The Role of Stokes drift in Dynamics of Bohai Sea, China under Typhoon Condition

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Abstract

The role of Stokes drift production (SDP), including Coriolis-Stokes forcing, small scale Langmuir circulation and resolved-scale Craik-Leibovich vortex forcing, in ocean dynamics of Bohai Sea (BS), China under typhoon condition is systematically investigated for the first time, utilizing a coupled wave-current modeling system, which is verified to be capable of well simulating the ocean dynamical processes. The effects of SDP on the turbulent mixing and further the dynamics during the entire typhoon period, including the pre-typhoon, during-typhoon, and after-typhoon stages, are comprehensively detected and discussed. Experimental results show that SDP greatly enhances the turbulent mixing at all depths in BS under typhoon condition, the increase can be up to 7 times that of the normal weather. At the same time, SDP generally strengthens the sea surface cooling by more than 0.4, with the maximum SST decrease exceeding 2 at the during-typhoon stage, about 7 times that in normal weather. SDP-induced current speed decrease can be over 0.2m/s, and change in current direction is generally opposite to the wind direction, suggesting that to a certain extent Stokes drift depresses the impact of high wind speed on current by intensifying the turbulent mixing. MLD is distinctly increased by ~$O(1)$ during typhoon due to SDP, in deep water region the deepening is greater than 5m, and the maxima can be ~7.5m. In addition, the continuous impacts of SDP on SST, current and MLD at the after-typhoon stage present a hysteretic response between SDP and typhoon action.

The Role of Stokes drift in Dynamics of Bohai Sea, China under Typhoon Condition

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Key Points:

- Stokes drift greatly enhances the turbulent mixing at all depths in Bohai Sea under typhoon condition, about 7 times that in normal weather.
- Stokes drift strengthens the sea surface cooling under typhoon condition, the maximum decrease is roughly 7 times that in normal weather.
- The mixed layer depth is increased by ~$O(1)$ during typhoon due to Stokes drift. A hysteretic response presents at the after-typhoon stage.

Abstract

The role of Stokes drift production (SDP), including Coriolis-Stokes forcing, small scale Langmuir circulation and resolved-scale Craik-Leibovich vortex forcing, in ocean dynamics of Bohai Sea (BS), China under typhoon condition is systematically investigated for the first time, utilizing a coupled wave-current modeling system, which is verified to be capable of well simulating the ocean dynamical processes. The effects of SDP on the turbulent mixing and further the dynamics during the entire typhoon period, including the pre-typhoon, during-typhoon, and after-typhoon stages, are comprehensively detected and discussed. Experimental results show that SDP greatly enhances the turbulent mixing at all depths in BS under typhoon condition, the increase can be up to 7 times that of the normal weather. At the same time, SDP generally strengthens the sea surface cooling by more than 0.4℃, with the maximum SST decrease exceeding 2℃ at the during-typhoon stage, about 7 times that in normal weather. SDP-induced current speed decrease can be over 0.2m/s, and change in current direction is generally opposite to the wind direction, suggesting that to a certain extent Stokes drift depresses the impact of high wind speed on current by intensifying the turbulent mixing. MLD is distinctly increased by ~$O(1)$ during typhoon due to SDP, in deep water region the deepening is greater than 5m, and the maxima can be ~7.5m. In addition, the continuous impacts of SDP on SST, current and MLD at the after-typhoon stage present a hysteretic response between SDP and typhoon action.

Keywords: Stokes drift production, Langmuir turbulence, Turbulent mixing, Typhoon, Coupled model

1 Introduction

The surface waves can greatly affect the circulation and thermohaline structures thus modulate the production and dissipation in the upper ocean. Stokes drift production (SDP) and wave breaking have been identified to be two main ways that surface waves affect the upper ocean structures and dynamics. Previous studies (Noh et al., 2004; Kantha & Clayson, 2004; Li et al., 2013) have proved that the wave breaking effect is limited within several meters immediately below the ocean surface. It's widely confirmed that Stokes drift plays a key role in upper ocean dynamic and thermal mechanism. SDP affects the turbulent mixing of upper ocean principally via large scale Coriolis-Stokes forcing (CSF), small scale Langmuir circulation (LC) and resolved-scale Craik-Leibovich vortex forcing (CLVF). Due to SDP (refers to CSF, LC and CLVF thereafter), the instability of the vertical shear of the upper ocean tends to be increased and the momentum and heat will penetrate into the deeper depths, making the mixed layer thicker.

By introducing the Stokes drift, many modifications have been put forward based on the Mellor-Yamada closure scheme (M-Y2.5), a typical second-moment turbulent closure model, to improve the parameterization of turbulent mixing. Kantha and Clayson (2004, KC04) added the kinetic energy induced by LC into the M-Y2.5 parameterization, and solved the issue that the simulated mixing layer is too thin. Harcourt (2015, H15) adopted inhomogeneous pressure-strain rate as well as pressure-scalar gradient closures and modified the stability function in the second-moment model to match CLVF term. Based on above improved parameterizations, the mechanisms between wave processes and upper ocean thermal structures under normal weather were discussed (Li et al., 1993; Sun et al., 2003; Polton et al., 2007; Zhang et al., 2012; McWilliams et al, 2012; LI et al., 2013; Pearson et al, 2015), suggesting that LC can enhance the upper ocean mixing notably.

Typhoon, as an extreme weather event, drastically exerts on the ocean surface, induces intense waves with wave height up to 15m and drives strong currents with speed as large as >1m/s (Ginis et al., 2002). As a consequence, thermohaline structures can be greatly changed. As the direct contributor to the typhoon energy budget, sea-air flux remarkably dictates the typhoon intensity (Emanuel et al., 1999). Both SSTs and currents are used to calculate sea-air heat and momentum fluxes in the typhoon prediction models. The responses of SST and current to typhoon are significantly determined by the upper-ocean turbulent mixing. Thus, it's necessary to accurately estimate the turbulent mixing, in particular the wave-induced part, under the extreme weather condition of typhoon. The effects of wave-induce mixing on thermal response to typhoon in the Yellow and East China Seas, South China Sea and east of the Luzon Strait had been discussed previously (Zhang et al., 2017; Li et al., 2014; Zhang et al., 2012). However, the combination impacts of SDP (CSF, LC, CLVF) on turbulent mixing and ocean dynamics under typhoon conditions have never been comprehensively studied in BS. The main reason for this could be that the tropical storms can not easily reach BS region.

BS with shallow depth but complex topography locates on the west coast of the Pacific Ocean, composed of the Liaodong Bay, the Bohai Bay, the Laizhou Bay and the Central Sea Area (Fig. 1(a)). Extra-tropical storm and coldwaves often pass through and influence this region, and typhoon can hit infrequently. BS has some important ports including Tianjin Port and Dalian Port, and it's close to megacities, such as Beijing and Tianjin. Once typhoon/storm surge occurs, coastal cities may suffer from serious economic loss, which inspires us to investigate the role of SDP in dynamic processes in BS under typhoon condition, based on which more accurately prediction model for disaster mitigation could be further developed.

In this study we simulate the influences of SDP on turbulent mixing under typhoon condition, and further detect the responses of ocean dynamics to the actions of typhoon in the presence of SDP effects. In our parameterization, Langmuir turbulence (via LC) is included in the turbulence model and both CSF and resolves-scale CLVF are added into the momentum equations of the ocean model. Case study of supertyphoon Matsa (2005) is then presented and discussed.

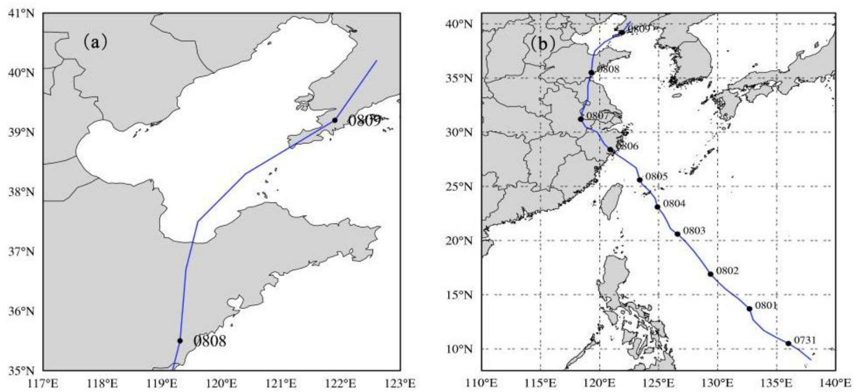

Figure 1. (**a**) The geographic location of BS; (**b**) The path (blue line) of supertyphoon Matsa in August 2005.

2 Methods

An one-way coupled wave-current modeling system (Fig. 2) is constructed by combination of the Princeton Ocean Model with the generalized coordinate system (POMgcs, Ezer & Mellor 2004) and the Simulating Waves Nearshore model (SWAN, Booij et al., 1999). The Stokes drift is calculated by wave variables output from SWAN and then introduced to POMgcs to represent SDP. The specific scheme is given in following sub-sections.

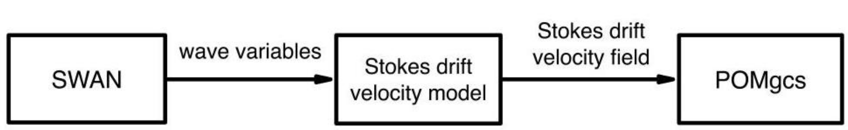

Figure 2. A brief diagram of the wave-current modeling system, illustrating the inputs and outputs among different modules.

2.1 Ocean current model

POMgcs, developed based on the Princeton Ocean Model (POM; Blumberg & Mellor, 1987), is a 3-D, primitive-equation, free-surface, coastal circulation model, in which the Mellor-Yamada 2.5 turbulence closure scheme is included. It has been widely used to simulate the ocean current/circulation.

When CSF and the resolved-scale CLVF are considered, the horizontal momentum equations in POMgcs can be modified as follows (McWilliams & Restrepo, 1999; Reichl et al., 2016; Cao & Deng, 2019):

$$\frac{\partial U s_k}{\partial t} + \frac{\partial U^2 s_k}{\partial x} + \frac{\partial UV s_k}{\partial y} + \frac{\partial U\omega}{\partial k} - fVs_k + gs_k\frac{\partial \eta}{\partial x} + g\frac{s_k}{\rho_0}\int_k^0 \left[s_k\frac{\partial \rho'}{\partial x} - (s_x+\eta_x)\frac{\partial \rho'}{\partial k'}\right] dk'$$
$$= \frac{\partial}{\partial k}\left[\frac{K_M}{s_k}\frac{\partial U}{\partial k}\right] + F_x + CSFX + CLVFX \tag{1}$$

$$\frac{\partial V s_k}{\partial t} + \frac{\partial V^2 s_k}{\partial y} + \frac{\partial UV s_k}{\partial x} + \frac{\partial V\omega}{\partial k} + fUs_k + gs_k\frac{\partial \eta}{\partial y} + g\frac{s_k}{\rho_0}\int_k^0 \left[s_k\frac{\partial \rho'}{\partial y} - (s_y+\eta_y)\frac{\partial \rho'}{\partial k'}\right] dk'$$
$$= \frac{\partial}{\partial k}\left[\frac{K_M}{s_k}\frac{\partial V}{\partial k}\right] + F_y + CSFY + CLVFY \tag{2}$$

with

$$s_x = \frac{\partial s}{\partial x}\ ,\ \ s_y = \frac{\partial s}{\partial y}\ ,\ \ \eta_x = \frac{\partial \eta}{\partial x}\ ,\ \ \eta_y = \frac{\partial \eta}{\partial y}\ ,\ s = z - \eta \tag{3}$$

$$CSFX = f\,V_s s_k \tag{4}$$

$$CSFY = -f\,U_s s_k \tag{5}$$

$$CLVFX = Vs\left[s_k\left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}\right) - (s_x+\eta_x)\frac{\partial V}{\partial k} + (s_y+\eta_y)\frac{\partial U}{\partial k}\right] \tag{6}$$

$$CLVFY = -Us\left[s_k\left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}\right) - (s_x+\eta_x)\frac{\partial V}{\partial k} + (s_y+\eta_y)\frac{\partial U}{\partial k}\right] \tag{7}$$

where *x*, *y* are the horizontal coordinates, *k* is the vertical coordinate, s_k is the kth

level thickness, ω is the vertical velocity, (U, V) are the horizontal components of the Eulerian mean current with (Us, Vs) the horizontal components of Stokes drift, f is the Coriolis parameter, ρ_o is the reference water density and ρ' is the density deviation, K_m is the vertical mixing coefficient, F_x is the horizontal viscosity term and F_y is the horizontal diffusion term. (*CSFX*, *CSFY*) are the horizontal components of CSF, respectively. (*CLVFX*, *CLVFY*) are the horizontal components of CLVF, respectively.

The parameterization H15, which is based on M-Y2.5, is introduced to represent LC. By considering the LC, the turbulent kinetic energy (TKE) and turbulent length scale equations are modified to as follows:

$$\frac{\partial q^2 s_k}{\partial t}+\frac{\partial U q^2 s_k}{\partial x}+\frac{\partial V q^2 s_k}{\partial y}+\frac{\partial \omega q^2}{\partial k}-\frac{\partial}{\partial k}\left[\frac{K_q}{s_k}\frac{\partial q^2}{\partial k}\right]$$

$$=-\frac{2}{s_k}\overline{u\omega}\left(\frac{\partial U}{\partial k}+\frac{\partial U_s}{\partial k}\right)-\frac{2}{s_k}\overline{v\omega}\left(\frac{\partial V}{\partial k}+\frac{\partial V_s}{\partial k}\right)+\frac{2g}{\rho_0}K_H\frac{\partial\tilde{\rho}}{\partial k}-2\frac{s_k q^3}{B_1 l}+F_q \tag{8}$$

$$\frac{\partial q^2 l s_k}{\partial t}+\frac{\partial U q^2 l s_k}{\partial x}+\frac{\partial V q^2 l s_k}{\partial y}+\frac{\partial \omega q^2 l}{\partial k}-\frac{\partial}{\partial k}\left[\frac{K_q}{s_k}\frac{\partial q^2 l}{\partial k}\right]$$

$$=\frac{E_1 l}{s_k}\left(-\overline{u\omega}\frac{\partial U}{\partial k}-\overline{v\omega}\frac{\partial V}{\partial k}\right)+\frac{E_6 l}{s_k}\left(-\overline{u\omega}\frac{\partial U_s}{\partial k}-\overline{v\omega}\frac{\partial V_s}{\partial k}\right)+E_1E_3 l\frac{g}{\rho_0}K_H\frac{\partial\tilde{\rho}}{\partial k}-\frac{s_k q^3}{B_1}\tilde{W}+F_l \tag{9}$$

with

$$\overline{u\omega}=-\left(K_M\frac{\partial U}{\partial k}+K_{MS}\frac{\partial U_s}{\partial k}\right) \tag{10}$$

$$\overline{v\omega}=\left(K_M\frac{\partial V}{\partial k}+K_{MS}\frac{\partial V_s}{\partial k}\right) \tag{11}$$

$$K_{MS}=qlS_{MS} \tag{12}$$

where q is TKE, l is turbulence length scale, K_H and K_q are the vertical diffusion coefficients for temperature and turbulence kinetic energy, $\tilde{\rho}$ is the corrected density, $\tilde{W}$ is the wall proximity function, F_q is the horizontal diffusion terms for TKE and F_l is for turbulence length scale. Model constants E_1=E_3=1.8, B_1=16.6, following Mellor and

Yamada (1982). E_6 is a new parameter related LT and its value equal to $4E_1$ following KC04. $\overline{u\omega}$ and $\overline{v\omega}$ are vertical turbulent flux term. K_{MS} is a new vertical kinematic viscosity coefficient derived from the new stability function S_{MS} in H15.

The modeling domain covers the whole BS region ranging from (37.083°N, 117.52°E) to (41.033°N, 122.47°E). The horizontal resolution is 1/20°×1/20°, which is thought to be fine enough for resolving the associated processes in this study. The water depth of the modeling region is represented by ETOPO2 topography dataset derived from National Oceanic and Atmospheric Administration (NOAA). 6 terrain-following coordinates are specified in the vertical, and all of the model outputs are interpolated to 6 standard z-levels, i.e. 0m, 5m, 15m, 25m, 35m, and 65m. The internal-mode time step of the current model is 200s, and external-mode time step is 3.33s.

The model initialization fields consist of temperature, salinity and current velocity, obtained from the China Ocean Reanalysis (CORA). The integration time of diagnostic experiments is spanning from 7 August to 10 August 2005, covering the entire duration that supertyphoon Matsa passed BS. A stable current field is achieved by spun up the current model for half a year. The simulation is forced by both heat fluxes and winds, derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP), respectively. In addition, the tidal elevation forcing at the open lateral boundaries includes four main tidal components of M_2, S_2, K_1 and O_1, derived from a 3-D tidal model (Han et al., 2006).

2.2 Ocean wave model

SWAN is a third-generation wave model based on spectral action balance equation, adopting the linear random gravity waves theory. It was widely used to simulate the regional sea surface waves. The modeling domain, topography, wind forcing, horizontal resolution and time step (200s) for wave simulations are all consistent with those used in current model. The output time interval of wave variables is 1h.

2.3 Typhoon winds and Stokes drift

Super-typhoon Matsa is selected as the representative study case, provided that there were not many strong typhoons can visit BS, and Matsa was one of the biggest. The wind field of Matsa is from the ECMWF dataset. Fig. 1(b) shows the Matsa's traveling path. Matsa was generated in the east of Philippines on 31 July 2005, developed to a strong typhoon on 4 August and made landfall in Zhejiang Province, China on 6 August. It entered BS on 8 August and weakened to an extra-tropical cyclone the day after. The influence time interval of Matsa in BS was mainly from 8 ~9 August 2005, when the maximum wind speed exceeded 20m/s. We are focusing on the period from 7~10 August 2005, covering the time frame from pre-typhoon stage to after-typhoon stage. Four plots in Fig. 3 respectively display the horizontal distribution of the 10-m winds at 0000 UTC from 7~10 August 2005.

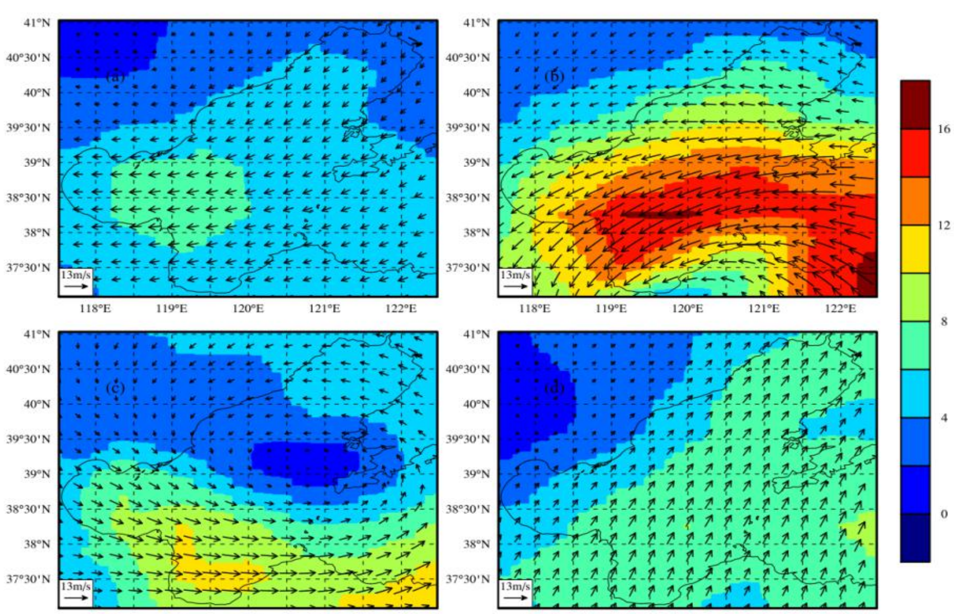

Figure 3. Horizontal distribution of 10-m wind direction and speed at 0000 UTC on (**a**)7th, (**b**)8th, (**c**)9th and (**d**)10th August 2005

The Stokes drift is calculated from the wave spectrum (Webb & Fox-Kemper, 2011) through the following equation:

$$U_s(z) = \frac{16\,\pi^3}{g}\int_0^\infty \int_{-\pi}^{\pi} (\cos\theta, \sin\theta, 0)\, f^3 S_{f\theta}(f,\theta)\, e^{\frac{8\pi^2 f^2}{g}}\, d\theta\, d f \qquad (13)$$

where $S_{f\theta}$ is the wave frequency-direction spectrum with θ the wave direction and f the wave frequency. The calculated Stokes drift from simulated wave variables is given in Fig. 4, showing that the direction of Stokes drift basically agrees with wind direction and the Stokes drift speed is positively correlated to wind speed, except when a complete typhoon cyclone has formed in BS on 9 August.

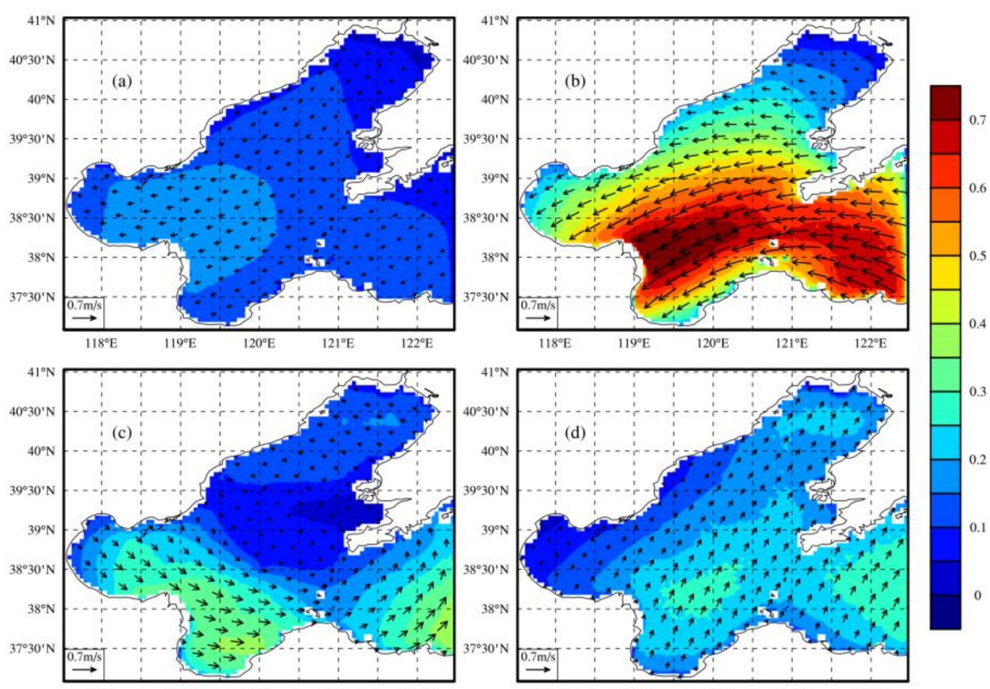

Figure 4. Horizontal distribution of Stokes drift direction and speed at 0000 UTC on (**a**) 7th , (**b**)8th , (**c**)9th and (**d**)10th August 2005

3 Model verification

Our simulations is validated via the comparison of tidal constants. The tidal constants from observations at 8 tidal stations (Table 1) in BS are compared to the tidal constants analyzed from the simulations performed by our modeling. Fig. 5 gives the fitted results of observed and simulated tidal amplitude for M_2 and K_1, showing a favorably good agreement. The corresponding tidal phase-lag also agrees well, denoting that there are no noticeable systematic errors exist in the simulations. These analyses demonstrate that the modeling is basically reliable.

Table1. Locations of eight tidal stations in BS

Number	Station	latitude/°N	longitude/°E
1	Xiaoqinghekou	37.33	119.06
2	Yantai	37.55	121.38
3	Longkou	37.65	120.32
4	North Huangchengdao	38.40	120.92
5	Lalian	38.87	121.68
6	Tanggu	38.98	117.78
7	Changxingdao	39.65	121.47
8	Tuanshanjiao	40.23	120.47

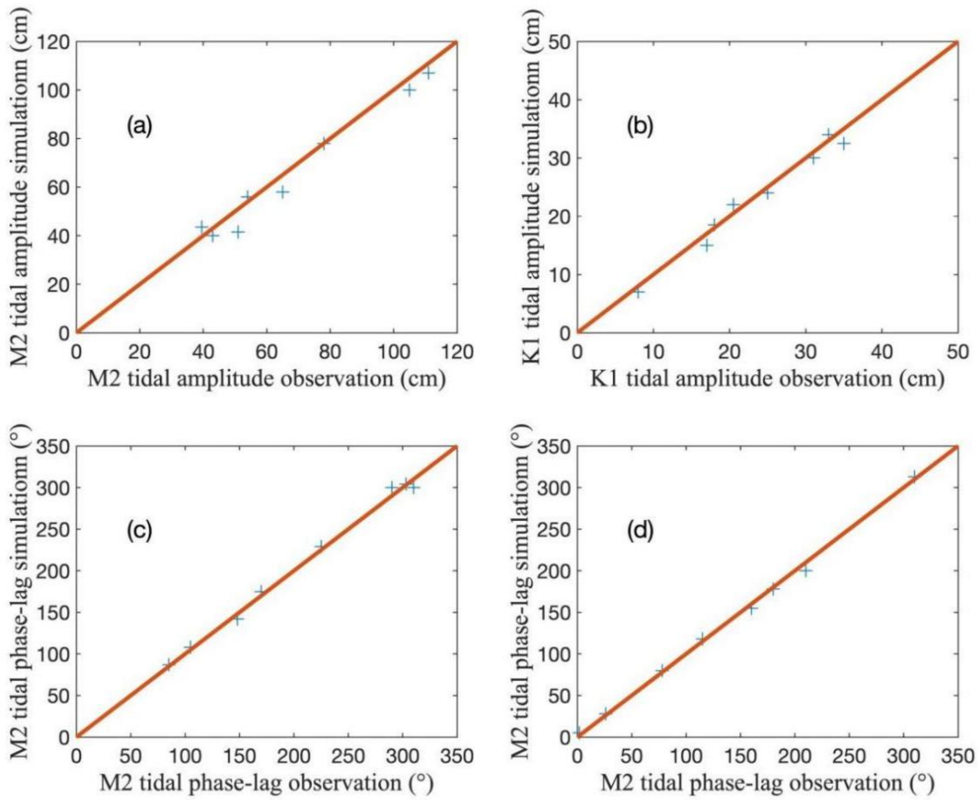

Figure 5. Fitted plots of observed amplitude and simulated amplitude of (**a**) M_2, (**b**) K_1 and observed phase-lag and simulated phase-lag of (**c**) M_2, (**d**) K_1.

4 Results

In our previous study (Cao & Deng, 2019), the specific effects of each SDP term (LC, CSF and CLVF) on ocean dynamics in normal weather have been comprehensively investigated and compared to each other, therefore we are not repeat this work again in typhoon condition given the limit of paper length. Two sets of diagnostic experiments are designed and conducted: WAVE-ALL, including all SDP terms; and WAVE-NON, without SDP. The WAVE-NON acts as coordinate/reference experiment, and the responses of ocean processes to typhoon as well as the impacts of SDP on turbulent mixing and ocean dynamics are detected by comparing the simulations of WAVE-NON with that of WAVE-ALL. We present and discuss our results in detail at 3 stages, i.e. pre-typhoon, during-typhoon and after-typhoon.

Before investigating the influences of SDP on SST, current and MLD, it's essential to figure out its effects on vertical turbulent mixing under typhoon condition. K_M is the vertical kinetic viscosity coefficient from WAVE-NON, and K_{MS} is that from WAVE-ALL. Fig. 6(a) shows the monthly-mean vertical kinetic viscosity coefficient under normal weather (June 2005), adopted from our previous study (Cao & Deng, 2019). The mixing coefficient at the pre-typhoon stage on 7 August (Fig. 6(b)) is generally consistent to that of the normal weather (Fig. 6(a)), the difference between them is generally less than 0.0012m^2/s. The slightly differences at 5m and 15m levels between Fig. 6(a) and Fig. 6(b) may be resulted from the more stably vertical stratification in August 2005. The impacts of Stokes drift on upper ocean mixing tend to be strengthened as the increase of depth, indicating that the waves can generally penetrate into the whole depth in BS. At the during-typhoon stage (8 August), the mixing coefficients (both K_M and K_{MS}) are greatly improved by about 1 order of magnitude, demonstrating that strong winds enable a large amount of TKE inject down to the deep, as a consequence of turbulent mixing enhance (Fig. 6(c)). Adding the SDP, the vertical kinetic viscosity coefficient is further increased. The difference between K_M and K_{MS} exceeds 0.008m^2/s, about 7 times that of the normal weather, denoting the very important role of Stokes drift in turbulent mixing under typhoon condition. The Stokes drift influences on mixing at during-typhoon stage are relatively strong in the upper 30m (Fig. 6(c)), whereas the effects are stronger within 30~50m at the pre-typhoon stage (Fig. 6(b)). At the after-typhoon stage (10 August), TKE injection is markedly decreased. As a result, K_M and K_{MS} generally decrease to the magnitude at pre-typhoon stage, however the values (Fig. 6(d)) are still larger than that in normal weather (Fig. 6(a) and 6(b)), suggesting that K_M and K_{MS} are gradually recovering to the level before typhoon. The deviation between K_M and K_{MS} on 10 August is similar to that at the pre-typhoon stage, with the maximum of ~0.001m^2/s appearing at 15m-layer, shallower than that at the pre-typhoon stage. The depth with maximum Stokes influence may transmit from the

15m-layer to deeper layers in few days and the impacts of Stokes drift will gradually recover to the level before typhoon.

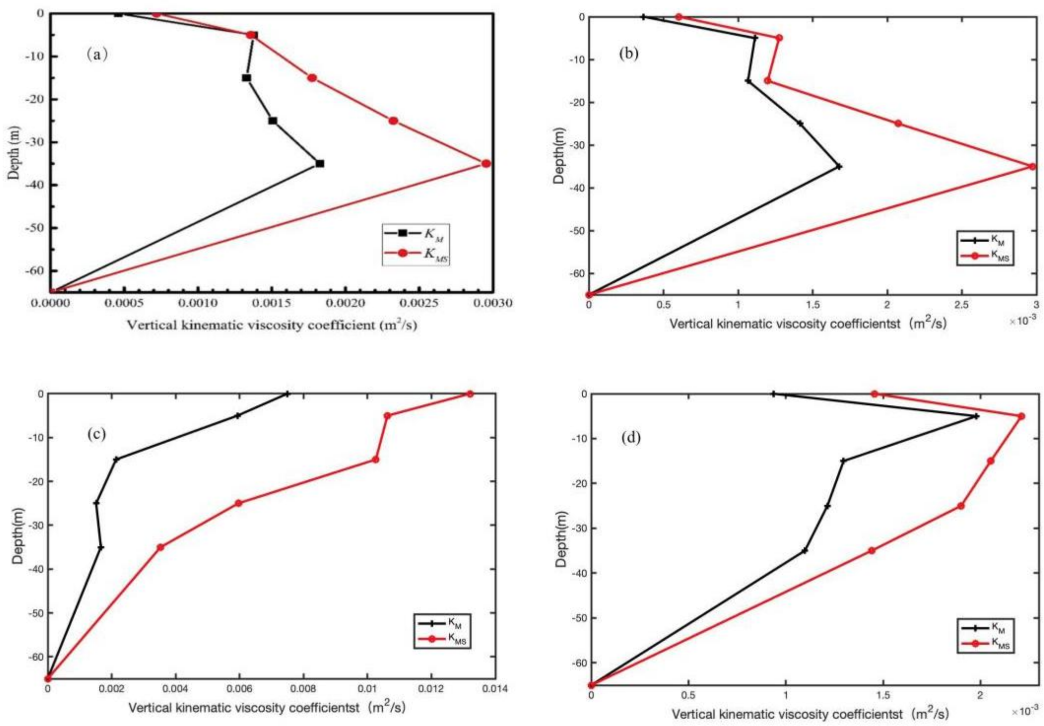

Figure 6. Vertical kinetic viscosity coefficient (**a**) in normal weather (adopted from Cao and Deng, 2019); Vertical kinetic viscosity coefficient simulated at 0000UTC on (**b**) 7th, (**c**)8th and (**d**)10th August 2005 in this study. (K_M is the kinetic viscosity coefficient from WAVE-NON, and K_{MS} is that from WAVE-ALL)

4.1 Pre-typhoon stage

This stage was before 8 August 2005, when Masta was close to but hadn't entered into BS. The horizontal distributions of SST simulated by WAVE-NON and WAVE-ALL on 7 August are shown in Fig. 7(a) and Fig. 7(b), respectively. Fig. 7(c) gives the difference of SST between the two simulations. SST from WAVE-ALL is lower than that from WAVE-NON in most of the region, indicating that SDP generally decreases the SST. Especially in the southern part of Liaodong Bay, the eastern part of the Bohai Bay, and Miaodao Islands, the SST reduction reaches ~0.3°C. This is similar to the summer case in normal weather previously discussed by Cao & Deng (2019). The difference in percentage (Fig. 7(d)) shows that larger changes appear near the Laizhou Bay and the Bohai Bay, and the maxima can be ~1.8%. In most of BS area, the effect of Stokes drift on SST is less than 0.4%, suggesting that the impact is relatively slight at the pre-typhoon stage, like that in the normal weather.

MLD is defined as the depth of the water layer at a temperature difference of 0.5°C from the sea surface following Yablonsky and Ginis (2008). The profile along 38.33°N, as the widest section crossing BS, is plotted to demonstrate the spatial variability of MLD. Fig. 8(a) shows that in most of the coastal water the mixed layer penetrates deep down to sea floor, indicating that water is well mixed. When longitude exceeds 119°E, MLD decreases rapidly and remains stably at ~1m. It is due to the obviously vertical stratification of temperature in summer and the marked temperature difference between surface and subsurface. In WAVE-ALL, the mixed layer is deepened slightly. However, this amount of change is negligible comparing to the entire water depth, denoting that the impact of Stokes drift is relatively weak under low-wind conditions.

Currents on 7 August mainly flow from Liaodong Bay, the Bohai Bay and the Bohai Strait towards the Central Area and the Laizhou Bay (bottom four panels in Fig. 7). The direction of current is largely controlled by winds and tides. As shown in Fig. 7(g), SDP slightly influences the surface current speed, with the maximum alternation being less than ±0.02m/s. Change of ~10% (Fig. 7(h)) occurs in the Central Area, due to the very small local current speeds. The most region of BS is changed by ~±5%. The vertical current speed profile along the 38.333°N section (Fig. 9(a) and 9(b)) also reveals that speeds are slightly reduced at almost all depths, to a certain extent rendering the currents more evenly distributed in the vertical.

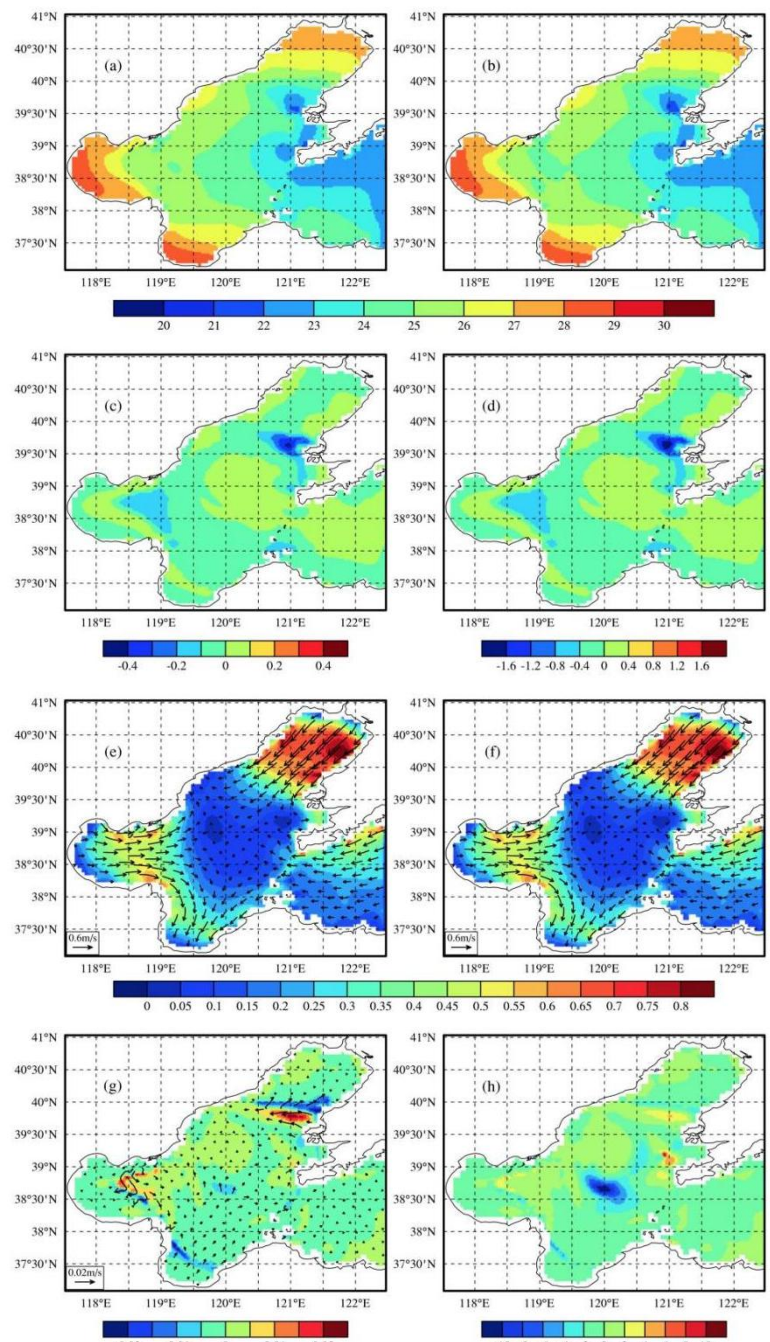

Figure 7. Horizontal distribution of (**a**) SST from WAVE-NON, (**b**) SST from WAVE-ALL, (**c**) SST difference between WAVE-NON and WAVE-ALL, (**d**) SST difference in percentage (%) between WAVE-NON and WAVE-ALL, (**e**) current from WAVE-NON, (**f**) current from WAVE-ALL, (**g**) current difference between WAVE-NON and WAVE-ALL, (**h**) current difference in percentage (%) between WAVE-NON and WAVE-ALL at 0000UTC on 7 August 2005. (Contours depict the current speed, while arrows represent the direction of current.)

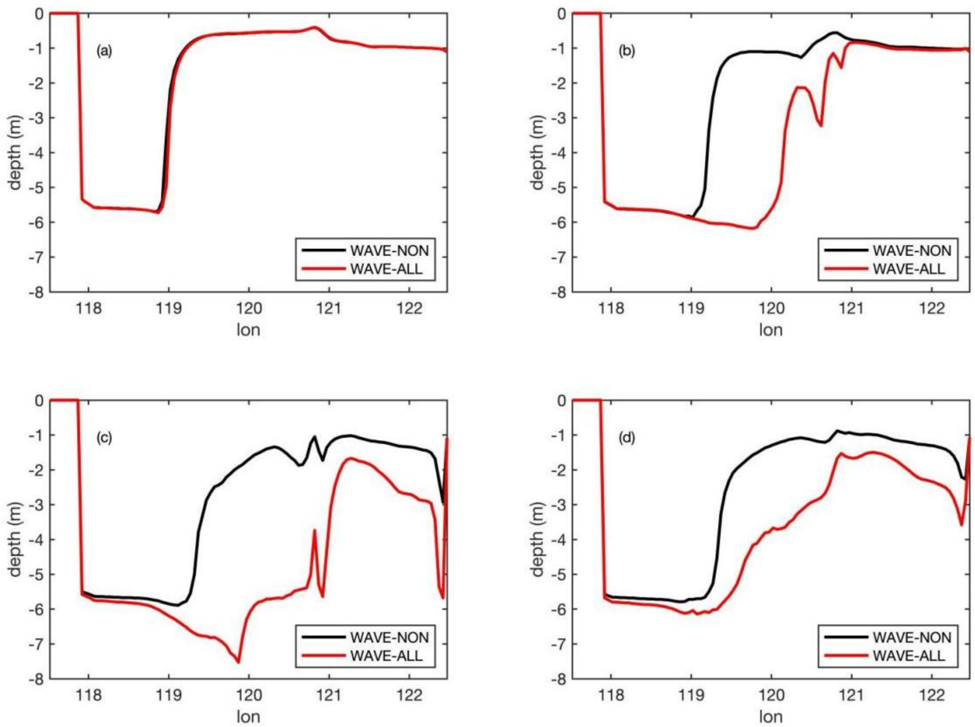

Figure 8. MLD from WAVE-NON and WAVE-ALL along the 38.333°N section at 0000UTC on (**a**) 7th , (**b**) 8th , (**c**) 9th , (**d**)10th August 2005

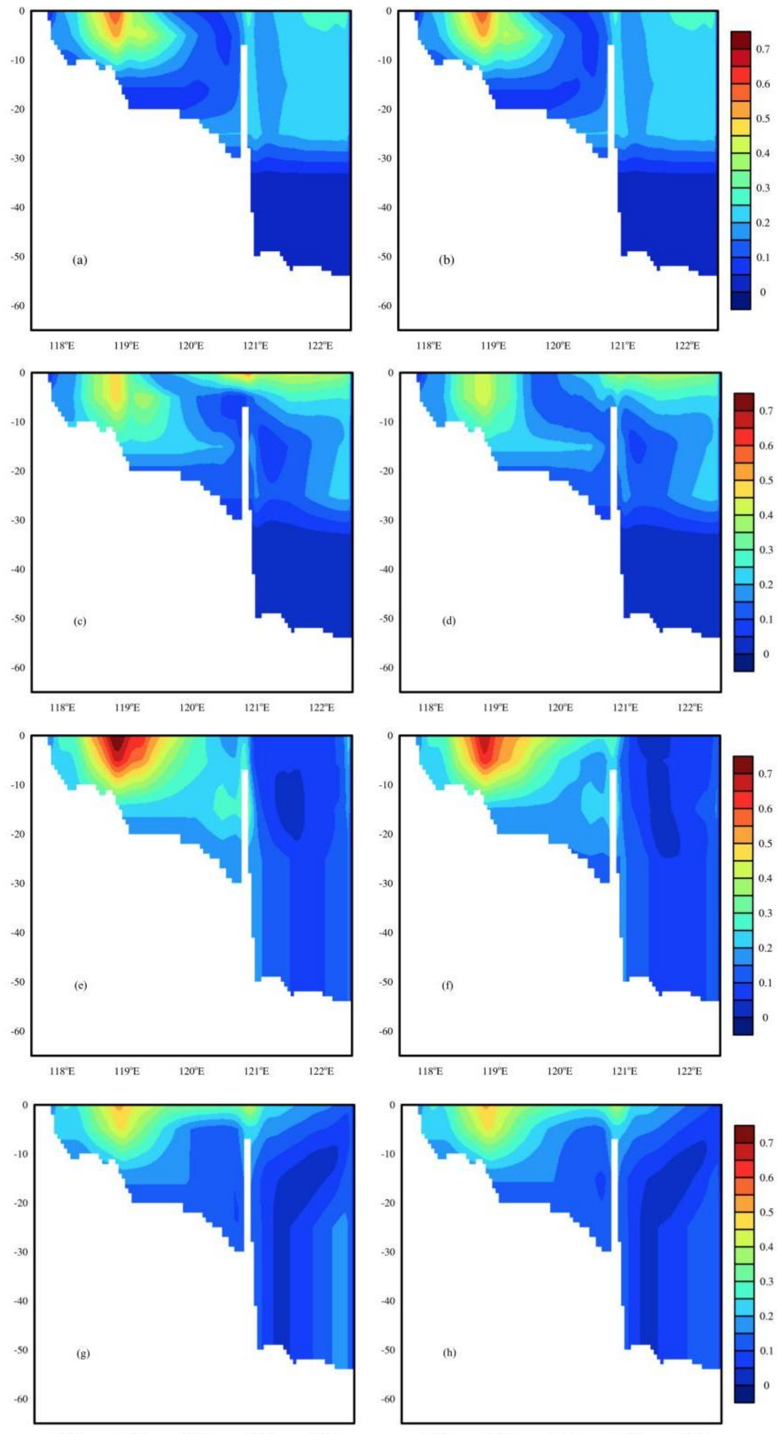

Figure 9. Vertical current speed profile along the 38.333°N from WAVE-NON (left) and WAVE-ALL (right) at 0000UTC on 7th (**a**, **b**), 8th (**c**, **d**), 9th (**e**, **f**), 10th (**g**, **h**) August 2005

4.2 During-typhoon stage

When Matsa entered BS on 8 August, the typhoon-induced cooling is great along the typhoon traveling path. The SST is rapidly decreased for more than 2℃ (Fig. 10(a)) compared to that on 7 August (Fig. 7(a)). The difference of SST between WAVE-NON and WAVE-ALL reaches a maximum of ~1.4℃ (Fig. 10(c)), the change is much larger than that at the pre-typhoon stage (Fig. 7(c)). The rate of SST change reaches ~6%, about $O(1)$ larger than that at the pre-typhoon stage. Reichl et al. (2016) have demonstrated that the total air-sea heat flux can be reduced by at least 10% with the decrease of 0.5°C in SST. Fig. 10(c) shows that SDP promotes the lifting of deeper cold water, resulting in an additional cooling at the surface, and Matsa largely strengthens the effect of SDP on ocean thermal processes, leading to obviously SST reduction and noticeably enlarged cooling range.

One day after Matsa entered BS (9 August), a greater range and intensity of cooling is further caused (Fig. 10(e)). SST is generally reduced by the action of SDP (Fig. 10(f)). The temperature changes in the Central Area and the Bohai Strait are noticeable, with the maxima of more than 2°C and the alternation in percentage exceeding 10% (Fig. 10(g) and 10(h)), because the relatively large water depth in this region facilitates the pulling of deeper cold water up to the surface by SDP effects. Although the intensity of winds on 9 August is significantly weakened compared to 8 August, the subsequent change of heat flux in the vertical caused by SDP is still existing, leading to a hysteretic change in SST.

MLD in the deep water region (approximately from 119°E to 121°E) is distinctly increased by ~5m on 8 August (Fig. 8(b)) due to SDP. The increase of MLD in the region from 121°E to 122.5°E is small, as the small SST difference in this area (Fig. 7(c)). Because of the continuously forcing of typhoon winds, the mixed layer is further deepened, with MLD in deep water region being greater than 3m, and the largest one reaching ~7.5m (Fig. 8(c)). However, on the contrary, MLD is rapidly decreased in the vicinity of the typhoon center, which is consistent with the result given by Reichl et al. (2016). Taking consideration of Stokes drift, MLD is generally deepened by ~$O(1)$.

The surface current is strengthened, especially in the Bohai Strait and the Central Area where the wind speed of typhoon is relatively high (top four panels in Fig. 11). The current velocity in the Liaodong Bay, where was not affected by typhoon, basically equals to that on 7 August (Fig. 11(a)). The maximum of Stokes drift-induced surface current speed decrease exceeds 0.2m/s, a huge impact evidenced in Fig. 11(d). The area with largest current speed change (Fig. 11(c)) coincides to the region with the most significant SST alternation (Fig. 10(c)), demonstrating that in this area SDP plays a greater role in vertical turbulent mixing and TKE.

Comparing to the vertical current profile on 7 August (Fig. 9(a)), Matsa forces the currents more evenly distributed within the entire shallow depth (Fig. 9(c)) on 8 August. The including of SDP further reduces the current speed at the whole depth in BS (Fig. 9(d)). However, owing to the short duration of typhoon action, the TKE transmitted from the atmosphere to the ocean is mainly limited to a depth of a few meters right below the sea surface. Therefore, the vertical current is stratified in the Central Area and the Bohai Strait, with large velocity difference between surface and deep waters.

On 9 August, one day after Masta intruded BS, the surface current speed is prominently decreased by about 0.3m/s in the region with high wind speed (Fig. 11(e)). Current is wholly directed to Laizhou Bay before typhoon, and flows basically along wind direction at the during-typhoon stage, illustrating that under typhoon condition wind is the dominant factor in controlling the ocean dynamics, even more important than tidal current. The influence of SDP on the current is further enhanced, and the current is generally weakened, particularly in northern Laizhou Bay. The maximum alternation in percentage (Fig. 11(h)) exceeds 100%, owing to the small current speed in the Central Area. The Stokes-induced differences in current direction between 8 and 9 August (shown in Fig. 11(c) and 11(g)) are both generally opposite to the wind direction, suggesting that at a certain degree the Stokes drift depresses the effect of strong winds on currents by strengthening the vertical turbulent mixing.

The current speed in the upper and lower layers is similar and the energy transported from the atmosphere to the ocean can fully inject into the whole depth (Fig. 9(e)). As a result of typhoon wind, currents generally flow along the same direction, and the current speed is increased obviously in the Bohai Bay and the Central Area (Fig. 9(c) and 9(e)). In contrast, the current speed is small in the Bohai Strait owing to it's close to the typhoon center and the opposite direction between wind and circulation. Adding the SDP, the vertical distribution of current speed (Fig. 9(e) and 9(f)) is noticeably changed, its magnitude is generally decreased.

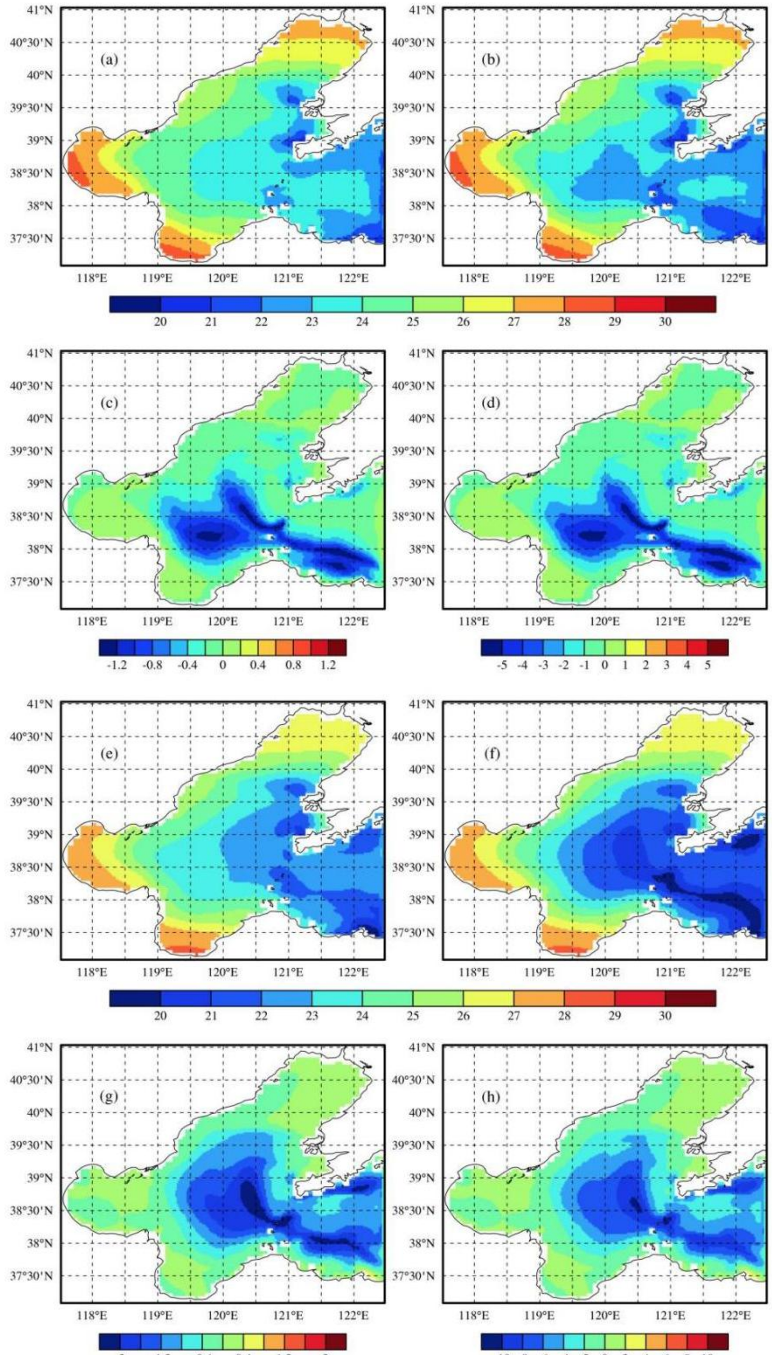

Figure 10. Horizontal distribution of (**a**) SST from WAVE-NON, (**b**) SST from WAVE-ALL, (**c**) SST difference between WAVE-NON and WAVE-ALL, (**d**) SST difference in percentage (%) between WAVE-NON and WAVE-ALL at 0000UTC on 8 August 2005 and (**e**) SST from WAVE-NON, (**f**) SST from WAVE-ALL, (**g**) SST difference between WAVE-NON and WAVE-ALL, (**h**) SST difference in percentage (%) between WAVE-NON and WAVE-ALL at 0000UTC on 9 August 2005.

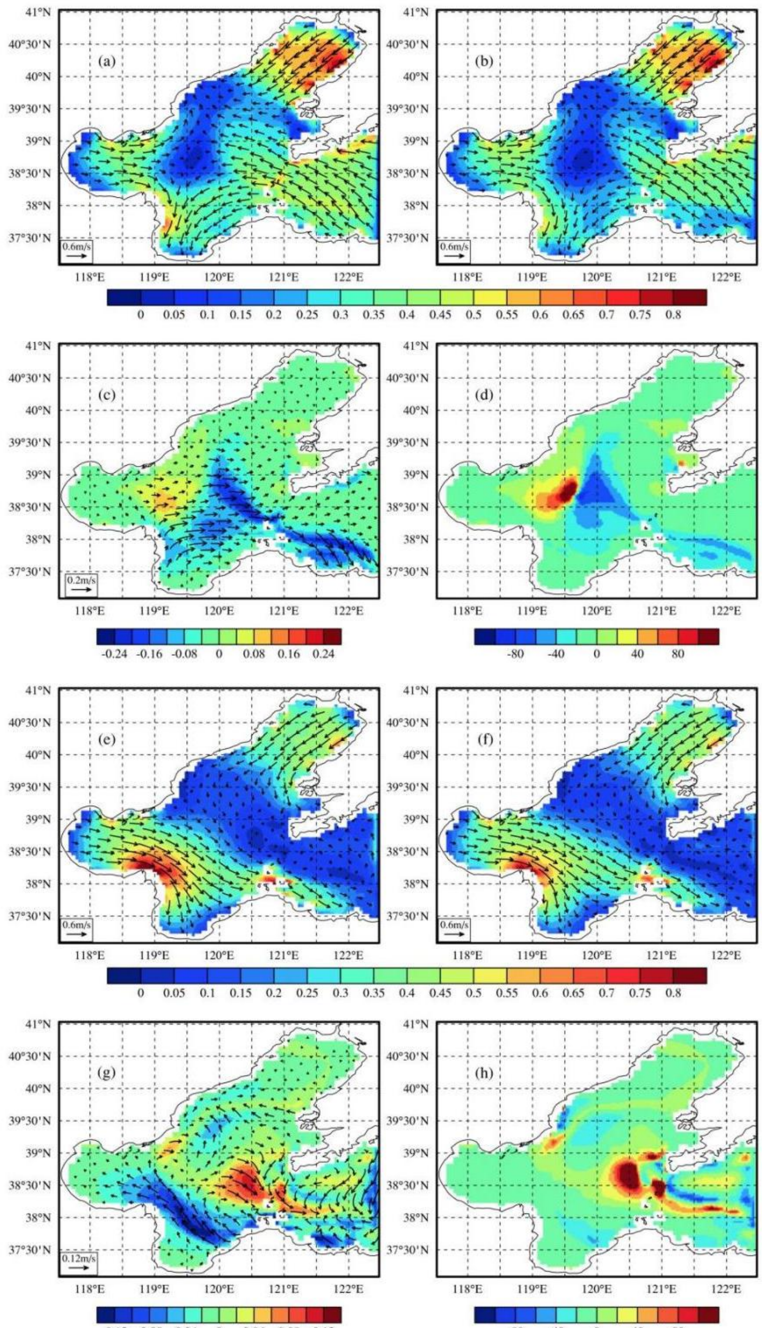

Figure 11. Horizontal distribution of (**a**) current from WAVE-NON, (**b**) current from WAVE-ALL, (**c**) current difference between WAVE-NON and WAVE-ALL, (**d**) current difference in percentage (%) between WAVE-NON and WAVE-ALL at 0000UTC on 8 August 2005 and (**e**) current from WAVE-NON, (**f**) current from WAVE-ALL, (**g**) current difference between WAVE-NON and WAVE-ALL, (**h**) current difference in percentage (%) between WAVE-NON and WAVE-ALL at 0000UTC on 9 August 2005.

4.3 After-typhoon stage

Matsa was weakened to an extra-tropical cyclone after 9 August. At this stage, SST rises gradually from 10 August (Fig. 12(a)) and later on. However, compared to the results on 7 August (Fig. 7(a)), SST is not fully recovered to the level before typhoon. SDP mainly reduces SST in the Bohai Strait and the Central Area, and the extent and range of the decreases (Fig. 12(c) and 12(d)) are similar to that on 9 August (Fig. 10(g) and 10(h)). The additional cooling at the after-typhoon stage indicates that SDP can not only affect SST at synoptic time scale, but also could impact the total heat budget at longer time interval. Without strong typhoon winds, MLD is decreased from 10 August. MLD simulated from WAVE-All is deeper than that from WAVE-NON (Fig. 8(d)), the SDP-caused MLD increase is about ~3.4m. The order of magnitude of MLD at this stage roughly coincides with that on 8 August, but MLD is generally deeper than that on 8 August, proving a hysteretic response between SDP and typhoon action.

At this stage, the circulation structure significantly differs from that at the pre-typhoon stage on 7 August. As shown in Fig. 12(e), the main direction of currents on 10 August is eastward, flowing from the Liaodong Bay and the Bohai Bay to the Laizhou Bay and the Bohai Strait, with relatively small speed in the Bohai Strait and the Liaodong Bay. SDP mainly decreases the surface current speed in the northern Laizhou Bay and the southern Bohai Strait (Fig. 12(g)), with the change ranging from 0.04 to 0.08m/s, demonstrating that the effect of Stokes drift is still persisting even after typhoon left the study area. The difference rate (Fig. 12(h)) is generally reduced because of the weakened winds, indicating that the impact of the Stokes drift on surface current is largely related to wind speed. As the varying of wind, current is changed from the surface deep down, forming a temporary current stratification (Fig. 9(g)). SDP promotes the integral change in all depths, which makes the vertical distribution of currents more uniformly (Fig. 9(h)), therefore weakens the stratification of flows.

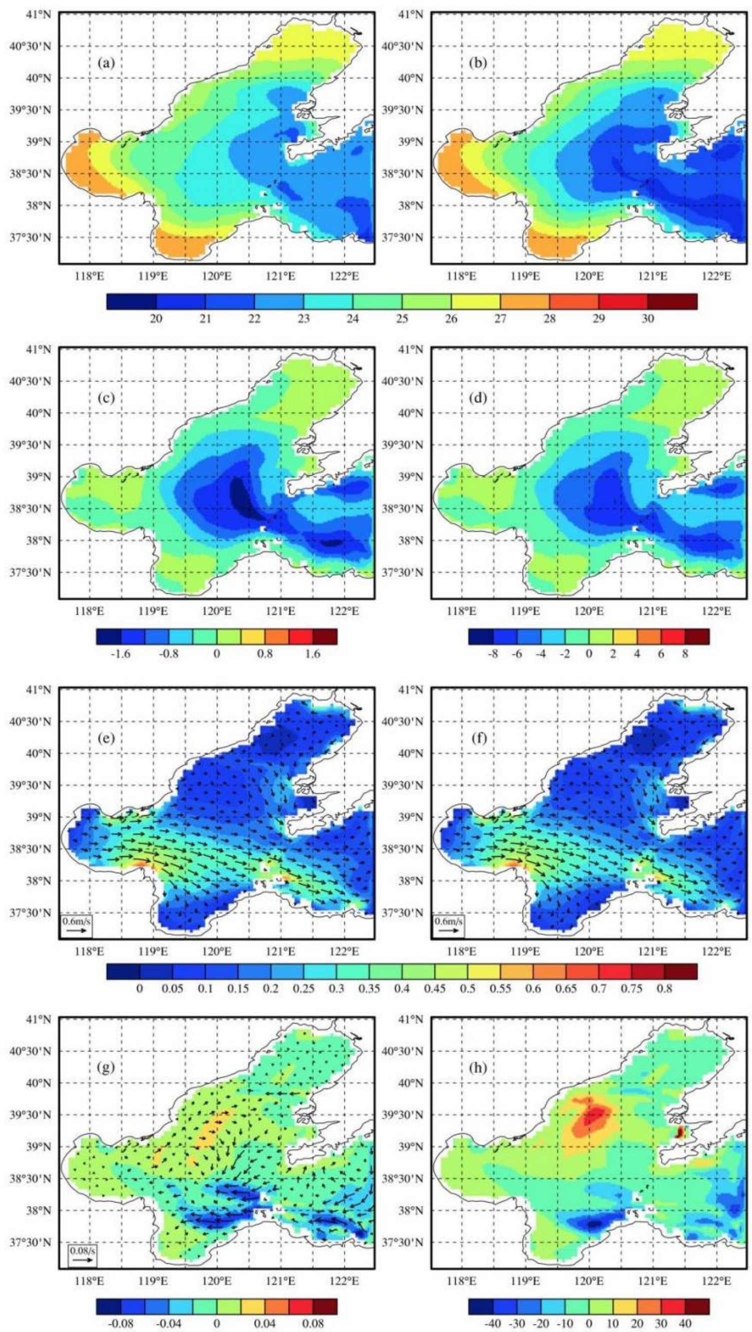

Figure 12. Horizontal distribution of (**a**) SST from WAVE-NON, (**b**) SST from WAVE-ALL, (**c**) SST difference between WAVE-NON and WAVE-ALL, (**d**) SST difference in percentage (%) between WAVE-NON and WAVE-ALL, (**e**) current from WAVE-NON, (**f**) current from WAVE-ALL, (**g**) current difference between WAVE-NON and WAVE-ALL, (**h**) current difference in percentage (%) between WAVE-NON and WAVE-ALL at 0000UTC on 10 August 2005.

5 Conclusions

It is emphasized that the specific role of SDP in turbulent mixing and dynamics in BS under typhoon condition is rarely known, given that no study was focused on this issue as the infrequently visit of tropical storms to the region. Here we using an one-way coupled POMgcs-SWAN modeling system to investigate the influences of Stokes drift on mixing and dynamics for the first time in BS under typhoon condition. Case study of supertyphoon Matsa (2005) is comprehensively performed and presented.

At the pre-typhoon stage, the impacts of SDP on SST, MLD and current are relatively slight and the structures of temperature and current are generally similar to the normal weather situation that was discussed in our previous study (Cao & Deng, 2019). As Masta acting on the study area at the during-typhoon stage, the turbulent mixing is greatly improved by about 1 order of magnitude, demonstrating that high wind speed enables a large amount of TKE injection down to the deep. The difference between K_M and K_{MS} exceeds $0.008 m^2/s$, about 7 times that at the pre-typhoon stage, proving that the Stokes drift plays a significant role on turbulent mixing under typhoon condition. As a result, SSTs and current speed are greatly reduced, whereas MLD is increased. However, the vertical temperature structure is not substantially changed, and the TKE transmitted from the atmosphere to the ocean is mainly confined to the surface layer. The flows are vertically stratified, and noticeable speed difference exists between surface and deep layers. One day after the acting of strong typhoon winds, the Stokes drift brings deeper cold water up to the surface, leading to stronger surface cooling and weakened temperature stratification. The temperature differences caused by Stokes drift in the Central Area and the Bohai Strait are notable, with the maxima of more than 2°C (>10%), because the relatively large water depth in this region facilitates the pulling of deeper cold water to the surface by SDP effects. Numerical results show that in high wind speed situation, the Stokes drift-induced SST decrease can be altered by $\sim O(1)$. The vertical temperature structure is also changed greatly, accompanied by a generally increase in

MLD, except a rapid decrease near the center of the typhoon. The vertical distribution of temperature tends to be more uniformly under the modulation of Stokes drift. Comparing to the maximum current speed change of ~0.02m/s caused by Stokes drift under the normal weather condition, the current speed is further reduced by over 0.2m/s at the during-typhoon stage, which is about 10 times that of the normal weather case. The maximum current change exceeds 100%, proving the notably influence of Stokes drift on surface current during typhoon period. In addition, after adding SDP, current direction change is generally opposite to the wind direction, suggesting that the Stokes drift depresses the effect of high wind speed on currents by intensifying the vertical mixing.

At the after-typhoon stage, although strong wind is almost passed, the mixing is still larger than that at pre-typhoon stage. The remained effect of SDP continuously keeps the relatively low SST, and the alternations in SST magnitude and range are similar to those at during-typhoon stage, indicating that SDP not only affects the SST at synoptic time scale, but also impacts the total heat budget at longer time scales. The Stokes drift-caused current speed change is decreased to 0.04~0.08m/s, and the alternation in percentage is also generally reduced because of the weakened winds, indicating that the impact of the Stokes drift on surface current is largely dependent on wind speed. However, the change of current speed is still greater than that at the pre-typhoon stage, and the change of current direction is opposite to the wind direction as well. Besides, SDP continuously promotes the coordinated changes at all depths, making the currents more uniformly in the vertical.

The combination impacts of SDP (CSF, LC, CLVF) on turbulent mixing as well as ocean dynamics under typhoon conditions are comprehensively analyzed and discussed. It’s manifestly illustrated that SDP is of great significance to ocean dynamical processes, in particular in typhoon weather. The impacts of these wave processes on ocean dynamics are essential to improve ocean prediction and disaster forecasting. In the actual ocean environment, the atmosphere, wave and circulation are always coupled, but here we only have an one-way coupled model. In the future, the fully coupled atmosphere-circulation-wave model can be further developed to study the influences of SDP on ocean dynamics in BS under typhoon condition. In addition, SDP not only affects the physical processes, but also alters the distributions of organics and nutrients in the ocean. Therefore, the role of SDP in the ocean bio-ecological processes should be an interesting topic for further research.

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