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Simulating a typhoon storm surge in the East Sea of China using a coupled model

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Abstract

A coupled numerical model with a $2' \times 2'$ resolution grid has been developed and used to simulate five typical typhoon storm surges (5612, 7413, 7910, 8114, and 9711) in the East Sea of China. Three main driving forces have been considered in this coupled model: wave radiation stress, combined wave–current bottom shear stress and wave-state-dependent surface wind stress. This model has then been compared with *in situ* measurements of the storm set-up. The effect of different driving force components on the total storm surge has also been investigated. This study has found that the coupled model with high resolution is capable of simulating the five typical typhoons better than the uncoupled models, and that the wave-dependent surface wind stress plays an important role in typhoon storm surge–wave coupling in this area and can increase the storm set-up by 1 m. The study of the five typhoon cases has shown that the general coupling effects could increase storm set-up by 20–32%. Thus, it is suggested that to predict typhoon storm surges in the East Sea of China, a storm surge–wave coupled model be adopted.

Keywords: East Sea of China; Coupled model; Typhoon storm surges; Wave effects

1. Introduction

The generation of waves and storm surges is closely related, as they are both generated by the wind. There exist strong nonlinear interactions between waves, tides and storm surges in shallow water. The study showed that the coupling of waves and tide–surge motion is driven by several mechanisms in which waves and the mean flow, or the water level associated with the tide and surge, interact with every component in the total motion, thus affecting all other motion. These mechanisms include mainly the wave-state-dependent surface wind stress, the wave–current interaction bottom stress, and the radiation stress. In the past 20 years, various studies [1–13] have considered wave–currents or waves and tide–surge interaction mechanisms in researching wave–currents and wave-storm surge interaction and these have achieved some success. However, in the case of disastrous weather, e.g., typhoons, little research on the storm surge–wave coupling effects has been carried out, particularly in the East Sea of China.

This paper focuses on the storm surge–wave coupling effects in the East Sea of China using a coupled storm surge–wave model, and specifically investigates the effects of waves on storm surges. For five typical typhoon conditions, the coupled model simulation results are compared with those from an uncoupled model to give quantitative estimates and an appraisal of the effects of waves on storm surges in the East Sea of China.

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2. Coupled storm surge–wave model and implementation

2.1. Coupled storm surge–wave model

The coupled storm surge–wave numerical model is composed of an advanced shallow water wave model and a two-dimensional tide–surge model. Two-way interactions between waves and the tide–surge motion are studied on the basis of wave-state-dependent surface stress, wave–current interaction bottom stress and radiation stress mechanisms. A detailed description of each component of the coupled storm surge–wave interaction model including the wave model and the tide–surge model, as well as the main physical coupling mechanisms are given by Yin et al. [9,10,14]. These studies considered the impact of individual main physical coupling mechanisms, such as radiation stress and wave–current interaction bottom stress, as well as surface wind stress and their net impact in the Bohai Sea.

In our present study, we focus on considering the impact of waves on typhoon storm surges in the East Sea of China using the proposed coupled model.

2.2. Initial and boundary conditions

The initial conditions state that currents and surface elevation are zero,

$$\zeta = u = v = 0 \tag{1}$$

Lateral boundary conditions are assumed to be zero for normal flow to the solid boundary and along the open boundary,

$$\zeta = \frac{P_b - P_o}{\rho g} + \sum f_i H_i \cos[\omega_i t + (v+u)_i - g_i] \tag{2}$$

where P_o and P_b are the values for atmospheric pressure outside a storm and at the open boundary, respectively; ρ is the density of seawater; g is gravitational acceleration; ω_i is the radian frequency; harmonic constants H_i and g_i are the amplitude and phase angle of each tidal constituent, respectively; f_i is the nodal factor of each tidal constituent; t is the time; $(v+u)_i$ is the initial phase, and u_i is the nodal correction angle. The 10 constituents in standard notation are K_1, O_1, P_1, Q_1, M_2, S_2, N_2, K_2, S_a, and S_{sa}.

2.3. The coupling procedure

Implementation of the coupling between wave and tide–surge models follows the procedure below:

(i) Prior to the coupling, the two models are initialized separately. Thus, the wave model is warmed up for 12 h, and the tide–surge model for 4 days. Initialization is performed in a manner permitting the synchronized coupling of the two models.
(ii) The wave model is run (in 3-min intervals) for 5 time intervals using the computed change in water depth (mean water depth plus tide–surge elevation) and inhomogeneous unsteady currents from the two-dimensional tide–surge model to obtain related wave parameters, such as the wave spectrum.
(iii) The wave-age-dependent surface wind stress, radiation stress and wave–current bottom stress are calculated using the wave spectrum and passed back to the tide–surge model.
(iv) The two-dimensional tide–surge model is run (in 15-min intervals) using the calculated radiation stress, surface wind stress and bottom stress. This gives newly computed elevations and currents, which are passed back to the wave model to repeat the sequence of computations.

During the simulation, computed results of interest, such as significant wave heights, mean wave periods, the directional wave spectrum, water surface elevations and current velocities, with and without the inclusion of waves and tide–surge interactions, can be output by the wave model and tide–surge model, as described.

3. Simulation and validation of storm surge–wave coupling effects

For the East Sea of China (25°–35°N, 119°00′–127°00′E, see Fig. 1), coupling simulations between the wave and tide–surge models are implemented with a $2' \times 2'$ spatial resolution for five typical typhoons. Typhoon wind fields are computed by the National Marine Environmental Forecast Center by nesting the Takahashi and Fujita typhoon models.

The effects of different driving force components on the storm surge set-ups are investigated and analyzed by

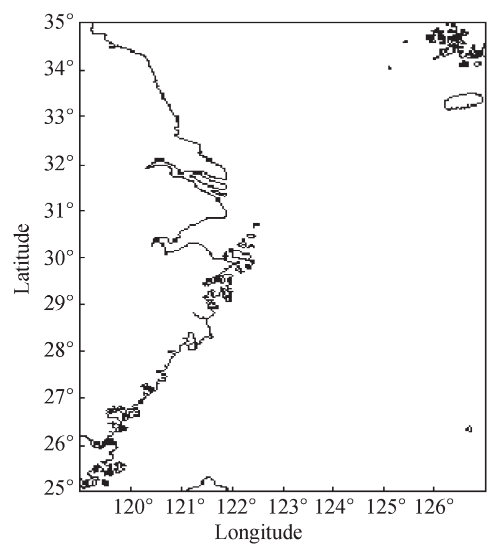

Fig. 1. Study area. Gao Qiao (31°23′N, 121°36′E), Gan Pu (30°23′N, 120°53′E), Lu Si (32°08′N, 121°37′E), Zhen Hai (29°57′N, 121°43′E), Zha Pu (30°36′N, 121°05′E), Wu Song (31°24′N, 121°30′E), Huang Pugang (31°15′N, 121°29′E).

comparing the simulated results from the coupled and uncoupled models.

Figs. 2–6 depict comparisons of the set-up results hindcasted in the coupled and uncoupled models using the actual measurements for typhoons 5612, 7413, 7910, 8114 and 9711. Included in the comparisons are the results using a pure storm surge model, the coupled model with only a radiation stress mechanism and the coupled model with all three mechanisms considered.

It is clearly seen from Figs. 2–6 that for typhoon 5612, both the simulated extreme value and its occurrence time from the coupled model agree better with the actual measured values than those from the pure storm surge model for almost all stations. In addition, the results simulated using the coupled model considering all three physical mechanisms agree best with the actual measured values. The set-up changes caused by radiation stress are generally small for almost all stations, while those caused by the combined wave–current bottom stress are negligible (and are not shown in the figures). The comprehensive net impact of all physical mechanisms (wave-state-dependent surface stress, wave–current interaction bottom stress and radiation stress mechanisms) on the storm surges is very obvious, above 1 m, with a maximum of 1.7 m (see Table 1). The comparative analysis demonstrates that the obvious effects are caused primarily by the wave-state-dependent surface stress. The average relative error of the extreme values from all stations is 10%. For typhoon 7413, the extreme values simulated by the coupled model considering all three physical mechanisms agree best with the measured values. The set-up changes caused by radiation stress are generally small for all stations, with a maximum of about 10 cm. The

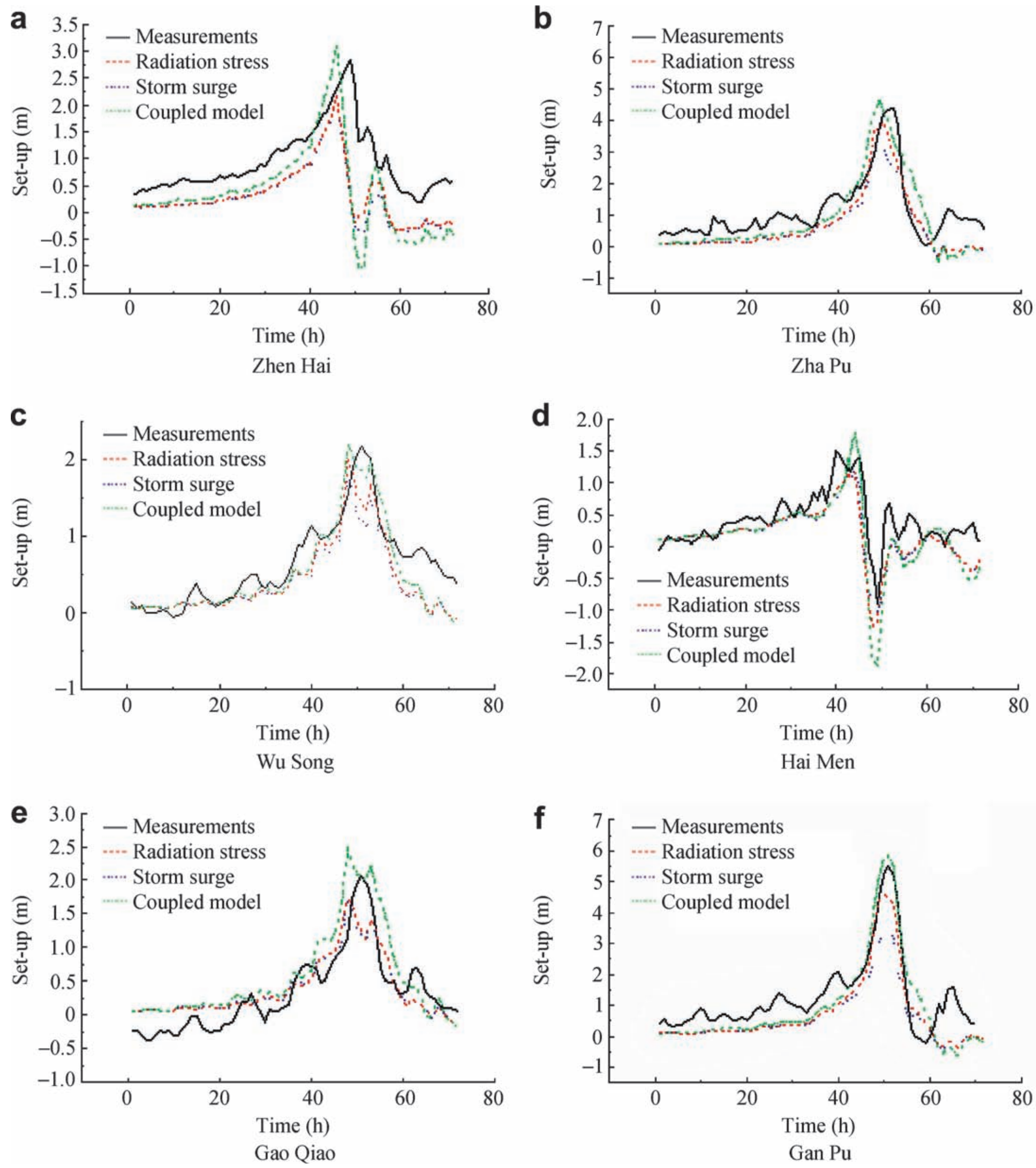

Fig. 2. (1956.07.31.02–1956.08.02.02) Comparisons of different simulated results and measurement in the different observed stations for 5612 typhoon. (a) Zhen Hai, (b) Zha Pu, (c) Wu Song, (d) Hai Men, (e) Gao Qiao, (f) Gan Pu.

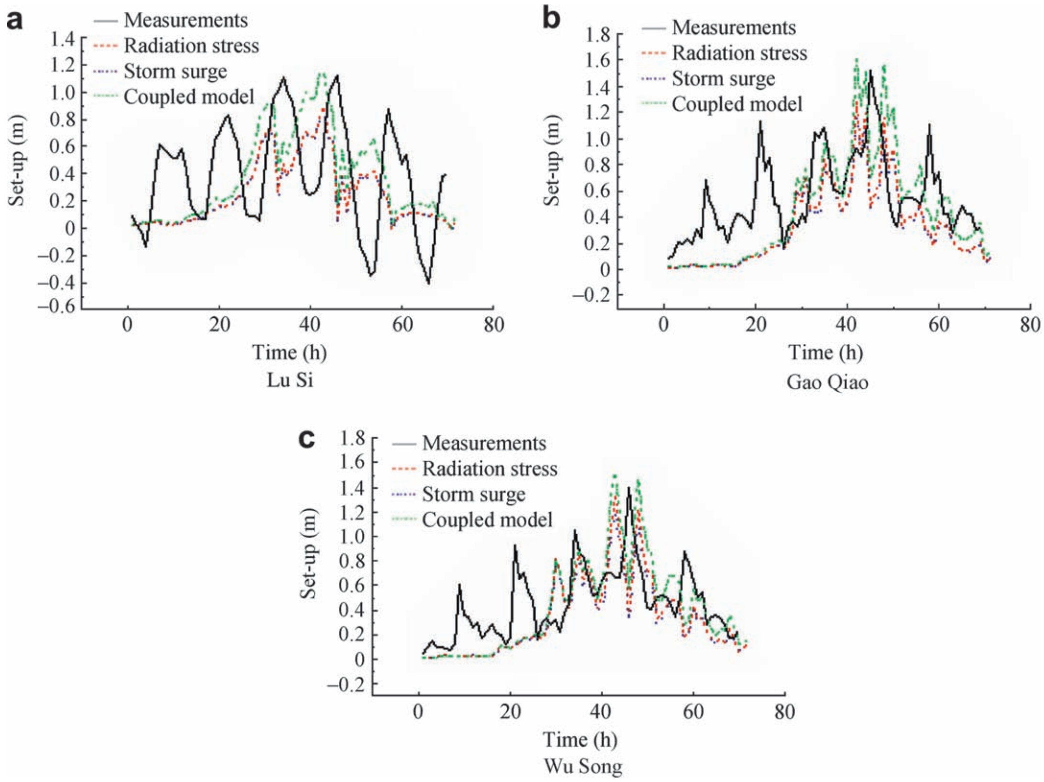

Fig. 3. (1974.08.18.02–1974.08.21.02) Comparisons of different simulated results and measurement in the different observed stations for 7413 typhoon. (a) Lu Si, (b) Gao Qiao, (c) Wu Song.

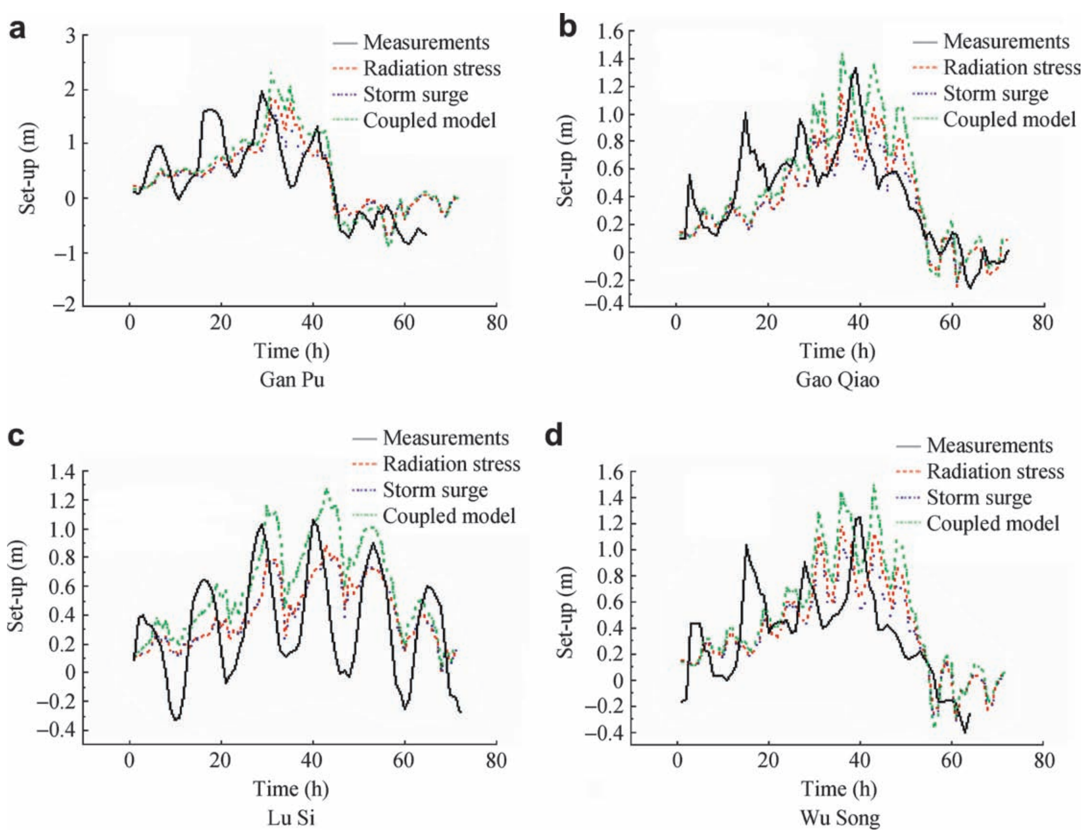

Fig. 4. (1979.08.23.08–1979.08.26.08) Comparisons of different simulated results and measurement in the different observed stations for 7910 typhoon. (a) Gan Pu, (b) Gao Qiao, (c) Lu Si, (d) Wu Song.

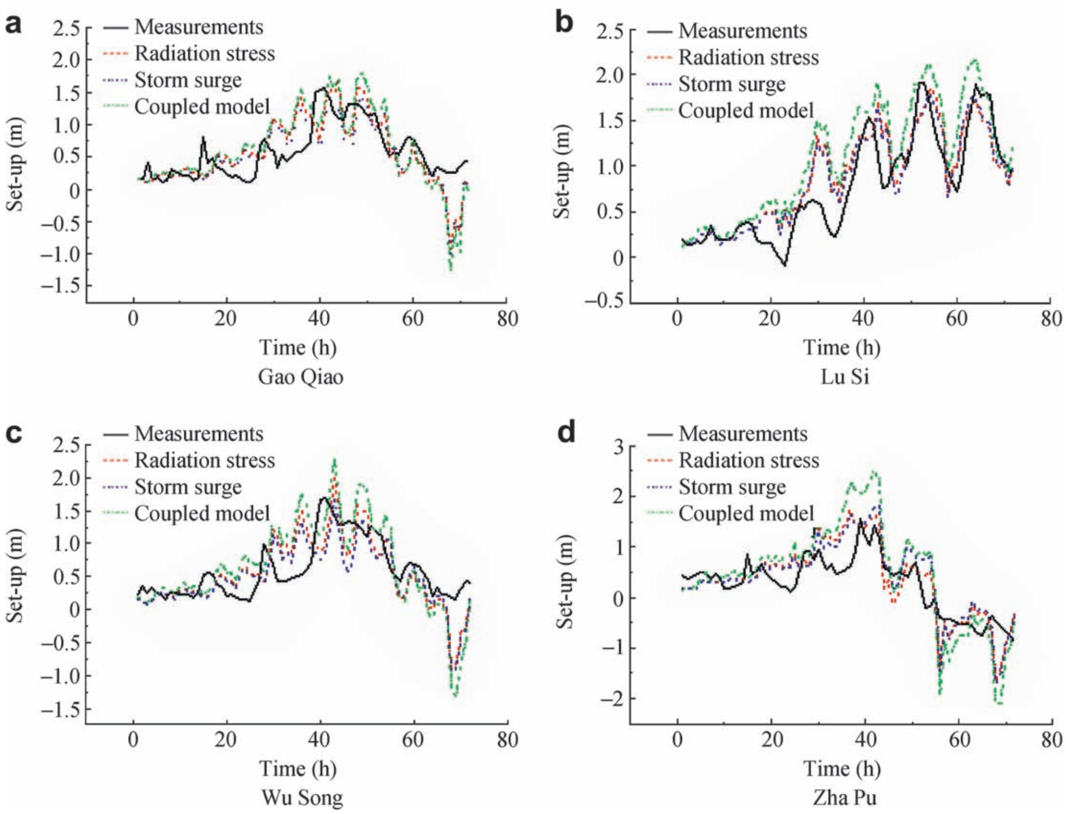

Fig. 5. (1981.08.30.08–1981.09.02.08) Comparisons of different simulated results and measurement in the different observed stations for 8114 typhoon. (a) Gao Qiao, (b) Lu Si, (c) Wu Song, (d) Zha Pu.

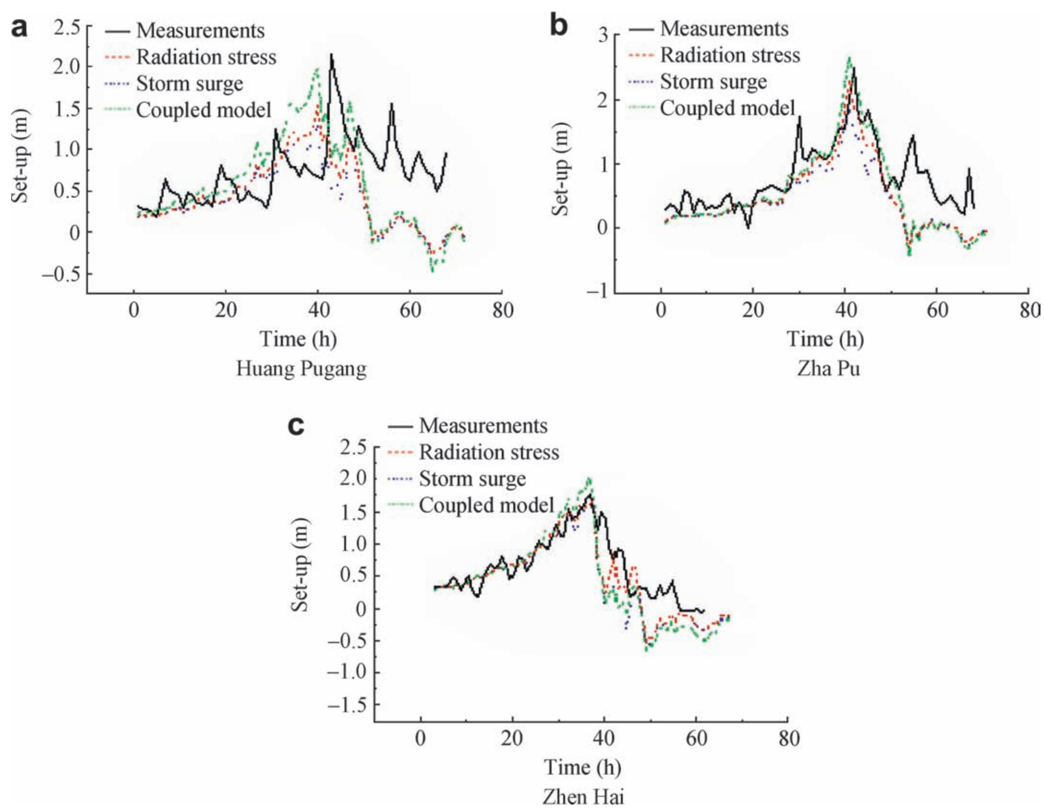

Fig. 6. (1997.08.17.02–1997.08.20.02) Comparisons of different simulated results and measurement in the different observed stations for 9711 typhoon. (a) Huang Pugang, (b) Zha Pu, (c) Zhen Hai.

Table 1
Comparisons of extreme value set-up for typhoon 5612

Station	Zhen Hai	Zha Pu	Wu Song	Hai Men	Gao Qiao	Gan Pu
Uncoupled (m)	2.2	4.0	1.9	1.4	1.9	4.5
Coupled (m)	3.2	4.9	2.2	1.9	2.7	6.2
Error (%)	45	22	15	35	42	37
Average (%)			32			

comprehensive net impact of all physical mechanisms is evident, with a maximum around 40 cm (see Table 2). The average relative error of the extreme values from all stations is 4.3%. For typhoon 7910, the extreme values simulated by the coupled model considering all three physical mechanisms agree best with the measured values. The set-up changes caused by radiation stress are generally small for all stations, with a maximum of about 15 cm. The comprehensive net impact of all physical mechanisms is evident, with a maximum around 50 cm (see Table 3). The average relative error of the extreme values from all stations is 13.2%. For typhoon 8114, the extreme values simulated by the coupled model considering all three physical mechanisms agree best with the measured values, but the errors are a little larger for individual stations. The set-up changes caused by radiation stress are generally small for all stations, with a maximum of about 10 cm. The comprehensive net impact of all physical mechanisms is evident, with a maximum around 60 cm (see Table 4). The average relative error of the extreme values from all stations is 19%. For typhoon 9711, the extreme values simulated by the coupled model considering all three physical mechanisms agree best with the actual measurements. The set-up changes caused by radiation stress are generally small for all stations, with a maximum of about 30 cm. The comprehensive net impact of all physical mechanisms is evident, with a maximum around 60 cm (see Table 5). The average relative error of the extreme values from all stations is 10% (For the details, see Tables 6–10). Tables 1–5 give the comparisons of the extreme set-ups from the coupled model and uncoupled model (pure tide storm surge model) to uncover the impact of waves on the pure storm surge set-ups. The results show that the range of effects is 20–32%, indicating that waves can evidently increase the storm surge set-up.

For the East Sea of China, an important finding of the storm surge–wave coupling study is that the effects of the wave-state-dependent surface stress on storm surges are very evident, with a maximum above 1 m, particularly with an extreme wind velocity. The wind stress formulations adopted by traditional storm surge models exclude the wave-state effects, regarding waves as being in a fully developed state. As a matter of fact, in the vicinity of depressions and fronts and in certain limited circumstances near coasts, waves are always in a developing state, and young wing waves are usually steeper and rougher than old wind waves and therefore extract more momentum. Accordingly, wave-state-dependent surface stress gives more force to storm surges. Thus, the studies of the five typical typhoons in the East Sea of China show that wave-state-dependent surface stress has a very obvious impact on storm surge.

Table 2
Comparisons of extreme value set-up for typhoon 7413

Station	Lu Si	Wu Song	Gao Qiao
Uncoupled (m)	0.9	1.3	1.3
Coupled (m)	1.22	1.6	1.7
Error (%)	33	23	30
Average (%)		28	

Table 3
Comparisons of extreme value set-up for typhoon 7910

Station	Gan Pu	Lu Si	Wu Song	Gao Qiao
Uncoupled (m)	2.0	0.9	1.1	1.2
Coupled (m)	2.5	1.3	1.5	1.5
Error (%)	25	44	36	25
Average (%)			32	

Table 4
Comparisons of extreme value set-up for typhoon 8114

Tab.1	Zha Pu	Wu Song	Lu Si	Gao Qiao
Uncoupled (m)	1.9	2.1	1.9	1.4
Coupled (m)	2.5	2.4	2.2	1.7
Error (%)	31	14	15	21
Average (%)			20	

Table 5
Comparison of extreme value set-up for typhoon 9711

Station	Zhen Hai	Zha Pu	Huang Pugang
Uncoupled (m)	1.6	2.3	1.7
Coupled (m)	2.1	2.9	2.2
Error (%)	31	26	29
Average (%)		28	

4. Conclusions

With the focus on typhoons in the East Sea of China, a coupled storm surge–wave numerical model with a $2' \times 2'$ resolution grid has been developed and applied to simulate five typical typhoon storm surges. The simulated results for the five typhoon cases show that the results from the coupled model agree better with the measured values than those from the pure storm surge model for almost all

Table 6
Relative error analysis of extreme value set-up for typhoon 5612

Station	Zhen Hai	Zha Pu	Wu Song	Hai Men	Gao Qiao	Gan Pu
Measured (m)	2.8	4.8	2.1	1.6	2.3	5.9
Simulated (m)	3.2	4.9	2.2	1.9	2.7	6.2
Error (%)	14	2	4	18	17	5
Average (%)			10			

Table 7
Relative error analysis of extreme value set-up for typhoon 7413

Station	Lu Si	Wu Song	Gao Qiao
Measured (m)	1.2	1.5	1.6
Simulated (m)	1.22	1.6	1.7
Error (%)	1	6	6
Average (%)		4.3	

Table 8
Relative error analysis of extreme value set-up for typhoon 7910

Station	Gan Pu	Lu Si	Wu Song	Gao Qiao
Measured (m)	2.2	1.1	1.3	1.4
Simulated (m)	2.5	1.3	1.5	1.5
Error (%)	13	18	15	7
Average (%)		13.2		

Table 9
Relative error analysis of extreme value set-up for typhoon 8114

Tab.1	Zha Pu	Wu Song	Lu Si	Gao Qiao
Measured (m)	1.7	2.0	2.1	1.6
Simulated (m)	2.5	2.4	2.2	1.7
Error (%)	47	20	4	6
Average (%)		19		

Table 10
Relative error analysis of extreme value set-up for typhoon 9711

Station	Zhen Hai	Zha Pu	Huang Pugang
Measured (m)	1.8	2.7	2.4
Simulated (m)	2.1	2.9	2.2
Error (%)	16	7	8
Average (%)		10	

stations, and the average errors are between 4.3% and 19%. This indicates that the developed coupled model is reliable for the simulation of typhoon storm surges in the East Sea of China. The study results demonstrate that the coupling of wave-storm surges has obvious effects on set-up and can increase set-up by 20–32%. For the East Sea of China, an important finding of the storm surge–wave coupling study is that the effects of the wave-state-dependent surface stress on storm surges are very evident, with a maximum over 1 m, especially with an extreme wind velocity. This study shows that the coupled storm surge–wave model clearly improves the forecasting of storm surges. Thus, it is strongly recommended that a storm surge–wave coupled model should be adopted for the forecast of storm surges.

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