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

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We have been investigating roles of oceanic fine structures in climate and its variability by using high-resolution, primitive equation based, global atmosphere, ocean and ocean-atmosphere coupled models, and a regional 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) Termination of Baiu rainband, 2) Decadal variability of oceanic heat content in the North Pacific, 3) Seasonality of submesoscales around the Kuroshio Extension, and 4) Momentum transfer from wind to surface waves and ocean currents in a coupled atmosphere ocean surface-wave model.

Keywords: oceanic fine structures, air-sea interaction, Baiu rainband, oceanic heat content, oceanic submesoscales, surface wave

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, influence of the Kuroshio Extension to climatological termination of Baiu rainband is presented. A new dynamics of North Pacific oceanic heat content variability, in which oceanic frontal variability plays a central role, is proposed in Section 3. Seasonality of submesoscales around the Kuroshio Extension is reported in Section 4. Development of a coupled atmosphere ocean surface-wave model with an explicit treatment of momentum transfer from wind to surface waves and then to ocean currents under a tropical cyclone condition is reported in Section 5.

2. Baiu rainband termination in AFES and CFES

Baiu is a summer rainband stretching from eastern China through Japan towards the Northwest Pacific. The climatological termination of the Baiu rainband is investigated using a stand-alone atmospheric general circulation model (AFES) forced with observed sea surface temperature (SST) and a coupled GCM (CFES) with the same atmospheric component. The Baiu rainband over the North Pacific abruptly shifts northward and weakens substantially in early July in AEFS (Fig. 1c) while it persists around 40°N through summer in CFES (Fig. 1b). The mid-troposphere westerly jet and its thermal advection explain this meridional position of the simulated Baiu, but ocean surface evaporation modulates the precipitation intensity. In AFES, deep convection in the subtropical Northwest Pacific sets in prematurely, displacing the westerly jet northward over cold ocean surface earlier than in observations (Fig. 2e). The suppressed surface evaporation over the cold ocean suppresses precipitation despite that mid-tropospheric warm advection and vertically integrated moisture convergence are similar to those before the westerly jet's northward shift (Fig. 2f). As

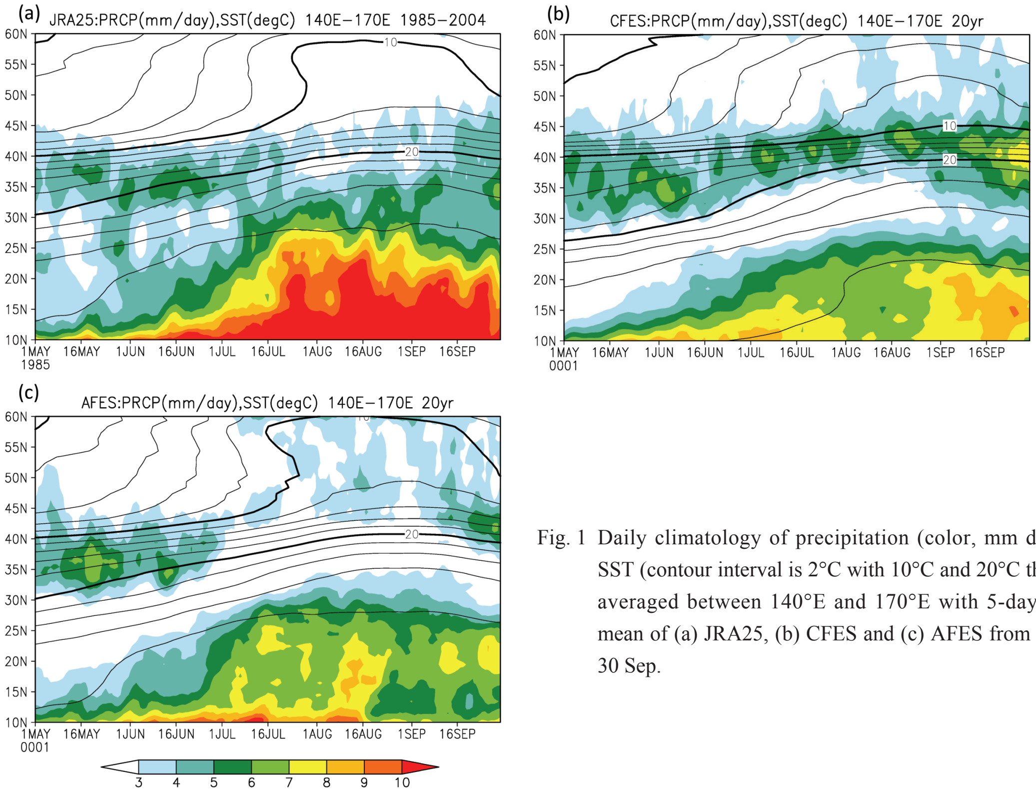

Fig. 1 Daily climatology of precipitation (color, mm day^{-1}) and SST (contour interval is 2°C with 10°C and 20°C thickened) averaged between 140°E and 170°E with 5-day running mean of (a) JRA25, (b) CFES and (c) AFES from 1 May to 30 Sep.

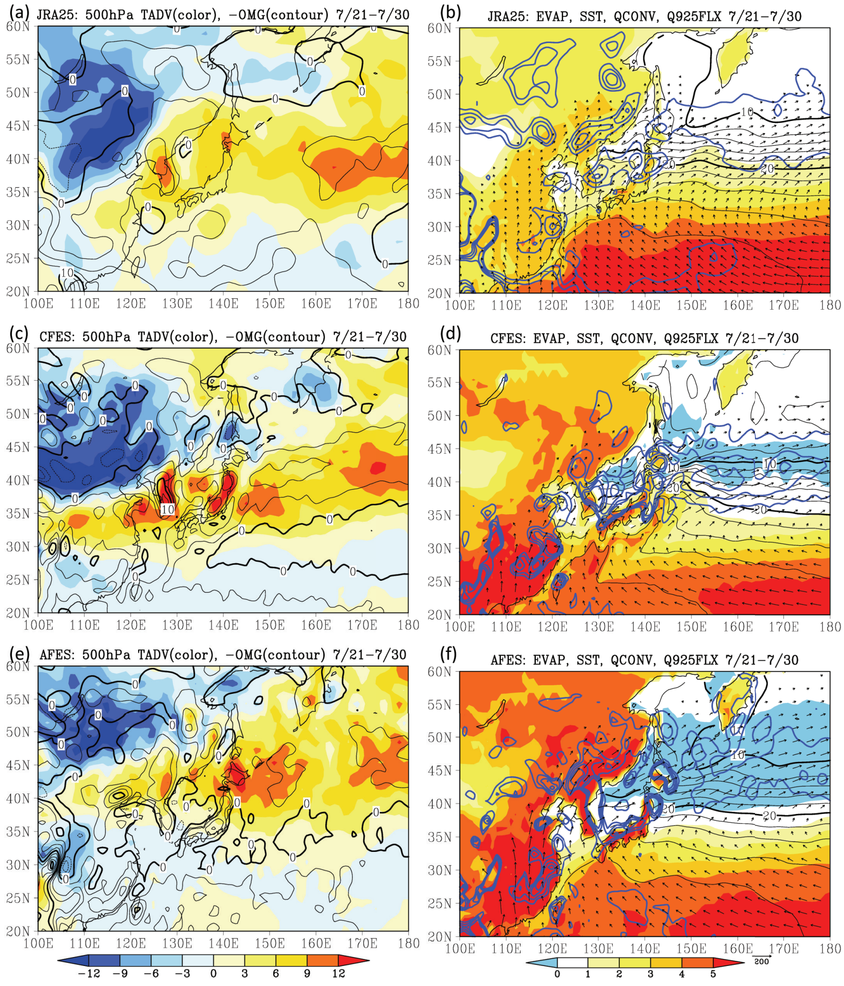

Fig. 2 (left) 10-day mean between 21 July and 30 July of horizontal temperature advection (color, 10^{-6} K s^{-1}) and vertical p-velocity with negative sign (contour interval is 2.5 × 10^{-2} Pa s^{-1} with 0 and 10 × 10^{-2} Pa s^{-1} thickened) at 500 hPa. (right) surface evaporation (color, mm day^{-1}), SST (black contour, contour interval is 2°C with 10°C and 20°C thickened), moisture flux at 925 hPa (vector over 20 kg kg^{-1} m s^{-1}) and vertically integrated moisture convergence (3, 5, 7, and 9 mm day^{-1} are plotted with blue contours). (a) (b) JRA25, (c) (d) CFES, and (e) (f) AFES.

a result, Baiu abruptly weakens after the northward shift in AFES. In CFES, cold SST biases in the subtropics inhibit deep convection, delaying the poleward excursion of the westerly jet. As a result, the updraft induced by the strong westerly jet and Baiu both persist over the Northwest Pacific through summer in the CFES (Fig. 2c). The results indicate that the westerly jet as well as ocean evaporation underneath is important for the Baiu rainband, suggesting a role of ocean in this important climate phenomenon.

3. Dynamics of North Pacific oceanic heat content variability on decadal time-scale

Upper ocean heat content (OHC) is at the heart of the natural climate variability on interannual-to-decadal time-scales, providing climate memory and the source of decadal prediction skill. In the mid-latitude North Pacific Ocean, OHC signals are often found to propagate eastward as opposed to the frequently-observed westward propagation of sea surface height, a variable similar to OHC representing the ocean subsurface state. We investigate this dichotomy using a 150-year CFES control integration (Taguchi and Schneider 2013 [1]). Simulated OHC signals are distinguished in terms of two processes that can support eastward propagation: higher baroclinic Rossby wave (RW) modes that are associated with density perturbation, and spiciness anomalies due to density compensated temperature and salinity anomalies. Our analysis suggests a unique role of the Kuroshio/Oyashio Extension (KOE) region as an origin of the spiciness and higher mode RW signals and we hypothesize a new mechanism for North Pacific decadal variability that links the westward- and eastward-propagating anomalies, as summarized in Fig. 3. First, wind-forced, westward-propagating equivalent barotropic RW (Process 1. in Fig. 3) causes meridional shift of the subarctic front in the KOE region (2. in Fig. 3). The associated anomalous circulation crosses mean temperature and salinity gradients and thereby generates spiciness anomalies (3. in Fig. 3). These anomalies are then advected eastward by the mean currents (4. in Fig. 3), while the associated surface temperature anomalies are damped by air-sea heat exchange. Furthermore, the accompanying surface buoyancy flux generates higher baroclinic, eastward propagating RW (5. in Fig. 3). The result suggests that the large OHC variability in the western boundary currents and their extensions is associated with the spiciness gradients and axial variability of oceanic fronts. The hypothesis derived from the CFES simulation will be verified by future studies using Argo profiling float data, ocean reanalysis products, and other coupled CGCMs.

4. Seasonal variations of submesoscales around the Kuroshio Extention

Recent observations such as satellite observed SST and ocean color capture not only oceanic mesoscale phenomena (~100 km) of fronts and mesoscale eddies but also submesoscales (~10 km) such as smaller eddies and elongated thin filaments. Recent studies of idealized high-resolution simulation also suggest that submesoscales induce strong vertical motions with fine horizontal scale and influence to large-scale and ecological fields. However, their spatial distribution and temporal variations in the basin scale ocean have not been revealed due to lack of observations. We have investigated submesoscales around the Kuroshio Extension and their seasonal variations in a high-resolution North Pacific simulation using OFES (OGCM for the Earth Simulator) at 1/30° horizontal resolution [2]. In the late winter, submesoscales are ubiquitous around the Kuroshio Extension (Fig. 4a). Vertical motions are strong in the mixed layer, which is deep in the season, and their horizontal scales are as fine as horizontal submesoscales. However, the mesoscales larger than submesoscales are dominant in late summer (Fig.

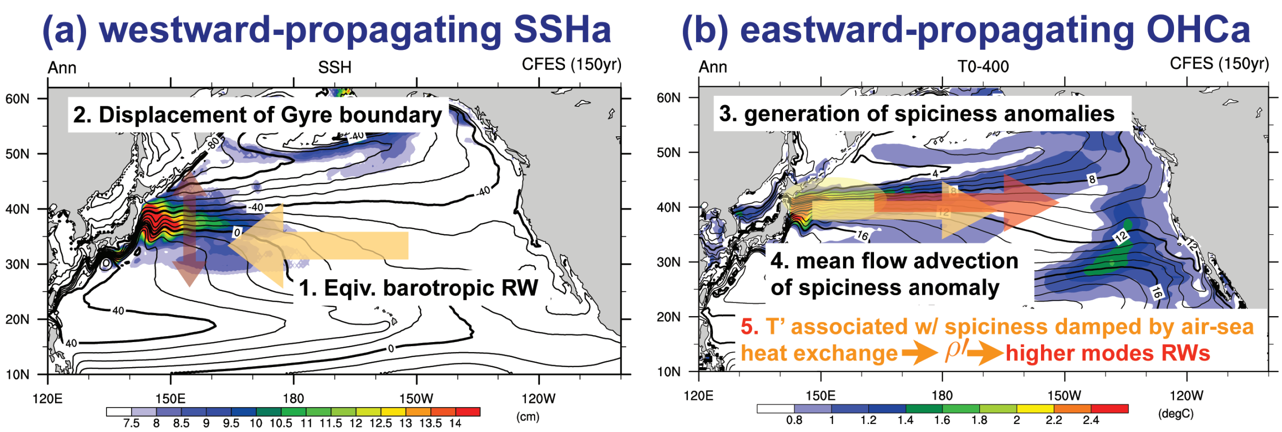

Fig. 3 Schematics of generation and propagation mechanism of decadal-scale ocean heat content (OHC) anomalies in the North Pacific. (a) mean (contours) and standard deviation (color shading) of annual mean sea surface height anomalies based on a 150-year long CFES control integration. Orange and red arrows schematically indicate westward-propagating, equivalent barotropic Rossby waves and the resultant latitudinal displacement of gyre boundary, respectively. (b) as in (a) but for OHC anomalies as measured with the temperature anomalies averaged over upper 400-m depth. Orange and red arrows schematically indicate eastward-propagating spiciness anomalies and higher barolcinic mode Rossby waves, respectively.

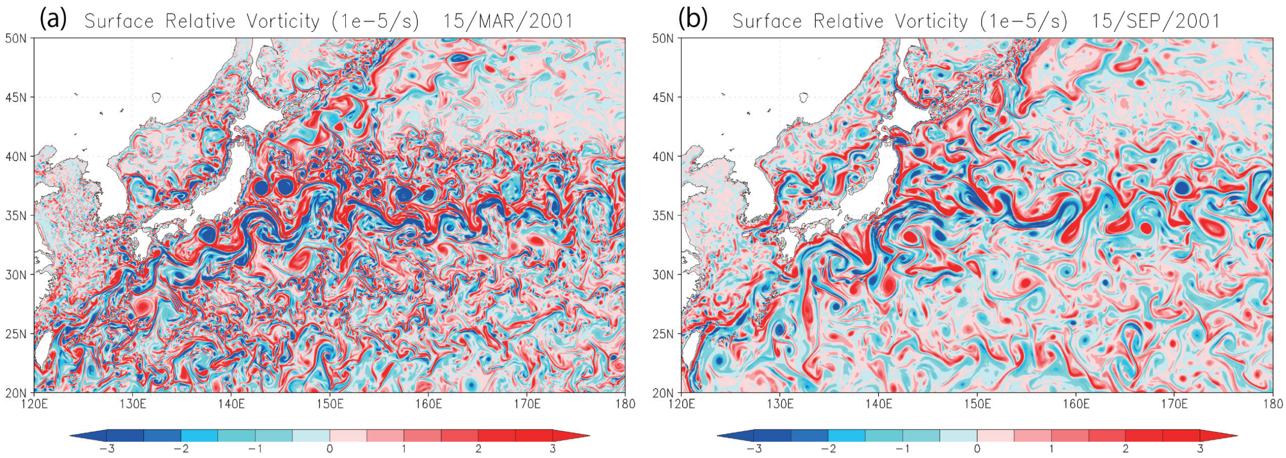

Fig. 4 Daily mean surface relative vorticity (10^{-5} s^{-1}) on (a) March 15 and (b) September 15, 2002 in the North Pacific OFES at 1/30° resolution.

4b) when the mixed layer depth is shallow. The vertical motions with mesoscales mostly appear below the mixed layer. These results show seasonality of submesoscale activities around the Kuroshio Extension. Future studies are necessary to examine what mechanisms induce the ubiquitous submesoscales in late winter. We are also conducting this simulation with a simple NPZD type biological model to see influence of submesoscales to oceanic ecosystem and its seasonal variability, which are our future studies.

5. Transfer of momentum from wind to surface waves and ocean currents in a coupled atmosphere ocean surface-wave model

The traditional bulk formula for wind stress on ocean circulation models is based on only 10 m wind speed, and is directed downwind. However under high wave conditions, the drag coefficient for wind stress might be better parameterized using quantities associated with surface gravity waves, such as significant wave height, wave age, and the direction of waves. Previous studies suggest that the net momentum flux from air (i.e. wind) to water (i.e. ocean current and surface waves) is given by the sum of the skin stress and the wave stress associated with the generation of surface waves, while the net momentum to ocean current is given by the sum of the skin stress and the dissipation-induced stress associated with the breaking of surface waves (Fig. 5). We have developed a coupled atmosphere ocean surface-wave model based on CReSS (Cloud Resolving Storm Simulator), NHOES (NonHydrostatic Ocean model for ES), and the surface-wave model of Donelan et al. (2012) [3]. This coupled model adopts the dissipation (rather than the roughness) approach for estimating the momentum flux to ocean currents. A byproduct of this approach is the availability of the dissipation rate of surface wave energy which is then used as the source term of the TKE equation for the oceanic mixed layer. We have investigated the impact of these effects on the hindcast simulation of tropical cyclones. Figure 6 shows a snapshot of a tropical cyclone translating northeastward. The eye of surface waves (color) lags behind the eye of wind speed (contour), indicating that the regions of significant wind stress to ocean currents (i.e. the sum of the skin stress and the dissipation-induced stress) is somewhat different from the regions of high wind speed.

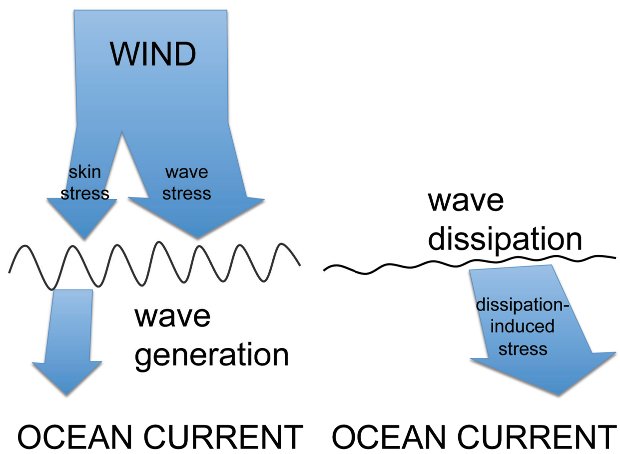

Fig. 5 Schematic of momentum transfer from wind to surface waves and then to ocean currents (Aiki and Greatbatch, 2013 [4]).

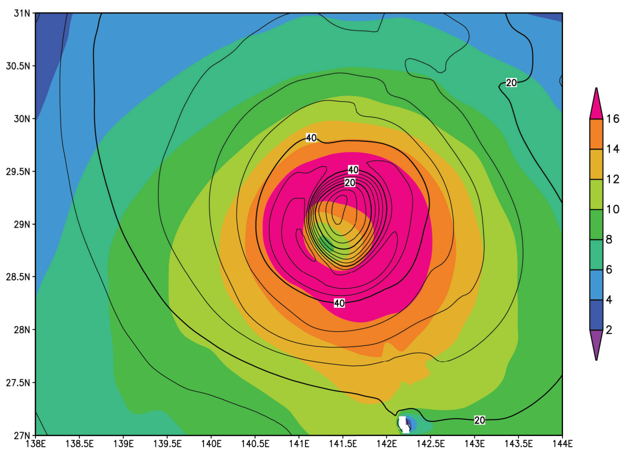

Fig. 6 A snapshot of surface-wave significant height (m, color) and wind speed (m/s, contour) in a hindcast simulation of a tropical cyclone.

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, global atmosphere, ocean and coupled models, and a regional non-hydrostatic ocean-atmosphere coupled model. In this fiscal year, the roles of oceanic mesoscales (fronts and eddies) as well as oceanic submesoscales and surface waves are investigated. We will study more on interactions between small and large scales and their influence on climate and its variability.

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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

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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を、全球または領域の大気、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。全球大気モデルと全球大気海洋結合モデルを用い 1）梅雨降水帯の終焉と、全球大気海洋結合モデルを用い 2）北太平洋の貯熱量の十年変動メカニズムを明らかにした。また、高解像度北太平洋海洋モデルを用い 3）黒潮続流域の海洋サブメソスケール現象の季節変動を明らかにした。さらに、4）台風のような強風条件下では、波浪の生成と消散を経由して風から海流へ運動量が伝達されるという理論をもとに、物理的な整合性のとれた大気海洋波浪結合モデルを開発した。

キーワード : 海洋の微細構造 , 大気・海洋相互作用 , 梅雨降水帯 , 海洋貯熱量 , 海洋のサブメソスケール現象 , 波浪