# Understanding Roles of Oceanic Fine Structures in Climate and Its Variability

Project Representative
Hideharu Sasaki Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology

Authors
Hideharu Sasaki Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology
Masami Nonaka Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology
Akira Kuwano-Yoshida Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology
Satoru Okajima Research Center for Advanced Science and Technology, The University of Tokyo
Yoshikazu Sasai Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology

We have been investigating roles of oceanic fine structures in climate and its variability by using high-resolution, primitive equation based, atmosphere, ocean and ocean-atmosphere coupled models, and a non-hydrostatic ocean-atmosphere coupled model. In this report, we present the following four topics, for all of which the oceanic fine structures play crucial roles. 1) Uncertainty in the Kuroshio Extension jet interannual variability, 2) Cyclogenesis response to the Kuroshio-Oyashio sea surface temperature (SST) front, 3) Large-scale atmospheric response to SST anomalies in the midlatitude North Pacific, and 4) Oceanic submesoscale variability and its impacts on the physical and biological fields.

**Keywords**: Oceanic fine structures, Sea surface temperature front, Kuroshio Extension jet, Cyclogenesis, Large-scale atmospheric response, Oceanic submesoscales, Oceanic biological field

## 1. Introduction

We have been leading researches on roles of oceanic fine scale structures in climate and its variations using atmosphere, ocean, and atmosphere-ocean coupled simulations on the Earth Simulator. Local air-sea interactions associated with oceanic fine structures such as fronts and eddies, which have significant potential impacts to modify local atmospheric and oceanic conditions and thus regional and larger scale climate systems, are observed in the world ocean. Oceanic fronts along the Kuroshio and Gulf Stream affect not only near-surface atmosphere but also entire troposphere, suggesting active roles of the mid-latitude ocean in the weather and climate. Furthermore, contributions of oceanic submesoscales smaller than mesoscale structures to large-scale oceanic field and oceanic ecosystems are implied in resent high-resolution satellite image and oceanic simulations. Oceanic surface wave and its dissipation should be considered to estimate surface momentum flux, which could reproduce realistic air-sea interactions with high surface wave.

We highlight in this report our recent progress in researches on the roles of oceanic fine structures in climate and its variability using simulations. In Section 2, uncertainty in the Kuroshio Extension jet interannual variability is discussed by conducting ensemble simulations of eddy-resolving ocean general circulation model (OGCM) hindcast experiment. In Section 3, a role of the Kuroshio-Oyashio sea surface temperature (SST) front on cyclogenesis is revealed by using atmospheric general circulation model (AGCM). In section 4, large-scale atmospheric response to SST anomalies in the midlatitude North Pacific is assessed by ensemble AGCM sensitivity experiments. Impacts of oceanic submesoscale variability on the physical and biological fields in a high-resolution coupled physical-biological ocean model are reported in Section 5.

## 2. Uncertainty in the Kuroshio Extension jet interannual variability

The Kuroshio and Kuroshio Extension (KE) transport huge amount of heat into midlatitude, and have significant impact in the climate system in the North Pacific sector. Further, recent studies have suggested that decadal changes in the speed of the Kuroshio and the upstream KE jet can influence natural mortality of infant Japanese sardine. Understanding of variability in the path and intensity of the KE jet is thus of social and scientific importance. It has been suggested that, on the one hand, interannual to decadal variability in the KE jet is induced by large-scale atmospheric variability. On the other hand, numerical model studies have shown that such KE jet variability can appear as oceanic intrinsic variability under wind field without interannual variability. Then, in the present study, we examined oceanic intrinsic variability under interannually varying atmospheric field.

To investigate intrinsic variability in the North Pacific Ocean, we have conducted eddy-resolving OGCM ensemble hindcast experiment with slightly different conditions and an identical interannually varying atmospheric forcing. One can consider differences in the simulated fields are caused by oceanic intrinsic variability. In our experiment, slight differences in time step and/or in the initial conditions, which corresponds to just 10-day difference in a hindcast integration, induce remarkable differences not only eddy fields but also larger spatiotemporal scale fields. As shown in Fig. 1, interannual variability in the KE jet speed shows substantial difference among the members, indicating it is significantly influenced by the intrinsic variability. Also, so are the SST and salinity fields in their frontal zones in the western North Pacific. In contrast, interannual variability in the tropical Pacific is strongly governed by the external atmospheric forcing, and deterministic.

Although the number of ensemble members is quite limited in our experiment due to limited computational resources, the results indicate that interannual variability in the midlatitude western boundary current (WBC) and its extension region can include significant uncertainty. While it is, of course, impossible to examine uncertainty in the real ocean, our results based on a realistic OGCM imply that there is significant uncertainty in the real KE and we can observe just one realization of its variability. This means that for investigation of such variability with eddy-resolving OGCM hindcast simulations, multi ensemble integration is necessary to take account of the uncertainty. At the same time, it is expected that the uncertainty is model dependent, and multi-model experiment is also necessary as the next step. The strong dependence on the initial condition also suggests that for prediction of the WBC and its extension, initialization of the prediction model by assimilating observed data may not be sufficient, and multi ensemble prediction is necessary.

## 3. Cyclogenesis response to the Kuroshio-Oyashio SST front

To understand the role of SST fronts associated with the Kuroshio, Oyashio and their extensions, two AGCM experiments are conducted. AGCM for the Earth Simulator (AFES) with T239L48 is used. The control experiment (CNTL) is integrated for 20 years with high-resolution observed SST, while the sensitivity experiment (SMTH) is integrated with smoothed SST fronts (Fig. 2a). The local pressure tendency analysis suggests that in winter, rapid deepening of extratropical cyclones increases over the SST fronts in CNTL run compared

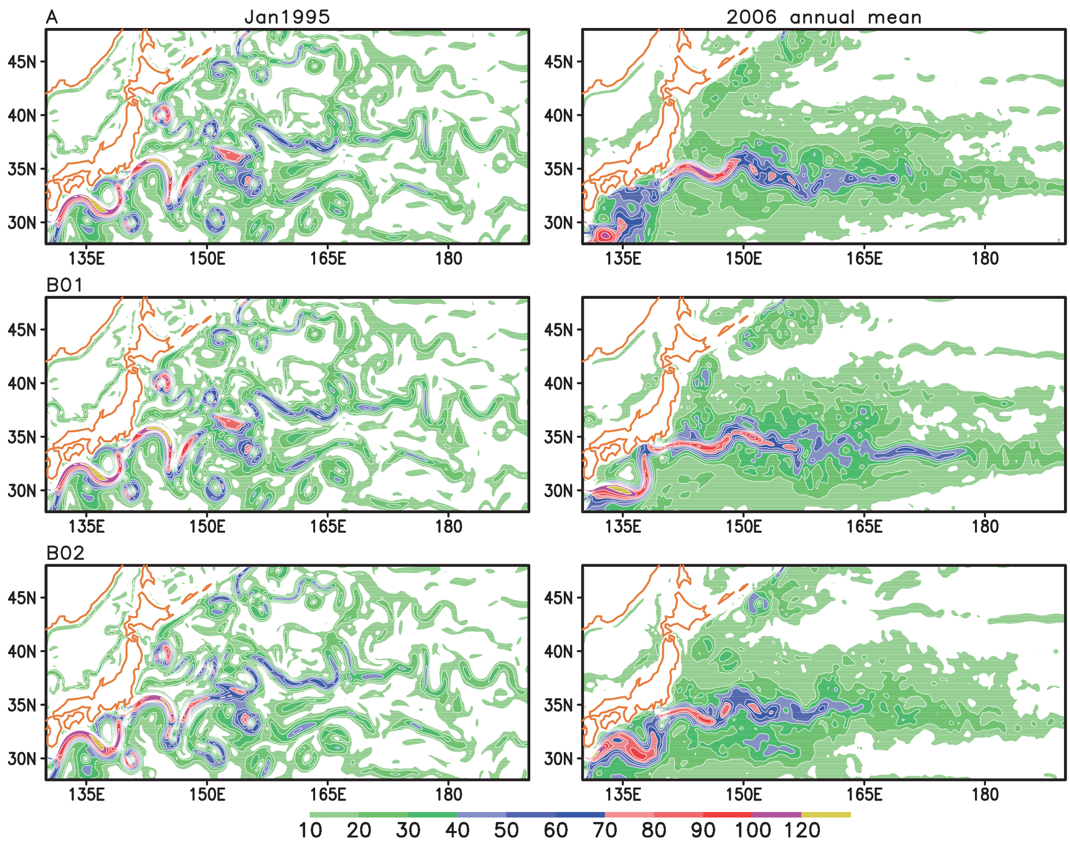


Fig. 1 100-m depth current speed (cm/s) in each member of the three-member ensemble hindcast experiment. (left panels) Monthly mean in January 1995, the first month of the experiment. (right panels) Annual mean in 2006.

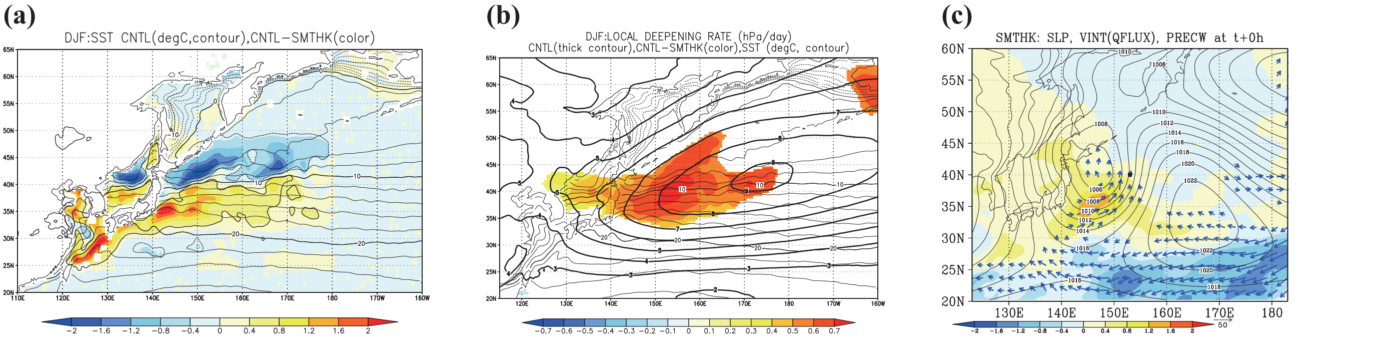


Fig. 2 (a) SST difference between CNTL and SMTH in DJF (°C, color), CNTL SST (°C, contour). (b) Pressure tendency rate difference between CNTL and SMTH with 95% significant level (hPa/day, color). Positive means pressure deepening. Bold contour is positive-only average of pressure tendency rate in CNTL. SST in CNTL (°C, thin contour). (c) Composites of SLP in CNTL (hPa, contour), and differences of vertical integrated moisture amount (mm, color) and vertical integrated moisture flux (mm m/s, vector) between CNTL and SMTH when pressure tendency rate is larger than 1 hPa/h at 153°E, 40°N (closed circle).

with SMTH run (Fig. 2b). The composite analyses for rapid deepening over the SST fronts suggest that moisture provided from Kuroshio along south coast of Japan flows into cyclones, and the enhanced latent heat release associated with precipitation leads to the more rapid deepening of cyclones (Fig. 2c).

## 4. Large-scale atmospheric response to SST anomalies in the midlatitude North Pacific in October

The influence of extratropical SST anomalies on large-scale extratropical atmospheric circulation has long been believed to be insignificant (e.g. Kushnir et al., 2002 [1]), based partly on results from sensitivity experiments with low-resolution AGCM. In this study (Okajima et al. 2014 [2]), their importance in forcing large-scale atmospheric anomalies is assessed through analysis of ensemble sensitivity experiments using AFES at higher resolution (~1° horizontal resolution and 56 vertical levels), focusing on the prominent warm SST anomalies observed in 2011 summer and autumn along a prominent oceanic frontal zone in the western North Pacific. Each of the experiments comprises 10 ensemble members integrated from June to October. The anticyclonic anomaly observed in October 2011 is well reproduced as a robust response of AGCM forced only with the warm SST anomaly associated with the poleward-shifted oceanic frontal zone in the midlatitude Pacific (Figs. 3a and 3b). The equivalent barotropic anticyclonic anomaly over the North Pacific is maintained under strong transient eddy feedback forcing associated with the poleward-deflected stormtrack (Fig. 4). Energy converted from the climatological-mean circulation also contributes substantially to the maintenance of the anticyclonic anomaly particularly in the model, indicative of its characteristic as a dynamical mode inherent to the co-existence of the extratropical climatological-mean flow and oceanic frontal zone (not shown). As the downstream influence of the anomaly, abnormal warmth and dryness observed over the northern U.S. and southern Canada in October are also reproduced to some extent (not shown). The corresponding AGCM response over the North Pacific to the tropical SST anomalies is in the same sense but substantially weaker and less robust (Fig. 3c), suggesting the primary importance of the prominent midlatitude SST anomaly in forcing the large-scale atmospheric anomalies observed in October 2011. Our results present another piece of evidence that a midlatitude SST anomaly has the potential to actively force large-scale atmospheric anomalies in the extratropics.

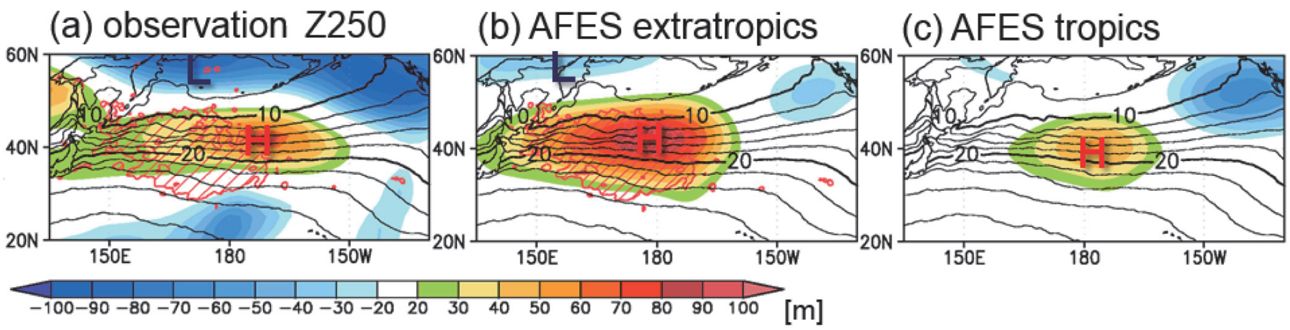


Fig. 3 (a) Map of monthly 250-hPa height anomalies (color) in October 2011 based on the JRA-25 data, superimposed on the climatological-mean SST in October (contour). Red hatches indicate SST anomalies warmer than the climatology by more than +1°C. (b)-(c) Same as in (a), respectively, but for the ensemble response of the sensitivity experiment for the SST anomaly in (b) the midlatitude North Pacific and (c) the Tropics.

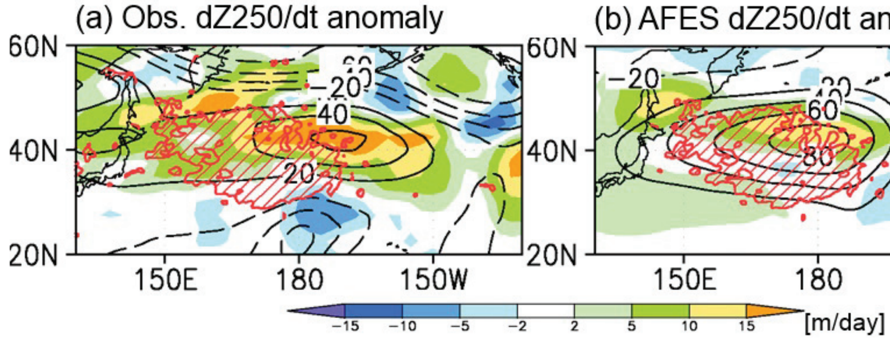


Fig. 4 (a) Anomalous geopotential height tendency at 250-hPa (m/day, color) induced by anomalous heat and vorticity fluxes associated with transient eddies, superimposed on 250-hPa height anomaly (contour, zero line is omitted). (a) is for October 2011 based on the JRA-25 data. Red hatches indicate SST anomalies warmer than the climatology by more than +1°C. (b) Same as in (a), but for the ensemble response of the sensitivity experiment for the SST anomaly in the midlatitude North Pacific.

## 5. Oceanic submesoscale variability and its impacts on the physical and biological fields

Ocean color satellite imagery reveals the smaller-scale variability (O(1-10km)) in the surface chlorophyll distribution. As a limited high quality ocean color satellite, we try to understand the submesoscale dynamics on the surface phytoplankton field using a high-resolution coupled physical-biological model. The model covers North Pacific (20˚S to 66˚N, 100˚E to 70˚W). The horizontal resolution is 1/30˚ and the vertical levels are 100. We also focus on the seasonality of submesoscale dynamics effects on the surface phytoplankton distribution. In the Kuroshio Extension, eddy activity is the highest and the seasonality of submesoscale dynamics is shown. In the south of the Kuroshio Extension, the model presents

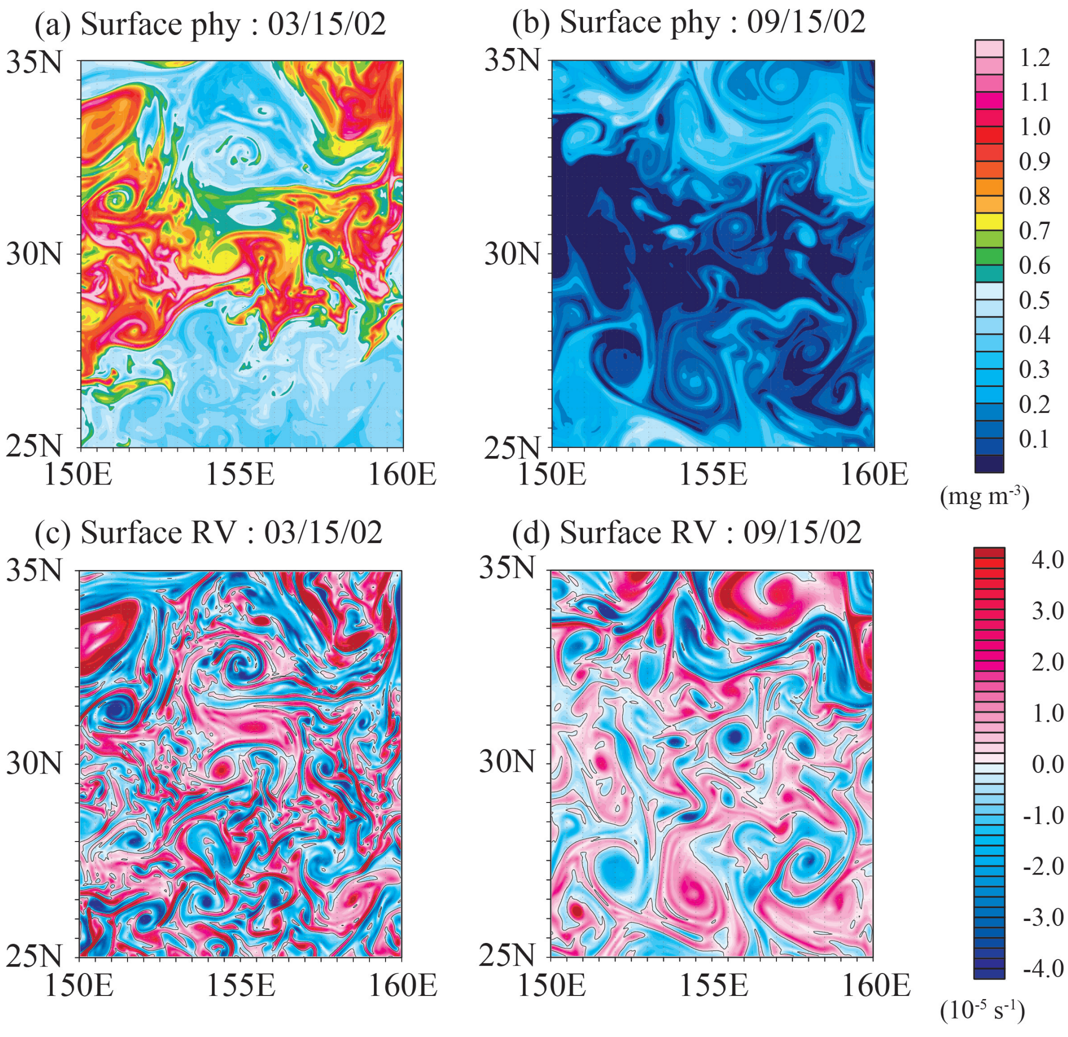


Fig. 5 Surface phytoplankton concentration (mg/m$^3$) (a-b), and surface relative vorticity (10$^{-5}$ 1/s) (c-d) in the Kuroshio Extension region of 150˚E – 160˚E and 25˚N – 35˚N on March 15, 2002 and on September 15, 2002 in the model.

the similar pattern of submesoscale variability in the surface phytoplankton field in early spring, but in fall, this submesoscale pattern is weak because the mesoscale variability is dominant (Fig. 5). In winter, the energetic submesoscale variability is associated with the smaller scale of vertical velocity, which produces the submesoscale pattern of nitrate field. The submesoscale pattern of phytoplankton field in winter and early spring is formed by the submesoscale vertical injection of nitrate and the light intensity condition. The seasonality of submesoscale dynamics is significant to the phytoplankton production.

## 6. Conclusion

We have briefly reported research activities to investigate roles of oceanic fine structures in climate and its variability by using high-resolution, primitive equation based, atmosphere, ocean and coupled models. In this fiscal year, uncertainty in the Kuroshio Extension jet interannual variability are discussed, and the cyclogenesis response to the Kuroshio-Oyashio SST front and its mechanism are revealed. Large-scale atmospheric response to SST anomalies in the midlatitude North Pacific is investigated. In addition, large response of oceanic submesoscales on physical and biochemical fields are revealed.

## References

[1] Kushnir, Y., W. A. Robinson, I. Bladé, N. M. J. Hall, S. Peng, and R. Sutton, “Atmospheric GCM response to extratropical SST anomalies: Synthesis and evaluation”, Journal of Climate, 15, 2233-2256, 2002.

[2] Okajima S., H. Nakamura, K. Nishii, T. Miyasaka, and A. Kuwano-Yoshida, “Assessing the importance of prominent warm SST anomalies over the midlatitude North Pacific in forcing large-scale atmospheric anomalies during 2011 summer and autumn”, Journal of Climate, 27, 3889-3903, 2014.

# 海洋の渦・前線とそれらが生み出す大気海洋現象の解明

課題責任者
佐々木英治　　海洋研究開発機構　地球シミュレータセンター
著者
佐々木英治　　海洋研究開発機構　地球シミュレータセンター
野中　正見　　海洋研究開発機構　地球環境変動領域
岡島　　悟　　東京大学　先端科学技術研究センター
吉田　　聡　　海洋研究開発機構　地球シミュレータセンター
笹井　義一　　海洋研究開発機構　地球環境変動領域

海洋の渦・前線などの空間的に小さいスケールの現象が、気候の形成やその変動に及ぼす影響や役割について、大気、海洋、結合モデルを用いて研究を行っている。この報告書では、次の四つの研究成果を取り上げた。渦解像北太平洋海洋モデルを用い 1）黒潮続流ジェットの経年変動の不確実性を調べ、全球大気モデルを用い 2）黒潮・親潮続流の海面水温フロントに対する低気圧発達の応答と、3）中緯度北太平洋域の海面水温偏差に対する大規模大気循環場の応答を示し、それぞれのメカニズムを明らかにした。さらに、高解像度北太平洋海洋生態系モデルを用い 4）海洋のサブメソスケール現象が物理場と生態系に大きな影響を及ぼしていることを示した。

キーワード: 海洋の微細構造, 海面水温フロント, 黒潮続流ジェット, 低気圧の発達, 大規模大気応答,
海洋のサブメソスケール現象, 海洋生態系