Formulation of the effect of breaking surface waves on entrainment and its impact on Typhoon Hai-Tang in 2005

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1. Introduction

The most important process associated with TC-ocean interaction is sea-surface cooling (SSC) caused by the passage of a tropical cyclone (TC). SSC plays a role in weakening mesovortices formed on spiral bands within a TC-scale cyclonic circulation during TC intensification phase. The weakened mesovortices leads to the suppression of TC intensification [Wada, 2009]. In addition, the state of ocean waves is closely related to both air-sea momentum and enthalpy transfers through the variation of roughness length. In particular, drag coefficients level off at very high wind speed [e.g., Powell et al., 2003; Donelan et al., 2004]. Here, we address the relationship between the state of ocean waves and SSC The state of ocean waves possibly affects the formation of SSC through the effect of breaking surface waves. Therefore we need to clarify how breaking surface waves affect the formulation of SSC in an atmosphere-wave-ocean coupled system. In this study, we formulate the effect of breaking surface waves on entrainment under the assumption that breaking surface waves are expressed as a function of wave-induced stress. In addition, we investigate the impact of entrainment induced by breaking surface waves on the ocean response to Typhoon Hai-Tang in 2005. Moreover, we investigate the influence of wave-ocean interaction on Hai-Tang's intensity predicted by the atmosphere (NHM)-wave (MRI-III)-ocean (MLOM) coupled model [Wada et al., 2009]. In this study, central pressure (CP) is used as the reference of best-track intensity.

2. Wave-ocean interaction

Surface currents calculated by the ocean model are provided to the ocean wave model and wave-induced stresses are provided to the ocean model as the ocean-wave coupling procedure between MRI-III and MLOM [Wada et al., 2009]. Wave-induced stresses are calculated by the ocean wave model as follows.

$$\tau_w = \rho_w g \int \frac{S_{in}}{c_p} d\theta d\omega \,, \tag{1}$$

where τ_w indicated the wave-induced stress, ρ_w is the sea-water density, g is the gravitational acceleration, S_{in} indicates the wind-input source term in the action balance equation, and c_p is the phase velocity at the peak of the spectrum. θ is the wave direction and ω is the wave frequency. The parameter m_d for breaking surface waves induced by wind stress [Wada et al., 2009] is calculated under the assumption that the effect of breaking surface waves is expressed as a function of wave-induced stress and surface wind stress.

$$m_d = c_{wm} \frac{\tau_w}{\tau} \Delta t \,, \tag{2}$$

where τ indicates the surface wind stress and Δt is the time step of the ocean model. C_{wm} is the constant value and is assumed to be 2. Surface wind speed and surface wind stresses calculated in the atmosphere model are provided to the ocean wave model. Roughness lengths is calculated by the wave steepness [Taylor and Yelland, 2001], which is calculated in the ocean wave model.

3. Experiment Design

Table 1 lists four numerical experiments for investigating the sensitivity of breaking surface waves to SSC and Hai-Tang's prediction during its intensification phase. The initial integration time is 1200 UTC 12 July in 2005. At the beginning, three runs are performed using the atmosphere-wave-ocean coupled model [Wada et al., 2009] with a horizontal grid spacing of 3km. The abbreviations mean only atmosphere model (A3), atmosphere-ocean coupled model (AO3) and atmosphere-wave-ocean model (AWO3). In addition, another run is performed using the same atmosphere-wave-ocean coupled model except for m_d =175 (AWO3C).

The specification in the atmosphere model for the present numerical-prediction experiments is as follows. The number of horizontal grid is 1441 x 841 with a horizontal grid spacing of 3 km. The number of vertical level is 40 at which the interval is variably stretched from 40 m at the lowermost layer near the surface and 1180 m at the uppermost layer. The top height is nearly 23 km. The specification for atmospheric initial and boundary conditions and oceanic initial conditions are described in Wada et al. [2009].

Table 1 Abbreviation of Each Numerical Experiment, Horizontal Resolution, and Model Speculation

Experiment	Horizontal resolution (km)	Model
A3	3km	NHM
AO3	3km	NHM + MLOM
AWO3	3km	NHM+MRI-III+MLOM & Eq.(3)
AWO3C	3km	NHM+MRI-III+MLOM & m_d=175

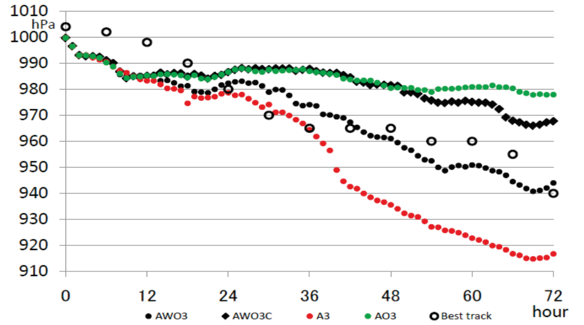

Fig. 1 Time series of Hai-Tang's best-track central pressure every six hours and hourly predicted central pressures in A3, AO3, AWO3, and AWO3C.

4. Results

Figure 1 depicts the time series of best-track CPs, archived by the Regional Specialized Meteorological Center, every six hours and its hourly predicted CPs from 1200 UTC on 12 July (0h) to 1200 UTC on 15 July (72h). At the early integration, hourly predicted CPs indicate rapid intensification, while a change in best-track CPs is small compared with the change in hourly predicted CPs. After 9h, a difference in hourly predicted CPs become significant between A3, AO3, and AWO3. From 15h to 24h, Hai-Tang's intensification is suppressed due to SSC.

After 24h, a trend in hourly predicted CPs in AO3 turns to differ from the trends in A3 and AWO3 and similar to the trend in AWO3C. The impact of a difference in the specifications between AO3 and AWO3C on predicted CP becomes significant after 48h. In contrast, a difference in predicted CPs between AWO3 and AWO3C becomes significant at 15h. The difference occurs earlier than that in predicted CPs between AO3 and AWO3C. This suggests that the parameter m_d plays an important role in predicting Hai-Tang's intensity.

At 72h, predicted CPs in A3 are extremely lower than the best-track CPs, while those in AO3 are higher than the best-track CPs. Even though predicted Hai-Tang excessively develops after 42h in AWO3, predicted CPs are rather comparable to the best-track CPs than the other predicted CPs (Fig. 1). Therefore, the introduction of Eq. (2), for calculating the effect of breaking surface waves on entrainment using wave-induced stress calculated in the ocean wave model, leads to the improvement of Hai-Tang's intensity prediction in that Hai-Tang's intensification in AWO3 is better reproduced than that in AWO3C.

Figure 2 displays the horizontal distribution of initial mixed-layer depth and SSC at 72h. SSC is enhanced around Hai-Tang's center and on the right side of predicted Hai-Tang's track. SSC saliently occurs where initial mixed-layer depth is relatively shallow (Red circle in Fig. 2). This suggests that SSC is controlled not only by Hai-Tang's intensity but also the variation of pre-existing oceanic condition, particularly the distribution of mixed-layer depth.

It should be noted that we can use Eq. (2) only when the atmosphere-wave-ocean coupled model is used. We may need another formulation without coupling the ocean wave model because the computational cost for running the ocean wave model is expensive.

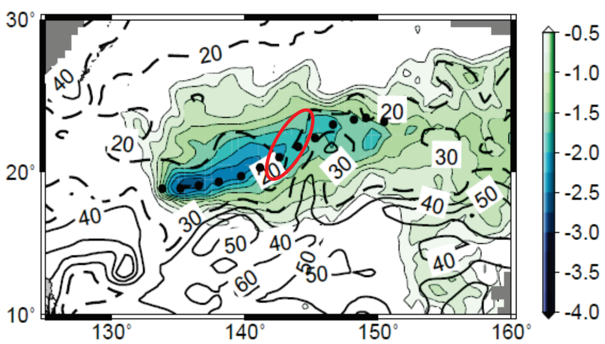

Fig. 2 Contours indicate horizontal distributions of initial mixed-layer depth (solid lines indicate depths more than 40m and dashed lines indicate depths less than 30m) at 1200 UTC on 12 July (upper panel) and shading indicates SSC at 72h from the initial time.

References

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