2.3 ON ENGINEERING HURRICANES

William R. Cotton and Stephen M. Saleeby

Department of Atmospheric Science, Colorado State University, Fort Collins, CO

1. INTRODUCTION

In the last year there have been two papers that have proposed that seeding hurricanes with small hygroscopic particles, as opposed to conventional giant hygroscopic particle seeding, could lead to the reduction in their intensity (Cotton et al., 2007; Rosenfeld et al., 2007). The Cotton et al. (2007) paper was based on preliminary results of simulations of the impact of African dust on hurricane intensity (Zhang et al., 2007), which showed that dust acting as CCN influenced the storm development by inducing changes in the hydrometeor properties, modifying the storm diabatic heating distribution and thermodynamic structure, and ultimately influencing the storm intensity through complex dynamical responses. Some simulated storm intensities showed a monotonic decrease in storm intensity with increasing concentrations of CCN under certain configurations of the model but this trend was easily modified just by introducing slight variations in the GCCN profile. Thus, Zhang et al. (2007) concluded that the physical processes responsible for the impact of dust as nucleating aerosols on hurricane development need to be examined in the future under a wide range of environmental conditions.

Since then Henian Zhang has carried out more simulations that illustrate that the response is by no means simple or monotonic with increasing CCN concentrations. In some cases increasing CCN by only 1/cc at initial times leads to a large response in hurricane intensity.

2. DESCRIPTION OF THE SIMULATIONS

The simulations reported by Zhang et al. (2007) and Zhang (2008) were designed to investigate the influence of Saharan dust serving as CCN, GCCN, and IN on the dynamics of an idealized TC. The simulations used the Regional Atmospheric Modeling System (RAMS) version 4.3 (Cotton et al., 2003). The simulations were initialized with the pressure, temperature and wind fields of an axisymmetric MCV consistent with observations obtained from several pre-TC MCVs (Montgomery et al., 2006). Three nested domains with horizontal resolutions of 24, 6 and 2 km 10 were used. The numbers of horizontal grid points for Domain 1, Domain 2 and Domain 3 were 80 × 80, 102 × 102 and 152 × 152. There were 40 unevenly spaced vertical levels extending from the surface to 30 km with a minimum grid spacing near the surface of 300 m and a maximum vertical grid spacing of 1 km at higher altitudes. The Rayleigh friction absorbing layer extended from 20 km to 30 km. The vortex was allowed to grow for 3 days in a zero wind environment over the ocean with a constant sea surface temperature (SST) of 29C. Pre-TC MCVs are usually found on the southern edge of the SAL, which is a transient zone with hot and dry SAL air to the north and warm moist marine air to the south. Intrusion of dry air from the SAL into the convective systems could limit the impact of dust as nucleating aerosols. To focus on the impacts of dust in the SAL acting as CCN, a horizontally uniform Jordan sounding (Jordan, 1958), which is like a composite of soundings from both the SAL and non-SAL environments (Dunion and Velden, 2004), was used.

The two-moment microphysics scheme described in Cotton et al. (2003) and Saleeby and Cotton (2004), which emulates bin microphysics for collection and sedimentation, was used in the simulations. Saleeby and Cotton *(*2004) described the extension of that scheme to include two modes of droplets and explicit activation of CCN and GCCN. The initial CCN distribution was horizontally homogeneous. Results from three sensitivity tests with different CCN vertical profiles introduced at the time of initialization of the MCV were described by Zhang et al. (2007), representing clean, polluted and highly polluted scenarios. The clean simulation (hereafter “Clean”) was initialized with a constant CCN concentration of 100 cm^{-3} from the surface to 25 km. Dust particles were assumed to reside in a layer between 1 and 5 km (Karyampudi et al., 1999). To represent elevated dust particles in the SAL, the polluted simulation (hereafter “Polluted”) was initialized with a CCN concentration of 1000 cm-3 between 1 km and 5 km. The double polluted simulation (hereafter “Double”) was initialized with a CCN concentration of 2000 cm^{-3} in the same layer. The CCN concentration below 1 km and above 5 km in “Polluted” and “Double” was 100 cm^{-3}. The CCN were further assumed to be mostly hydrophobic with a water solubility of 10% to represent desert dust particles coated with sulfate. As described by Saleeby and Cotton (2004), the percentage of CCN activated during a time step depends upon temperature, vertical velocity, CCN median radius and number concentration. We will also show results of simulations in which CCN is introduced in Grids #1 and #2 at 36h and then 60h, respectively in the simulation. These two simulations more closely resemble what might be expected when a TC is seeded with pollution-sized CCN to reduce storm intensity.

Corresponding author address: William R. Cotton, Colorado State Univ., Atmos. Sci. Dept., Fort Collins, CO 80523; e-mail: cotton@atmos.colostate.edu

3. RESULTS

Figure 1 is a reproduction of the figure from Zhang et al., 2007 which shows the results of varying CCN concentrations at the time of start-up of the initial MCV. Shown are simulated maximum sea level pressure (SLP) and maximum surface winds as a function of time. The figure shows that after 36h major differences in maximum SLP and surface winds develop in response to varying CCN concentrations. The large amplitude differences in maximum surface winds of over 20m/s is what motivated the author to propose that seeding of TCs with small hygroscopic aerosols could be a viable means of reducing the intensity of TCs (Cotton et al., 2007). Note that the time at which the greatest response to CCN occurs corresponds to the time in which spiral rainbands form in the simulation. Zhang (2008) concluded that the spiral rainbands divert enthalpy from the eyewall region thus contributing to a weakening of the storm.

Note that Zhang (2008) repeated these simulations with CCN increased to 101/cc and found that significant differences in storm intensity although the scenario of response was similar to that for CCN=100/cc (see Figure 2). Additional simulations with small changes in the warm bubble used as part of the initialization procedure led to similar large differences after 36h or so. She also introduced a wider range of CCN concentrations ranging from 100/cc, to 500/cc, to 1000/cc, to 1500/cc, to 2000/cc as shown in Figure 2. These results reveal a non-monotonic response to increasing CCN amounts. Thus these simulations reveal that the response to CCN introduced during the initial spin up of the vortex do not represent the type of response that would be expected in seeding mature TCs. It is more like seeding MCVs or pre-TC tropical storms where the expected response is more chaotic. We therefore expect that introducing enhanced CCN later in the simulated storm lifecycle is more representative of what might happen in seeding actual mature TCs. Note that the simulations do not reveal any significant response to enhanced CCN in the eyewall region or within a radius of 45km. This is because the enhanced CCN are washed out well before they are transported close to the eyewall. Throughout the simulations CCN concentrations in the eyewall region remain low and probably unrealistically low (about 1/cc or less) owing to the fact that sea-spray generation of CCN is not simulated.

Figure 3 illustrates the simulated storm response to introducing variable CCN concentrations in only the outer grids of the model at 36h about the time that spiral rainbands become significant in the simulated storm dynamics. Again a wider range of CCN concentrations from 100/cc, to 500/cc, to 1000/cc, to 1500/cc, to 2000/cc is introduced. The response to increasing CCN is still significant being a maximum difference of about 20m/s, but less than when introduced at the time of initial vortex spin-up and moreover the response is not monotonic to increasing CCN.

Figure 3 also illustrates the simulated storm response to introducing variable CCN concentrations in only the outer grids of the model at 60h when the storm is quite mature. This shows that the response to seeding with pollution-sized CCN in a mature storm is quite small.

4. IMPLICATIONS TO HYGROSCOPIC SEEDING OF HURRICANES

The results of further simulations of the effects of Saharan dust acting as CCN suggest that there is some potential for weakening TCs by seeding them with pollution-sized (small) CCN but the response is by no means monotonic with increasing aerosol and certainly not as spectacular as suggested by Cotton et al. (2007), particularly for a mature TC that is within 60h of land-fall. Nonetheless these simulations do not directly simulate small particle hygroscopic seeding beneath active spiral rainbands outward of 45km radius where the strongest response is observed in Zhang et al's. (2007) simulations. The next step (when funding becomes available) is to emulate the actual release and transport and dispersion of seeding material beneath active spiral rainbands by a fleet of something like C-130's. Owing to the dangers of flying beneath these storms in a TC environment droppable pyrotechnic flares which produce pollution-sized CCN need to be developed. In addition natural production of CCN by sea-spray should be simulated. If such idealized simulations show that seeding directly beneath spiral rainbands in more mature storms is effective and monotonic with higher generator outputs, then the simulations should proceed to more realistic cases like Katrina. Until that work is accomplished, the question of whether there is a potential for hygroscopic seeding to significantly weaken hurricanes remains unresolved. In addition, potential adverse consequences of such activities and the process of decision making and liability must be addressed.

Acknowledgements: The authors would like to acknowledge Brenda Thompson for her assistance with this paper. The authors would like to thank Henian Zhang for providing the figures adapted from her dissertation paper. This material is based upon work supported by the National Science Foundation under Grant No. ATM-0526600. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

5. REFERENCES

Cotton, W.R., R.A. Pielke, Sr., R.L. Walko, G.E. Liston, C.J. Tremback, H. Jiang, R.L. McAnelly, J.Y. Harrington, M.E. Nicholls, G.G. Carrió, J.P. McFadden, 2003: RAMS 2001: Current status and future directions. *Meteor. Atmos Physics*, **82**, 5-29.

Cotton, W.R., H. Zhang, G.M. McFarquhar, and S.M. Saleeby, 2007: Should we consider polluting hurricanes to reduce their intensity? *J. Wea. Mod.*, **39**, 70-73.

Dunion, J. P., and C. S. Velden, 2004: The impact of the Saharan Air Layer on Atlantic tropical cyclone activity, *Bull. Am. Meteorol. Soc.*, **85**, 353–365.

Jordan, C. L., 1958: Mean soundings for the West Indies area. *J. Meteorol.*, **15**, 91–97.

Karyampudi, V. M., et al., 1999: Validation of the Saharan dust plume conceptual model using Lidar, Meteosat, and ECMWF data. *Bull. Am. Meteorol. Soc.*, **80**, 1045-1074.

Montgomery, M. T., M. E. Nicholls, T. A. Cram, and A. B. Saunders, 2006: A vortical hot tower route to tropical cyclogenesis. *J. Atmos. Sci.*, **63**, 355– 386.

Rosenfeld, D., A. Khain, B. Lynn, and W.L. Woodley, 2007: Simulation of hurricane response to suppression of warm rain by sub-micron aerosols. *Atmos. Chem. Phys.*, **8**, 5647-5674.

Saleeby, S.M., and W.R. Cotton, 2004: A large droplet mode and prognostic number concentration of cloud droplets in the Colorado State University Regional Atmospheric Modeling System (RAMS). Part I: Module descriptions and supercell test simulations. *J. Appl. Meteor.*, **43**, 182-195.

Zhang, H., 2008: Impact of Saharan dust as CCN on the evolution of an idealized tropical cyclone. Ph.D. dissertation, University of Illinois at Urbana-Champaign, Urbana-Champaign, IL, 238 pp.

Zhang H., G. M. McFarquhar, S. M. Saleeby, W. R. Cotton, 2007: Impacts of Saharan dust as CCN on the evolution of an idealized tropical cyclone. *Geophys. Res. Lett.*, **34**, L14812, doi:10.1029/2007 GL029876.

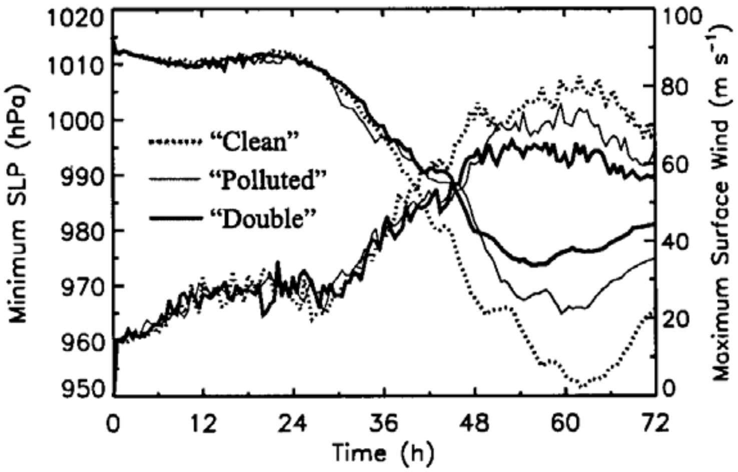

Figure 1. Temporal evolutions of the MSLP and maximum surface wind for ''Clean'' (dotted line), ''Polluted'' (thin solid line) and ''Double'' (thick solid line). (From Zhang et al., 2007).

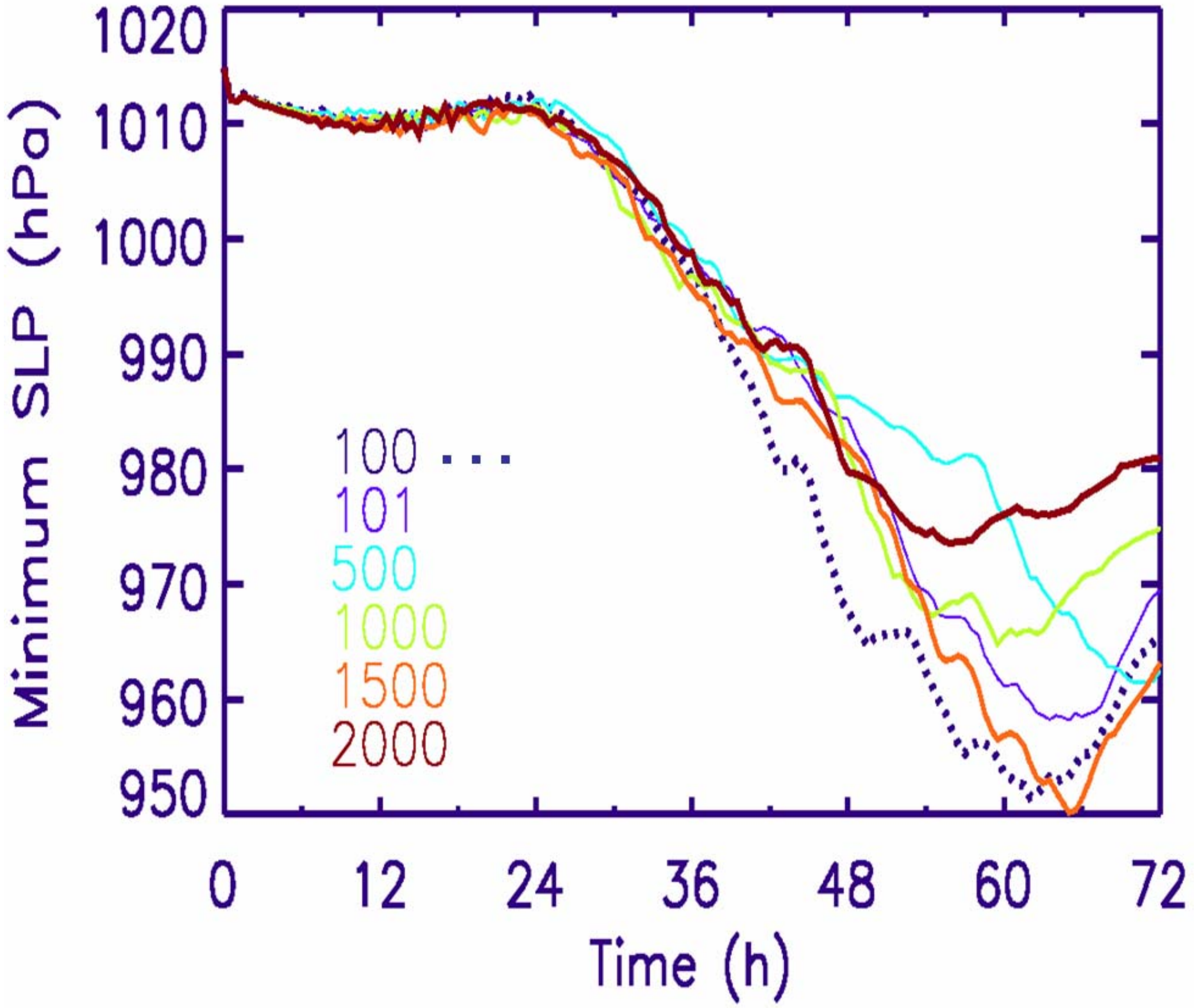

Figure 2. Simulated variation in maximum surface winds as a function of CCN concentrations for the runs with CCN introduced during initial spin-up. [From Zhang, 2008.]

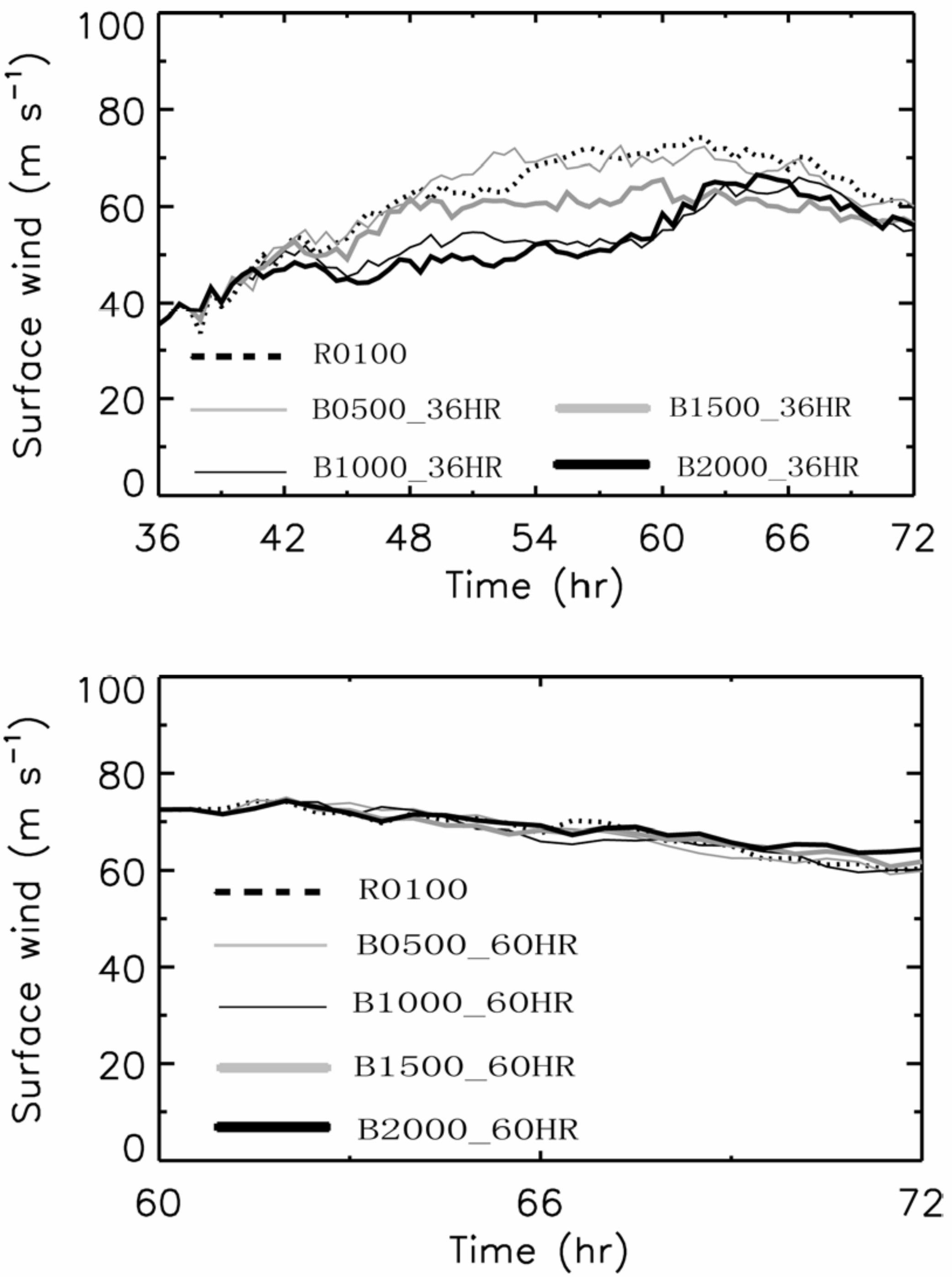

Figure 3. Simulated variation in maximum surface winds as a function of CCN concentrations for the runs with CCN introduced at the boundaries at 36h (top) and at 60h (bottom). [From Zhang, 2008; and personal communication.]