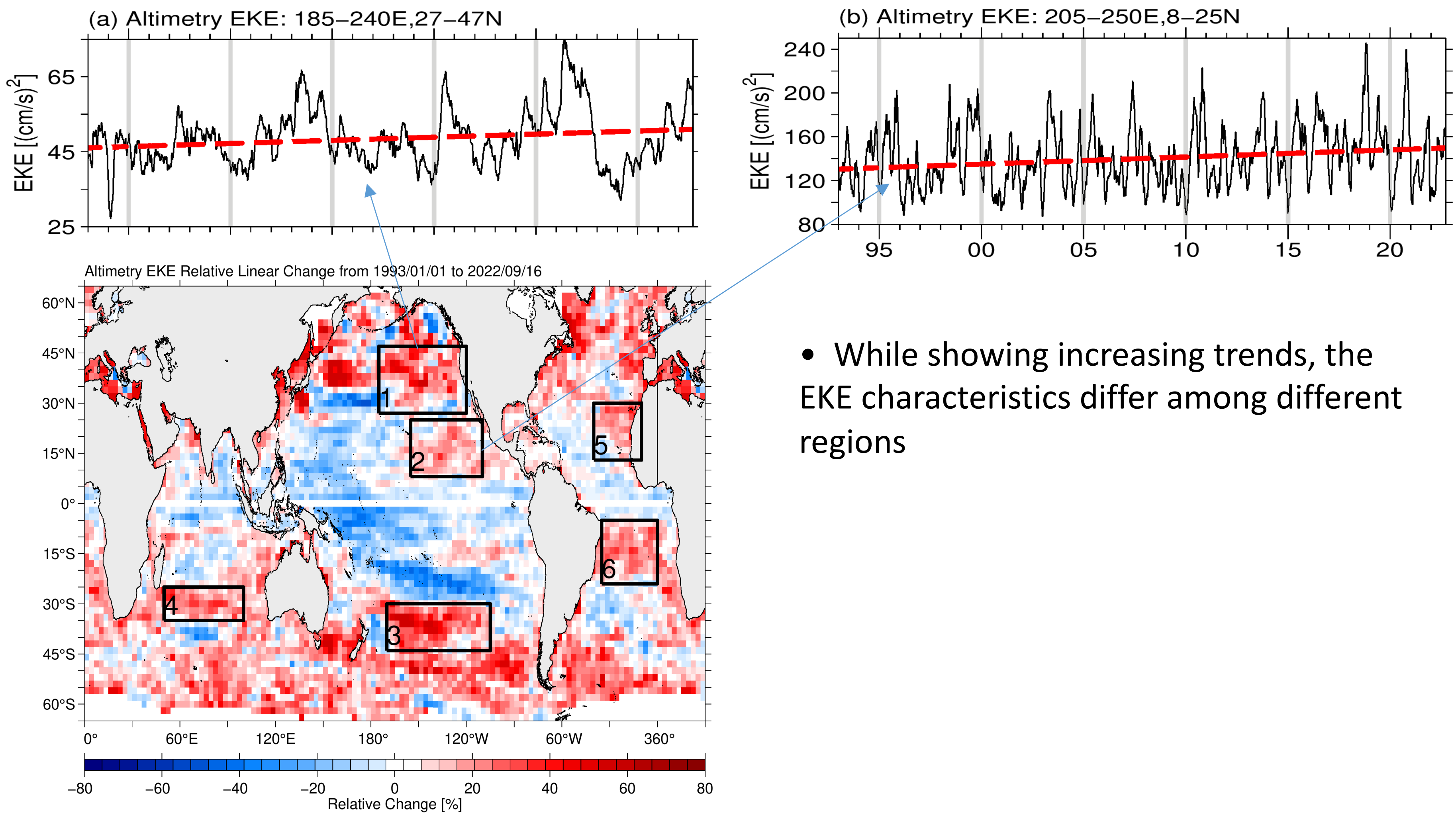
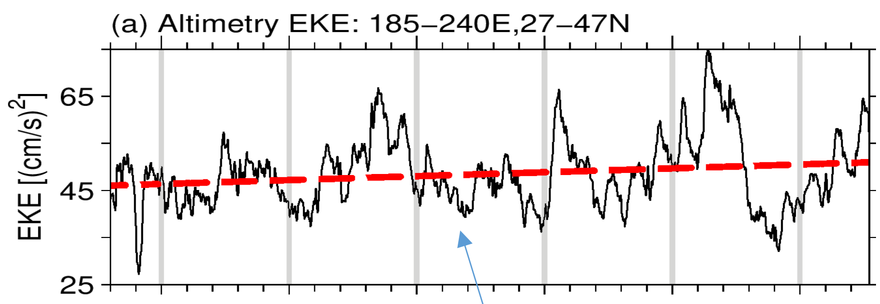
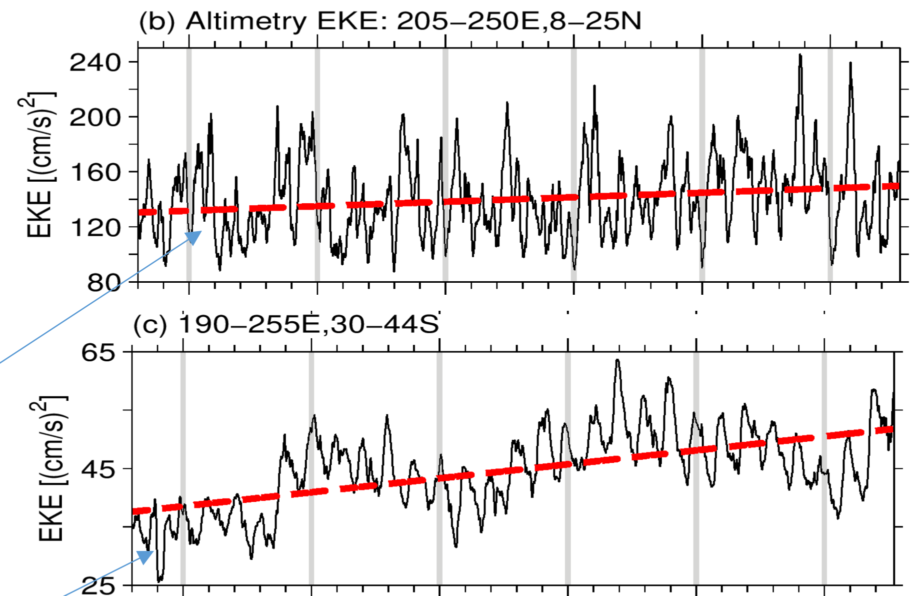
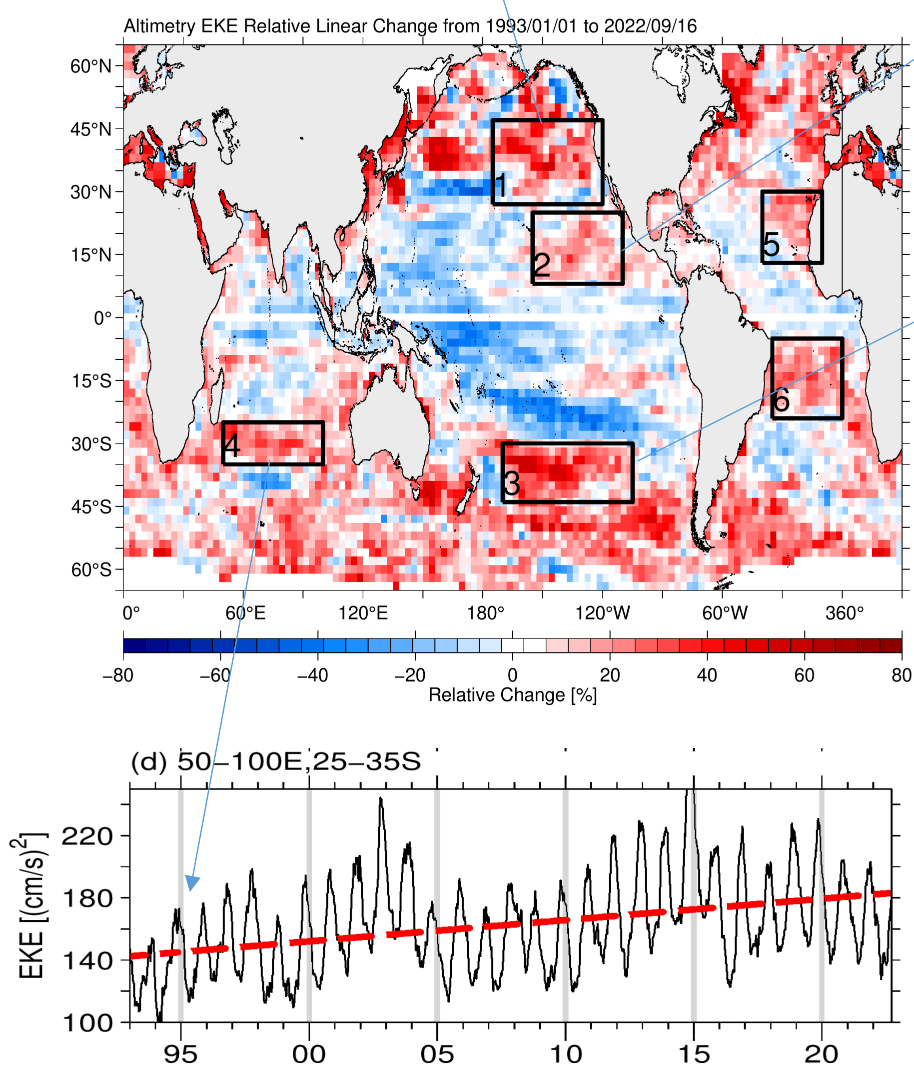
- 3-decade accumulation of altimetry data allows us now to examine EKE linear trends; right map shows relative EKE change over the past 30-year period
- Increasing trends are seen in most of the interior quiescent world oceans
- EKE trend has a spatial pattern different from that of regional sea level rise trend, even though both patterns (as we will see below) are related to wind forcing



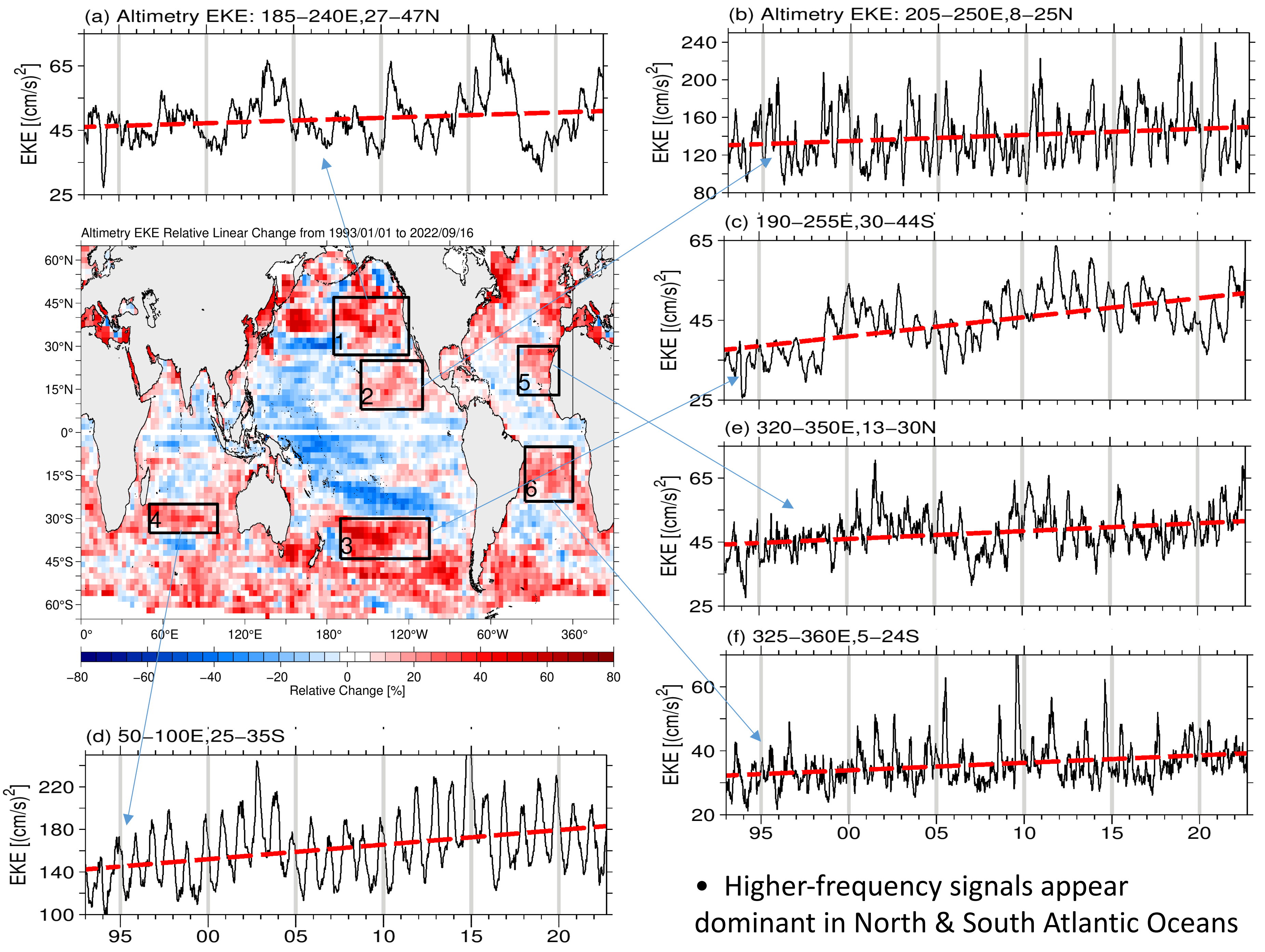

- While showing increasing trends, the EKE characteristics differ among different regions



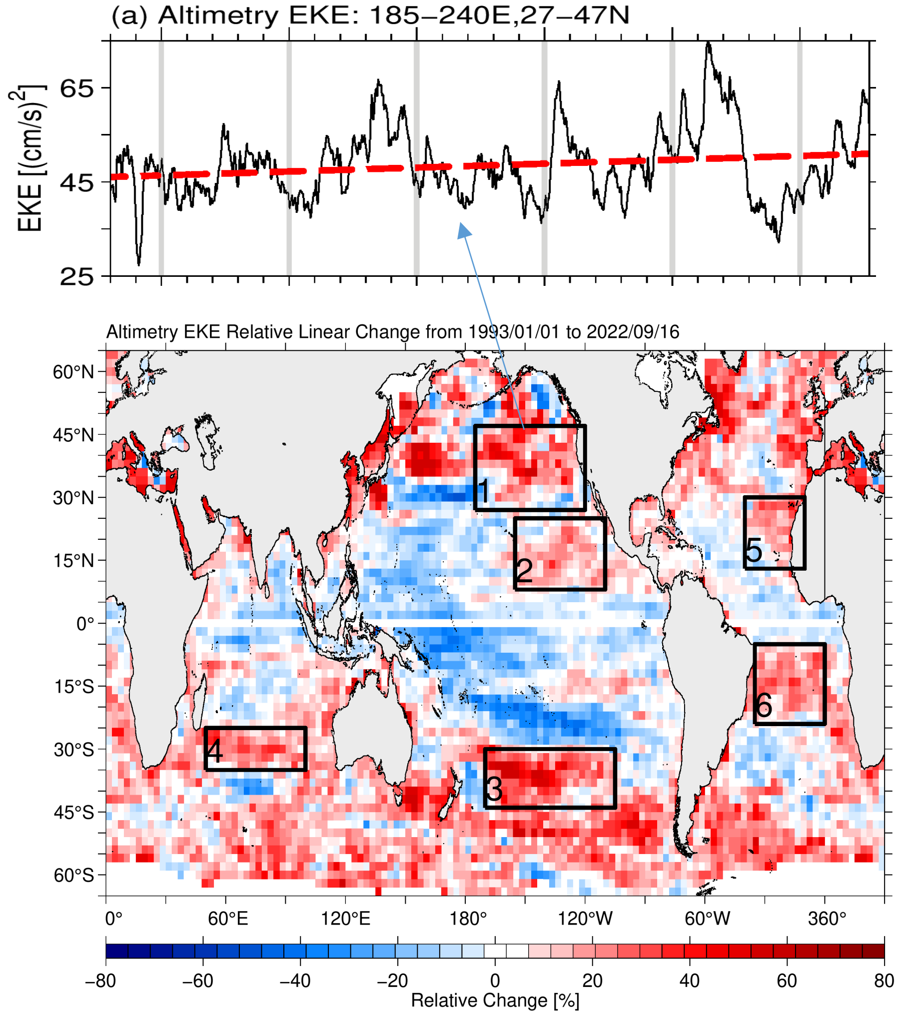



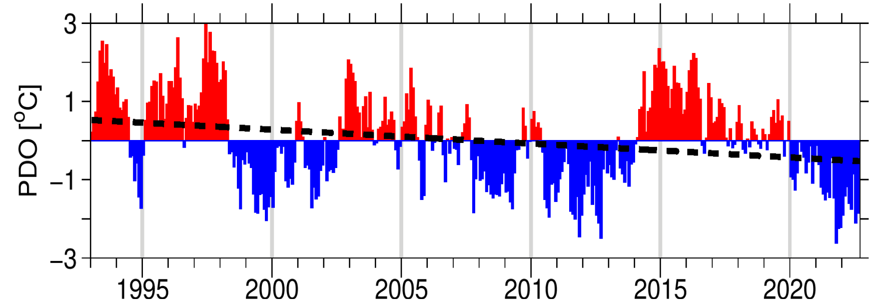




- Interior South Indian & Pacific Oceans reveal dominance of coherent seasonal-to-interannual modulations

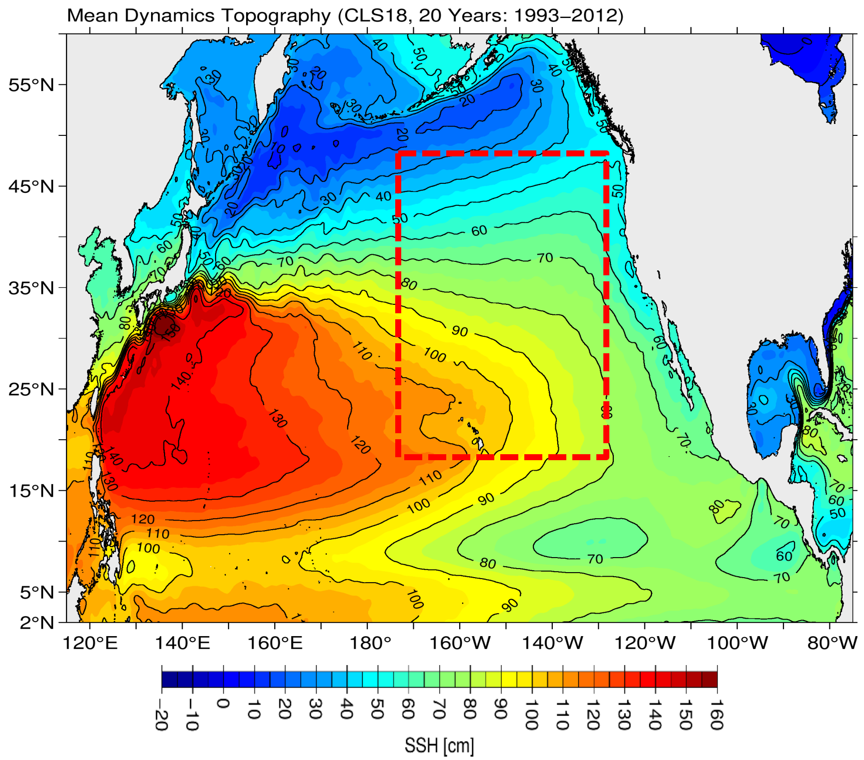



- Higher-frequency signals appear dominant in North & South Atlantic Oceans

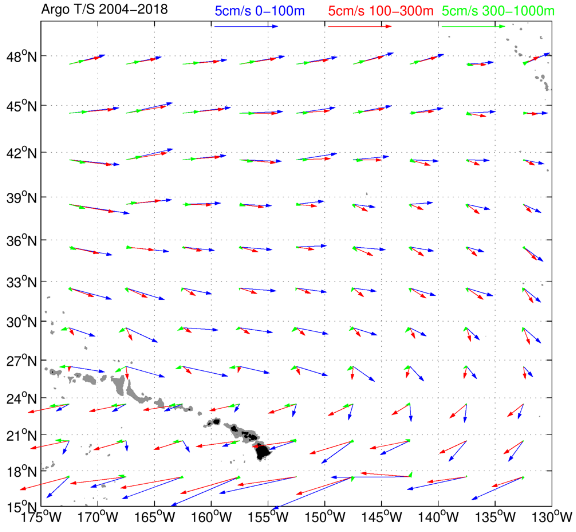



- This presentation will explore causes for the EKE trend in the NE Pacific region
- Given the low-frequency EKE signals in the region, it's natural to seek connection with the PDO-related wind forcing
- A negative PDO index trend exists, although there is little concurrent interannual-to-decadal EKE variability that matches the PDO forcing

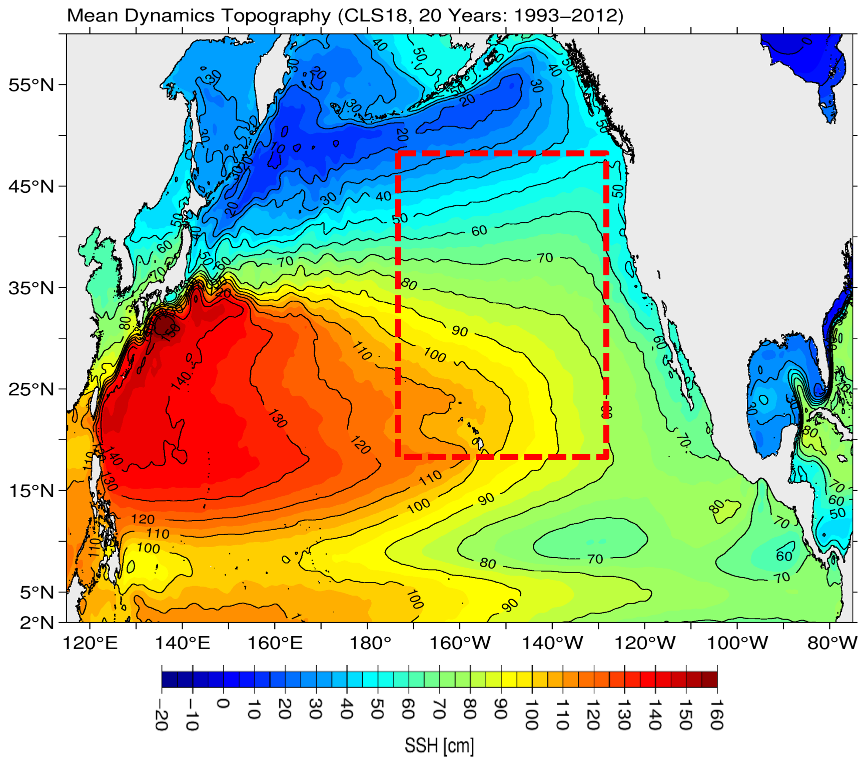



Upper ocean velocities based on 2004-2018 Argo data




**Question:** What drives the interannual & longer timescale EKE variability in the NE Pacific Ocean?

- Located in the NE quadrant of the wind-driven subtropical gyre, the upper ocean flows veer clockwise with increasing depth → β spiral structure
- Although the time-mean circulation in the region is weak, O(a few cm/s), the β spiraled flow system is baroclinically unstable, especially for the meridional components

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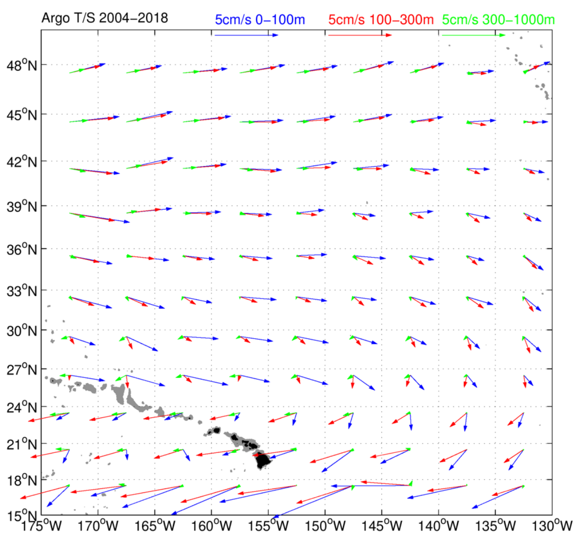



- Regional EKE growth can be quantified by stability analysis using a 3½-layer QG model by specifying observed upper ocean velocity & stratification data:

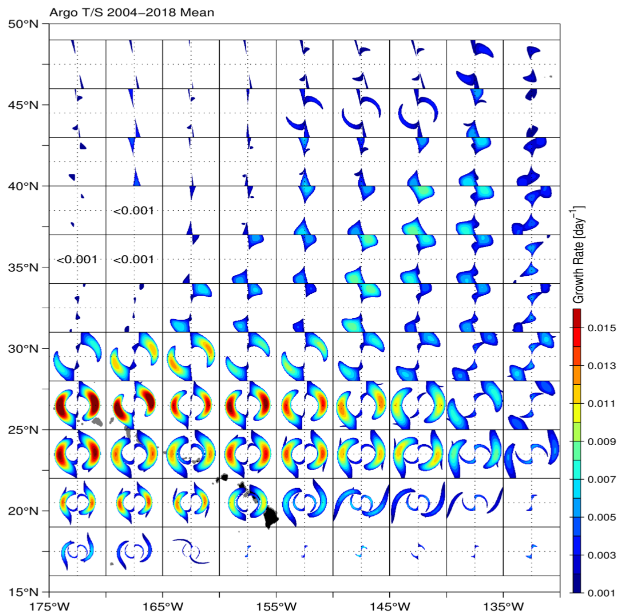
$$\left(\frac{\partial}{\partial t} + \vec{U}_n \cdot \nabla\right) q_n + J(\phi_n, \Pi_n) = 0, \quad (n = 1, 2, 3)$$

where $q_n$ is perturbation PV, $\Pi_n$ mean PV, $\phi_n$ perturbation streamfunction, &

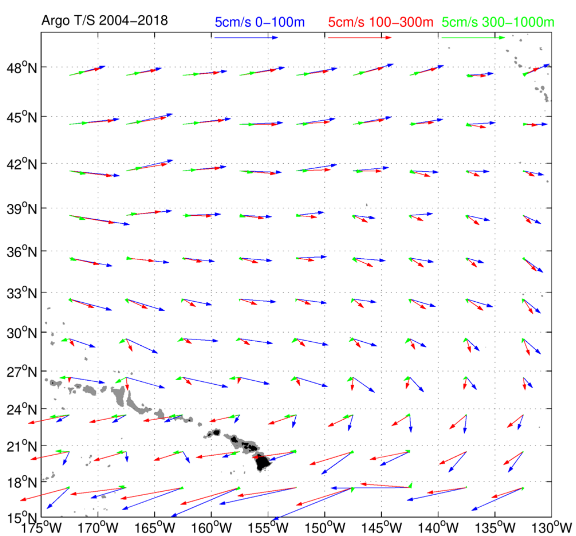
$$\begin{cases} q_1 = \nabla^2\phi_1 + F_1(\phi_2 - \phi_1) \\ q_2 = \nabla^2\phi_2 + F_2(\phi_1 - \phi_2) + G_2(\phi_3 - \phi_2) \\ q_3 = \nabla^2\phi_3 + G_3[\phi_2 - (1+\gamma)\phi_3], \end{cases}$$

$$g'_{ji} = g\frac{(\rho_j - \rho_i)}{\rho_0}, \; F_i = \frac{f_0^2}{g'_{21}H_i} \;\; G_i = \frac{f_0^2}{g'_{32}H_i} \;\; \gamma = \frac{\rho_4 - \rho_3}{\rho_3 - \rho_2},$$

Unstable wave growth rate $\omega_i$ as a function of $k$ & $l$ under 2004-2022 mean condition




Upper ocean velocities based on 2004-2022 Argo data

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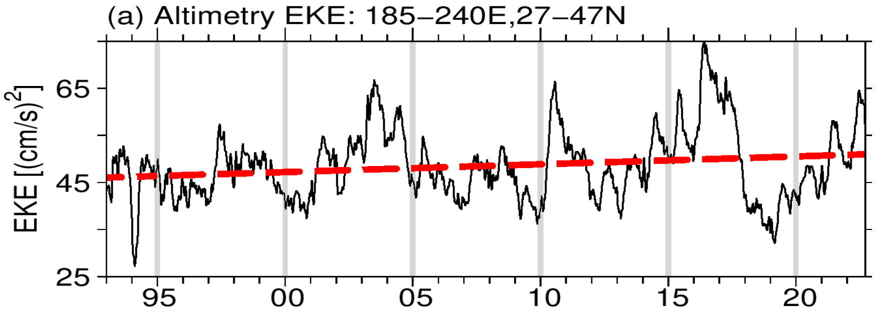
- Assume normal-mode solutions for $\phi_n$ :

$$\phi_n = A_n e^{i(k \cdot x + l \cdot y - \omega \cdot t)},$$

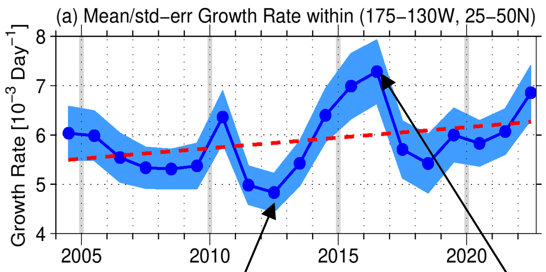
growth rate $\omega_i$ of unstable waves can be found by solving an eigen-value problem

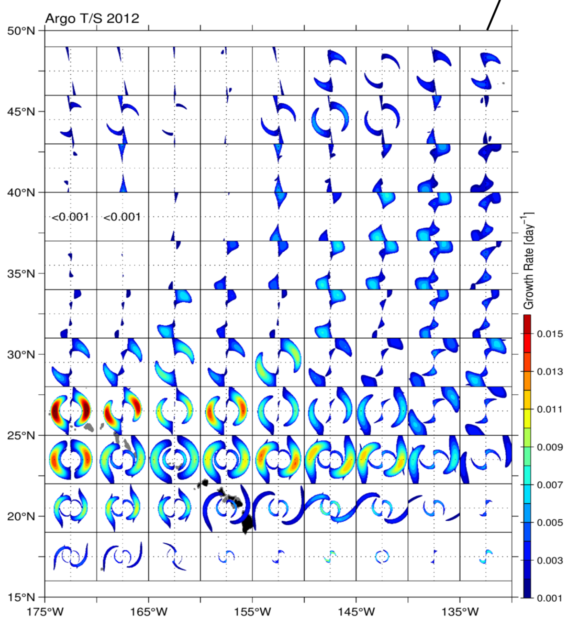


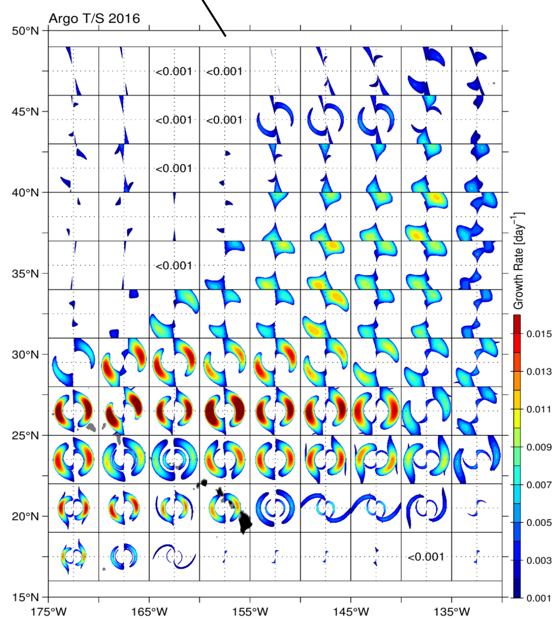

- Using yearly-varying upper ocean velocity & stratification data from Argo, we evaluated the growth rate variations in the NE Pacific

→ Favorable correspondence exists between the area-averaged growth rate & altimeter-measured EKE changes

Growth rate averaged in NE Pacific



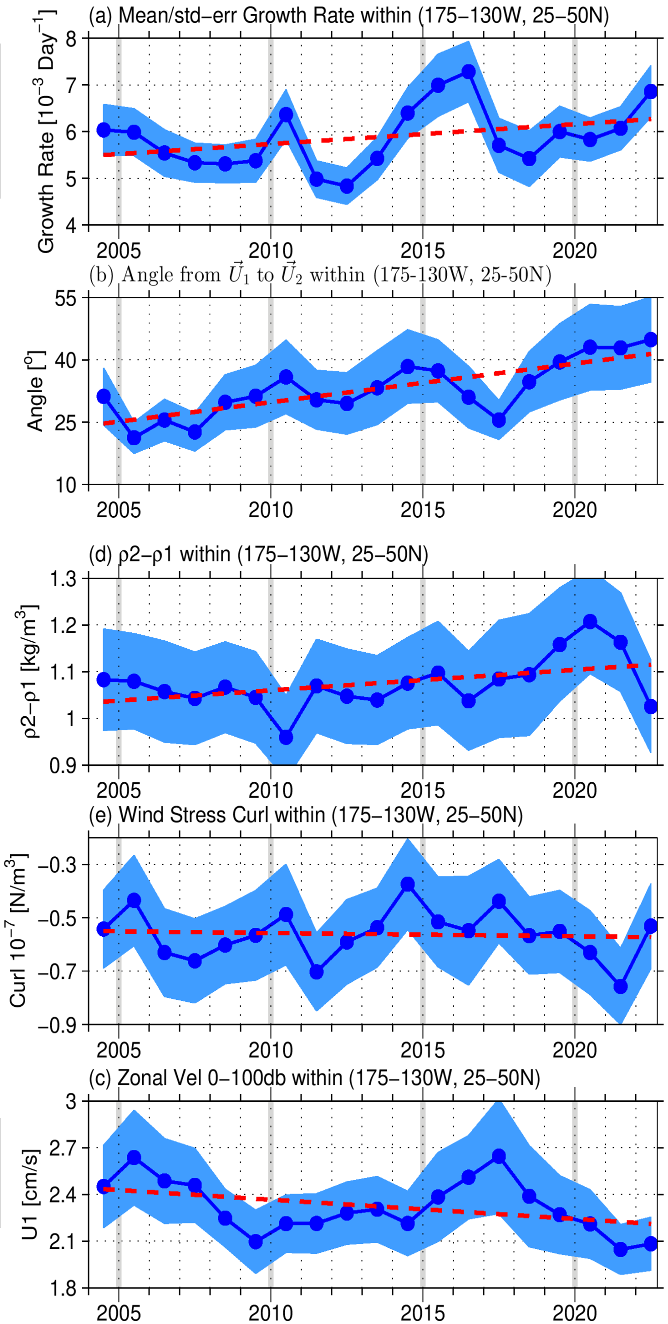
growth rate averaged in NE Pacific

angle θ between $\boldsymbol{U}_1$ & $\boldsymbol{U}_2$

stratification $\rho_2 - \rho_1$

wind stress curl

magnitude of $U_1$




- Sensitivity study reveals the increased instability is largely due to the increase in angle θ between surface & subsurface flow vectors in the past 2 decades

**Question:** What caused the angle in the upper ocean velocity field to increase during the past 2 decades?

- Dynamically, θ change with depth is given by

$$\frac{\partial \theta}{\partial z} = \frac{gw}{fU^2}\frac{\partial \rho}{\partial z}$$

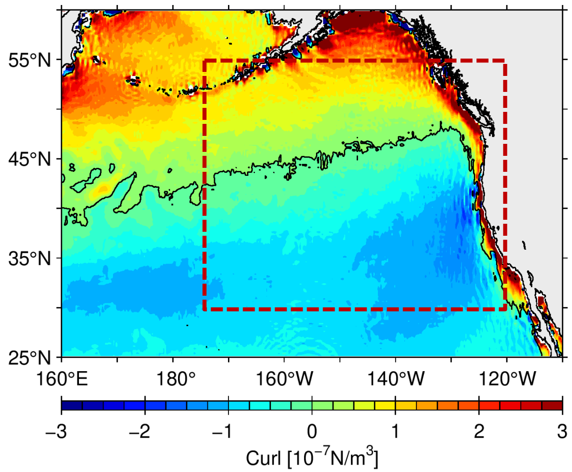
where $w$ is vertical velocity (~ $w_{Ek}$ < 0 in NE Pacific), & $U$ is flow speed

- In past 2 decades, amplitudes of $w$ & $\partial \rho/\partial z$ increased while that of $U$ decreased

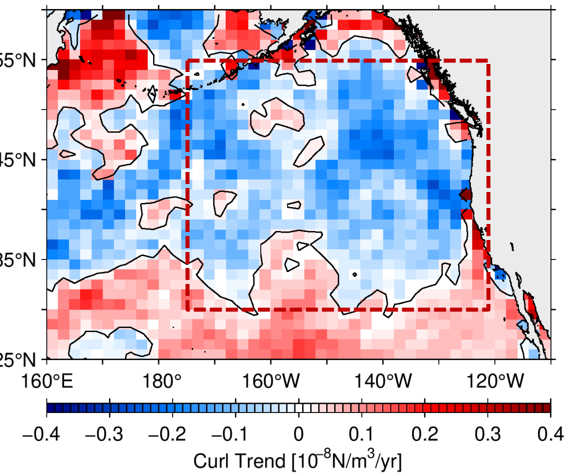
→ all of which contributed to the increase in $\partial \theta/\partial z$, hence the regional instability

- Increase in $\partial \rho/\partial z$ is related to the upper ocean warming

ERA5 wind stress curl climatology




ERA5 wind stress curl trend

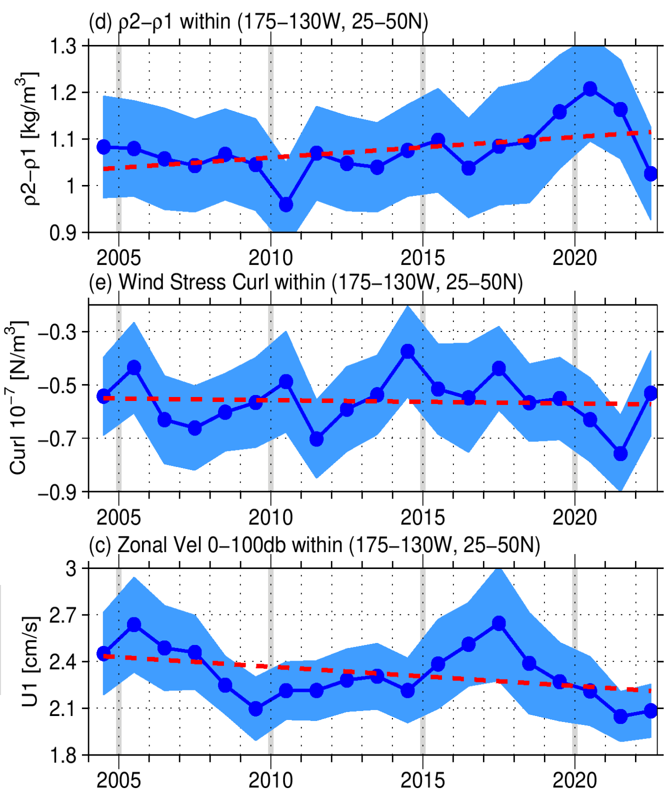



- Increase in $|w|$ is related to the PDO phase transition from positive to negative (i.e., weakening of the Aleutian Low)

stratification $\rho_2 - \rho_1$

wind stress curl

magnitude of $U_1$



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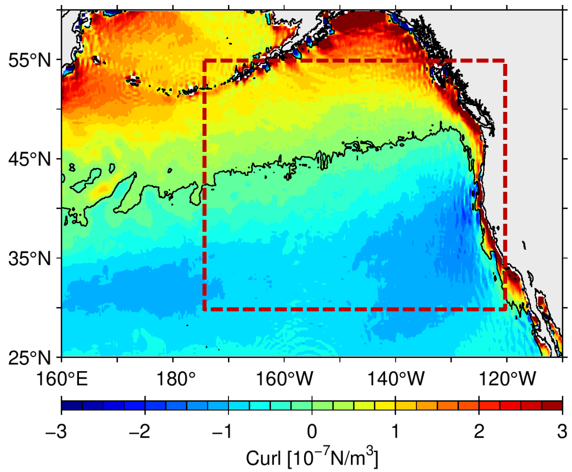


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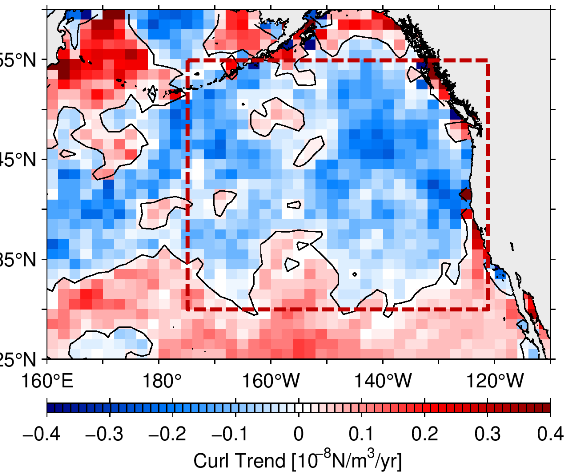
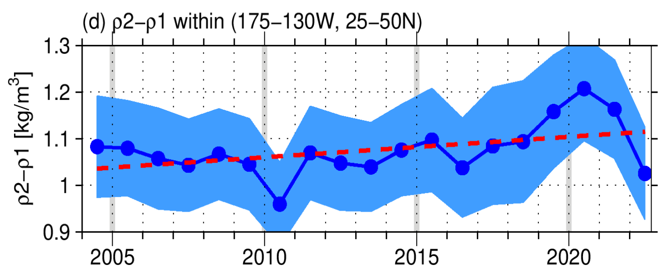


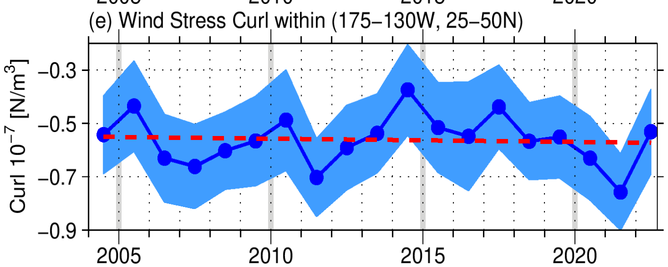

- Increase in $|w|$ is related to the PDO phase transition from positive to negative (i.e., the weakening of the Aleutian Low)

**Question:** Given the increase in negative wind stress curl (or Ekman pumping), why did the upper ocean velocity decrease?

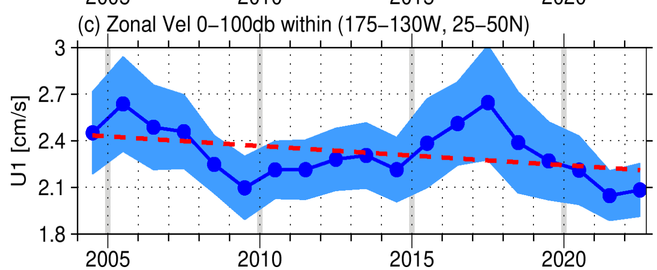
stratification
$\rho_2 - \rho_1$



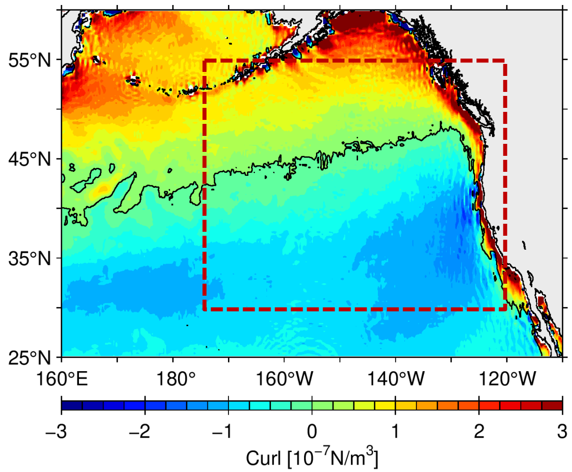

wind
stress curl



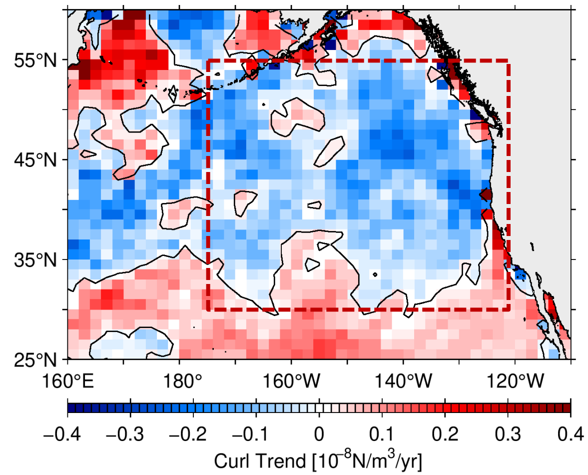

magnitude of $U_1$



ERA5 wind stress curl climatology




ERA5 wind stress curl trend

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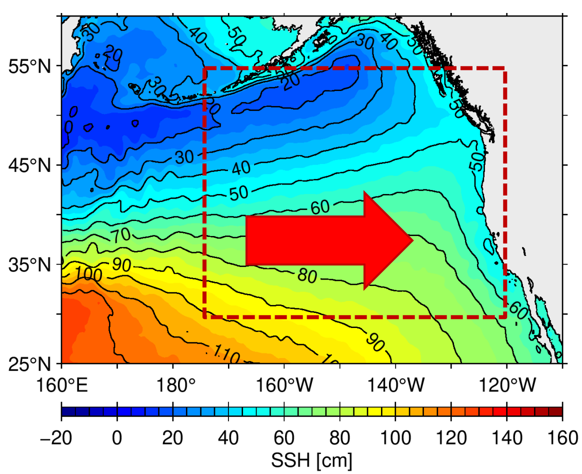
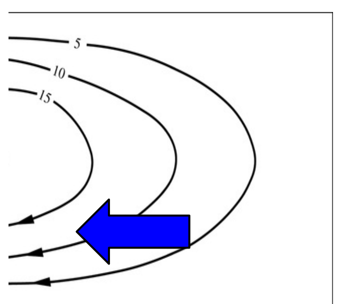
CLS18 mean dynamic topography




- The increasing negative wind stress curl forcing generates a regional clockwise anomalous circulation

- Its location is such that the anomalous-wind-induced westward zonal flow would oppose the climatological eastward zonal flow in the NE quadrant of the subtropical gyre

## Takeaway Message

- In many of the weak EKE interior world oceans, there exist overall increasing EKE trends over the past 3 decades

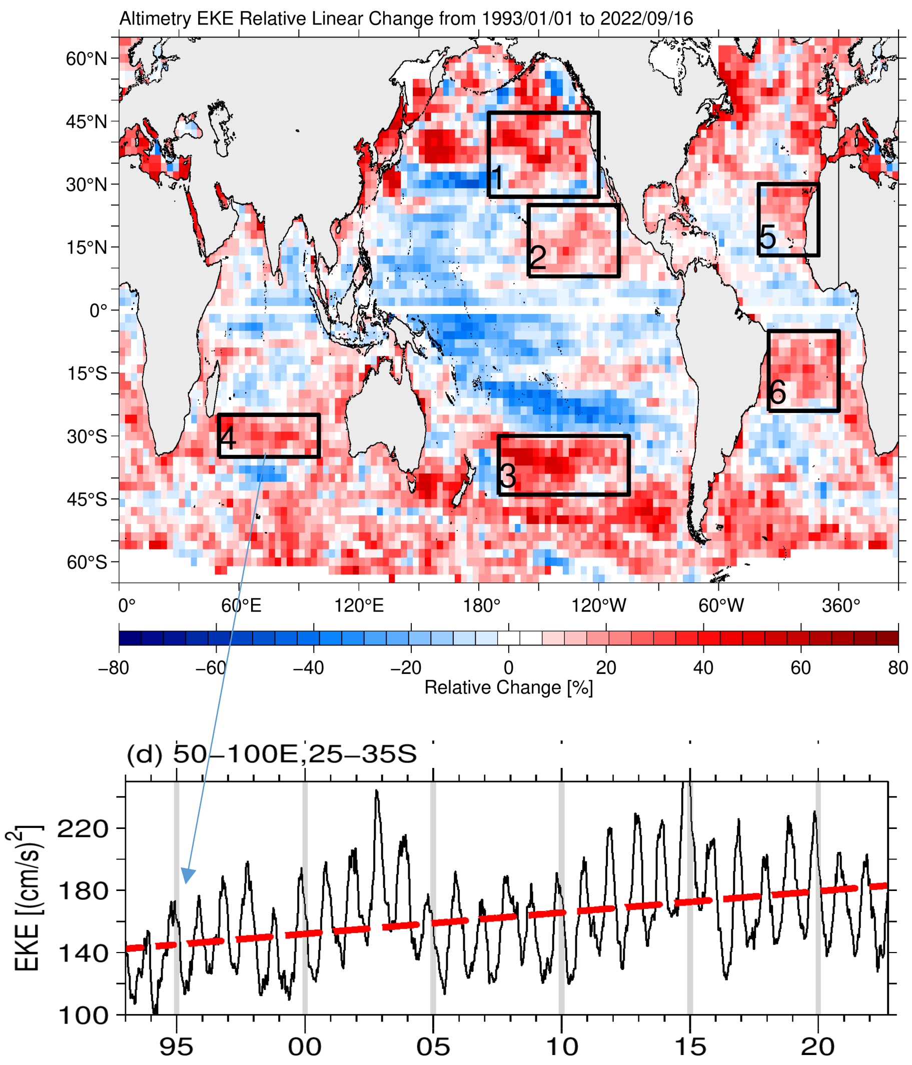
- In the wind-driven subtropical gyre of the NE Pacific, the increasing EKE trend is caused by enhanced baroclinic instability related to ***broadened*** β-spiraled upper ocean velocity structure

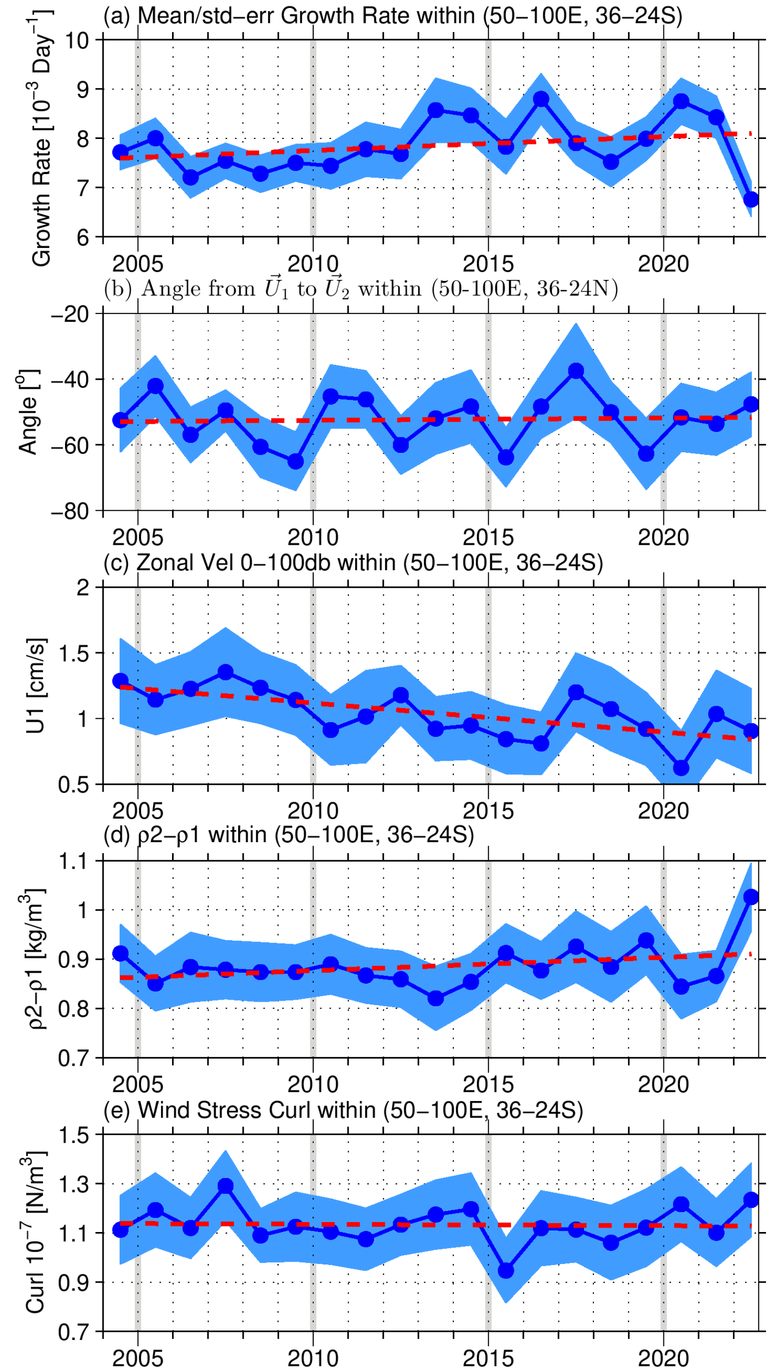
- This broadening in β-spiraled velocity structure is contributed by 3 concurrent processes:

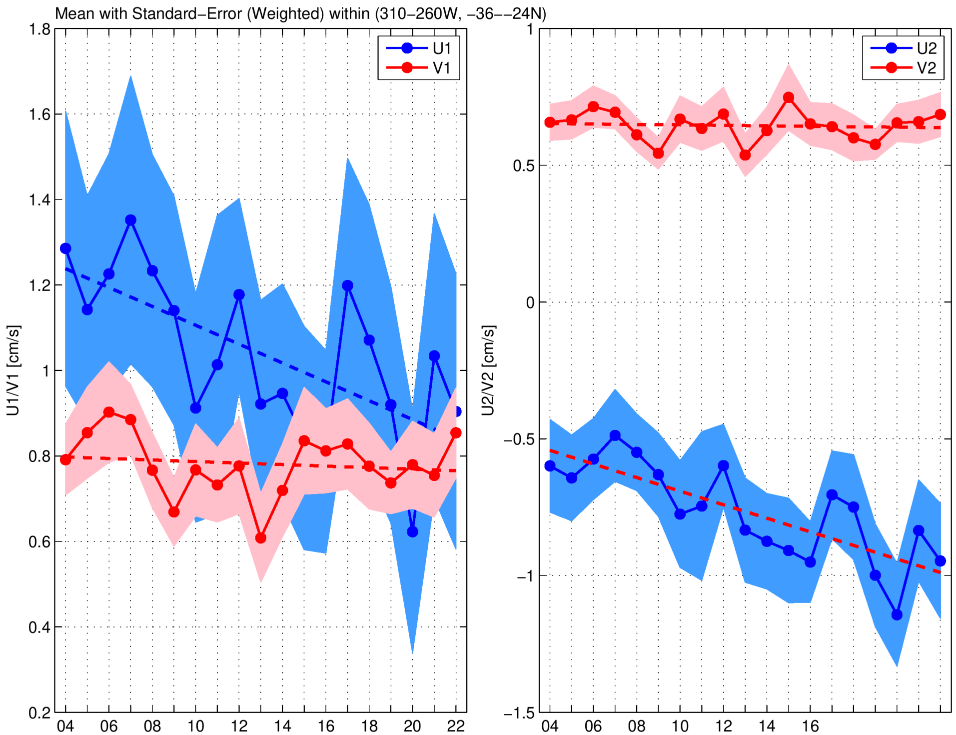
  1. Enhanced upper ocean stratification resulting from ocean warming,
  2. Increased Ekman pumping relating to the positive-to-negative phase shift of the PDO forcing, &
  3. Spin-up of an anomalous regional Sverdrup circulation that weakens the zonal flow in the NE Pacific subtropical gyre

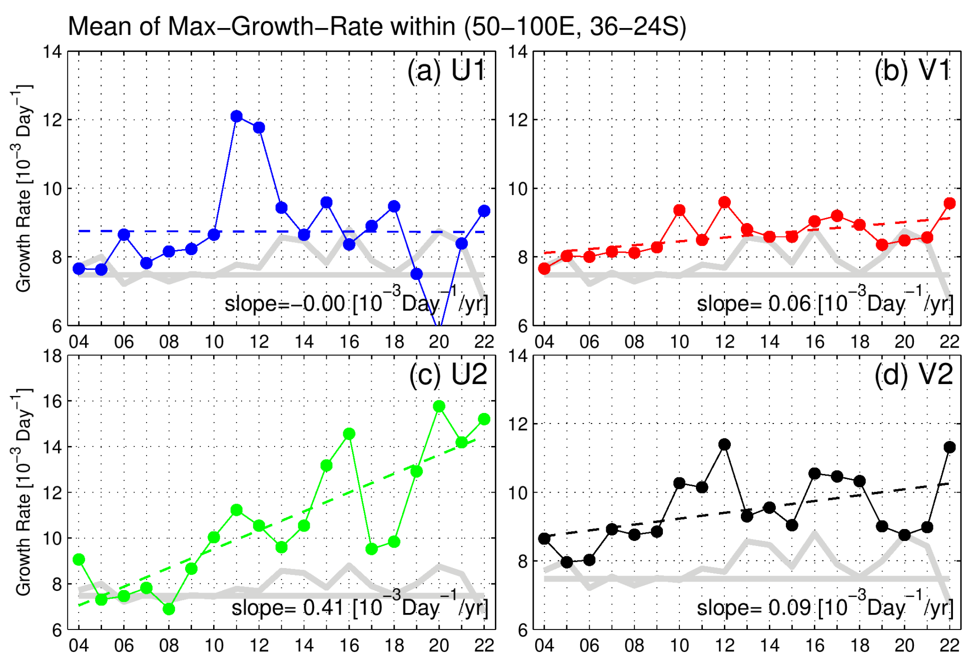
- Our preliminary analyses indicate that the increasing EKE trends have different governing dynamics in different oceanic regions

- Slight angle increase, amplitude of $w$ constant, $\partial\rho/\partial z$ increases & $U$ decreases

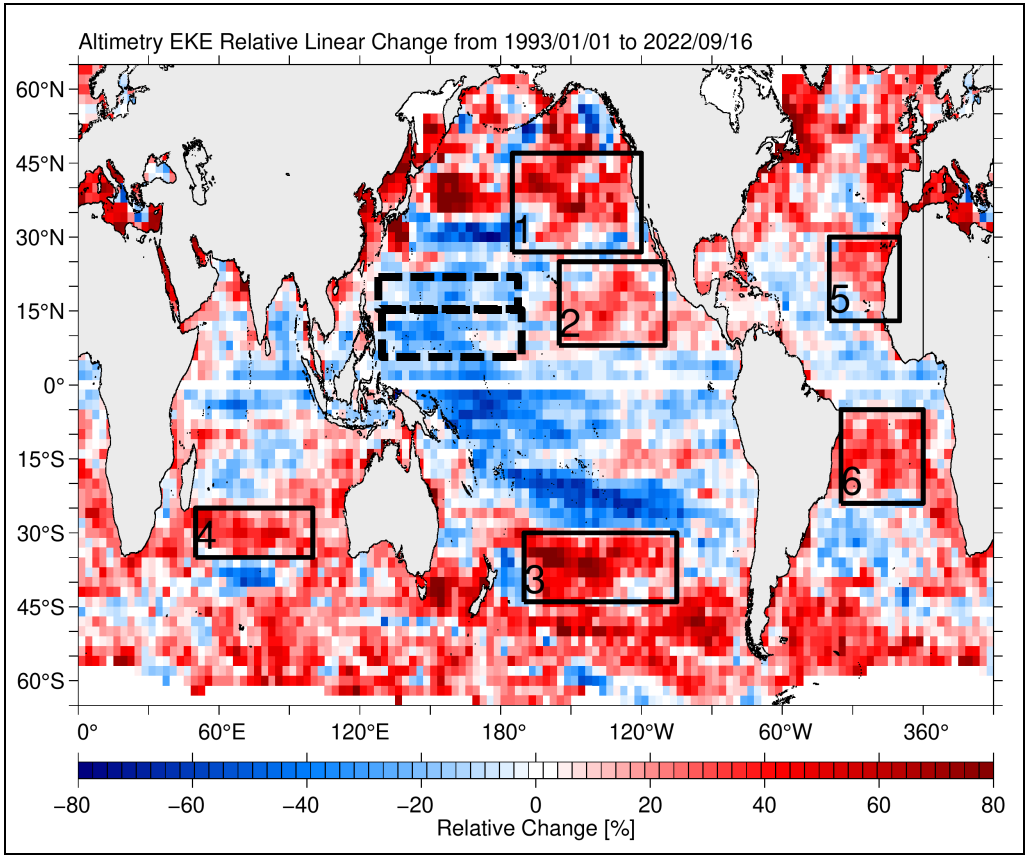


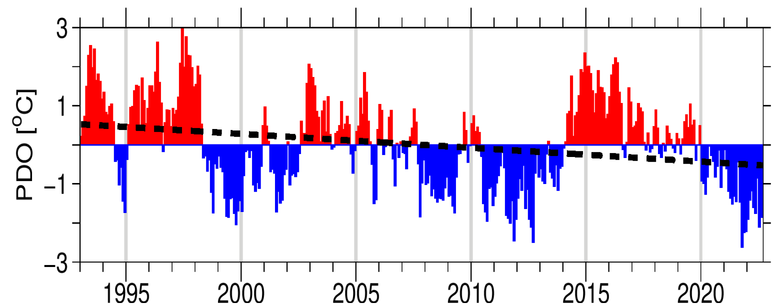



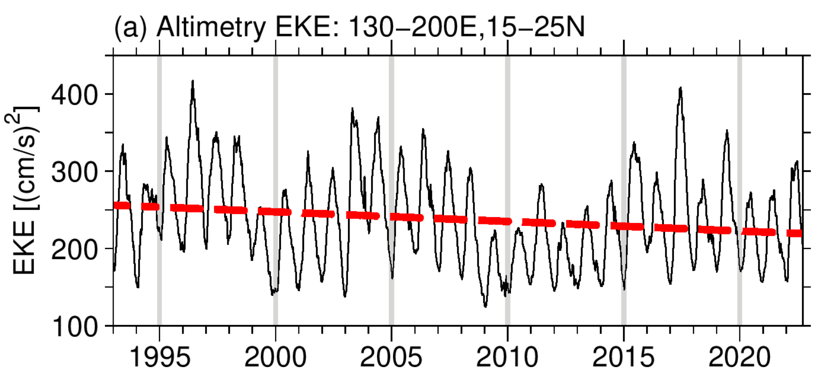


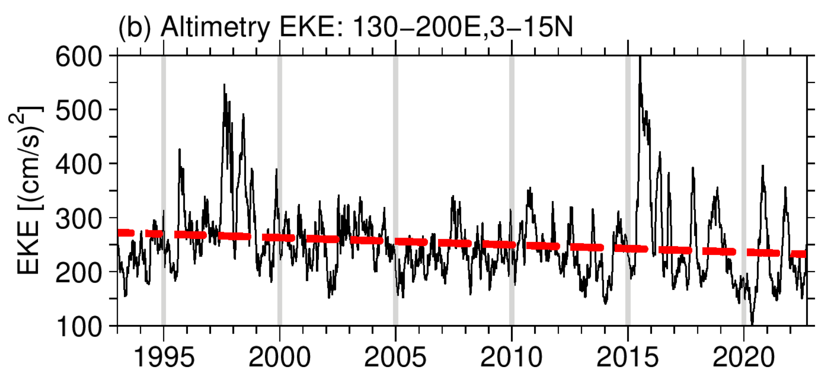



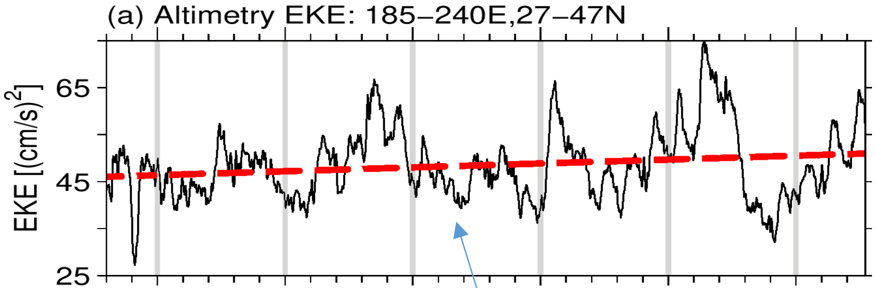

2022/10/19 /home/xray/schen/FLEAT2022/instability_region4/testing_UVR

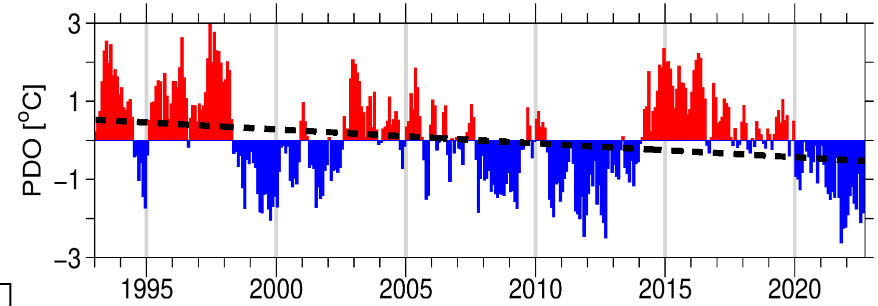

Altimetry EKE Relative Linear Change from 1993/01/01 to 2022/09/16
60°N
45°N
30°N
15°N
0°
15°S
30°S
45°S
60°S
0°
60°E
120°E
180°
120°W
60°W
360°
1
2
3
4
5
6
−80
−60
−40
−20
0
20
40
60
80
Relative Change [%]

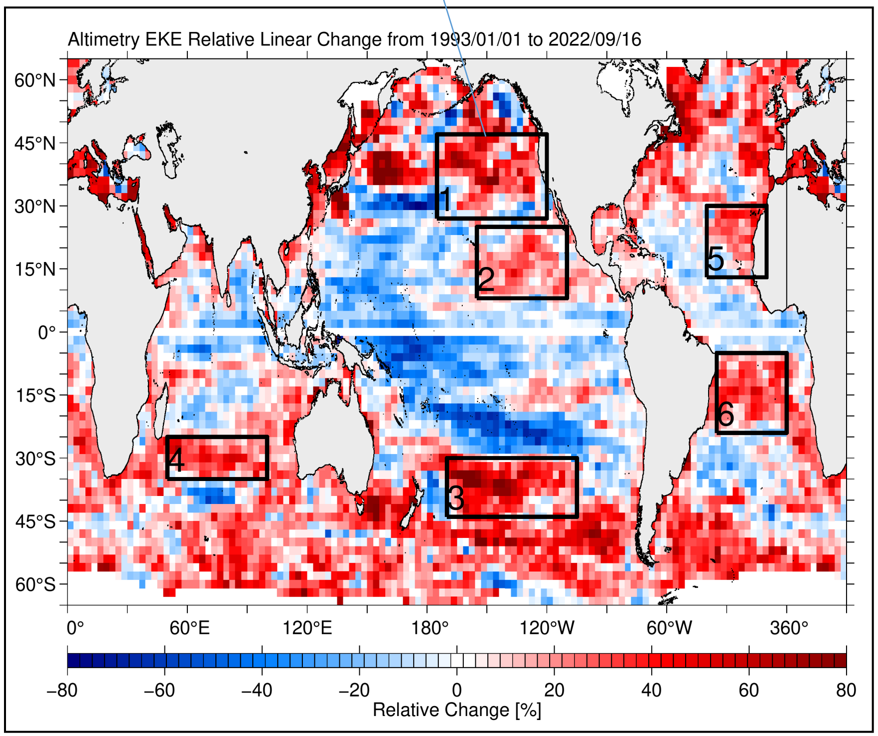

PDO [°C]
3
1
−1
−3
1995
2000
2005
2010
2015
2020

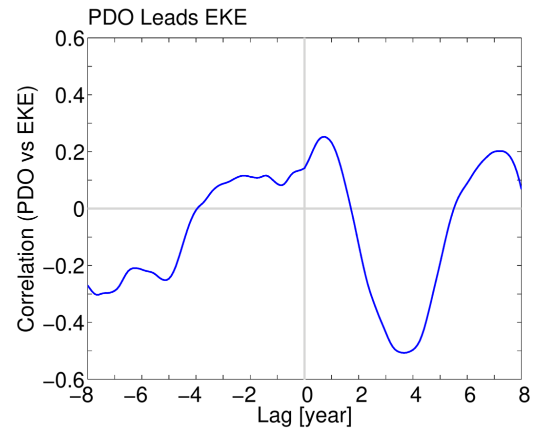

(a) Altimetry EKE: 130−200E,15−25N
EKE [(cm/s)²]
400
300
200
100
1995
2000
2005
2010
2015
2020


(b) Altimetry EKE: 130−200E,3−15N
EKE [(cm/s)²]
600
500
400
300
200
100
1995
2000
2005
2010
2015
2020



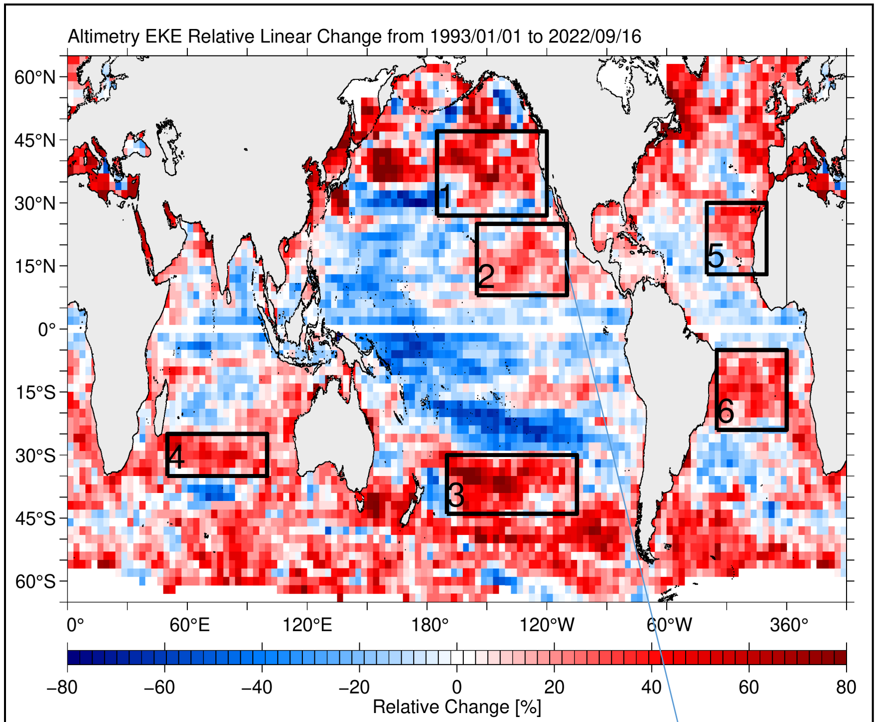



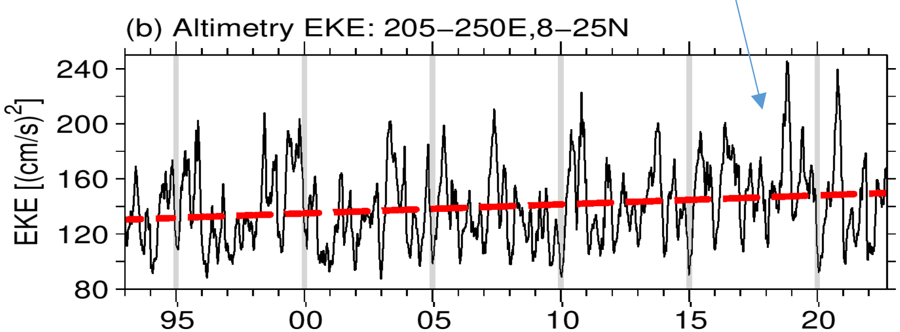



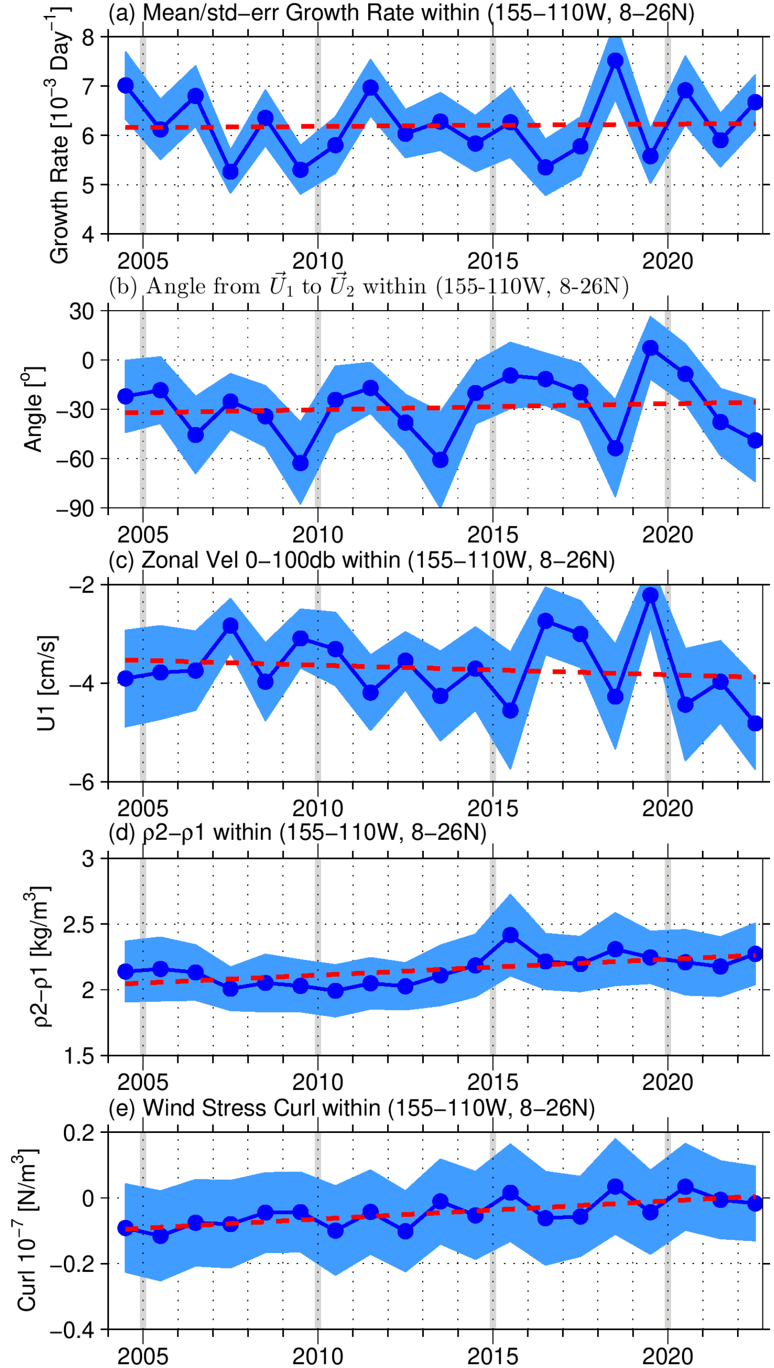

- Although PDO index shows a negative trend, the interannual-decadal PDO variability doesn't match the EKE signals.

- Given the low-frequency EKE signals in the NE Pacific, it's natural to seek connection with the PDO wind forcing

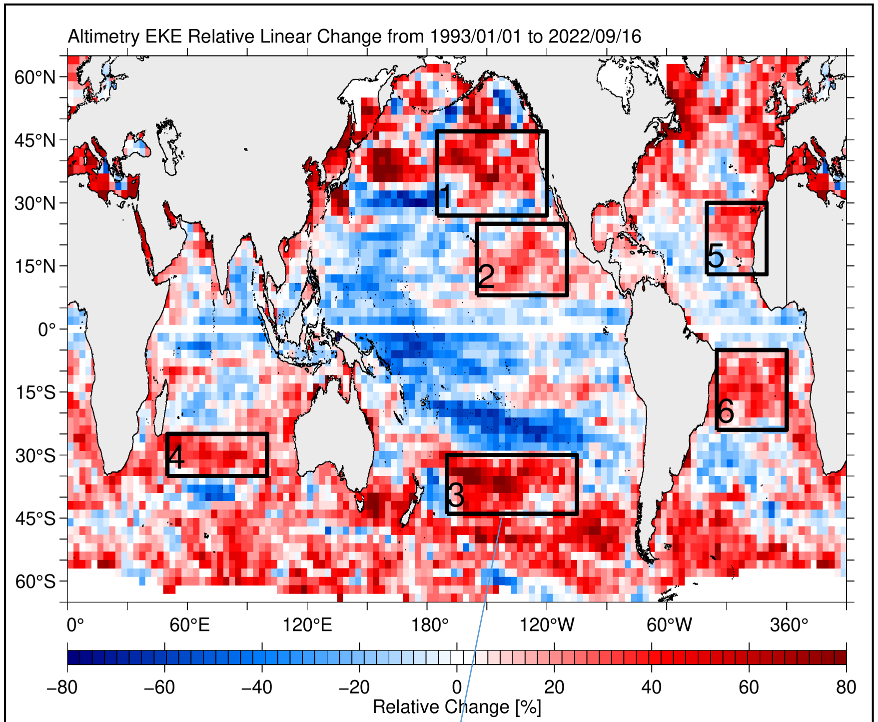
- Little angle change, amplitude of $w$ decreases and $\partial\rho/\partial z$ & $U$ increases, cancelling out effects on $\partial\theta/\partial z$

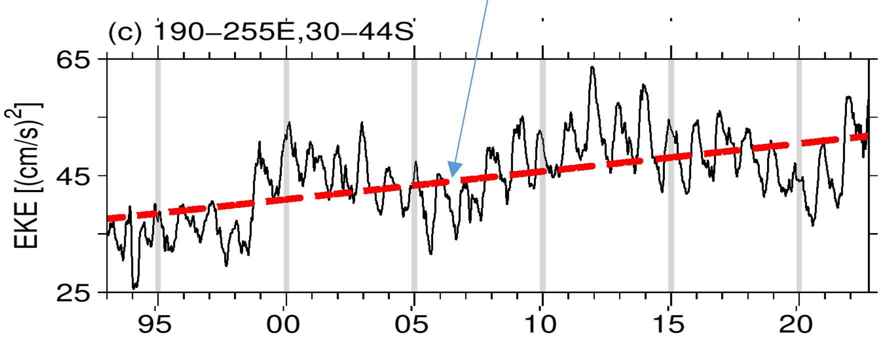


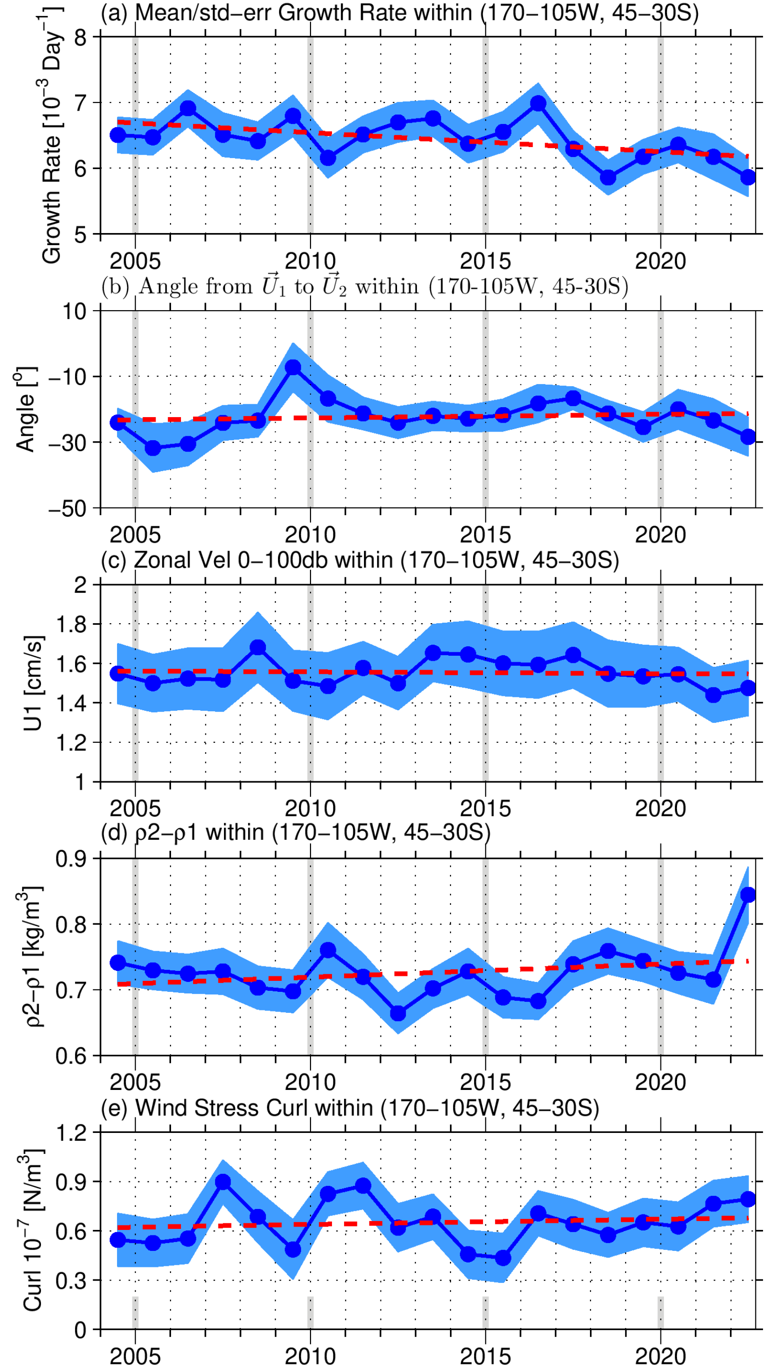



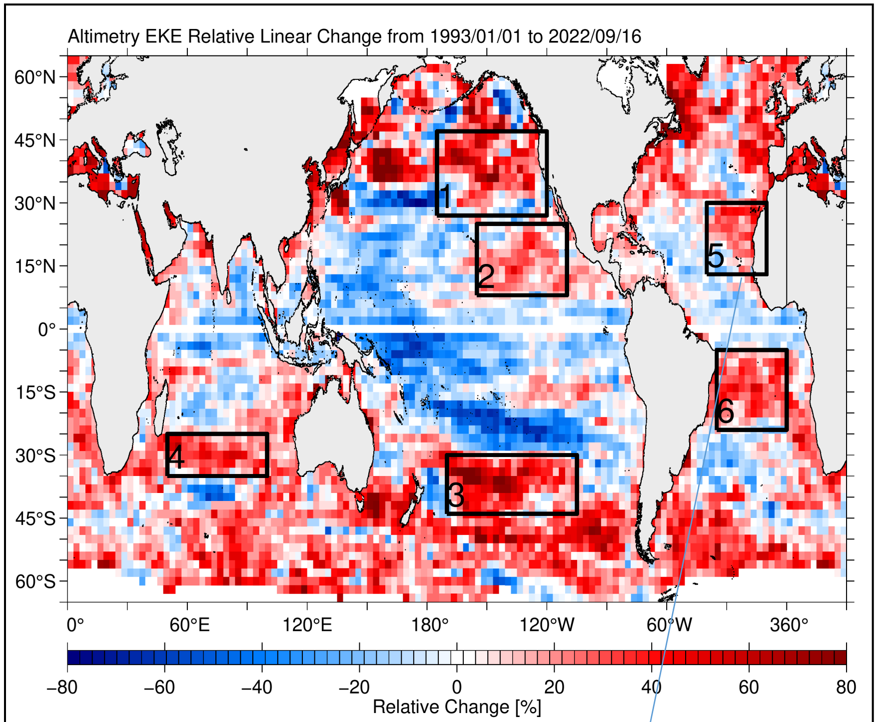
- Little angle change, *w* & *U* largely constant & *∂ρ/∂z* increase

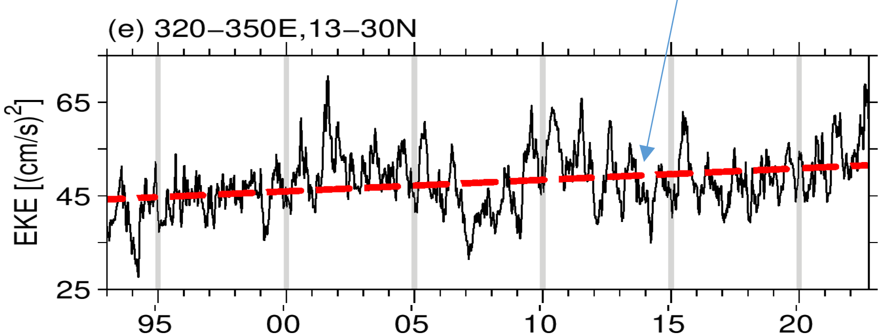


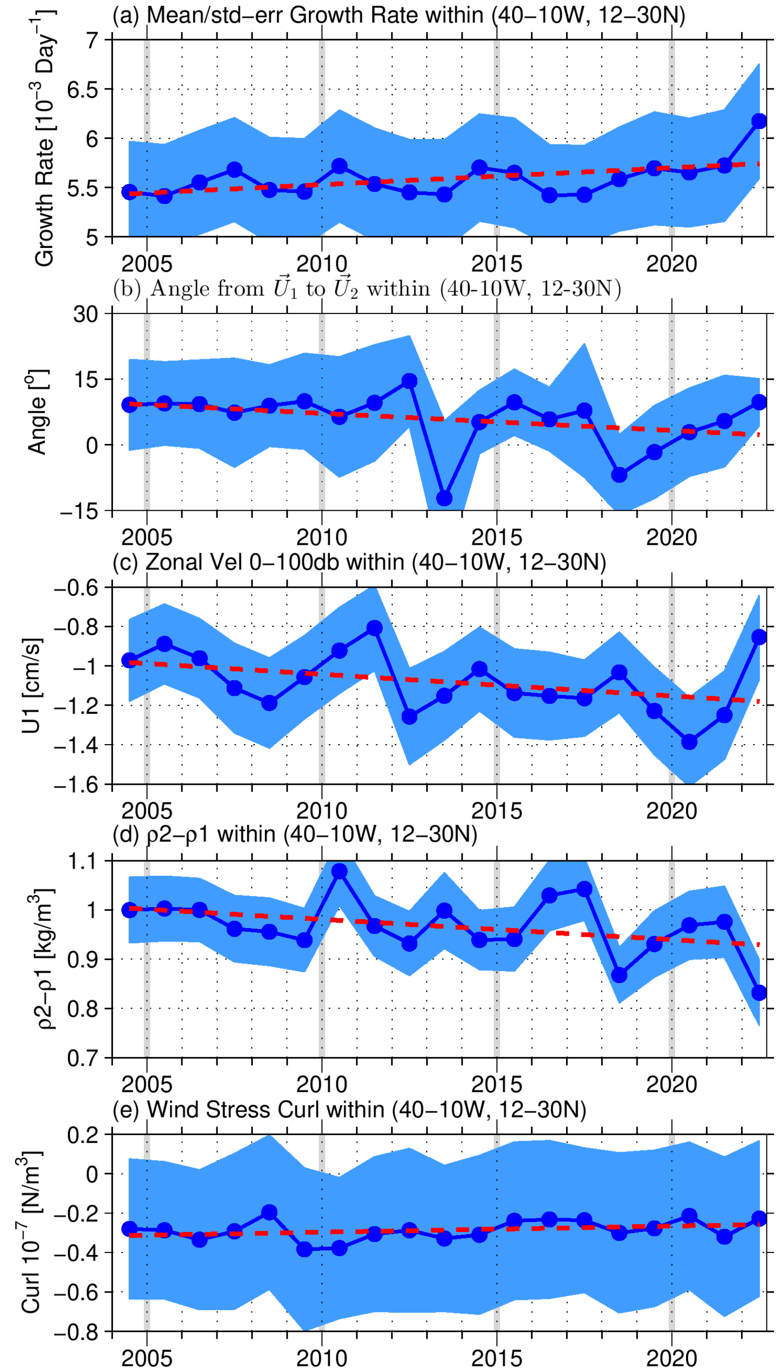



- Angle decreases, amplitude of *w* constant, *∂ρ/∂z* decreases & *U* increases



- Angle increases, amplitude of *w* decreases, *∂ρ/∂z* increases & *U* increases