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Sensitivity Experiments for Tropical cyclone intensity to the sea surface temperature distribution pattern around the Kuroshio currents

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1. INTRODUCTION

The ocean affects tropical cyclones (TCs) through the sea surface and greatly controls intensity of TCs (e.g., central pressure, rain rate and wind speed) by the sea surface temperature (SST). Intensity of TCs changes in moving on the area of large SST gradient or of local cold/warm SST distribution.

On the other hand, the ocean also varies by the air-sea interaction through mixing/upwelling in the upper layer in the ocean produced by TCs passing on the ocean surface and decrease of the SST is observed after passing of TCs. In numerical experiments, it is reported that suppression of the intensity, the central pressure, caused by the air-sea interaction is more in the TCs' of slow moving (Bender et al., 1993). Cold wake observed after passing of a TC also contributes to suppression of the TC's central pressure (Bender and Ginis, 2000).

The intensity of a TC moving northward in the western North Pacific is suppressed/enhanced by the local SST distribution around the Kuroshio currents off Japan Honshu islands which has meridional sharp SST gradient of about 1K/latitudinal-degree and locally cold/warm region by aligned vortex patterns of several 100km scales. Intensity suppression by the air-sea interaction is also included. To investigate intensity change of the TC to the SST distribution of horizontal fine pattern with vertical ocean layers, numerical experiments were performed: sensitivity experiments employed idealized SST distributions of fixed time variation and atmosphere-ocean coupled experiments with one-dimensional and three-dimensional oceans.

In this paper, we report on work in the numerical experiments to the intensity change of Typhoon (TC) T0914, Choi-wan, which moved across the Kuroshio currents in mid-September in 2009.

2. NUMERICAL MODELS

Three-dimensional regional models in hydrostatic system were utilized in our experiments. CReSS (Cloud Resolving Storm Simulator, Tsuboki and Sakakibara, 2002) was utilized for the atmosphere part in the all experiments. For the ocean part, three ocean models were utilized selectively, depending on the experiments. One is the fixed SST model with no-time variation of the SST from the initial time. The one-dimensional ocean coupled model represents time-variation of the SST, which treats the upper layer and performs as the slab ocean with 30m depth including vertical heat transfer. Three-dimensional ocean coupled model represents the time-varying SST with receiving heat, momentum and fresh water fluxes on the sea surface from the atmosphere. In this study, NHOES (Non Hydrostatic Ocean model for the Earth Simulator, Aiki et al., 2006) was utilized for the three-dimensional atmosphere-ocean coupled experiments.

A three-dimensional atmosphere-ocean regional coupled model, CReSS-NHOES, has been developed originally to simulate non-hydrostatic meteorological and oceanic phenomena. Both models of CReSS and NHOES are well-developed three-dimensional regional models. MPI decomposition is employed for

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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. CReSS-NHOES utilized hybrid parallelization method achieves high performance in calculation on the Earth Simulator.

2. DESIGN OF NUMERICAL EXPERIMENTS

Numerical experiments were performed for 10-days starting from 00 Z in September 16, of horizontal resolution at 4 km with 380 x 480 grids in 19N-38N, 120E-135E latitudinal-longitudinal domain. Vertical coordinate system is starched, from 200 m on the ground to 400 m to the upward of 60 layers for the CReSS, and from 2 m near the surface of 100 layers for the NHOES. For initial/boundary conditions, JMA/GPV dataset (0.5 degree of horizontal resolution) was employed for the atmosphere and JCOPE2 reanalysis dataset (1/12 degree of horizontal resolution) employed for the ocean.

Five types of oceans were designed in the numerical experiments to Choi-wan. For sensitive experiments with fixed SST ocean model, three types of oceans were prepared which were based on the observed SST at the initial time. The fixed SST experiment (fixed SST) was employed the original SST distribution at the initial time, the meridional smoothed experiment (smoothed) was employed 10-dgree running mean meridionally to the SST of the fixed experiment, and zonally averaged and meridional smoothed experiment (z-smoothed) was employed zonal average to the SST of the smoothed experiment, respectively (Table 1).

3. NUMEICAL SIMULATION OF CHOI-WAN

Numerical simulations for the experiments of Choi-wan were performed on the Earth Simulator, which achieved high-performance in the simulation.

In the experiments, Choi-wan was successfully simulated in representing a typical structure in the mature stage of a TC, and the simulated tracks (center of the TC determined by the minimum pressure at the sea level) coincided with the observation reported in the JMA Besttrack (Figure 1). Besides, in the coupled experiments the time variation of the SSTs at the local point at KEO buoy (32N, 145E) showed a good coincidence in decreasing with the observation when Choi-wan was passing over the buoy (Figure 2). During the simulation period, Choi-wan moved into the domain from the south edge in September 16 and moved out from the north east corner in September 22. Simulation data of 120 hours from the start of the integration were analyzed to investigate intensity change of Choi-wan.

3. 1. SUPPRESSION IN THE CENTRAL PRESSURE

Figure 3 shows the time variation of the central pressure of Choi-wan. Decreasing of the central pressures was suppressed in the experiments to the experiment of the fixed SST. At 60 hour of the integration time, difference of the central pressure is not clear among the experiments, and then, during 60 to 96 hours, suppression of the central pressure was evident. At the time of 60 hour, Choi-wan located in south edge of the Kuroshio currents zone and approached to the region of the sharp meridional SST gradient (Figure 4). At the time of 100 hour, Choi-wan almost passed over the region of the meridional large SST gradient and located in the north east edge. Time variation of the central pressure showed large differences in the period among the experiments when the Choi-wan moved on the Kuroshio currents zone of large SST gradient. That suggests the intensity suppression of the TC controls the SST distribution in the Kuroshio currents zone.

3. 2. NON-COUPLED SENSITIVITY EXPERIMENTS

Comparing with the experiment of the fixed SST, sensitivity of the intensity of the TC appeared in the central pressure suppression to the SST distributions is to be clarified among the three experiments utilizing the fixed SST ocean model.

At 80 hour of the integration time, remarkable suppression appears among the experiments. The central pressure suppressed of 13 hPa in the smoothed experiment compared with that in the fixed SST experiment, and 15 hPa in the z-smoothed experiment. Compared with the patterns focusing in the SST distribution around the Kuroshio currents zone, filament-like vortex patterns disappeared in the smoothed experiment (Figure 5), and z-smoothed experiments. In addition, the SST pattern of zonally varying was removed in the z-smoothed experiment. More suppression of the central pressure occurred in the experiment of smoothed SST with meridionally smoothing during the passing Kuroshio currents. Difference of the magnitude in the suppression between the smoothed and z-smoothed experiments suggests that meridional fine distribution with large SST gradient around the Kuroshio currents zone much contributed to control of the intensity of Choi-wan.

Difference between the experiments with removing meridional/zonal SST gradients also implies that the axi-asymmnetic contribution around the TC center occurred in the Kuroshio currents zone. To clarify the axi-asymmnetic contribution to the intensity of the TC, local distribution of the heat flux from the sea surface was compared about the TC center. Figure 6 shows the time variation of the latent heat flux distribution averaged within 100 km radius around the TC center following along the track. To consider the local contribution to the intensity of the TC, the heat flux around the TC center was divided into 4-quadrants geometrically, north-south and east-west. During 70-80 hours of the integration time, the latent heat flux was reduced in the western quadrants in the smoothed and z-smoothed experiments to that in the fixed SST experiment. During 70-85 hours, the flux was reduced in the south-east quadrant in the smoothed experiments. Those suggests that the local SST distribution around the Kuroshio currents zone contributed change of the intensity through the heat flux on the sea surface in the western side of the moving TC, Choi-wan, resulting in the suppression of the TC central pressure. In the north-east quadrant, the magnitude of the fluxes in the fixed and smoothed experiments were close and greater of about 60 W/m2 than that in z-smoothed experiment during 60-90 hours. This suggests, in the same way, that the reduction of the flux in the zonally smoothed experiments explains the contribution the zonal distribution of the SST around the Kuroshio currents zone. The sensible heat flux also showed the same characteristics of local contribution as in the latent heat flux in the time variation.

3. 3. NON-COUPLED SENSITIVITY EXPERIMENTS

To investigate the intensity change of TCs with air-sea interaction, numerical experiments utilizing with 1-D and 3-D ocean coupled model were performed. Both coupled experiments showed intensity suppression to the fixed SST experiment shown in Figure 3.

In the comparison of the local heat fluxes (sensible plus latent fluxes) divided into the 4-quadrants between the coupled experiments, remarkable reduction occurred in the 3-D coupled experiment about 80 hour of the integration time (Figure 7). At the time, the central pressures deepened at the maximum in the both experiment and suppression occurred at the maximum in the 3-D experiment. That suggests that reduction of the heat fluxes from the sea surface by the three dimensional air-sea interaction occurred in the experiment of the 3-D ocean coupled, representing in the suppression of the central pressure, although the difference of the SST between the experiments was not clear (not shown the figure).

During the period, it was the mature period and the moving speed of Choi-wan was about 20m/s or more, which is too fast to receive the colder SST by cooling caused by upwelling in the three-dimensional ocean, compared with the previous study by Bender et al., 1993. However, the variation of the local heat fluxes decreased remarkably in the intensity suppression of Choi-wan which moved fast around the Kuroshio currents. That suggests that three-dimensional air-sea interaction contributed to suppress the intensity of Choi-wan in moving over the Kuroshio currents.

4. CONCLUSION

Sensitivity of the intensity of a TC, Choi-wan's central pressure, to the SST was investigated in numerical experiments utilizing a regional atmospheric model, CReSS, with non-coupled and coupled ocean models. Suppression occurred around the Kuroshio currents zone of large SST gradient. The intensity of Choi-wan was controlled through the axi-asymmetic local heat fluxes from the ocean around the TC center across the Kuroshio currents zone. Non-coupled sensitivity (idealized) experiments showed that meridional SST pattern greatly contributes to suppression in the case of Choi-wan. Coupled experiments (1-D and 3-D oceans) showed the air-sea interaction also contributes to suppression. The intensity suppressed more in the 3-D ocean coupled experiment to the 1-D ocean coupled, moving over the Kuroshio currents zone, which implies that three dimensional ocean responses to a TC suppresses more the intensity of the TC in the Kuroshio currents.

Regional contribution based on axi-asymnetic local heat fluxes from the ocean surface in the Kuroshio currents zone was shown in the comparison of the experiments. The heat fluxes of locally distributed was gathered to the center of the TC by the TC circulation, and affected totally the intensity of the Choi-wan itself resulting in the suppression of the intensity.

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The Earth Simulator was utilized for main simulation in this study.

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Table 1. Experiments of ocean types and setting

Ocean type	z-direction	y-direction	x-direction
fixed SST	Surface (SST)	-	-
smoothed	surface (SST)	10-deg running mean	-
z-smoothed	surface (SST)	10-deg running mean	zonal average
1-D coupled	30m depth, 60 layers	-	-
3-D coupled	Real, 100 layers	-	-

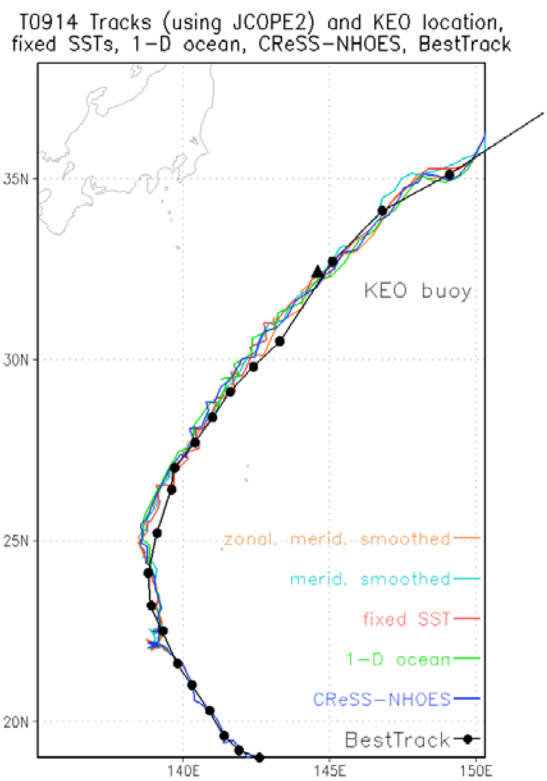

Figure 1. Tracks of Choi-wan and the experiment domain. Colored lines are simulated tracks and black with dots is JMA Besttrack, respectively. The KEO buoy location indicates in triangle mark.

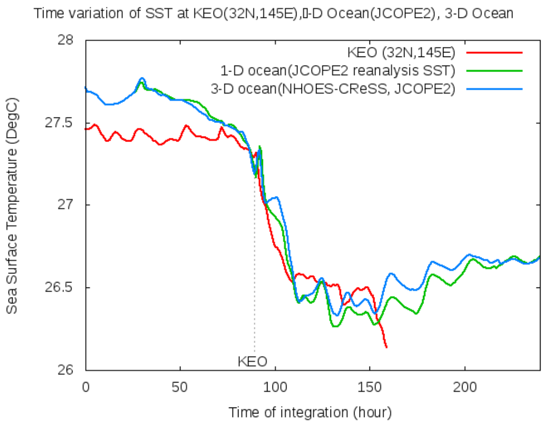

Figure 2. Time variation of the SST at the KEO buoy. Dotted line indicates the time of Choi-wan passing over the KEO buoy at 89 hour of the integration time (http://www.pmel.noaa.gov/ocs/disdel/disdel.html).

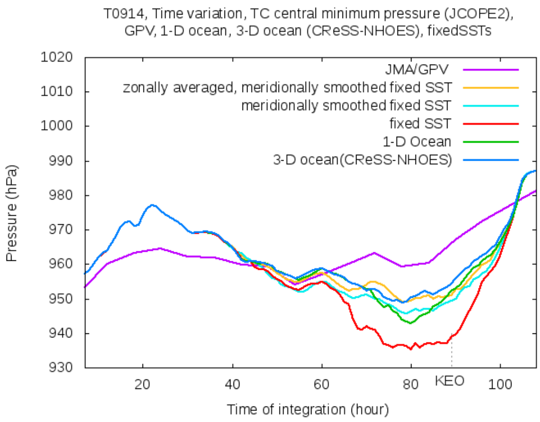

Figure 3. Time variation of the central pressure of Choi-wan from 7 to 108 hour of the integration time. The dotted line with KEO label indicates the time of Choi-wan passing over the KEO buoy.

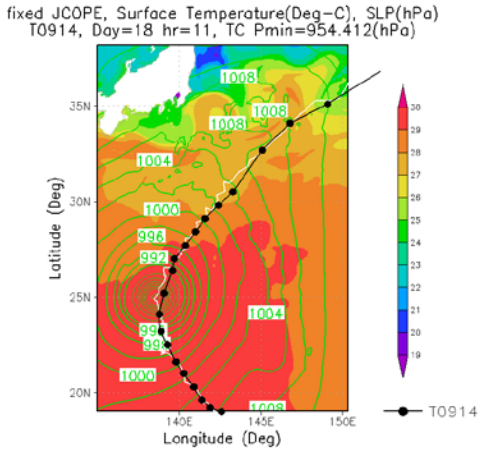

Figure 4. Sea level pressure (green contours), the SST distribution (colored) and the tracks in the experiment of the fixed SST (white line) at 60 hour of the integration time. Black line with dots shows the JMA Besttrack.

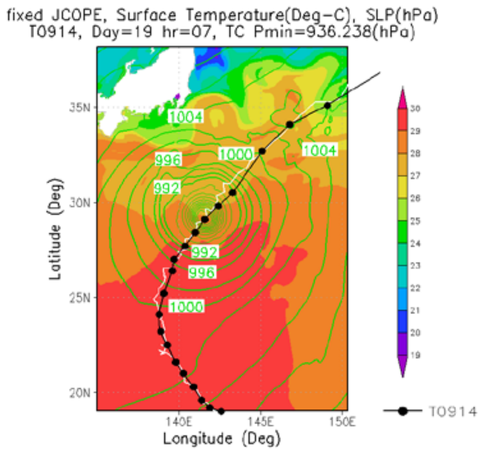

Figure 5. Same as shown in Fig.4 at 80 hour.

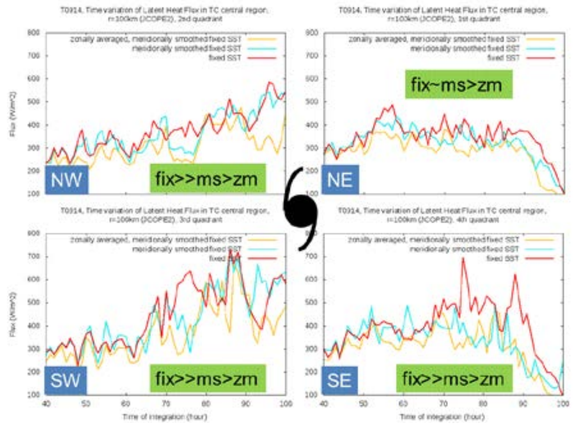

Figure 6. The time variation of the latent heat flux averaged within 100 km radius around the TC center, divided into 4-quadrants: north-east (upper right), north-west (upper left), south-west (lower left) and south-east (lower right) quadrants, respectively. The lines indicate the local fluxes in the fixed SST (red), smoothed (sky blue), z-smoothed (orange) experiments, respectively.

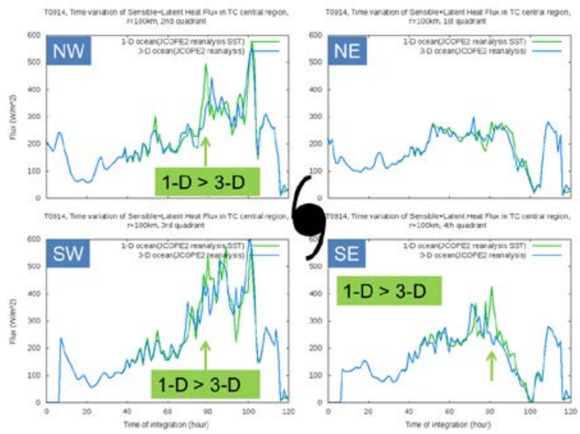

Figure 7. The time variation of sum of the sensible and latent heat fluxes averaged within 100 km radius around the TC center, divided into 4-quadrants for the coupled experiments with one-dimensional (green line) and three-dimensional (blue line) ocean, respectively.