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Sea spray induced air-sea heat and salt fluxes based on the wave-steepness-dependent sea spray model

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Abstract

Sea spray, which comprises amounts of small ocean droplets, plays a significant role in the air-sea coupling, atmospheric and oceanic dynamics, and climate. However, it remains arduous to arrive at estimates for the efficiency and accuracy of the sea spray induced air-sea heat and salt fluxes. This is because the microphysical process of sea spray evolution in the air is of extreme complexity. In this study, we iteratively calculated the sea spray induced air-sea heat and salt fluxes at various weather condition. To do so, we implemented one novel wave-steepness-dependent sea spray model into a bulk air-sea fluxes algorithm and utilized other sea spray models as comparisons. Based on the improved wave-dependent bulk turbulent algorithm, we observed that despite the negative contribution of sea spray to the sensible heat fluxes, the sea spray positively contributes to the air-sea latent heat fluxes, leading to an overall increase in the total air-sea heat fluxes. The additional heat fluxes caused by sea spray may be the missing critical process that can clarify the discrepancies observed between measured and modelled Tropical Cyclone's development and intensification. In addition to heat fluxes, we observed that sea spray has significant impacts on the air-sea salt fluxes. As the sea salt particles are one of the main sources of the atmosphere aerosol, our results imply that sea spray could impact global and regional climate. Thus, given the significance of sea spray on the air-sea boundary layer, sea spray effects need to be considered in studies of air-sea interaction, dynamics of atmosphere and ocean.

Key words: sea spray, air-sea heat fluxes, air-sea salt fluxes, wave

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1 Introduction

Sea spray, or ocean spray, consists of liquid water ejected from the ocean surface because of wind shearing, wave breaking, and related physical mechanisms (Veron, 2015) (Fig. 1). As the composition of these water droplets is generally equal to that of the ocean surface water, once the sea spray is ejected into the atmosphere, the sea spray enlarges the surface area between the ocean surface and the atmosphere (Andreas, 1992, 1995). Sea spray subsequently contributes to the momentum, enthalpy, and ocean salt transfer during and/or after its evaporation and crystallization. Therefore, it plays a critical role in the atmosphere-ocean coupling (Andreas and Emanuel, 2001; Bao et al., 2011; Ma et al., 2020; Sroka and Emanuel, 2021).

Once sea spray is released to the atmosphere, it rapidly adjusts to the speed of local winds in a few seconds (Veron, 2015; Sroka and Emanuel, 2022). At developing sea, where the velocity of local winds is normally larger than that of waves, sea spray is expected to gain momentum from surrounding airflow and transfer it to the surface waves once falling back to the ocean (Rastigejev and Suslov, 2022). This positively contributes to the energy input from the winds to ocean surface current, which in turn results in positive feedback on the air-sea interaction (Zhang et al., 2017; Xu et al., 2021a). However, other studies argued that sea spray limits the air-sea momentum transfer. This is because parts of small water droplets reside in the air for days to weeks, the existence of them inhibits the wind energy input from the atmosphere into the ocean (Emanuel, 1995; Powell et al., 2003; Jarosz et al., 2007; Soloviev et al., 2014). Under this circumstance, even if the sea spray positively contributes to the momentum transfer from the atmosphere to ocean, the total air-sea momentum fluxes could be constant or even decreased. While it is still debatable how the sea spray dynamically affects the air-sea interactions, there is consensus that sea spray significantly influences the air-sea momentum transfer (Veron, 2015; Sroka and Emanuel, 2021, 2022).

In addition to momentum transfer, sea spray modulates the heat transfer from the ocean to atmosphere (Andreas, 1992, 1998; Andreas and Decosmo, 1999, 2002) (Fig. 1). Riehl (1948) initially proposed that the sea spray could potentially provide considerable heat to the atmosphere. Later, due to the difficulty of the experimental conduction in the field, Wu (1974) studied sea spray in a wind-wave tank and observed that the sea spray induced heat fluxes account for more than 13% of the air-sea total heat fluxes. However, results of Wu (1974) are limited to winds up to 13.4 m/s only. As such, more experiments were required to expand the sea spray observation at strong winds and obtain the general theory. In the late 1980s, a series of experiments were conducted, such as the Humidity Exchange Over the Sea (HEXO).

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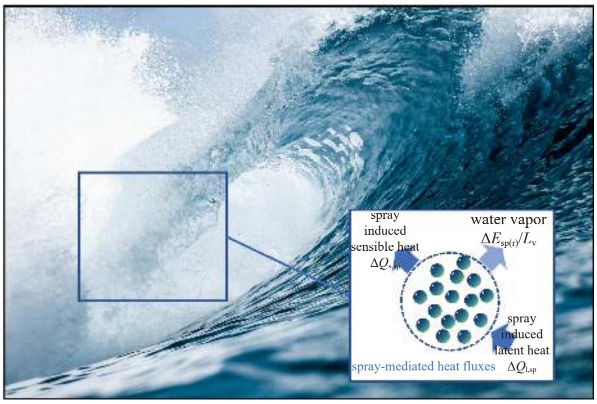

Fig. 1. Schematic illustration of the spray droplets, showing the spray-mediated heat fluxes.

Based on HEXO, Andreas (1992, 1998) proposed a wind dependent sea spray model that is developed to estimate the sea spray induced sensible and latent heat fluxes. It was pointed out that, once wind speed exceeds 11–13 m/s, the heat fluxes induced by sea spray become a significant fraction of the total air-sea heat fluxes, an observation consistent with Zhang and Lou (1995). Therefore, sea spray is expected to contribute to the air-sea heat transfer, and thus needs to be fully understood and considered through air-sea coupling.

Sea spray, in addition to dynamical and thermal effects, contributes to the air-sea salt transfer between the atmosphere and ocean (Veron, 2015). Sea spray of small radius, can stay in the air for days to weeks after being ejected into the atmosphere (Textor et al., 2006). While in the air, sea spray is subjected to evaporation, thereby crystallizing to salt particles (Andreae and Rosenfeld, 2008). The crystallized sea salt particles are considered a major source of atmospheric aerosols which inevitably affect global and regional climate. In addition to impacts on the increase of aerosol, sea salt can attach to the surface of the offshore industry, destroy their interfacial system, and cause inner aggregate raveling via chemistry reaction (Syrett, 1976; Zhou et al., 2020). Thus, as sea spray has significant impacts on air-sea interaction, climate, and ocean offshore industry, we need to understand how it interacts in the air-sea coupling system through the estimation of the sea spray induced heat and salt fluxes.

In this study, we aim to investigate the impacts of sea spray on air-sea heat and salt fluxes. To do so, we implemented various sea spray models into a bulk turbulent air-sea fluxes algorithm in Section 2, including a novel wave-steepness-dependent sea spray model that was developed on the basis of unique *in-situ* sea spray observations. Note, we also implemented other sea spray models as comparisons. Section 3 present the results and discussion, followed by the conclusions of this study in Section 4.

2 Methodology

2.1 *Sea spray models*

In this study, we adopted the novel nondimensional sea spray model of Xu et al. (2021b) to derive the sea spray volume fluxes generated at the ocean surface. This sea spray model is based on proxy-measurements of sea spray obtained from an offshore platform on the Western Shelf of Australia (Voermans et al., 2019). Observations of sea spray were measured concurrently with wind and wave properties and the sea spray volume flux is given by

$$\frac{V_{\rm sp}}{U_{10}} = 1.99\sqrt{s} \times 10^{-8}, \tag{1}$$

where the $V_{\rm sp}$ is instantaneous sea spray volume fluxes produced at ocean surface; $s = \frac{H_{\rm s}k_{\rm m}}{2}$ is the mean wave steepness where $H_{\rm s}$ is the significant wave height, and $k_{\rm m}$ is the mean wave number; U_{10} is the 10-m reference height wind speed. The reader is referred to Xu et al. (2021b) for a thorough description of the model. Additionally, we utilized other sea spray models as comparisons. Please refer to Andreas (1992), and Zhao et al. (2006) for more information.

2.2 *A bulk turbulent air-sea fluxes algorithm*

Before the sea spray model of Andreas et al. (2008) can be used for the estimation of sea spray induced fluxes, we need to parameterize the microphysical process of sea spray evolution in the air. To do so, we adopted a bulk turbulent air-sea fluxes algorithm for high-wind sea spray conditions (Andreas et al., 2008). In this algorithm, the air-sea heat fluxes can be parameterized as

$$H_{\rm l,tot} = H_{\rm l,int} + H_{\rm l,sp}, \tag{2}$$

$$H_{\rm s,tot} = H_{\rm s,int} + H_{\rm s,sp}, \tag{3}$$

where $H_{\rm l,tot}$, and $H_{\rm s,tot}$ are air-sea latent heat, and sensible heat fluxes, respectively; $H_{\rm l,int}$, and $H_{\rm s,int}$ are the interfacial direct air-sea latent heat, and sensible heat flux, respectively; $H_{\rm l,sp}$, and $H_{\rm s,sp}$ are the sea spray induced latent, sensible fluxes, respectively. The interfacial direct air-sea heat fluxes (i.e., $H_{\rm l,int}$, and $H_{\rm s,int}$) in Eqs (2) and (3) can be computed as

$$H_{\rm s,int} = \rho_{\rm a}c_{\rm p}C_{Hr}S_{\rm r}(\theta_{\rm s} - \theta_{\rm r}), \tag{4}$$

$$H_{\rm l,int} = \rho_{\rm a}L_{\rm v}C_{Er}S_{\rm r}\left(Q_{\rm s} - Q_{\rm r}\right), \tag{5}$$

where $\rho_{\rm a}$ is the density of air; $c_{\rm p}$ is the air specific heat; $L_{\rm v}$ is the latent heat of vaporization; C_{Hr} and C_{Er} are Stanton and Dalton number, respectively; $S_{\rm r}$ is the effective wind speed; $\theta_{\rm s}$ and $\theta_{\rm r}$ are averaged potential temperature at the reference height (subscript r) and sea surface (subscript s), respectively; $Q_{\rm s}$ and $Q_{\rm r}$ are the water vapor mixing ratio (i.e., vapor pressure of liquid at the specific temperature) at the reference height (subscript r) and sea surface (subscript s), respectively. Please refer to the Fairall et al. (1996); Fairall et al. (2011) for more information about the determination of these parameters in the turbulent bulk algorithm.

To derive the total air-sea heat fluxes in Eqs (2) and (3) in addition to the interfacial direct air-sea heat fluxes, we need iteratively compute the sea spray induced latent heat, and sensible heat fluxes (i.e., $H_{\rm l,sp}$, and $H_{\rm s,sp}$). Based on the algorithm of Andreas et al. (2008), $H_{\rm l,sp}$, and $H_{\rm s,sp}$ can be formulated as below

$$H_{\rm l,sp} = \alpha Q_{\rm l,sp}, \tag{6}$$

$$H_{\rm s,sp} = \beta Q_{\rm s,sp} - \left(\alpha - \gamma\right) Q_{\rm l,sp}, \tag{7}$$

where $\alpha = 15.15$ is the moisture coefficient that defines the contribution of sea spray to the latent heat flux; $\beta = 2.46$ is the coefficient that determines the amount of spray-induced sensible heat fluxes; $\gamma = 1.77$ is the correction coefficient that adjust the spray-induced heat fluxes because of the cooling effect caused by spray evaporation (Andreas et al., 2015). In addition, $Q_{\rm l,sp}$ and $Q_{\rm s,sp}$ can be obtained by

$$\begin{cases} Q_{\mathrm{l,sp}} = -\rho_w \cdot L_\mathrm{v} \cdot \left\{1 - \left[\dfrac{r(\tau_f)}{r_0}\right]^3\right\} \cdot V_{\mathrm{sp}}, & \tau_f \leqslant \tau_r \\ Q_{\mathrm{l,sp}} = -\rho_w \cdot L_\mathrm{v} \cdot \left[1 - \left(\dfrac{r_{\mathrm{eq}}}{r_0}\right)^3\right] \cdot V_{\mathrm{sp}}, & \tau_f > \tau_r, \end{cases} \tag{8}$$

and

$$Q_{\mathrm{s,sp}} = \rho_w \cdot c_{ps} \cdot (T_w - T_{\mathrm{eq}}) \cdot \left[1 - \mathrm{e}^{\left(-\frac{\tau_f}{\tau_T}\right)}\right] \cdot V_{\mathrm{sp}}, \tag{9}$$

where r_0 is the initial radius of generated sea spray droplets; r_{eq} is the equilibrium radius of spray droplets in the air; τ_r is the time scale to define r_{eq}; ρ_w is the ocean water density; c_{ps} is specific heat capacity of water; T_w is initial temperature of generated sea spray droplets (i.e., the sea surface temperature); T_{eq} is the equilibrium temperature of sea spray in the air; τ_f is the period of sea spray staying in the air; τ_T is the empirical characteristic e-folding time scale of sea spray. These parameters are determined based on the microphysical sea spray model proposed by Andreas (1989, 1990, 1992). In principle, they extended one cloud microscope model of Pruppacher and Klett (1978), and constructed one sea spray iterative algorithm for describing the thermal and moisture of water drops from the time they are produced until they adapted to the ambient atmospheric environments.

To estimate the sea spray induced salt fluxes, based on Eq. (4) and the theory of Andreas (2010), the salt fluxes (i.e., $M_{\mathrm{s,sp}}$) caused by sea spray can be parameterized as below

$$M_{\mathrm{s,sp}} = \frac{sH_{\mathrm{l,sp}}}{L_\mathrm{v}(1-s)}, \tag{10}$$

where $s = S/1\,000$ is the fractional salinity, and S is the initial salinity of sea spray droplets. Please refer Andreas et al. (2008) for more details of these parameters.

3 Results and discussion

3.1 *Sea spray volume fluxes*

Figure 2 shows the variation in modelled sea spray volume fluxes with 10-m wind velocity for different but typical values of the mean wave steepness (i.e., $H_\mathrm{s}k_\mathrm{m}/2$=0.1 to 0.4). The estimation of sea spray volume fluxes based on Andreas (1992) is shown for comparison. Overall, sea spray volume fluxes increase with wind velocity. The increase of wind velocity from 10 m/s to 40 m/s leads to an increment of the sea spray volume flux of about one order of magnitude. Under various wind conditions, increased wave steepness enhances the sea spray flux. However, as the volume flux scales with steepness to the power 1/2, this increase is less pronounced than that with wind speed. We note that, in contrast with the sea spray model of Xu et al. (2021b), Andreas (1992) does not explicitly includes wave properties. It is here where the sea spray model of Xu et al. (2021b) distinctively differs from the sea spray model of Andreas (1992). While wave peak frequency is introduced into the sea spray model of Zhao et al. (2006) through wave age, it has severe limitations in representing the generation of sea spray by waves, as it does not includes the severity of the sea state.

3.2 *Sea spray induced heat fluxes*

To investigate the heat and salt fluxes induced by the sea spray at the air-sea surface, we hereafter make the following assumptions about the atmospheric and oceanic condition: 20℃ averaged air temperature, a 27℃ averaged sea surface temperature, 1 000 hPa averaged sea surface pressure, 80% relative humidity, and 34 averaged sea surface salinity. In light of this, we can utilize these stable environmental variables as input for the bulk turbulent air-sea fluxes algorithm of Andreas et al. (2008) (i.e., Eqs (2)–(10)), and estimate the contribution of sea spray to the air-sea heat fluxes through implementing the sea spray model of Xu et al. (2021b) (i.e., Eq. (1)), Andreas (1992), and Zhao et al. (2006).

Figure 3 presents the variation in the air-sea sensible heat fluxes (SHF) with surface winds. We note, the sea spray induced sensible heat fluxes decease with surface wind velocity ramping up. In particular, by introducing sea spray through Xu et al. (2021b) for $H_\mathrm{s}k_\mathrm{m}/2=0.4$, the air-sea sensible heat fluxes are decreased up to 450 W/m² for a strengthening of U_{10} from 10 m/s to 40 m/s. At certain wind, sensible heat fluxes decrease further with increased mean wave steepness, demonstrating the impacts of different wave states on the sea spray induced sensible heat fluxes. Specifically, for U_{10}=40 m/s, the air-sea sensible heat fluxes are decreased by about 350 W/m² if steepening the waves from $H_\mathrm{s}k_\mathrm{m}/2=0.1$ to 0.4. In comparison with results without sea spray, the inclusion of sea spray via Xu et al. (2021b) decreases sensible heat fluxes between atmosphere and ocean, resulting in negative air-sea sensible heat fluxes. This is consistent with the results of sea spray models of Andreas (1992) and Zhao et al. (2006).

Figure 4 demonstrates the variability in air-sea latent heat fluxes (LHF) in response to surface winds. The sea spray induced latent heat fluxes rise with the increase of the wind velocity, albeit, at different magnitude for the different sea spray models. Namely, by the inclusion of the sea spray model of Xu et al. (2021b), for $H_\mathrm{s}k_\mathrm{m}/2=0.4$, the sea spray induced latent heat fluxes

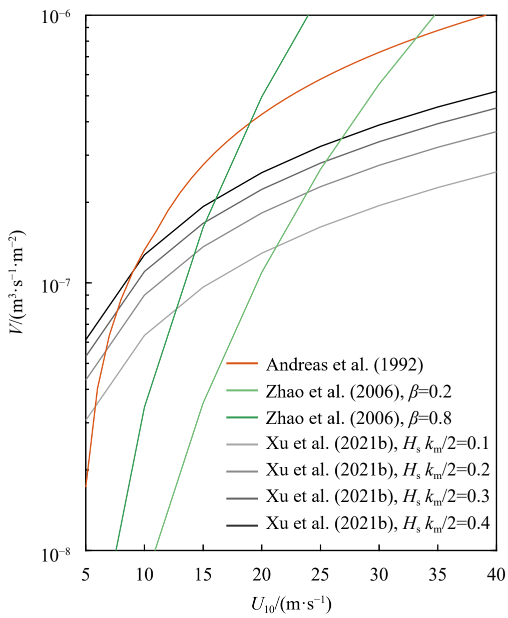

Fig. 2. Sea spray volume fluxes against the 10-m reference height wind speed U_{10}.The solid black lines are the sea spray volume fluxes based on Xu et al. (2021b) for different values of the mean wave steepness (i.e., $H_\mathrm{s}k_\mathrm{m}/2$ varies from 0.1 to 0.4 with an increment of 0.1), the solid red line is based on Andreas (1992), and the solod green lines are based on (Zhao et al., 2006) for different values of the wave age (β) (i.e., $\beta=0.2$ and 0.4, respectively).

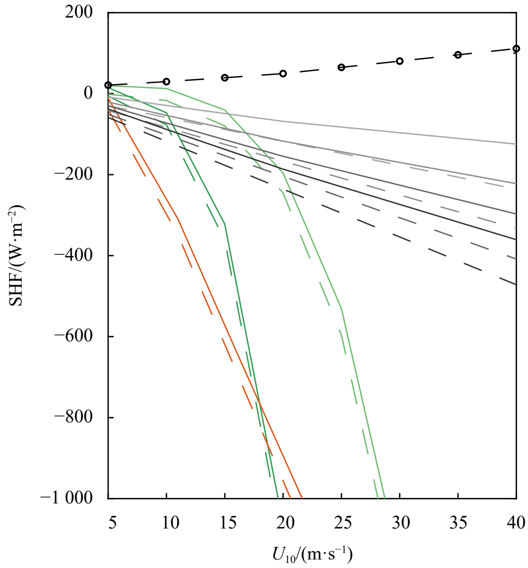

Fig. 3. The air-sea sensible heat fluxes (SHF) against the 10-m reference height wind speed U_{10}. The sea spray induced sensible heat fluxes, $H_{s,sp}$, is based on Xu et al. (2021b) (the dashed black lines with same gray value as in Fig. 2), Andreas (1992) (the dashed red line), and Zhao et al. (2006) (the dashed green lines with same color value as in Fig. 2), respectively. The interfacial direct sensible heat fluxes without sea spray, $H_{s,int}$, is the dash black line with circle marks, and the air-sea sensible heat fluxes with sea spray, $H_{s,tot}$, are the solid black, red, and green lines for Xu et al. (2021b), Andreas (1992), and Zhao et al. (2006), respectively (please see the legend in Fig. 2).

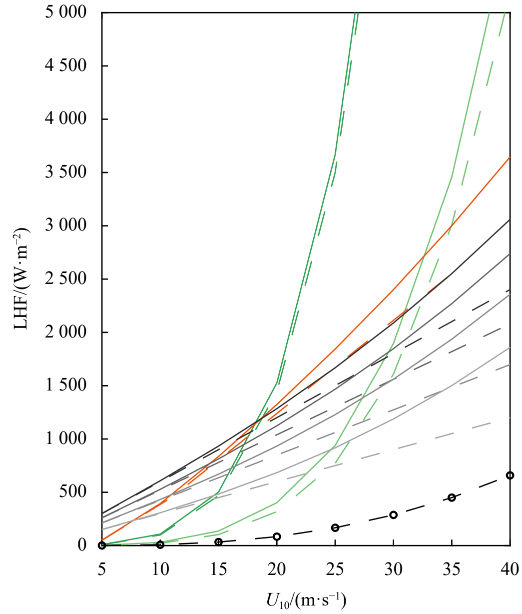

Fig. 4. The air-sea latent heat fluxes (LHF) against the 10-m reference height wind speed U_{10}. The sea spray induced latent heat fluxes, $H_{l,sp}$, is based on Xu et al. (2021b) (the dashed black lines with same gray value as in Fig. 2), Andreas (1992) (the dashed red line), and (Zhao et al., 2006) (the dashed green lines with same color value as in Fig. 2), respectively. The interfacial direct latent heat fluxes without sea spray, $H_{l,int}$, is the dash black line with circle marks, and the air-sea latent heat fluxes with sea spray, $H_{l,tot}$, are the solid black, red, and green lines for Xu et al. (2021b), Andreas (1992), and Zhao et al. (2006), respectively (please see the legend in Fig. 2).

are increased by about 3 500 W/m² for winds increasing from 10 m/s to 40 m/s. For constant wind conditions, the sea spray induced latent fluxes increase with mean wave steepness. Specifically, for U_{10}=40 m/s, the latent heat fluxes caused by sea spray increase from 1 200 W/m² for $H_s k_m/2=0.1$ to 2 500 W/m² for $H_s k_m/2=0.4$. Additionally, the air-sea latent heat fluxes are also presented both with $H_{l,sp}$ and without the effect of sea spray $H_{l,sp}$ in Fig. 4. In contrast to the effects of sea spray on air-sea sensible heat fluxes, sea spray reinforces the air-sea latent heat fluxes. In particular, at extreme weather condition (e.g., U_{10} = 40 m/s and $H_s k_m/2=0.4$), the air-sea latent heat fluxes are lifted up to about 50% (i.e., from 2 400 W/m² to 3 600 W/m²) by the inclusion of sea spray. We note that it is specifically during extreme weather events that the sea state tends to be steeper (Taylor and Yelland, 2001; Collins III et al., 2018). Therefore, sea spray is expected to have a critical role in the air-sea latent exchange process, especially under severe wave and atmosphere conditions, such as Tropical Cyclones (TCs).

Figure 5 shows the change of air-sea total heat fluxes (i.e., SHF+LHF) with surface winds. We observe that the sea spray impacts on the sea spray induced total heat fluxes are largely consistent with the latent heat fluxes caused by sea spray. Specifically, the air-sea heat fluxes are increase by up to 42% when U_{10}=40 m/s and $H_s k_m/2=0.4$ by introducing the sea spray model of Xu et al. (2021b). That is, the total heat fluxes because of sea spray increase with the strengthening of winds and rise with an increase in wave steepness. We note that, while the air-sea sensible heat fluxes become negative with the introduction of sea spray (Fig. 3), sea spray greatly increases the air-sea latent heat fluxes (Fig. 4), resulting in a net increase of the total air-sea heat fluxes (Fig. 5). This is because of the sea spray induced latent heat fluxes (positive) larger than sensible heat fluxes caused by sea spray (negative). Once ejected into the air, sea spray droplets would, although slowly, evaporate, which consumes an enormous quantity of heat (Gall et al., 2008; Liu et al., 2012). However, sea spray positively contributes to the air-sea latent heat which is substantial with respect to the air-sea sensible heat. As the sea spray induced heat fluxes consists of sensible and latent heat fluxes, we, thus, can expect a positive result of heat fluxes caused by sea spray (Andreas et al., 2008).

As the air-sea heat fluxes are the main source of energy for generating and maintaining the development of TCs (Montgomery and Farrell, 1993; Chan, 2005; Webster et al., 2005; Xu et al., 2021a), the inclusion of sea spray into the air-sea heat transfer can increase the intensity of TCs (Andreas and Emanuel, 2001; Zhang et al., 2017, 2021). Current studies suggest that the direct interfacial air-sea heat exchange is not large enough to explain underestimate of TCs' intensity (Emanuel, 2003, 2005). As the sea spray induced heat fluxes augment the air-sea interfacial heat transfer, we therefore suspect that it is the spray induced heat fluxes that cover the gap in the balance of air-sea heat budget in TC systems (Andreas and Emanuel, 2001; Zhang et al., 2021). This is because sea spray can redistribute the heat and moisture between the temperature and humidity fields in the air-sea boundary layer, which is consistent with current studies (Liu et al., 2011; Zhao et al., 2017; Garg et al., 2018). To investigate the impacts of sea spray on TCs system, we plan to conduct numerical experiments of TCs based on sea spray models in future studies.

3.3 *Sea spray induced salt fluxes*

Given the same atmospheric and oceanic conditions as in

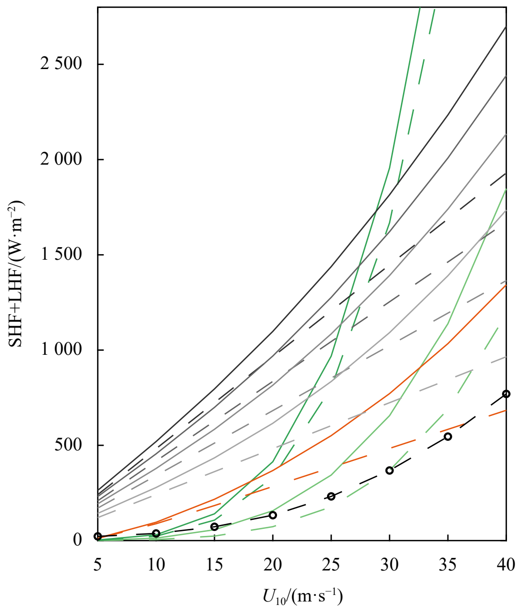

Fig. 5. The total air-sea heat fluxes (SHF+LHF) against the 10-m reference height wind speed U_{10}. The sea spray induced heat fluxes, $H_{\rm l,sp}+H_{\rm s,sp}$, is based on Xu et al. (2021b) (the dashed black lines with same gray value as in Fig. 2) , Andreas (1992) (the dashed red line), and (Zhao et al., 2006) (the dashed green lines with same color value as in Fig. 2), respectively. The interfacial direct air-sea total heat fluxes without sea spray, $H_{\rm l,int}+H_{\rm s,int}$, are the dash black line with circle marks, and the air-sea total heat fluxes with sea spray, $H_{\rm l,tot}+H_{\rm s,tot}$, are the solid black, red, and green lines for Xu et al. (2021b), Andreas (1992), and Zhao et al. (2006), respectively (please see the legend in Fig. 2).

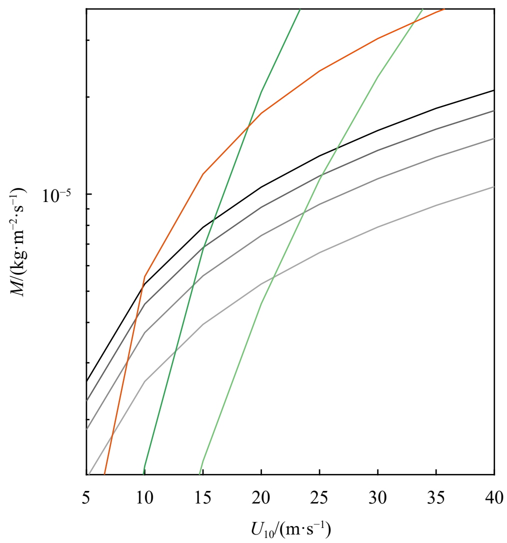

Fig. 6. The sea spray induced salt fluxes (M) against the 10-m reference height wind speed U_{10}. The black lines are the sea spray induced salt fluxes, $M_{\rm s,sp}$, based on Xu et al. (2021b) for different $H_{\rm s}k_{\rm m}/2$ which varies from 0.1 to 0.4 with an increment of 0.1 (gray value as in Fig. 2), Andreas (1992) (the red line), and (Zhao et al., 2006) (the green lines with same color value as in Fig. 2), respectively (please see the legend in Fig. 2).

Section 3.2, we can derive the sea spray induced sea salt fluxes for different wind speeds and wave states (Fig. 6). We observe that the sea spray induced salt fluxes are consistent with sea spray induced volume fluxes (Fig. 2). This can be represented through the inclusion of different sea spray models. Namely, the sea spray induced salt fluxes increase with the wind velocity and wave steepness.

Based on data of the fifth-generation atmospheric reanalysis of the global climate (ERA-5) produced by the European Centre for Medium-Range Weather Forecasts, we estimated the annual average of sea spray induced salt fluxes in 2010. Here, we take the sea spray model of Xu et al. (2021b) as an example (Fig. 7). We note, the global sea spray-modulated salt fluxes distribution is highly consistent with the 10-m wind speed, U_{10} (Fig. 8) and mean wave steepness, $H_{\rm s}k_{\rm m}/2$ (Fig. 9). That is the global sea salt fluxes is roughly zonally oriented with larger fluxes (3.5×10^{-7} (kg/(m^2·s)) occurring over the Southern Ocean and subtropical latitudes of the global oceans because of the stronger winds and energetic wave state. Exceptions to this zonal pattern are the regions of North Pacific and Gulf Streams. Smaller fluxes are presented over the equatorial cold tongues and high latitudes in the North Hemisphere. In contrast to low latitudes, while the $H_{\rm s}k_{\rm m}/2$ are large in high latitudes of North Hemisphere (i.e., 70°–80°E), winds are less strong, which results in less sea spray-modulated salt fluxes. As such, the salt fluxes vary in large spatial and temporal scale. This is critical for studies of regional and global climate (Pandis et al., 1992; Seinfeld and Pandis, 2008), as

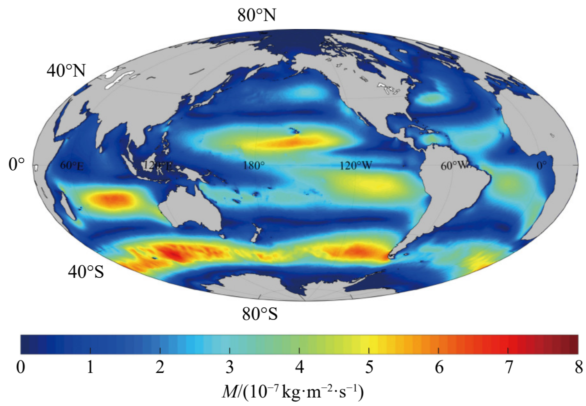

Fig. 7. The sea spray induced salt fluxes (M) based on the fifth-generation atmospheric reanalysis of the global climate (ERA-5) produced by the European Centre for Medium-Range Weather Forecasts for the annual average of 2010.

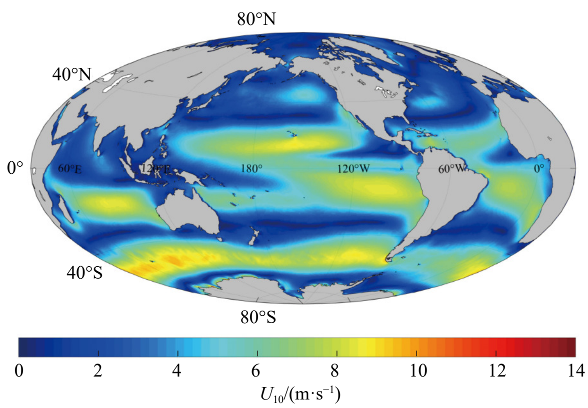

Fig. 8. The 10-m wind speed, U_{10}, based on the fifth-generation atmospheric reanalysis of the global climate (ERA-5) produced by the European Centre for Medium-Range Weather Forecasts for the annual average of 2010.

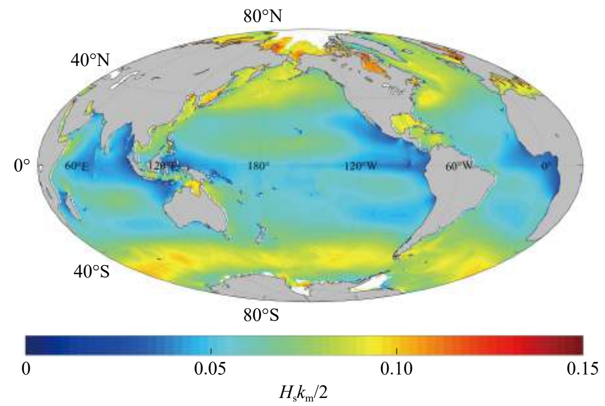

Fig. 9. The mean wave steepness, $H_sk_m/2$, based on the fifth-generation atmospheric reanalysis of the global climate (ERA-5) produced by the European Centre for Medium-Range Weather Forecasts for the annual average of 2010.

air-sea salt fluxes caused by sea spray account for over 90% of aerosols in the maritime boundary layer (Pandis and Seinfeld, 1989; Kanakidou et al., 2005), nearly equals to 50% of natural aerosol flux, and represent more than 30% of total global flux of aerosol (Textor et al., 2006). Thus, it is critical to accurately estimate the sea spray-modulated salt fluxes for studies in climate.

4 Conclusions

In this present work, we investigate the contributions of sea spray to the air-sea heat and salt fluxes. In doing so, we implemented one novel wave-steepness-dependent sea spray model into a bulk turbulent air-sea fluxes algorithm. By adopting the improved wave-state-dependent air-sea fluxes algorithm, we estimate the air-sea heat and salt fluxes with and without sea spray. To make the advantage of using wave-steepness-dependent sea spray model clear, we utilized other sea spray models as comparisons.

We observe that, while adopting different sea spray models, the sea spray induced sensible heat fluxes are negative (i.e., decrease the interfacial direct air-sea sensible fluxes). However, the latent heat fluxes induced by the sea spray are positive, which increases the interfacial direct air-sea latent heat fluxes. As the latent heat fluxes are substantial in comparison with sensible heat fluxes, the total sea spray-modulated heat fluxes are positive. That is, the air-sea heat fluxes increase when introducing sea spray. The contribution of sea spray to air-sea heat fluxes become similar in magnitude as the atmospheric and oceanic environment getting more and more energetic. Therefore, the additional heat fluxes from the sea spray to the atmosphere might be the critical physical process that can explain the current inconsistencies between the observations and simulations of Tropical Cyclones' intensification. Therefore, sea spray needs to be considered in current operational forecasting models of the Tropical Cyclones.

In addition to heat fluxes, we estimated sea spray-induced air-sea salt fluxes on the basis of the novel wave-steepness-dependent sea spray model. Through atmosphere, ocean and wave datasets of ERA-5, we derived the annual average of sea spray-induced salt fluxes in 2010. We observe that, the spatial distribution of sea spray-induced salt fluxes agrees with the 10-m wind speed, U_{10} (Fig. 8), and mean wave steepness, $H_sk_m/2$ (Fig. 9). That is, global sea salt fluxes follow a zonal pattern. Larger sea spray-modulated salt fluxes located in high and subtropical latitudes in the South Hemisphere where the wind and wave states are severe. Additionally, smaller salt fluxes caused by the sea spray are presented in high latitudes in North Hemisphere and the north of India Ocean. As the sea spray modulated salt fluxes vary in large spatial and temporal scale, we expect that they can implicitly affect global climate and need to be considered in related studies.

It should be noted that current models and algorithm related to sea spray still differ for sea spray droplets by up to six orders of magnitudes in various observations. More field and/or laboratory experiments of sea spray with concurrent winds and waves are needed for future validation of sea spray effects on air-sea heat, momentum, and salt transfer. However, despite the uncertainties in this study, we substantiate that the impacts of sea spray on air-sea coupling are significant and require to be considered in studies of air-sea interactions, regional and global climate.

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