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

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We have been running high-resolution primitive equation and non-hydrostatic, atmosphere, ocean and coupled, global and regional models in order to investigate air-sea interaction where oceanic structures of small spatial scale play important roles. In this report, we present the following four topics. 1) Deep oceanic zonal jets that seem to be driven by fine-scale wind stress curls. 2) Preliminary results from a 1/30-degree resolution North Pacific Ocean circulation simulation. 3) Internal variability of the Kuroshio Extension Current using a four-member ensemble ocean hindcast. 4) Oceanic internal solitary-like gravity waves generated by a typhoon in a coupled atmosphere–ocean non-hydrostatic simulation.

Keywords: Oceanic zonal jets, oceanic submesoscale structures, Kuroshio Extension Current, internal solitary-like gravity waves, air-sea coupled simulation

1. Introduction

We have been studying relatively small spatial scale interaction of the atmosphere and ocean. In this report, we present oceanic variability driven by winds and oceanic internal fluctuation. In chapter 2, deep oceanic zonal jets driven by fine-scale wind stress curls will be presented. Submesoscale oceanic structures simulated by 1/30-degree resolution ocean circulation will be discussed in chapter 3. The Kuroshio Extension Current (KEC) seems to fluctuate by oceanic internal dynamics. Chapter 4 shows a study on KEC variability by a four-member ensemble re-forecast experiment. Oceanic internal solitary-like gravity waves (ISWs) play an important role for vertical mixing. We report ISWs induced by a typhoon in a non-hydrostatic atmosphere–ocean coupled model in chapter 5.

2. Deep oceanic zonal jets driven by fine-scale wind stress curls

Oceanic alternating zonal jets at depth have been detected ubiquitously in observations and OGCMs (Ocean General Circulation Models). It is often expected that the oceanic jets can be generated by purely oceanic processes. Recently, Kessler and Gourdeau [1] (KG) provided another view of the "wind-driven" oceanic zonal jets. Specifically, they analyzed climatological geostrophic currents and satellite-observed wind stress to find bands of meridionally narrow eastward deep currents in the subtropical South Pacific as consistent with zonal Sverdrup jets forced by meridional fine-scale wind stress curls. Regarding this "wind-driven jet", however, it is yet to be understood what give rise to such fine-scale wind stress curl structure. The objective of this study is to explore a possible air-sea interaction between the oceanic zonal jets and the fine-scale wind curls using a high-resolution CFES (Coupled GCM for Earth Simulator) [2].

Figure 1a shows the annual mean vertically integrated zonal current in the south pacific from the 23-year CFES integration. The model represents zonally striated structures, including eastward jets embedded in large-scale westward flows in equatorward sides of subtropical gyres. The zonally averaged meridional structure of the zonal jets turns out to be well represented by that of the zonal currents inferred by the Sverdrup relation with the wind stress field taken from the CFES output (Fig. 1b). Thus, there exist in the CFES integration the deep zonal jets driven by the fine-scale wind stress curl as KG's observational analysis. Further analysis shows that the eastward Sverdrup transport peaks in the central South Pacific basin are primarily forced by the meridional gradient of the wind stress curl in the region slightly to the west, which then originates from the meridionally fine-scale wind stress curl itself (Fig. 1d). We found this fine-scale wind stress curl structures are spatially well correlated with the SST laplacian fields (Fig. 1c), suggestive of the wind stress field induced by pressure adjustment in ABL

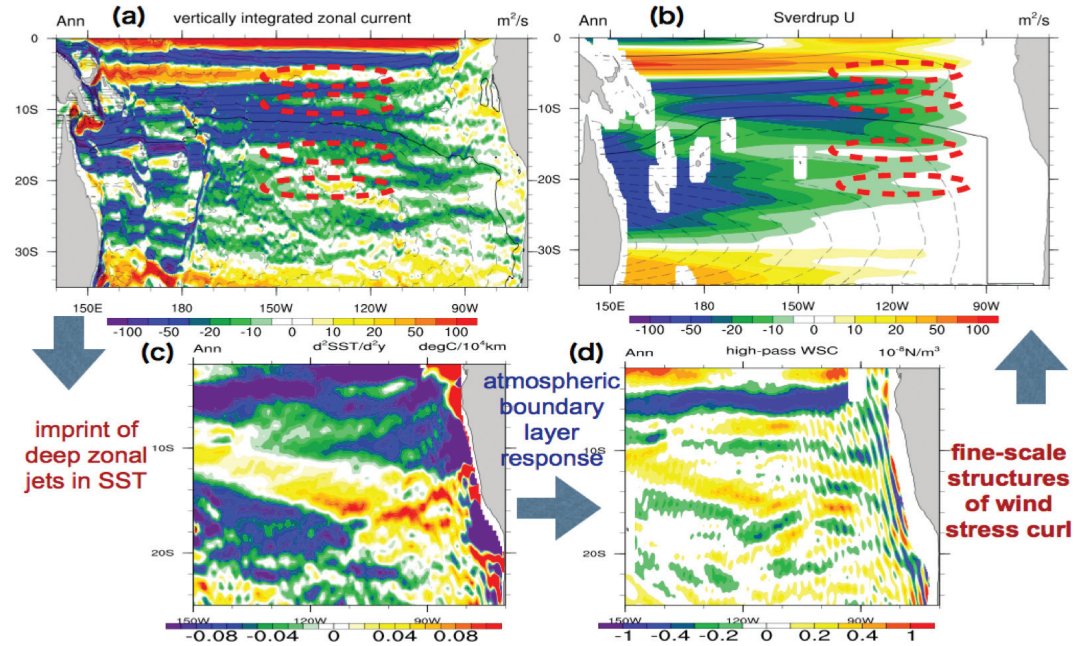

Fig. 1 (a) Vertically integrated zonal current. (b) Zonal currents inferred by the Sverdrup balance with simulated wind stress. (c) SST laplacian. (d) Meridionally high-pass filtered wind curl. All fields are annual mean based on CFES run.

(atmospheric boundary layer) to fine-scale SST structures. Our analysis suggests that the air-sea interaction plays a role in generating the fine-scale wind curls and in constraining the oceanic deep jets to satisfy the Sverdrup balance with the fine-scale wind curls.

3. Scale interactions in the ocean

Recent observations such as satellite observed SST and ocean color capture not only mesoscale eddies (~100km) but also smaller eddies and filaments of submesoscale (~10km) at the sea surface. Some idealized models also succeeded to demonstrate the submesoscale oceanic structures [3, 4]. Intense vertical motions exited by the submesoscales could influence vertical stratification in the subsurface and surface large-scale oceanic fields. Biological fields could be also affected by small-scale nutrient injection triggered by submesoscales [3]. In the next generation OGCMs that can demonstrate realistic basin-scale circulations, upper-layer submesoscales with intense vertical motions need to be represented or should be parameterized.

Motivated by recent development, we have started conducting a high-resolution North Pacific simulation at 1/30° horizontal resolution using the OFES (OGCM for the Earth Simulator) [5, 6] based on GFDL MOM3 (Geophysical Fluid Dynamics Laboratory Modular Ocean Model Version 3). Relative

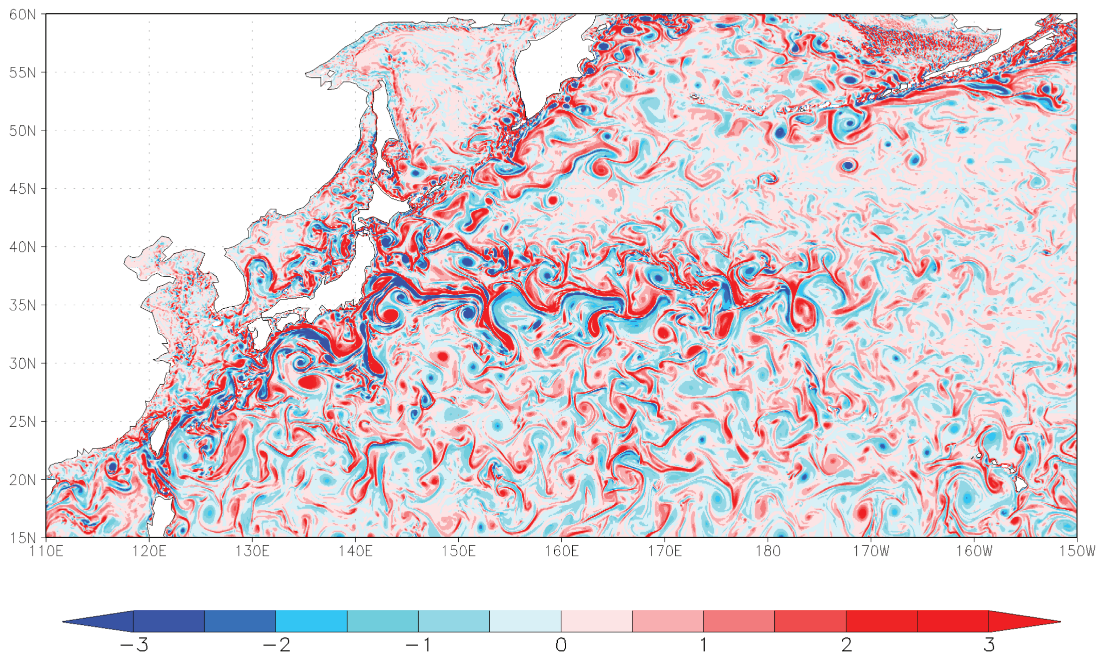

Fig. 2 Surface relative vorticity (10^{-5} s^{-1}) after 2-year spin-up integration in the North Pacific OFES at 1/30° resolution.

vorticity field from 2-year spin-up integration shows ubiquitous mesoscale and submesoscale structures around the Kuroshio current, Oyashio current, and subtropical countercurrents (Fig. 2). Intense vertical motions characterized by submesoscales are also found from the sea surface to the subsurface (not shown). This preliminary result shows that the OFES at 1/30° resolution could simulate small-scale oceanic structures of mesoscale and submesoscales in the realistic basin-scale circulations. We plan to simulate marine ecosystem using the North Pacific OFES at 1/30° resolution with a simple biological model.

4. Internal variability in the Kuroshio Extension Current

It has been known that the KEC (Kuroshio Extension Current) has intrinsic, internal variability independent from the external forcing. For example, Taguchi et al. [7] clearly show its existence based on the eddy-resolving OFES. Although it has been shown that interannual variability in KEC is strongly affected by wind variations, this mean that internal variability is also included in the KEC variability, inducing uncertainty there. Then, we investigate possible influence of internal variability to the KEC variability.

For this purpose, a four-member ensemble experiment driven by an identical atmospheric field is conducted with different initial conditions based on the OFES North Pacific model. Each initial condition is obtained from the same day (January 1st) of different years of the climatological integration, which is forced by the long-term mean atmospheric field.

We estimate the internal variability from differences among the ensemble members. The estimated internal variability are large in the Kuroshio Current and KEC regions, and its amplitude is similar to or larger than the wind-induced variability estimated from the ensemble mean. This is also the case in the KEC speed (Fig. 3a), suggesting significant uncertainty included in it. However, if we focus on the most dominant mode of interannual variability in the western North Pacific region obtained by the EOF (empirical orthogonal function) analysis, differences among the members are small (Fig. 3b). This suggests much reduced uncertainty in the most dominant mode. The number of experiments is, however, still very small, and similar experiments will be conducted further.

5. Oceanic non-hydrostatic wave trains generated by typhoons

Tidally generated oceanic wave trains with waves 2-7 km in length have been often observed by satellite-borne Synthetic Aperture Radars. These trains are the surface expressions of ISWs (internal solitary-like gravity waves) at the depth of thermocline. Wave trains of this type are among the largest non-hydrostatic phenomenon in the ocean, and highlight the differences between the dispersion relations of hydrostatic and non-hydrostatic internal gravity waves [8]. Oceanic non-hydrostatic dynamics becomes important when wavelengths become shorter than 5 km that is the typical depth of see floor. Shorter waves propagate slowly and longer waves propagate fast. In contrast to previous studies focusing on tidal internal waves, this study shows that ISW trains can be generated by typhoons.

Using a coupled atmosphere–ocean non-hydrostatic three-dimensional model, CReSS–NHOES (Cloud Resolving Storm Simulator-Non-Hydrostatic Ocean model for the Earth Simulator), we have performed two separate hindcast simulations for typhoon Choiwan 2009, one with non-hydrostatic pressure in the ocean component of the model and one without it. Choiwan passed the Ogasawara Islands on 20 Septempber 2009. The cyclonic wind stress of the typhoon induces divergent ocean flows at sea surface, resulting in the doming of thermocline that radiates away as internal gravity waves. Simulated internal gravity waves are significant to the east of typhoon, and propagate at the speed of waves in the first baroclinic mode. Gradually ISW trains with waves about 5-10 km in length and about 1 hour in period are formed in the non-hydrostatic run (Figs. 4 and 5, left). Such saturation of wave frequency is consistent with the dispersion relation of non-hydrostatic internal gravity waves. No ISW is formed in the hydrostatic run where the leading edge of waves is too significant and there is no tail of wave trains (Figs. 4 and 5, right). By applying the above twin simulations to some other

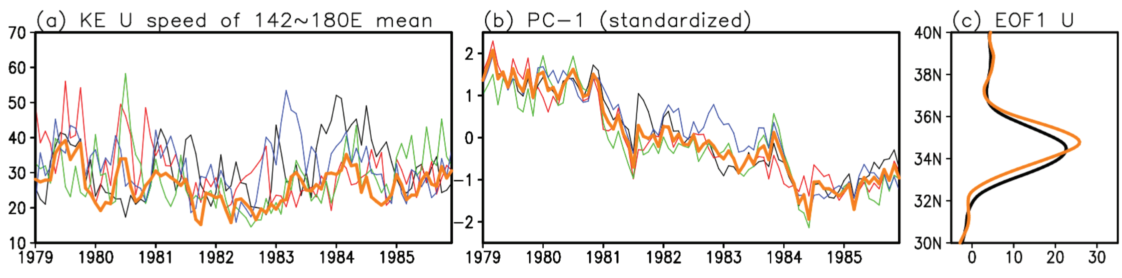

Fig. 3 (a) Time series of the simulated 100-m depth KEC speed averaged in 142-180E in the ensemble experiment. Thin curves are for the ensemble members, and the thick one is for the ensemble mean. (b) The same as (a) but for the principle component of the first EOF mode of sea surface height, which is associated with intensification and meridional shift of KEC as shown in (c). (c) Meridional profile of the seven-year mean 100-m depth zonal current (black), and that for the first EOF mode (orange). Both are from the ensemble mean.

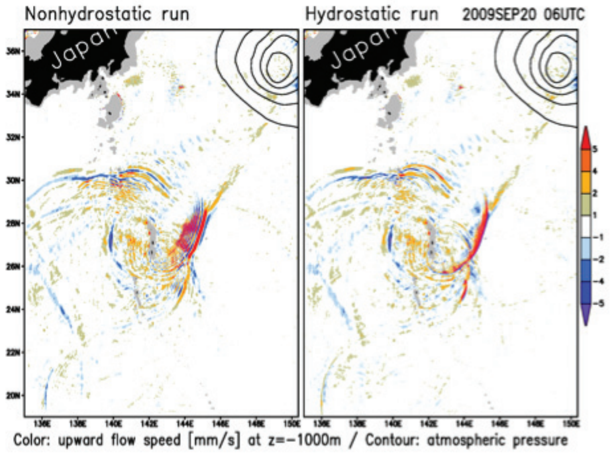

Fig. 4 Distributions of the vertical component of velocity at 1000 m depth [color, mm/s] and sea surface pressure [contour interval = 5 hPa] in the nonhydrostatic run (left) and the hydrostatic run (right).

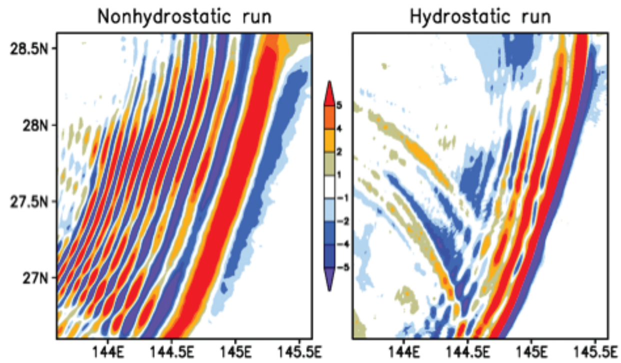

Fig. 5 Same as Fig. 1 except for the close-up views.

typhoons, we have confirmed that the generation of ISW trains is common in non-hydrostatic runs, which may have implications for the vertical mixing in the real ocean.

6. Conclusion

We briefly reported simulation results of primitive equation and non-hydrostatic atmosphere, ocean and coupled models to investigate roles of oceanic fine structures in climate and its variability. This year, we have concentrated on oceanic fine structures induced by wind or by ocean internal dynamics. We will study more on fine-scale air-sea interaction in the near future.

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海洋微細構造が生み出す気候形成・変動メカニズムの解明

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海洋の空間的に小さいスケールが重要な役割をはたす大気海洋結合作用を研究するために、我々は高解像度のプリミティブ方程式と非静力学の全球、または領域の大気、海洋、結合モデルを使っている。この報告書では、次の四つのトピックを取り上げる。1）小さなスケールの風応力により励起される海洋の深層帯状ジェット。2）北太平洋 1/30 度解像度海洋循環シミュレーションの初期結果。3）4 メンバーアンサンブル海洋シミュレーションによる黒潮続流の内部変動。4）非静水圧大気・海洋結合シミュレーションによる、台風が励起した海洋の孤立波的内部重力波。

キーワード: 海洋帯状ジェット, 海洋サブ・メソスケール構造, 黒潮続流, 孤立的内部重力波,
大気・海洋結合シミュレーション