Eddy−Mean Flow Interaction in the Decadally−Modulating Bimodal Kuroshio Extension System

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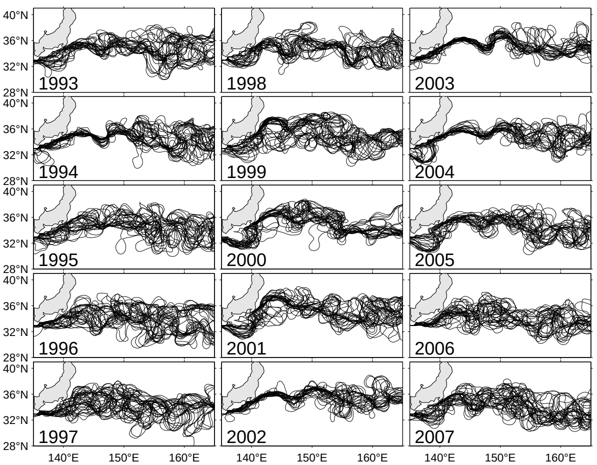
ABSTRACT

Satellite altimeter sea surface height (SSH) data of the past 15 years are used to investigate the decadal changes of the Kuroshio Extension (KE) system that oscillated between a stable and an unstable dynamic state. During the stable state of 10/1992–06/1995 and 01/2002–12/2005, the KE jet was intense and had a northerly zonal mean path and a well-defined southern recirculation gyre. During the unstable state of 07/1995–12/2001 and 01/2005–present, the KE jet had a reduced eastward transport and a more southerly flow path. Transitions between the two dynamic states are caused by the basin-scale wind stress curl forcing in the eastern North Pacific related to the Pacific decadal oscillations (PDOs). During the positive PDO phase, the intensified Aleutian Low generates negative SSH anomalies in the eastern North Pacific through Ekman divergence. As these wind-induced negative SSH anomalies propagate to the west as baroclinic Rossby waves, they weaken the zonal KE jet and shift its path southward. As its path is pushed southward (∼32°N), the deep-reaching KE jet has to ride over the shallow Shatsky Rise, generating localized disturbances that lead to their subsequent development west of the Shatsky Rise. The sequence opposite to that listed above occurs when the PDO changes to its negative phase. During the unstable state of the KE system, the enhanced eddy interaction is found to strengthen both the southern recirculation gyre and quasi-stationary meanders along the KE's upstream path.

1.Decadally-modulating KE System



Yearly paths of the Kuroshio and Kuroshio Extension defined by the 170-cm contours in the weekly SSH fields. As can be inferred from the mean SSH map, the 170-cm SSH contour is located near the $\partial h/\partial y$ maxima and serves as a good indicator for the KE jet axis. In the region between the coast of Japan and the Shatsky Rise around 158°E, it is clear that the KE paths were relatively stable in 1993–1995 and 2002–2005. In contrast, spatially variable paths dominated from 1996 to 2001 and from 2006 to present.

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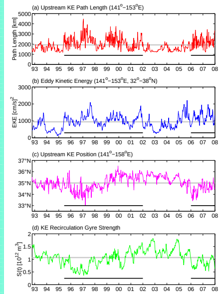


(a) Upstream KE path length integrated from 141°E to 153°E. With better temporal resolution than the yearly maps, the KE jet changed from a stable to an unstable state in mid 1995 and late 2005, and the transition from the unstable to stable state took place near the end of 2001.

(b) Eddy kinetic energy in the upstream KE region of 32°–38°N and 141°–153°E.

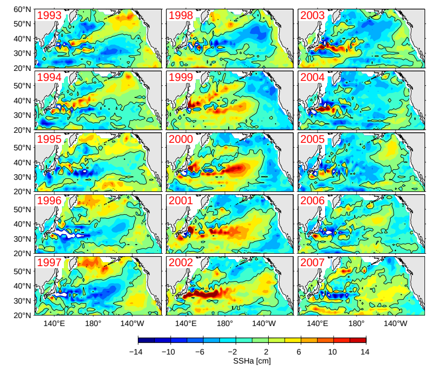
(c) Latitudinal position of the KE averaged from 141°E to 158°E. There exists a general tendency for the mean KE path to shift southward when the KE's dynamic state changes from a stable to unstable state; in addition, this southward shift tends to be followed by a gradual northward migration of the mean KE path.

(d) Strength of the KE recirculation gyre defined by

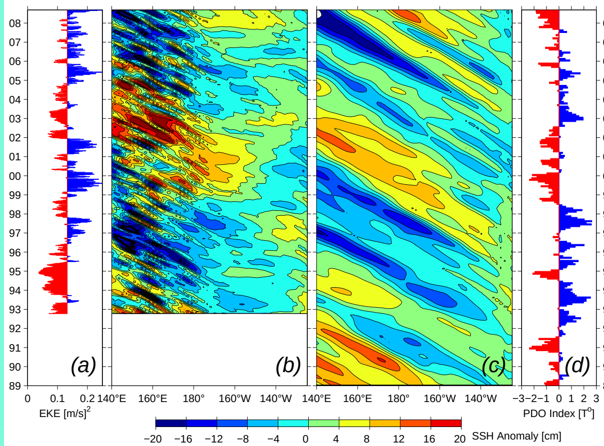
$$R(t) \equiv \int\int_A h(x,y,t)\, dx\, dy,$$

where A denotes the area south of the KE jet from 141°E to 158°E within which the SSH value exceeds 2.0 m. The time series of $S(t)$ resembles the time series of the KE's latitudinal position (panel c), indicating that the decadal strengthening/weakening of the KE's southern RG is in sync with the lateral migration of the KE's path.

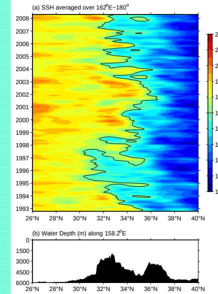
2. Forced Response of KE System



Maps of yearly averaged sea surface height anomaly field.



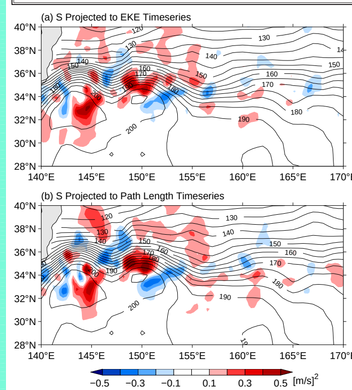
(a) Time series of EKE in the upstream KE region of 141°–153°E and 32°–38°N. Here, EKE is calculated using the weekly SSH anomaly data by assuming geostrophy. (b) SSH anomalies along the zonal band of 32°–34°N from the satellite altimeter data. (c) Same as panel b but from the wind-forced baroclinic Rossby wave model. (d) PDO index.



(a) SSH values averaged downstream of the Shatsky Rise from 162°E to 180°. The black contour denotes the 170 cm isoline, which approximates well the axis of the KE jet. (b) Water depth along 158.2°E where the Shatsky Rise is located. One consistent feature occurring prior to the KE's transition from a stable to an unstable state in mid 1995 and end of 2005, is the *southward* migration of the broad-scale, downstream KE jet axis from ∼35°N to ∼32°N.

The latitudinal migration of the broad-scale KE jet has a profound effect upon the stability of the upstream KE jet because of the presence of the Shatsky Rise. Along 158°E, where the Shatsky Rise is situated, panel b shows a deep passage with depth exceeding 4,500 m exists around 35°N. This deep passage allows the northerly-positioned KE jet to pass over the Shatsky Rise without triggering perturbations. When the KE jet migrates southward to ∼32°N, panel b indicates that the main body of the KE jet runs into the shallow portion of the Shatsky Rise with a depth of ∼2,000 m and this interaction with the shallow topography of the Shatsky Rise by the southerly KE jet provides the initial perturbations in the KE jet around 158°E. Once they are generated, these perturbations propagate westward and their subsequent interactions with the intense, upstream KE jet lead to an elevated eddy kinetic energy state of the KE system west of the Shatsky Rise.

3. Eddy's Impact on Circulation



The eddy forcing upon the mean streamfunction is defined as the following

$$S(x,y,t) = \nabla^{-2}\left(-\nabla\cdot\overline{\mathbf{u}'\zeta'}\right),$$

where $\mathbf{u}' \equiv (u', v')$ is the surface anomalous velocity vector, $\zeta' = \partial v'/\partial x - \partial u'/\partial y$ is the anomalous vorticity, and the term $-\nabla\cdot\overline{\mathbf{u}'\zeta'}$ denotes convergence of eddy vorticity flux. $-\nabla\cdot\overline{\mathbf{u}'\zeta'}$ is often dominated by small-scale features and it is more informative to consider S by applying the inverse Laplacian operator ∇^{-2} to $-\nabla\cdot\overline{\mathbf{u}'\zeta'}$. Physically, S represents the eddy forcing upon the mean streamfunction, or SSH, field. A positive (negative) S represents an acceleration of an anticyclonic (cyclonic) circulation. Eddy-induced acceleration $S_p(x,y)$ of the mean streamfunction field projected to (a) the time series of the level of eddy kinetic energy and (b) the time series of the KE path length, as follows:

$$S_p(x,y) = \frac{\langle S(x,y,t)\,E(t)\rangle}{\sqrt{\langle E(t)\,E(t)\rangle}}.$$

There is a general anticyclonic forcing inside the RG south of the upstream KE jet, indicating that the enhanced eddy activity during the unstable state of the KE system works to strengthen the southern RG. Along the path of the meandering KE jet, both panels reveal a general tendency for a cyclonic forcing in the trough, and an anticyclonic forcing in the ridge, of the KE's quasi-stationary meanders.

4. Summary

The dominant mode of the KE variability is characterized by its oscillations between a stable and an unstable dynamic state. The cause for the bimodal KE oscillations can be sought in the wind stress curl forcing over the eastern North Pacific related to the Pacific decadal oscillations.

The relevance of the linear Rossby wave dynamics in controlling the phase transitions of the KE dynamic state does not negate the important roles played by the nonlinear dynamics. In fact, it is the nonlinear interaction of the deep-reaching KE jet with the Shatsky Rise that determines the level of eddy kinetic energy in the upstream KE region between Japan and the Shatsky Rise. In the usptream KE region, the elevated eddy activity during the unstable state of the KE system works to strengthen the southern RG and the meandering quasi-stationary meanders. This gradual strengthening of the southern RG can potentially force the upstream KE path northward and contribute, by combining with the incoming wind-driven positive SSH anomalies from the east, to the KE's transition to a stable dynamic state.