Understanding Roles of Oceanic Fine Structures in Climate and Its Variability

Project Representative
Hideharu Sasaki — Application Laboratory, Japan Agency for Marine-Earth Science and Technology

Authors
Hideharu Sasaki — Application Laboratory, Japan Agency for Marine-Earth Science and Technology
Bunmei Taguchi — Application Laboratory, Japan Agency for Marine-Earth Science and Technology
Takafumi Miyasaka — Research Center for Advanced Science and Technology, The University of Tokyo

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 three topics, for all of which the oceanic fine structures play crucial roles. 1) Oceanic scale interaction triggered by rich submesoscales in winter, 2) Large-scale ocean-atmosphere response to oceanic frontal zone in the wintertime North Pacific, and 3) Multidecadal modulations of the low-frequency climate variability in the wintertime North Pacific.

Keywords: oceanic fine structures, sea surface temperature front, atmosphere-ocean coupled system, oceanic submesoscales, Pacific decadal variability.

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 recent 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.

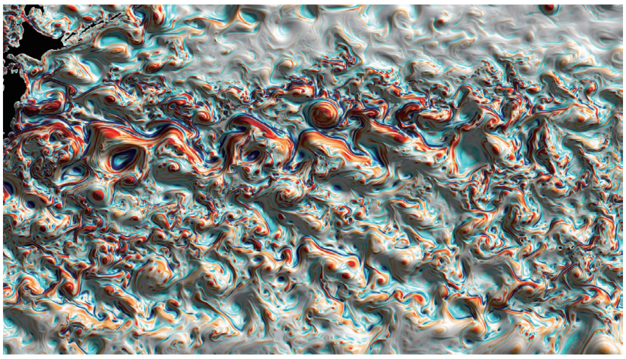
We highlight in this report our recent progress in researches on the roles of oceanic fine structures in climate and its variability using simulations. In Section 2, oceanic scale interaction triggered by active submesoscales in winter is revealed in a high-resolution ocean model. In Section 3, large-scale ocean-atmosphere responses to oceanic frontal zone in the wintertime North Pacific are examined by coupled GCM (CGCM) sensitivity experiments. In section 4, multidecadal modulations of the low-frequency climate variability in the wintertime North Pacific is assessed by observations and a centennial CGCM control integration.

2. Oceanic scale interaction triggered by rich submesoscales in winter

It is well known that there are ubiquitous mesoscale eddies with diameter from 100km to 300km around the strong currents such as the Kuroshio and Gulf Stream. The mesoscale eddies transport heat and various tracers including CO_2, and then play a role in global heat balance and fishery resource. Recently, the satellite images capture submesoscale eddies and filamental structures in the scale smaller than several 10s km in various regions in the world ocean. However, the clear images are rare due to clouds and are not useful to investigate oceanic dynamics. And the in-situ high-resolution observations are still not enough to study oceanic submesoscale due to their small temporal and space covering. Then, we conducted a North Pacific high-resolution simulation at a horizontal resolution of 1/30 degree to reproduce large oceanic circulation with meso and submeso scale structures.

Our simulation demonstrates well rich submesoscales in the Northwestern Pacific in winter (Fig. 1a). The submesoscales are active with strong vertical motions within the deep mixed layer. The winter submesoscales are generated by the mixed layer instability, which are induced by the transfer from potential energy to kinetic energy at the submesoscale within the mixed layer. At the same time, energy transfers from small to large scale in the wide scale range from submesoscale (about

(a) March 15



(b) September 15

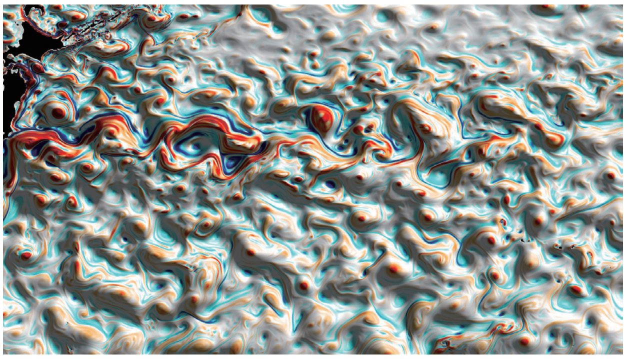


Fig. 1 Surface relative vorticity (color: The color of warm anticyclonic (cold cyclonic) eddy is red (blue)) and sea surface height (brightness) on March 15 (a) and September 15 (b) in 2002 in the high-resolution North Pacific simulation.

30km) to mesoscales [1]. These results show that the rich submesoscales generated within the deep mixed layer in winter influence much on mesoscales and large circulation. In contrast to winter, the dominant oceanic scale becomes large in summer (Fig. 1b). The mixed layer instability does not work well due to the shallow mixed layer.

The new satellites such as SWOT (Sea Water Ocean Topography) mission, which can observe the sea surface height at resolution of a few km, will be launched in several years. The combination with the future observations and high-resolution simulations will provide data to investigate global oceanic dynamics with fine scale structures including submesoscales.

3. Large-scale ocean-atmosphere responses to oceanic frontal zone in the wintertime North Pacific

In the extratropical North Pacific, the subarctic frontal zone (SAFZ) swings in latitude responding to basin-scale wind change and thus generates pronounced sea surface temperature (SST) variability there on interannual-to-decadal time-scale. To address possible climatic implications of interactions between the SAFZ variability and the atmosphere, we examine large-scale ocean-atmosphere responses to the latitudinal shifts of SAFZ by conducting ensemble sensitivity experiments with an ocean-front resolving coupled GCM (CFES, CGCM for the Earth Simulator). In the experiments latitudinal shifts of

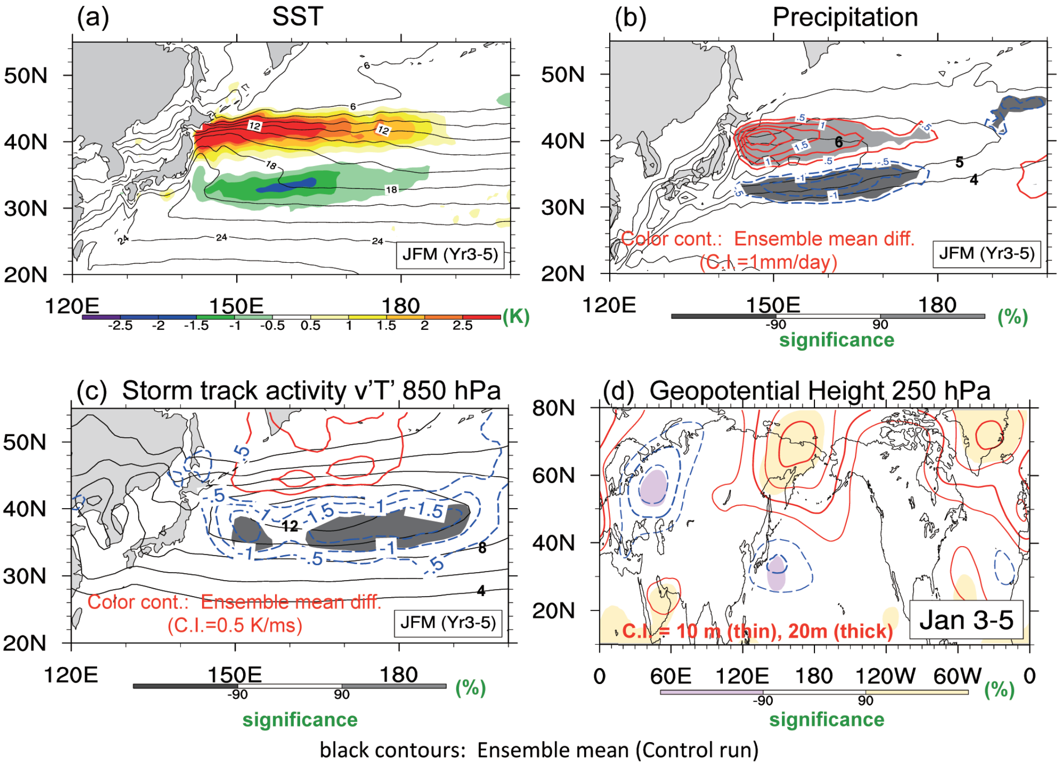


Fig. 2 Ocean-atmosphere response to extratropical wind stress anomaly as measured with ensemble mean differences of CGCM experiments (sensitivity minus control runs). (a) SST response (shading) averaged over three winter (January through March) during the free integration period. (b) Precipitation response (color contoured) with statistical significance (gray shading). (c) As in (b) but storm track activity at 850 hPa level. (d) As in (b) but geopotential height at 250 hPa level. Black contours in (b-d) show ensemble mean of each fields in the control run.

simulated SAFZ are deliberately induced by idealized wind stress anomaly imposed in the central North Pacific during the coupled integration. These partially constrained integrations are followed by further free integrations without wind stress anomaly, during which simulated ocean-atmosphere response is examined.

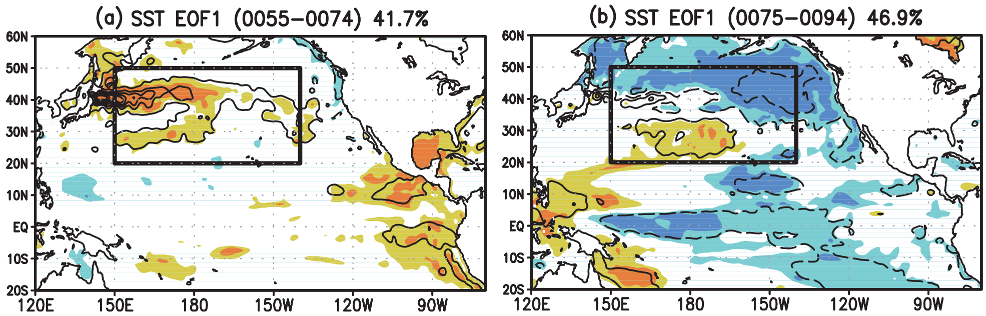
Responding to negative wind stress curl associated with easterly wind anomaly in the central North Pacific, simulated sub-polar gyre weakens and SAFZ shifts northward during the constrained integration period, leading to positive SST anomalies along the SAFZ (Fig. 2a). Significant local responses to the SST anomalies such as precipitation increase (Fig. 2b) and northward shift of storm track are found over the SAFZ during the subsequent free integration period (Fig. 2c). These local atmospheric responses result in significant basin-scale responses (Fig. 2d) consistent with diagnostic analysis of observations and the CGCM control integration [2].

Further composite analysis with respect to the SAFZ warming across ensemble members reveals the existence of two regimes in the atmospheric circulation response and its feedback on the ocean. Namely, ensemble composite with large (moderate) SAFZ warming tends to be accompanied by weakened (enhanced) Aleutian Low acting as positive (negative) feedback (not shown). The positive (negative) feedback promotes persistency (phase transition) of latitudinal position and SST anomalies in SAFZ (not shown), a dynamical feedback that can be crucial for Pacific decadal variability.

4. Multidecadal modulations of the low-frequency climate variability in the wintertime North Pacific

The North Pacific decadal variability (PDV) is known to manifest itself as two distinct spatial patterns. Observations since 1950 reveal that the wintertime PDV underwent notable modulations of their dominance in SST variability and accompanying atmospheric variability [3]. Until the 1980s, decadal SST variability was strongest along the SAFZ, the boundary between the warm Kuroshio and cool Oyashio waters. The SAFZ variability was highly correlated with decadal variability of the surface Aleutian Low but not simultaneously with tropical SST variability. Since the 1990s, however, this extratropical ocean-atmosphere variability has lost its predominance, taken over by SST variability in the subtropical frontal zone (STFZ). It accompanies subtropical anticyclone variability, exhibiting significant anticorrelation with tropical SST variability.

Similar PDV modulations are simulated in a centennial integration of CFES under fixed CO_2 concentration [3]. Horizontal resolution of the ocean component of CFES is 0.5°, which enables to simulate pronounced meridional SST contrast across oceanic fronts. This integration includes a bidecadal epoch (55th-74th year) where strong SAFZ variability, which is uncorrelated with tropical SST variability but correlated with the Aleutian Low variability, is dominant (Figs. 3a, 3c). In the following epoch (75th-94th year), however, the corresponding dominant mode represents STFZ variability in strong anticorrelation with tropical SST variability (Figs. 3b, 3c) and subtropical high variability. This experiment with fixed CO_2


(a) SST EOF1 (0055–0074) 41.7%

(b) SST EOF1 (0075–0094) 46.9%

(c) 21–yr running standard deviation of SST

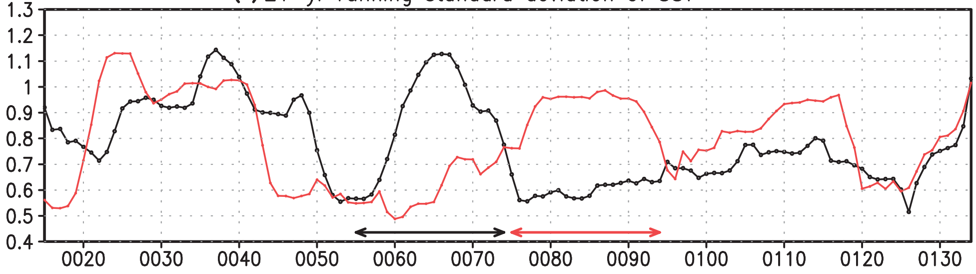


Fig. 3 Linear regression of decadal SST anomalies in winter (contoured for ± 0.2, 0.6, 10.0, … °C) onto the principal component of the first mode of empirical orthogonal function analysis for (a) 55th-74th year and (b) 75th-94th year of CFES integration. Lighter (heavier) color denotes 90% (99%) confidence level. (c) Twenty-one year running standard deviation of decadal SST anomalies averaged near center of action of variability in SAFZ (black) and STFZ (red).

suggests that observed modulations of PDV may be caused by internal dynamics of the atmosphere-ocean coupled system.

5. 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, scale interactions in oceanic field, energy transfer from submesoscales to mesoscale and large scale, are revealed in the Northwestern Pacific. Also, large-scale ocean-atmosphere responses to an oceanic frontal zone are examined using a coupled GCM. In addition, the mechanism of multi-decadal modulations of the PDV is investigated, which maybe caused by internal dynamics of the atmosphere-ocean coupled system.

References

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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　アプリケーションラボ

著者
佐々木英治　　海洋研究開発機構　アプリケーションラボ
田口　文明　　海洋研究開発機構　アプリケーションラボ
宮坂　貴文　　東京大学　先端科学技術研究センター

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、次の三つの研究成果を取り上げた。高解像度北太平洋海洋モデルを用い 1）冬季に活発になるサブメソスケール渦がもたらすスケール間相互作用を調べ、全球大気海洋結合モデルを用い 2）北太平洋亜寒帯前線帯の南北変位が海盆スケールの大気 - 海洋循環に影響を及ぼすこと、3）太平洋十年規模変動の長期変調が大気海洋結合系の内部力学からもたらされる可能性があることを明らかにした。

キーワード : 海洋の微細構造 , 海面水温フロント , 大気海洋結合系 , 海洋のサブメソスケール現象 , 太平洋十年規模変動