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An integrated turbulent simulation and parameter modeling study on sea-spray dynamics and fluxes

Zhan-Hong Wan[a,c], Jian-Bin Zhu[a], Ke Sun[b,*], Kun Zhou[b]

[a] *Ocean College, Zhejiang University, Zhoushan 316021, China*
[b] *The State Key Laboratory of Refractories and Metallurgy, Wuhan University of Science and Technology, No. 947, HePing Dadao, QingShan, Wuhan 430081, China*
[c] *State Key Laboratory of Satellite Ocean Environment Dynamics, Hangzhou 310012, China*

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ABSTRACT

Sea spray droplets are generated in the processes of wave breaking and bubble bursting, which has a remarkable influence on the marine surface boundary layer, especially at high wind speed like typhoon. This paper presents an integrated study with Large-eddy simulation (LES) on wind-wave-droplet coupled transport and spray-flux parameterization methods, which includes a sea-spray generation function, a drag coefficient (C_D) and a heat flux coefficient (C_K). The results show a large magnitude and variation similarity to authorized laboratory data and previous models for 10–500μm droplets. The C_D fundamental parameters are not only determined by the droplet number, but also influenced by wave-age & wind-wave Reynolds number. With a comprehensive consideration of the these effects, C_D shows a tendency of decrease at high wind speed from 33 m/s, and its maximum value is 1.96×10^{-3}. This phenomenon could be explained by a droplet-induced lubricating layer at air-sea interface. The revised C_K trend changes obviously and increases with wind increase. The heat transfer is enhanced 66.4% due to droplet effects at 60 m/s. LES results demonstrated that spray droplets concentrate around effective wave height 15 cm with Gaussian distribution, and the peak concentration increases 3.37 times with wind speed increasing 1.67 times.

1. Introduction

The omnipresence of sea spray droplets produced by bubble bursting and wave breaking in the air-sea interface has been proved to have a significant influence on the transfer of air sea momentum flux and heat flux (Grenier et al., 2013; Smith and Harrison, 1998; Wang et al., 2001; Zhang, 1981). Earlier researchers separated the droplets into wave breaking droplets and bubble bursting droplets on the basis of generation mechanism, meanwhile, droplets produced by bubble bursting can be divided as film droplets and jet droplets (Spiel, 1998).

With the development of the observation technology of field and laboratory study, spume spray droplets produced by wave breaking have been proved to dominate the radii that are large enough to have a sufficient amount to affect the interaction occurred at the air sea interface (Andreas, 1998; De Leeuw, 1999; Latorre and Ryan, 1989; Paul and Ismail, 2012). Different sea spray generation functions (SSGF) had been presented by many scholars on the basis of the observed data from the field and laboratory studies. Up to now, however, the perspective of the SSGFs has not become consistent. Due to the limitation of the adverse conditions in the open ocean, it is hard to measure the accurate radii and number of droplets, therefore, laboratory study data would play an important role to the database of droplets measurement. De Leeuw (1986) firstly measured the droplets with the radii from 10 to 100 μm by using a Rotorod inertial impactor in North Atlantic in 1983, and depict the droplets' distribution in vertical direction. The results show that the concentration of droplets decreases with radii almost linearly. Fairall et al. (2009) conducted an experiment named the Spray Production and Dynamics Experiment (SPANDEX) at the University of New South Wales Water Research Laboratory. A phase Doppler system was used to measure the droplet concentration and the experiment was mainly aimed to investigate the scale of spume droplets related to wind/stress interactions with actively breaking waves. Much more accurate data had been obtained during the experiment, and the energy balance between the wind energy flux and wave breaking had been analyzed.

With the increase of wind energy inject, more spume droplets are generated, especially in the hurricane condition, the effect of spume droplets is noteworthy. With the combined action of turbulence and gravity, droplets with the certain radii can suspend in the air for a period of time and the smaller ones stay longer (Lin et al., 2015; Qian

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[*] Corresponding author. Tel.: +86 027 68862989.
E-mail addresses: wanzhanhong@zju.edu.cn (Z.-H. Wan), randal.soon@gmail.com (K. Sun).

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and Lin, 2011; Sun and Lu, 2013). The existence of droplets in the marine surface boundary layer (MSBL) changes the basic state of the air-sea interface, and thus affects different physical processes occurred in the interface (Andreas, 2004). When Powell et al. (2003) discovered that drag coefficient reduced at high speeds in tropical cyclones with the method of GPS data analysis, almost all the subsequent investigations consistently confirm that large number of droplets can change the tendency of drag coefficient variation from increase to decline. Makin (2005) assumes that the existence of the droplets compose a layer which can be called Spray Boundary Layer. The layer prevents the turbulence from approaching to the sea surface, so it can prevent the drag coefficient from sustained increase. Andreas (2002) believes that, the sea spray droplets are generated at the circumstance of wind speeds larger than 7 m/s, so the generation of droplets must cost the energy and momentum of wind speeds and thus it can reduce the drag coefficient. Meanwhile, the sea spray droplets can redistribute the exchange of momentum between the ocean and the atmosphere.

Recently, an advanced and accurate Large-Eddy Simulation (LES) has been regarded as a focusing method for turbulent particle flow and heat and mass transfer. Sullivan et al. (2004, 2007) have conducted a remarkable effort to employ this method to study surface gravity wave effects in the oceanic boundary layer. Liang et al. (2012) have successfully investigated the bubble and gas transfer on ocean subsurface by LES. Zhu et al. (2014) have preliminarily simulated the generation of sea spray droplets after wave break with LES and subgrid scale (SGS) model, and have depicted the distribution of droplets with different radii at different given height above the sea surface, which may support the further investigation of the movement of sea spray droplets after wave break. However, the adoption of the LES in accurate and complicated sea spray study is far from fully understanding.

Therefore, this paper plans to develop an combined large eddy simulation (LES) and flux parameterization method to incorporate sea-spray effects. At first, a LES model coupled with a modified subgrid-scale model is formed to simulate sea-spray dynamics and to include the wind-wave effects in Section 2. In section 3.1, we will discuss the SSGF with a series of comprehensive functions. Wind speed, wave state and the effect of sea spray droplets are taken into accounts in the computation of drag coefficient in Section 3.2. Section 3.3 states the deduction of revised heat flux coefficient. Section 4 presents the calculated results and in-depth discussion compared to laboratory data and previous models. Section 5 briefly gives the conclusions.

2. Model sea-spray to atmosphere dynamics

This paper aims to study the generation and transport mechanism of sea-spray droplets as shown in Fig. 1. According to the wave generation mechanism, turbulent wind energy is injected into the ocean as wave energy. When the wave is travelling with periodic height and slope extremes, wave and bubbles in the sea break up, and then spray droplets appear. This study treats the wave breakup process as turbulent energy dissipation with energy spectral and dissipation scales. The energy brought by wind is transferred to wave energy, and finally dissipated by spray droplets. These processes are resolved by combined turbulent conservation equations and droplet transport laws in the following sections.

2.1. Turbulent flow modeling by LES approach

This section adopts the advanced Large-Eddy Simulation (LES) method to resolve the conservation equations of sea spray in turbulent wind-sea flow (Zhou et al., 2014; Zhou and Chan, 2011; Zhu et al., 2014). With building dynamic LES simulation model, subscale turbulent kinetic energy is integrated into the model. Considering the wave effects on sea spray, the parameterized conservation formula include equations of moments, subscale turbulent kinetic energy and density change as follows

$$
\begin{aligned}
\frac{\partial\overline{u_i}}{\partial t} &= -\frac{\partial}{\partial x_j}(\overline{u_j}\overline{u_i}+\tau_{ij})-\delta_{i3}\frac{g\overline{\rho}}{\rho_o}-\frac{\partial\pi}{\partial x_i}-\varepsilon_{ijk}f_j(\overline{u_k}+{u_k}^{St})+\varepsilon_{ijk}{u_j}^{St}\overline{\omega_k}\\
&\quad+\sum_m\overline{A_i^m}\frac{\partial e}{\partial t}=\cdots-{u_j}^{st}\frac{\partial e}{\partial x_j}-\tau_{ij}\frac{\partial {u_i}^{st}}{\partial x_j}+\sum_m W^m\frac{\partial\overline{\rho}}{\partial t}\\
&= -\frac{\partial(\overline{u_j}\overline{\rho}+\tau_{j\rho})}{\partial x_j}-{u_j}^{st}\frac{\partial\overline{\rho}}{\partial x_j}
\end{aligned}
\tag{1}
$$

where u_i is fluid velocity; t is time; x_i is space coordinate; τ_{ij} is viscous stress; g is gravitational acceleration; $\rho$and $\rho_o$mean fluid instant density and reference one, respectively; δ_{i3} is Kronecker delta function; $\pi$is general pressure field; ε_{ijk} means the permutation tensor; f_j is Coriolis frequency; $u^{St}$is Stokes-drifted velocity; ω_k is vorticity component; e is subscale turbulent kinetic energy; ${A_i}^m$ means the m individual moment brought by wave breakup; W^m is the m energy brought by wave breakup, which could be modeled by the subscale characteristic length, wave age, wind speed and enough individual wave breakers during the simulation (Sullivan et al., 2007); $\tau_{j\rho}$ is subscale density flux; the subscripts i, j and k stand for coordinate component.

The main resolving route of LES is to regard the turbulent flow as large eddies and small eddies. The large ones are affected obviously by the flow and then can be directly simulated. However, the small ones are assumed to be homogenous and then can be filtered and calculated by revised subgrid-scale (SGS) models.

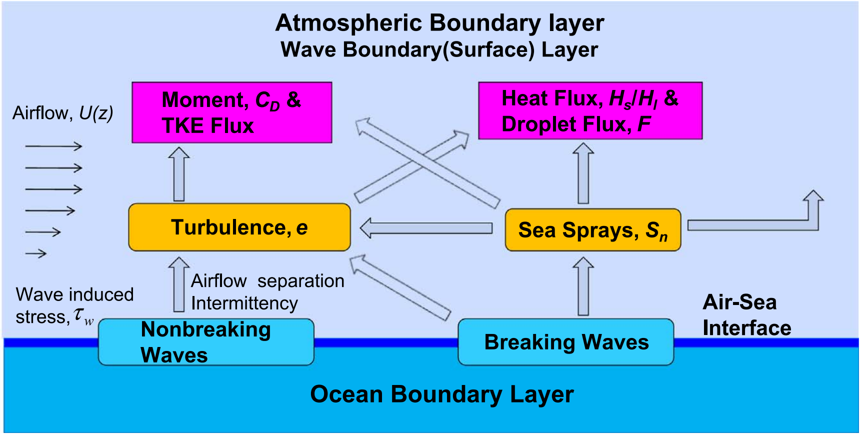

Fig. 1. Schematic diagram of the wind-wave-spray generation and transportation (Note: $U(z)$, vertical wind or airflow velocity profile; τ_w, wind-wave induced stress; C_D, drag coefficient; TKE, turbulent kinetic energy; e, subscale TKE; H_s, sensible heat flux; H_l, latent heat flux; F, droplet flux; S_n, source flux function for droplets).