The study of the effects of sea-spray drops on the marine atmospheric boundary layer by direct numerical simulation

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Abstract. The detailed knowledge of turbulent exchange processes occurring in the atmospheric marine boundary layer are of primary importance for their correct parameterization in large-scale prognostic models. These processes are complicated, especially at sufficiently strong wind forcing conditions, by the presence of sea-spray drops which are torn off the crests of sufficiently steep surface waves by the wind gusts. Natural observations indicate that mass fraction of sea-spray drops increases with wind speed and their impact on the dynamics of the air in the vicinity of the sea surface can become quite significant. Field experiments, however, are limited by insufficient accuracy of the acquired data and are in general costly and difficult. Laboratory modeling presents another route to investigate the spray-mediated exchange processes in much more detail as compared to the natural experiments. However, laboratory measurements, contact as well as Particle Image Velocimetry (PIV) methods, also suffer from inability to resolve the dynamics of the near-surface air-flow, especially in the surface wave troughs. In this report, we present a first attempt to use Direct Numerical Simulation (DNS) as tool for investigation of the drop-mediated momentum, heat and moisture transfer in a turbulent, droplet-laden air flow over a wavy water surface. DNS is capable of resolving the details of the transfer processes and do not involve any closure assumptions typical of Large-Eddy and Reynolds Averaged Navier-Stokes (LES and RANS) simulations. Thus DNS provides a basis for improving parameterizations in LES and RANS closure models and further development of large-scale prognostic models. In particular, we discuss numerical results showing the details of the modification of the air flow velocity, temperature and relative humidity fields by multidisperse, evaporating drops. We use Eulerian-Lagrangian approach where the equations for the air-flow fields are solved in an Eulerian frame whereas the drops dynamics equations are solved in a Lagrangian frame. The effects of air flow and drops on the water surface wave are neglected. A point-force approximation is employed to model the feed-back contributions by the drops to the air momentum, heat and moisture transfer.

1. Introduction
Detailed knowledge of the interaction of turbulent wind with surface water waves is necessary for correct parameterization of turbulent exchange at the air-sea interface in prognostic
models. At sufficiently strong winds, sea-spray droplets interfere with the wind-wave interaction. The results of field experiments and laboratory measurements show that mass fraction of air-borne spume water droplets increases with the wind speed and their impact on the carrier air-flow may become significant [1].

Until recently, two approaches were mainly employed in numerical modeling of spray-mediated turbulent transfer in marine atmospheric boundary layer. The first approach relies on phenomenological modeling in the framework of RANS equations. This approach considers Reynolds-averaged equations for the air flow where the effects of spray drops are modeled by introducing source terms accounting for mass, momentum, and heat exchange between the air and drops [2-4]. To a large extent, the predictions of this approach depend on the assumptions made about the details of the interaction between drops and the carrier air flow.

The dynamics of droplets in marine atmospheric boundary layer was also extensively studied with the use of Largangian stochastic approach [5-7]. In these models, the droplet equation of motion is solved numerically in a Lagrangian framework. The surrounding, mean air-flow component is prescribed as a logarithmic boundary-layer approximation whereas the stochastic component is obtained as a numerical solution to a Langevin equation with random forcing that mimics turbulent fluctuations in the air-flow “seen” by the drop. Largangian stochastic models provide very important information on droplets dynamics and estimates of droplet-mediated exchange in the marine atmospheric boundary layer. However, it is recognized that these models are unable to reproduce the two-way interaction between the droplets and turbulent boundary-layer eddy structures [6].

A first attempt to perform DNS of a droplet-laden air-flow over waved water surface was performed only recently [8]. In that study, a turbulent Couette air-flow over waved water boundary was considered as a model of marine atmospheric boundary layer. However, only the momentum exchange between the drops and the carrier air-flow was considered whereas the effects of drops on the humidity and temperature of the carrier air were not taken into account.

In the present paper, we present results of DNS of droplet-laden, two-way-coupled, turbulent Couette air-flow over waved water surface and, in particular, take into account effects of air-water latent heat exchange related to droplets evaporation, and droplet-mediated sensible heat exchange which generally occurs in case of a finite temperature difference between air and water. To our knowledge, this is the first DNS study of such flow. The carrier, turbulent Couette-flow configuration in DNS is similar to that used in previous numerical studies (cf. [10] and references therein). Discrete spherical droplets are tracked in a Lagrangian framework, and their impact on the carrier flow is modeled with the use of a point-force approximation. The droplets parameters in DNS are matched to the typical known spume-droplets parameters in laboratory and field experiments. Section 2 below presents the governing equations and numerical method. Numerical results are discussed in Section 3, and final conclusions and discussion are provided in Section 4.

2. Numerical method
We perform direct numerical simulation of turbulent, droplet-laden Couette flow above waved water surface. The schematic of the numerical experiment is similar to that used in our previous DNS study of turbulent, droplet-laden air-flow over waved surface [8] (Fig. 1). A Cartesian framework is considered where x-axis is oriented along the mean wind, z-axis is directed vertically upwards and y-axis is orthogonal to the mean flow and parallel to the wave front. We prescribe two-dimensional, x-periodic water wave with amplitude $a$, wavelength $\lambda$.
and phase velocity \( c \). The maximum wave slope considered in our DNS is \( ka = 2\pi a / \lambda = 0.2 \).

The rectangular computational domain has sizes \( L_x = 6\lambda \), \( L_y = 4\lambda \) and \( L_z = \lambda \) in the \( x \)-, \( y \)-, and \( z \)-directions, respectively, and the air flow is assumed to be periodical in the \( x \)- and \( y \)-directions. DNS is performed in a reference frame moving with the wave phase velocity, \( c \), so that the horizontal coordinate in the moving framework is \( x' = x - ct \), where \( x' \) is the coordinate in the laboratory reference frame. Then the lower boundary, representing the wave surface, is stationary in the moving reference frame. The no-slip boundary condition is prescribed at the lower boundary, so that the wind velocity at the boundary coincides with the velocity in the water wave. The no-slip boundary condition is also prescribed at the upper horizontal plane moving in \( x \)-direction with bulk velocity \( U_0 \). This condition provides an external source of momentum due to the viscous shear stress, which compensates viscous dissipation in the boundary layer and makes the flow statistically stationary. Air and water surface temperatures (\( T \), measured in Kelvins, K) and fractional relative humidity (\( H \)) are prescribed at the top and bottom boundary planes, respectively, as \( T_w \) and \( H_w \) at \( z = 0 \) and \( T_a \) and \( H_a \) at \( z = L_z \); typically \( T_w > T_a \) and \( H_w > H_a \).

The numerical algorithm is based on the integration of full, 3D Navier-Stokes equations for the carrier air-flow velocity and equations for the air temperature and relative humidity coupled with the Lagrangian equations for each drop coordinate, velocity, temperature and mass. The equations for the air flow velocity, temperature and relative humidity are written under the Boussinesq approximation in the well-known form [9]:

**air-flow velocity:**

\[
\frac{\partial U_i}{\partial t} + \frac{\partial(U_i U_j)}{\partial x_j} = -\frac{1}{\rho_a} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} + \delta_{ik} g \frac{T}{T_a} + \sum_{n=1}^{N_t} f_{Ui}^n ,
\]

**continuity:**

Fig. 1. Schematic of numerical experiment: \( L_x, L_y, L_z \) are the domain sizes in the horizontal (\( x \)), spanwise (\( y \)), and vertical (\( z \)) directions; \( a \) and \( \lambda \) are the surface water wave amplitude and length; \( T_w, H_w \) and \( T_a, H_a \) are the temperature and fractional relative humidity at the water surface and at the top (air) boundary, respectively; \( U_0 \) the bulk velocity of the air-flow, and \( g \) is the acceleration due to gravity. Drops are denoted by black dots.
\[
\frac{\partial U_j}{\partial x_j} = 0, \quad (2)
\]

air temperature:
\[
\frac{\partial T}{\partial t} + \frac{\partial (TU_j)}{\partial x_j} + \frac{\partial (T_{\text{ref}} U_j)}{\partial x_j} = \kappa \frac{\partial^2 T}{\partial x_j^2} + \sum_{n=1}^{N_d} f^n_T, \quad (3)
\]

relative humidity:
\[
\frac{\partial H}{\partial t} + \frac{\partial (HU_j)}{\partial x_j} + \frac{\partial (H_{\text{ref}} U_j)}{\partial x_j} = D \frac{\partial^2 H}{\partial x_j^2} + \sum_{n=1}^{N_d} f^n_H, \quad (4)
\]

where \( x_i = x, y, z \), \( U_j(i = x, y, z) \) are the velocity components, \( P \) is pressure, \( \rho_a \) the air density at temperature \( T_a \) and pressure \( P_a \); \( T \) and \( H \) are instantaneous deviations of the air temperature and fractional relative humidity from their respective initial, reference profiles, \( T_{\text{ref}}(z) \) and \( H_{\text{ref}}(z) \); \( \nu \) and \( \kappa \) are the air kinematic viscosity and thermal diffusivity; and \( D \) is the diffusivity of water vapor. We consider linear reference profiles of air temperature and relative humidity in the form:

\[
T_{\text{ref}}(z) = T_w + (T_a - T_w) \frac{z}{\lambda}, \quad (5)
\]

\[
H_{\text{ref}}(z) = H_w + (H_a - H_w) \frac{z}{\lambda} \quad (6)
\]

The last terms on the right hand side of Eqs. (1), (3) and (4), \( f^n_T \), \( f^n_H \), and \( f^n_H \), are feedback contributions (to be defined below) of \( n \)-th droplet \((n = 1, \ldots, N_d)\) to the rate of change of air momentum, temperature, and humidity; \( N_d \) is the total, constant number of droplets considered in DNS.

Discrete spherical drops of diameter \( d_n \) and temperature \( T_n \) are tracked in a Lagrangian framework. Thus, for each \( n \)-th droplet we solve the equation for the coordinate and velocity, \( r^n \) and \( V^n \), and also take into account droplet evaporation/condensation and heat exchange with the surrounding air. Thus the following equations are solved simultaneously with Eqs. (1)-(4) for each \((n\)-th\) drop [2]:

drop coordinate:
\[
\frac{dr^n}{dt} = V^n, \quad (7)
\]

drop velocity:
\[
\frac{dV^n}{dt} = \frac{1}{\tau_n} \left( U_i(r^n) - V^n \right) \left( 1 + 0.15 \text{Re}_d^{0.687} \right) - \delta \gamma g, \quad (8)
\]

drop temperature:
\[
\frac{dT^n}{dt} = 2\pi \kappa d_n \left( T_a(r^n) - T_n \right) \left( 1 + 0.25 \text{Re}_n^{0.25} \right) + L_n \frac{dm_n}{dt}, \quad (9)
\]

drop mass \((m_n = \rho_n \pi d_n^3 / 6)\):
\[
\frac{dm_n}{dt} = 2\pi \gamma d_n \rho_n \left( H(r^n) - H_n \right) \left( 1 + 0.25 \text{Re}_n^{0.25} \right). \quad (10)
\]
In Eqs. (7) - (10), \( r^n_i = x^n_i, y^n_i, z^n_i \) are Cartesian drop coordinates, and derivative over time \( (d/dt) \) is taken along the droplet trajectory.

In Eq. (8), \( U_n(r^n) \) is the instantaneous air-flow velocity at the location of \( n \)-th drop, \( g \) is the gravitational acceleration, and \( \tau^n \) is the drop response time,

\[
\tau^n = \frac{d^2_n \rho_n}{18 \nu \rho_a},
\]

(11)

where \( \rho_a \) is the salt solution density of the \( n \)-th drop. The correction of the viscous drag force on the drop by the surrounding air in Eq. (8) is introduced taking into account that particle Reynolds number, defined as [10]

\[
Re_n = \frac{|U(r^n) - V^n| d^n}{\nu},
\]

(12)

is finite.

Equation (9) describes the rate of change of the drop temperature, \( T_n \) (assumed to be uniform throughout the drop volume), due to the heat flux from/to the surrounding air and latent heat flux due to drop evaporation/condensation. The former flux is proportional to the instantaneous difference of the air temperature at the drop location, \( [T_a(r^n) = T(r^n) + T_{ref}(z_n)] \), and \( T_n \), and thermal conductivity coefficient, \( \kappa' \) [not to be confused with the thermal diffusivity coefficient \( \kappa \) in the right hand side of Eq. (3)], modified by noncontinuum gas-kinetic effects [11,12]. When computing the heat flux we also take into account ventilation effects due to finite Reynolds number, \( Re_n \), of the drop. The latent heat flux is proportional to the rate of change of drop mass and factor \( L_v \) is the latent heat of vaporization [11].

Equation (10) describes the rate of change of the drop mass. The right hand side of Eq.(10) includes the modified diffusivity of water vapor, \( D' \), the saturated vapor density, \( \rho_{sat}' \), and the difference between the surrounding relative humidity and relative humidity at the surface of the drop, \( Q_m \) (cf. [11,12] for details).

The integration of Eqs. (1) - (4) is performed in curvilinear coordinates \((\xi,y,\eta)\) which transform the lower wavy boundary, \( z_s(x) = a \cos k \xi(x) \), into a plane boundary at \( \eta = 0 \) [8]. The instantaneous air-flow velocity, temperature and relative humidity at the location of \( n \)-th droplet, \( U_s(r^n), T_s(r^n) \) and \( H(r^n) \), are evaluated by interpolation after mapping, Eqs. (17) and (18), the droplet Cartesian coordinates onto curvilinear coordinates.

Equations (1)-(4) are discretized in a rectangular domain with sizes \( 0 < x < 6 \lambda, 0 < y < 4 \lambda, \) and \( 0 < z < \lambda \) by employing a finite difference Adams-Bashforth method [13] of the second-order accuracy on a uniform staggered grid consisting of \( 360 \times 240 \times 180 \) nodes. An additional mapping is employed to compress the grid in the vertical direction near the boundaries in order to resolve the viscous boundary layer [8].

The air-flow bulk Reynolds number in DNS is defined as:

\[
Re = \frac{U_\lambda}{\nu},
\]

(13)

and set equal to \( Re = 15000 \). Two different wave-slopes, \( ka = 0.1 \) and \( ka = 0.2 \), are considered. We also prescribe the wave celerity to be sufficiently small, \( c/U_0 = 0.05 \), which
 corresponds to “slow” waves and strong wind-forcing conditions [8]. When prescribing the air temperature and fractional relative humidity at the waved surface and upper boundary we consider a situation typical of a tropical cyclone, and take \( T_a = 27 + T_k \) (K) and \( T_w = 28 + T_k \) (K) (where \( T_k = 273.15 \) K), and \( H_w = 0.98 \) and \( H_a = 0.8 \) [14,15]. Under these conditions, the effect of unstable temperature stratification on the air dynamics can be considered as negligible. Nevertheless, we take into account the buoyancy forces in the air momentum equation and prescribe a dimensionless gravity acceleration [analogous to the Earth’s gravitational acceleration] to be equal to 0.01.

At the lower-plane boundary (\( \eta = 0 \)) the no-slip (Dirichlet) condition for the air velocity, temperature, and relative humidity is prescribed. The air-flow velocity here coincides with the velocity of the water in the surface wave. At the upper boundary (\( \eta/\lambda = 1 \)) the no-slip condition for the wind velocity is prescribed with respect to the plane moving with non-dimensional velocity (1-\( c \)). The deviations of the air temperature and relative humidity form respective reference profiles \( T_{ref}(z) \) and \( H_{ref}(z) \), Eqs. (5) and (6), are put to zero at both the waved surface and the upper boundary. Periodical boundary conditions are prescribed for all fields at the side boundaries of the computational domain, namely, at \( \zeta/\lambda = 0, 6 \) and \( y/\lambda = 0, 4 \).

Equations (7)-(10), are integrated in the Cartesian framework with the use of the second-order Adams method for the coordinate, Eq. (3), and Adams-Bashforth method for the velocity, Eq. (4). The inverse transform from the Cartesian to curvilinear droplets coordinates is preformed by an iterative Newton’s method [8].

The feed-back contributions of each drop to the rate of change of air flow momentum, temperature and moisture, \( f_{\bar{u}}^{n} \) , \( f_{\bar{T}}^{n} \), and \( f_{\bar{H}}^{n} \), in Eqs. (1), (3) and (4) are modelled with the use of a point-force approximation. Thus the contributions by \( n \)-th droplet are evaluated by distributing them to the nearest eight grid nodes surrounding the droplet in the form [8]:

\[
\begin{align*}
  f_{\bar{u}}^{n} &= \frac{\pi d_n^3}{6} \frac{\rho_a}{\rho_n} \frac{1}{\tau_n} \left( V_{\bar{u}}^{n} - U_{\bar{u}}(r^n) \right) \left( 1 + 0.15 \text{Re}_n^{0.67} \right) \frac{w(r^n, r)}{\Omega_g}, \\
  f_{\bar{T}}^{n} &= 2\pi \kappa d_n \left( T_{\bar{T}}^{n} - T_{\bar{T}}(r^n) \right) \left( 1 + 0.25 \text{Re}_n^{0.25} \right) \frac{1}{\rho_a c_a} \frac{w(r^n, r)}{\Omega_g}, \\
  f_{\bar{H}}^{n} &= \frac{1}{\rho_n \kappa u_n} \frac{dm_n}{dt} \frac{w(r^n, r)}{\Omega_g},
\end{align*}
\]

where \( w(r^n, r) \) is a geometrical weighting factor inversely proportional to the distance between \( n \)-th droplet located at \( r^n = (x^n, y^n, z^n) \) and the grid node located at \( r = (x, y, z) \), and \( \Omega_g \) (\( r \)) is the volume of the considered grid cell. Thus for each individual droplet, eight weighting factors are defined (for each of the surrounding grid nodes) and normalized so that the sum of the partial feedback contributions by the drop distributed to these nodes exactly equals the respective total feedback contribution. Therefore, there is no numerically-induced loss or gain of momentum, heat and moisture in the drops-air exchange processes.

We consider diameters of initially injected drops uniformly distributed in the range \( 100 \leq d \leq 300 \mu m \). As is known from observations [1], for drop with diameter \( d \approx 200 \mu m \), the ratio of drop terminal settling velocity, \( V_g = \tau_n g \), to the product \( \kappa u_n \) (where \( \kappa = 0.4 \) is the Karman constant) is of the order of unity. This ratio (\( V_g / \kappa u_n \))
indicates whether gravitational settling of the droplets is important as compared to the advection by turbulent eddies in the boundary layer [1]. In present DNS, ratio \( V_g/\kappa u_* \approx 1 \) for drop with diameter \( d_n = 200 \, \mu m \) and response time, Eq. (11), \( \tau_g \tilde{\lambda}/U_0 = 0.5 \). In order to investigate the impact of the drop mass fraction \( C_m \) and surface wave slope \( (ka) \) we also consider different cases of \( ka \) and \( C_m \).

![Diagram of trajectories](image)

Fig. 2. The side view of the trajectories of drops injected with different diameters at injection, \( d_0 \): (a) \( d_0 = 100 \, \mu m \, V_g/(u_* \kappa) = 0.25 \); (b) \( d_0 = 200 \, \mu m \, V_g/(u_* \kappa) = 1 \). The trajectories are sampled at discrete time moments with increment \( \Delta t = 0.2 \lambda /U_0 \) in DNS with wave slope \( ka = 0.2 \). The trajectories obtained during the total simulation time \( (100 \leq t U_0 / \lambda \leq 300) \) are shown in grey color, whereas black color shows trajectories of drops from the moment of injection to the moment of their fall into the water.

3. Numerical results

Figure 2 presents a side view of the trajectories of drops with different diameters at injection obtained in DNS with wave slope \( ka = 0.2 \). [The trajectories obtained during the total simulation time \( (100 \leq t U_0 / \lambda \leq 300) \) are shown in grey color.] The figure shows that a relatively small drop [case (a), \( d_0 = 100 \, \mu m \, V_g/(u_* \kappa) = 0.25 \)], once injected, travels throughout the domain over many wavelengths without falling back into the water. Motion of larger drops [cases (b) \( d_0 = 200 \, \mu m \, V_g/(u_* \kappa) = 1 \)] is mostly confined to a near-water-surface layer at \( z/\lambda < 0.1 \). In this case, drop injected above the upwind side of the surface wave typically travel about one wavelength in the streamwise direction and falls back onto the water surface, either at the lee-side of the wave crest or in the vicinity of the wave trough.

Figures 3 and 4 show instantaneous heights of the drops above the water surface \( \eta_d = z_d - z_s(x_d) \) (a); drops diameters normalized by the diameter at injection \( (d/d_0) \) (b); the difference of the drops temperatures and the surrounding air temperature \( (T_d - T_a) \) (normalized by the water-air temperature difference, \( \Delta T \) ) (c); and the fluxes of momentum \( (J_x^d) \) (d), and sensible \( (Q_s^d) \) and latent \( (Q_L^d) \) heat (e) and the resulting enthalpy flux
\((Q_S^d + Q_L^d)\) from the drops to the surrounding air (normalized by the air heat capacity, density, and air-water temperature difference, \(\Delta T\)) (f). In terms of these fluxes, equations (8) and (9) describing the dynamics of the \(x\)-component of drop momentum and the drop temperature can be rewritten in the equivalent form:

\[
\begin{align*}
\frac{m_d}{\rho_d} \frac{dV_x^d}{dt} &= -f_x^d, \\
\frac{m_d c_w}{\rho_d} \frac{dT_d}{dt} &= -Q_S^d - Q_L^d.
\end{align*}
\]
where

\[ f_x^d = 3\pi d \nu \left( V_x^d - U_x (r^d) \right) \left( 1 + 0.15 \, \text{Re}_d^{0.687} \right) \],
\[ Q_S^d = 2\pi \kappa' d \left( T_d - T_a (r^d) \right) \left( 1 + 0.25 \, \text{Re}_d^{0.25} \right) \],
\[ Q_L^d = -L_v \frac{dm_d}{dt} \],

where drop mass \( m_d = \rho_d \pi d^3 / 6 \), and \( r^d \) and \( \text{Re}_d \) are the drop coordinate and Reynolds number. Other notations are the same as in Eqs. (8), (9). Similarly to the definitions of net fluxes in Eqs. (14) - (16), the signs of the \( f_x^d \), \( Q_S^d \) and \( Q_L^d \) in Eqs. (19) - (21) are such that the fluxes are from the drop to the surrounding air.
Fig. 5. Mean vertical profiles of drops concentration, $C$, (a), momentum flux, $f_x$, (c), and sensible and latent heat fluxes, $Q_{SL}$, (e), and distributions of $C$, $f_x$ and $Q_{SL}$ over drop diameter (b,d, and e, respectively).

Figures 3b shows that diameter of a drop with $d_0 = 100 \mu m$ monotonically decreases due to evaporation, especially at times $U \theta (t - t_{inj}) / \bar{\lambda} > 1$ when the drop leaves the relatively moist near-surface layer ($\eta_d / \bar{\lambda} < 0.1$, Fig. 3a) and travels far above the water surface where the air is more dry. The drop temperature is slightly above the water surface temperature at times $U \theta (t - t_{inj}) / \bar{\lambda} < 0.01$ and decreases until time $U \theta (t - t_{inj}) / \bar{\lambda} = 0.2$ due to the sink of heat due to evaporation, and remains approximately constant at times $0.2 \leq U \theta (t - t_{inj}) / \bar{\lambda} \approx 2$ (Fig. 3c). During this time interval, the drop resides near the water surface ($\eta_d / \bar{\lambda} < 0.1$, Fig. 3a) and is in a state of “wet bulb”, i.e. the latent heat flux, $Q_L^d$, “consumed” by the drop evaporation, is almost exactly compensated by the diffusive heat flux from the surrounding air, $Q_S^d$ (Figs. 3d-
Fig. 6. Mean profiles of air velocity, temperature, and relative humidity for wave slope $ka = 0.1$ (a,c,e) and $ka = 0.2$ (b,d,f).

f) [14] and as a result their sum, which also equals the enthalpy flux from drop to air, vanishes:

$$Q_S^d + Q_L^d \approx 0.$$  \hspace{1cm} (22)

As is also illustrated in Figs. 3d, the drop takes away momentum from the surrounding air (since being “torn off” from the water surface it is accelerated by the wind) at times $U_0(t - t_{inj})/\lambda < 0.4$. At later times, the exchange of momentum between the drop and air is relatively weak (near zero).

The dynamics of drop with $d_0 = 200 \mu m$ (Fig. 4) is qualitatively similar to that of drop with $d_0 = 100 \mu m$. However, in this case, the “wet bulb” state is not reached since the drops relatively quickly falls back to the water surface. The drop cools below the surrounding air temperature at time $U_0(t - t_{inj})/\lambda \approx 0.1$, i.e. by the order of magnitude longer as compared to
drop with $d_0 = 100 \mu m$ (cf. Figs. 3c and 4c). Figure 4b also shows that the rate of change of drop diameter due to evaporation is much smaller as compared to case $d_0 = 100 \mu m$.

Figure 5 presents mean vertical profiles of drops concentration, and momentum and sensible and latent heat fluxes (a, c, d) and distribution of average drops heights, and momentum and heat fluxes over drops diameter obtained in DNS for different wave slope ($ka = 0.1$ and $0.2$). Figure 6 illustrates modifications of the air mean velocity, temperature, and humidity profiles by the drops, as compared to unladen flow.

Figures 5a and 5b show that drops concentration peaks at $\eta/\lambda \approx 0.01$, mostly due to drops with diameters about $300 \mu m$. Momentum and sensible heat fluxes are negative, i.e. drops impose additional drag on the air and reduce wind velocity and also reduce the air temperature (Figs. 5b, d and 6a-d). On the other hand, drops provide positive latent heat flux (i.e., water vapor) to the air and increase relative humidity (Figs. 5e and 6e, f). As seen from Figures 5d, f, the drop contribution to momentum and sensible and latent heat fluxes with diameter.

4. Conclusions
We have performed direct numerical simulation (DNS) of turbulent atmospheric boundary layer over waved water surface and investigated the possible impact of sea spume drops on the momentum and sensible and latent heat exchange processes that are known to be of primary importance for parameterizations in large-scale prognostic models. DNS reveals many important details of both individual drops dynamics and the feedback effects by drops on the air flow. The results show that drops impose additional drag on the air, reduce air temperature and increase the relative humidity. The resulting enthalpy flux is found to be positive due to dominant contribution of latent heat (i.e. water vapor) by large drops.

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