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Study on the local air-sea interaction under typhoon by using non-hydrostatic atmosphere-ocean coupled model

비정역학 대기-해양 결합모델을 이용한 태풍시 대기-해양 상호작용 연구

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1. INTRODUCTION

Regional Environment Simulator (RES) developed in Hiroshima University, Japan is a meso-scale coupled model cluster that can be utilized in the study of regional disasters and environmental problems mainly concerning with natural water circulation. RES consists of three parts (Fig. 1); 1) atmosphere-surface waves-ocean circulation, 2) atmosphere-land surface process-hydrological circulation and 3) coastal and estuarine circulation. Each part is constructed with state-of-the-art public domain numerical models being synchronously combined with model coupler. Therefore, RES can give us detailed insights from various aspects by considering coupled processes between the component models about specific problems. For instance, RES has been used for the study of storm surge by typhoons and hurricanes, wintertime abnormal high waves in East Sea, dam-made lake circulation, summertime heavy rainfall and runoff in Japan, estuarine circulation at a river mouse in Indonesia and wave overtopping in coastal region. Most recently, a project on the impacts of reduced discharge of freshwater and sediment from Yangtze River basin on the adjacent East Asian Seas has been initiated using the RES as a significant tool for the environment assessment and multidisciplinary environmental science. In this study, the local air-sea interaction under typhoon with regards to typhoon and ocean responses to each other has been investigated using the non-hydrostatic atmosphere-ocean coupled model which is the core circulation part of the RES.

Local air-sea interaction under typhoon condition is quite important in the forecast of the track and intensity of typhoon. Due to advanced computing technologies, improved dynamic models and satellite observations, the forecast of typhoon track have been gradually improved. However, due to our limited understanding of the air-sea interaction the forecast of typhoon intensity variation is a still difficult task to be explored.

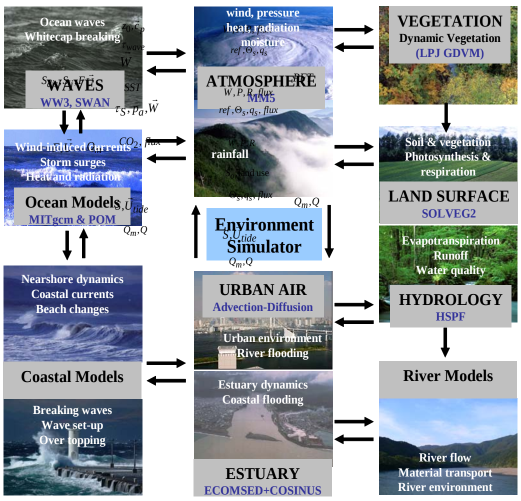

Fig.1.Framework of Regional Environment Simulator

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It has been well studied that there is a positive and negative feedbacks mechanism in typhoon-ocean interaction. As the generation of typhoon is related to the SST higher than 26°C (Wendland, 1977), typhoons are growing and become intensified due to the increased evaporation rate by strong surface wind stress. The increased moisture supply results in the enhancement of latent heat flux that drives the circulation of typhoon. This is the positive feedback in the inception and development stage of typhoons. As the typhoon gets stronger, the turbulent mixed layer gets developed and deepened by the strong wind stress, resulting in the decrease of SST. The SST reduction is due to the current velocity shear production that brings the cool thermocline water to turbulent mixed layer. Consequently, the reduction of SST leads to the decrease of typhoon intensity. This is the negative feedback in typhoon-ocean interaction. Thus SST variation is very important in the intensity change of typhoon and have been well studied both theoretically (Emanuel, 1986) and numerically (Chang, 1979; Tuleya and Kurihara, 1982; Bender et al. 1993). Recently the observation by satellites confirms the SST reduction as much as 5°-6°C in the cold wake of slowly moving typhoons (Nelson, 1996; Monaldo et al. 1997; Wentz et al. 2000).

In most of the numerical simulation studies (Bender et al., 1993, Bender and Ginis, 2000, Hodur, 1997, and Chan et al., 2001) the typhoon-ocean interaction was investigated with regard to the intensity and track changes of typhoons and the ocean states are idealized as homogeneous and quiescent or simulated with primitive equation ocean models. Although the simulated SST reductions in those studies are agreed with observed data and other numerical studies, the ocean response to typhoon that deepens the ocean mixed layer and causes the SST reduction by bringing up the cool thermocline water to mixed layer is not well studied and described by the coupled models under a real typhoon.

The objectives of this study is to investigate the dynamic ocean response to typhoon as well as that of typhoon in terms of ocean mixed layer, mixed-layer currents and temperature profiles in the wake of typhoon in addition to SST changes by means of a three-dimensional non-hydrostatic atmosphere and ocean coupled model.

2. ATMOSPHERE-OCEAN COUPLED MODEL DESCRIPTION and CONFIGURATION

2.1 Atmosphere and Ocean Models

The atmospheric circulation in a coupled simulation model and in RES is described by mesoscale model, MM5, developed at Pennsylvania State University (PSU)-Natinal Center for Atmospheric Research (NCAR). This model is based on non-hydrostatic, compressible form of governing equations in spherical and sigma coordinates with physical processes such as precipitation physics, Planetary Boundary Layer (PBL) processes and atmospheric radiation processes incorporated by a number of physics parameterizations. Further details of MM5 are referred to Grell et al. (1995).

As emphasized by Bender and Ginis (2000), the realistic modeling of ocean response need the highly accurate representation of ocean mixed layer in the upper-ocean and stratified region below since the ocean response to typhoon is very sensitive to the ocean mixed-layer processes. Therefore, the ocean model used in the present study and in RES adopted a general ocean general circulation model, MITgcm (Marshall et al. 1997a, b), developed from Massachusetts Institute of Technology. This model is a non-hydrostatic three-dimensional model based on the incompressible Navier-Stokes equations with Boussinesq approximation formulated in finite volume method.

2.2 Simulation Design of Typhoon ETAU and Initial Conditions

The two atmosphere and ocean models are synchronously coupled with the model coupler, OASIS (Valcke, 2006). The coupled model for the local air-sea interaction simulation was applied to the real Typhoon ETAU (Fig. 2). In this application, the results from three simulations were described: (i) the MM5 simulation was carried out alone without coupling to ocean, (ii) MITgcm run was conducted alone without coupling to atmosphere and (iii) the coupling run between MM5 and MITgcm was carried out through the typhoon-ocean interaction. In the MM5-alone case, the initial value of SST used in MITgcm was kept constant in the surface boundary condition during the period of simulation. In the MITgcm run without coupling, the ocean state was described by the density gradient in initial condition and boundary flow at open boundaries without the external forcing through the surface. In the coupling simulation, MITgcm obtained the surface heat flux, momentum flux by wind and sea surface pressure from MM5 integration while MM5 got the variable SST values from MITgcm integration for multiple common time steps. The simulations were performed for 90 h from 0000 UTC 5 August to 1800 UTC 8 August in 2003 until the typhoon made landfall.

The initial state of ocean is very important in real-case typhoon-ocean interaction that the ocean response to typhoon highly relies on the initial temperature, salinity profiles and current field. There are two ways of obtaining the realistic initial ocean state; (i) from the global ocean general circulation model if available and (ii) from necessary spinup of the ocean circulation using available climatological ocean data together with high-resolution SST data.

In the present simulation of Typhoon ETAU, the near operational forecasting data from the high-resolution JCOPE (Miyazawa, 2004) regional ocean model was incorporated for the initial condition of ocean states. The initial temperature, salinity profiles and currents field were interpolated onto the ocean model grid for the 3 August 2003 at the start time of coupling process. The boundary flows at open boundaries were also taken from the JCOPE model data.

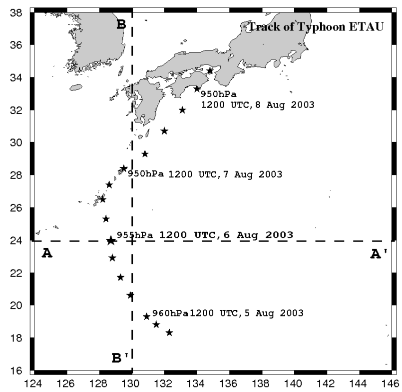

Fig. 2. Every 6h observed track of Typhoon ETAU and computational domain.

3. MODELING RESULTS

The ocean responses to Typhoon ETAU in the coupled run were presented in terms of the currents in ocean mixed layer (Fig. 3), SST cooling (Fig. 4) and changes of vertical temperature profile. The asymmetric divergent currents in ocean mixed layer that result from the wind stress acting on the inertially rotating flow were clearly revealed. The SST cooling due to the cool thermocline water brought by the velocity shear between ocean mixed-layer currents and thermocline currents was shown. Large SST reductions were found in the east of Okinawa with 5.25℃ and in the east of initial position of typhoon with 5℃ and these values were validated with satellite (TRMM Microwave Imager radiometer) observed SST values of about 5℃ and 4.75℃, respectively (Fig. 5).

In typhoon response in the coupled run, the net heat flux (sensible plus latent) was reduced about 350-400W/m2 in the cold wake of typhoon and its distribution well coincided with the distribution of SST anomaly mainly due to the decrease of latent heat flux. Accompanied by the decrease of net heat flux, the total precipitation and the equivalent potential temperature were reduced 5% (about 300mm) and 6-7 K in maximum locations, respectively.

In general, the typhoon intensity got decreased due to the negative feedback of the ocean and the typhoon became weak turning into a low level in Hurricane category or tropical storms when it made landfall. However, the Kuroshio Warm Current (KWC), the high horizontal gradient of SST, has a significant effect that keeps or even enhances the typhoon intensity when the typhoon passes over KWC. Fig. 6 shows the observed minimum sea level pressures of Typhoon ETAU with the simulation result of coupled and non-coupled run.

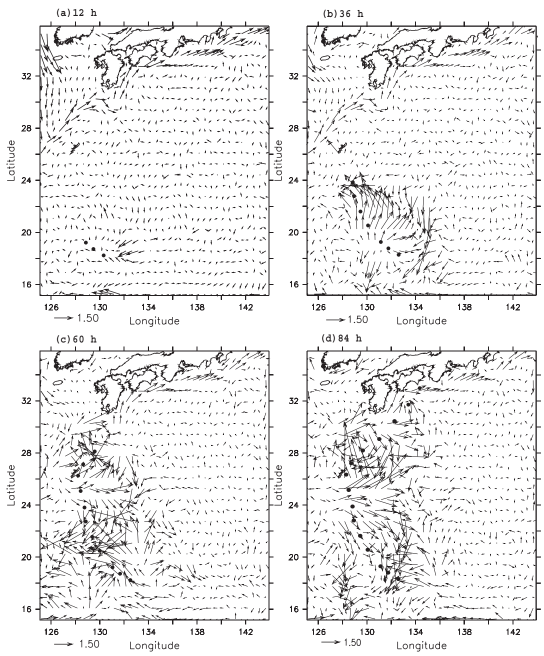

Fig.3. The currents velocities (m/s) in ocean mixed layer at (a) 12 h, (b) 36 h, (c) 60 h and (d) 84 h in coupled run. (The typhoon motion every 6h in black circles)

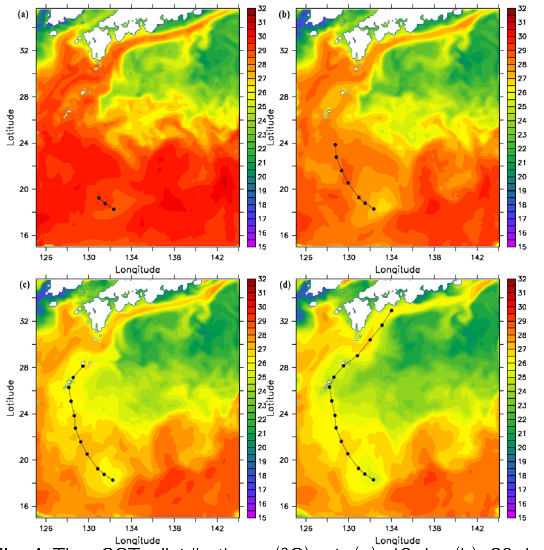

Fig. 4. The SST distributions (°C) at (a) 12 h, (b) 36 h, (c) 60 h and (d) 84 h in coupled run. (The typhoon motion every 6h in black circles)

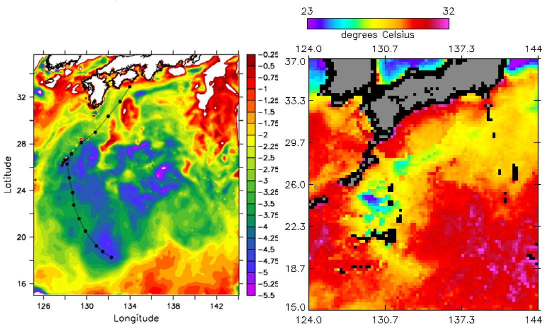

Fig. 5. The SST anomaly at 84 hrs in coupled run (left) and TRMM satellite observed 3-days mean SST (right) at 8 August 2003.

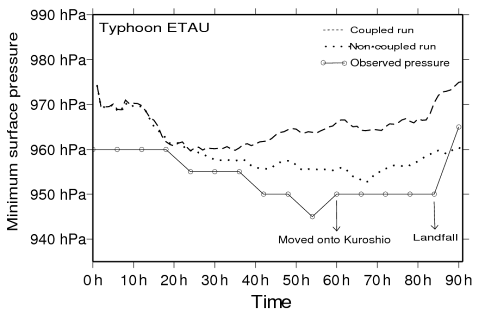

Fig. 6. Time series of minimum sea level pressure from the simulation and observed values (blank circles indicate every 6 h).

4. CONCLUSION

In this study, the local air-sea interaction under Typhoon ETAU was investigated using the non-hydrostatic atmosphere-ocean coupled model. The local ocean response shows general accordance with satellite observations in SST. By imposing more accurate initial and boundary conditions, it is possible to get more deep insights to both typhoon circulation and local ocean response by the coupled model and thus RES.

In this study, the influences of surface wind waves are not considered which not only effect the typhoon circulation through the surface roughness and heat flux but also have effects on the surface currents in terms of wave breaking (whitecapping in deep water and depth-induced wave breaking in shallow water) and turbulence production in surface boundary layer.

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