Assessing A New Approach to Tropical Cyclone Modification by Hygroscopic Smoke

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1. Introduction

The Department of Homeland Security (DHS) asked NOAA/ESRL in Boulder to organize a workshop on possible new scientific theory and approaches to tropical cyclone (TC) modification in February, 2008. Scientists from around the world presented a number of hypotheses and new ideas. On this basis the DHS funded the Hurricane Aerosol and Microphysics Program (HAMP). The PIs were the authors of this extended abstract. The initial success of HAMP to show plausibility of hurricane modification resonated with the aftermath of STORMFURY that led to an early termination of a scientifically very productive and successful program. One of several tangible results of the program is the recognition that aerosols can affect hurricane intensities, and when taken into account the predictions can be improved. Here we report some of the HAMP observational and theoretical work results of aerosols effects on TCs.

2. The theoretical basis

TCs are energized by the huge amount of latent heat that is released by the condensation of water and its subsequent precipitation. Therefore, it can be expected that changes in the precipitation-forming processes that would change or redistribute the precipitation in the TC would also redistribute the latent heating and respectively affect the dynamics of the storm and its intensity. This concept was first invoked in the Stormfury hurricane-mitigation experiment (Willoughby et al., 1985) that focused on glaciogenic seeding of vigorous, convective, clouds within the eye wall. The Stormfury experiment failed to show a detectable effect on the seeded hurricanes. It is now understood that the amount of supercooled water in the hurricanes is too small to expect much of a seeding effect upon freezing, and this small amount of water freezes naturally quickly above the 0°C level. This is because the cloud drops in tropical maritime clouds become sufficiently large to undergo effective coalescence and produce warm rain well below the freezing level. Much of the rain precipitates without ever freezing.

Much more recently Rosenfeld et al. (2007) and Cotton et al. (2007) independently hypothesized that the invigoration of convective clouds near the periphery of the TC might be achievable by adding hygroscopic aerosols that slow the warm rain-forming processes. This was postulated to take place at the expense of the eye wall by intercepting some of the energy being transported toward the inner core and weaken the storm.

The basis for the cloud invigoration hypothesis was reviewed by Rosenfeld et al. (2008). Adding large concentrations of smoke aerosols to marine tropical clouds can delay the formation of warm rain to above the 0°C isotherm within the cloud. This is done by the nucleating activity of cloud condensation nuclei (CCN) aerosols. Large concentrations of CCN nucleate larger concentrations of smaller cloud drops. The smaller drops are slower to coalesce into rain drops. The cloud water that did not precipitate as rain can either re-evaporate at low levels, or rise with the updraft above the freezing level, creating enhanced amounts of supercooled water, and thereby produce ice hydrometeors with the consequent enhancement of the release of the latent heat of freezing. This added heat release invigorates the convection and may enhance rain amounts in a moist and weakly sheared tropical atmosphere (Fan et el., 2009) Greater amounts of supercooled water with stronger updrafts and more ice hydrometeors are expected to produce more lightning. Simulations show that the invigoration also enhances the downdraft and low level evaporative cooling (Khain et al, 2005; van den Heever and Cotton, 2007).

3. Simulations of aerosol impacts on TC

Rosenfeld et al. (2007) and Cotton et al. (2007) independently simulated TCs with suppressed coalescence, and showed that this reduces their maximum wind intensities. The simulations of Rosenfeld et al. (2007) showed that the suppressed warm rain caused low-level cooling in the lowest 3 – 4 km, probably due to re-evaporation of some of the cloud water that did not precipitate and due to the enhanced colder downdrafts from the invigorated convection at the periphery. The added aerosols in the simulations of Zhang et al. (2009), Carrio and Cotton (2011) and Krall and Cotton (2011) also invigorated the convection at the spiral rain bands and enhanced cold-pools by producing downdrafts and evaporative cooling of rain. These cold-pools blocked the surface radial inflow transporting high θe air into the eyewall, and led to its weakening and widening, in a mechanism similar to that of an eyewall replacement. Convection outside the eyewall was previously observed to introduce air with low equivalent potential temperature (θe) into the boundary layer inflow, resulting in blocking of the inflow of the warm air to the eyewall (Powell, 1990). In Krall and Cotton's simulations, however, when pollution aerosols were swept into the storm core the storm actually intensified. Subsequently, as aerosol were scavenged before reaching the storm core, only convection in the outer rainbands were intensified, and the storm weakened, consistent with the working hypothesis. That work plus Carrio and Cotton's (2011) targeted seeding simulations suggests that the response to aerosols critically depends on the locations of where the aerosols actually infect the storm.

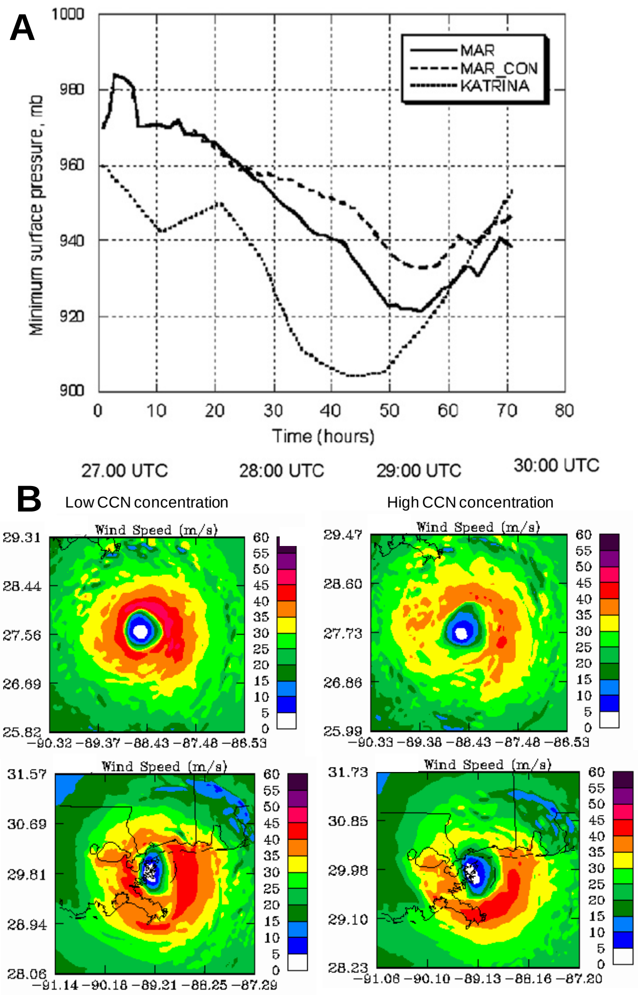

Figure 1. Simulations of aerosol effects on Hurricane Katrina. A. Time dependence of minimum pressure for low (MAR) and high (MAR_CON) CCN concentrations at the periphery of the storm. B maximum wind speed low and high CCN concentrations at the periphery of the storm at 28 Aug. 22 Z (upper row) and during landfall 29th at 12Z (From Khain et al., 2010)

Sensitivity simulations of Hurricane Katrina to the impacts of pollution aerosols showed similar results (Khain et al., 2008a and 2010, Khain and Lynn, 2011) using the Weather Research and Forecast (WRF) Model with the implementation of a spectral bin microphysical (SBM) scheme. Penetration of continental aerosols to the TC periphery caused by the TC circulation approaching the land was simulated. As a result of the aerosol penetration, concentration of CCN (at 1% of supersaturation) increased at the TC periphery (radial distance from the center > ~200 km) from 100 cm^{-3} to about 1000 cm^{-3}. This increase in CCN concentration in the lower atmosphere and successive penetration of these CCN into rain bands at the TC periphery resulted in an increase of 16 hPA in the central pressure of the storm, as shown in Fig. 1a (Khain et al., 2010). Maximum wind speed weakened by 10-15 m/s and the area of strong winds significantly decreased (Fig. 1).

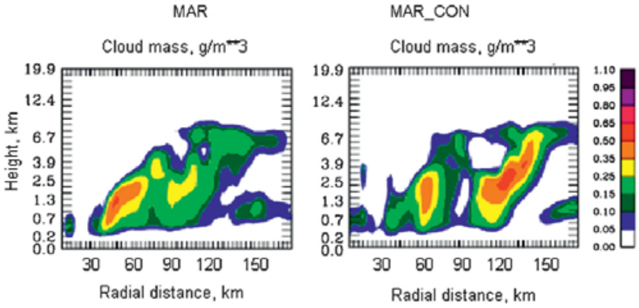

Figure 2: The cross section of azimuthally averaged cloud water content (g/m^3) in simulations (left) maritime and (right) polluted at times when the maximum difference in the TC intensities took place (From Khain et al., 2010). Note that the polluted case (right) developed stronger and more water-rich clouds at the storm periphery, whereas the eye is not well defined and widened.

The simulation showed that penetration of continental aerosol to the TC periphery leads to dramatic intensification of convection at the TC periphery which competes with the convection in the eyewall (see Fig. 2).

Building on the earlier dust simulations of Zhang et al., (2007; 2009), Carrio and Cotton (2011) performed idealized simulations of the direct seeding of CCN in the outer rain band region of a hurricane. The Regional Atmospheric Modeling System was used in those idealized simulations that included a two-moment microphysics scheme which emulates bin microphysics for drop collection, ice particle riming, and sedimentation. New algorithms for sea-spray generation of CCN and precipitation scavenging were added (Carrio and Cotton, 2011). These simulations supported the hypothesis that much of the variability to enhanced CCN concentrations found in the Zhang et al. (2009) simulations was due to the variable intensity of outer rainband convection when the enhanced CCN advected into that region. Moreover, the environmental CCN are not always transported from the storm environment into outer rain band convection as transport is at the mercy of the local flow in those regions. Furthermore, those simulations showed a clear step-by-step response of the hurricane to the direct seeding of enhanced CCN in the outer rainband of the storm as described in the basic hypothesis.

4. Quantitative Relations Between Aerosol Amounts and TC Intensity

Although the observational and modeling evidence suggests that aerosols affect the structure of a TC, the major uncertainty is whether these structural changes are manifested as changes in TC intensity as indicated by the model simulations. Rosenfeld et al. (2011) used observed TC data and forecasted TC data to statistically analyze the relationships between TC intensity and aerosol quantities at the TC's periphery. They separated the aerosol's effect on TC intensity from all other effects by using data of TC prediction models that take into account all meteorological and sea surface temperature properties, but not the aerosols. The models used were the dynamically based GFDL (Bender et al. 2007) and the statistically based SHIPS (DeMaria et al. 2005) models. The hypothesis was that if greater aerosol amounts actually act to decrease storm intensity, the forecast model would tend to over-predict the observed intensities of the more "polluted" storms. Rosenfeld et al. (2011) tested this hypothesis by examining the prediction errors of the maximum sustained wind velocities (dVmax) and their statistical relationship with the aerosol optical depth (AOD) that was calculated by the Goddard Chemistry Aerosol Radiation and Transport (GOCART) hindcast model (Chin et al., 2000). The GOCART was used to obtain aerosols under cloudy conditions and to avoid measurement artifacts due to meteorological conditions. The results showed that the variability of aerosol quantities in a TC's periphery can explain about 8% of the forecast errors of the TC. Indeed, the actual intensities of polluted TCs were found to be on average lower than their predicted values, providing additional evidence for the hypothesis. Quantitatively, an increase in AOD by 0.01 is associated on average with a decrease of 0.3 knots in the peak wind speed. No distinction between aerosol types could be made. It was also found that TC intensity might be more susceptible to the impacts of aerosols during their developing stages and less in the TC's mature and dissipating stages, consistent with the modeling results of Zhang et al., (2009).

5. Summary

Based on the above observations and simulations, our present understanding of the effect of aerosols on tropical clouds and cyclones is summarized in the following links in the conceptual chain, which is illustrated in Fig. 3:

a. Small (sub-micron) CCN aerosols in the form of particulate pollution and/or desert dust nucleate larger numbers of smaller cloud drops that slow the coalescence of the cloud drops into rain drops.
b. The CCN aerosols present in the peripheral clouds of the hurricane slow the rain forming processes there.
c. The delayed formation of rain decreases the amount of early rainout from the rising air; hence more water can ascend to freezing levels as supercooled water where ice precipitation particles form.
d. The greater amount of freezing water aloft releases extra latent heat that invigorates the convection. The invigoration and the added supercooled water are manifested in greater cloud electrification and lightning discharges.

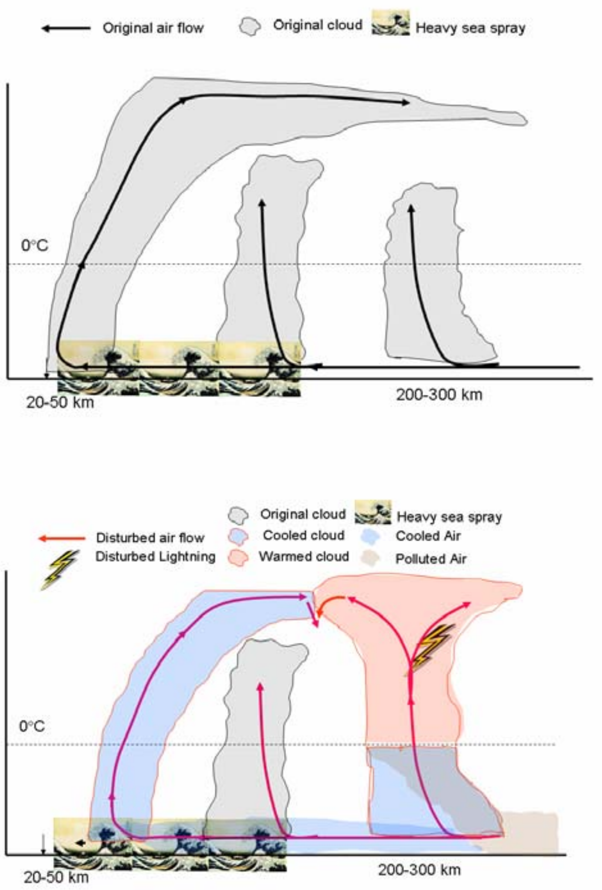

Figure 3: Conceptual model of aerosol impacts on tropical cyclones. The undisturbed and disturbed states are shown in the top and bottom panels, respectively. In the bottom panel, pollution or dust aerosols slow warm rain in the peripheral clouds causing invigoration and electrification of the clouds and warming aloft, coupled with stronger downdrafts and intensified low-level cool-pools. Strong nucleation and precipitation scavenging and sea spray from the rough sea promotes warm rain in the inner cloud bands and eyewall clouds, which reduces the suppression effect due to any remaining pollution aerosols that were not washed down, so that little aerosol-induced invigoration can occur there. The convection in the outer cloud band decreases the inflow towards the eyewall. The cold-pools also partially block the inflow, causing cooling, weakening and widening of the eyewall, leading to weaker winds.

e. The greater vigor of the clouds draws more ascending air at the periphery of the storm, thereby bleeding the low-level airflow towards the eye wall. The weakened convergence towards the center causes the central pressure to rise;

less air ascends in the eye wall, and there is respectively lower maximum wind speed.

f. The intensified ice precipitation in the peripheral clouds melts and evaporates at the lower levels, thereby cooling the air that converges into the center of the storm.
g. Stronger low-level cooling produces cold-pools which favor the intensification of storm cells in the outer rain bands, which transport more water vertically leading to enhanced latent heating and stronger convection in a positive feedback loop.
h. Additional low-level cooling occurs when the cloud drops that did not precipitate and did not ascend to the freezing level re-evaporate.
i. The storm is further weakened by cooling of the low-level air that converges to the center, in addition to the air bleeding effect that was discussed in the first five points. The cooler air has less buoyancy and hence dampens the rising air in the eye wall, thereby weakening further the convergence and the maximum wind speed of the storm.
j. Under hurricane force winds very intense sea spray is lifted efficiently by roll vortices in the BL and induces rain of mostly sea water at the height of the convective cloud base. This restores the warm rain processes and offsets the delaying effect of small CCN aerosols on rain forming processes. Furthermore the core of the TC is nearly saturated at low levels thus cold-pool formation in that region is inhibited. Therefore the CCN aerosol effect would be most effective in the peripheral clouds of the storm, where the winds are still not very strong. Strengthening of the winds there would reduce the sensitivity of the storm to the weakening effect of the CCN aerosols.

These links in the conceptual model are still a hypothesis that requires additional investigation. However, its physical plausibility underline the importance of understanding precipitation forming and evaporation processes in TC clouds and the need to further observe and simulate them and the resultant cold-pools properly in order to obtain additional improvements in TC prediction models.

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