

# Regional patterns of interannual sea level variability: Case of the Japan/East Sea

O.O. Trusenkova

V.I.II'ichev Pacific Oceanological Institute, FEB RAS

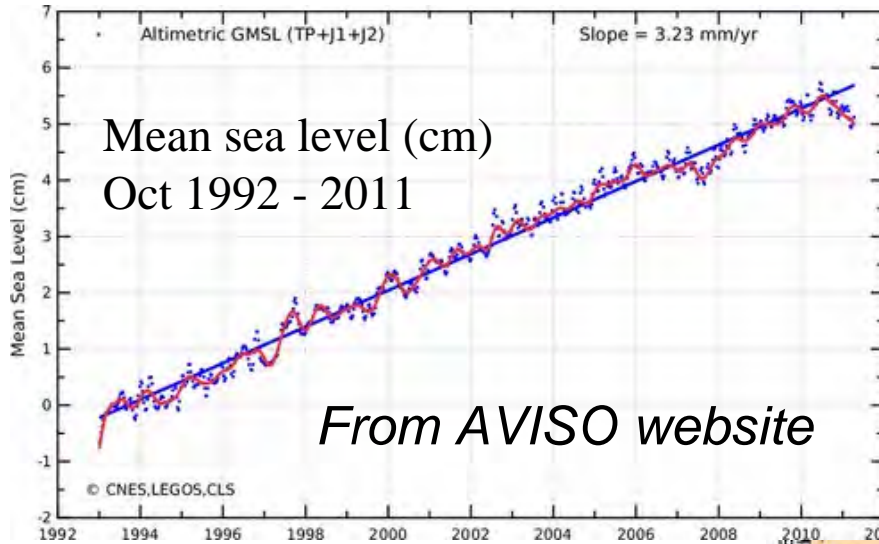
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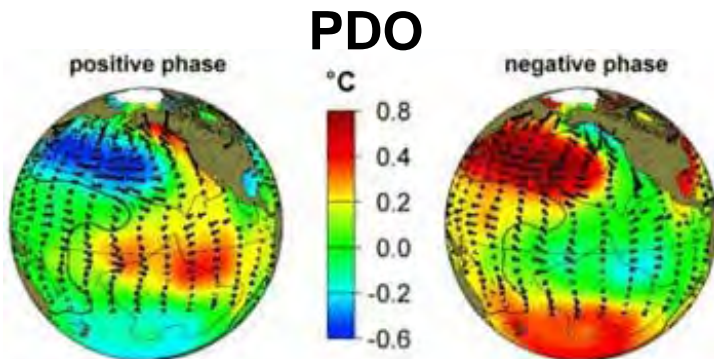
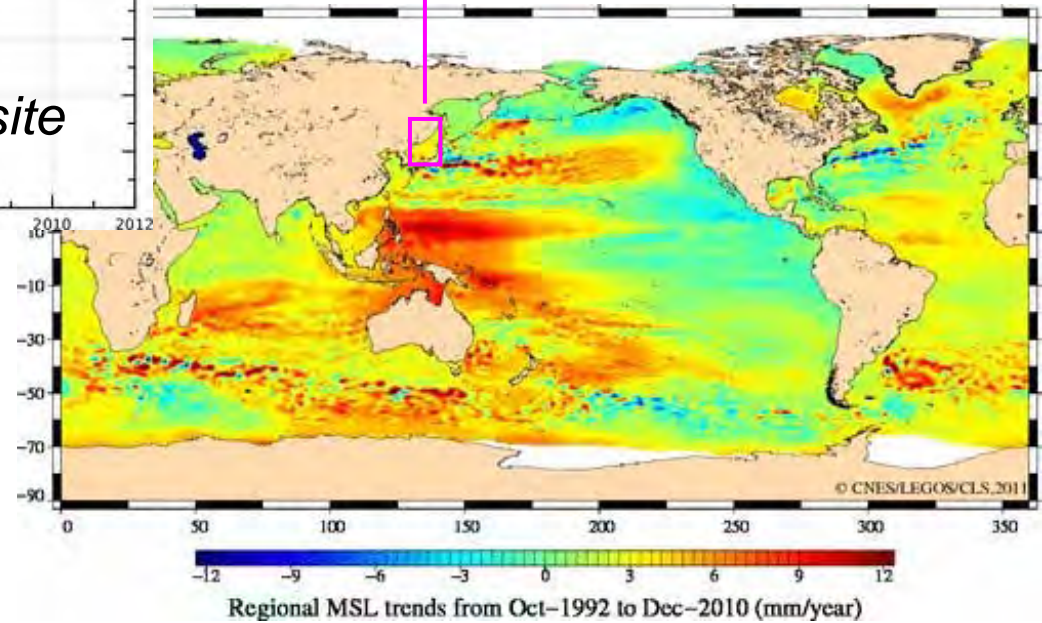
*S1 - Climate variability versus anthropogenic impacts*

# Introduction: global sea level from satellite altimetry



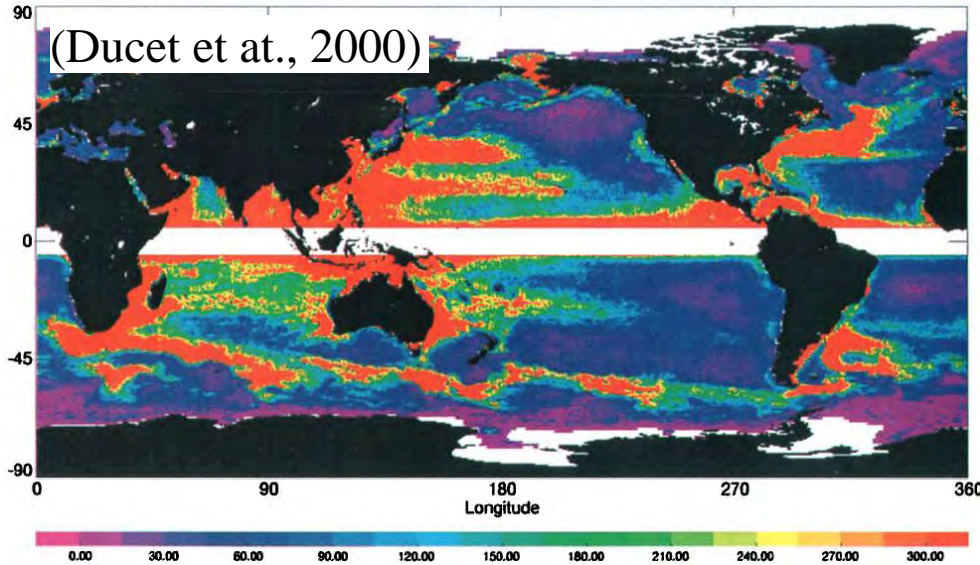
Regime of the Japan/East Sea is substantially forced by the throughflow

*From AVISO website*



Spatial distribution of linear trends (since October 1992)

# Introduction: synoptic energetics from satellite altimetry

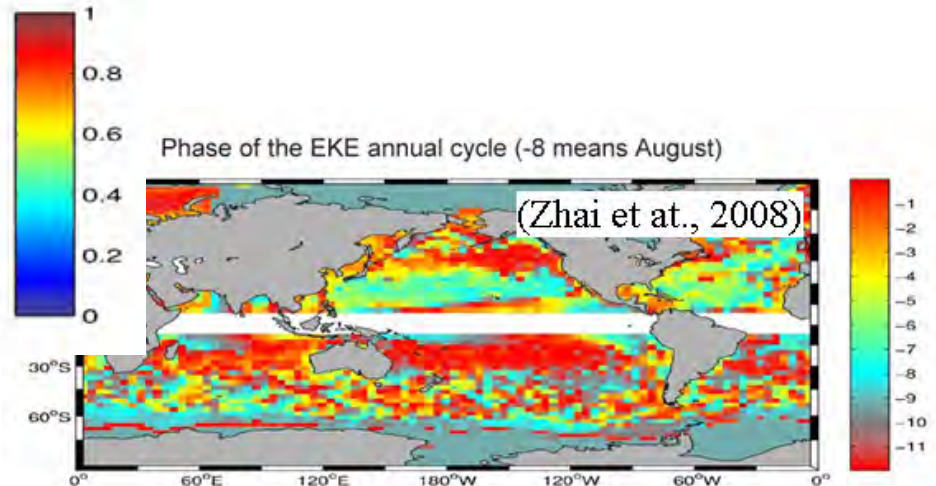
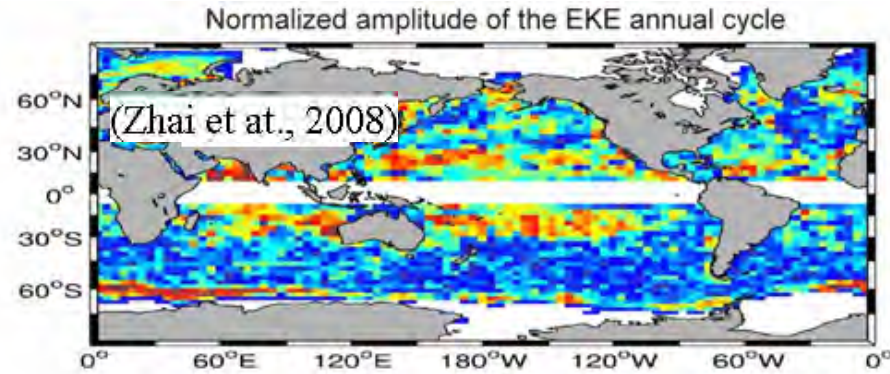


Geostrophic eddy kinetic energy

$$E_m = (u'^2 + v'^2)/2, \text{ where}$$
$$u' = -(g/f)\partial\eta/\partial y, v' = (g/f)\partial\eta/\partial x,$$

$\eta$  is altimetric sea level anomaly

Much less is done on interannual variability



# Purpose

To analyze interannual and, if possibly, decadal variability of sea level, circulation, and synoptic energetics in the Japan/East Sea using the whole available altimetric record.

# Data

AVISO weekly reference  $1/4^\circ$ -gridded sea level anomalies, October 1992 - July 2011,  $35.5^\circ$ - $48^\circ$ N,  $127.5^\circ$ - $142^\circ$ E.

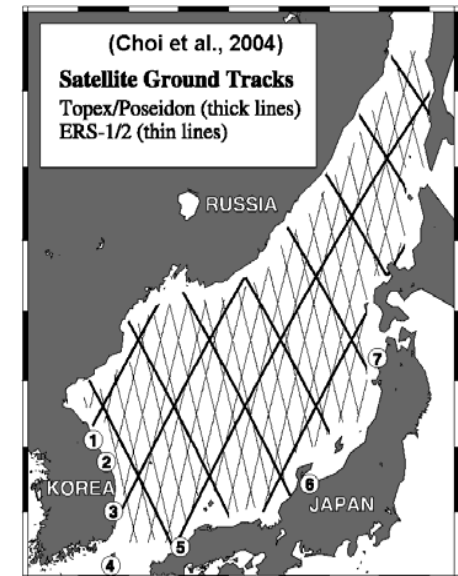
$EKE = (u'^2 + v'^2)/2$  where

$u' = -(g/f)\partial\eta/\partial y$ ,  $v' = (g/f)\partial\eta/\partial x$ ,  $\eta$  - altimetric SLA  $\rightarrow$  geostrophic & ergodic & spatial scales  $> 25$  km.

(Noise level increased by differentiation.)

Filtering for noise removing, using Morler mother wavelet of the 6-th order, with the 20-week cut-off period. Similar results for the cut-off periods of 9 and 13 weeks but lower eigenvalues.

Interannual SLA and EKE  $\sim$  1.3-year cut-off period.



# Techniques of EOF analysis

EOF analysis: a set of orthogonal patterns focused on areas of large variance:

$X(\mathbf{r}, t) = \sum A_k(\mathbf{r}) \cdot B_k(t)$ , where  $X(\mathbf{r}, t)$  is original signal,  $A_k(\mathbf{r})$  is eigenvector,  $B_k(t)$  is principal component (PC).

1) Covariances for computing eigenvectors  $\rightarrow$  weaker signals can be lost.

Correlations (normalized  $X$ )  $\rightarrow$  detection of small amplitude anomalies.

2) Natural patterns are not necessarily orthogonal. However, orthogonality is intrinsic to EOF patterns.

3) Successive decompositions after the removal of contribution from a leading mode before every next step:

Residual sampling:  $X_a(\mathbf{r}, t) = X(\mathbf{r}, t) - A_1(\mathbf{r}) \cdot B_1(t) = \sum A'_k(\mathbf{r}) \cdot B'_k(t)$ .

Using correlations allows for new modes in successive decompositions, i.e. it is possible that  $A'_k \neq A_{k+1}$  and  $B'_k \neq B_{k+1}$  if natural modes are non-orthogonal.

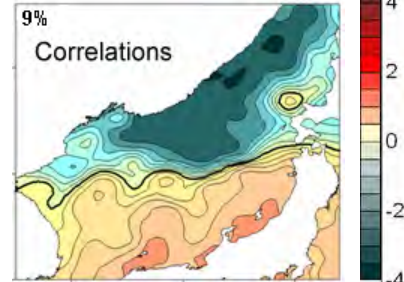
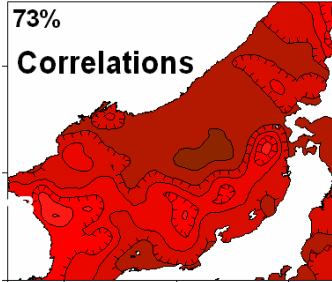
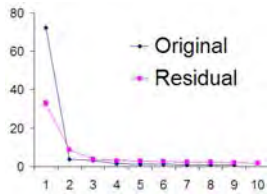
In contrast, using covariances would only result in successive removing of a leading mode, with  $A'_k = A_{k+1}$  and  $B'_k = B_{k+1}$ .

Sea level and circulation strength  
in the Japan/East Sea

# Interacting SLA modes in the Japan/East Sea

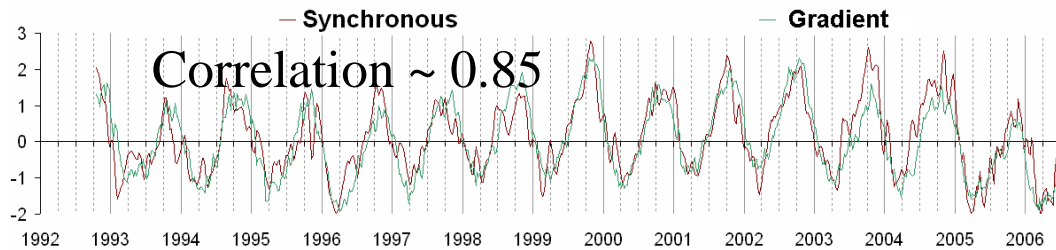
Synchronous Mode

Gradient Mode

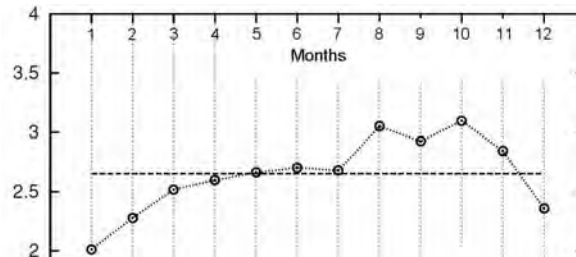


Original sampling

Residual sampling



Transport  
in the Korea Strait  
(Fukudome et al., 2010)

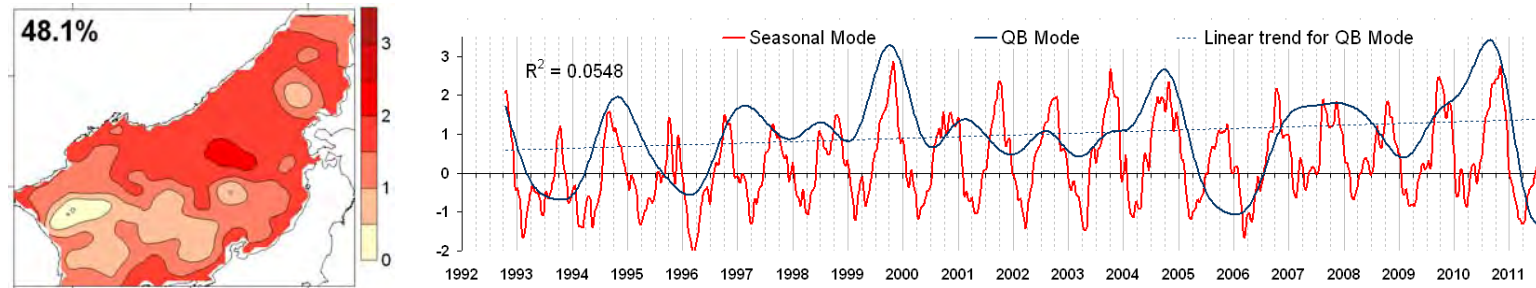


The sea level rise and meridional gradient sharpening (circulation strengthening) in the warm season and the reverse phase in the cold season.

Seasonal extremes of the Synchronous and Gradient Modes in October and March.



# Quasi-biennial Synchronous Mode (from low-pass filtered SLA)



No statistically significant linear trend.

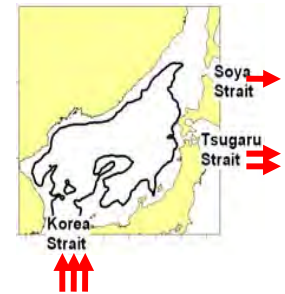
QB and decadal variability.

SLA caused by the volume imbalance.

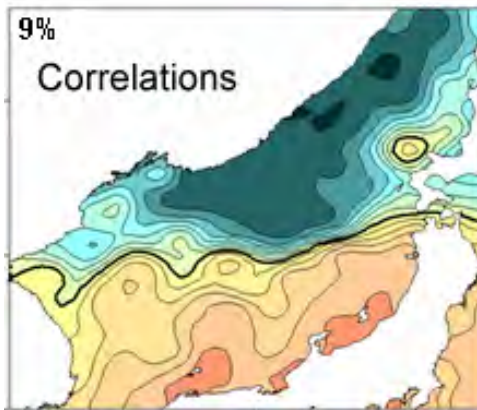
Imbalance of transports through the straits: SLA of 0.5-3 cm correspond to 0.4-2% of volume imbalance.

Stronger anomalies in 1999, 2004-2005, 2010 (decadal variability).

Indirect forcing from the atmospheric QBO (Baldwin et al., 2001)?



## No interannual counterpart of the Gradient Mode

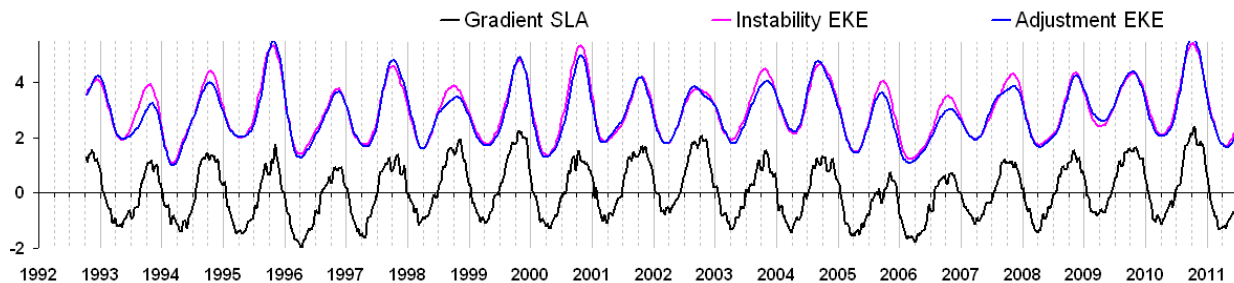
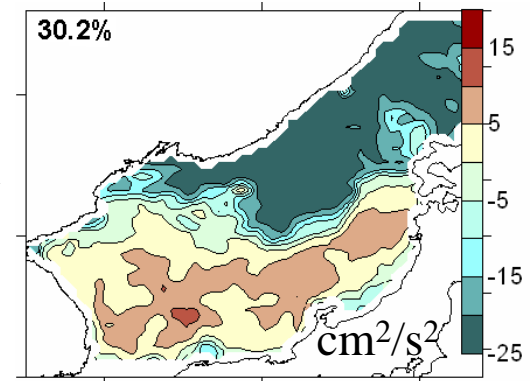
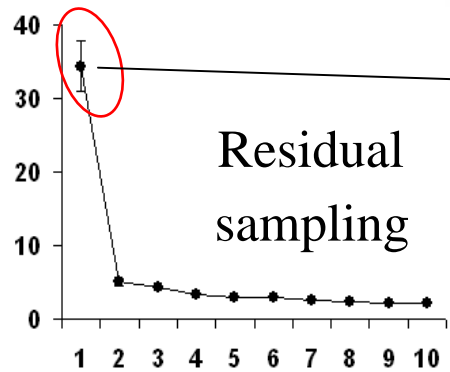
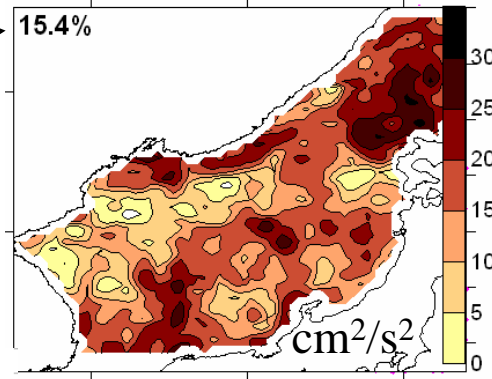
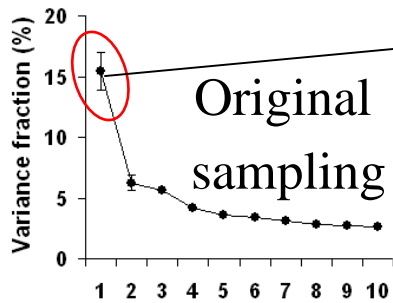


Only seasonal!

Stratification as a stabilizing factor: interannual oscillations are too weak.

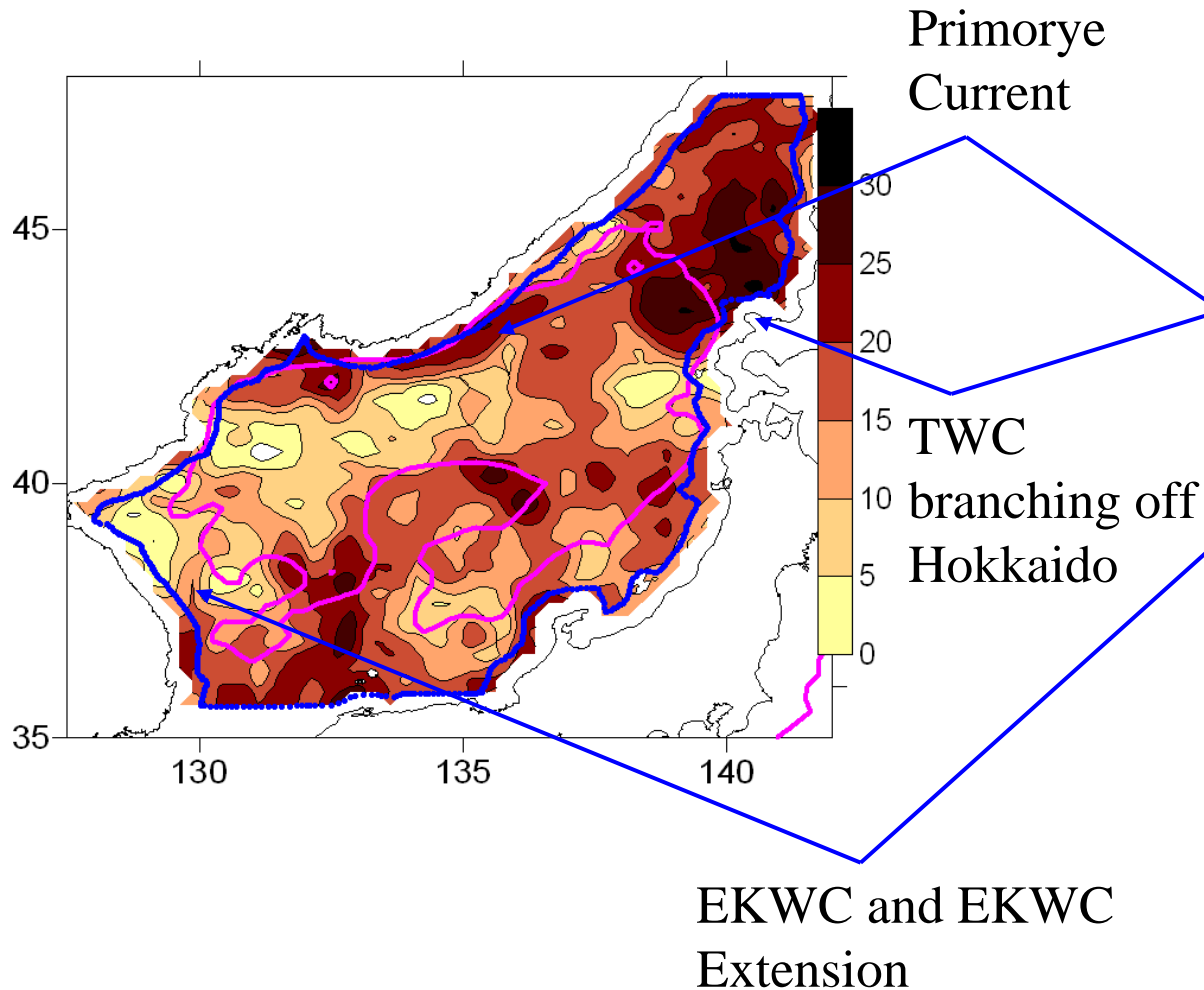
# Synoptic energetics in the Japan/East Sea

# Leading EKE modes (the same from the original and residual SLA)

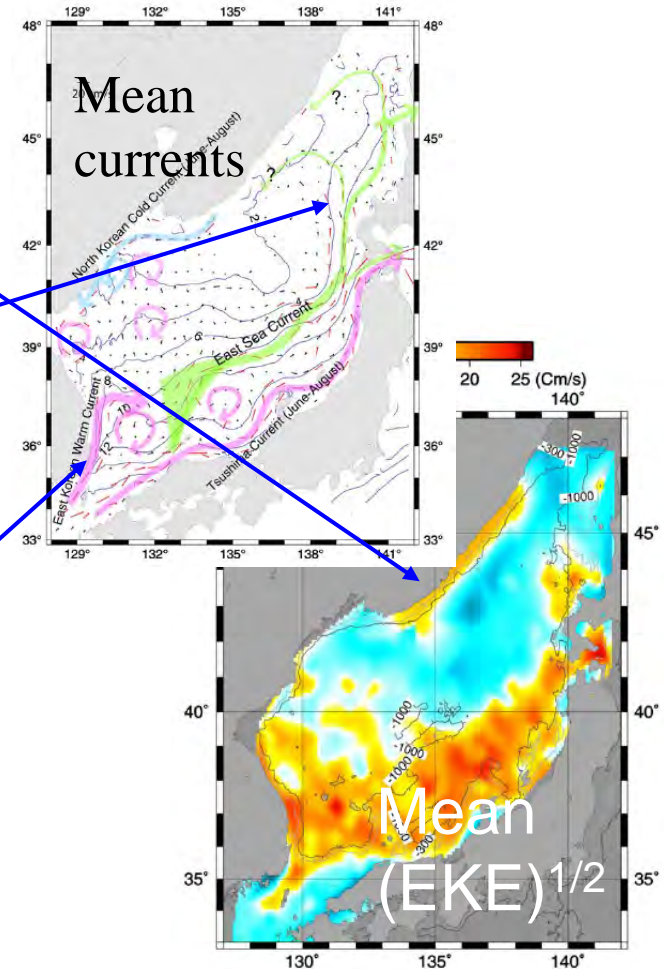


Correlation with the  
SLA Gradient Mode  
Mode  $\sim 0.84$ .

# Instability of mean currents

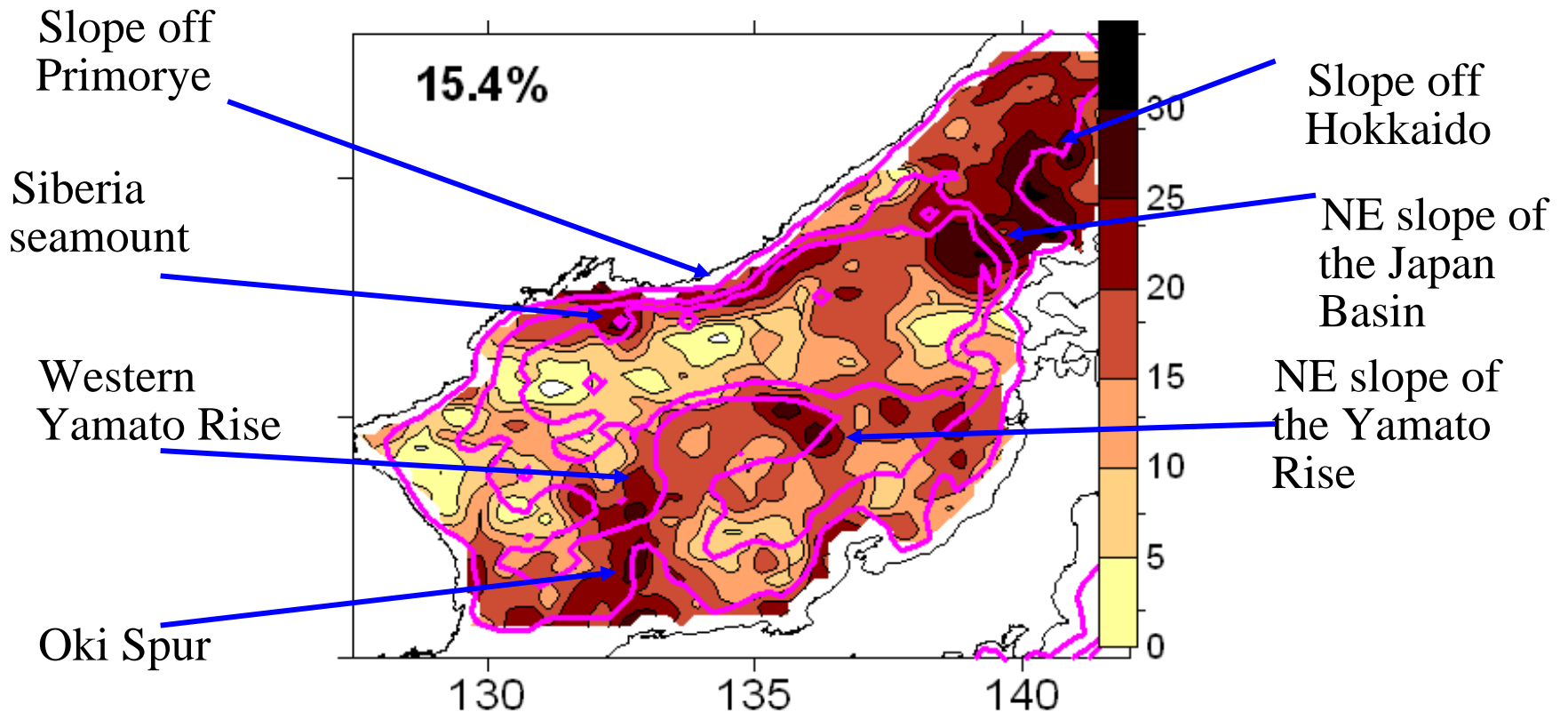


From surface drifters



(Lee and Niiler, 2005)

# Interactions with bathymetry

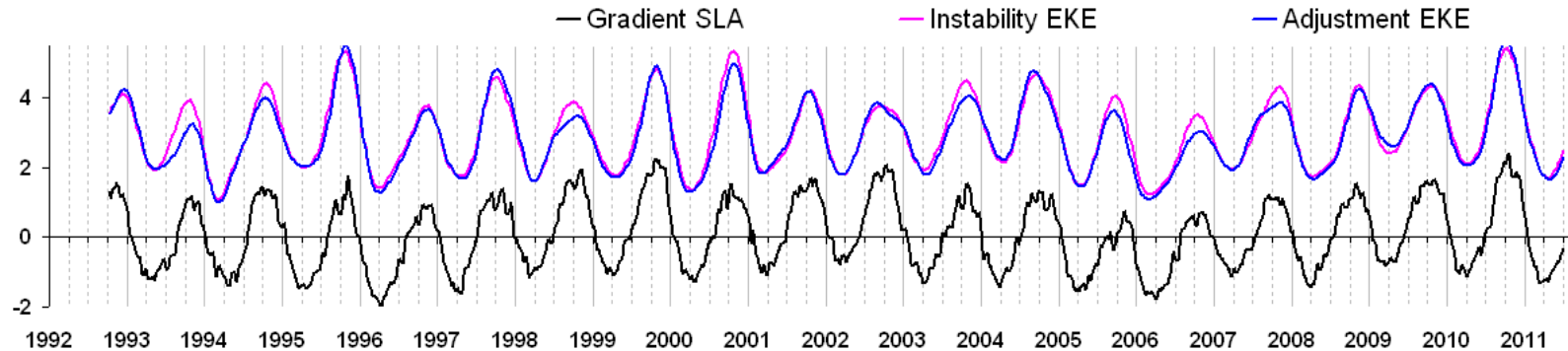
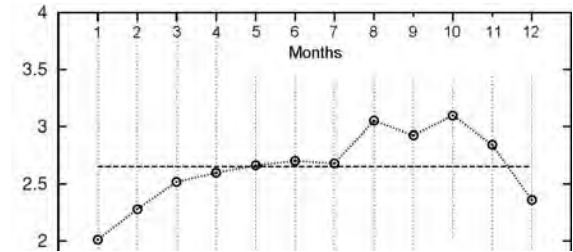
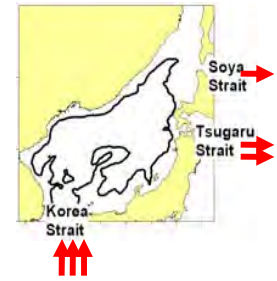
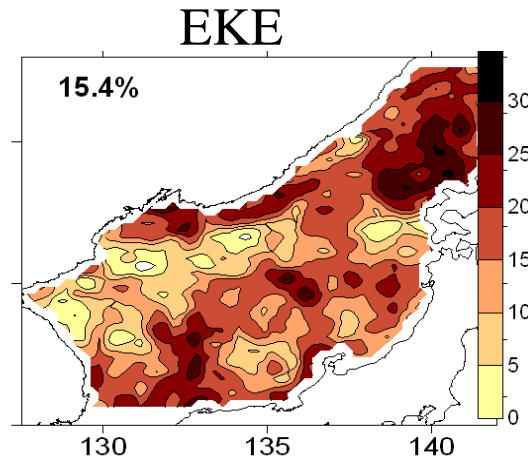
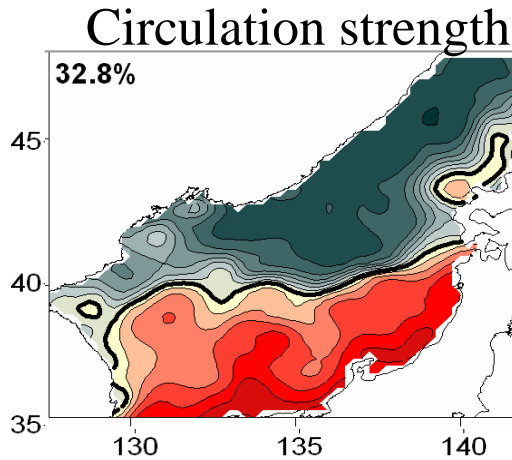


The 500, 2000, and 3000 m isobaths

EKE generated by hydrodynamic instability

Baroclinic instability is usually considered.

# Shear instability



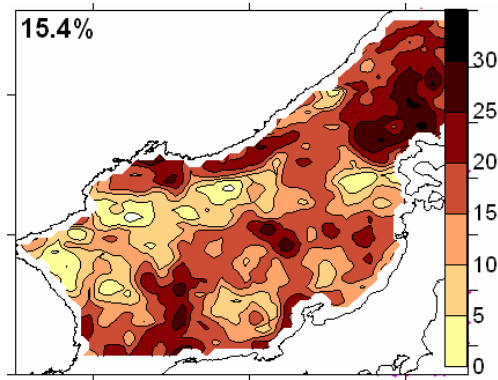
Seasonal variation of the circulation strength and EKE are the same → instability increase due to the increased current shear.

Synchronized barotropic and baroclinic instability as a possible cause of the very intense mesoscale dynamics in the Japan Sea

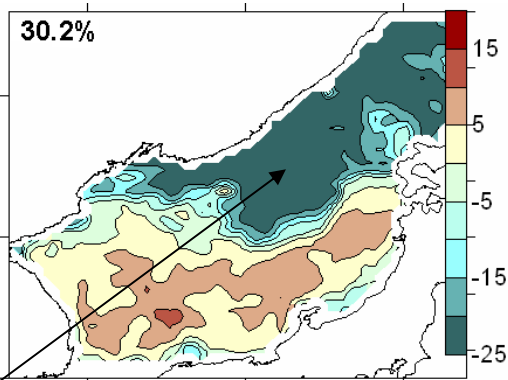


# Adjustment mode: adjustment to the mean EKE

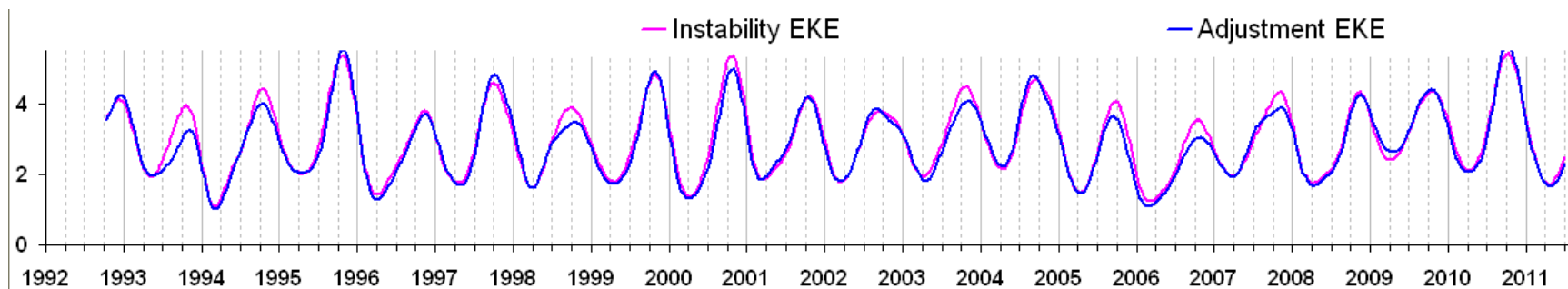
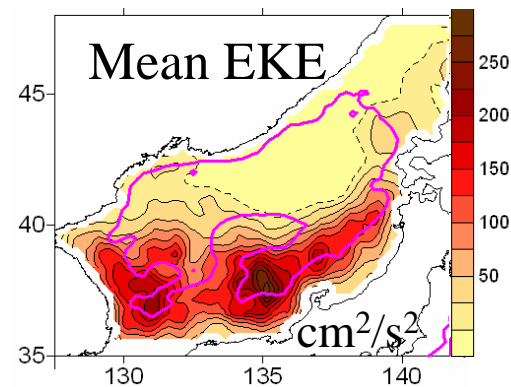
Original sampling  
Instability Mode



Residual sampling  
Adjustment Mode

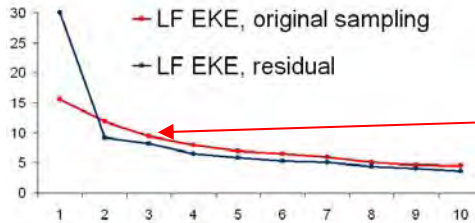


Uniform northern core

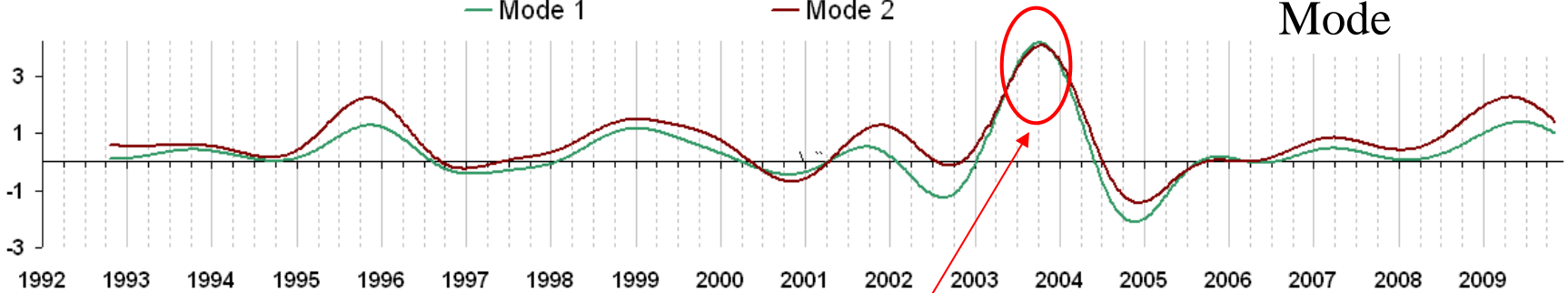
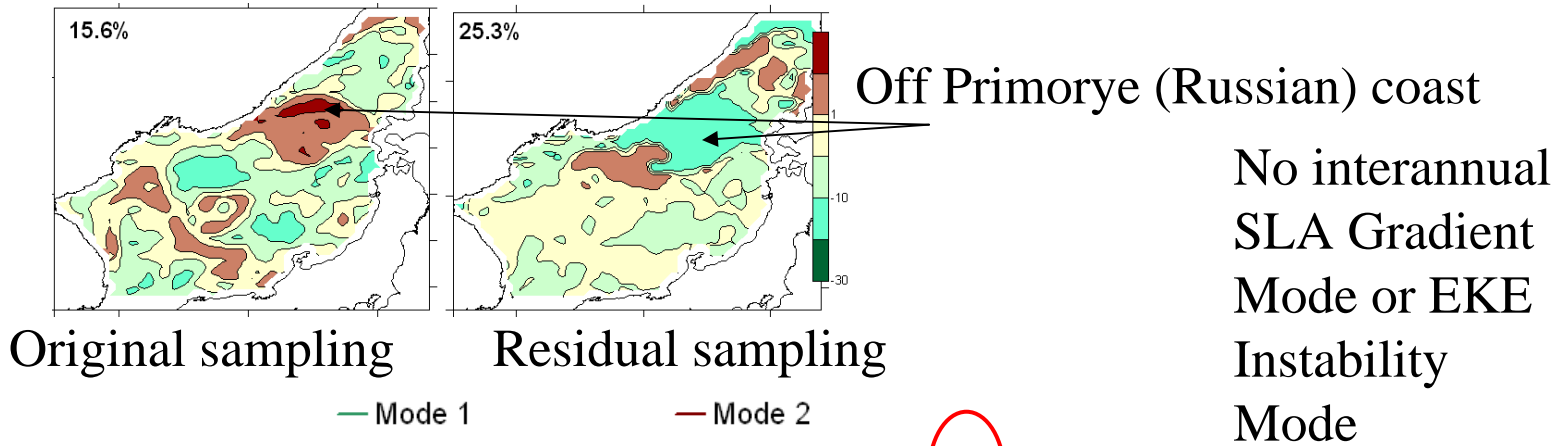


Correlation ~ 0.98

# EKE: weak interannual variability: the only strong event in fall 2003

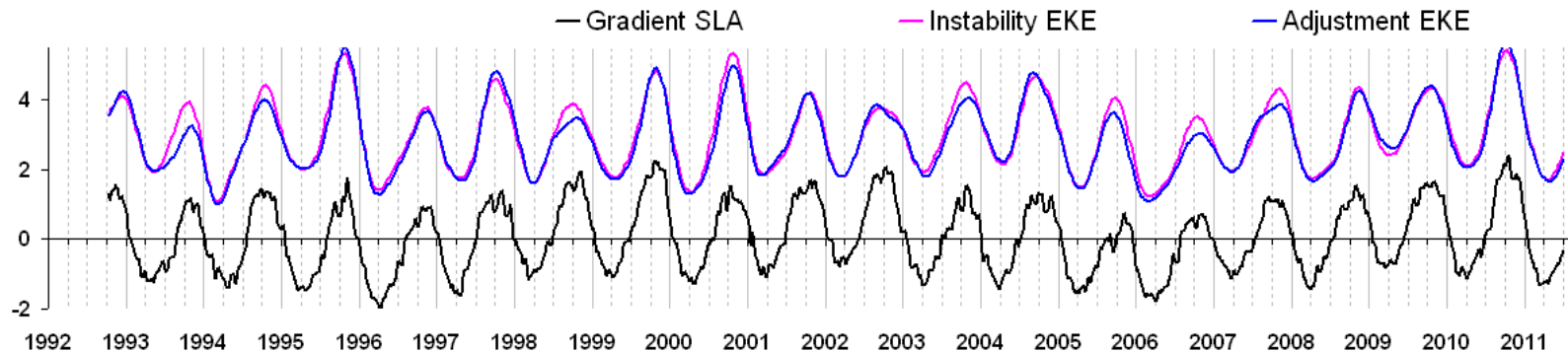


Degenerate eigenspectrum  
from the original sampling



Anomalous warm conditions off the Primorye coast in fall 2003 (Vanin, 2004)

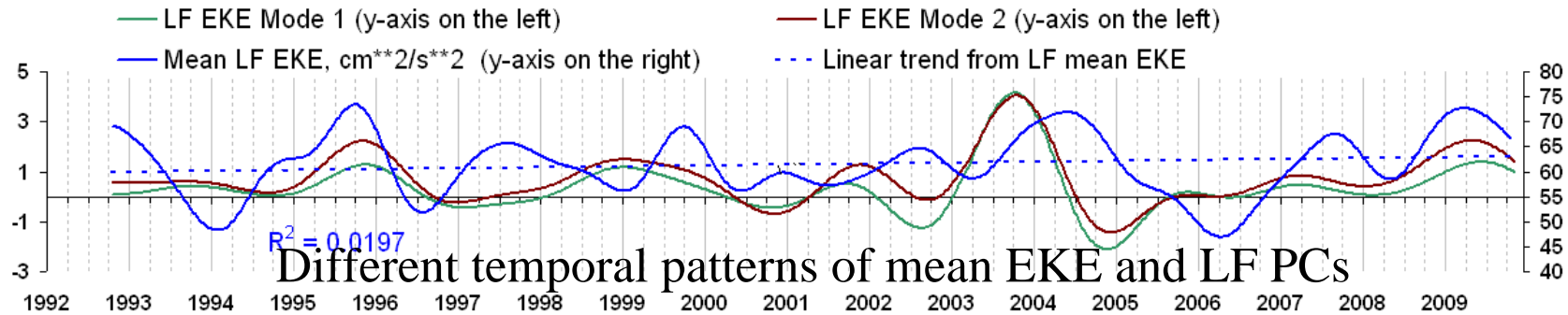
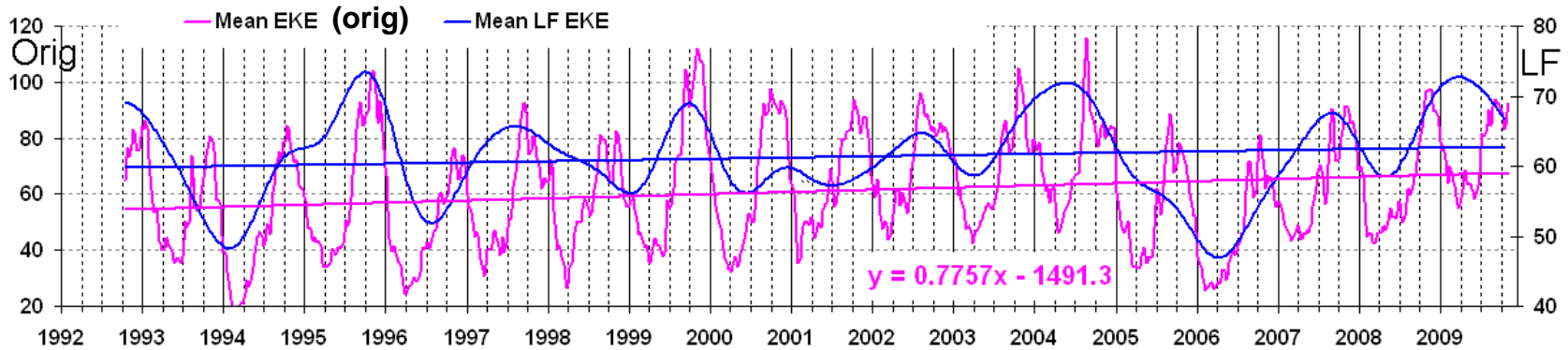
# No interannual counterpart of the EKE Instability Mode or SLA Gradient Mode



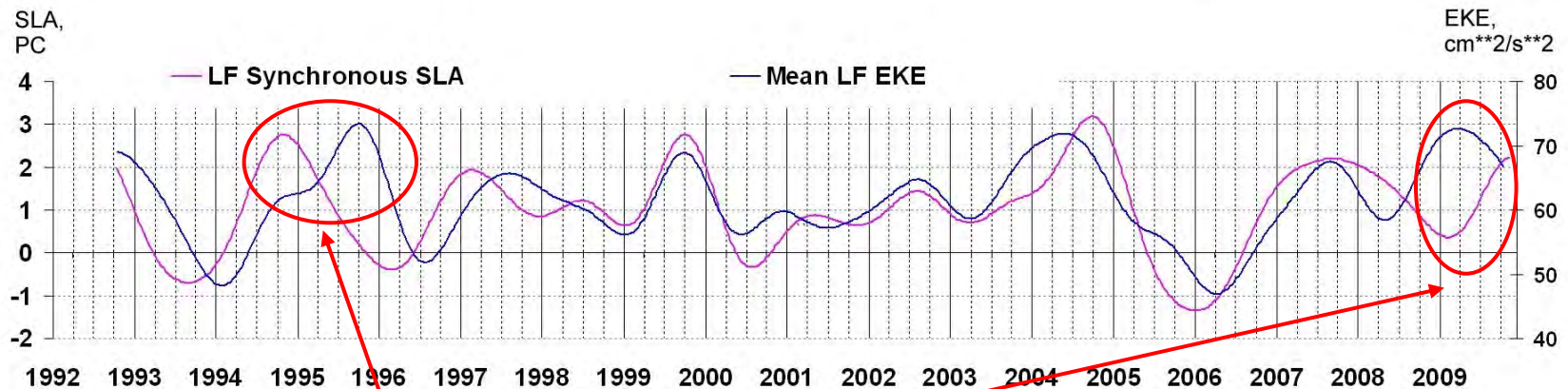
Interannual variability only in intensity of the seasonal SLA and EKE modes.

# Mean EKE – QB variability

Mean EKE:  $0.9 \text{ cm}^2/\text{s}^2$  per year for 1993-2007 (Son et al., 2011),  
 $\sim 0.8 \text{ cm}^2/\text{s}^2$  per year for 1993-2009



# SLA and EKE

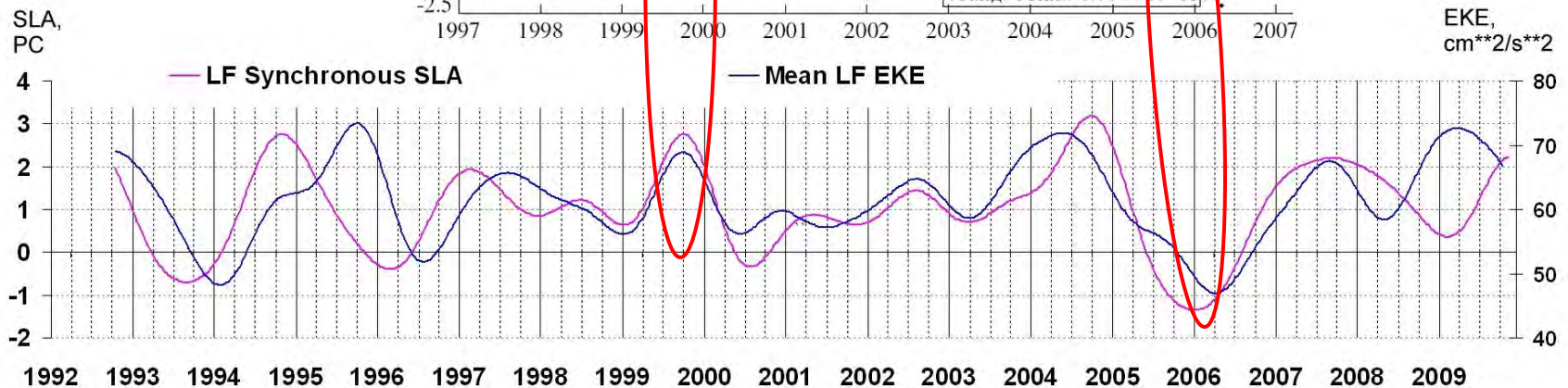
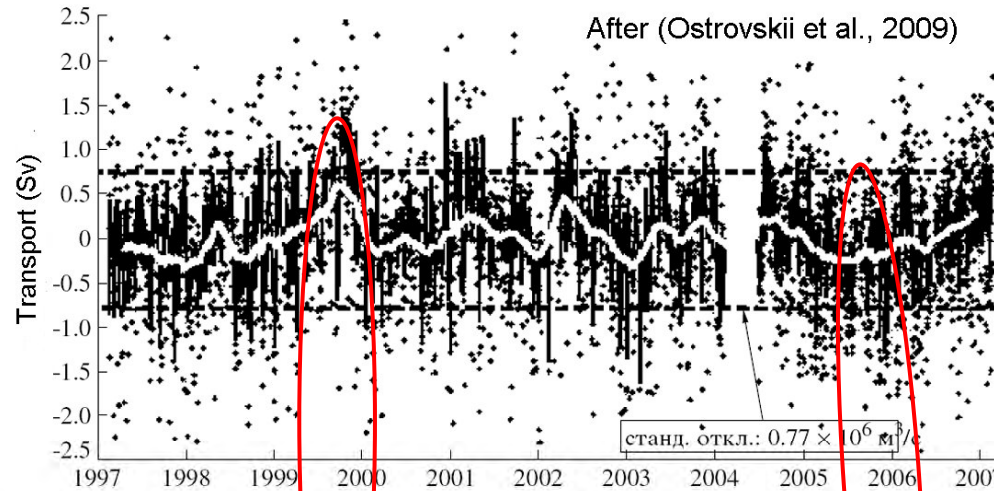


Close resemblance of low-frequency SLA and mean EKE, although with some discrepancies.

Correlated at 0.54 for the whole record and at 0.61 from mid 1996 through early 2008.

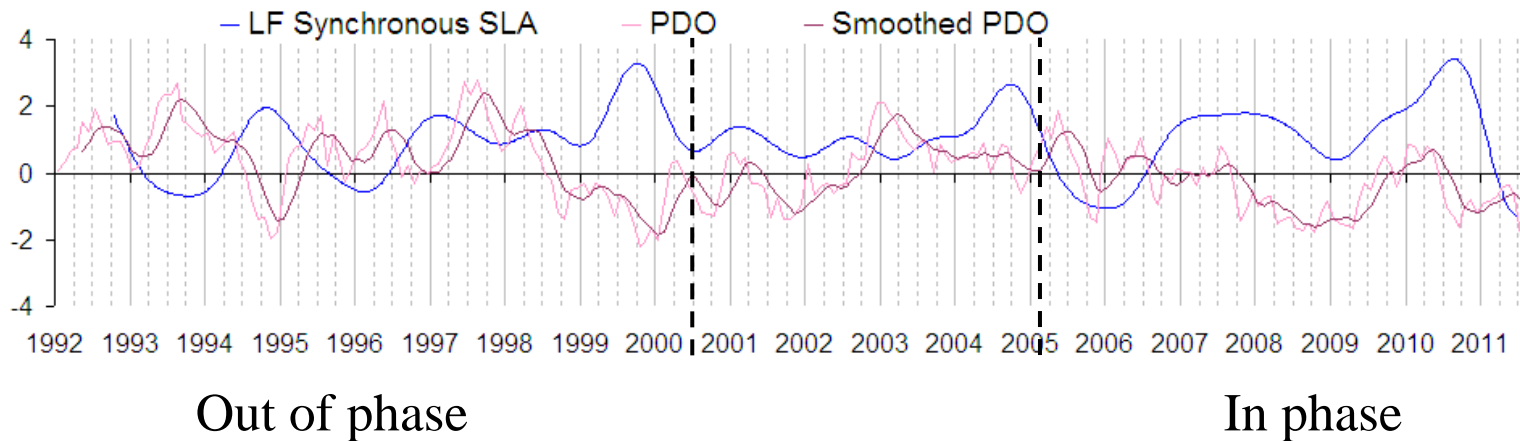
# Relationship with transport in the Korea Strait

From ADCP  
mounted  
onboard of  
*Camelia* Ferry




Considerable sea level rise in 1999 and decline in July 2005 through June 2006 corresponds to the transport in the Korea Strait being largest (smallest) in 1999 (2005) (Ostrovskii et al., 2009).

# Changing linkage with PDO




Positive SLA with negative PDO explained by transport variations in the Korea Strait (Gordon and Giulivi, 2004)

# Interannual regimes of the east - west seesaw in SLA, EKE, and SST (S9 poster)



## East-west regime shifts in the Japan/East Sea

Oлга Trusenkova (trolia@pol.dvo.ru) and Dmitry Kaptenko  
V.I. Il'ichev Pacific Oceanological Institute, Vladivostok, Russia

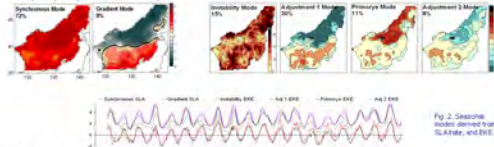


**Introduction** The previous analyses of altimetric sea level anomalies (SLA), eddy kinetic energy (EKE), sea surface temperature (SST) in the Japan/East Sea revealed modes of variability representing the east - west seesaw, with similar but not the same spatiotemporal patterns (Trusenkova et al., 2000, 2009, 2010, 2011). This seesaw corresponds to two major pathways of warm water transport from the Kuroshio/Oyashio midward (Fig. 1). Our attention has been previously focused on the lower modes (Fig. 2), while the variability deserves a detailed analysis.

**Purpose of the study** To analyze joint variability in sea level, rate of its change, EKE, and SST, related to the east - west seesaw in the Japan/East Sea, reveal time scales, and establish interannual regimes in the transport pathways.

**Data** Area: 35.5°-48°N, 127.5°-142°E. AVISO weekly/daily reference 1/4°-gridded SLA, from October 1992 onwards; rate of sea level change  $R = \partial\eta/\partial t$  where  $\eta$  is SLA,  $t$  is time.  $EKE = \langle u^2 + v^2 \rangle$  where  $u, v = \langle \partial\eta/\partial x, \partial\eta/\partial y \rangle$  are geostrophic velocity components, and  $\langle \cdot \rangle$  is Gaussian correlation. Daily 1/4°-gridded SST from Japan Meteorological Agency, from October 1993 onwards; SST anomalies (SSTA) computed by removing the leading mode of the original SST. Smoothing of Rate, EKE, and SST by wavelet filtering, with cut-off periods of 9, 20, and 2 weeks, respectively.

**Method** Derivation of non-orthogonal modes of variability by successive decompositions to EOF based on spatial correlations, with removing the contribution of the leading mode before the every next step. (Only statistically significant modes considered)  $X(t, y) = \sum A_n(t)B_n(x, y)$ , where  $X(t, y)$  is original signal,  $A_n(t)$  is eigenvector from spatial correlation matrix,  $B_n(x, y)$  is principal component (PC). Residual sampling  $X_n(t, y) = X(t, y) - A_n(t)B_n(x, y)$  is subjected to decomposition at the next step:  $X_{n+1}(t, y) = \sum A_{n+1}(t)B_{n+1}(x, y)$ . Using correlations allows for new modes in successive decompositions, i.e. it is possible that  $A_n$  and  $B_n$  are natural modes but non-orthogonal. In contrast, using covariances would only result in successive removing of a leading mode, with  $A_n = A_{n+1}$  and  $B_n = B_{n+1}$ .

**Background: seasonal SLA/Rate/EKE modes**  
SLA (its spatial systems are the same)  


**East - West SLA/Rate/EKE/SST Mode** In the **positive phase** sea level rises along the western coast (Fig. 3), enhancing the mean dynamic topography (Fig. 4). SLA sees rises of the mid Honshu (Fig. 3), and EKE increases in the southwestern and eastern sea (Fig. 5). In contrast, in the **negative phase** the sea level and SST rise in the western sea and the northwestern sea becomes more dynamically active due to the increased EKE.

The strongest spatial loadings of the EKE pattern are linked to the zero contours of the SLA Gradient and East-West Modes (Fig. 5). The southwest - northwest EKE seesaw is also related to the different flow patterns derived from surface drifters (Fig. 11 after Lee and Niler, 2010). Systems of anticyclonic eddies in the NW sea (Fig. 10) are an efficient device of the northward transport of warm water (Blanke et al., 2002).

SLA evolves on annual, quasi-biennial (QB), and interannual time scales; Rate manifests the semiannual periodicity only; SST features the annual, QB, and interannual time scales; and EKE has QB and interannual variability only (Figs. 3, 6-8).

On the seasonal time scale, the positive phase develops in late summer (SLA) through fall (SST), and negative phase develops in SLA from fall through spring, weakening in winter, while a weakly develops in spring (only in SST (Fig. 3, 6)). SLA and SST are moderately correlated, with SLA leading with 1-2.5 month lag (Fig. 3). The rate of the summertime phase change and wintertime weakening of the SLA mode is almost the same (Fig. 6, 8). The SLA mode was weak before 2000, with low-wavenumber power (Fig. 7). Temporal pattern of the EKE mode has been similar to that of the SLA mode in the periods of strong oscillations, in particular since 2000, including the extreme event in 2000 and the transitions from the strong positive phases (2000, 2004) to the strong negative phases (2003, 2009), with correlation of 0.7 (Fig. 6).

**Fig. 1** Mean pathways of warm water transport (courtesy by V. Lobkovsky)

**Fig. 2** Seasonal modes derived from SLA/Rate, and EKE

**Fig. 3** Spatial patterns of the East - West mode from SLA (contours), Rate (contours), and SST

**Fig. 4** Mean mode of sea level (above sea mean mode)

**Fig. 5** Spatial patterns of the East - West mode from SLA (contours), Rate (contours), and SST

**Fig. 6** EKE - West seesaw

**Fig. 7** Wavelet spectra from PC of the East - West SLA and Rate Modes

**Fig. 8** Correlation between PC of the East - West Modes from SLA and SST

**Fig. 9** Temporal patterns of the East - West Mode

**Fig. 10** Mean mode of sea level (above sea mean mode)

**Fig. 11** Flow patterns in the southwestern sea (SLA contours, drifter tracks to contours from Lee and Niler, 2010) Magenta contours outline the strongest negative loadings of the EKE mode

**Conclusion**

- The east - west seesaw between two major pathways of the northward transport of warm water from the Kuroshio/Oyashio manifests itself in SLA/Rate, SST, and EKE
- In the positive phase the warm water transport mostly occurs along the eastern coast, while in the negative phase the transport activates in the western sea
- The pathway seesaw develops on semiannual, annual, QB, and interannual time scales
- The interannual regimes of the positive phase occurred in 1993-1995, 2000, 2004-2005, and 2010 - onwards, while the regimes of the negative phase occurred in 1999, 2001-2003, and 2007-2009.
- The extreme positive and negative events occurred in 2000 and 2003, respectively. The SLA Mode was weak before 2000.



# Conclusion

- Neither sea level nor eddy kinetic energy in the Japan/East Sea reveal linear trends for the last two decades but rather they manifest oscillatory patterns.
- Sea level and mean EKE manifest QB and decadal variability.
- The Synchronous and Gradient Modes of sea level are coupled on the annual time scale, manifesting the same seasonal variation.
- The SLA Gradient Mode and Instability EKE Modes manifest the same seasonal variation, implying that shear instability is important for the EKE generation.
- There are no interannual counterparts of either SLA Gradient Mode or EKE Instability mode.
- Weak interannual variability of EKE can be attributed to the stability of the meridional sea level gradient, i.e. of the intensity of mean currents (on interannual time scale).
- Interannual variability of the mean EKE is due to the subtropical (southern) area and seems to be related to the transport variations in the Korea Strait.



Thank you!