THE RISE AND FALL OF HAMP

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Abstract. In spite of its short period of existence, a great deal was accomplished during the Hurricane-Aerosol-Microphysics Program (HAMP). The research supports the original hypotheses that seeding with high concentrations of pollution sized aerosols in the outer rainbands of hurricanes can lead to significant weakening of a storm. This was demonstrated by simulations of both idealized storms and actual case studies and with advanced bin-emulating microphysics and spectral bin microphysics. It was also evident in satellite analysis of actual storms. There still remains much to unravel about the intricacies of aerosol interactions with tropical cyclones. First we need to understand the causal mechanisms for storm weakening at very high concentrations of CCN as storm rainfall and cold-pools are substantially reduced. Second, the aerosol influence has to be put in perspective of other factors influencing TC intensity including SST, wind shear, and the moisture content of the lower troposphere. Research under HAMP has also spun-off a strategy for parameterizing sea-spray generation in tropical cyclones, a process that is not only important to aerosol generation by the storm but also to the bulk thermodynamics of the storm system.

1. INTRODUCTION

Motivated by Zhang et al.'s (2007) and Rosenfeld et al.'s (2007) simulations, Cotton et al. (2007) and Rosenfeld et al. (2007) hypothesized that seeding hurricanes with pollution-sized aerosols could lead to a chain of responses leading to the eventual mitigation of the storm intensity. In the outer rainbands, increasing CCN concentrations results in reduced collision/coalescence, increased supercooled water aloft, enhanced convection (latent heat of freezing) and ultimately enhanced precipitation and low level cooling (evaporation). The increase in low level cold-pool coverage in the outer rainband region blocks the flow of energy into the storm core inhibiting the intensification of the tropical cyclone (TC). However, the amount of suppression of the strength of the TC depends on the timing between the transport of CCN to the outer rainbands and the intensity and lifecycle stage of the outer rainband convection. The outer rainband convection needs to be strong in order for the transport of supercooled liquid water aloft to take place. Note that Rosenfeld et al. (2007) arrived at a similar hypothesis using an entirely different dynamic model with simplified bulk microphysics.

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The hypotheses by Cotton et al. and Rosenfeld et al. and subsequently Khain et al. (2008a), as well as a few other hurricane mitigation hypotheses, motivated Rear Admiral (retired) Jay M. Cohen, Undersecretary of Homeland Security for Science and Technology of the United States Department of Homeland Security (DHS), at the time, to propose a workshop to develop a program to study the potential for hurricane mitigation. William D. Laska became the DHS Program Manager of a project that eventually became called the Hurricane and Aerosol Microphysics Program (HAMP). A science team composed of Woodley, Cotton, Golden, Ginis, Khain, and Rosenfeld was formed and funds were established to begin research on hurricane mitigation. It was indicated that this would be a three- year program of study with the potential of continuation after that. The first year's funding came in two blocks. The first block was processed through NOAA, then to CIRA, then to CSU, with Cotton as the PI. Owing to huge delays in NOAA processing the project, and that NOAA skimmed off about 20% of the overall budget to support NOAA management of the program, Wil Laska decided to not process any additional funds through NOAA but instead to fund Woodley Weather Consultants (WWC) directly for the second block of funds. The two blocks together amounted to one year funding of HAMP, but owing to delays much of that effort had to be compacted into a seven-month period, prolonged a bit by several months of no-cost extensions. Moreover, HAMP had hardly gotten underway when DHS administrators began to back off on supporting the notion of a hurricane mitigation project. Hence the program was renamed from HURMIT (Hurricane Mitigation) to HAMP and the effort was now focused on impacts of aerosols and microphysics on hurricane intensity prediction. Finally, by November, we were told that HAMP would not be continued after the one year of support, presumably a result of changes in DHS management. Thus HAMP experienced a rise and fall in a little over one year and one year of actual funding.

In spite of this brief period of existence, a great deal was accomplished in this research effort. What follows is a brief overview of the accomplishments of the project and what still needs to be done in the area of hurricane mitigation research.

RESEARCH ACCOMPLISHMENTS

2. COTTON'S GROUP: AEROSOLS, COLD-POOLS, AND HURRICANE INTENSITY MODULATION

Introduction

Zhang et al. (2007, 2009) examined the impacts of dust acting as CCN inserted into a hurricane environment. The simulations by Zhang et al. (2009) revealed a non-monotonic response such that increases in CCN concentrations weakened the storm, while further increases in CCN concentrations either strengthened or had no impact on it. That study did not reveal why such peculiar behavior should occur. We hypothesize that much of that variability 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 rainband convection as transport is at the mercy of the local flow in those regions. Furthermore, the hurricane is a huge aerosol scavenging machine such that virtually none of the dust made its way into the interior of the storm owing to strong washout.

A detailed description of the RAMS model setup is given in Carrio and Cotton (2010) and Woodley (2010). Model improvements that were made as part of this project include implementation of a targeted seeding algorithm, development of a prognostic scheme to take into account sea-salt surface sources based on empirical formulae (O'Dowd, 1999). Scavenging of aerosol by precipitation was implemented, based on the empirical scheme of Chate et al. (2007) linking scavenging coefficients to rainfall rates. Model improvements were tested in an interactive-nested-multi-grid framework and used for hurricane studies.

Exploration of Methods to Mitigate the Intensity of Tropical Storms

Full details of the simulations and results are given in Woodley (2010). We designed a series of "virtual flight" simulations for which the time of aerosol insertion, as well as the aerosol release rates are varied (see Figure 1). Simulated responses in the outer rainbands included greater amounts of supercooled water, stronger updraft velocities, greater rainfall rates, and more vigorous cold-pools. The results were monotonic with CCN concentrations except for very high values when much of the condensed water mass is thrust into anvils. This research has clearly shown that aerosols can have an appreciable impact on tropical cyclone intensity. The results show that the aerosol impacts are greatest in the outer rainbands of a TC and that the mechanism is largely linked to the strength of cold-pools. These results are consistent with the findings of Reimer et al. (2010) who found that varying wind shear impacted TC intensity by varying the strength of cold-pools in the outer rainbands. There are some unresolved issues, however. At very high seeding rates or very high concentrations of pollution CCN ingested in a storm like tropical cyclone NURI (Krall, 2010; Krall and Cotton, 2010) rainfall rates are substantially reduced and cold-pools are virtually non-existent. Nonetheless the simulated storms weakened but not as much as at lower CCN concentrations. Clearly there is an alternate method for storm weakening in response to enhanced CCN concentrations different from that proposed by Cotton et al. (2007).

The major impact of this research on hurricane intensity prediction is that it highlights the importance of low-level cold-pools, particularly in the outer rainbands on hurricane intensity. It means that methods for diagnosing cold-pool strength and area in real time need to be developed for hurricane intensity prediction. In addition, operational forecast models need to be implemented that can explicitly represent the variability of TC cold-pools due to variations in wind-shear, environmental moisture, and aerosols.

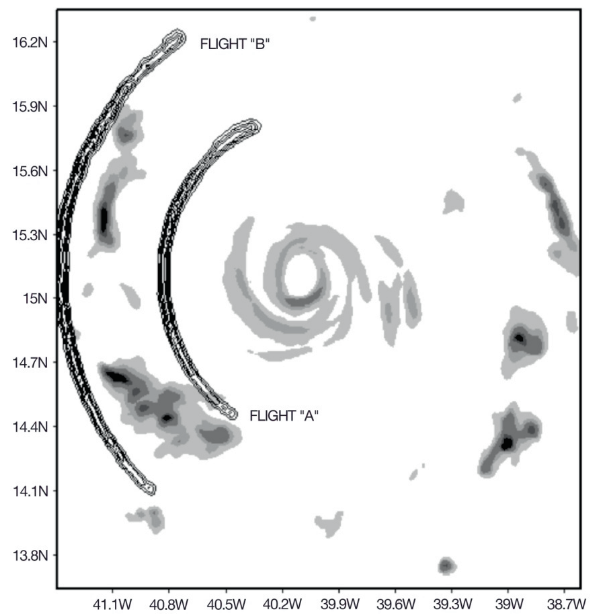

Figure 1: Virtual flights over internal and external radii.

3. ROSENFELD'S GROUP: OBTAIN SATELLITE OBSERVATIONS OF POLLUTION AEROSOLS SUPPRESSING WARM RAIN AND INVIGORATING SPIRAL CLOUD BANDS OF TROPICAL CYCLONES

The hypothesis that increased CCN aerosols decrease the intensity of tropical cyclones is supported by statistical analyses showing that aerosols can explain part of the storm prediction errors variability. In this study we present observational support to key links in the conceptual model describing the way by which aerosols might be affecting the intensity of the storms. For full details see Woodley (2010). The main observations are:

- Pollution aerosols were observed to reduce the cloud drop size and suppress the warm rain forming processes in the external spiral cloud bands of the storms; whereas adjacent unpolluted spiral bands had much larger cloud drops and produced readily warm rain.
- The polluted rain bands produced stronger precipitation radar reflectivities extending to greater heights, whereas in the adjacent pristine rain bands only moderate reflectivities were confined to below the freezing level. This supports the hypothesis link that the aerosols cause invigoration of the convection at the periphery of the storm.
- Frequent lightning flashes were observed in the polluted spiral cloud band, but none anywhere else in the storm. This further supports the invigoration hypothesis.
- The cloud drop size in polluted clouds increased substantially when the clouds moved inward to the storm in the areas with higher winds over the sea surface. This supports the link in the hypothesis that the sea spray raised by the high winds seeds the polluted clouds and restores the warm rain processes in them when they move inward to areas with high wind speeds.

An example is hurricane Gustav, near the east coast of the United States, which shows how air pollution is drawn into the storm. Clouds off the southeastern shores of the United States appear to exhibit reduced r_e (rectangle 4 of Fig. 2) compared to the clouds closer to the storm center (rectangles 3 and 5 of Fig. 2). The GOCART AOT replicates this pattern of carbonaceous and sulfate aerosols coming off the southeastern United States and ingested into the TC, being replaced by sea salt inside the storm. In Fig. 2, the T-r_e relations show that at the periphery (rectangle 4), the r_e remains under 15 μm until the height of -5°C indicating suppressed warm rain. In comparison, it can be seen that closer to the center of the storm (rectangle 3) the r_e reaches 15 μm already at the height of about 13°C, indicating active warm rain processes at much lower heights than in rectangle 4.

These results show that a) effects of aerosols should be taken into account in the prediction of TC intensity, and b) the results support the HAMP hypothesis that small soluble aerosol particles ingested into clouds at a storm's periphery can reduce the intensity of the TC, as might be the case in a TC approaching a polluted landmass.

A NASA/MODIS-Terra image from 21 August 2008 02:55 UTC is shown in Figure 2. The colors in the figure signify the solar reflectance at different wavelengths: red for visible reflectance, green for 3.7-μm reflectance (approximating cloud top particle effective radius, r_e), and blue for the inverse of 10.8-μm brightness temperature. The rectangles enclose areas corresponding to the graphs below the satellite image, which present the evolution of r_e [μm] on the x-axis as a function of cloud top temperature [°C] on the y-axis. The significance of the colors and the **interpretation** of the T-r_e relations are first described in Rosenfeld and Lensky (1998) for Gustav which occurred on 10 September 2002 15:40 UTC. According to the redder colors and the T-r_e relation in rectangle 3, cloud drops constituting the clouds closer to the center of the storm are by far larger, indicating washout of the aerosols and/or the effect of the sea spray, induced by the storm's winds, creating large drops, which restores the warm rain processes. However, in region 5, which encompasses part of the developing eye, where convection should be the strongest, the r_e is not the largest.

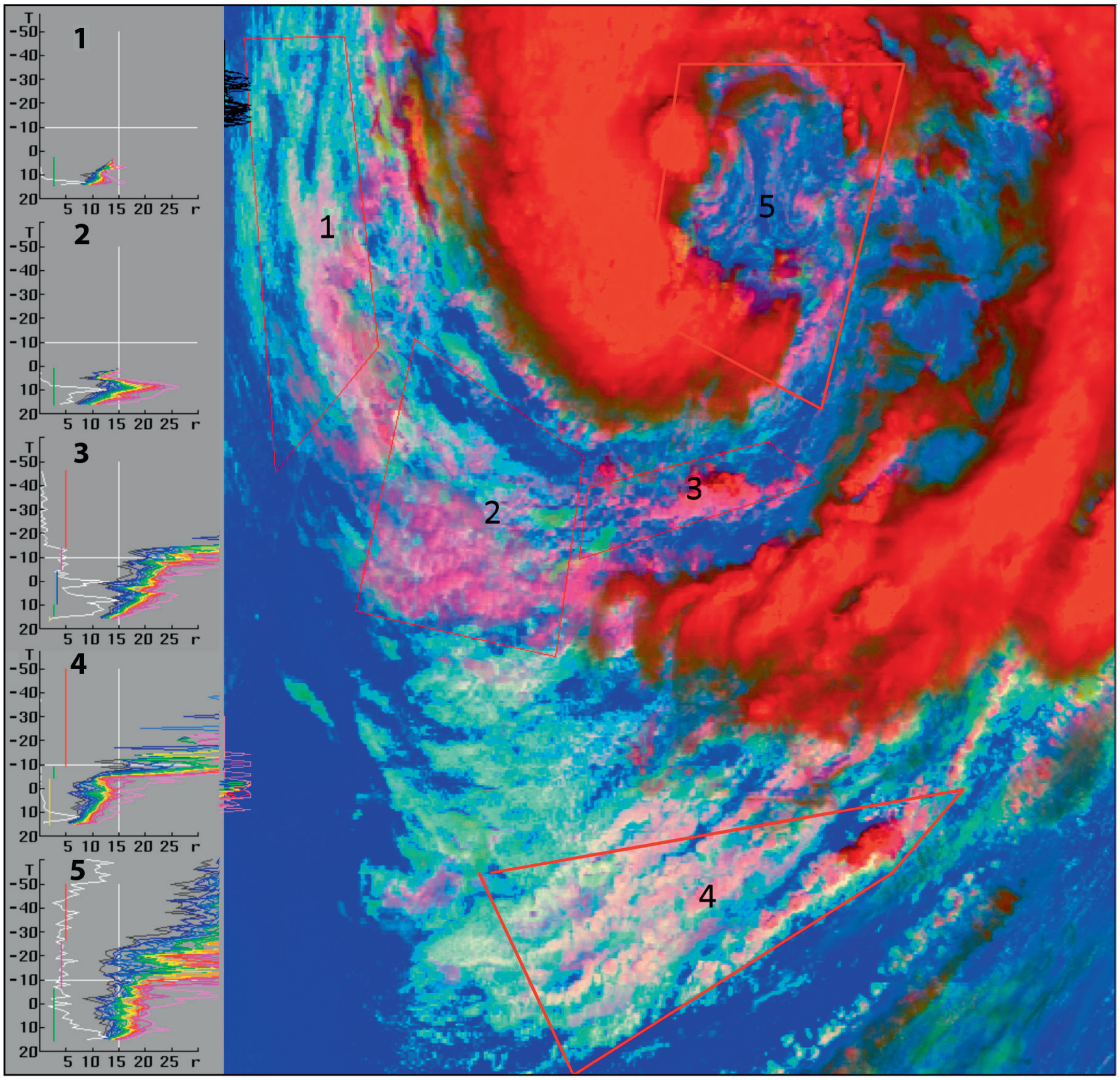

Figure 2: Tropical cyclone Gustav off the coast of South Carolina, from MODIS Terra.

4. KHAIN'S GROUP: TESTING THE SENSITIVITY OF TC INTENSITY TO CONCENTRATION OF SMALL AEROSOLS

During the HAMP project a significant step toward creation of a new tropical cyclone model with an advanced microphysics was made. A spectral bin microphysics (SBM) scheme developed at the Hebrew University of Jerusalem and based on solving the equation system for size distribution functions for water drops and hydrometeors of several types was modified and tested using *in situ* observations in deep convective clouds(e.g. Khain et al., 2004, 2008b; Khain and Lynn, 2009). The model accurately reproduces the observed cloud structure. The model is especially designed to describe cloud-aerosol interaction. For this purpose, the model calculates the size distribution function of aerosol particles which act as cloud condensational nuclei (CCN). In simulations of single maritime deep convective clouds, significant invigoration of cumulus clouds was observed when CCN concentrations were enhanced (Khain et al., 2008a). This justifies the application of the microphysical scheme to simulation of the effects of aerosols on clouds. Detailed comparison of the droplet size distributions calculated in the model and measured *in situ* in some field experiments demonstrates the ability of the scheme to accurately simulate clouds and aerosol effects on their microphysics and dynamics (Khain et al., 2008b).

The SBM has been implemented into WRF, which resulted in the first TC model with spectral bin microphysics (Khain et al. 2010). The new WRF/SBM model with resolution of 3 x 3 km on the innermost grid was used to simulate land-falling hurricane Katrina and tropical depression Debbie. It was shown that SBM reproduces the evolution of land-falling TC and TC genesis much more accurately than bulk-parameterization schemes. Simulations with this new model demonstrate that TC intensity is significantly modified by variations in CCN concentrations. It was shown that hurricanes approaching the land ingest a lot of aerosols at their periphery. Increases in CCN concentrations at the TC periphery leads to intensification of convection at the TC periphery and to weakening of the TC.

Figure 3 shows the fields of maximum wind speed 28 Aug. 21 z (upper panels), and 22 z in runs MAR and MAR_CON. In the first run (MAR), CCN concentration was assumed typical for clean maritime conditions (~100 cm^{-3} at 1% supersaturation). In the second run (MAR-CON), the initial CCN concentration was assumed low over the sea. At the same time, the CCN concentration over the land was assumed equal to 1500 cm^{-3}. Note that this concentration is comparatively low for continental conditions. So, the aerosol effects are possibly underestimated in this run.

One can see a significant decrease in the maximum wind speed up to 15-20 m/s, i.e. by 20-25% (Khain et al., 2010). Minimum pressure increased by 16 mb as compared to that obtained in simulations, where only low concentration maritime CCN were assumed. This decrease is substantially stronger than was reported by Khain et al. (2008a). One of the reasons is that Khain et al. (2008a) used a bulk-parameterization scheme that is less sensitive to aerosols, as well as the fact that an artificial approach to parameterize aerosol effects by inhibiting warm rain was used in Khain et al. (2008a).

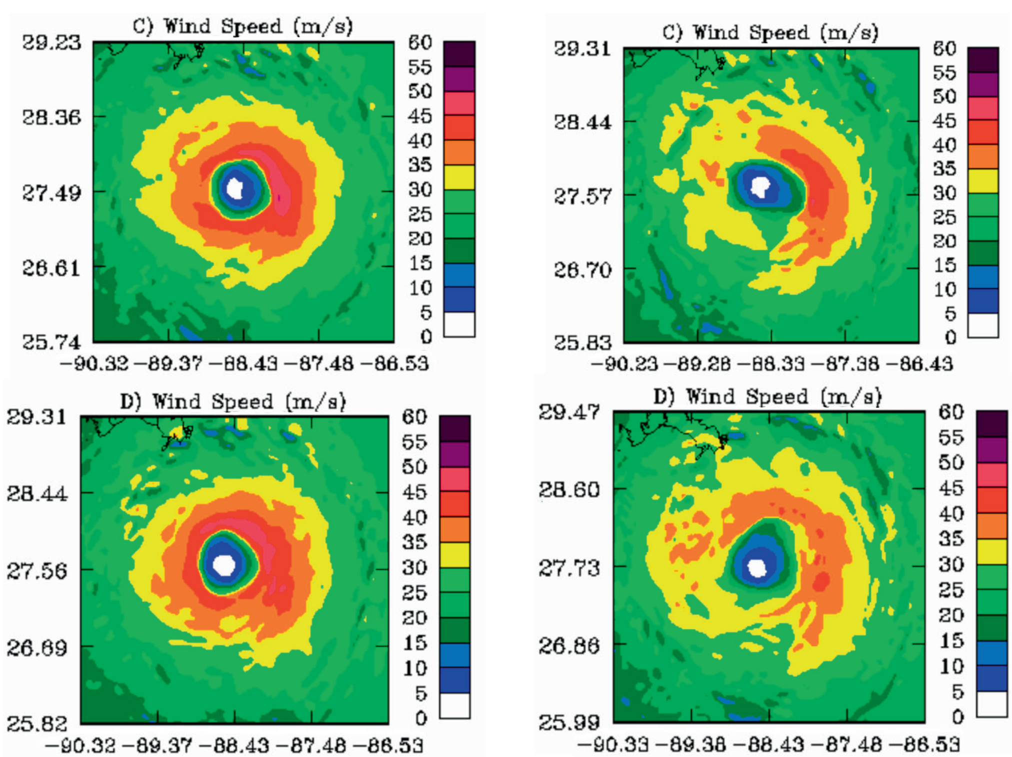

Figure 3: The fields of maximum wind speed 28 Aug. 21 z (upper panels), and 22 z. in runs MAR (left) and MAR_CON (right).

The WRF/SBM predicted weakening of Katrina well before its landfall, which agrees with observations. In contrast, all existent TC forecast models (non-coupled with the ocean) did not predict TC weakening until landfall.

These results show that a) effects of aerosols should be taken into account in the prediction of TC intensity, and b) the results support the HAMP hypothesis that a TC can be weakened by insertion of small soluble aerosol particles into the base of clouds in the periphery of the storm.

These results indicate that a) SBM model reproduced TC genesis (pressure and wind fields) much more precisely than the bulk schemes, b) the SBM model simulates more realistic microphysical cloud structures; and c) dust hinders TC development, invigorating convection at the TC periphery. An important application of the WRF/SBM system is an improvement of TC forecasts by calibration of existent bulk-parameterization schemes.

Recently, a detailed microphysical model of the boundary layer for strong wind conditions has been developed in which spray formation and transport by large eddies in the BL was simulated. It was shown that large eddies in the TC boundary layer lead to well mixed BL, and significantly increase latent heat flux from the surface. It was shown also that convective cells transport spray drops of radii up to 100 μm to the cloud base of deep convective clouds (Spund et al., 2011). It is likely that effects of these spray drops penetrating clouds in the eyewall of TC should affect dynamics and microphysics of these clouds, and therefore, the TC intensity. It is hypothesized that this is the main mechanism that affects TC intensity. This mechanism has not been investigated before.

In summary, the development of the WRF model with the novel spectral bin microphysics opens a new generation of TC models with advanced microphysics that are sensitive to atmospheric aerosols. Further details can be found in Woodley (2010) as well as in a chapter of a book (Hurricane research, Khain and Lynn 2010).

5. GINIS-KHAIN'S GROUPS: DEVELOPMENT AND IMPLEMENTATION OF INNOVATIVE PHYSICS PACKAGES FOR NEW-GENERATION, HIGH-RESOLUTION, COUPLED HURRICANE-WAVE-OCEAN MODELS

The main focus of this group has been a) to implement the Hebrew University bin microphysics package into high-resolution coupled hurricane-wave-ocean models combined with b) explicit simulations of sea spray and c) new strategies for wind-wave-current interactions. The coupled models are built based on two NOAA operational TC prediction models. The first model is the GFDL/University of Rhode Island (URI) tropical prediction system that has been operational at NOAA's National Centers for Environmental Prediction (NCEP) since 1995 and at the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) since 1996. The URI group has made major contributions to the improvements of this model over the years since it became operational (Bender et al., 2007). The second coupled model is the WRF model, a non-hydrostatic mesoscale model. There are two versions of WRF available to the research community: Hurricane WRF (HWRF) developed at NCEP (Surgi et al., 2007) and Advanced Hurricane WRF developed at NCAR (Davis et al., 2008). Both WRF versions are designed for simulation and prediction of fine-scale atmospheric phenomena, capable of utilizing horizontal grid lengths of a few kilometers or less.

Here we describe the URI group's work on the development of a new air-sea interface module and sea spray parameterization. The model is based on the NOAA WAVEWATCH III wave model, the equilibrium wave spectrum model by Hara and Belcher (2002) and the conservation of momentum and energy (Hara and Belcher, 2004) by explicitly resolving the form drag due to non-breaking waves. The new parameterization takes into account the impact of air-flow separation due to breaking waves on the wave BL (Kukulka and Hara, 2008a and b).

Under HAMP funding the URI research group in collaboration with Khain developed an efficient 2-D LES model that explicitly simulates roll vortices and their interaction with the 3-D mean flow in the marine BL. This model is based on an approach that has been originally developed by Khain et al. (1986) and Ginis et al. (2004) for an atmospheric BL model in non-rotating fluid. Our proposed approach to parameterization of roll vortices in a TC model resembles a recently emerging approach of "super-parameterization" of the cloud physics processes in general circulation models (Grabowski, 2001; Randall et al., 2003). Super-parameterization consists of a cloud resolving 2-D model embedded into a general circulation model, allowing explicit cloud simulations. This approach is ideally suited for parallel computers and can operate with one to two orders of magnitude fewer computations than a 3-D cloud-resolving large-scale model. Similarly, our proposed methodology can be called super-parameterization of the MBL that includes a roll vortex-resolving 2-D LES model embedded into the 3-D equation system representing a TC model. Further details can be found in Woodley (2010).

In summary, implementation of accurate parameterization of the BL processes including spray effects will significantly improve the representation of TC-ocean interaction and calculation of surface fluxes. We believe that these two improvements, taken together, will lead to dramatic improvement of understanding of TC physics and prediction of TC intensity.

6. SUMMARY AND CONCLUSIONS

In spite of its short period of existence, a great deal was accomplished during HAMP. The research supports the original hypotheses proposed by Cotton et al. (2007), Rosenfeld et al. (2007), and Khain et al. (2008) that seeding with high concentrations of pollution sized aerosols in the outer rainbands of hurricanes can lead to significant weakening of a storm. This was demonstrated by simulations of both idealized storms and actual case studies and with advanced bin-emulating microphysics and spectral bin microphysics. It was also evident in satellite analysis of actual storms.

There still remains much to unravel about the intricacies of aerosol interactions with tropical cyclones. First we need to understand the causal mechanisms for storm weakening at very high concentrations of CCN as storm rainfall and cold-pools are substantially reduced. Second, the aerosol influence has to be put in perspective with other factors influencing TC intensity including SST, wind shear, the moisture content of the lower troposphere.

Research under HAMP has also spun-off a strategy for parameterizing sea-spray generation in tropical cyclones, a process that is not only important to aerosol generation by the storm but also to the bulk thermodyamics of the storm system.

In our view this research should be continued, for the dual purpose of improving the accuracy of hurricane prediction, and gaining knowledge that may lead some day to our ability to reduce their intensity.

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Abbreviations and Acronyms used:

AOT	—	aerosol optical thickness
BL	—	boundary layer
GOCART	—	Goddard Chemistry Aerosol Radiation and Transport
MBL	—	marine boundary layer
MODIS	—	moderate resolution imaging spectroradiomenter
r_e	—	effective radius