SIMULATION OF SPRAY DROPLETS OVER THE OCEAN SURFACE

by

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Spray droplets, ejected from the ocean surface, are known to transport in the marine atmospheric boundary-layer, in which they exchange momentum and heat with the atmosphere. This paper gives a numerical approach to description of sea spray drops. Large eddy simulation is used to perform the air-flow over the sea surface while simultaneously tracking the trajectories of Lagrangian point-particle elements designed to represent spray particles in air, the particle momentum relaxation time, the suspension time, the velocity of particles in different radii and different wind speeds are discussed. This simplified model shows that the contribution of droplet particles to the air-sea momentum transport cannot be ignored. The spray droplets suspended over the sea surface are once formed, they will accelerate to the local wind speed in less than 1 second, and thereby the drops can extract momentum from the wind, reduce sea surface wind speed and eventually plunge back into the ocean. The averaged particle concentration is balanced by an equivalent production of new particles.

Key words: *spray, Euler-Lagrange, momentum exchange, CFD*

Introduction

Sea spray, or ocean spray, consists of small water droplets, formed through a number of different processes at the air-ocean interface, the region where atmosphere and ocean meet, and is chiefly composed of three types of droplets: film, jet, and spume. Named after their production mechanisms, film and jet droplets are both formed from whitecap bubbles through *indirect* processes [1], *via* the bursting of bubble surfaces and from the collapse of bubble cavities, respectively. Film droplets tend to have radii between 1 and 2.5 μm, while distributions of jet droplets generally peak around 10 μm [2]. The spume generation mechanism yields little spray for low wind speeds, but is significant when the 10-m wind speed exceeds 7-11 m/s [3]. Spume droplets are generally larger than jet and film droplets, with spume of radii r_0 ~ 20 μm being the most common; however, 20 μm droplets are the smallest spume droplets produced, and significant amounts of spume exist with radii up to (or beyond) 500 μm, especially at higher wind speeds [4, 5].

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Once created, spray droplets are carried up and down by turbulence. Under the comprehensive action of wind, gravity, inertia, and turbulent mix, the activity area of droplets can be at some heights above the sea surface, so droplets may have a significant effect on the latent and sensible heat transfer between the atmosphere and the ocean. Its effects on heat transfer are also widely studied in many other areas, such as fuel combustion [6-8] and cooling system [9, 10]. When sea spray droplets are thrown into air, they accelerate almost immediately to the local wind speed. This process extracts momentum from the near-surface wind and therefore slows it down. When these droplets then crash back into the sea, they transfer this momentum to the sea surface as a surface stress [11]. Thus, at least conceptually, sea spray has the potential to change the near-surface distribution of the momentum and stress on the interface of air and seawater. Andreas [11] concluded that spray supports about 10 % of the surface stress for a wind of 30 m/s, and supports all of the surface stress for wind of about 60 m/s. The flux of momentum must be related to the number of droplets with different radii, or the volume flux of droplets.

However, the sea spray generation function (SSGF) $\mathrm{d}F/\mathrm{d}r_0$, which plays an important role in estimating how much spray transfers momentum to the sea surface, given by different authors may have a tremendous difference. Andreas [12] reviewed 13 versions of the SSGF for r_0 values between 1 and 500 μm, and found that at any given wind speed and r_0 these functions range over six orders of magnitude. Recently, more and more studies represent that the influence of wind-wave interaction on the sea surface wind stress plays an important role in the study of air-sea interaction [13]. After introducing of parameter, R_B, that specified the coupling effect of wind forcing and wind waves, Zhao *et al.* [14] suggested that windsea Reynolds number, R_B, not the wind speed U_{10} traditionally applied, should be used to describe sea spray production and proposed a new SSGF as a function of R_B for spume droplets based on available observational data from field and laboratories.

For the simulated study of granular flow, there are two approaches, the Euler-Euler method and Euler-Lagrange method [15]. In this paper, we attempt to develop an Euler-Lagrange model to simulate the spray droplet over the ocean surface.

Droplet motion and numerical details

The fluid phase is governed by the incompressible Navier-Stokes equations, including a particle feedback force in the momentum equations. These include mass conservation:

$$\nabla u = 0 \tag{1}$$

and momentum conservation:

$$\rho \frac{\partial u}{\partial t} + \rho (u\nabla) u = -\nabla p + \mu \nabla^2 u + \rho \mathrm{g} - S_\mathrm{p} \tag{2}$$

where the additional source term, S_p, is a source term representing the modeled transfer of momentum between the carrier and dispersed phases. Depending on the particle concentration, we can make assumptions and neglect the source term, S_p, in the momentum equation. If we consider the case of a dilute suspension with a volume fraction of particles Φ_p lower than 10^{-6}, the particles' effects on the flow and turbulence are negligible. This is usually denoted one-way coupling, *i. e.* the flow affects the particles but the particles don't affect the flow. In that case, the additional source term, S_p, is neglected.

As a consequence of very low volume fraction of particles, inter-particle collisions are also neglected. For a higher volume fraction, $\Phi_p \in [10^{-6}, 10^{-3}]$, the particles enhance production or dissipation. This is two-way coupling and in that case the source term is included in eq. (2). For a dense suspension, the particle-particle interactions must also be taken into account with a model for collision, fig. 1.

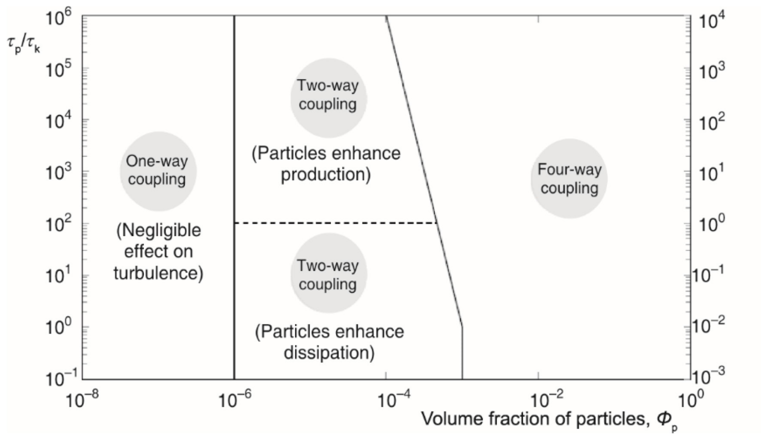

Figure 1. Classification of phase-coupling mechanisms

Momentum exchange between spray and the turbulent airflow in MABL is described within the Lagrangian stochastic model of turbulent transport developed by Edson and Fairall [16]. We consider a separate droplet and calculate the momentum delivered (or gained) by the droplet to the airflow during its *life cycle* from being injected to the air to dropping on the surface [17-19]. The droplet is considered as a small sphere of radius, r, under the forcing of the viscous resistance and gravity, the interaction between the droplets is neglected:

$$\left(\frac{4}{3}\pi r^3 \rho_\mathrm{p}\right)\frac{\mathrm{dv}}{\mathrm{d}t} = F_\mathrm{D} + \frac{4}{3}\pi r^3 \rho_\mathrm{p}\mathrm{g} \tag{3}$$

where v is a droplet velocity, ρ_p – the droplet density, g – the acceleration due to gravity, and F_D – the viscous drag:

$$F_\mathrm{D} = \frac{1}{2}\rho_\mathrm{f} C_\mathrm{Dp}\pi r^2 (u - \mathrm{v})\,|u - v| \tag{4}$$

In Stokes flow with small particle Reynolds number, $\mathrm{Re}_\mathrm{p} = 2r|u - v|/\nu$, where ν is the kinematic viscosity of the air, $F_\mathrm{D} = 6\pi r\mu(u - v)$, and the drag coefficient is thus given by $C_\mathrm{Dp} = 24/\mathrm{Re}_\mathrm{p}$. For larger Reynolds number, we use the following relationship [17, 18]:

$$C_\mathrm{Dp} = \frac{24}{\mathrm{Re}_\mathrm{p}}\left(1 + 0.15\mathrm{Re}_\mathrm{p}^{0.687} + \frac{0.0175\mathrm{Re}_\mathrm{p}}{1 + 4.25\cdot 10^4\,\mathrm{Re}_\mathrm{p}^{-1.16}}\right) \tag{4}$$

Model descriptions

The simulations use a 1 km × 1 km × 500 m domain with 80^2 points in (x, y) and 40 points in z. The grids are distributed uniformly in the horizontal and with 10 expansion ratios in the vertical directions. Driving winds of 10-m wind speed U_{10} = 60 m/s are imposed upon the domain. The equations of governing the carrier fluid phase, eqs. (1) and (2), are solved numerically using a large eddy simulation code. The particle represented in the simulations are assumed to be smaller than the Kolmogorov turbulence length scale, and the particle volume fraction is assumed small so that the interactions between droplets, such as collisions or coalescence, can be ignored.

Spume droplets, due to their large relative size, have the potential to transfer considerably more mass, momentum, and heat than jet or film droplets. Droplets with radius of 200 μm are introduced in our case with the sea spray generation function approximated using a bin width of 200 μm. The integrated spray generation equals to the spray generation at 200 μm multiplied by a factor of roughly 3:

$$\int_{1\mu m}^{500\mu m} \frac{\mathrm{d}F}{\mathrm{d}r_0}\mathrm{d}r_0 = 3\left(\left.\frac{\mathrm{d}F}{\mathrm{d}r_0}\right|_{200\ \mu\mathrm{m}} \times 200\ \mu\mathrm{m} \right) \tag{6}$$

To calculate the sea spray generation at 200 μm, we chose the results of Wan *et al.* [20], who used the windsea Reynolds number to determine the production ratio of spume droplets in the radius range from 10 μm to 200 μm:

$$\frac{\mathrm{d}F}{\mathrm{d}r_0} = \begin{cases} 1.43\cdot 10^{-3} R_B^{1.5} r_0^{-0.5} & 10 \le r_0 \le 30\ \mu\mathrm{m} \\ 7.84\cdot 10^{-3} R_B^{1.5} r_0^{-1} & 30 \le r_0 \le 75\ \mu\mathrm{m} \\ 4.41\cdot 10^{1} R_B^{1.5} r_0^{-3} & 75 \le r_0 \le 200\ \mu\mathrm{m} \\ 1.41\cdot 10^{13} R_B^{1.5} r_0^{-8} & 200 \le r_0 \le 500\ \mu\mathrm{m} \end{cases} \tag{7}$$

Therefore, the cases presented here allow preliminary examination of the effects of large spume droplets (200 μm) on surface wind speeds.

Results and discussions

Figure 2 presents the differences of 10m-mean wind speed caused by spray droplets. When the particles are introduced at 200 seconds, they begin obtaining the momentum from the wind and slow it down. Clearly, the simulated spray particles reduce the 10m-mean surface wind by an average of about 5%.

Figure 3 shows the current number of parcels and each parcel contains many particles. It is obvious that, at a given wind speed, the loss of spray particles-predominantly to the sea surface by turbulent deposition and gravitational sedimentation-will be balanced by an equivalent production of new particles.

Figure 4 displays the particle age in the domain. As the radius of particles become larger, the effect of gravity and fluid viscous drag will be greater when they enter the fluid. Meanwhile, the particle drag force rises with the increase of wind speed. Therefore, the suspension period of particles with same radius will last longer at higher wind speed, but the difference decreases as the particle radius increases.

The particle enters the computational domain at a certain initial velocity, and then influenced by the velocity of the surrounding fluid, which cause it to accelerate to the local wind speed rapidly. Figure 5 shows that the phase when the particle accelerates to the local wind speed is very short. The smaller particle radius is, the shorter momentum relaxation time will be, and as the wind speed becomes larger, the particle momentum relaxation time gets shorter.

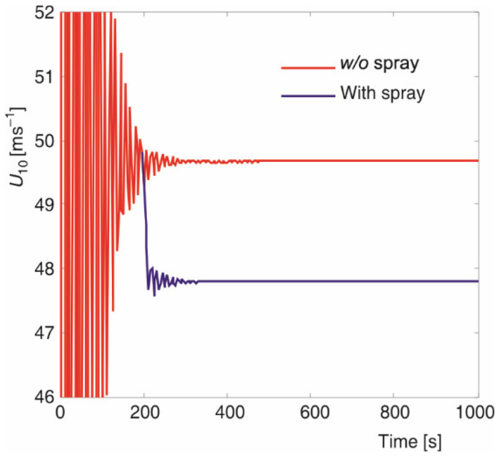

Figure 2. Mean wind speed at z = 10 m

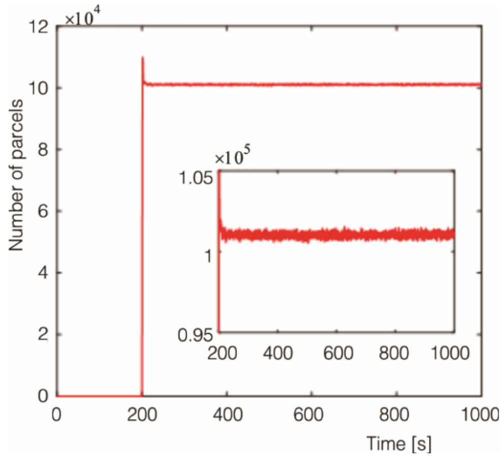

Figure 3. Current number of parcels

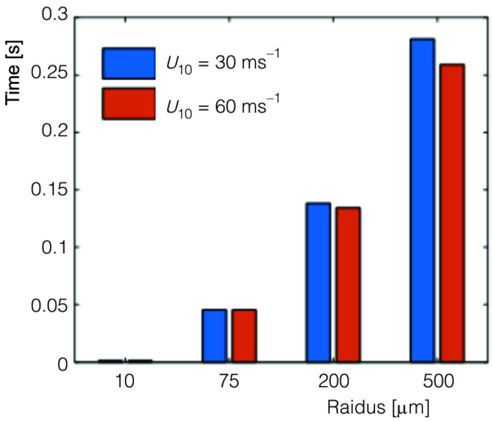

Figure 4. Particle momentum relaxation time in different radii and different wind speeds

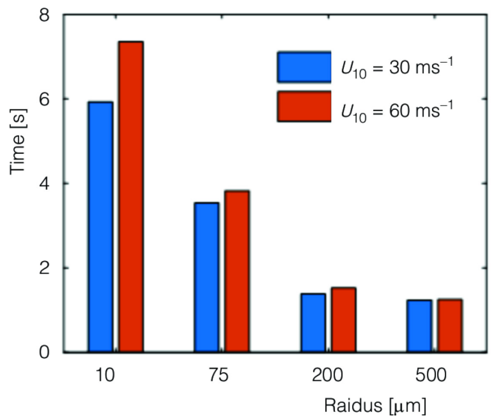

Figure 5. Particle suspension time in different radii and different wind speeds

Figure 6 shows that the velocity of the particle is related to its height. Meanwhile, the comparison of the three different speeds also demonstrates that the fluid is affected by not only turbulent dissipation but also particle drag, which means in the particle suspension layer. There is a great difference between the initial wind speed and the actual wind speed.

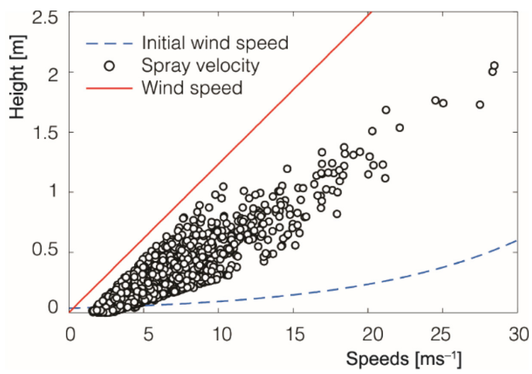

Figure 6. Spray velocity and the profiles of wind speed in height direction

Conclusion

In this study, an Euler-Lagrange model is used to perform the interactions between the particle and the fluid to represent the motion of spray in the air in which particle-particle interactions are neglected. Once created, spray droplets accelerated almost immediately to the local wind speed. This process extracts momentum from the wind and therefore slows the wind near the surface. However, these droplets are massive and eventually fall back into the sea, balancing the production of new particles. Besides, the particle age and momentum relaxation time are related to its radius and wind speed. As the wind speed increases, they tend to arrive to the wind speed more quickly and stay longer in the flow. The velocity of the particle is related to its position over the surface and its distribution is just the same as the wind speed.

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Nomenclature

C_{Dp} – drag coefficient (= 24/Re_p), [–]
F_D – viscous drag [= $6\pi r\mu(u - v)$], [N]
dF/dr_0 – sea spray generation function, [$m^{-2}s^{-1}\mu m^{-1}$]
g – gravity acceleration, [ms^{-2}]
r_0/r – spray radius, [μm]
R_B – windsea Reynolds number, [–]
Re_p – particle Reynolds number (= $2r|u - v|/\nu$), [–]
t – time, [s]
u – flow velocity, [ms^{-1}]
U_{10} – 10-m wind speed, [ms^{-1}]
v – droplet velocity, [ms^{-1}]

Greek symbols

Φ_p – volume fraction of particles,[–]
ρ – flow density, [kgm^{-3}]
ρ_f – fluid density, [kgm^{-3}]
ρ_p – spray droplet density, [kgm^{-3}]
μ – viscosity, [m^2s^{-1}]
ν – kinematic viscosity, [m^2s^1]

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