Interannual Variability of the North Pacific Subtropical Countercurrent and its Associated Mesoscale Eddy Field

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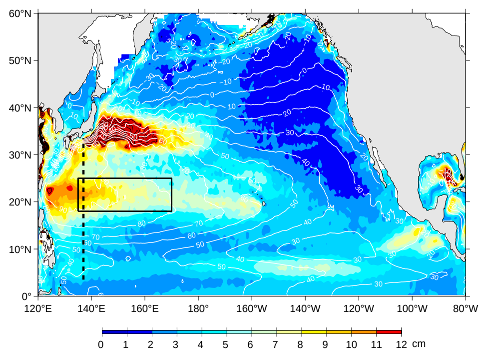
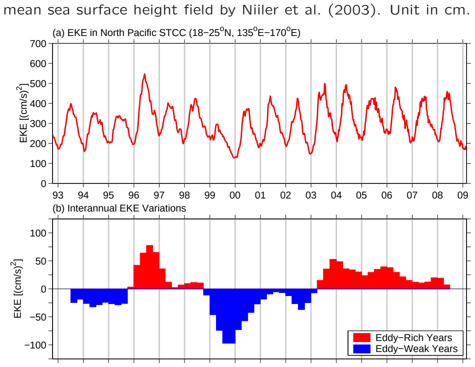
ABSTRACT

Interannual changes in the mesoscale eddy field along the Subtropical Countercurrent (STCC) band of 18°–25°N in the western North Pacific Ocean are investigated with 16 years of satellite altimeter data. Enhanced eddy activities were observed in 1996–1998 and 2003–2008, whereas the eddy activities were below average in 1993–1995 and 1999–2002. Analysis of repeat hydrographic data along 137°E reveals that the vertical shear between the surface eastward-flowing STCC and the subsurface westward-flowing North Equatorial Current (NEC) was larger in the eddy-rich years than in the eddy-weak years. By adopting a $2^1/_2$-layer reduced-gravity model, we show that the increased eddy kinetic energy level in 1996–1998 and 2003–2008 is due to enhanced baroclinic instability resulting from the larger vertical shear in the STCC-NEC's background flow. The cause for the STCC-NEC's interannually-varying vertical shear can be sought in the forcing by surface Ekman temperature gradient convergence within the STCC band. Rather than El Niño–Southern Oscillation signals as previously hypothesized, interannual changes in this Ekman forcing field, and hence the STCC-NEC's vertical shear, are more related to the *negative* Western Pacific index signals.

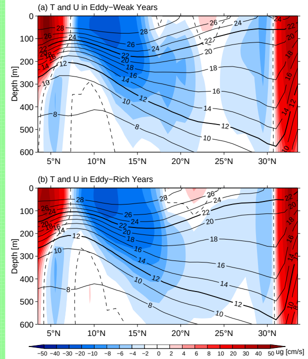
1. Interannual changes in STCC's eddy field and in mean STCC-NEC

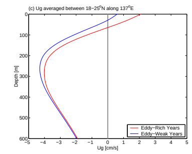


The above figure shows the root-mean-squared sea surface height variability in the North Pacific based on high-pass filtered satellite altimeter data from October 1992 to April 2009. White contours denote the mean sea surface height field by Niiler et al. (2003). Unit in cm.



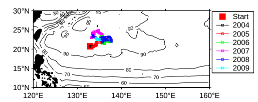
(a) Eddy kinetic energy time series in the North Pacific Subtropical Countercurrent (STCC) band of 18°–25°N and 135°–170°E. (b) Interannual changes of the EKE time series after a one-year running mean is applied to the original, weekly time series shown in (a); the time series is presented seasonally.



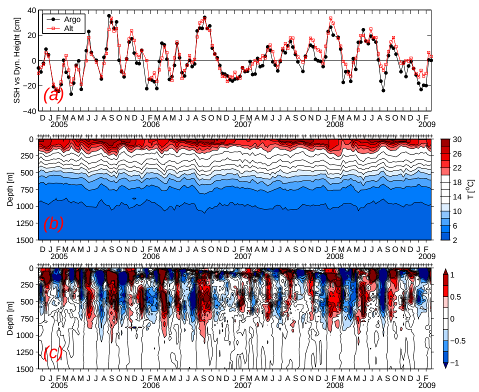


(a) Latitude-depth section of temperature (solid contours) and zonal geostrophic velocity (colored shading) along 137°E from the JMA repeat hydrographic surveys during the STCC's eddy-weak years of 1993–1995 and 1999–2002. The geostrophic velocity is referenced to 1,000 dbar and dashed lines denote the zero velocity contours. (b) Same as (a) except for during the STCC's eddy-rich years of 1996–1998 and 2003–2008. (c) Zonal geostrophic velocity profiles averaged in the 18°–25°N band along 137°E in the eddy-rich versus eddy-weak years.

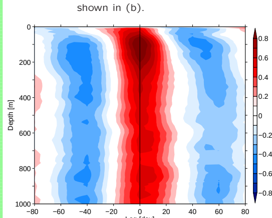
2. Vertical structures from Argo profiles



Trajectories of Argo profiling float 2900432. Contours are the mean SSH field from Niiler et al. (2003) with unit in cm.



(a) Time series of the surface dynamic height anomalies (0/1500 dbar) calculated from the profiling float T–S data vs the SSH anomalies measured by satellite altimeters. (b) Vertical temperature profiles derived from the Argo float 2900432. (c) Temperature anomaly profiles after a high-pass filter with a 180-day cutoff period is applied to the time series shown in (b).



Lagged correlation coefficients between the temperature anomalies at 100 m and those at other depths. A positive lag here denotes the lead by the 100 m-depth temperature anomalies.

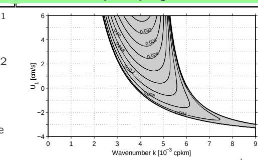
Notice that with the mesoscale eddies propagating westward, a positive (negative) time lag is equivalent to a positive (negative) longitudinal lag in space. Therefore, the center of the temperature anomalies exhibits an eastward phase tilt with *increasing* depth. This phase tilt is against the vertical shear of the STCC-NEC system, which tilts eastward with *decreasing* depth. Dynamically, this implies that the observed mesoscale eddies are able to grow at the expense of the vertically-sheared STCC-NEC system, or that the background STCC-NEC system is *baroclinically* unstable.

3. Baroclinic instability analysis for interannually-varying STCC-NEC

Following Qiu (1999), we consider the $2^1/_2$-layer QG model:

$$\left(\frac{\partial}{\partial t}+U_n\frac{\partial}{\partial x}\right)q_n+\frac{\partial\Pi_n}{\partial y}\frac{\partial\phi_n}{\partial x}=0,\quad n=1,2$$

where $\Pi_1=\beta+\frac{f_0^2}{g'H_1}(U_1-U_2)$ and $\Pi_2=\beta-\frac{f_0^2}{g'H_1}(U_1-U_2-\frac{\rho_2-\rho_1}{\rho_3-\rho_2}U_2)$. As shown in the figure on the right side, the vertically-sheared STCC-NEC system in the 18°–25° band of the western North Pacific Ocean is *always* baroclinically unstable since U_1 is positive and U_2 is less than $-1\,\mathrm{cm\,s^{-1}}$. While always being unstable, the magnitude of the instability is sensitive to the background vertical shear between the surface STCC and subsurface NEC. When the surface STCC is strengthened due to the convergent Ekman temperature flux forcing as shown in the next section, the enhanced baroclinic instability of the STCC-NEC system likely resulted in the increased EKE level in the 18°–25° band as observed in 1996–1998 and 2003–2008.



Growth rate dependence on U_1 when U_2 is fixed at $-4.0\,\mathrm{cm\,s^{-1}}$. in the $2^1/_2$-layer STCC-NEC model. Shaded areas denote the baroclinically unstable domain. Contour units are day^{-1}.

4. Cause: atmospheric forcing

Given that the observed mean flow changes in the STCC-NEC band between the eddy-rich and eddy-weak years are largely confined to the surface 150-m layer, it makes sense to seek the cause for these changes in the regional atmospheric forcing field. Since the vertical shear in the zonal geostrophic velocity (U_g) is related to the meridional temperature (T) gradient through the thermal wind balance:

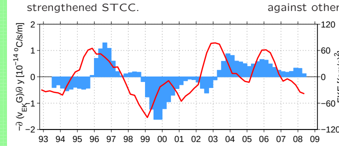
$$f\frac{\partial U_g}{\partial z}=-\alpha\frac{\partial T}{\partial y},\qquad(1)$$

investigating the international changes in the surface STCC becomes equivalent to examining the regional meridional temperature gradient changes in the surface 150-m layer. We utilize $G\equiv-\partial T/\partial y$ in place of the meridional temperature gradient. Thus defined, a positive G value indicates an enhanced surface thermocline tilt, or equivalently a strengthened STCC.

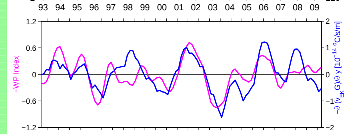
With the STCC existing in the region between the midlatitude westerlies and low-latitude trade winds, an important process that contributes to the interannual changes in G along the STCC band is the Ekman convergence forcing. Mathematically, this process can be expressed by

$$\frac{\partial G}{\partial t}\simeq-\frac{\partial}{\partial y}(v_{Ek}G),\qquad(2)$$

where $v_{Ek}=-\tau^x/\rho_o fH_o$ is the meridional Ekman velocity averaged in the surface layer. To quantify the RHS of Eq. 2, we use the monthly τ^x data from the NCEP reanalysis and the monthly Reynolds SST data. Averaged over 1993–2008 and in the band of 18°–25°N and 135°–170°E, the $-\partial(v_{Ek}G)/\partial y$ term has a positive value 1.77×10^{-14} °C m^{-1}s^{-1}, indicating that this Ekman forcing term works to maintain the thermocline tilt of STCC against other frontolysis processes.



Comparison between the interannually-varying Ekman forcing term $-\partial(v_{Ek}G)/\partial y$ (solid line) and the interannually-varying EKE time series in the STCC band (shaded bars).



Comparison between the interannually-varying *negative* Western Pacific index (solid line) and the Ekman forcing term $-\partial(v_{Ek}G)/\partial y$ (dashed line).

5. Summary

A. Enhanced eddy activities were observed in 1996–1999 and 2003–2008, whereas below-average eddy activities were detected in 1993–1995 and 2000–2002. From the JMA repeat hydrographic data, we found the vertical shear between the STCC and NEC was larger in the eddy-rich years than in the eddy-weak years.

B. Argo profiles reveals that the temperature anomalies have a vertical phase tilting upward to the west, against the vertical shear of the STCC and the NEC. This indicates that baroclinic instability is the energy source for the enhanced eddy signals. By simplifying the vertically-sheared STCC-NEC system to a $2^1/_2$-layer reduced-gravity system, we found that the observed EKE level was high in 1996–1999 and 2003–2008 was due to the more intense baroclinic instability resulting from the larger vertical shear.

C. We found that the forcing by Ekman temperature gradient convergence in the STCC band matches well with the interannually-varying EKE signals with a lead of ~9 months, and that the *negative* WP index serves as a good indicator for the interannually-varying STCC and its associated mesoscale eddy field.