Lagged simulations of the oceanic initial condition for Typhoon Choi-wan (2009)

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1. Introduction

On 19 September 2009, the eye of Typhoon Choi-Wan passed ~40 km to the southeast of the Kuroshio Extension Observatory (KEO) surface mooring, located at 32.3ºN, 144.5ºE. Bond et al. (2011) reported the large variation (~50 μatm) in $\Delta p\mathrm{CO_2}$ (=$p\mathrm{CO_2}^{sea}$-$p\mathrm{CO_2}^{air}$: surface oceanic partial $\mathrm{CO_2}$ minus surface atmospheric partial $\mathrm{CO_2}$) observed during the typhoon passage. Nearly forty percent of $\Delta p\mathrm{CO_2}$ (~ 20 μatm) was explained by rapidly falling $p\mathrm{CO_2}^{air}$ during the passage. Thus, approximately sixty percent of $\Delta p\mathrm{CO_2}$ should be explained by a rapid increase of surface $p\mathrm{CO_2}^{sea}$ during the typhoon passage. However, the atmosphere-wave-ocean model could not fully simulate the rapid increase of surface $p\mathrm{CO_2}^{sea}$ under given atmospheric and oceanic initial conditions. Excessive sea-surface cooling and resultant low surface $p\mathrm{CO_2}^{sea}$ compared with observations at the KEO surface mooring may be caused due to uncertainties of atmospheric and oceanic initial conditions. In order to understand the effect of oceanic initial conditions on the simulation of the oceanic response to Choi-wan (2009), lagged ensemble numerical simulations for Choi-wan associated with the oceanic initial condition were carried out by the atmosphere-wave-ocean coupled model providing daily oceanic reanalysis data individually from 12 to 25 September in 2009. The daily oceanic reanalysis data were calculated by the Meteorological Research Institute Ocean Variational Estimation system (MOVE: Usui et al. (2006)).

2. Experiment design

The lagged ensemble numerical simulations were performed by a nonhydrostatic atmosphere model coupled with the multilayer ocean model, the ocean wave model and the oceanic carbon equilibrium scheme. The model specification was as follows: The computational domain was 3240 km x 3960 km with a horizontal grid spacing of 6 km. The model had 40 vertical levels with variable intervals from 40 m for the lowermost (near-surface) layer to 1180 m for the uppermost layer. The model had maximum height approaching nearly 23 km. The time step of the nonhydrostatic model was 20 seconds. The length of the time step of the ocean model was six times (that is 120 seconds) that of the atmosphere model. The time step of the ocean wave model was 10 minutes. Each initial depth of the oceanic mixed layer was determined every oceanic reanalysis data from 12 to 25 September in 2009, by assuming a difference in the value of density from the surface of no more than 0.25 kg $\mathrm{m^{-3}}$ and the depth of the mixed layer was limited to 200 m. The base of the thermocline was limited to 600 m and water depth was limited to 2000 m.

The integration hour was 96 hours. However, we used the results of numerical simulations from the initial time to 84 hours. The lateral boundary condition with the width of lateral boundary sponge layer of 1080 km (180 grids) was changed every six hours. The momentum, sensible and latent heat fluxes were given to the ocean model. It should be noted that the normalization of dissolved inorganic carbon (DIC) and total alkalinity (ALK) to a salinity of 34.1 from a salinity of 35.0 was done at the initial time of numerical simulations. In addition, ALK at the initial time were determined from the following formula.

$$ALK_{init} = \begin{cases} 2500.9T_i^{-0.0029} & T > 18.0 \\ 2299.818 & T \le 18.0 \end{cases}, \qquad (1)$$

where T_i is water temperature at the i-th level of the multilayer ocean model. DIC at the initial time are determined from the formula as described in Wada et al. (2011).

The KEO reference station is a highly instrumented moored buoy located at 32.3ºN, 144.5ºE, in the recirculation gyre south of the Kuroshio Extension (Cronin et al., 2008). In this study, we use data from the KEO mooring, including hourly meteorological data, hourly sea-surface temperature, sea-surface salinity and 3 hourly $p\mathrm{CO_2}$ from a Moored Autonomous $p\mathrm{CO_2}$ system (Bond et al., 2011) for validation of the ensemble numerical simulation results.

3. Results

3.1. Sea-level pressure and surface air temperature

Figure 1 shows time series of sea-level pressure (Fig.1a) and surface air temperature (Fig.1b) observed at the KEO mooring and simulated at the corresponding grid to the KEO buoy site. Lowest simulated sea-level pressure appeared three hours after lowest best-track one. Simulated air temperatures were higher just before the passage of simulated typhoon than the observations, and were lower after the passage.

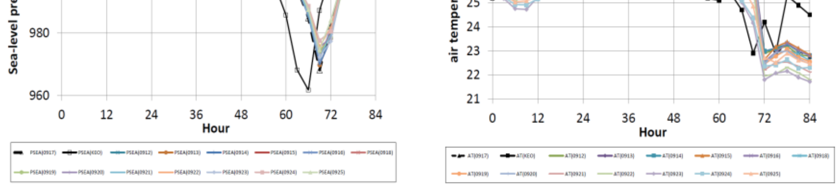

Fig.1 Time series of (a) sea-level pressure and (b) surface air temperature observed at the KEO mooring (black line) and simulations

3.2 Oceanic ingradients

Figure 2 shows time series of sea-surface temperature (Fig.2a) and sea-surface salinity (Fig.2b) observed at the KEO mooring and simulated at the corresponding grid of the KEO buoy site. Simulated sea-surface temperature varied at the initial time with a range of 26.5 °C to 28 °C. Excessive sea-surface cooling occurred after the passage of the typhoon in all simulations compared to the observations. In contrast, simulated sea-surface salinity showed that the evolution quite differed among oceanic initial conditions from 12 to 25 September in 2009.

Figure 3 shows time series of surface $p\mathrm{CO_2}^{sea}$ (Fig. 3a) and that normalized to a temperature of 29 °C (Fig. 3b). The evolution of surface $p\mathrm{CO_2}^{sea}$ was closely related to that of sea-surface temperature (Fig. 2a): Simulated surface $p\mathrm{CO_2}^{sea}$ rapidly decreased after the passage.

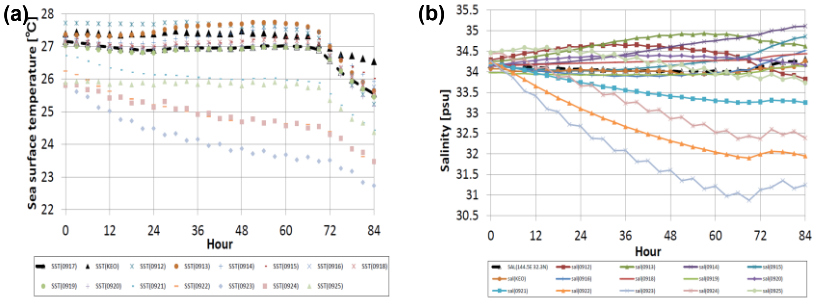

Fig.2 Same as Fig. 1 except for (a) sea-surface temperature and (b) sea-surface salinity.

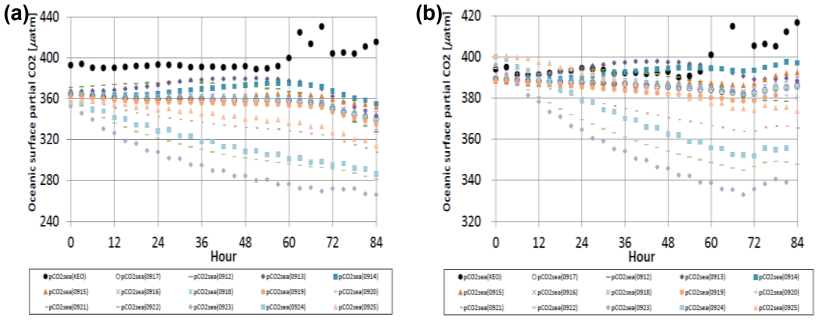

Fig.3 Same as Fig. 1 except for (a) surface $p\mathrm{CO_2}^{sea}$ and (b) surface $p\mathrm{CO_2}^{sea}$ normalized to a temperature of 29 °C.

The evolution of surface $p\mathrm{CO_2}^{sea}$ normalized to a temperature of 29 °C showed that normalized surface $p\mathrm{CO_2}^{sea}$ increased after the passage of simulated Choi-wan. The evolution of surface $p\mathrm{CO_2}^{sea}$ normalized to a temperature of 29 °C was similar to that of sea-surface salinity. In Fig. 3, both the evolutions of surface $p\mathrm{CO_2}^{sea}$ and the normalized one quite differed from those of observation. However, some of simulations partly captured a variation in surface $p\mathrm{CO_2}^{sea}$ and the normalized one except the rapid variation during the passage of the typhoon (Fig. 3a). Pre-existing oceanic condition (before 17 September in 2009) would be favorable to simulate a variation in surface $p\mathrm{CO_2}^{sea}$ and post-existing oceanic condition (after 20 September in 2009) would be necessary to simulate the increases in sea-surface salinity and the normalized surface $p\mathrm{CO_2}^{sea}$ after the passage of the typhoon.

4. Conclusions

Lagged ensemble simulations for the typhoon associated with the oceanic initial condition were carried out by the atmosphere-wave-ocean coupled model providing daily oceanic reanalysis data from 12 to 25 September in 2009 as oceanic initial conditions in order to understand the effect of oceanic initial conditions on the simulation of the oceanic response to Typhoon Choi-wan in 2009. We could find the impact of the oceanic initial condition on simulated sea-level pressure and surface air-temperature only during the passage of the typhoon. In contrast, we could clearly find the impact on simulated sea-surface temperature, sea-surface salinity, surface $p\mathrm{CO_2}^{sea}$ and that normalized to a temperature of 29 °C during and after the passage of the typhoon. In addition, some of simulations could partly capture a variation in surface $p\mathrm{CO_2}^{sea}$ and the normalized one after the passage of the typhoon even though we find no rapid variation during the passage of the typhoon.

This study suggests that oceanic initial condition can affect the evolution of surface $p\mathrm{CO_2}^{sea}$ by passage of the typhoon. In addition, the results of validation using the observations at the KEO mooring imply that the three-dimensional ocean circulation model will be required to simulate the variation in oceanic ingredients by passage of the typhoon under given atmospheric conditions. Moreover, atmospheric ensemble approach will be needed to estimate uncertainties of atmospheric conditions, including the improvement of track simulations. These are future subjects in this study.

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