Towards Predictive Cloud (Hurricane) Modeling

Jon Reisner
Los Alamos National Laboratory
EES-16/MSD401 Jon Reisner
Los Alamos, NM 87545
phone: (505) 665-1888 fax: (505) 665-3415 email: reisner@lanl.gov

Award Number: N0001408IP20101

LONG-TERM GOALS

The long-term goal of the proposed research is to develop a modeling architecture that sets the stage for future capabilities that are beyond the current generation of weather prediction models such as the Weather Research Forecast (WRF) model.

OBJECTIVES

The objectives of the current work are as follows:

1. The constant eddy-diffusivity assumption employed in the hurricane model of Reisner et al. [1] will be replaced with a turbulence model[2] that selectively applies diffusion in a smooth manner near cloud boundaries so that the boundaries can be spatially resolved with any excessive evaporation associated with the turbulence model being minimized in these areas due to the application of a limiter.

2. The Reisner microphysical scheme[3] employed in WRF will be significantly modified to ensure convergence of a Newton-based solver. The newly modified scheme will also include a bulk aerosol model to allow for the impact of various types of aerosol on, for example, hurricane dynamics.

3. A particle model[4] that resolves the radius spectra of various hydrometers will be used to develop new smooth bulk parameterizations, especially for the collision-coalescence process.

4. A lightning model[5] will be coupled to the Reisner microphysical scheme to enable the model to simulate lightning activity for various convective events and to fine-tune key microphysical processes such as collision-coalescence that are important in charging.

5. The entire equation set will be solved using the Jacobian Free Newton Krylov solution procedure[5] employing a physics-based preconditioner to improve numerical efficiency and to determine whether time scales are being resolved in the model, i.e., Newton's method will not converge if time scales are not resolved.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2008	**Annual**	**00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE
Towards Predictive Cloud (Hurricane) Modeling

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Los Alamos National Laboratory,EES-16/MSD401 Jon Reisner,Los Alamos,NM,87545

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
The long-term goal of the proposed research is to develop a modeling architecture that sets the stage for future capabilities that are beyond the current generation of weather prediction models such as the Weather Research Forecast (WRF) model.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**9**	

APPROACH

A simulation-based approach using Los Alamos's HIGRAD model was undertaken to address the objectives of this award. The P.I. of this project was responsible for both the development and running of the HIGRAD model. HIGRAD was involved in both idealized moist bubble simulations as well as realistic simulations of historical hurricanes. All simulations were conducted using Los Alamos's open high performance computing platform.

WORK COMPLETED

In a paper[2] that presented ideas that could be used in the next generation of weather prediction models and that was written by the P.I. of this award, a microphysical model was employed that was appropriate for non-drizzling stratus clouds. Hence, to extend the ideas presented in that paper to convective clouds, a new differentiable microphysical model appropriate for convective clouds is required. Thus, the primary component of work that was completed for this project was the development of a differentiable bulk microphysical model that also included a relatively simple model for lightning[4]. Currently, the microphysical scheme is being tested within a Newton based solution procedure to determine both its differentiability in time and numerical properties. Also, results from this bulk microphysical model are being compared against a higher-fidelity particle model. Note, the current target problems are a two-dimensional moist bubble and a realistic eastern Pacific hurricane, Guillermo.

Thus, objectives 1,2, 3, 4, and 5 have been, at the minimum, at least partially addressed. Objective 1, developing a smooth cloud edge diffusion model, has been achieved not only in the context of idealized simulations, but also in hurricane simulations. Objectives 2, 4, and 5 have been also been attained with the bulk differentiable microphysical model being both developed and tested within realistic hurricane simulations.

RESULTS

The smoothed or differentiable version of the Reisner et al microphysical model[2] was first tested in highly idealized moist bubble simulations. Figure 1 shows results from two simulations of the many sensitivity simulations conducted with time step size being the only difference between the two simulations. As can be seen in the figure, visual differences between the two simulations are small suggesting temporal errors are indeed relatively minor. In fact, a more detailed mathematical analysis of these differences does reveal that the temporal error scales in agreement with the order of accuracy of the chosen temporal integrator. Therefore these results, along with the ability of the entire model to converge within Newton's method, tentatively indicate that the entire model is differentiable in time and produces relatively small temporal errors, i.e., this result meets objective two of the proposed work.

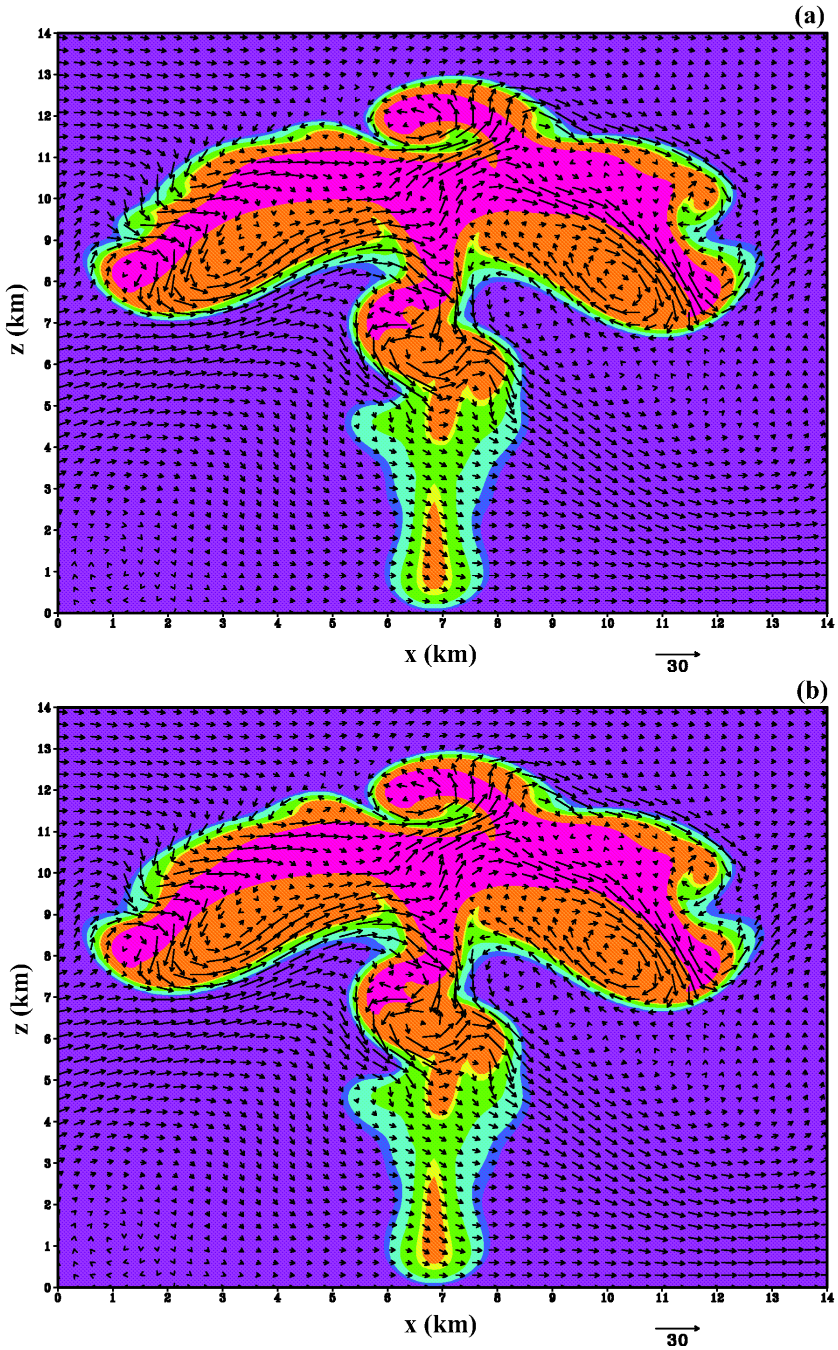

Figure 1: Contours of the combination of rain water, snow, and graupel from two moist bubble simulations with the only difference between the simulations being the time step size with (a) 0.25 s, and (b) 0.125 s.

Next, the HIGRAD model was used in simulations of Hurricane Guillermo. Hurricane Guillermo occurred in the eastern Pacific and during a portion of its rapid intensification period an airborne dual Doppler radar observed the hurricane. Using the first radar observation to nudge key model variables within HIGRAD over a period of 7200 s, the model produced a hurricane with a surface pressure that was near the observed surface pressure of 960 mb. After obtaining a reasonable initial field, the model was run in a “predictive” mode to begin the examination of key model parameters that are primarily responsible for rapid intensification.

Figures 2-5 show the surface pressure and rain fields at 7200 s and 2100 s from two hurricane simulations with the only difference between the two simulations being that the second simulation did not include the impact of evaporative cooling. As can be seen in Figs. 2-3, differences between the two simulations at the start of the predictive time period are small with the minimum surface pressures being roughly near the observed value of 960 mb. But, in stark contrast, large differences in the surface pressure and rain fields are evident at 21000 s. The differences can be directly attributable to whether or not evaporative cooling was included in the simulation, i.e., the simulation without cooling (see Fig. 4b) produced a significantly stronger vortex than the simulation that included the cooling (see Fig. 4a).

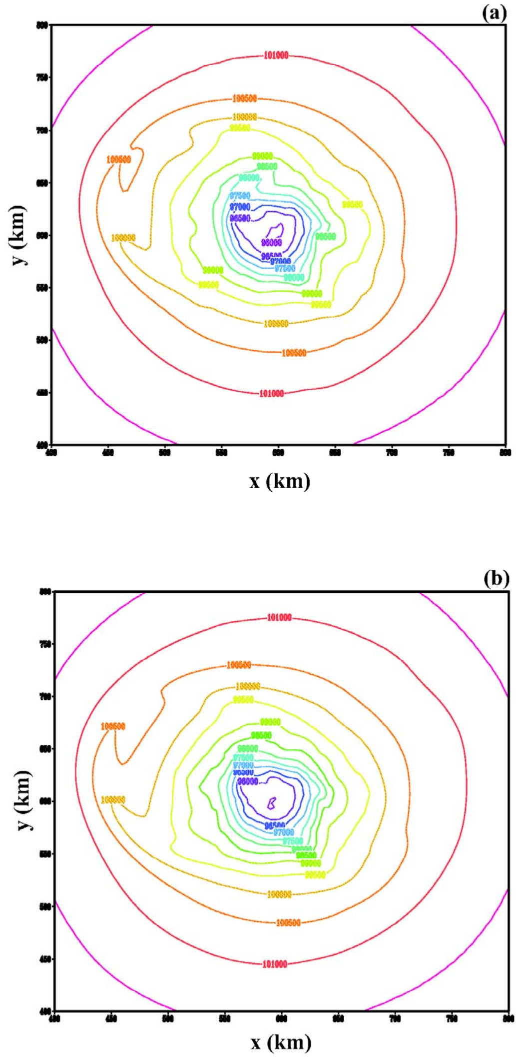

Figure 2: Contours of minimum surface pressures from two simulations of Hurricane Guillermo at the start of the predictive cycle. Panel (a) is from the simulation that included evaporative cooling, whereas panel (b) is from the simulation that did not include the forcing.

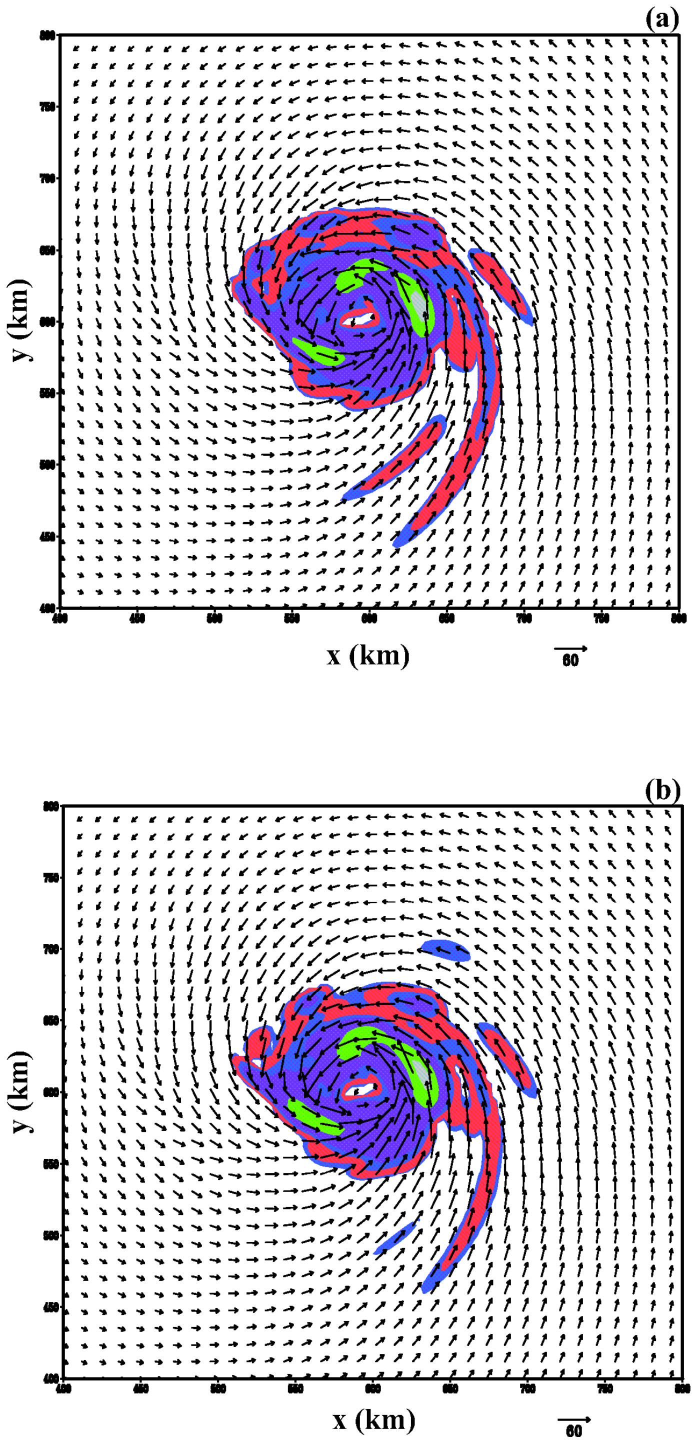

Figure 3: Same as Fig. 2, except for contours of rain water with every third wind vector being shown with the horizontal resolution being a constant 4 km.

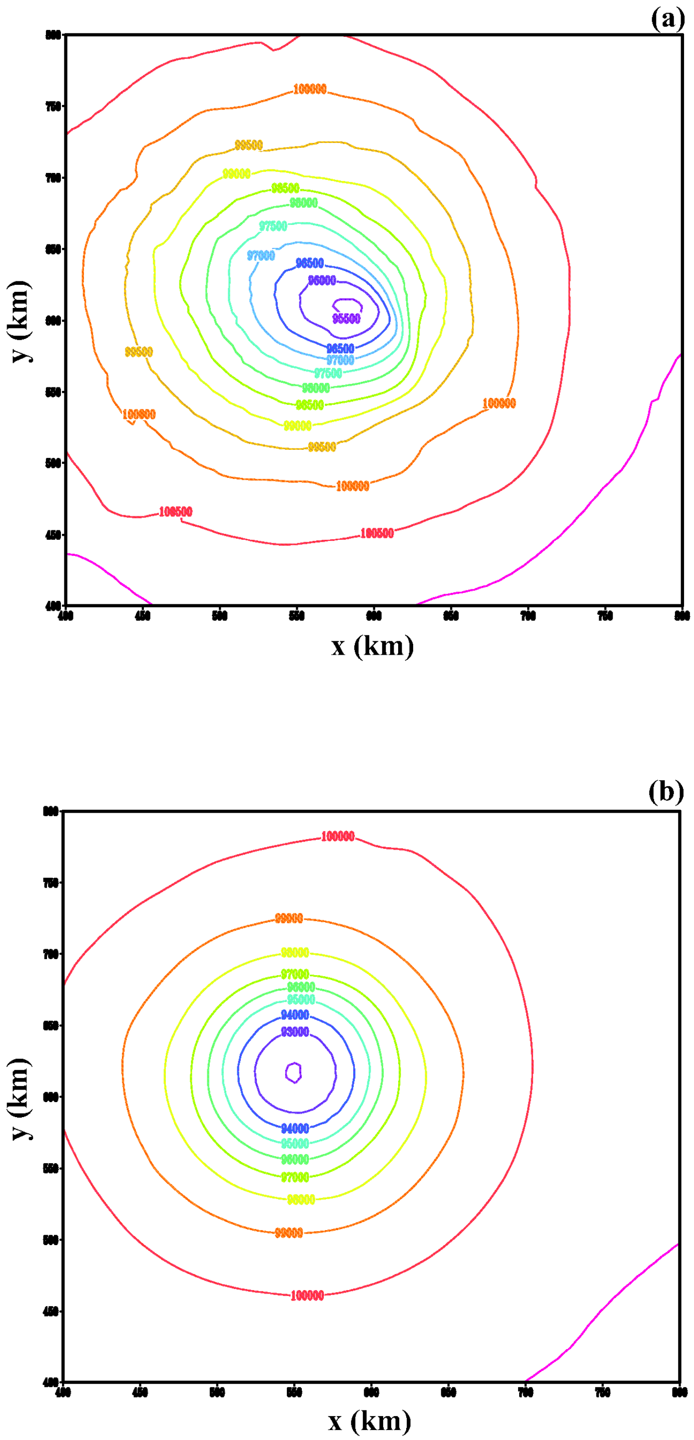

Figure 4: Same as Fig. 2, except 3.8 h later in time.

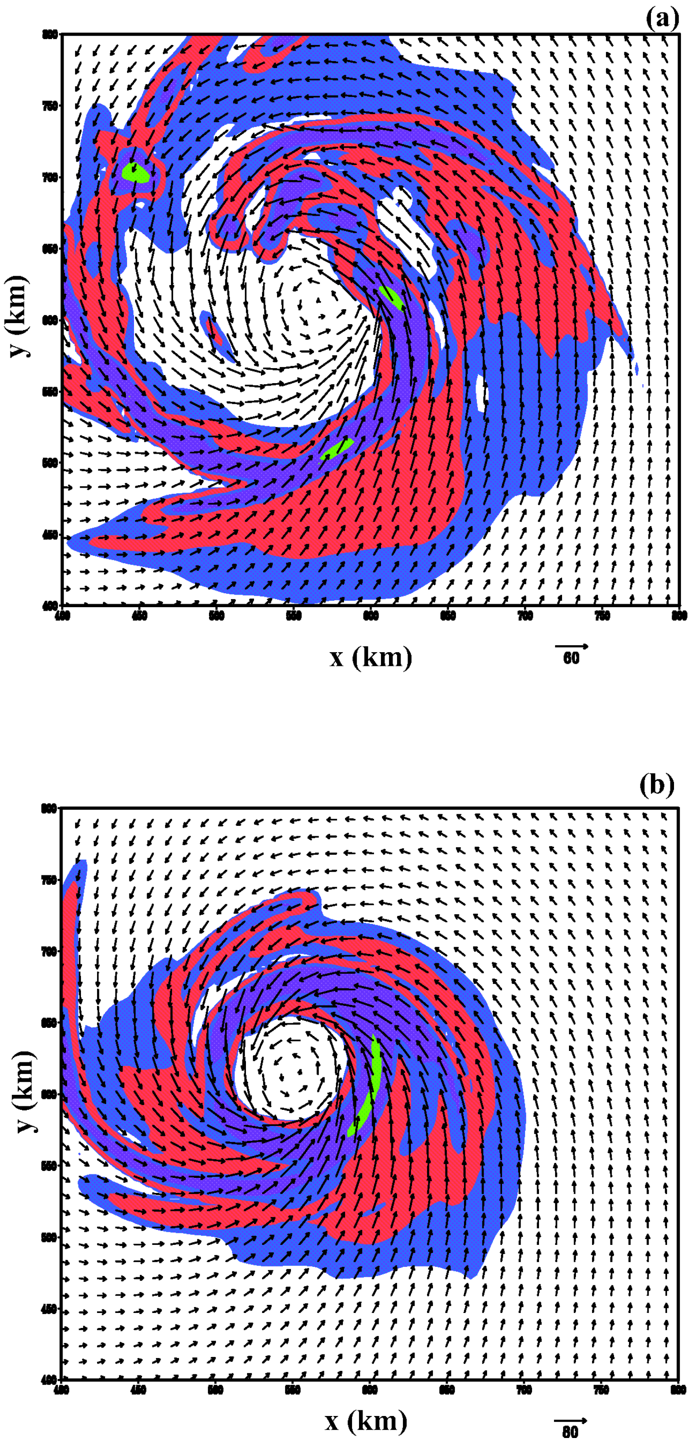

Figure 5: Same as Fig. 3, except 3.8 h later in time.

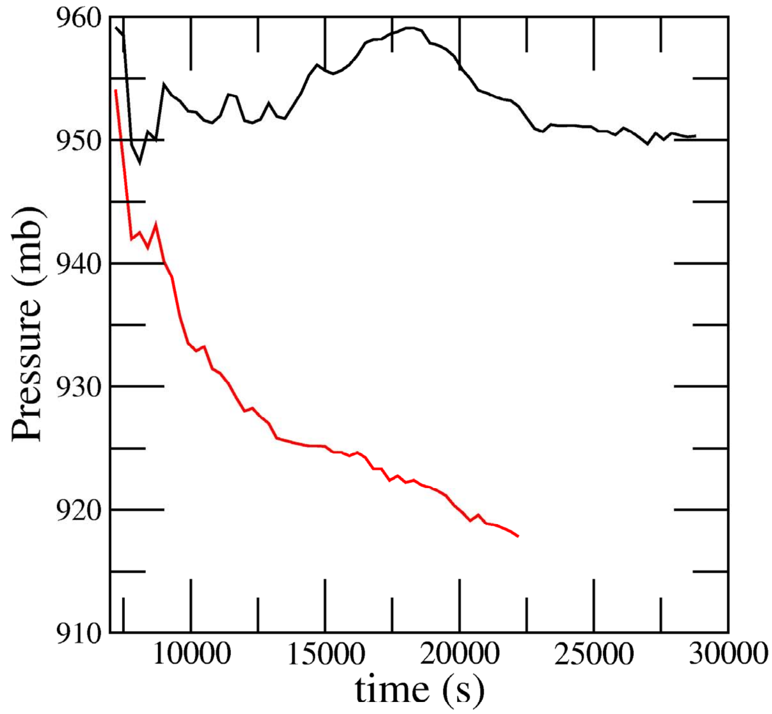

Figure 6: Surface pressure versus time from simulation one (black line) and simulation two (red line). Note, the second simulation was not run for the entire time period due to the simulation producing a surface pressure that was much lower than the observed pressure.

Figure 6 shows a plot of minimum surface pressure as a function of time that was produced by the two hurricane simulations. As evident in the figure, the simulation that included evaporative cooling exhibited some fluctuations in surface pressure, whereas the simulation that did not include evaporation showed a rapid decrease of surface pressure with minimal oscillations. But, during this 6 hour time period the observed decrease in surface pressure was from 960 mb to 947 mb. Hence, the second simulation vastly overestimated the pressure falls, while the first simulation slightly underestimated the pressure falls. However, while the first simulation produced a pressure fall at the end of the 6 hour time period that was close to the observed pressure, the oscillations in surface pressure produced by this simulation may by unphysical and related to the model incorrectly representing evaporative processes and/or imbalances in the initialization procedure with the impact of either of these processes on the pressure field being investigated in the future, i.e., these findings will form the basis of a future paper.

IMPACT/APPLICATIONS

Even though a majority of the time utilized within this award was used to develop the smooth microphysical subroutine, initial results employing the microphysical routine embedded within HIGRAD appear promising and suggest that on of the primary determinants for a model to accurately simulate the intensification of a hurricane is how the model represents evaporation. Over the next few months extensive testing of the smooth microphysical subroutine, including the impact of an evaporative limiter will be conducted with the primary application of the entire model, including this subroutine, being the simulation of historical hurricanes such as Guillermo, Rita, and Katrina.

Once this testing is completed, then a paper or papers will be written up from the primary findings of the hurricane simulations with a tentative hypothesis for the first paper being as follows: If a “smooth” hurricane model is “properly” initialized and reasonably represents evaporative processes, then the model should have little trouble forecasting the rapid intensification phase of a given hurricane. Note that different data assimilation approaches, such as the ensemble Kalman filter, will be utilized to initialize the historical hurricanes, instead of the nudging used in the previous two simulations , with these approaches not only utilizing radar data, but also lightning data during the assimilation process.

RELATED PROJECTS

This project directly supplements an internal Los Alamos funded project investigating the impact of lightning on hurricane intensification.

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