Aerosol effects on intensity of landfallig hurricanes as seen from simulations with WRF model with spectral bin microphysics

A. Khain(1), B. Lynn(1) and J. Dudhia (2)
(1) Department of Atmospheric Sciences, The Hebrew University of Jerusalem, Israel
(2) NCAR, USA

Abstract

The evolution of a super hurricane (Katrina, August 2005) was simulated using the Weather Research and Forecasting Model (WRF; version 3.1) with explicit (non-parameterized) spectral bin microphysics. The new computationally efficient spectral bin microphysical scheme (FAST-SBM) implemented in the WRF calculates at each time step and in each grid point size distributions of atmospheric aerosols, water drops, cloud ice (ice crystals and aggregates) and graupel/hail. The Tropical Cyclone (TC) evolution was simulated during 72 hours beginning with its bypassing the Florida coast (27 Aug 2005) to its landfall just east of New Orleans, Lousianna (near the end of 29 August). It is shown that continental aerosols invigorated convection largely at TC periphery, which led to its weakening prior to landfall. Maximum weakening by ~15 mb took place ~24 h before landfall, just after its intensity had reached its maximum. The model results indicate the existence of another (in addition to decrease in the surface fluxes) mechanism of weakening of TCs approaching the land. Evolution of lightning structure within the TC is calculated and compared with that in Katrina.

1. Introduction

Tropical cyclones (TCs) are known for their destructive power, particularly as they make landfall. The prediction of TC intensity represents a difficult task. Well known factors affecting TC intensity are heat and moisture surface fluxes and wind shear. Implementation of TC-ocean coupling into prognostic TC models led to a significant improvement of forecast of TC intensity. These mechanisms represent thermodynamical factors affecting the convection intensity. During the past decade it was found that aerosols (including anthropogenic ones) substantially affect cloud microphysics and consequently the rate of latent heat release, the dynamics and the precipitation (see, overviews by Levin and Cotton, 2009; Khain et al 2009; Rosenfeld et al, 2008). In particular, it was found that small aerosols invigorate tropical convection increasing vertical velocities and cloud top heights of deep convective clouds (Khain et al, 2004, 2005, 2008b; Koren et al 2005; Lynn et al, 2005a,b, Wang 2005, Lee et al 2008 ; Khain 2009). Thus, aerosols affect cloud microphysics and dynamics.

An indirect evidence of aerosol effects on TC intensity can be derived from enhanced lightning at the periphery of landfalling TCs (Khain et al 2008a). They showed that a penetration of continental aerosols to clouds at the TC periphery and successive convection invigoration is the mechanism contributing substantially to lightning formation at the TC periphery. An increase in concentration of small aerosols increases droplet concentration and decreases droplet size. The net effect is the decrease in the collision rate, delay in raindrop formation and warm rain production. As a result, small droplets ascend in cloud updrafts and continue growing by condensation. It leads to an increase in supercooled water content, which intensifies the riming, i.e. ice-water collisions accompanied by freezing of liquid water. Both processes are accompanied by extra latent heat release leading to increase in cloud updrafts and sometime to an increase in cloud top height (Khain 2009). Aerosol-induced increase in supercooled cloud water content (CWC) and vertical velocities foster lightning formation, when collisions of ice crystals and graupel take place in the presence of supercooled droplets. Khain et al (2008a) simulated the evolution of hurricane Katrina (August 2005) during its movement in the Gulf of Mexico using a two nested grid Weather Research Model (WRF, NCAR version V.2) with the Thompson et al. (2006) one-moment bulk-parameterization. Effects of continental aerosols were simulated by preventing by shutting off the drop-drop collisions only at the hurricane periphery. A similar approach was used by Rosenfeld et al (2007). The results obtained in these idealized simulations allowed Khain et al (2008a) to conclude that continental aerosols that penetrated the TC periphery caused enhanced lightning flashes in the areas of penetration. It was also shown that aerosols, invigorating clouds at 250-300 km from the TC center, decrease the convection intensity in the TC eyewall leading to some TC weakening. Similar results were reported by Rosenfeld et al (2007), who proposed a method of TC mitigation by seeding of clouds at the TC periphery near their cloud base with small aerosol particles of 0.05 μm to 0.1 μm in radius. Simulations of the evolution of an idealized TC using Regional Atmospheric Meteorological System (RAMS) (Zhang et al, 2007) supported the conclusion that aerosols (for instance, Saharan dust) can substantially affect the intensity of TCs.

To take into account microphysical factors (such as aerosols) properly, advanced microphysical schemes are required. The problem of the adequate description of convection in TC models remains one of the most difficult problems in the TC modeling. The current operational TC forecast model developed at the Geophysical Fluid Dynamics Laboratory used large scale convective parameterizations until 2006 (Kurihara 1973, Arakawa and Shubert 1974). Since 2006 this model used a simplified Arakawa-Schubert scheme for cumulus parameterization and simplified version of the Ferrier bulk-parameterization (Ferrier 2005) for large-scale condensation in cases when supersaturation in grid points is reached (Bender et al 2007). The simplified bulk scheme treats only the sum of the hydrometeor classes (referred as the total condensate) in the advection in both horizontal and vertical direction. Both schemes are insensitive to aerosols.

The development of one and two-moment bulk parameterization schemes was an important step toward the improvement in the description of convective processes and precipitation in numerical models. The comparatively small number of prognostic equations makes the schemes computationally efficient, so they are widely utilized in simulating different cloud-related phenomena such as supercell storms, squall lines, etc. These schemes were used recently for simulation of TCs (e.g., Zhang et al, 2007; Fierro et al, 2007).

Note that the bulk-parameterization schemes have significant limitations in describing microphysical processes affecting the shape of size distributions (Khain 2009). The second approach to simulate microphysical processes is the utilization of spectral bin microphysics (SBM), in which a system of kinetic equations for size distributions of particles of different classes is solved. The equation system solves the equations for advection, settling, collisions, freezing, melting, etc. for each mass bin (each particle size). This method is much more accurate than the bulk-parameterization as regards its ability to simulate cloud dynamics and microphysics and precipitation [see comparisons of SBM vs bulk schemes in Lynn et al., 2005b, Lynn and Khain 2007, Li et al. 2009a,b, Iguchi et al., 2008; Khain and Lynn, 2009; Khain et al 2009].

In this study the evolution of hurricane Katrina over the Gulf of Mexico is simulated with WRF, in which cloud microphysics is described using computationally efficient spectral bin microphysics scheme, in which all microphysical processes are described explicitly.

2. Model and experimental design

.1 Spectral bin microphysics scheme

The SBM scheme implemented into the WRF (Skamarock et al., 2005, version 3) has been described by Khain et al (2004) and Lynn et al (2007). The original scheme is based on solving the kinetic equation system for the size distributions of seven classes of hydrometeors: water drops, three types of crystals (columnar-, plate- and branch-type), aggregates (snow), graupel and hail. Each hydrometeor class is described by a size distribution function defined on the grid of mass (size) containing 33 doubling mass bins. The minimum particle mass corresponds to that of the 2 μm radius droplet. Aerosol particles are also described by a size distribution function containing 33 size bins. The size distributions are calculated in the course of the model integration. Using the values of supersaturation, the critical size of aerosol particles to be activated to drops is calculated. Aerosol particles exceeding the critical size are activated and the corresponding mass bins in the aerosol size distribution become empty. The SBM also takes into account possible droplet nucleation during dry air entrainment through the lateral cloud boundaries. An efficient and accurate method of solving the stochastic kinetic equation for collisions (Bott, 1998) was extended to a system of stochastic kinetic equations calculating water-ice and ice-ice collisions. The collision kernels for each pair of particles are calculated using an accurate superposition method (Pinsky et al, 2001, Khain et al 2001) and used in the form of lookup tables. The ice nuclei activation is described using an empirical expression suggested by Meyers et al. (1992) and applying a semi-lagrangian approach (Khain et al 2000) to allow the utilization of the proposed diagnostic formulas in a time dependent framework. Secondary ice generation is described according to Hallett and Mossop (1974). The rate of drop freezing follows the observations of immersion nuclei by Vali (1974, 1975), and homogeneous freezing according to Pruppacher (1995). Breakup of raindrops is described following Seifert et al (2006).

The SBM model does not requires any tuning of the scheme parameters and was successfully used *without any changes* for simulation of deep maritime convection (Khain et al, 2004, 2008b), continental clouds including pyro-clouds (Khain et al, 2008b), squall lines (Lynn et al, 2005a,b; Tao et al 2007; Li et al 2009a,b; Khain et al, 2009), supercell storms (Khain and Lynn 2009) and arctic stratiform clouds (Fan et al, 2009).

Since the treatment of 8 size distributions requires a significant computer time, a Fast-SBM has been developed in which all ice crystals and snow (aggregates) are calculated on one mass grid (one distribution function). The ice particles with sizes below 150 μm are assumed to be crystals, while the larger ones are assigned to aggregates (snow). Similarly, high-density particles (graupel and hail) are also combined into one size distribution (graupel). As a result, the number of size distributions decreases from 8 to 4 (aerosols, water drops, low density ice, high density ice). Note that Fast-SBM keeps the main advantages of SBM: a kinetic equation system is solved using the non-parameterized basic equations, particles of each size have their own settling velocity, particles depending on their mass have different densities, etc. The test simulations showed that Fast-SBM requires less than 20% of the time of the full SBM, which makes it possible to use the Fast-SBM on standard PC-clusters. The comparison of results obtained by the Exact and Fast SBM in simulation of tropical cloud systems (Khain et al 2009) shows that the Fast SBM produces microphysical and dynamical structure as well as accumulated rain at the surface quite similar to those simulated with Exact SBM.

2.2 Experimental design

A set of simulations were used to study possible aerosol effects on the evolution of Hurricane Katrina (August 2005) in the Gulf of Mexico about three days (beginning with 27 August 00 z) prior to landfall (on about 12z 29 August). A two nested girded WRF (version 3.1) was used, and the nest moved using a cyclone-following algorithm. The resolution of the finest and the outer grid was 3 km and 9 km, respectively. The number of the vertical levels was 31, with the distances between the levels increasing with the height. The SBM is applied at the finest grid of 400 x 400 km sizes. The initial fields were taken from the Global Forecast System Reanalysis data. The lateral boundary conditions were updated every six hours using the data as well. The Gulf of Mexico surface water temperatures were initialized on 27 August 00 z , and was not updated during the experiments. According to the reanalysis data the SST taken along the TC track reached its maximum near the shore (the place of the TC landfall).

Cloud droplets arise on aerosol particles (AP) playing the role of Cloud Condensational nuclei (CCN). *The initial* (at t=0) CCN size distribution is calculated using the empirical dependence of concentration of activated CCN N_{ccn} on supersaturation with respect to water S_w (in %) $N_{ccn} = N_o S_w^k$ as described by Khain et al (2000). N_o and k are the measured constants for determining the AP concentration and shape of the AP size distribution. At t>0 the equation for the size distribution of non-activated AP is solved. The initial AP concentration was assumed constant within the lowest 2 km layer and decreased exponentially with height with a characteristic scale of 2 km. Aerosols were transported over the entire computational area similarly to other scalars like the mixing ratio.

To investigate possible aerosol effects on microphysics and the dynamics of the TC two simulations were carried out: a) in the first “MAR” simulation N_o was set equal to 100 cm^{3}, typical of maritime atmosphere over the whole computational area b) in the second, semi-continental MAR_CON case the initial CCN concentration over the land N_o was set equal to 1500 cm^{3}, typical of continents under not very polluted conditions. Initially, over the sea N_o was set equal to 100 cm^{3} in all simulations. In all simulations the slope parameter k was set equal to 0.5. When TC enters the Gulf of Mexico, its circulation transports aerosols from the land to sea, so that some continental aerosols penetrate clouds within TC and affect their microphysics and dynamics. In all simulations the maximum size of dry AP is equal to 2 μm, which give rise to droplets of radius 8 μm at cloud base. No giant CCNs that could arise at high winds as a result of spray formation were assumed to occur in the simulations.

3. Results of simulations

Figure 1 shows the time dependence of minimum pressure in all simulations and in Katrina. One can see that the model TC has lower intensity during the first ~50 h of simulations as compared to that of Katrina. Note in this connection that the WRF initialization used was not a TC forecast initial condition, so that no specific adjustment procedures were used to adopt the TC structure derived from the crude resolution (100 km) reanalysis data to the intensity of the real TC at t=0 (27 Aug 00z). Hence,

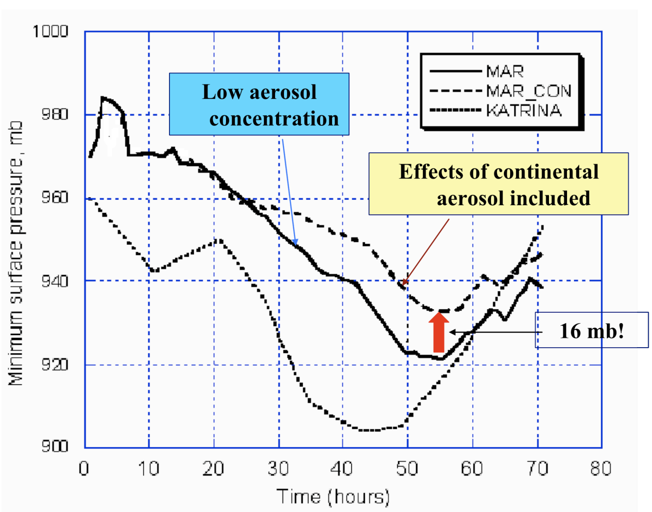


Figure 1. Time dependence of minimum pressure in numerical experiments and hurricane Katrina (August 2005)

some relaxation period was required to get the model TC intensity close to the observed one. Yet, the accurate prediction of the Katrina's intensity was not the primary purpose of the study. The main purpose of the simulations was to compare the TC intensity and structure in the simulations with and without aerosol effects on the TC clouds in a strong hurricane, which is able to ingest aerosols from the continent. Figure 1 shows that TC in the "MAR_CON run turned out substantially weaker, so that at the time instances when the TC reached its maximum intensity the minimum pressure in its center was about ~16 mb higher than in the MAR run. Note that lower (as compared to Katrina) intensity of the model TC leads likely to an underestimation of aerosol effects, because of a weaker TC involves lower AP amounts into the TC circulation.

Results shown in Figure 1 indicate the existence of an important factor affecting the TC intensity. In the analysis of the aerosol fields we addressed two main questions. The first one was: whether a significant aerosol concentration can enter the TC periphery when it is located at comparatively large distance from coastal line, and second, whether aerosols can penetrate the TC eye. Aerosol fields simulated in the MAR run (not shown) indicate very uniform distribution of AP concentration (which is very low) because the AP concentration over land was assumed equal to that over the sea.

Figure 2 shows the fields of the AP concentration maximum in MAR_CON run at August 28th, at 23z (left) and at August 29th, at 9 z (right) on the fine grid. The analysis of Figures 2 shows that: a) the AP concentration at the TC periphery approach concentrations similar to those over the continent; b) Over a significant area the aerosol concentration decreases while approaching the TC center partially because of the activation of aerosols to cloud droplets; and c) aerosols can penetrate the TC eyewall clouds along comparatively narrow streams.

at 23z (left) and at August 29th, at 9 z (right) on the fine grid.

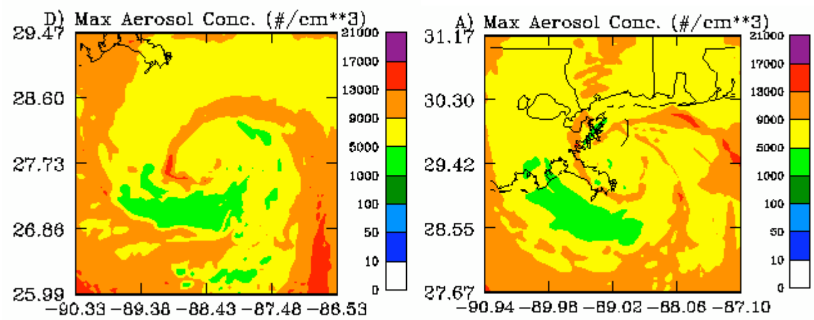


Figure 2: Fields of maximum AP concentration in MAR_CON simulation at August 28th,

Figure 3 compares the fields of the column-maximum droplet concentrations (upper row) and cloud water mass content (CWC) (clouds with radii below 40 μm) in clouds in simulations MAR (left) and MAR-CON (right) at August 28^{th} 22z on the fine grid (46h, Figure 1). One can see that in the MAR run droplet concentration does not exceed 50-100 cm^3 , which is typical droplet concentration in clouds arising in clean maritime air. Zones of maximum droplet concentration in the MAR run at the TC periphery indicate zones of higher vertical velocities in rain bands. In MAR-CON, the penetration of continental aerosols led to an increase in droplet concentration at the TC periphery in the zone of high aerosol concentration, as well as in the eyewall. In the MAR-CON run the maximum droplet concentration reached 500 cm^3 (especially high concentrations are at TC periphery) , which is substantially higher than those in typical maritime clouds. An increase in droplet concentration within the eyewall in the MAR-CON run indicated that aerosols penetrated to the TC eyewall in the simulations.

The CWC dramatically increases (mainly supercooled water content) as a result of aerosol penetration: while the maximum CWC reached 0.6 gm^{-3} in the MAR run, the CWC in the MAR-CON run exceeded 1.6 gm^{-3}. The CWC increased largely at the TC periphery where concentration of aerosols is higher.

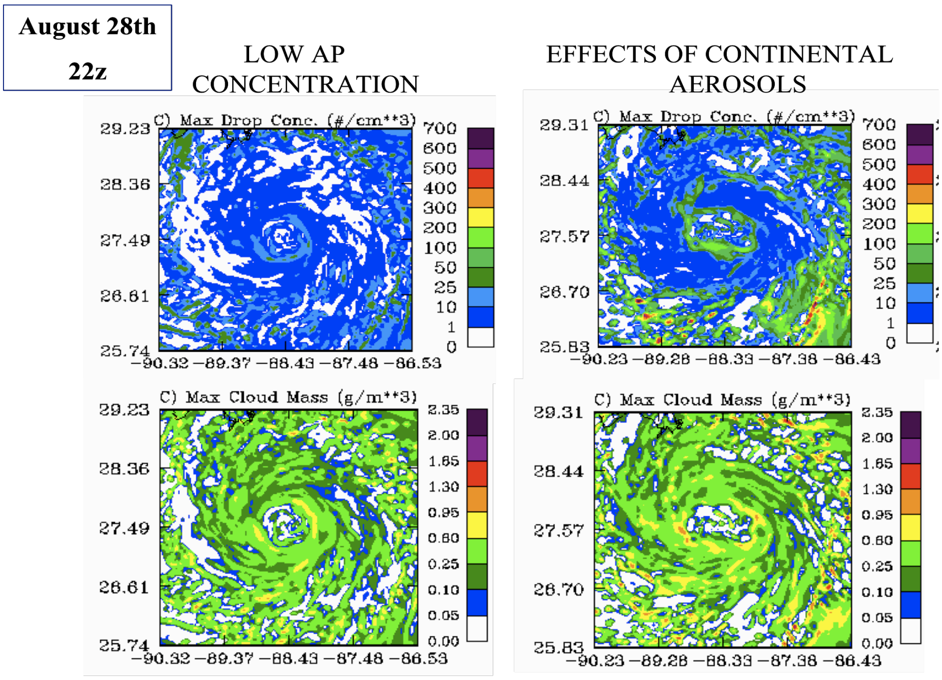


Figure 3. Fields of the maximum droplet concentrations (upper low) and cloud droplet content (CWC) in simulations MAR (left) and MAR-CON (right) at August 28th 22z at the fine grid.

The aerosol-induced changes in warm microphysics resulted in corresponding changes in ice microphysics. The penetration of larger amount of drops above the freezing level led to an increase in graupel and snow (aggregates) contents at TC periphery (**Figure 4**).

August 28th

22z

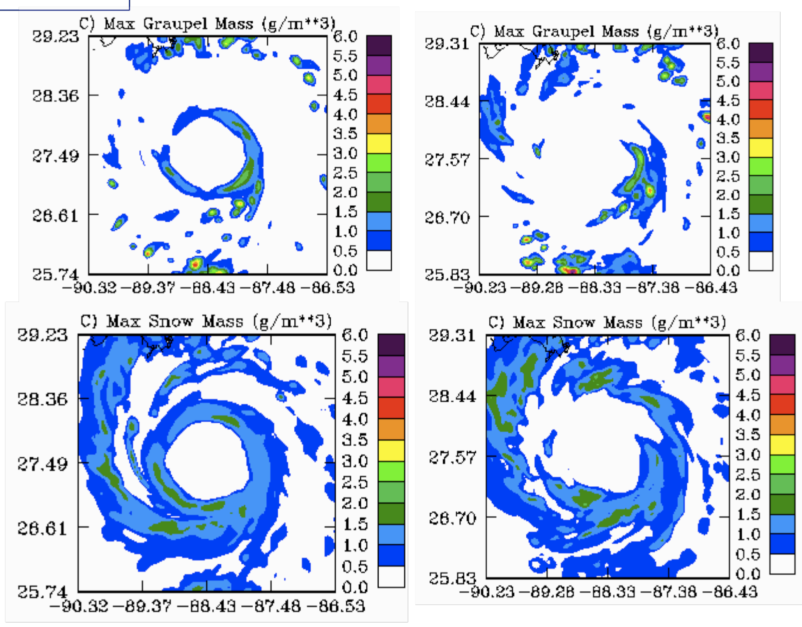


Figure 4: *The same as in Figure 3, but for fields of graupel (upper row) and snow (lower row) contents*

Note that convection invigoration of clouds at the TC periphery weakens the updrafts in the eyewall, which immediately resulted in the decrease and even disappearance of graupel and snow in the eyewall. Extra latent heat release caused by droplet condensation and freezing at the periphery causes an increase in vertical updrafts velocities and cloud top height (**not shown**). The values of maximum vertical velocities exceed 10 m/s which are rare for maritime TC clouds (Jorgensen et al, 1985). At the same time namely such high velocities are required to form lightning. The increase in cloud top height within polluted air was observed from satellites (Koren et al, 2005) and simulated in many recent studies dedicated to aerosol effects on cloud dynamics (see review by Khain 2009). As it was discussed above, Khain et al (2008a) suggested that the evolution of lightning within TC approaching the land results from the ingestion of continental aerosols iinto the TC periphery. The present study strongly supports this finding. For instance, **Figure 5** presents the fields of *Lightning Potential Index* (LPI) at 28 Aug. 20 z, and 22 z (t=44 and 46 h in Fig. 1). The LPI was introduced by Lynn and Yair (2009). The LPI is the volume integral of the total mass flux of ice and liquid water within the "charging zone" (0 to -20°C) of the cloud. The LPI has the same meaning as the lightning probability parameter introduced by Khain et al (2008a). Figure 5 shows also lightning in Katrina (2005) at two different time instances (Shao et al, 2005). The squares show the location of the fine grid approximately corresponding to these time instances. One can see that while in the MAR run the LPI is the highest in the eyewall all the time. Note that simulations of lightning in TC using bulk-parameterization scheme (Fierro et al 2007) (in which aerosol effects were not taken into account) also indicate that lightning was concentrated in the TC central area independently on the stage of TC evolution.

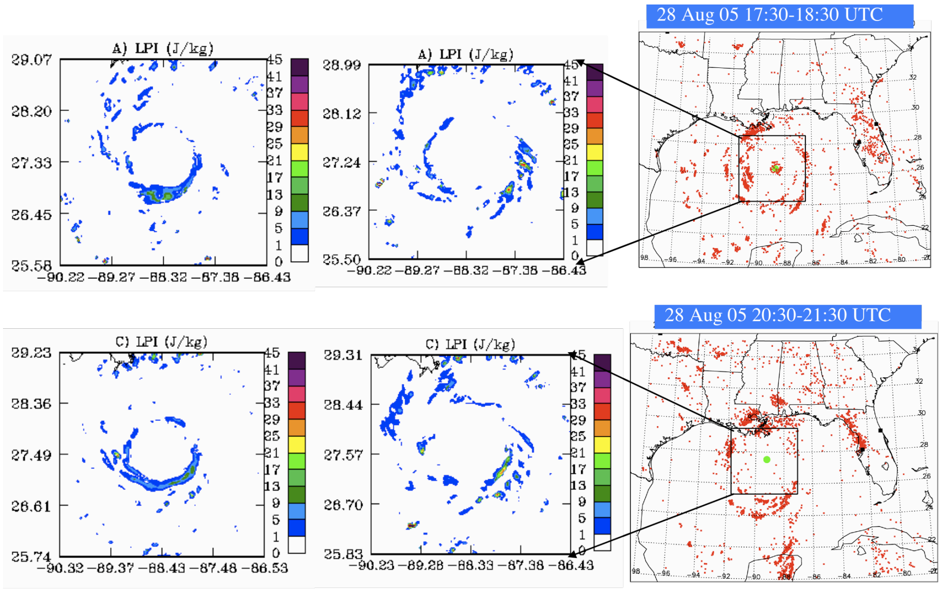
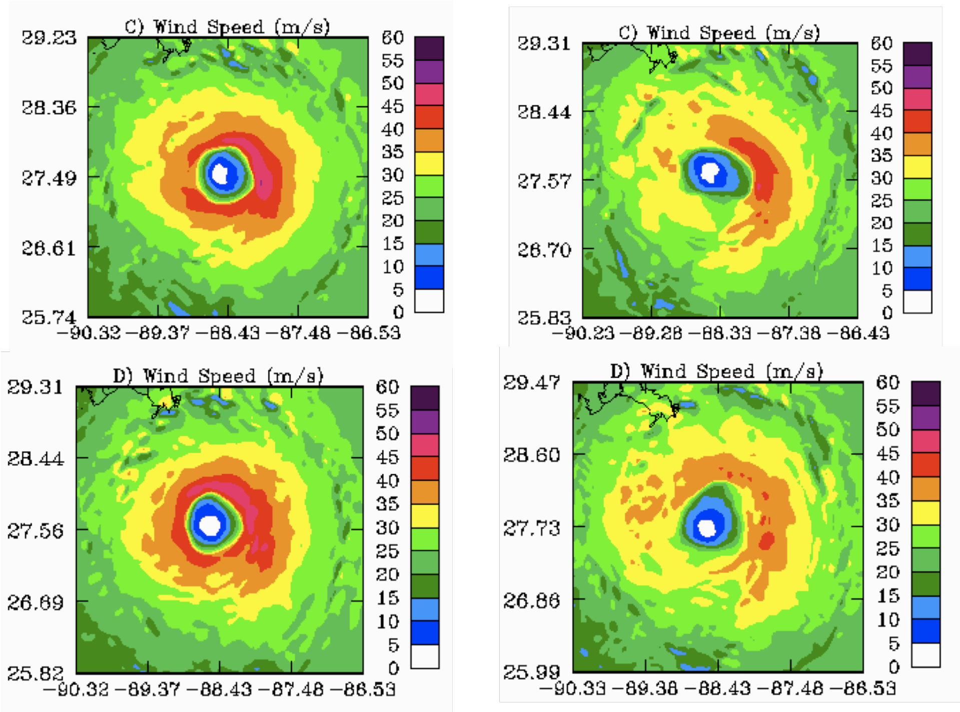


Figure 5. *The fields of Lightning Potential Index (LPI) calculated in MAR and MAR-CON runs at 28 Aug. 20 z, and 22 z. The lightning in Katrina (2005) is also presented (after Shao et al, 2005). Zones of lightning are marked by red dots; the TC eye is marked green. The square shows the location of the fine grid corresponding to these time instances.*

Figure 5 shows the time instance of the dissipation of the internal lightning ring in the course of intensification of convection and lightning at the TC periphery. One can see that disappearance of lightning in the eyewall in MAR-CON run agrees well with the behavior of lightning in Katrina. The disappearance of lightning in the eyewall in the MAR-CON takes place about 5-6 hours before the TC weakening. **Figure 6** shows the fields of maximum wind speed 28 Aug. 21 z (upper panels), and 22 z in runs MAR and MAR_CON. One can see a significant decrease in the maximum wind speed up to 15 m/s, i.e. by 20-25%. This decrease is substantially stronger than it was reported by Khain et al (2008a). One of the reasons is that Khain et al (2008a) used the bulk-parameterization scheme that is not sensitive to aerosols, as well as the fact that an artificial approach to parameterize aerosol effects by warm rain preventing was performed within the frame of this scheme.



4. Discussion and conclusions

Figure 6: The fields of maximum wind speed 28 Aug. 21 z (upper panels), and 22 z. in runs MAR (left) and MAR_CON (right).

For the first time TC evolution was calculated using explicit spectral bin microphysics (SBM). Simulations with resolution of 3 km, were made with the WRF/SBM. The evolution of Katrina was simulated during 72 hours beginning after it had just bypassed Florida to 12 hours after landfall. In these simulations the effects of continental aerosols ingested into its circulation TC on the TC structure and intensity were investigated. It is shown that continental aerosols invigorate convection (largely at the TC periphery), which leads to TC weakening. Maximum TC weakening took place ~20 h before landfall, when the TC intensity reached its maximum. The minimum pressure increased by ~16 mb, and maximum velocity decreased by about 15 m/s. The difference in the intensities remains significant even during the TC landfall. Thus, the results indicate that there is another (in addition to decrease in the surface fluxes) mechanism of weakening of TCs approaching the land. This mechanism is related to effects of continental aerosols involved into the TC circulation. Note that the weakening and the inner core collapsing was simulated in spite of the fact that the SST maximum was located near the coastal line, and no TC-ocean interaction was taken into account.

The application of the TC models with the spectral bin microphysics seems to open the way to improve prediction of TC intensity, wind and precipitation and lightning of landfalling hurricanes. Many studies have focused on reproducing the rapid intensification, but not on the collapse of the inner core and subsequent weakening as the storm approached the coast. The results also open the possibility to mitigate TC intensity by seeding of clouds at the TC periphery with small aerosol particles as it was discussed by Rosenfeld et al (2007) and Khain et al (2008a).

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References:

Arakawa, A. and Shubert W.H., 1974: Interaction of a cumulus cloud ensemble with the large-scale environment. Part. 1. *J. Atmos. Sci.,* 31, 674-701

Bender, M. A., I. Ginis, R. Tuleya, B. Thomas, and T. Marchok, 2007: The operational GFDL coupled hurricane-ocean prediction system and a summary of its performance. Mon. Wea. Rev., 135, 3965-3989

Bott, A., 1998: A flux method for the numerical solution of the stochastic collection equation *J. Atmos. Sci.,* **55**, 2284-2293.

Fan J., M. Ovtchinnikov, J. Comstock, S McFarlane and A. Khain, 2009: Modeling Arctic mixed-phase clouds and associated ice formation. *J. Geophys. Res. 114, D04205, doi:10.1029/2008JD010782*.

Ferrier, B. S., 2005: An efficient mixed-phase cloud and precipitation scheme for use in operational NWP models. Eos, Trans. Amer. Geophys. Union, 86 (Spring Meeting Suppl.) abstract A42A-02.

Fierro A.O. , L. Leslie, E. Mansell, J. Straka, D. MacGorman, and C. Ziegler, 2007: A high-resolution simulation of microphysics and electrification in an idealized hurricane-like vortex. *Meteorol. Atmos. Phys*. **98**, 13-33, Doi: 10.1007/s00703-006-0237-0.

Hallett, J., and S. C. Mossop, 1974: Production of secondary ice crystals during the riming process. *Natur*e, **249**, 26-28.

Iguchi, T., T. Nakajima, A. Khain, K. Saito, T. Takemura, and K Suzuki: 2008: A study of the cloud microphysical properties influenced by aerosols in an East Asia region using a meso-scale model coupled with a bin microphysics for clouds J. Geophys. Res. 113, D14215, doi: 10.1029/2007JD009774, pp 28.

Jorgensen, D. P., E.J. Zipser, and. M.A. LeMone, 1985: Vertical motions in intense hurricanes. *J. Atmos. Sci.,* **42**, 839-856.

Khain A. P. 2009: Effects of aerosols on precipitation: a review. Environ. Res. Lett. 4 (2009) 015004.

Khain, A. P., M. Ovtchinnikov, M. Pinsky, A. Pokrovsky, and H. Krugliak, 2000: Notes on the state-of-the-art numerical modeling of cloud microphysics. *Atmos. Res.* **55**, 159-224.

Khain A.P., Pinsky, M.B., M. Shapiro and A. Pokrovsky, 2001a: Graupel-drop collision efficiencies. *J. Atmos. Sci.,* **58**, 2571-2595.

Khain A., A. Pokrovsky, M. Pinsky, A. Seifert, and V. Phillips, 2004: Effects of atmospheric aerosols on deep convective clouds as seen from simulations using a spectral microphysics mixed-phase cumulus cloud model Part 1: Model description. *J. Atmos. Sci* **61**, 2963-2982.

Khain, A.P., D. Rosenfeld and A. Pokrovsky, 2005: Aerosol impact on the dynamics and microphysics of convective clouds. *Quart. J. Roy. Meteor. Soc.*, **131**, 2639-2663.

Khain, A. N. Cohen, B. Lynn and A. Pokrovsky, 2008a: Possible aerosol effects on lightning activity and structure of hurricanes. *J. Atmos. Sci*. 65, 3652-3667.

Khain A.P., N. BenMoshe, A. Pokrovsky, 2008b: Aerosol effects on microphysics and precipitation in convective clouds with a warm cloud base: an attempt of classification. J. Atmos. Sci., 65, 1721-1748.

Khain, A.P. and B. Lynn, 2009: Simulation of a super cell storm in clean and dirty atmosphere. J. Geophys. Res. (in press).

Khain, A. P, L. R. Leung, B. Lynn and S. Ghan, 2009: Effects of aerosols on the dynamics and microphysics of squall lines simulated by spectral bin and bulk parameterization schemes , J. Geophys. Res. (in revision)

Koren I., Y. J. Kaufman, D. Rosenfeld, L. A. Remer, Y. Rudich, 2005: Aerosol invigoration and restructuring of Atlantic convective clouds, *Geophys. Res. Lett.,* **32***,* L14828, doi: 10.1029/2005GL023187.

Kurihara, Y., 1973: A scheme of moist convective adjustment. Mon. Wea. Rev., 101, 547-553.

Levin Z., and W.R. Cotton, 2009: Aerosol pollution impact on precipitation: A scientific Review, *WMO/IUGG report*, Springer, 386 pp.

Li X, W-K. Tao, A.P. Khain, J. Simpson and D. E. Johnson, 2009a: Sensitivity of a Cloud-Resolving Model to Bulk and Explicit Bin Microphysical Schemes. Part I: Validation with a PRE-STORM Case. J. Atmos. Sci. 66, 3-21..

Li X, W-K. Tao, A.P. Khain, J. Simpson and D. E.Johnson, 2009b: Sensitivity of a Cloud-Resolving Model to Bulk and Explicit Bin Microphysical Schemes. Part II: Cloud Microphysics and Storm Dynamics Interactions. J. Atmos. Sci. 66, 22-40.

Lynn *B*., A. Khain, J. Dudhia, D. Rosenfeld, A. Pokrovsky, and A. Seifert 2005a: Spectral (bin) microphysics coupled with a mesoscale model (MM5). Part 1. Model description and first results*. Mon. Wea. Rev.* **133**, 44-58.

Lynn *B*., A. Khain, J. Dudhia, D. Rosenfeld, A. Pokrovsky, and A. Seifert, 2005b*:* Spectral (bin) microphysics coupled with a mesoscale model (MM5). Part 2: Simulation of a CaPe rain event with squall line *Mon. Wea. Rev.*, **133**, 59-71.

Lynn B., and Y. Yair, 2009: Prediction of lightning flash density with the WRF model. Submitted to *Adv. Geophys.*

Meyers, M. P., P. J. DeMott, and W. R. Cotton, 1992: New primary ice-nucleation parameterizations in an explicit cloud model. *J. Appl. Meteor.*, **31**, 708-721.

Pinsky, M., A. P. Khain, and M. Shapiro 2001: Collision efficiency of drops in a wide range of Reynolds numbers: Effects of pressure on spectrum evolution. *J. Atmos. Sci.* **58**, 742-764.

Pruppacher, H. R., 1995: A new look at homogeneous ice nucleation in supercooled water drops. *J. Atmos. Sci.,* **52**, 1924-1933.

Rosenfeld D., A. Khain, B. Lynn, W.L. Woodley 2007: Simulation of hurricane response to suppression of warm rain by sub-micron aerosols. *Atmos. Chem. Phys. Discuss*., **7**, 5647-5674.

Rosenfeld D., U. Lohmann, G.B. Raga, C.D. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissell, M.O. Andreae, 2008: Flood or Drought: How Do Aerosols Affect Precipitation? Science, 321, 1309-1313

Seifert, A. and K. Beheng, 2006: A two-moment cloud microphysics parameterization for mixed-phase clouds. Part 1: Model description, Meteorol. Atmos. Phys. 92, 45-66.

Shao X.M., J. Harlin, M. Stock, M. Stanley, A. Regan, K. Wiens, T. Hamlin, M. Pongratz, D. Suszcynsky. and T. Light, Los Alamos National Laboratory, Los Alamos, N.M, 18 October 2005, Katrina and Rita were lit up with lightning, *EOS*, **86**, No.42, page 398-399.

Skamarock, W.C., J.B. Klemp, J. Dudhia, D.O. Gill, D.M. Barker, W. Wang, and J.G. Powers, 2005: A description of the Advanced Research WRF Version 2. NCAR Tech Notes-468+STR.

Thompson, G., R. R. Rasmussen, and K. Manning, 2004: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part 1: Description and sensitivity analysis, *Mon. Wea. Rev.*, **132**, 519-542.

Vali, G., Freezing rate due to heterogeneous nucleation. *J. Atmos. Sci.,* **51**, 1843-1856, 1994.

Wang C., 2005: A modeling study of the response of tropical deep convection to the increase of cloud condensational nuclei concentration: 1. Dynamics and microphysics. *J. Geophys. Res*., **110**; D21211, doi:10.1029/2004JD005720.

Zhang H., G.M. McFarquhar, S.M. Saleeby and W.R. Cotton, 2007: Impacts of Saharan dust as CCN on the evolution of an idealized tropical cyclone. Geophys. Res. Lett., **34**, L14812, doi: 10.2029/2007GL029876.