Understanding Roles of Oceanic Fine Structures in Climate and Its Variability

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We have conducted high-resolution simulations with primitive equation or non-hydrostatic atmospheric, oceanic and coupled models in order to understand mechanisms of variations of the atmosphere–ocean system with relatively small spatial scales in the oceanic part. We report in this paper decadal variations in the North Pacific, Kuroshio Extension Current fluctuations, sea-ice variations in the Arctic Sea, and typhoon development.

Keywords: atmosphere–ocean interaction, sea surface temperature front, oceanic Rossby wave, sea ice variability, typhoon development

1. Introduction

In this project, high-resolution simulations are conducted using primitive equation or non-hydrostatic models of atmosphere, ocean and coupled atmosphere–ocean systems to investigate roles of oceanic fine structures in climate and its variability. This project is mainly composed of four topics: 1. Effects of oceanic fine structures to global circulations; 2. Scale interactions in the ocean; 3. Responses of large-scale atmospheric circulation to ocean and sea-ice variability; 4. Mechanisms of typhoon genesis and development under interactions with the ocean. This report summarizes the achievements made in the fiscal year 2009.

2. Effects of oceanic fine structures to global atmospheric and oceanic circulations

We conducted relatively long-term simulations with two different horizontal resolutions using the latest version of CFES (Coupled model for the Earth Simulator) [1], which has many improvements from the previous one [2, 3] such as a new large-scale condensation scheme in AFES (Atmospheric model for the Earth Simulator) for better representation of low-level clouds [4]. The higher resolution version, called "CFES standard," has the resolutions of T239 (about 50 km) and L48 for the atmosphere and 0.25º (about 25 km) and 54 levels for the ocean. The lower resolution version, called "CFES mini," has half the horizontal resolution of CFES standard and will be used for centennial-scale and ensemble simulations.

By the end of FY2008, 23-years of integration with CFES standard was completed. With its high-resolution that permits eddies in the oceanic component, CFES standard simulates frontal structures and their variability in the mid-latitude western boundary currents in a realistic manner. In addition, since its atmospheric component is fine enough to resolve local orography and boundary-layer response to ocean surface structures including meandering fronts and mesoscale eddies, these oceanic fine-scale signatures are clearly reflected in the surface atmospheric fields as revealed by high-resolution satellite observations.

Evidence emerges that sea surface temperature (SST) gradients associated with the mid-latitude western boundary currents exert deep and large-scale influences on the mean state of the atmosphere beyond local responses in the marine atmospheric boundary layer [3, 5, 6, 7]. However, it remains to be investigated whether slow oceanic frontal variability may affect time-varying atmospheric state and contribute to enhance the low-frequency variance in the mid-latitude climate.

To investigate North Pacific decadal SST anomalies and their atmospheric influence as well as other climate variability, CFES mini has been integrated for 120 years. This century-long coupled simulation represents a sharp mean SST front in the North Pacific subarctic frontal zone (SAFZ; Fig. 1b). Pronounced decadal SST variations are confined within SAFZ

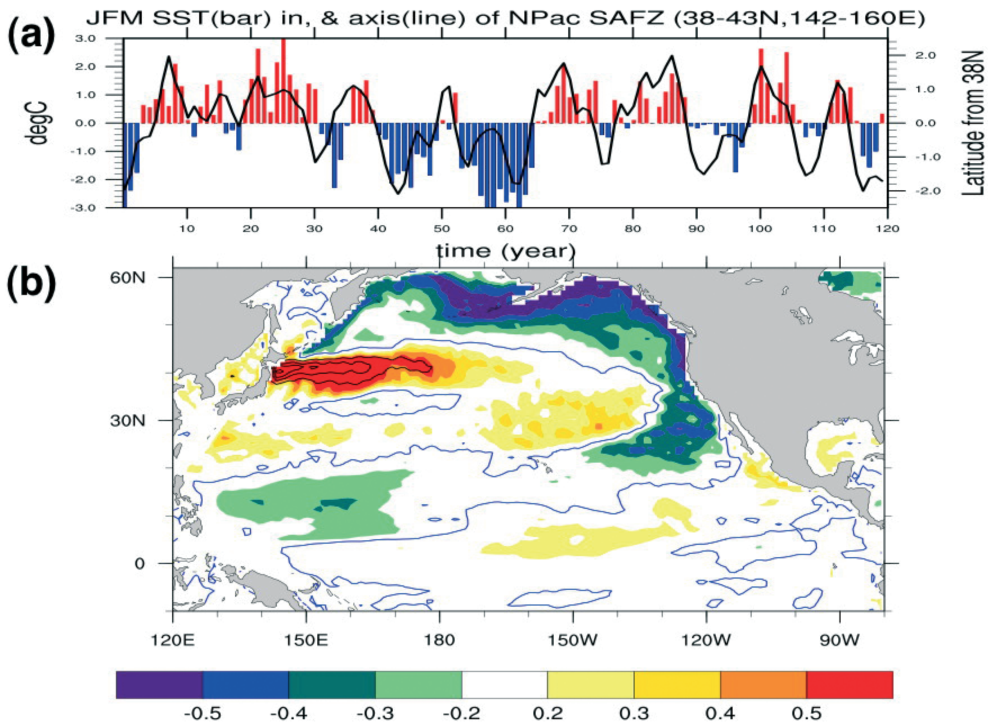

Fig. 1 Wintertime North Pacific decadal SST variability simulated in CFES mini. (a) Time series of wintertime SST anomalies averaged over the subarctic frontal zone (SAFZ; color bar) and meridional migration of the axis of the subarctic front (black line). (b) Correlation (color) and regression (contour; interval is 0.5K per one standard deviation of the reference time series) map of SST field associated with the decadal-scale SST anomalies latitudinally confined to SAFZ.

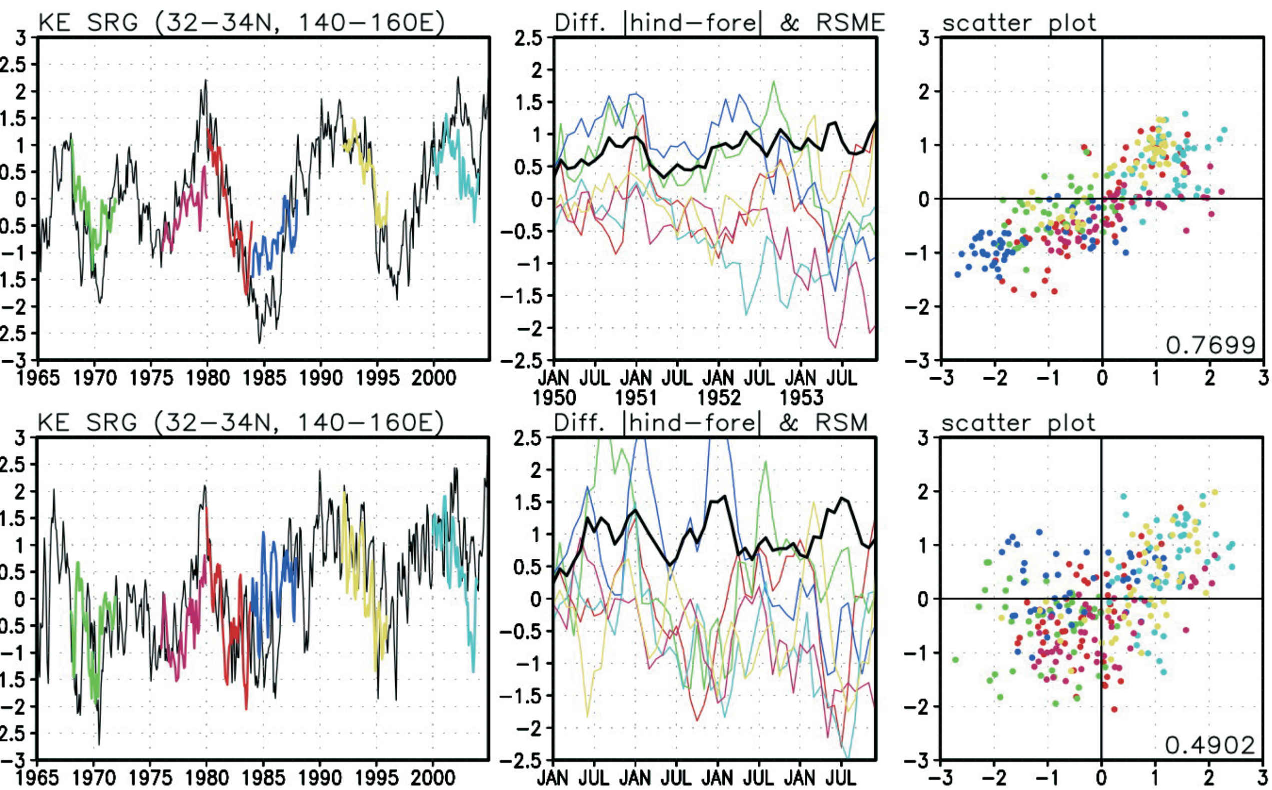

Fig. 2 (Left) Time series of area mean sea surface height anomalies (SSHAs) in (32–34N, 140–160E) in the OFES hindcast (black) and forecast (colors) integrations, (middle) their differences, and (right) their scatter plot in the overlapping periods. In the middle panel, thick black curve indicates root-mean-square of the differences. Number in the right panel shows the corresponding correlation coefficient. Upper panels are for broad-scale SSHAs applied 5-degree longitude and latitude running mean, and lower panels are for unfiltered SSHAs. SSHAs are standardized by their standard deviations in the hindcast integration.

and are well correlated with meridional migration of the front (Fig. 1a), a feature consistent with recent high-resolution OGCM studies that highlight the importance of oceanic frontal variability in generating decadal SST anomalies. Associated with the latitudinally confined SST anomalies, simulated atmospheric storm track in the North Pacific is systematically modulated as it is anchored by near-surface baroclinicity that changes in accordance with the SAFZ variations (not shown). When the SST anomalies are positive, the storm track is shifted northward, which induces anti-cyclonic surface mean flow feedback in subpolar central Pacific. The weakened Aleutian low suppresses southward-flowing Oyashio current off Japan coast, and causes northward migration of SAFZ, which in turn reinforces the initial SST anomalies. These results suggest a positive feedback between the SST anomalies and the associated atmospheric response, which could contribute to persistence of the Pacific decadal SST anomalies.

3. Scale interactions in the ocean

Previous studies have suggested importance of Rossby wave propagation for Kuroshio Extension (KE) Current variations. Then, to investigate if KE Current decadal variations are predictable through Rossby wave propagation, we have conducted six four-year forecast experiments with OFES (Ocean model for the Earth Simulator) driven by long-year mean atmospheric field that does not include information of the 'future'. In each case, the corresponding field in the OFES hindcast integration is given as initial condition, and anomalies in the initial condition propagate westward as Rossby waves, providing predictability for several years. Note that the hindcast integration is driven by atmospheric forcing which includes information of the 'future'.

In Fig. 2, we examined predictability of sea surface height (SSH) variations to the south of the KE region, which is important to induce variations in the KE Current. In the region, time series of the broad-scale SSH anomalies (SSHAs) in the hindcast is well followed by those in the forecast integrations and their correlation is 0.77 (upper panels), consistent with Schneider and Millers' results [8]. Also, their root mean square difference is almost less then one standard deviation for four years. In the lower panels, it is found that unfiltered SSHAs including frontal-scale variations also follow the hindcast and their correlation is about 0.5, implying some predictability for frontal-scale KE Current variations. Indeed, in some forecast

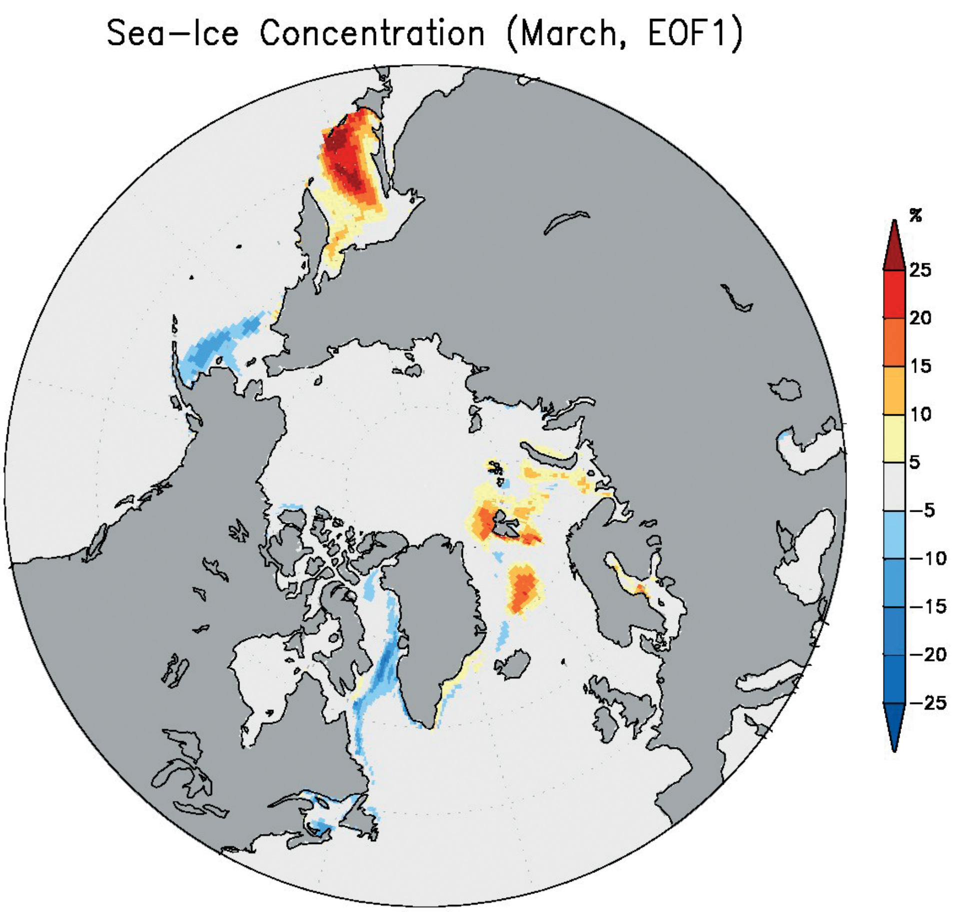

Fig. 3 First EOF of March sea-ice concentration over the Northern Hemisphere for the first through 23rd model year of a coupled atmosphere–ocean simulation with a high-resolution version of CFES ("CFES standard").

integrations, variations in the KE Current jet found in the hindcast are fairly reproduced (not shown).

4. Responses of large-scale atmospheric circulation to ocean and sea-ice variability

Kuwano-Yoshida *et al.* [7] investigate the precipitation response to the SST front associated with the Gulf Stream using AFES simulations forced by observed and smoothed SST data. A convective rain band over the Gulf Stream in the observed SST run disappears in the smooth SST run, and the heights of cumulus convection and updrafts depend on seasonality of atmospheric vertical stability. Sampe *et al.* [6] conduct idealized "aquaplanet" experiments using AFES with zonally uniform SST. The transient eddy activity in each of the winter and summer hemispheres is organized into a deep storm track along the SST front with an enhanced low-level baroclinic growth of eddies. It is suggested that the potential importance of midlatitude atmosphere–ocean interaction in shaping the tropospheric general circulation.

Previous studies [e.g., 9, 10] identified a double-dipole pattern of wintertime sea-ice variability over the Northern Hemisphere from satellite observations, which is composed of one dipole between the Labrador Sea and the Nordic (Greenland, Barents, and Kara) Seas and the other between the Bering Sea and the Okhotsk Sea, and revealed its close link to anomalous atmospheric circulation such as North Atlantic Oscillation. Figure 3 shows the first EOF of March sea-ice concentration over the Northern Hemisphere in CFES standard for the first through 23rd model year, and the double-dipole pattern is realistically reproduced. Detailed analysis of this phenomenon as simulated in CFES standard is under way, and a working hypothesis on its mechanism will be verified through some numerical experiments with AFES.

5. Mechanisms of typhoon genesis and development under interactions with the ocean

A three-dimensional atmosphere–ocean regional coupled model has been developed to simulate non-hydrostatic meteorological and oceanic phenomena. Two well-developed parallel models on the Earth Simulator are employed: CReSS [Cloud Resolving Storm Simulator, 11] is for the atmosphere part and NHOES [Non-Hydrostatic Ocean model for the Earth Simulator, 12] is for the ocean part. MPI decomposition of CReSS–NHOES is utilized for inter-node communications. One MPI sub-domain of a process is applied for one horizontal region of CReSS and NHOES. Intra-node parallelization is also employed with OpenMP for CReSS and microtask for NHOES.

Three experiments are conducted. Two experiments are CReSS-only simulations and the other is a CReSS–NHOES coupled simulation of T0505 (HAITANG) that landed on China

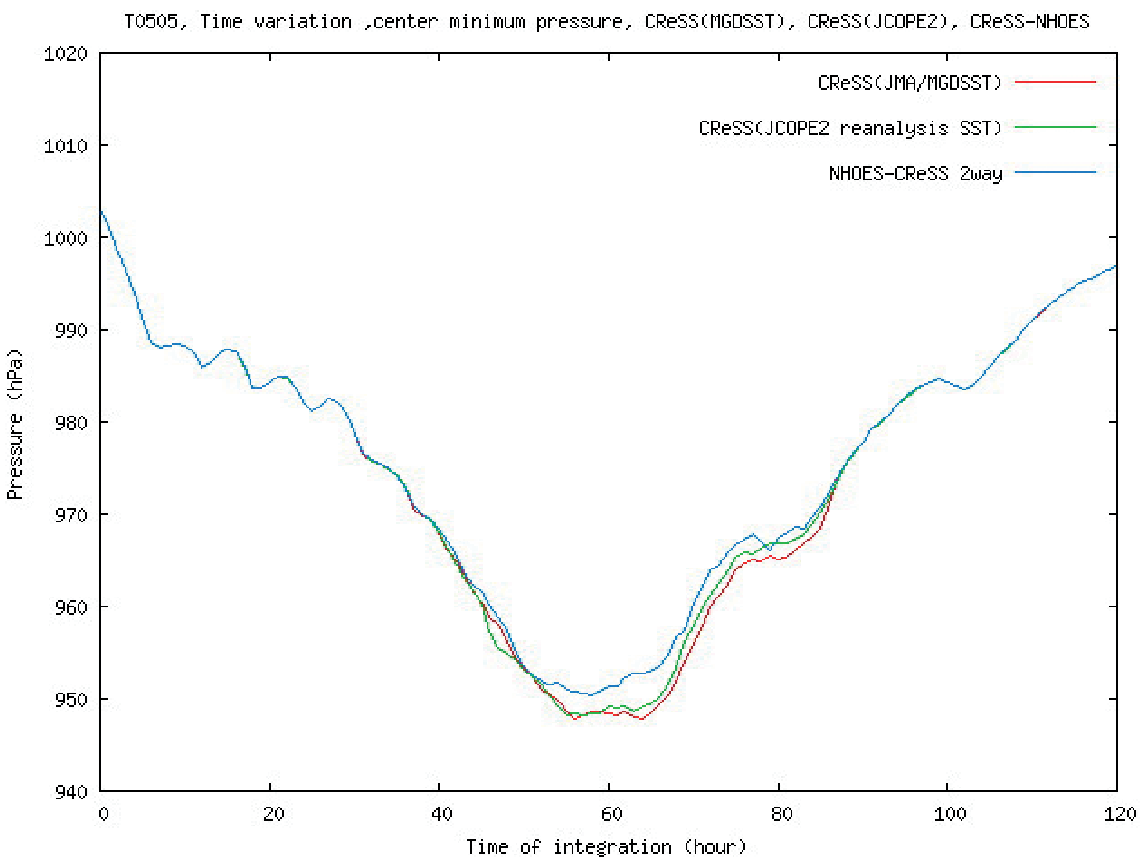

Fig. 4 Time variation of the central minimum pressure in T0505 on the sea level, during the first 5 days. The calculation was started from 00Z, on September 15, in 2005.

coast after passing the Taiwan Island during the active period as a typhoon. The CReSS-only model system has a vertically one-dimensional slab-ocean model. The JMA/RANAL dataset is utilized for the initial and lateral conditions for the atmosphere in the three experiments. The CReSS–NHOES coupled simulation utilizes the JCOPE2 reanalysis for the initial and lateral conditions of the ocean. The two CReSS-only experiments use JCOPE2 or JMA/MGDSST for the initial condition. The horizontal resolutions were 4 km in CReSS and 1 km in NHOES. The vertical resolution of the ocean was from 2 m near the surface. The numerical simulations were performed for 15 days with 4 nodes on the Earth Simulator.

Remarkable differences resulting from air–sea interaction are shown in the comparison of the experiments with successfully

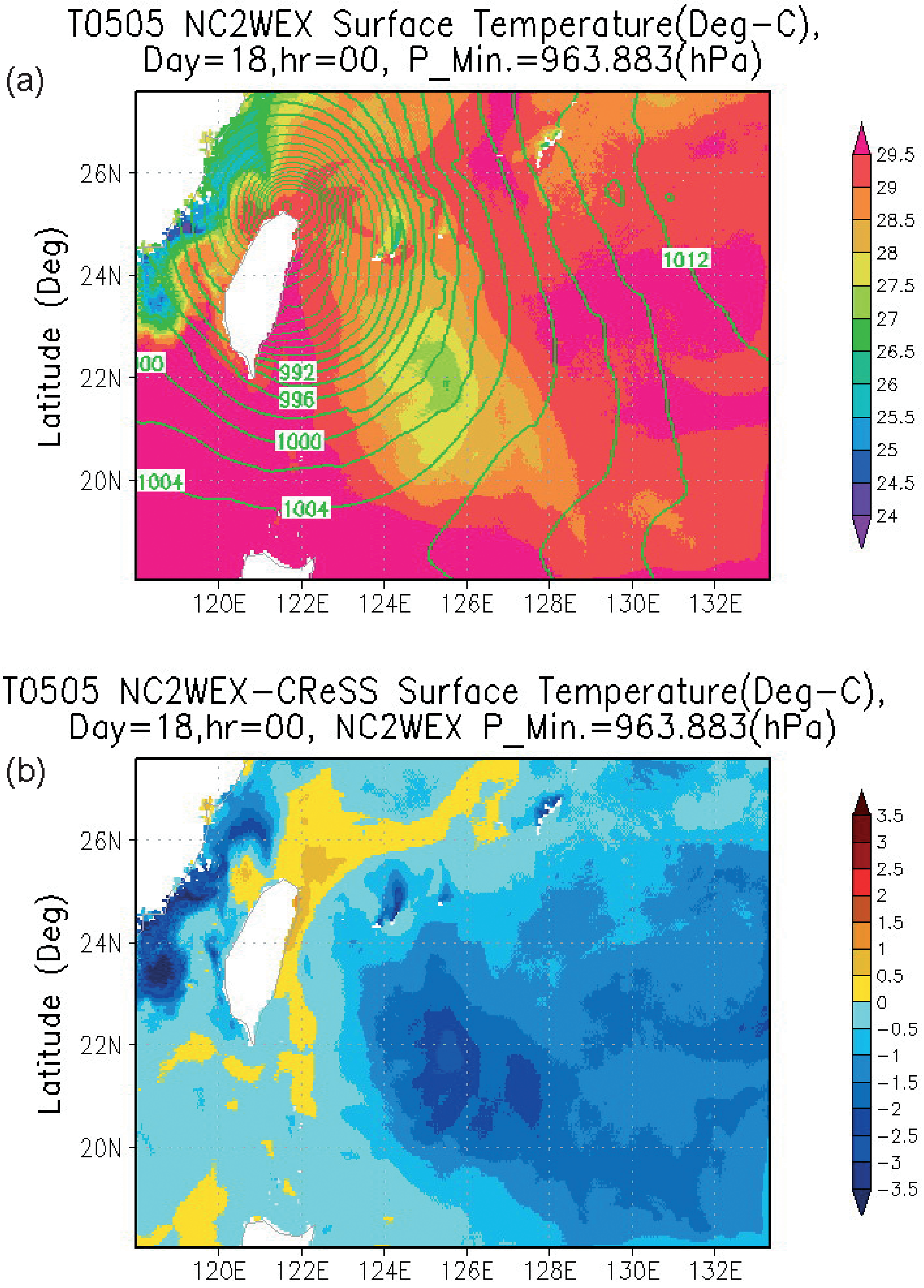

Fig. 5 SST distribution and the anomaly after 72 hours integration. (a) SST distribution (colors) and the sea level pressure (contours) in the CReSS–NHOES experiment, (b) SST anomalies of the coupled experiment to the non-coupling experiment.

simulating typical structures of T0505. In the mature stage of T0505, the central minimum pressure of the typhoon is suppressed by 5 hPa in the CReSS–NHOES coupled simulation, compared to that in the non-coupled experiments (Fig. 4). It is found in the coupled experiment that cooler SST region appeared and lasted in the southeast of T0505 after passing over the Philippine Sea (Fig. 5).

6. Concluding remarks

We briefly reported simulation results of primitive equation or non-hydrostatic atmosphere, ocean and coupled models to investigate roles of oceanic fine structures in climate and its variability. Long-term integrations using CFES at two resolutions reveals pronounced decadal variations of atmosphere and ocean in the North Pacific and sea ice in the Arctic Sea. OFES experiments are conducted to investigate predictability of Kuroshio Extension Current variations through Rossby wave propagation. Roles of atmosphere–ocean interaction in typhoon development are investigated by CReSS–NHOES simulations.

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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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非静水圧と静水圧の大気、海洋、結合モデルを用いて高解像度シミュレーションを行い、比較的細かい空間スケールの海洋変動を伴う大気海洋システムの変動のメカニズムの解明を試みた。この論文では、北太平洋の十年スケール変動、黒潮続流域変動、北極海の海氷変動、台風の発達について報告を行う。

キーワード:大気海洋相互作用, 海面水温前線, 海洋ロスビー波, 海氷変動, 台風の発達