Interannual variations in the Oyashio current and the subarctic front in the western North Pacific

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Background

- Realistic representation of the Kuroshio Extension and subarctic fronts in the OFES
- Center of action of large scale decadal SSTAs in the North Pacific is found along these fronts
- Oyashio tend to be enhanced when the subarctic front is cooled
Background 2

- Interannual variations in the Oyashio current and its mechanisms have not been clarified enough due to limited observation (length).

  Barotropic wave propagation (e.g., Sekine 1988, Hanawa 1995)
  
  High correlation between interannual variations in the southern most latitude of the Oyashio 1st branch and Sverdrup transport

  Baroclinic wave propagation (Qiu 2002)
  
  Contribute to interannual variability (based on observations in 1990s)
Purposes

To investigate

• Mechanism for Oyashio interannual variability
  (relation with wind-stress field)
• Influence of the Oyashio variations on SSTAs
  along the subarctic front

based on the OFES hindcast integration with its
54-yr data length.
Model: OFES (the Ocean model For the Earth Simulator)

Based on MOM3 (GFDL/NOAA), significantly modified on the parallelization procedures.

Solve primitive equations in spherical coordinate. Boussinesq and hydrostatic approximations are adopted.

Bi-harmonic horizontal mixing, & the KPP vertical mixing scheme.

Near-global model basin: 75°S-75°N, 0-360°E.

0.1 degree horizontal resolution, 54 vertical levels (max 6065m).

Surface heat fluxes are given by the bulk formula. Fresh water flux & SSS restoring to monthly climatology. NCEP reanalysis fields are used for wind stress and all atmospheric fields for the fluxes.

After 50-year spin-up integration by monthly climatology fields,
a hindcast integration for 1950-2003 with daily mean fields.
Kuroshio tends to overshoot, but two fronts are well represented.
Interannual variability in SST in the subarctic front

Area-mean SST in [40-42N, 147.5-152.5E]
Annual mean in OFES & JMA-SST

Warm bias in OFES

Although amplitude are larger, interannual variations are well represented.
Seasonal variation in Oyashio is enhanced in winter, consistent with observations. Wintertime area mean value will be investigated. Warm: northward, cold: southward speed.
Interannual variability in the area-mean Oyashio

Area mean northward velocity in [40–45N, 143–151E]

Use mean velocity in the large area as an index to exclude influence of eddies.

Vertical mean velocity
100m depth velocity [100m]–[vertical_mean]

Examine lagged correlations between wind-stress field and barotropic and baroclinic components of the Oyashio.

Wintertime enhancement is associated with changes in barotropic component.
Lagged correlation between barotropic component and curl $\tau$.

High simultaneous correlations in the whole North Pacific.

Almost no correlations in 1-yr lead and 1-yr lag.

Barotropic Oyashio variations by wind curl via barotropic wave propagation.

Can the variations be explained by changes in Sverdrup transport?

Lagged correlation of curl $\tau$ (shades) and regression of wind stress vectors (left) and surface current vector (right) with the vertical-mean area averaged Oyashio velocity based on Jan.-Mar. OFES hindcast fields.
Comparison between Oyashio and Sverdrup transports

Sverdrup transport integrated whole zonal width is too large

Sverdrup transport integrated to the west of 170E is appropriate

Around the Emperor Seamounts (170-180E), Barotropic waves tends to be disturbed.

JFM mean and 40-45N averaged

Simulated Oyashio transport between W.B.-151E (positive: southward)

Sverdrup transport integrated between 145-170E (positive: northward)

Sverdrup transport integrated between 145E-E.B. (positive: northward) Right vertical axis.

r = -0.68
r = -0.75
Lagged correlation between 100-m Oyashio velocity and Ekman pumping

Lagged correlation of Ekman pumping (shades) and regression of wind stress vectors (left) and surface current vector (right) to 100-m depth area-mean Oyashio velocity based on Jan.–Mar. OFES hindcast fields.

- Simultaneous correlation with local wind forcing
- Contribution of local forcing
- Correlation with 3-yr lead wind forcing around 170E

Suggest contributions of baroclinic wave propagations
Lagged correlation between baroclinic Oyashio and Ekman pumping

Lagged correlation of Ekman pumping (shades) and regression of wind stress vectors (left) and surface current vector (right) to baroclinic component of the area-mean Oyashio velocity based on Jan.–Mar. OFES hindcast fields.

- Simultaneous correlation with local wind forcing
- Correlation with 3-yr lead wind forcing around 170E

Correlations in the eastern basin is weak compared to the counterpart for 100-m depth Oyashio.
Summary of correlation analyses

Barotropic component: Propagation of barotropic waves

- Sverdrup transport based on the whole zonal width is too large
- Sverdrup transport to the west of 170E is comparable to the simulated Oyashio transport
- Barotropic wave propagations tend to be disturbed around 170–180E (the Emperor Seamount)

Baroclinic component:

- Simultaneous correlation with local forcing
- Correlation with 3-yr lead forcing around 160–170E
- Contribution of baroclinic wave propagation

100-m depth Oyashio:

- Contributions of both barotropic & baroclinic components
- Large influence of simultaneous wind forcing
- Contribution of 3-yr lead forcing via baroclinic wave propagation

How do the Oyashio variations influence the subarctic front?
Lagged correlation between Oyashio and SST

Lagged correlation (dashed contours) and regression (shades) of SST and 100-m depth area-mean Oyashio velocity based on Jan.–Mar. OFES hindcast fields. Solid contours show long-year mean fields.

Oyashio enhancement

Cooling near northern Japan

Cooling propagates/extends eastward along the subarctic front
Lagged correlation between Oyashio and SSH

Oyashio enhancement
Negative anomalies near northern Japan
Negative anomalies propagate/extend eastward along the subarctic front
SSTAs can be associated with subsurface changes.
Lagged correlation between isopycnal PV and Oyashio variations

Lagged correlation (contours) and regression (shades) of PV on $\sigma = 27.0$ and 100-m depth area-mean Oyashio velocity based on Jan.–Mar. OFES hindcast fields. Top-left panel shows long-year mean PV field on the surface.

Low PV waters extend eastward along the subarctic front after Oyashio enhancement.

Advection may induce changes in the frontal region.

$$PV = \frac{1}{\rho_0} \frac{\partial}{\partial z} (f + \frac{\partial v}{\partial x} \frac{\partial u}{\partial y})$$
Lagged correlation between sea surface heat flux and Oyashio variations

Downward heat flux anomalies associated with the cool SSTAs along the subarctic front after Oyashio enhancement, damping the SSTAs.

The SSTAs are not caused by atmospheric thermal forcing, but caused by oceanic processes.
Summary

Interannual variations in 100-m depth Oyashio:
Contribution of both barotropic and baroclinic components
Contribution of 3-yr lead forcing by baroclinic wave
Large contribution of simultaneous forcing
Following Oyashio enhancement
cooling off northern Japan
cooling propagate eastward along the subarctic front
This cooling is not caused by atmospheric thermal forcing.
(Surface heat flux anomalies tend to damp the SSTAs.)
These results suggest ocean-to-atmosphere feedback in the subarctic frontal region associated with the Oyashio variations.
Lagged correlation between *baroclinic* Oyashio and SST

Lagged correlation (contours) and regression (shades) of SST to baroclinic component of the area-mean Oyashio velocity based on Jan.–Mar. OFES hindcast fields.
Lagged correlation between *barotropic* Oyashio and SST

Lagged correlation (contours) and regression (shades) of SST to vertically averaged area-mean Oyashio velocity based on Jan.–Mar. OFES hindcast fields.
Lagged correlation between *decadal* variations in Oyashio and SST

Lagged correlation (contours) and regression (shades) of SST to 100-m depth area-mean Oyashio velocity based on 5-yr running mean Jan.–Mar. OFES hindcast fields.
Lagged correlation between *decadal* variations in 100-m Oyashio velocity and Ekman pumping

Lagged correlation of Ekman pumping (shades) and regression of wind stress vectors (left) and surface current vector (right) to 100-m depth area-mean Oyashio velocity based on 5-yr running mean Jan.–Mar. OFES hindcast fields.
Lagged correlation between decadal variations in baroclinic Oyashio and Ekman pumping

Lagged correlation of Ekman pumping (shades) and regression of wind stress vectors (left) and surface current vector (right) to baroclinic component of the area-mean Oyashio velocity based on 5-yr running mean Jan.–Mar. OFES hindcast fields.
Seasonal variations in SSHA: Satellite obs. vs. OFES

Satellites (AVISO-Merged SLA) vs. OFES

1993–2003 mean SSHA (Anomaly from annual mean of 1993–98)
Seasonal variation in surface current vector

Oyashio is enhanced in winter, consistent with observations

Wintertime area mean value will be investigated

Warm: northward, cold: southward speed
Interannual variability in the area-mean Oyashio

Area mean northward velocity in [143-151E, 40-45N]

Vertical mean velocity = 0.43
100m depth velocity = 1.08 [cm/sec]

Examine lagged correlations between wind-stress field and barotropic and baroclinic components of the Oyashio.

Use the large area mean as an index to exclude influence of eddies.

Standard deviations of interannual variability of the Oyashio.

Vertical mean velocity = 0.43
100-m depth velocity = 1.08 [cm/sec]
Lagged correlation between barotropic component and curl $\tau$

High simultaneous correlation in the whole North Pacific

Almost no correlations in 1-yr lead and 1-yr lag

Barotropic Oyashio variations due to barotropic wave propagation

Can the variations be explained by Sverdrup balance?
Lagged correlation between the baroclinic component and Ekman pumping

Simultaneous correlation with local wind forcing

Contribution of local forcing

Correlation with 3-yr lead wind forcing around 170E

Suggest contribution of baroclinic wave propagation

Wintertime (Jan.-Mar) lagged correlation of Ekman pumping (shades) and regression of wind-stress vector to the baroclinic component of the area-mean Oyashio current.

UV regression vectors are plotted only for |both r|>0.25.
C.I.=0.1x10^-4 cm/s (shading shows r.)
Lagged correlation between 100-m Oyashio velocity and Ekman pumping

Similar to the relation between the baroclinic component and the wind forcing

Simultaneous correlations are found in relatively wide region

Contribution of barotropic component
Correlation between decadal Oyashio and Ekman pumping variations

Lagged correlation (shades) and regression (contours) of Ekman pumping and regression of surface current vector to 100-m depth area-mean Oyashio velocity based on 5-yr running mean Jan.–Mar. fields.

Examine relations between longer time scale variations based on lagged correlations of 5-yr running mean fields.

Similar to the relation of the interannual variations, and high correlation region moves westward continuously.
Lagged correlation between Oyashio and SST

Oyashio enhancement

Cooling near northern Japan

Cooling along the subarctic front

propagate eastward
Eastward propagation of SSTAs in OFES & JMA-SST

JFM-mean SST anomalies (Anomalies from 1950-99 mean. Trends are removed.)

Center of negative SSTAs appear near Japan and propagate eastward along the subarctic front.
Lagged correlation between decadal Oyashio and SST variations

Eastward propagation of cool SSTAs after Oyashio enhancement

Steady cool SSTAs along northern Japan

Lagged correlation (shades) and regression (contours) of SST and regression of surface current vector to 100-m depth area-mean Oyashio velocity based on 5-yr running mean Jan.-Mar. OFES fields.

SST leads 3 yrs

SST lags 1 yr

Lag 0

Winds lead

Winds lag
Lagged correlation between isopycnal PV and Oyashio variations

Lagged correlation (shades) and regression (contours) of PV on $\sigma = 27.0$ and regression of surface current vector to 100-m depth area-mean Oyashio velocity based on Jan.-Mar. OFES hindcast fields.

Low PV waters extend eastward along the subarctic front after Oyashio enhancement.

Advection may induce changes in the frontal region.

$$PV = \frac{1}{\rho_0} \frac{\partial \rho}{\partial z} (f + \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y})$$
Lagged correlation between sea surface heat flux and Oyashio variations

Lagged correlation (shades) and regression (contours) of surface heat flux and regression of surface current vector to 100-m depth area-mean Oyashio velocity based on Jan.-Mar. OFES fields.

Upward heat flux anomalies associated with the cool SSTAs along the subarctic front after Oyashio enhancement, damping the SSTAs.

The SSTAs are not caused by atmospheric thermal forcing, but caused by oceanic processes.
SSHの経年変動

OFES hind: annual mean Oyashio region SSH 1993-95

OFES年平均SSH場
1993-95年平均（上）と1997-99年平均（下）

気候値水温塩分から計算した力学的高度
+1993-95年平均（上）、1997-99年平均（下）

海面高度偏差 Qiu (2002)
月毎の親潮流量とSverdrup流量の比較

月平均の

西岸-151Eで積分し、40-45Nで平均した親潮流量

145-170Eの風curlを積分し40-45Nで平均したSv流量

145E-東岸の風curlを積分し40-45Nで平均したSv流量

経年変動と同様に

海盆全域から計算したSverdrup流量は過大

天皇海山列（170E）以西のSverdrup流量が適当
西部北太平洋域で平均した海面高度偏差の季節・経年変動

AVISO & OFES Sea level anomaly (from 93-98 mean)
134-161E, 28-51N area mean

134E-161W, 28-51Nで領域平均した海面高度偏差（1993-98年平均からの偏差）
領域平均親潮流速の鉛直平均成分とEkman pumpingとのラグ相関

十年規模順圧成分とEkman pumpingとのラグ相関

領域平均親潮流速の鉛直平均成分とEkman pumpingとのラグ相関（色）、回帰係数（等値線）、及び、海面流速との回帰係数（ベクトル）。1-3月平均場の5年移動平均経年変動相関場。
十年規模傾圧成分とEkman pumpingのラグ相関

領域平均親潮流速の傾圧成分とEkman pumpingとのラグ相関（色）、回帰係数（等値線）、及び、海面流速との回帰係数（ベクトル）。1-3月平均場の5年移動平均経年変動相関場。
Appendix 1

天皇海山列は親潮変動に影響を与えるのか？
親潮流量とSverdrup流量の比較

海盆全域から計算したSverdrup流量は過大
天皇海山列（170E）以西のSverdrup流量が適当
170-180E付近で順圧波伝播の不連続・減衰

順圧波の伝播特性を見るため、11日の移動平均を差し引いて短周期変動を取り出した40-45N平均の海面高度変動の時間-経度diagram

OFES-hind; 40°-45°N mean Oyashio transport (W.B.~151°E) [Sv]
40°-45°N mean Sverdrup transport (145°-170°E) [-Sv]
40°-45°N mean Sverdrup transport (145°E-E.B.) [-Sv]

順圧波伝播の不連続、減衰

\[ r = -0.68 \]
\[ r = -0.75 \]
順圧波伝播の具体例

11日のハイパスフィルターをかけた海面高度偏差。一日毎のsnapshotをplotした。

順圧波の西方伝播が見られるが、170E付近以西では伝播が明確に見られない。
ラグ相関係数分布でみた順圧波伝播

11日のhigh-pass filterを施した海面高度偏差の175-185E、40-45N平均に対するラグ相関図。

170E以西ではsignalの西方伝播が明確でなくなる。
天皇海山列の東側でSverdrup balanceしているのか？

東岸から天皇海山列の東側（180-185E、実線）と西岸付近（155-160E、破線）まで積分した北向き流量（赤）とSverdrup流量（黒）。40-45N平均。

<table>
<thead>
<tr>
<th></th>
<th>155-160E</th>
<th>180-185E</th>
</tr>
</thead>
<tbody>
<tr>
<td>標準偏差</td>
<td>Sverdrup流量</td>
<td>17.92</td>
</tr>
<tr>
<td></td>
<td>OFES</td>
<td>9.27</td>
</tr>
<tr>
<td>相関係数</td>
<td></td>
<td>0.65</td>
</tr>
<tr>
<td>回帰係数</td>
<td></td>
<td>1.26</td>
</tr>
</tbody>
</table>

(Sv/OFES)

天皇海山列の東側でも、ある程度Sverdrup balanceしており、西岸付近との相違は、天皇海山列での順圧波伝播が遮られることとconsistentではある。
Appendix 2

OFES における北太平洋十年規模変動
The two fronts in the KOE region

Two strong SST fronts, the Kuroshio Extension (KE) front and the subarctic (Oyashio) front, are represented separately in the OFES simulation.
Decadal SSTAs


Large scale distributions are well represented.

SSTAs in the OFES have cores along the SST fronts, especially along the subarctic front, suggesting importance of meridional migration of the fronts.
T, S anomalies on meridional sections T, S anomalies extend vertically associated with meridional migration of the fronts. Max. of anomaly is found in the surface (subsurf.) layer in the subarctic (KE) front region.

JFM 145-160E mean latitude-depth sections of T, and S in 1984-88 (top), 1976-80 (middle), and 1968-72 (bottom).
In both the OFES and observations, the KE front is intensified in the cool period (top). While the KE current is also intensified, cool anomalies are found there. JFM 145-160E mean latitude-depth sections of $T$ in 1984-88 (top), and 1968-72 (middle) in the OFES (left) and observed data (right). Shades are meridional gradient of $T$. (Bottom) Shades: $T$ difference from 1968-72 to 1984-88.
Oyashio, Oyashio Extension, Kuroshio Extension currents are enhanced in 1984-88, cool period.

Enhanced southward cool water transport may have some role to induce cool SSTAs.

JFM mean sea surface currents for 1984-88 (top) and for 1968-72 (bottom). Shadings show speeds.
Decadal variability is represented well in the OFES hindcast run, at least at the sea surface.
Appendix 3

亜寒帯前線域での渦位分布とその変動

\[ PV = \frac{1}{\rho_0} \frac{\partial \rho}{\partial z} \left( f + \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \]
長期及び5年の平均等密度面上渦位と流速分布

27.0σ上の渦位と深さ分布（1-3月平均）

黒潮続流前線側に高渦位、亜寒帯前線沿いからその北側に低渦位水

低渦位水は親潮源流域及び、オホーツク海から供給される
等密度面上の渦位分布：5年移動平均

27.0σ上の渦位と深さ分布（1-3月平均）

80年代に低渦位水がより南側に張り出すように変化
等密度面上の渦位偏差：5年移動平均

27.0σ以上の渦位偏差と深さ分布（1-3月平均）

80年代に低渦位偏差が亜寒帯前線沿いに東方へ拡がる
84-85年にかけて低渦位偏差が亜寒帯前線沿いに東方へ拡がる（小さい規模の変動が大きくなりあまり明確ではない）
風分布からみた親潮変動、海面水温変動
風応力分布は、100m深親潮との相関分布と良く一致。3年後の親潮との相関が低い。
風応力分布は、100m深親潮との相関分布と良く一致。3年後の親潮とも相関を持つ。
45-50N Ekman 湧昇と親潮他の相関回帰係数

160-180E Ekman 湧昇との相関

親潮源流域と同時相関、亜寒帯前線上のSSTAと良いラグ相関を持つ。

大気からの間接的なforcingの影響が亜寒帯前線域に現れることを示唆する。