Improvement of Representation of the Cloud-Aerosol Interaction in Large-Scale Models

Final report

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I. Main directions of investigations and results

The investigations were performed in several directions.

1) One of the important topics was the effect of aerosols on microstructure and intensity of tropical cyclones. We simulated several TC (Hurricane Katrine, Hurricane Irene using WRF with spectral bin microphysics. It was shown that aerosols located in the TC center tend to intensify hurricanes (Tropical depressions), while aerosols at the TC periphery tens to weaken TCs. Moreover, aerosols can change the TC size intensifying formation of the secondary eyewall. *In summary, it was shown that effects of aerosols on TC intensity as important as the TC-ocean coupling and should be taken into account not only in research studies, but also in the TC forecast models (ref [1]-[3]).*

2) We developed new approaches to describe atmosphere-ocean interaction under strong wind speeds. New method to describe production of sea spray under strong wind conditions has been developed and the role of sea spray on microphysics of the hurricane boundary layer has been investigated. *It was found that spray intensifies deep convective clouds (ref. [3-6]). It was shown that spray substantially affect entire boundary layer microphysics and thermodynamics. Spay is advected to cloud base by large-scale eddies.*

3) Significant efforts were dedicated to improvement of representation of mixed-phase microphysics in cloud models with spectral bin microphysics. Unique and novel methods of description of drop freezing, hail formation and wet growth of hail have been developed and included into the Hebrew University Cloud model and WRF. *It was shown that increase in the aerosol concentration increases the size of hail stones and increases precipitation. (ref. [7-10]).*

4) A novel semi empiric parameterization of heterogeneous ice nucleation by multiple chemical species of aerosol was developed and implemented to WRF and HUCM. (ref. [11]). This method showed significant advantages over the earlier methods. *The method significantly decreased uncertainty as regards heterogeneous drop freezing.*

5) Effects of aerosols (including aerosols of different size) on formation of ice concentration, on snow, precipitation were investigated by simulations of different clouds and cloud ensembles and comparison with observations. *It is shown that bin-microphysics provided the best agreement with observations. (ref. [12-17, 31]). The overview of findings concerning the bin microphysics and its role in investigation of aerosol effects is presented in ref. [18].*

6) The formation of drizzle in stratocumulus clouds was investigated using a unique Lagrangian-Eulerian model, in which Largangian parcels move within a turbulent-like field. *It was shown that first large droplets which are able to trigger efficient collisions arise in "lucky" parcels ascending from ocean surface and reaching the top of cloud being close to adiabatic. These adiabatic parcels were shown to determine the values of effective radius (radiative properties) of stratocumulus clouds. (ref. [19-21])*

7) Analytical and semi-analytical investigations have been performed for analysis of formation of droplet size distributions in warm clouds (ref. [22-25])

Besides, theoretical investigations were dedicated to analysis of water-ice interaction in mixed phase cloud parcels. The factors affecting glaciation time because of competition between droplets and ice particles for water vapor were found (ref. [26, 27]).

8) Recently, several fundamental studies were carried out aiming better understanding of mixing processes at cloud ages of warm microphysics clouds. *Four regimes of mixing were found (homogeneous, intermediate, inhomogeneous and extreme inhomogeneous), each being characterizes by different droplet size distributions and other microphysical properties*. (Ref. [28-30]).

The investigations led to better understanding the cloud microphysical processes, precipitation formation processes and their representation in cloud-resolving models.

Below we will consider in brief each topic.

1. Effect of aerosols on microstructure and intensity of tropical cyclones.

We simulated Hurricane Katrina 2005 and Hurricane Irene using WRF with spectral bin microphysics.

It was shown that aerosols intensify convection. In case TC approaches the land, continental aerosols penetrate TC periphery and intensify convection at the TC periphery. This leads to TC weakening. Figure 1 shows maximum wind speeds in the simulated TC (Katrina) in cases of no continental aerosol penetration and with the effects of the aerosols taken into account. Substantial TC weakening is clearly seen.

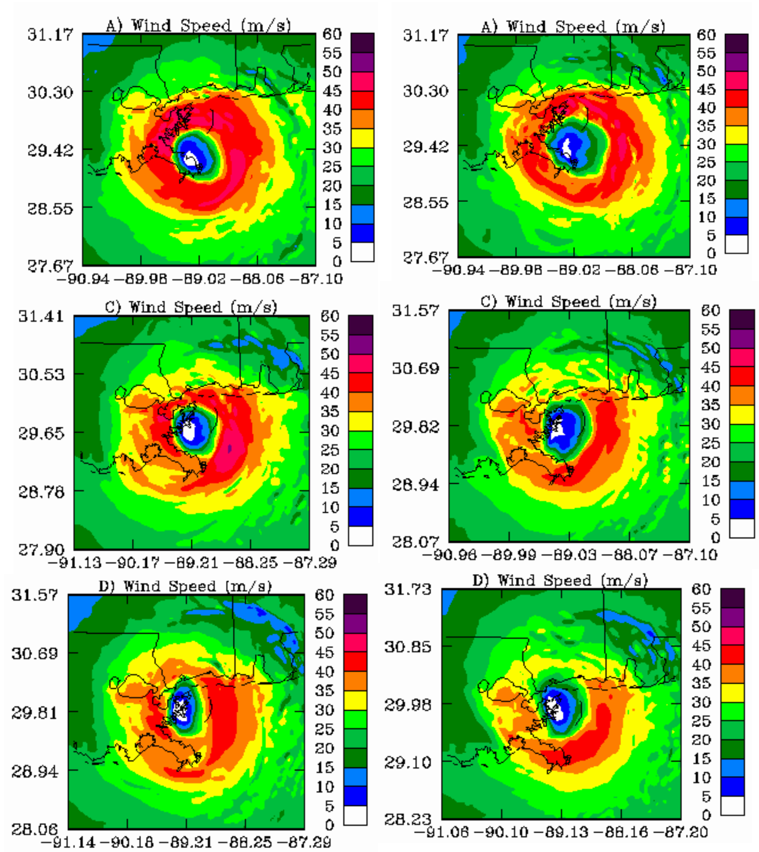

Fig. 1 The fields of the maximum wind speeds in Katrina in simulations with low aerosol concentration (left) and when effect of continental aerosols is taken into account (right).

Specific feature of hurricane Irene was the fact that maximum wind began decreasing while minimum pressure continued decreasing. It means that weakening of the TC was accompanied to its deepening. It is a very rare unusual situation. Our simulations showed that this behavior is caused by aerosols which intensify the secondary outside eyewall. As a result, the radius of the TC increased and weakening was accompanied by the TC deepening.

The model showed a very accurate intensity forecast.

The main conclusion is: aerosols is an important factor affecting the TC intensity. The aerosol effects should be taken into account along with other well-known factors like SST.

2. Effects of sea spray on intensity of deep convective clouds.

The role of sea spray that forms at strong winds on the TC intensity is typically related to the effects of spray of the roughness of the surface and on drag coefficient.

We found that large eddies in the boundary layer transport a significant amount of spray upward so a lot of spray droplets penetrates the deep convective clouds. We investigated the role of sea spray on the intensity of such clouds using the Hebrew University cloud model (HUCM) with spectral bin microphysics. Spay production was calculated using a model of the boundary layer, where vertical transport of droplets is performed by large eddies.

Figure 2 shows fields of vertical velocity in clouds in 3 simulations: no spray, spray produced under wind speed of 30 m/s and under wind speed of 50 m/s.

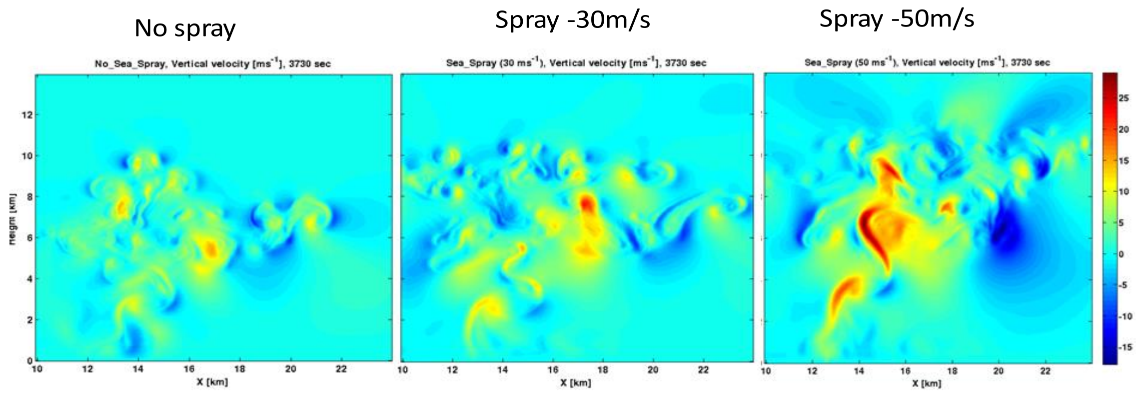

Figure 2 Fields of vertical velocity in clouds in 3 simulations: no spray (left), spray produced under wind speed of 30 m/s (middle) and under wind speed of 50 m/s (right).

One can see that vertical velocity and cloud top height increase with the increase in the spray source.

Figure 3 shows fields of total ice content in these three simulations.

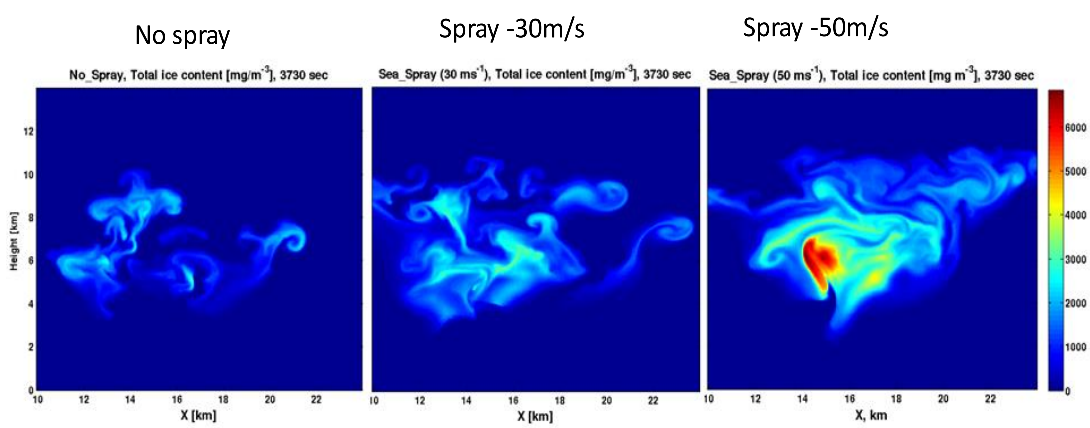

Figure 3. Fields of total mass content in clouds in 3 simulations: no spray (left), spray produced under wind speed of 30 m/s (middle) and under wind speed of 50 m/s (right).

One can see that total ice mass content increases with the increase in spray source.
The results indicate that sea-spray may be a very important factor affecting intensity of tropical and extratropical storms. Accordingly, this effect should be taken into account in the forecast models. Sea spray can be also an important source of maritime aerosols.

3. Iimprovement of representation of mixed-phase microphysics in cloud models with spectral bin microphysics

Significant progress was reached in the improvement of representation of mixed-phase microphysics. A detailed algorithm of time dependent mixing was developed and implemented into HUCM. In more detail this topic is described in the scientific report of Co-PI of the Project, Dr. V. Phillips. As a result, the model calculates now the liquid water fraction in hail and graupel. This allowed to simulate the hail formation as well as polarimetric radar signatures from hail and other particles.

Figure 4 demonstrates the field of differential reflectivity (Z_{DR} column) and hydrometeors size distributions for different levels in the maximum core of the column The mass distributions of drops consists of two modes corresponding to cloud droplets and raindrops At high altitudes raindrops freeze. Mass of large freezing drops increase at the expense of rain drops (z=5-5.5km). Quite close to freezing levels (z=3.5-4.5km) the most contribution to Z_{DR} is from liquid and freezing drops. Some of hail and rain drops penetrate back to the zone of updrafts and continue collect small droplets. Larger raindrops produce larger Zdr . Size distributions of hail are presented in the right column. As can be seen, all sizes of hail growth in wet regime up to 5.5 km (blue color). Even at very high altitude (around 6.5km), large hail continues to grow by wet regime. This hail is responsible for high Zdr.

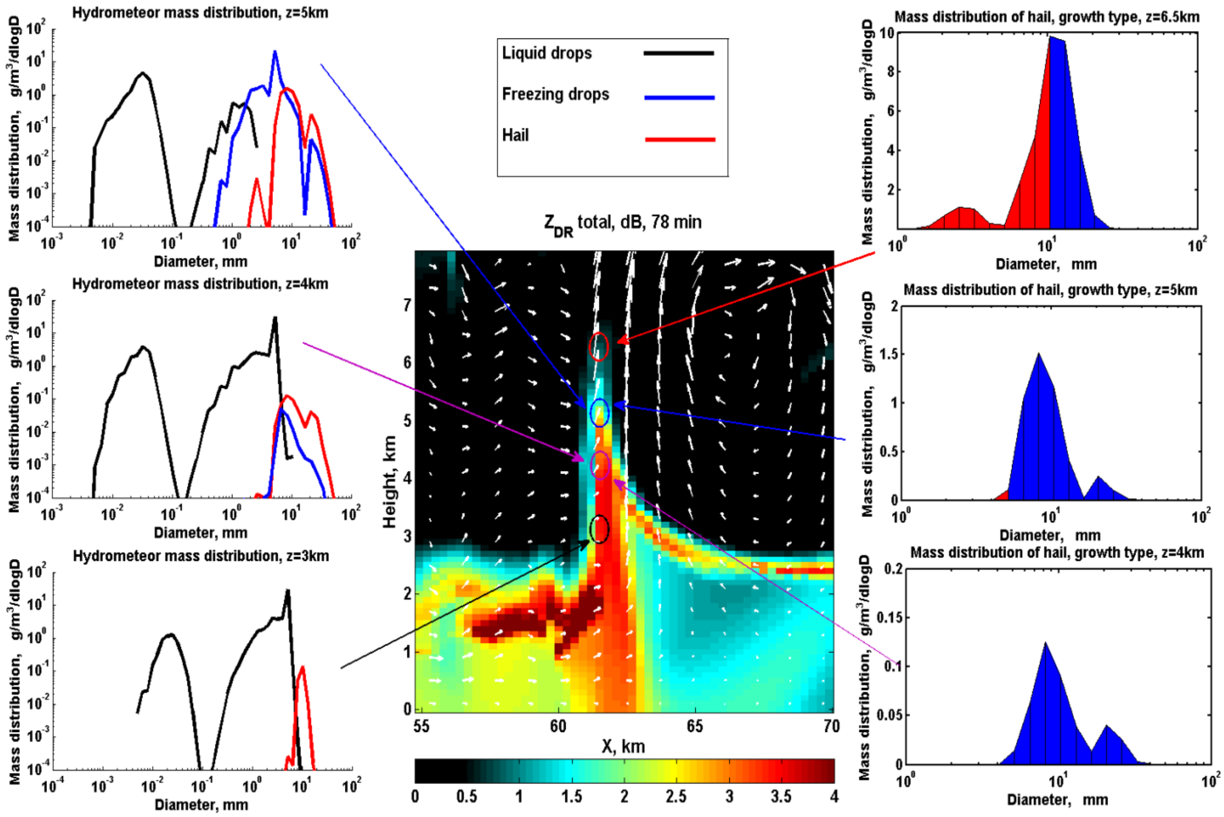

Figure 4. Z_{DR} (colored shading; dB) at t=78min. The white little arrows indicate on background wind fields. Different markers show locations at which particle mass distributions are taken in the zone of Z_{DR} column (x=61.5km). The mass distributions are shown in the outset left panels as log-log plots for every 1 km in height, starting at 3 km up to 5 km. The liquid-drops mass distribution is in black (including rain and cloud water), hail is in red, and freezing-drops distribution is in blue. The growth regime: wet (blue) and dry (red) growth is shown for hail in the outset right panels as semi-log plots for different levels above freezing levels.

In simulations with low CCN concentration amount of supercooled liquid decreases and hail cannot grow efficiently in updrafts. Moreover, it grows by dry growth. As a result, Zdr is much lower (see fig. 5).

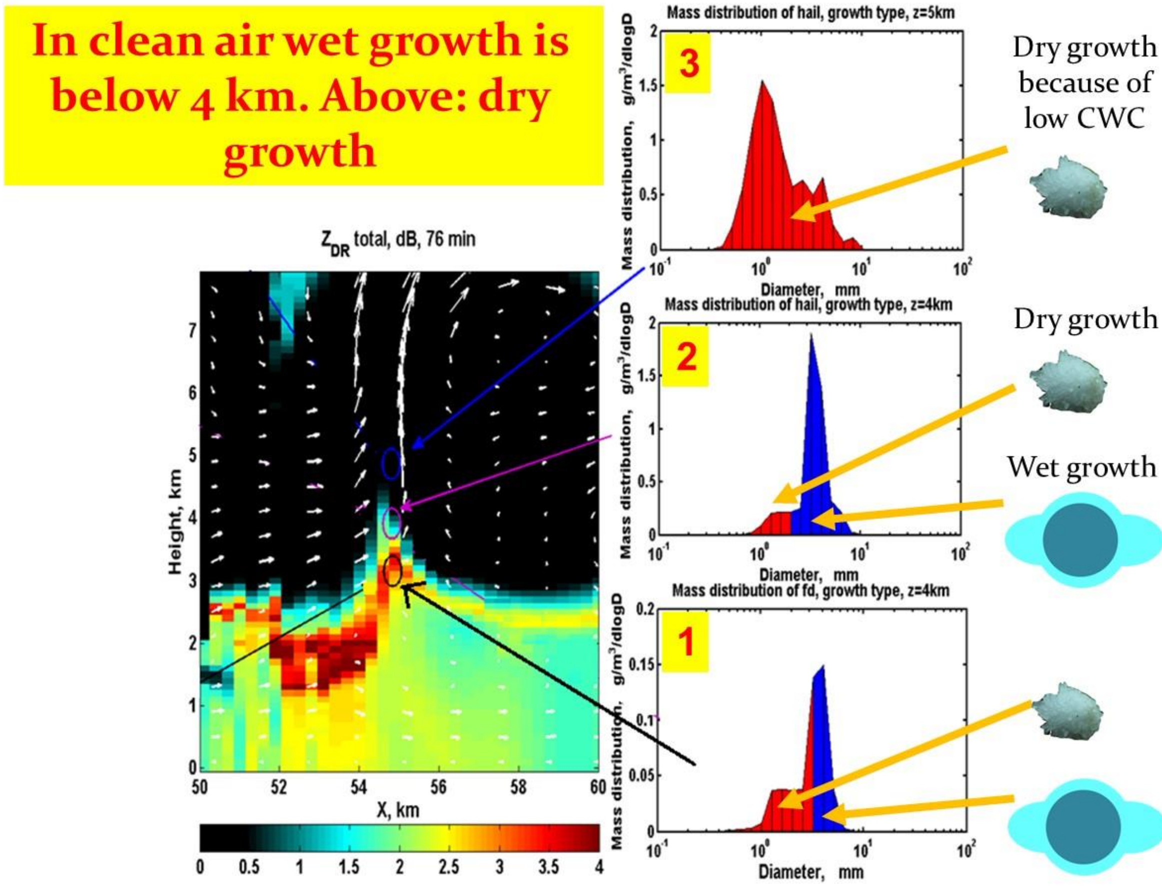

Fig. 5. The same as in Fig. 4, but for low CCN concentration.

Figure 6 shows the field of mean volume radius of hail in cases of high and low aerosol concentration. One can see that in case of high aerosol concentration hail is larger and reaches the surface. In case of low arerosol concentration hail particles are small and melt not reaching surface.

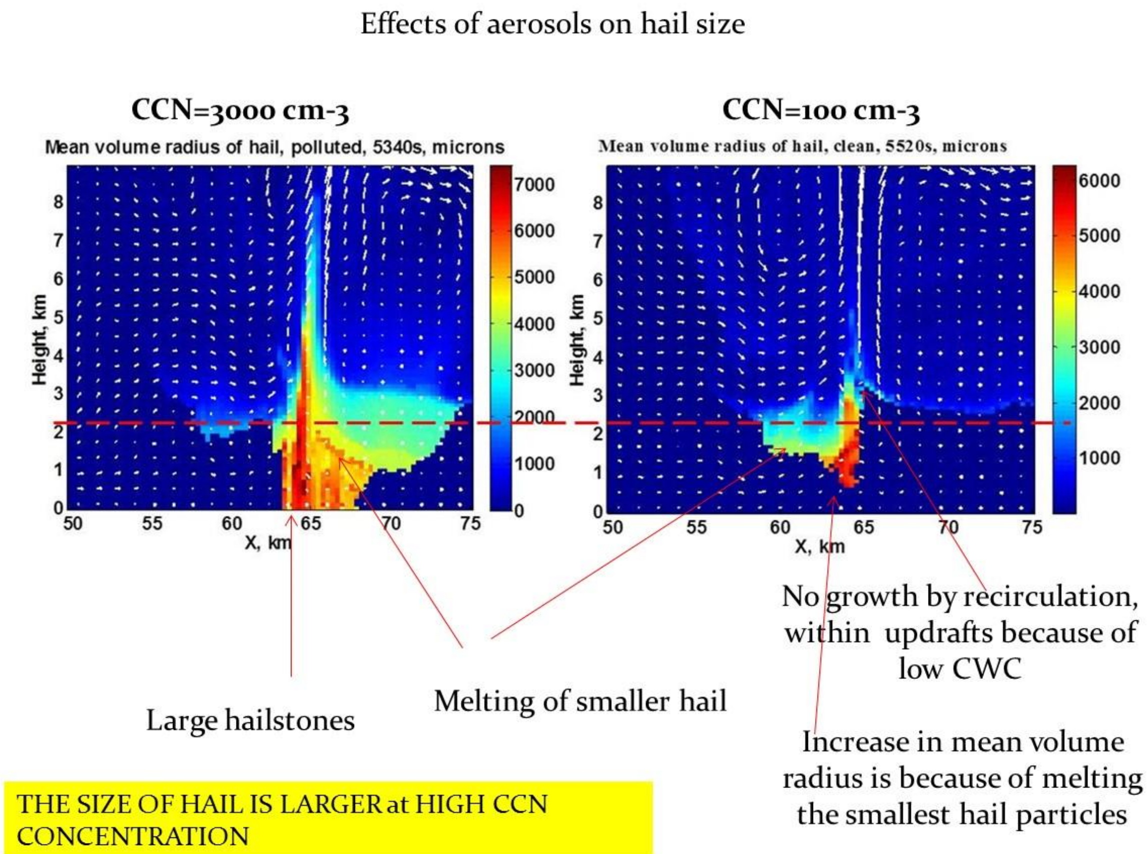

Figure 6. Fields of mean volume radius of hail in cases of high (left) and low (right) aerosols concentrations.

We got the following fundamental conclusions:

- Hail forms only in polluted clouds. Increase in the CCN concentration increases the risk of strong hail shafts,
- Formation of hail, its size as well as vertical velocity in clouds and aerosol concentration can be evaluated using signatures of polarimetric radar. Close relationship between hail formation and the value of differential reflectivity is found.

4. Implementation of a novel semi empiric parameterization of heterogeneous ice nucleation to HUCM

Aerosol particles typically content soluble and insoluble fractions. It means that aerosols can serve both as CCN and IN. The parameterization of heterogeneous nucleation developed by

Phillips et al. (2013) was implemented into HUCM. This parameterization allows to describe both droplet nucleation and then drop freezing due to activation of immersion IN.

5. **Effects of aerosols on formation of droplet and ice concentration**

A new method of calculation of droplet concentration has been developed. Droplet concentration is determined to a large extent by supersaturation maximum near cloud base. The maximum is located a few tens of meters above cloud base. It means that the supersaturation maximum is not resolved by cloud resolving models. In the theoretical study by Pinsky et al. (2012) an expression for supersaturation maximum is found. Using this formula an iteration procedure was developed allowing to calculate supersaturation maximum and droplet concentration. The algorithm is illustrated in **Figure 7**.

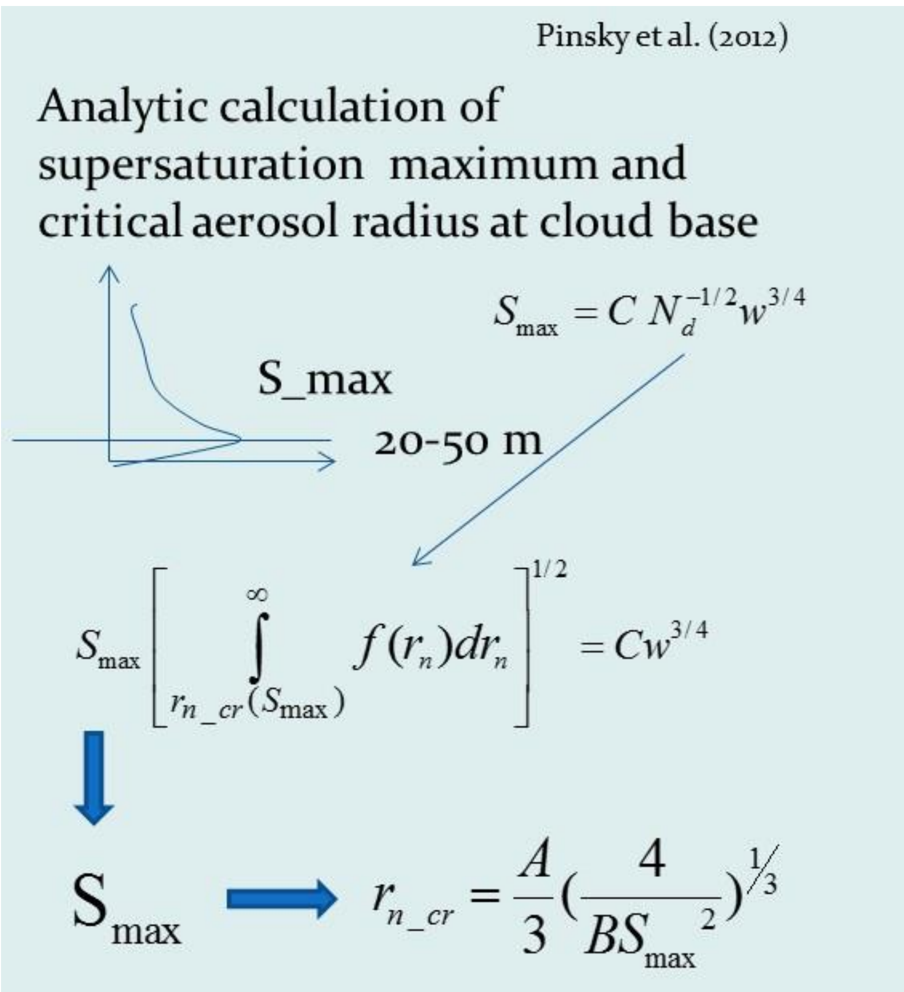

Figure 7. Algorithm of calculation of supersaturation maximum at cloud base using vertical velocity calculated in the model.

Figure 8 shows fields of droplet concentration in a deep convective cloud using the standard approach (determination of concentration using supersaturation in grid points) (left) and using new approach (right).

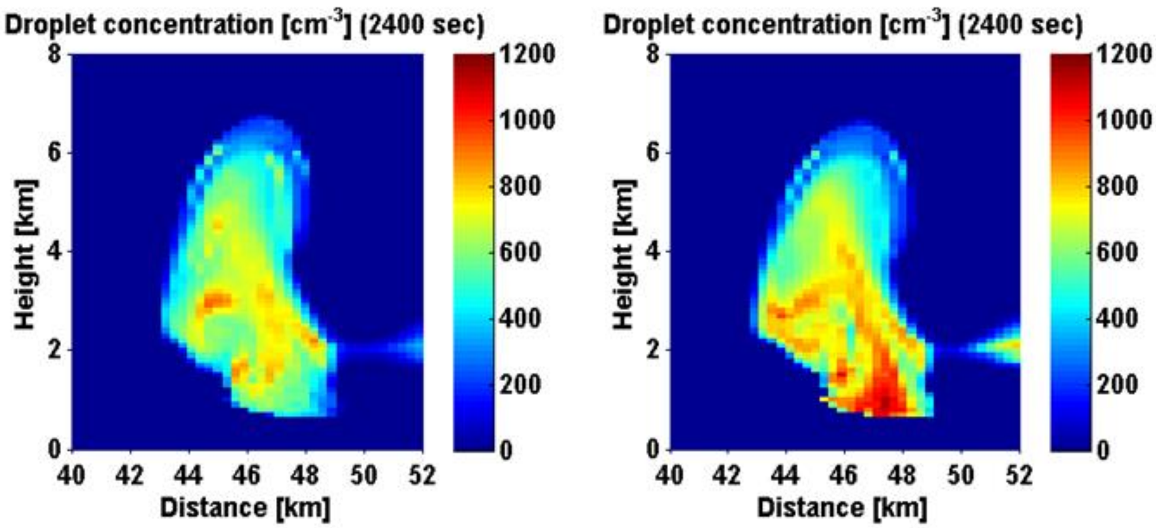

Figure 8. **F**ields of droplet concentration in a deep convective cloud using the standard approach (left) and using new approach (right).

One can see a dramatic difference in the droplet concentrations and a significant improvement reached using the new approach.

This method of calculation of droplet concentration is suitable for cloud-resolving models and large-scale models. It allows evaluate effect of aerosols on cloud microphysics.

Khain et al. (2012) [12] and Ilotoviz et al. (2016) investigated effects of smallest aerosols on droplet concentration and ice concentration at upper cloud levels. It is shown that the smallest CCN in the aerosol spectra play an extremely important role: they are activated at high levels (>6 km) and intensify riming. Moreover, the droplet nucleated on these aerosols produce ice crystals by homogeneous freezing at tops of deep convective clouds. Figure 9 shows the fields of concentrations of ice crystals in anvils of deep convective clouds in simulations with HUCM in cases a) no smallest CCN in the aerosol spectra; b) The smallest CCN are included. One can see that smallest aerosols increase the concentration of ice crystals by order of magnitude.

These smallest aerosols lead to intensification of lightning.

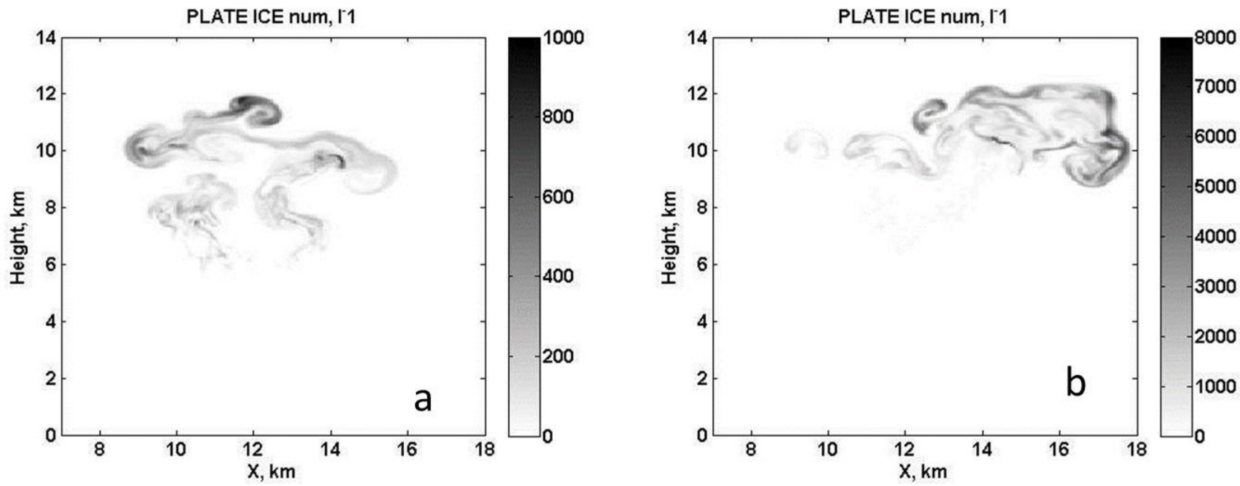

Figure 9. Concentrations of ice crystals in anvils of deep convective clouds in simulations with HUCM in cases a) no smallest CCN in the aerosol spectra; b) The smallest CCN are included.

6. The formation of drizzle in stratocumulus clouds

Maritime stratocumulus clouds (Sc) cover enormous areas or Earth surface and determine the radiative balance of the atmosphere. Formation of drizzle dramatically decreases the surface covered by Sc clouds and leads to a decrease in the Earth albedo. Formation of drizzle is a fine microphysical phenomenon. Drizzle drops with radii of about 100 μm form within the narrow cloud layer of ~300 m depth. In cumulus clouds, drops of such size typically form at distances substantially exceeding 300 m above cloud base even in maritime clouds with low CCN concentration. In convective clouds, supersaturation is typically larger and turbulence is more intense than in Sc. In addition, convective clouds are not limited by inversion from above, so there is enough time for droplets to grow by diffusion and collisions up to raindrop sizes during their ascent. A relevant simulation of formation of wide DSD containing large droplets, that would allow triggering efficient collisions within a limited time interval is a comprehensive task requiring an accurate description of diffusion growth, collisions, mixing and sedimentation.

The problem of drizzle formation can be formulated as follows: does drizzle may form at any location within Sc due to favorable fluctuations of some parameters, or the source and location where drizzle forms can be predicted? Several factors favoring drizzle formation have been investigated.

The problem of drizzle formation was addressed in a set of the studies (Magaritz-Ronen et al., 2014; Magaritz-Ronen et al. 2016 [20-21]). In these studies, a hybrid Lagrangian-Eulerian model (LEM) of the maritime BL was used. Sc clouds observed in two research flights RF01 and RF07 in the field experiment DYCOMP II were simulated.

Comparison with data measured in observations indicates that the model reproduces quite fine microphysical properties of real Sc. (Tab. 1)

Tab. 1. Comparison of calculated values with data measured during RF01 and RF07

	RF01	No-drizzle case	RF07	Drizzle case
Cloud base (m)*	585	530–600	310	350–450
$\bar{q}_t$ (g kg^{-1})	9	9	10	10
LWC$_{max}$ (g kg^{-1})	0.5	0.6	0.8	0.8
Drizzle flux (mm day^{-1})**	Below detection level	Below detection level	0.6 (±0.18)	0.5
Droplet concentration (cm^{-3})	~150	~190	~150	~160
The range of effective radii at 820 m (μm)		8–12	10–14	10–14
Mean effective radius of DSD near the surface (μm)		75	100	100
Maximum effective radius near the surface (μm)		100	160	200
Maximum radar reflectivity (dBZ)	−12	-10	10-12	10-12

* The evaluation of the cloud-base height was carried out using profiles of LWC; the vertical profiles of the LWC in the cloud layer were extrapolated from above to the level where the extrapolated value was equal to zero.
** Model value is an average over the entire run; the drizzling detection level (threshold) was about 0.03 mm day^{-1}.

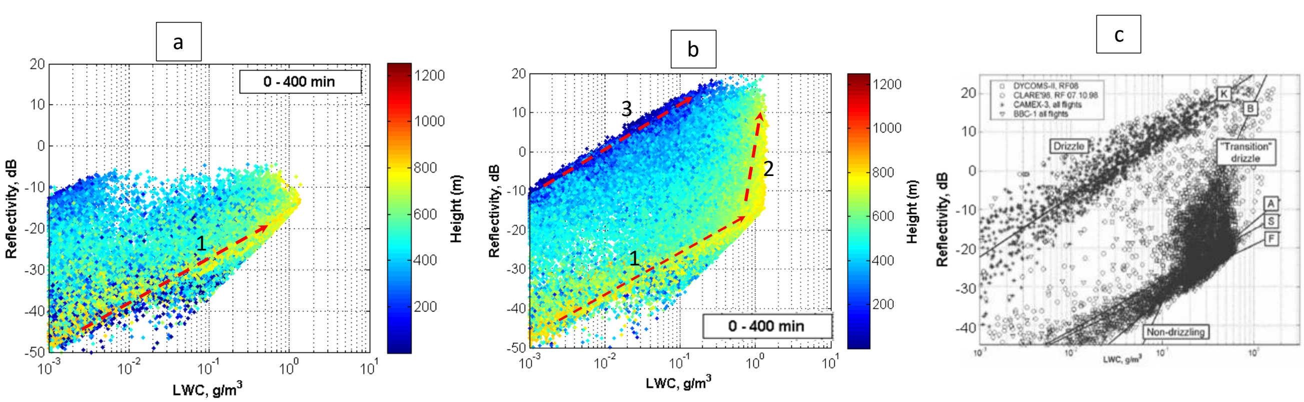

Fig. 10. The *Z*–LWC scattering diagrams for clouds simulated in (a) RF01, (b) simulated in RF07 and (c) calculated using measured DSD in Sc clouds in different field experiments. Each point in diagrams (a) and (b) denotes location of a separate parcel marked every 5 min. Color scale in these diagrams denotes the height of parcels above the surface. Dashed lines indicate different stages of cloud development in the simulations. Lines A, S, and F in diagram (c) show different approximations of *Z*-LWC dependence using in-situ measurements.

The simulated by LEM *Z*–LWC scattering diagrams are compared with diagrams obtained from observations (panel (c), designed using the measured DSDs in different Sc clouds (non-drizzling, drizzling and including heavy- drizzling). One can see that dots in the scatter diagrams are concentrated along three lines (Fig. 10) representing 3 stages of cloud evolution: diffusional growth (1), intense collisions (2) and drizzle regime when high reflectivity forms, below cloud base (3). The superposition of these three zones results in the scattering diagram in Fig. 10. The good agreement between *Z*–LWC dependence scattering diagrams simulated by the model (panel b) and the observations data (panel c) demonstrates the model's ability to reproduce very fine microphysical features of real clouds, which makes it applicable for investigation of drizzle formation processes.

The diagrams allow to analyze the stages of cloud evolution leading to drizzle formation. At the stage of diffusion growth (line 1), the radar reflectivity increases as LWC increases, with the slope of relationship in log-log coordinates equal to two. This slope forms because for relatively narrow DSD radar reflectivity (the 6-th moment of DSD) is proportional to square of the LWC (the third moment of DSD). The stage of intense collisions corresponds increasing radar reflectivity at nearly the same LWC (line 2). One can see that the RF01 cloud does not pass the stage of intense collisions, and, as a result, does not produce drizzle. Triggering efficient collisions takes place when LWC reaches about 1 g/m^3 and the maximum radar reflectivity reaches -20 to -15 dBZ. Since LWC increases with height, intense collisions and first drizzle drops formation begin near cloud top. Drizzle drops formed at this stage fall down to parcels containing lower LWC and to non-cloud parcels below the cloud base. As a result, in parcels below cloud base high radar reflectivity occurs at small LWC. Line 3 corresponding to drizzle drops is parallel to line 1.

The parcels where first drizzle drops form have LWC~1 $g\ m^{-3}$. This value exceeds the maximum horizontally averaged value of 0.8 $g\ m^{-3}$ and is close to the adiabatic value. Analysis of the calculated statistics of the values of effective radius shows that r_{eff} in parcels near cloud top is 11-12 µm, which agrees with the measurements. However, drizzle forms first in parcels having the largest LWCs (called here as “lucky” parcels). The maximum LWC in a lucky parcel near cloud top can be reached if the LCL of this parcel is lower than of other neighboring parcels. Accordingly, humidity in such lucky parcel should be larger than in all neighboring parcels. Statistical analysis showed that lucky parcels spend significant time near surface getting water vapor from ocean surface and then ascend within a comparatively wide updraft zone of a large eddy (Magaritz-Ronen et al., 2016 [20-21]). The significant width of the updraft allows ascending lucky parcels remain actually undiluted.

Thus, the fundamental problem concerning drizzle formation has been solved. Drizzle in maritime Sc arises in undiluted parcels (lucky air volumes) ascending from

***7)* Formation of droplet size distributions in warm clouds**

Analytical and semi-analytical investigations have been performed for analysis of formation of droplet size distributions in warm clouds (ref. [22-25]). These studies found that vertical profiles of supersaturation, effective radius and some other quantities are universal. These laws can be used for modification of existent schemes of parameterizations.

The mechanism of first raindrops formation was investigated by Khain et al (2013) [17]. It was found that first raindrops form near cloud top in zones of maximum liquid water content and of maximum of intensity of turbulence that increases the collision efficiency. Effective radius in these zones reaches 15 mkm.

This conclusion is of fundamental importance. It shows that adiabatic processes (maximum LWC takes place in adiabatic air volumes) play dominating role in formation of precipitation. It opens the possibility to determine the height of rain formation, as well as to improve prediction of rain amount.

8) Turbulent mixing

Several fundamental studies were carried out aiming better understanding of mixing processes at cloud ages of warm clouds. *Four regimes of mixing were found: homogeneous, intermediate, inhomogeneous and extreme inhomogeneous)* (Ref. [28-30]). Each regime is characterized by different droplet size distributions and other microphysical properties.

It was found that in contrast to the existing concepts, mixing always leads to broadening of droplet size distributions. It was found that width of DSD affects the result of mixing.

The studies create the basis for new steps for investigation of this phenomenon.

II. Other scientific activities

a) There were several mutual visits of PI (A. Khain) to Lund and Co-PI, (Dr. V. Phillips) to Jerusalem to close collaboration.

b) PI and Co-PI, as well as several students participated in ARM meetings and important international conferences on Cloud Physics.

c) Important collaboration as regards to simulation of tropical convection, tropical cyclones, sea-spray effects are established with: Prof. I. Ginis (URI), Dr. A. Korolev (MeteoCanada), Dr. J. A. Zhang , University of Miami; Dr. Ruby Leung(PNNL) , Dr. Jian Wen Bao , NOAA, and many other scientists.

III. Main Conclusions

The goals of the Project were achieved. Many fundamental finings in the area of warm and ice microphysics were made. Cloud –resolving models (such as WRF/sbm) were significantly improved. The results obtained have created a solid base for performance of the Project submitted.

Publications written under support of the DoE grant (Members of our science team are in bold)

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