Variability and mixing in the Kuroshio and impact on ecosystem and climate
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Outline
1. Kuroshio interdecadal-scale variation & impact on Japanese sardine
2. Climate variability of PDO and its relation to mixing variability
Sardine spawns south of Japan in winter around the Kuroshio. Eggs and larvae are transported by the strong Kuroshio Current and juveniles migrate northward in spring and summer in the Kuroshio-Oyashio Extension Region. Sardine recruitment could be determined by environments along these transport routes.

Huge inter-decadal catch variability
Peaks in the 1930s and the 1980s (>4 million tons) 40% of total landings in Japan, 1/20 of the world total
Poor catch period (<10,000 ton)
Decline after 1988

Sardine Catch in Japan

$X \times 10^3$ tons

1988


0 1,000 2,000 3,000 4,000 5,000

Oyashio

Kuroshio

Kuroshio Extension
Inter-decadal western North Pacific variability: 10-years mean Feb-SST anomalies

- **Warm:** 1940s-1950s and 1988- present
- **Cold:** 1970-1987
Annual survival index of Japanese sardine is well correlated with the winter mixed layer depth (MLD) and winter-spring SST along the Kuroshio path where sardine larvae are transported. The correlation is significant within 0.5 degree north from the current axis. Deeper winter ML indicates greater nutrient supply to photosynthetic surface layer and greater plankton production that is food for fish larvae.
Winter-MLDs 0-0.5° north of the Kuroshio axis are correlated with April Chl-a density in both the SeaWiFS obs. and OFES-NPZD model (Nishikawa et al. 2013 MEPS)

Along the transport route from the Kuroshio axis to 0.5deg north of the axis, winter-MLD and spring Chl-a are positively correlated for both the observation using SeaWiFS Chl-a and 3D ecosystem model. This suggests that the nutrient supply through winter large MLD leads to enhanced spring bloom and thus food availability variability in spring cause the survival variability of sardine.
Enhanced turbulent mixing and vertical nitrate flux in the High Chl-a 0-0.5°N of the Kuroshio axis in spring (Kaneko et al. 2012; 2013GRL)

Turbulent vertical mixing is enhanced ±50km of the Kuroshio axis. In particular, turbulent nitrate flux is large by the large diffusivity and nitrate vertical gradient from the axis to 50km north of the axis. This area corresponds to the high Chl-a band where positive correlation is detected between winter MLD and spring Chl-a. This large nitrate diffusive supply could transmitt the winter nitrate condition to spring surface layer even after spring Stratification and bloom and could prolong the influence of winter MLD to food availability for sardine larvae.
Cause of winter-MLD • SST variability along the Kuroshio axis: Bulk-mixed layer model with particle tracking

(Nishikawa and Yasuda 2011, Journal of Oceanography)

Bulk-mixed layer model was applied to the OFES, and factors were analyzed along particle trajectories


Velocity : Heat flux=2: 1

Current velocity and surface heat flux are the two dominant factors: Slow current and stronger winter cooling contribute to sardine favorable conditions of winter larger MLD and lower SST

Net heat flux

Velocity along Kuroshio

— high-SST • shallow-MLD
— low-SST • deep-MLD
Japanese sardine responds to inter-decadal Pacific climate variability through winter SST & MLD variability along the Kuroshio Front which depends on current speed and cooling that controls spring bloom and food availability for larvae and juveniles through winter nutrient supply from subsurface and enhanced turbulent mixing.
Coherent variability of 17-20\textsuperscript{th} century J. Sardine and N.W.US climate: Over-arching climate variability: Pacific Decadal Oscillation (PDO)

- Old documents shows repeat good/bad catch in 50-70 years cycle (Tsuboi 1987)
- High Tair in NW-US: low-SST and High catch in Japan (Yasuda et al. 1999 FO)

17-20\textsuperscript{th} century sardine catch variability is related with NW-US spring air temp (Yasuda et al. 1999 FO)

Japanese sardine and NW-US temperature relationship is explained by basin-wide climate mode of Pacific Decadal Oscillation (PDO); For positive PDO, Aleutian Low Pressure is strong and low-SST in the western Pacific due to enhanced north-westerly wind and high-SST along the western coasts of America due to poleward wind anomaly.
What is the cause of the bi-decadal variability?

Inter-decadal component of PDO is well approximated by bi-decadal and penta-decadal (3X bi-decadal) components. These two changed sign simultaneously suggesting some connections (Minobe 2000).

What is the cause of the bi-decadal variability?
Bi-decadal variability of climate/fisheries and vertical mixing

18.6-yr period tidal oscillation-induced mixing variability
(e.g. Yasuda et al. 2006)

- SST is 2 degC near the Kuril Straits
  Due to cooling by strong tidal mixing

18.6-yr tidal oscillation: Moon orbit changes the inclination with the mean 23.4 deg and the amplitude 5 deg with the 18.6-yr period

- Diurnal tidal amplitude changes up to 20%
- 20% variability of strong tidal mixing could lead to big impacts. Indeed, in the Oyashio Water DO downstream of Kuril Straits with strong vertical mixing demonstrates clear 18.6-yr period variability. The bi-decadal fisheries and climate variations could be related with the tidal period.
Significant 18.6-yr signal in the PDO (Pacific Decadal Oscillation) records reconstructed from tree rings (Yasuda 2009GRL)

Statistically significant 18.6yr signal is detected in PDO time-series reconstructed from tree-rings. In the 3-4\textsuperscript{th} (9-12\textsuperscript{th}) year after maximum diurnal tide, mean-POD is significantly negative (positive).

\[ CI95\% = 1.96 \times std / \sqrt{N} / 18.6 \]
Bi-decadal SST/SLP/SSS pattern synchronized with 18.6-yr cycle (Yasuda et al. 2006; Osafune & Yasuda 2006; 2010; 2012; konda, MS-thesis)

TideMax+3yr winter-SST

SSS(TideMAX-MIN)

---- 95%-confidence

Salinity & winter-Temp. vertical profiles in the Subarctic North Pacific

T & S take minimum at surface and increase with depth. Enhanced mixing makes T & S increase near surface
Evidence of enhanced turbulence in Kuril and Aleutian Straits with direct microstructure measurements


1-3 order of magnitude greater diffusivity were observed in the Kuril and Aleutian Straits

e.g. Itoh et al.(2010JGR; 2012GRL)
Yagi & Yasuda (2012GRL)
Climate air-sea coupled model experiments with 3D tidal mixing distribution and its 18.6-yr variations (Tanaka et al. 2012JC)

\[ D = \rho g \langle \mathbf{U} \cdot \nabla (\zeta_{EO} + \zeta_{SAL}) \rangle - \rho g \nabla \cdot (\mathbf{U} \zeta) \quad \varepsilon = \frac{q}{\rho} E(x,y) F(z) \]

3D distribution of $\varepsilon$ and its 18.6yr variation are implemented in the air-sea-ice coupled climate model (MIROC3), following parameterization [St.Laurent et al. 2007;Jayne 2009] and tide-model currents [Egbert & Ray 2003]. The efficiency $q=1$ for subinertial $K1$ and $O1$, and $q=0.3$ for others [Tanaka et al. 2010] and the amplitudes of 18.6-year period variability are ($K1$:23% (=1.11)$^2$, $O1$:41%, $M2$: 7.5%).

18.6-yr amplitude

(red: diurnal  blue: out of phase)
Comparison of SST/SLP between observations and climate model experiments with 18.6-yr mixing variability
(Hasumi et al. 2008GRL; Tanaka et al. 2012 J. Climate)

Anomaly patterns over the north Pacific are consistent with observed bi-decadal patterns. Model results with only Okhotsk-Kuril mixing variability yielded similar patterns, indicating the importance of Okhotsk-Kuril mixing on climate variability.
Pathway of bi-decadal climate variability originating from 18.6-yr tidal mixing variability in the Kuril Straits
(Hasumi et al. 2008GRL; Tanaka et al., 2012JC; Osafune & Yasuda 2013JGR)

Stronger tidal mixing around the Kuril Straits induces positive winter SST anomaly and subsurface density anomaly. These anomalies propagate along the Oyashio current and produce the positive SSTa in the downstream Kuroshio-Oyashio Extension regions. The SSTa is maintained by the long-lived subsurface density anomaly which induces surface current and SSTa. This SSTa weakens the Aleutian Low Pressure and amplifies the SSTa due to the weakened Westerly. This mid-latitude air-sea interaction could make 18.6yr variability noticeable.
Summary

• Japanese sardine responds to inter-decadal Pacific climate variability as PDO through the Kuroshio Front winter SST & MLD which depends on current speed and cooling and controls spring food availability for larvae and juveniles through enhanced turbulent mixing and nutrient supply from subsurface.

• Bi-decadal PDO component is related with 18.6-yr period tidal oscillation which determines the phase of the bi-decadal variability.

• One possible path is from Kuril Strait strong tidal mixing zone to Kuroshio-Oyashio Extension area and to the Aleutian Low through mid-latitude air-sea interaction.

• Many issues on under-sampled vertical mixing and its impact on ocean circulation, biogeochemistry, climate and ecosystem.
**Overarching Goals**

Explore vertical mixing in western North Pacific & impacts on circulation, biogeochemistry, climate and ecosystem:

- Deep Circulation in the N.P.  
  (quantify upwelling through vertical mixing)
- Processes to sustain ocean ecosystem  
  (quantify transport of nutrients to ecosystem)
- Long-period variability and forecast of ocean/climate/fisheries  
  (Reproduce bi-decadal and related period variability and their mechanisms)

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