Decadal Variability, Impact and Mechanism of the Kuroshio Extension System

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North Pacific western boundary current: the Kuroshio and its Extension

- Kuroshio is the WBC driven by basin-scale Ekman pumping forcing
- Transport increases progressively from off Philippines (~10Sv) to south of Japan (~60Sv)
- Renamed “Kuroshio Extension” east 140°E; eastward transport > 120Sv ↔ southern RG
- Brings a great amount of heat poleward and is highly dynamically unstable
KE has the highest mesoscale eddy variability in the Pacific Ocean.

Satellite altimetry-derived high-frequency (<300 days) EKE

- max: 2287 cm²/s²
- max: 1314 cm²/s²
KE has the highest low-frequency circulation variability in world oceans.

Satellite altimetry-derived high- vs. low-frequency EKE:

- Max: 813 cm$^2$/s$^2$
- Max: 1165 cm$^2$/s$^2$
• Observed multi-variate decadal — introducing the KE index
• KE variability as an “externally” wind-forced response
• Impact on regional SST and sea level trend signals
• Mechanism underlying the dominant decadal variability (its difference form the Gulf Stream system)
Annual maps of bi-weekly paths of the Kuroshio/KE jet

Alternation between stable versus unstable phases
Dynamically stable vs. unstable phases of the KE system


Other dynamical quantities representing the decadal KE variability

Typical yearly SSH patterns in **unstable/contracted vs. stable/elongated** phases

- **(a) Upstream KE Path Length (141°–153°E)**
- **(c) KE Strength (140°–165°E)**
- **(d) Upstream KE Position (141°–165°E)**
- **(d) KE Recirculation Gyre Strength**
Forming of a comprehensive index representing the KE variability

Qiu et al. (2014, J Clim)

KE index: average of the 4 dynamical quantities (normalized)
Regression between the KE index and AVISO SSH anomaly field

**KE index**: represented well by SSH anomalies in the southern RG box (31-36°N, 140-165°E)

KE index from dynamical properties

Box-averaged SSH time series
Regression between the KE index and AVISO SSH anomaly field

**Implications**

- Examining KE index becomes equivalent to examining SSH anomalies in this key box.
- Dynamically, it is easier to explore SSH changes than circulation/eddy changes.
- Because mid-latitude SSH changes are largely governed by wind-forced baroclinic adjustment.

**KE index**: represented well by SSH anomalies in the southern RG box (31-36°N, 140-165°E)
Decadal KE variability lags the negative PDO index by ~ 3 years \( (r = 0.74) \)

- Center of PDO wind forcing is in **eastern** half of Pacific basin
- \(-\) PDO corresponds to an enhanced Aleutian Low that generates \(+\) SSHAs through Ekman convergence
- 3~4-yr lag is required cross-basin adjustment time
Decadal KE variability lags the NPGO index by 2~3 yrs ($r = 0.83$)

- NPGO vs −PDO in 1989-2015: $r = 0.65$
- NPGO is SSHA-based and PDO is SSTA-based

Di Lorenzo et al. (2008, GRL)
Connections between PDO forcing, cross-basin SSH adjustment and KE index

Connections between PDO forcing, cross-basin SSH adjustment and KE index.
Quantifying the wind-forced SSH variability across the Pacific basin

- Rather than specific climate modes, the proxy KE index is governed by wind forcing along the 32°-36°N band across the North Pacific basin:

\[
\frac{\partial h}{\partial t} - c \frac{\partial h}{\partial x} = -\frac{g'}{\rho_0 g f} \nabla \times \tau
\]

- Hindcast of KE index using ECMWF interim $\nabla \times \tau$ data along the Rossby wave characteristics (e.g., Qiu & Chen 2005; Taguchi et al. 2007; Sugimoto & Hanawa 2009):

- Original time series: $r = 0.65$
- Low-pass filtered TS: $r = 0.87$
Extending the KE index into the beginning of the 20\textsuperscript{th} century

- Rather than specific \textit{climate modes}, the proxy KE index is governed by wind forcing along the 32\textdegree-36\textdegree N band across the North Pacific basin:

\[
\frac{\partial h}{\partial t} - c_R \frac{\partial h}{\partial x} = -\frac{g' \nabla \times \tau}{\rho_0 g f}
\]

- Hindcast of KE index using \textit{ECMWF ERA20C + interim } $\nabla \times \tau$ data along the Rossby wave characteristics:

Decadal-timescale KE variability is not confined to the recent satellite era
Comparison between the wind-derived vs. historical T/S-based KE indices

- KE index based on Ishii et al.’s (2006, JO) objectively analyzed T/S dataset:

  - Ability of baroclinic RW model to favorably hindcast the observed KE index indicates the dominance of linear wind-forced adjustment for the KE system
  - But ... this does not negate the importance of nonlinear eddy processes

![Graph showing dynamic height and SSHa comparison](image.png)

- (a) Dynamic Height (0/1500db, Ishii et al 2006), in 140–165°E, 31–36°N
- (b) Detrended; ECMWF ERA20C+interim Wind, Rossby Wave Model in 140–165°E, 31–36°N

$r = 0.76$
Caveat: Not all aspects of the decadal KE variability are linear!

- Regional sea level trend of 1993–present (3.2 mm/yr global-mean value subtracted)
- In mid-latitudes, regional sea level trend tends to have small meridional scales

Sasaki et al. (2014, JGR)
Quantifying wind- vs eddy-forced sea level variability in the 2-layer HIM

- Governing upper layer equations:

\[
\frac{\partial u_1}{\partial t} + u_1 \cdot \nabla u_1 + f k \times u_1 = -g \nabla h_1 + A_2 \nabla^2 u_1 - A_4 \nabla^4 u_1 + \frac{\tau}{\rho_1 H_1} - u_s' \cdot \nabla u_s',
\]

\[
\frac{\partial (h_1 - h_2)}{\partial t} + \nabla \cdot (H_1 u_1) = K_2 \nabla^2 (h_1 - h_2),
\]

where \(u_1\) is velocity vector and \(H_1\) is upper layer thickness.

- \(\frac{\tau}{\rho_1 H_1}\) denotes the external wind forcing; given by interannually varying monthly ECMWF data

- \(- u_s' \cdot \nabla u_s'\) denotes the oceanic eddy forcing; inferred from the weekly AVISO anomalous SSH data

- North Pacific domain: 0°-50°N, 120°E-75°W

- Mean upper layer thickness: \(H_1 = 500\) m

Qiu et al. (2015, JC)
Wind-forced non-eddy-resolving model tends to capture the broad-scale sea level trend pattern only

- It fails to simulate detailed trend pattern & signs around Japan

Wind-forced sea level trend

2-layer HIM for the N Pacific basin; it simulates well NP mean gyre circulation

- Forced by monthly ECMWF interim wind and/or AVISO-derived eddy momentum fluxes
• Wind-forced non-eddy-resolving model tends to capture the broad-scale sea level trend pattern only

• Nonlinear Eddy forcing can generate rectified regional sea level changes through momentum flux convergence: sea level drop (rise) northwest (southwest) of the eddy forcing

Haidvogel & Rhines (1983, GAFD)
Trends in eddy forcing leads to zonally-banded regional sea level trends:

- (+) sea level rise northwest (southwest) of the eddy forcing
- Enhanced eddy forcing trend in the downstream KE results in the observed decreasing (increasing) sea level trend north (south) of the KE jet
Observed sea level trend around Japan is a combination of wind & eddy forcing.

- The observed, zonally-banded, sea level trend around Japan (and along the STCC east of Taiwan) is caused by **combined external wind and oceanic eddy forcing**

Qiu et al. (2015, J Clim)
KE dynamic state affects regional SST and cross-front SST gradient

Semi-monthly KE paths

Feb-March SST maps
KE dynamic state affects regional SST and cross-front SST gradient

SST gradient across the KE path

KE index

Feb-March SST maps
Kuroshio/KE supplies heat to overlying atmosphere & anchors stormtracks

Time-mean net surface heat flux from air to ocean (W/m²; Cronin et al. 2009)

DJF 700mb rms v’T’ fluxes indicative of stormtracks variability (e.g. Nakamura et al. 2004)

zero wind-stress-curl line/stormtracks
A positive KE index (i.e., warmer SST & stronger SST front) favors a **poleward migration** of stormtracks/zero wind stress curl line.

- This migration causes a **dipolar wind stress curl anomaly** in the 31-36°N band: positive in the eastern Pacific basin (Qiu et al. 2014; J Clim).

- The + wind stress curl generates **SSH anomalies** and works to reverse the KE index after the SSHAs propagate westward into the KE.
KE interaction with stormtracks favors a delayed negative feedback loop

half of the adjustment cycle: ~5 years in the N Pacific basin
110-yr-long KEI time series allows a re-examination on decadal mechanism

- The wind data forcing the KEI may be decomposed into EOF modes
- EOF mode-1 represents monopole forcing and mode-2, dipole forcing

\[
\frac{\partial h}{\partial t} - c_R \frac{\partial h}{\partial x} = - \frac{g'}{\rho_0 g f} \nabla \times \mathbf{\tau}
\]
Spatial sea level pressure (SLP) patterns regressed to EOF mode PCs

- EOF mode-1 forcing has the characteristic NPO pattern
- EOF mode-2 forcing is zonally segmented
Spatial sea level pressure (SLP) patterns regressed to EOF mode PCs

- EOF mode-1 forcing has the characteristic NPO pattern
- EOF mode-2 forcing is zonally segmented; it bears resemblance to the KEI-induced SLP/wind curl pattern
- Both modes have little tropical SLP imprint

Anomalous wind stress curls regressed to KE index: 1977-2012
Both mode-1/2 wind forcing time series have little dominant frequencies

- The wind data forcing the KEI may be decomposed into EOF modes
- Both mode-1/2 PCs are mostly "white"!!
KE index forced by mode-1, mode-2, & combined wind forcing

- Mode-1-forced KEI has a red spectrum with no decadal peak (see red curves)
- Mode-2-forced KEI has a decadal peak but weak compared to mode-1 spectral level (blue curves)
- Sum of mode-1/2 forced KEI (pink curves) captures the total KEI (black curves) in time series and in spectral peak
Let forcing be white-noise & monopole/dipole (n=1, 2):

\[
\frac{\partial h(x, t)}{\partial t} - c_R \frac{\partial h(x, t)}{\partial x} = \sum_{n=1}^{2} \sin \left( \frac{n \pi x}{W} \right) w_n(t)
\]

Fourier-transformed SSH response:

\[
\hat{h}(x, \omega) = -\sum_{n=1}^{2} \frac{\hat{w}_n(\omega)}{c_R} \int_{0}^{x} \sin \left( \frac{n \pi x'}{W} \right) e^{i \omega (x-x')/c_R} dx'
\]

Fourier-transformed KE index:

\[
\overline{\hat{h}}(\omega) = \frac{1}{L} \int_{-W}^{W} \hat{h}(x, \omega) dx = \sum_{n=1}^{2} P_n(\omega) \hat{w}_n(\omega),
\]

where \( P_n(\omega) \) is transfer function (Qiu et al. 2007, JC)

- Analytical solutions for white-noise monopole & dipole forcing exist
- These solutions simulate well the KEI forced by mode-1 and 2, respectively
- If mode-1 and 2 are independent, the summed forced KE index fails to generate the decadal peak (see black curve below)
- Decadal peak requires mode 1 & 2 forcing in the NP basin be inter-related
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\[ h_{\text{pink}} = h_{\text{red}} + h_{\text{blue}} \]

\[ \hat{h}_{\text{pink}}^2 \neq \hat{h}_{\text{red}}^2 + \hat{h}_{\text{blue}}^2 \]
Mechanism for enhanced decadal variability of the KE system

- Aleutian Low intrinsic variability
- Basin-wide mode-1 white-noise forcing
- Reddening of KEI spectrum; no decadal peak
- Dipolar mode-2 forcing
- Enhanced KEI decadal variability

OCN-ATM feedback via stormtracks

Power Spectrum vs Frequency

- ECMWF ERA20C+interim Wind, RW Model in 140–165°E, 31–36°N
- ECMWF ERA20C+interim Wind, Rossby Wave Model in 140–165°E, 31–3
- W=100 Lon, L=25 Lon, hR=0.033m/s

 EOF 1
 EOF 2

10 yr

10 yr

10 yr
Summary

- KE dynamic state (i.e. EKE level, path latitude, & jet/RG strengths) is dominated by decadal variations.

- SSH anomalies in the southern RG box provide a good index for the fluctuating KE system; its variations are dictated by basin-wide wind forcing.

- Decadal KE variability affects the regional sea level trend, mixed layer properties, SST, and overlying stormtracks; eddy, diabatic & mixing processes important.

- While dominated by intrinsic (monopole) AL variability, KE decadal variations are enhanced by oceanic feedback of a dipolar atmospheric response in the 31°-36°N band.