Spray microphysics and effects on surface fluxes as seen from simulations using a Lagrangian model with spectral bin microphysics

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1. Introduction

Effects of spray on atmosphere-ocean interaction in regions of strong wind (hurricanes) attracts increased attention during past decade after results showing that wind speed near surface exceeds the value predicted by the classical theory of the BL (Powell et al 2003). In sets of studies this result was attributed to decrease in drag coefficient (or turbulence intensity) in the surface layer caused by spay. In set of studies using 1_D models of the surface layer it was shown that due to decreasing of spray loading with height, stability of the surface layer increases which can be expressed in terms of decrease in turbulent viscosity and drag coefficient (Kepert et al 2004, Fairall et al, 2009).

Spray formation dramatically exceeds the evaporating water surface which is believed should increase evaporation and to lead to cooling of the surface layer affecting heat and moisture fluxes from sea to the atmosphere.

There are two main types of models considering the vertical spray dispersion in the surface layer. In the first type of models trajectories of spray drops are simulated using Langivin equation which mimic turbulent diffusion of spray in the lowest few meters.

The models belonging to the second type are 1-D models of the boundary layer (better to say, the surface layer), according to which stationary vertical distribution of spray mass content is derived from a balance between turbulent diffusion spray directed upward and gravitational spray sedimentation. As a result of such approach the spray mass, especially related to the largest drops, rapidly decreases with height. Turbulent viscosity coefficient is calculated using 1.5 closure approach (k-theory) by solving the equation for turbulent kinetic energy. Being local, this theory describes effects of only smallest turbulent vortices on spray transport.

Note that in all types of models advection of spray by non-turbulent or largest turbulent vortices (large eddies) with scales of hundred meters was not taken into account. At the same time vertical velocities related to such vortices can reach 1-2 m/s. The effect of advective transport of spray may be quite important on vertical distribution of spray. Note that spray reaching penetrating clouds can efficiently affect microphysics and precipitation formation in clouds. Accordingly, it is quite important to describe adequately vertical distribution of spay mass as well as the size distribution of spray droplets at different levels, including those close to cloud base.

Second specific feature of the existing spray models is utilization of quite simplified microphysics (if any). At the same time processes of spray evaporation/condensation and well as collisions between droplets may be extremely important to determine humidity and temperature changes in the BL.

We present here the first results of the study the general purposes of which are:

1) To evaluate vertical distribution of spray mass, concentration taking into account spray advection by vortices in the BL with scales up to several hundred meters;

2) To calculate rates of temperature and humidity changes caused by evaporation/condensation, collision of spray.

3) To evaluate the changes in surface heat and moisture fluxes caused by these changes in temperature and humidity

4) To evaluate the comparative role of different microphysical processes on formation of size distributions of spray in the BL.

The study will be performed using the Lagrangian model of the boundary layer in which 1500 adjacent and interacting parcels move within a turbulent like flow (Khain et al 2008; Pinsky et al 2008; Magaritz et al 2009). This model was used for simulation of simulation of microphysical and thermodynamical structure of the cloud-topped BL, for simulation of droplet size distribution (DSD) and drizzle formation in stratiform clouds. Specific feature of the model is accurate representation of all warm rain microphysical processes and is an ideal tool for purposes if this study.

2. Description of the model

2.1 General features

The model is described in detail by Pinsky et al (2009) and Magaritz et al (2009). Here we present a brief model description. New improvements related to turbulent mixing between parcels, calculation of surface fluxes and as well as to spray formation are described in more detail. The spay evolution is calculated within the computational area of 300 m in horizontal and 400 m in vertical. The computational area is covered by 1500 adjacent Lagrangian parcels with characteristic linear size of ~8 m, which are advected in a turbulent like velocity field generated by a turbulent flow model. The velocity field is represented as a sum of a large number of harmonics with random amplitudes depending on time. Harmonics of the largest scales represent large eddies, which usually exist both in cloudy and cloud-free BL (e.g., LeMone, 1973; Ivanov and Khain, 1975, 1976; Stevens et al., 1999). The existence of such vortices (rolls) are typical of zone of strong wind in hurricanes (Ginis et al 2004). The velocity field obeys turbulent laws and the model parameters are calculated to agree with the correlation properties of the measured velocity field. At t = 0 min the Lagrangian air parcels, having the linear scale of about 8 m, are assumed equal and are distributed uniformly over the entire area. The parcels transport potential temperature and mixing ratio as well as aerosol/droplet size distributions. As a result of microphysical processes within the parcels and parcel motion, the vertical profiles of temperature and mixing ratio, DSD and AP size distribution change in each parcel. Corresponding changes in the BL are calculated by averaging over the parcels.

The microphysics of a single Lagrangian parcel includes the diffusion growth/evaporation equation used for wetted aerosols and water droplets, the equation for supersaturation and the stochastic collision equation describing collisions between droplets (Pinsky and Khain, 2002; Pinsky et al., 2008). The size distribution of cloud particles (both non-activated nuclei and droplets) is calculated on a single mass grid containing 500 bins within the 0.01 μm to 1000 μm radius range. The mass of each bin changes with time in each parcel according to the equation for diffusion growth. A small 0.01s time step is used to simulate adequately the growth of the smallest AP, so that the separation between non-activated nuclei attaining equilibrium (haze particles) and the growing droplets is simulated explicitly, without any parameterization. The collision droplet growth is calculated using a collision efficiency table with a high 1 μm resolution in droplet radii (Pinsky et al., 2001). Particle collisions are calculated with one second time interval.

The AP budget is calculated in the model. AP can exist in two "states" in the model: a) non-activated wet AP (haze particles) and b) AP dissolved within droplets. The mass of AP (the mass of salt) in droplets does not change during the condensation/evaporation process, unlike in the case of collision/coalescence where the dissolved AP mass in the drop-collectors increases. Total droplet evaporation leads to the formation of wet AP. Specific feature of spray particles is their high salinity. High salinity dramatically affects particle behavior. For instance salty particles may grow under undersaturation conditions. Specific features of spray microphysics are described below. Through drop collisions AP size distribution changes during the parcel recirculation within the BL. At t=0 min the BL is cloud free and all the parcels contain only non-activated AP. In ascending parcels crossing the lifting condensation level a fraction of the aerosols activate and droplets are formed. Non-activated aerosols and droplets can exist simultaneously in a single parcel. During the parcel's motion supersaturation can increase which can lead to the nucleation of new droplets and the formation of bimodal and multimodal DSD. If the supersaturation in the parcel is replaced by subsaturation droplets may evaporate partially or totally. In the latter case the cloud parcel can again contain only non-activated aerosols. In this way, microphysical processes in the cloud affect the aerosol size distribution as well as the DSD.

In the model the process of droplet settling is also taken into account. The algorithm for settling represents an extension of the widely used flux method (e.g. Bryan, 1966; Bott, 1989) to describe the advection and sedimentation in Eulerian models with irregular finite difference grids to the irregular grid formed by the centers of the parcels. In this sense, the model can be referred to as the hybrid Lagrangian-Eulerian model.

The effects of the microphysics on the dynamic (turbulent) structure are not taken into account explicitly. Instead, we generate a turbulent-like structure that corresponds to the dynamic structure typical of in the cloud-topped BL under strong winds (CTBL). This structure in nature is formed under the combined effects of many factors; latent heat release, radiation, thermal instability, wind shear and surface heat and moisture fluxes. In assimilating real dynamics we implicitly take into account all of these factors. Simulation of turbulent-like flows corresponding to different thermodynamic situations in the CTBL makes it possible to investigate the effects of the BL dynamics and thermodynamics on aerosol properties and the microphysical structure of stratocumulus clouds.

Microphysical processes of cloud drops lead to changes in the aerosol mass within droplets. One of the model's specific features is a very accurate description of microphysical processes due to utilization of a movable mass grid containing many mass bins and very accurate calculations of collisions by solving the stochastic collision equation, small time steps, etc.

The model takes into account the turbulent mixing between Lagrangian parcels following to Pinsky et al (2010). The mixing represents an extension of the classical K-theory (1.5 order closure) to the case of mixing of non-conservative values such as size distributions. The rate of mixing depends on the distance between the parcel centers. The turbulent coefficient is calculated using the Richardson 4/3 law.

The model calculates heat and moisture surface fluxes using standard aerodynamical expressions. The surface wind is calculated as a vector sum of the prescribed wind speed of the background flow and the turbulent velocity calculated in the model. The sea-air temperature and humidity gradients are calculated as differences between corresponding values at the ocean surface and at the centers of the lowest parcels located adjacent to the surface.

2.2 Spray treatment and simulation design

The size distributions and amount of spray depends of wind speed. The size range of spray is wide: from 0.01 μm to ~500 μm. Typically, in spray models only large particles with diameters exceeding 10 μm are considered. This is because the main effect of spray considered in these models is the creation of vertical profile of loading which increases stability of the surface layer. Indeed, the contribution of largest spray to creation of such loading stratification is dominating. From microphysical point of view, however, the particles of smaller size can also be important, because they can ascend to high levels and create a large amount of giant CCN affecting cloud microphysics and rain formation. That is why we match the spray source of large and small particles using available literature. The source function for spray with radii larger than 10 μm

was taken from Fairall et al (2009). Spray source function was used during model integration to change the size distributions in parcels adjacent to the surface. The changes of the size distributions were performed according the vertical profile of the source.

Note that spray is the source of largest aerosols in maritime atmosphere. Background aerosol distributions exist in the maritime BL even at low winds. Accordingly, in this study the distribution measured over the ocean during DYCOMS –II field experiment was chosen as a background (initial) AP distribution (Magaritz et al 2009). Concentration of APs in the background AP distribution with dry radii below 1 μm is comparatively high (~200 cm^{-3}), so spray source increases largely the concentration of particles with radii larger than 1 μm (dry sizes).

The important specific feature of spray is high salinity. The initial salinity of all spray particles was assumed equal to that of sea water. Salinity of particles changes during diffusion growth/ evaporation and collisions in the course of model integration. Salinity affects the rate particle growth. The net heating /cooling or drying/moistening rates caused by spray depend of the air depend on environmental humidity, particle size and salinity. Since the size and salinity of particles, as well as environment humidity change during diffusional growth/ evaporation and collisions and air mixing, the general effect of spray can be investigated only using accurate microphysical effects.

In all simulations the background wind was set equal to 30 m/s. The maximum vertical velocity fluctuations $\langle W'^2 \rangle^{1/2}(z)$ was set equal to 0.8 m/s which is ~2 times larger than in the BL at 10 m/s background wind. In future studies the sensitivity of the results to the $\langle W'^2 \rangle^{1/2}(z)$ will be investigated.

Initial profiles of temperature and mixing ratio are taken the same as in Kepert et al (2004). Initial mixing ratio and potential temperatures near the surface are 17 g/kg and 299 K, respectively.

4. Preliminary results

Figure 1 shows fields of vertical velocity and liquid water content in the control experiment at t= 135 min.

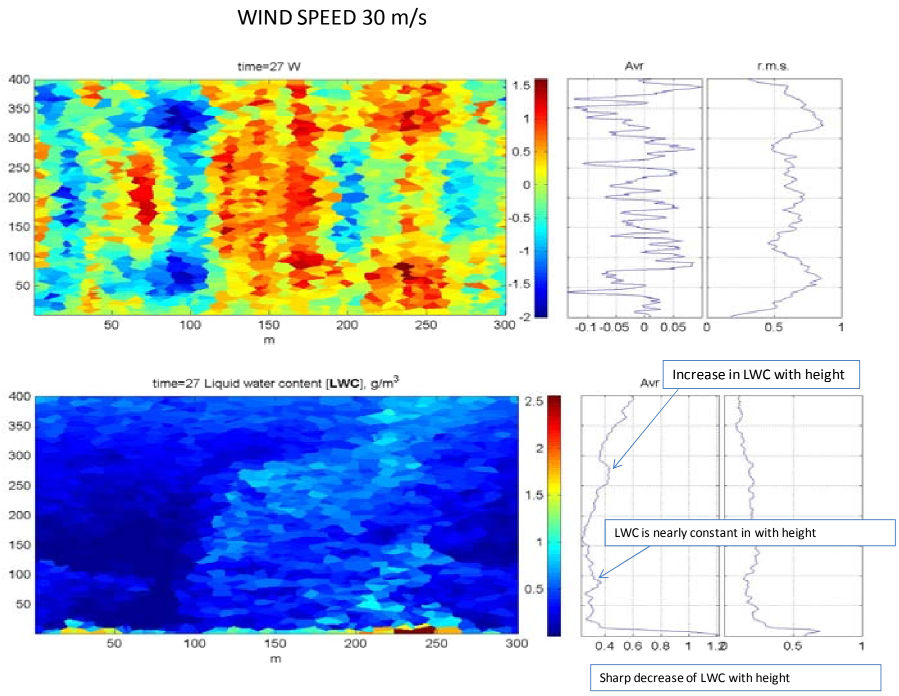

Figure 1. Fields of vertical velocity and liquid water content in the control experiment at t= 135 min.

One can see that updraft velocities in large eddies reach ~1.5 m/s. In zone of updraft there is enhanced liquid water content (total spray mass). Horizonally averaged vertical profile LWC(z) indicates 3 zones: a) the lowest zone of sharp decrease of LWC with height. This zone arises because of sedimentation of the largest spray; b) zone of nearly constant LWC. In this zone there is a budget between sedimentation and evaporation on one hand and by upward transport, on another hand; and c) where diffusion growth of spray dominates over sedimentation.

Note that 1-D models simulate actually only zone 1with strong exponential decrease in LWC with height. **Figure 6** shows the fields of rainflux at t=135 min.

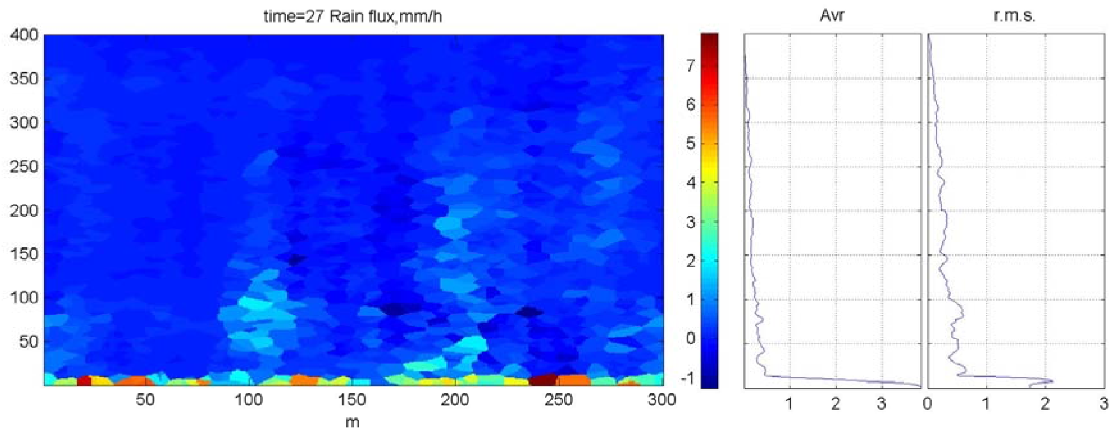

Figure 2 . Field of rainflux (left panel), vertical profile of horizontally averaged rain flux . The vertical profile of the rain flux r.m.s. are shown in the right panels.

Strong rainflux is formed by large spray falling to the sea surface from the lower 10 m-depth layer. One can see that diffusion growth and collisions of spray lead to formation of raindrops (drops with radius exceeding ~50 μm) and rainflux. Spray induced rain begins at about 300 m. Note that the maxima rainflux are located in downdrafts, when fall drop velocity is superimposed with downdraft velocity.

Formation of rain consisting of drops forming by spray collisions was not simulated by earlier models because both collisions and advection of spray by air velocity were not taken into account.

Figure 3 shows size distributions of wet particles (blue) and aerosols (red) within them in parcels located at different levels.

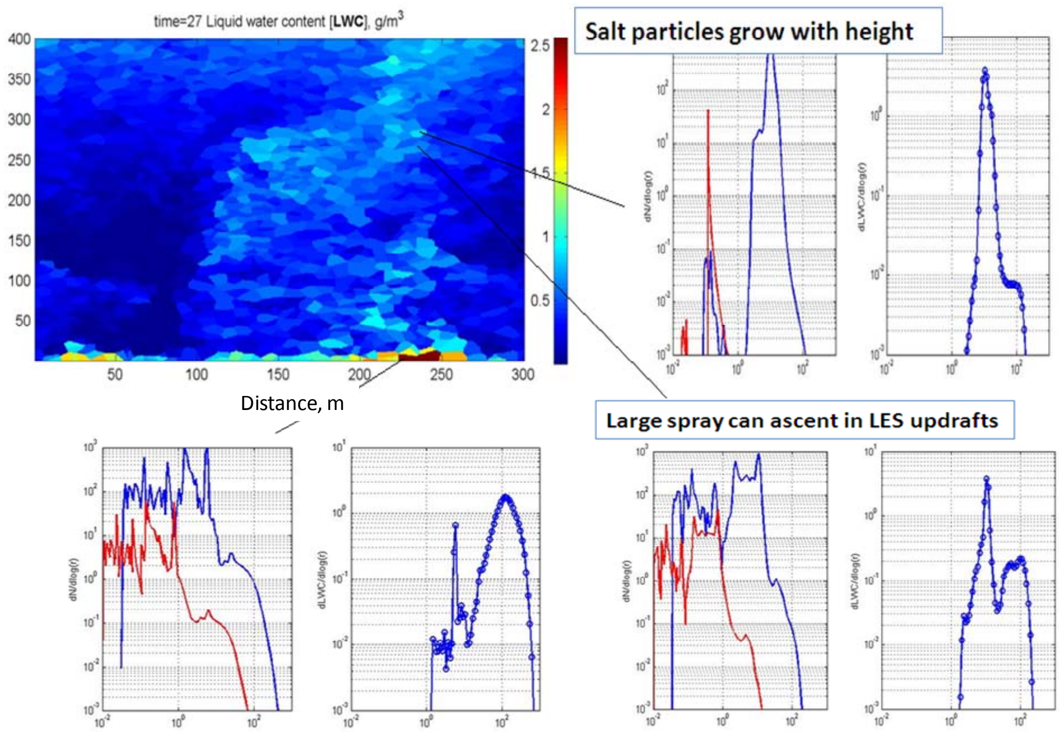

Figure 3. Number and mass distributions of drops (blue) and aerosol particles within drops (red) at different levels within the BL.

Spectra near the surface actually represent size distributions of spray drops formed near the surface. The mass spectrum is centered at radius of 100 μm. The maximum spray size is about 400 μm in radius. The part of the spectrum are r>10 μm corresponds to size distribution of spray in the 1-D model (Fairall et al 2009). Wet particles within the range $5 \cdot 10^{-2}$ μm to 10 μm are small wet particles forming at natural APs and in smallest spray. The maximum size of dry AP in the largest spray is ~100 μm. Figure 3 shows also size distributions of drops and aerosol particles in parcels located at 280 and 300 m. One can see that DSD in these parcels are quite different. Parcel located at 280 m contains giant "dry" aerosols with radii up to 10 μm. Raindrops growing on these APs exceed 100 μm in radius. The mass distribution depicts a pronounced maximum at the raindrop size. This spectrum shows that even large spay (with large AP size) reach levels of a few hundred meters ascending in the convective –scale updrafts. The

DSD in parcel located at 300 m contains relatively small "dry" APs. However, DSD growing on the aerosols are quite large, and reach 100 μm in radius. The process of collisions is efficient in this parcel as well.

Figure 4 shows effects of spray collisions on horizontally averaged droplet size distributions at 350 m. One can see that spray collisions lead to formation of a significant amount of heavy drizzle with radii of 100 μm **(in average).**

Horizontally averaged size distributions of droplets

No collisions with collisions

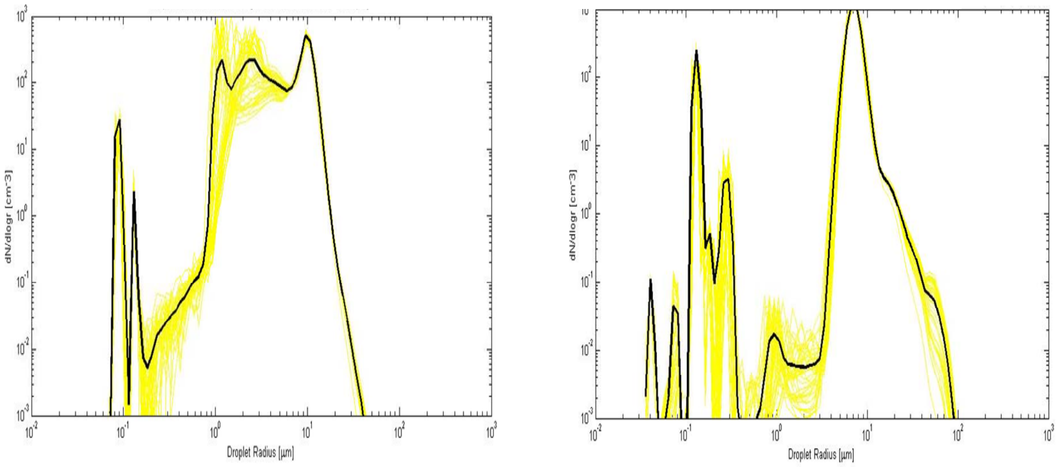

Figure 4. *Horizonatlly averaged droplet size distributions at t=3 h at height of 350 m in case of no collisions (left) and with collisions (right). Yellow color denotes the dispersion of the values.*

Figure 5 shows vertical profiles of absolute humidity in simulations with and without effects of spray taken into account.

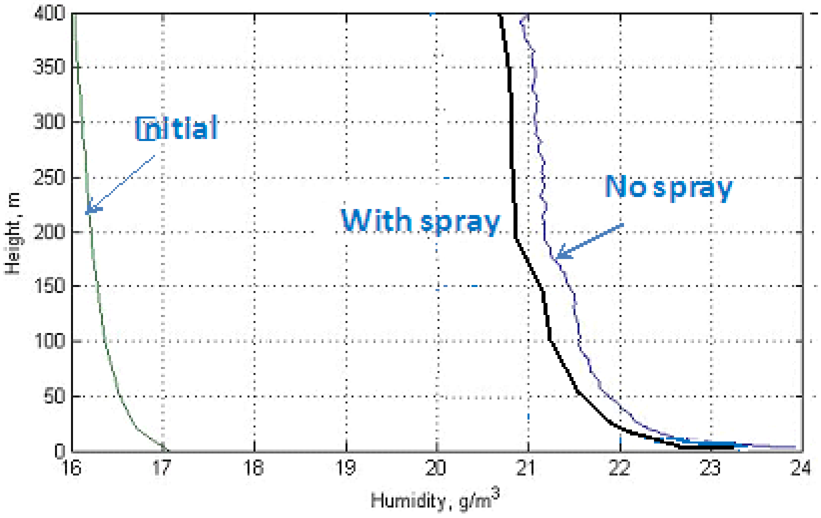

Figure 5. *Vertical profiles of absolute humidity in simulations with and without effects of spray taken into account.*

Initial relative humidity was comparatively low. It leads to the fact that first spray evaporated leading to increase in humidity as compared to the initial humidity.

However, the comparison with the results of the NO-SPRAY shows that spray production leads to lower humidity because of faster diffusion growth of salt spray.

5. Conclusions

Generation of spray near the surface was included into the 2_D model of the surface layer with very accurate description of microphysical processes. The model describes diffusion growth and collisions of droplets forming both on natural aerosol particles and on spray. The model calculates aerosol masses within drops. It is shown that large eddies in the BL transport spray particles to high levels. The collision of spray leads to formation of precipitation at heights of about of 300 m. Updrafts transport significant amount of large spray to cloud base, probably accelerating rain formation in clouds.

The preliminary results show that humidity of the BL rapidly increases to the high values which hinder spray evaporation. Moreover, in updrafts positive super saturation arises. So, the preliminary results do not show that evaporation of spray can increase the BL humidity, or change significantly the surface latent heat fluxes. At the same time a dramatic effect of spray of microphysics of the BL fostering formation of precipitation at low levels is demonstrated.

Actually formation of spray makes the definition of cloud base at high wind difficult. Spray induces precipitation within the whole BL including the lower 300 m layer.

In supplemental simulation in which collisions between spray were excluded, no rain was formed in the BL. Thus, the collisions play a crucial role in determination of microphysics of the BL.

More investigations are required to investigate the role of spray at different wind speeds and initial conditions.

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