Effects of Air-Sea Interaction on the East-Asian Monsoon Simulation: A Regional Climate Study

Eun-Jung Kim and Song-You Hong

Department of Atmospheric Sciences, Yonsei University, Seoul, Korea

1. Introduction

It is well known that the sea surface temperature (hereafter, referred to as SST) is a critical component which influences the exchange of energy between the atmosphere and ocean. Since SST influences atmosphere as well as is controlled by atmospheric conditions, accurate SST data from observation or predicted by model plays a crucial role in weather forecast and research. However, the spatial and temporal resolution of SST data is too poor to reflect accurate condition of ocean. Thus, representation of phenomena which occurs in air-sea interface has a limitation to reflect air-sea interaction in weather forecasts and climate simulation.

It is expected that simulations from RCMs produce better results than GCMs when the air-sea interaction is considered since RCMs represent more realistic condition. However, although simulations can produce more realistic results when air-sea interactions are considered in RCMs, receiving the initial condition due to long-term simulation is difficult and processes related to data assimilation between observed value and the model are complicated. For example, full RCMs ignore observed SST data and consider the SST constant value because RCMs deal with short range forecast.

The purpose of this study is to investigate the effects of air-sea interaction on the simulated East Asian monsoon by using the RCM. The monsoonal system is a kind of air-sea interaction because there are exchanges of heat and moisture between land and ocean. Since East Asia is affected by the Northern Pacific ocean, the inclusion of air-sea interaction in forecast model will also contribute to improving the forecast skill over East Asia. Wang et al. (2005) indicated that the coupled ocean-atmosphere processes are crucial in the monsoon regions where atmospheric feedback on SST is critical.

This study focuses on the impact of air-sea interaction by using three methods which represent what happen at air-sea interface. A model used in this study is the WRF model. The methods which represent the air-sea interaction in this study include 1) the ocean mixed layer model based on Pollard et al. (1973), 2) the prognostic sea surface skin temperature scheme based on Zeng and Beljaars (2005), and 3) the roughness length formula based on Donelan et al. (2004).

2. Methodology used in this study

Three methods were used in this study to represent air-sea interaction. The first method is the ocean mixed layer model based on Pollard et al. (1973). This model omits the entrainment and the horizontal advection and is also based on the assumption of no heat transfer between the individual columns so that temperature changes within a column can occur only through the vertical redistribution. If strong wind blows over the ocean, mixed layer which is assumed as a slab (fixed depth) is stirred. Then the mixed layer is deepened and water cooled due to the wind-induced mixing. As a result, the cooled SST changes the surface fluxes at the ocean.

The second method to represent the air-sea interaction is a prognostic scheme of sea surface skin temperature based on Zeng and Beljaars (2005), which reflects the surface energy heat budget of daily SST. In this scheme, skin temperature of sea surface is calculated by adding preexisting SST to sum of the cool skin and warm layer effects, which are combined of the net longwave radiation, the sensible heat flux, and the latent heat flux, molecular, and turbulent mixing processes. Therefore, a model can produce more realistic simulation than inputting the analyzed SST data without consideration of actual state.

The third method to reflecting the air-sea interaction is using the alternative roughness length based on Donelan et al. (2004). Since wind stress on the sea surface plays a role in driving force for ocean circulation, accurate representation of wind stress is important in modeling and forecasting for both atmospheric and oceanic dynamics. The surface stress parameterization in the control simulation uses a Charnock (1955) relation. The changed formulation of roughness length based on studies of Donelan et al. (2004) is used in the experiment which is intended to investigate the effects of surface roughness length.

3. Model and Experimental Setup

The model used in this study is the Weather Research and Forecasting (WRF; Skamarock et al., 2008) version 3.0 and five experiments are designed to investigate the effects of air-sea interaction on the simulated East Asian monsoon. The control experiment (CTL) employs daily SST. Each of the following experiments applies the effects of air-sea
interaction from the package used in the CTL experiment. The OML employs an ocean mixed layer model (Pollard et al., 1973) which uses the initial mixed layer depth as 30 m. The TDI and DRG experiments employ a prognostic sea surface skin temperature scheme (Zeng and Beljaars, 2005) and the alternative roughness length formulation (Donelan et al. 2004), respectively. The ALL experiment includes all three revised effects. SST and the initial mixed layer depth in this study are updated by 24-hour interval. The initial mixed layer depth used in the OMLDRG and ALL experiments is 30 m. The lapse rate used in the OML and ALL experiments is 0.14 K m$^{-1}$.

The simulations were performed for July 2006 and for December 2005. The model domain covered the East Asian region centered over the Korean peninsula. The model configuration is defined in the Lambert conformal space and the model has 1 domain with 48-km grid (110 × 110). The simulations were executed from 0000 UTC 1 July to 0000 UTC 1 August 2006 for summer case and from 0000 UTC 1 December 2005 to 0000 UTC 1 January 2006 for winter case. The entire grid system has 27 vertical layers with a terrain following sigma coordinate, and the model top is located at 50 hPa. Initial and boundary conditions were derived from the National Centers for Environmental Prediction (NCEP) Final analysis data (FNL) on 1°×1° global grids every six hours (hereafter FNL data). The observed SST data are based on the Optimally Interpolated Sea Surface Temperature (OISST) on a 1°×1° grid, which utilizes in situ and satellite-derived SSTs plus SSTs simulated by sea ice cover (Reynolds et al. 2002). In this study, experiments employ the weekly OISST as linearly interpolated in time to derive daily values. The precipitation data which are compared with each experiment were used the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) (Huffman et al., 2007).

4. Results

4.1 Control simulation

Figure 1 shows the differences between the CTL experiment and observation data in monthly averaged sea level pressure accumulated precipitation for two cases. The CTL runs for both cases reproduce fairly well in terms of distribution and pattern of the surface pressure and precipitation compared to observation (not shown). However, the CTL runs for all cases generally simulate the surface pressure weaker than that from the FNL data. In summer, the CTL experiment simulates the surface pressure weak in low-latitudes including the Northwestern Pacific Ocean during the summertime (Fig.1a) and in mid-latitudes during the wintertime compared to the FNL data (Fig.1c). Compared with the TMPA data, the CTL runs for both cases generally overestimate precipitation mainly over the ocean, which includes the Yellow sea, Japan, and near Taiwan for both cases (Figs.1b and 1d). However, the CTL run underestimates precipitation in the region between the Korean peninsula and Japan in summer.

![Fig.1](image)

4.2 Sensitivity tests

The OML experiment simulates higher sea level pressure and lower precipitation over the region from southeastern China to east of Japan including ocean than those from the CTL run (Fig.2a). It means that cooling effects by wind-driven mixing strengthen the surface pressure and suppress an excessive precipitation. It is also notable that the opposite effects can appear to the ocean mixed layer model over mid-latitudes. In figure 6a, in northeastward of the Korean peninsula, the OML run produces the low surface pressure compared to the CTL run, and it results in reducing the systemic biases from the analysis data (not shown).

The increased surface temperature over the ocean by solar heating induces the high surface heat fluxes (not shown) in TDI experiment. This produces weak high pressure system and excessive precipitation by forming an unstable condition compared to the CTL experiment (Fig.2b). The prognostic sea surface skin temperature scheme has both cooling and warming effects, whereas the ocean mixed layer model has only cooling mechanism of SST. Therefore, this method can produce better results on simulated EAM when used with the ocean mixed layer model or the other methods in regional atmospheric models.

It is apparent that the alternative roughness length formula has big effect on atmosphere as shown in figure 2c.
Fig. 2. The differences in 1-month averaged sea level pressure (mb, line), 850 hPa wind vector and 1-month accumulated precipitation (shaded) its differences between the CTL experiment and (a) the OML experiment (OML minus CTL), (b) the TDI experiment (TDI minus CTL), (c) the DRG experiment (DRG minus CTL) and (d) the ALL experiment (ALL minus CTL) for summer case. Solid line is positive bias and dotted line is negative bias.

The strong tendency of the surface pressure over the whole region and decreasing tendency of precipitation appear over the ocean. The DRG experiment also produces low surface latent heat flux and high sensible heat flux at surface of the ocean (not shown). Decreased precipitation induces diminish of the latent heat flux because phase variation related to liquid water and water vapor is reduced. It also induces the increase of the sensible heat flux due to the reduction of cooling caused by evaporation over precipitation area. The DRG run also largely reduces precipitation biases since the strengthened oceanic pressure system due to decreased surface flux causes the stable condition over the ocean. The reduced surface heat fluxes in the DRG experiment are mainly caused by decreased exchange coefficients. In figure 8b, exchange coefficient is significantly small in the DRG experiment compared to other experiments. This is because the exchange coefficients are logarithmically proportional to the roughness length. On the other hand, the DRG experiment reduces precipitation bias by overestimation over the East Sea region located between the Korean peninsula and Japan where the CTL run underestimates.

Figure 2d shows that consideration of all effects produces improved results compared to using each effect only. Although the averaged values are similar among the DRG and ALL experiments, the ALL experiment improves the patterns of pressure and precipitation compared to using each effect only (not shown). Figure 2d indicates that biases caused by using a prognostic sea surface temperature scheme only are canceled by using the other methods together.

Fig. 3. Averaged diurnal variation of (a) Sensible heat flux (W m$^{-2}$), (b) Latent heat flux (W m$^{-2}$), (c) 10-m wind speed (m s$^{-1}$), and (d) heat exchange coefficient over the ocean obtained from the CTL (line), OML (long dashed), TDI (short dashed), and DRG (long dash short dash) experiments for summer case.

Comparisons of monthly averaged daily variation of some values and differences from the CTL run and each experiment for summer and winter are shown in figure 3. Flux differences among the CTL, the OML and the TDI experiments are smaller in winter disable to distinct each experiment, whereas flux differences between the CTL and the DRG experiments are bigger than summer (Figs. 3a and 3b). These results are caused by different synoptic conditions of each season. The wind speed is high during the wintertime (not shown), thus cooling effect of the ocean mixed layer model can be bigger than in summer. However, the differences in air-sea temperature are extremely small in winter because strong wind drops the air temperature over the ocean compared to summer (not shown). Therefore, variation of surface heat flux induced by the ocean mixed layer model is smaller in winter than summer. Strong wind also reduces effects of diurnal heating in the TDI experiment. Therefore, net effects of a prognostic sea surface skin temperature scheme are small in winter since the differences in air-sea temperature by cooling of skin temperature at oceanic surface are smaller than those by heating in summer.

On the other hand, strong wind in winter reduces surface drag coefficient at higher rate. This leads to decrease exchange coefficient (Figs. 3c and 3d) significantly and hence it causes big reduction in surface heat flux. In other words, it can be said that the synoptic conditions determine the magnitude of feedback from the ocean.

Figure 4 exhibits the differences in monthly averaged surface pressure and accumulated precipitation between the CTL experiment and each
experiment for winter case. Effects of ocean mixed layer model and prognostic sea surface temperature scheme are small to be negligible in winter (Figs. 4a and 4b). On the other hand, effects of roughness length are large due to the drag coefficient which is in inverse proportion to wind speed. However, there is little effect in land regions because Siberian high affects dominantly during the wintertime (Fig.4c). Results of the ALL experiment are similar to those of the DRG experiment (Fig.4d).

Fig. 4. The differences in 1-month averaged sea level pressure (mb, line), 850 hPa wind vector and 1-month accumulated precipitation (shaded) its differences between the CTL experiment and (a) the OML experiment (OML minus CTL), (b) the TDI experiment (TDI minus CTL), (c) the DRG experiment (DRG minus CTL) and (d) the ALL experiment (ALL minus CTL) for winter case. Solid line is positive bias and dotted line is negative bias.

5. Summary and conclusion
This study investigates the effect of air-sea interaction over EAM during summer and winter by using a regional climate model. It is found that cooling of temperature at the water surface appears especially when there is significantly strong wind distribution when using the ocean mixed layer model. Cooled SST makes stable condition over the ocean and strengthens the pressure and reduces precipitation.

The prognostic sea surface temperature scheme induces warming effect by heating due to the surface energy budget and cooling effect by longwave radiation. Heated surface temperature at ocean makes the surface heat fluxes higher and unstable condition. This scheme has both effects of warming and cooling effects, whereas the ocean mixed layer model induces stable condition by having only cooling effect of SST. Therefore, both of these two methods must be considered in regional climate models and can produce good results by applying together.

Experiment which uses the alternative roughness length based on Donelan et al. (2004) effectively reduces surface heat flux by reducing the exchange coefficients. The changed roughness length makes the wind-driven mixing at air-sea interface efficiently without being disturbed by drag force.

It is remarkable that sum of the effects produces better results than those of being considered only one effect. Although each method has effect on air-sea interaction in independent way and mechanisms are different, applying effects together reduces the biases fairly well for both cases. This is because it reflects more realistic situation which occurs in air-sea interface.

It is also found that the magnitudes of each effect to air-sea interaction are different among the seasons due to the each synoptic condition. In summer, weak wind and strong solar insolation make the effects of diurnal heating bigger than winter, whereas strong wind enlarges the effects of alternative roughness length by larger reduction of surface roughness length in winter.

The results produced in this study may suggest that some simple methods that reflect the air-sea interaction in RCMs can improve the simulated EAM. Therefore, future efforts to reflect the realistic air-sea interaction are important to improve the EAM simulation.

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7. References