9.32 **USING NCSA/LEAD'S WORKFLOW BROKER TO STUDY STORM INTERACTION WITH WRF**

Brian F. Jewett[1], Robert B. Wilhelmson[1,2], Jay C. Alameda[2], and Albert L. Rossi[2]

[1]Atmospheric Sciences Department, University of Illinois at Urbana-Champaign
[2]National Center for Supercomputing Applications (NCSA), University of Illinois at Urbana-Champaign

1. INTRODUCTION

There are a wide range of environments and scenarios comprising what is broadly described as cell interaction. Examples of *mergers* associated with tornadogenesis include Ray et al. (1981), Carey et al. (2003), Lee et al. (2006a, b), and Wurman et al. (2007), while Lindsey and Bunkers (2005) document a case where merging disrupted a tornadic storm. Our results to date demonstrate that supercells developing in isolation can have *notably different* behavior than those developing in close proximity to one another. We are extending this work, using improved resolution and physics from the new WRF, and seek to improve our understanding of tornadoes in the context of storm interaction with a new emphasis on explicit simulation of tornadogenesis. Modeling such interaction raises important issues including: what metrics will be used to define and quantify the consequences of storm interactions; and, not inconsequentially, how will so many simulations be effectively made and analyzed?

In this document we briefly describe recent simulations and the use of NCSA's workflow broker system to efficiently manage these simulations and enable in-depth analysis of the results.

2. METHODOLOGY

A recent set of simulations was completed using environmental conditions representative of the Illinois tornado outbreak on 19 April 1996 to test the hypothesis that storm mergers were crucial to the formation of strong low level mesocyclones and subsequent tornadogenesis (Lee, et al., 2006a, b). In the set of three-hour idealized simulations, two supercell storms were triggered simultaneously using the Weather Research and Forecasting model (WRF ARW v2.2.1), Thompson microphysics, 1500- and 500-m grid spacing, and 70 vertical levels. Nested grids were used for higher resolution in the active convective region. The model was initialized using an unstable (3400 J kg^{-1}) and large bulk Richardson number (~100) sounding taken from a mesoscale MM5 simulation of the tornado outbreak, near the time and location of storm initiation along the modeled dryline. The hodograph (not shown) had sharp turning, with a 17.5 m s^{-1} vector change in the lowest 2.5 km. Seventy-five runs were completed in which the initial position of the second cell was placed at different locations, all south/west of the first (the control had no second cell). Both storms were initiated at the same time using temperature perturbations of 3˚C (first cell) and 2˚C (second), and data was saved each minute (later: every 12s). These simulations were carried out with the Workflow Broker system, which will be described separately in section 4.

3. RESULTS

Fig. 1 shows the peak vorticity for each run for any rotation center, and *duration* of rotation for a given center, plotted on a map of initial locations of the 2nd cell. This is ~1/4th of the possible domain: the 2nd cell is W-SW-S of the first cell in the domain shown. There are preferred regions for stronger rotation, particularly for

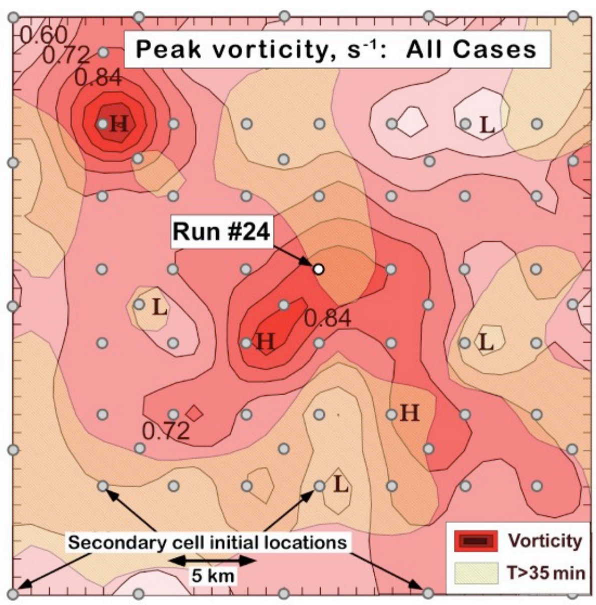

Fig. 1: X-Y map of initial 2nd-cell positions (circles) with contour/shaded fields overlaid of peak vorticity for each run (red) and time for which a surface rotation center exceeded 0.2 s^{-1} (tan). Initial primary cell near top right.

**Corresponding author address*: Brian F. Jewett, Univ. Illinois Atmospheric Sciences, 105 S. Gregory St., Urbana, IL 61801; e-mail: bjewett@uiuc.edu

the second cell approximately 20 km southwest of the first. Such a configuration (here with westerly shear) may allow vorticity from the rear flank of the northern cell to contribute to vorticity along the forward flank of the trailing storm. Such a storm configuration led to tornadogenesis in the study by Wolf and Szoke (1996).

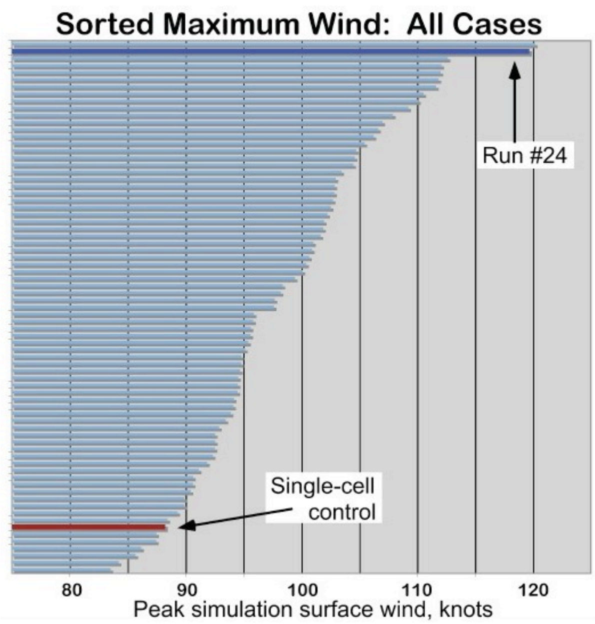

Fig. 2: Maximum surface wind for all simulations.

Our research in this area was motivated by prior observations and by early work noting *fundamentally different behavior* between control cases with a single cell in the given environment and *nearly any case with another cell* nearby. This finding holds in recent higher-resolution experiments (Fig. 2). The single-cell control case is markedly weaker than most with another storm, and many two-storm experiments had stronger rotation and winds and large areas of high winds (not shown).

One of the strongest cases, denoted Run 24, is identified in the above figures and shown in Fig. 3. Many of the cases in this set of experiments had strong rotation that was short lived, as seen by the lack of overlap between dark red (vorticity) and tan (duration) shading in Fig. 1. Run #24 was an exception with 62 m s^{-1} mesocyclonic winds and one rotation center that was identified for 46 minutes. Surface vorticity tracking is carried out automatically for each WRF run, and helps identify cases of interest. Data gathered following this center (Fig. 4) showed peak vorticity of 0.9 s^{-1}, a 12 hPa pressure fall, and a dynamically-driven downdraft as the rotation intensified. Fig. 3 depicts the time of greatest intensity.

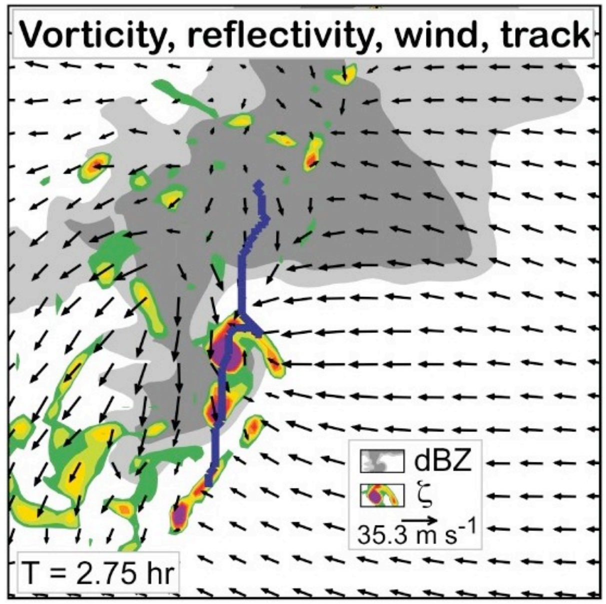

Fig. 3: Subregion with 2.75-h reflectivity (gray), vorticity (color), surface winds and a rotation center track (blue).

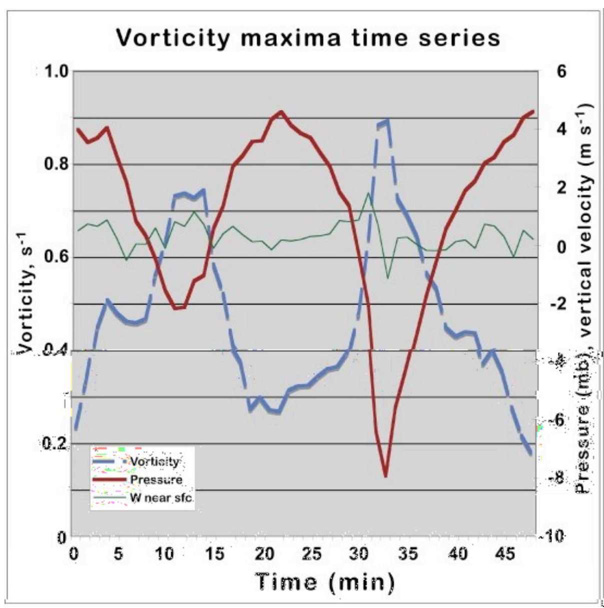

Fig. 4: Time series following rotation center in Fig. 3.

We are now using nesting to study such storm evolution at finer scales. The above case, nested further to 100m, produces a brief spinup seen in the wind field (Fig. 5, right) within the larger mesocyclonic circulation. Future work will nest to (at least) 100m for all cases in the latter part of each simulation. The objective of these new simulations is to further our understanding of when (and why) tornadogenesis is aided (or hindered) by storm interaction.

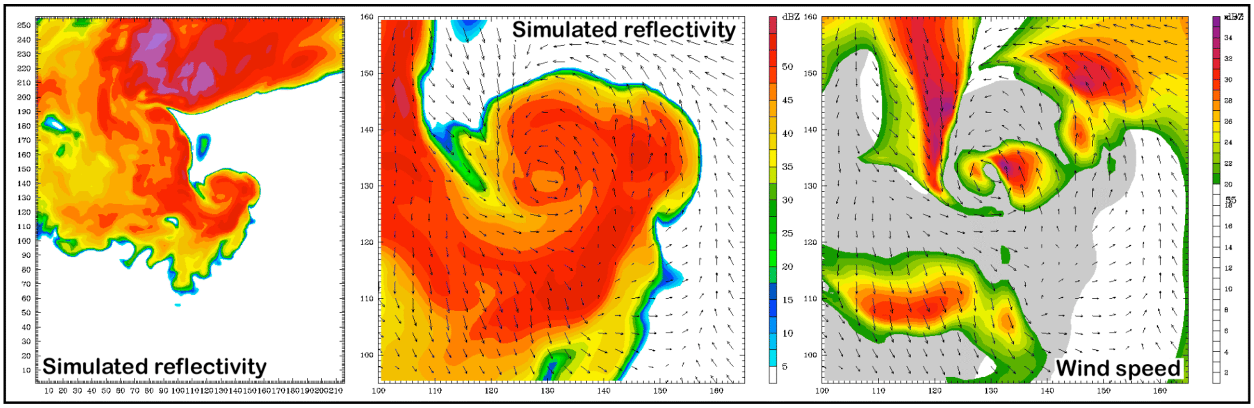

Fig. 5: Hook in 100-m simulation. Left / center: simulated reflectivity. Right: wind speed (color), reflectivity (gray).

4. THE WORKFLOW BROKER SYSTEM *(PWE)*

The set of simulations described above, and larger series planned in the near future, are made practical and efficient through use of software developed at NCSA at the University of Illinois. Supported in part by LEAD (Linked Environments for Atmospheric Discovery; *leadproject.org*), the system handles our complete end-to-end "workflow" and all tasks within it. Once created, such a workflow may be trivially changed to transfer computations from one machine to another, provided the necessary programs (e.g. WRF and plotting tools) are compiled there, and needed settings (e.g. memory, processors/node) are defined for that resource.

The workflow broker – now, after a recent major revision, known as the *Parameterized Workflow Engine (PWE)* - is designed to enable large parameter studies (see Alameda et al. 2008, P11.1, this volume). While not specific to Atmospheric Sciences applications, it has (to our benefit) used numerical simulations with WRF as a testbed, and is currently being used for three research projects at Illinois: storm interaction, mesoscale convective system (MCS) evolution, and mesoscale gravity wave studies (MGWs; see Pitcel et al., P9.23, this volume). It has proven to be a very powerful and general tool with which to carry out such experiments.

The *workflow* (an XML description) used for our storm interaction studies consists of the following steps:

- Prepare simulations. The number of runs resulting from permutations to key variables is determined, and all parameters are set for each WRF run. Defining all such parameters and the range to be spanned is trivial.
- Initial conditions: namelist substitution is used prior to running WRF's *real* (real-data) or *ideal* (idealized) initialization step.
- Execution: each simulation downloads all needed scripts, sounding files and executables, and namelists created earlier. Job execution is monitored, and any problems are documented and reported back to the user application *Siege*, the interface to *PWE*.
- Post-processing: model data is extracted from WRF history files, and over 50 metrics are diagnosed for each run including min, max and areal quantities for kinematic ,thermodynamic and microphysical fields. A separate algorithm then identifies surface vorticity maxima and computes vorticity magnitude, depth, track and longevity for each rotation center, as well as state variables following it, for all times.
- Archival: model/analysis data to mass storage.
- Web: images, animations and statistics are prepared and a web page created for each WRF simulation; all are downloaded to a web server for immediate or future interrogation.

The *PWE* system includes the ability to tie together these steps; diagnose and report any problems; create complicated inter-process steps in which dependencies and multiple parameterized nodes may be used; and do so efficiently. The recent revision was designed to enable very large parameter studies, up to thousands of runs, by requesting large computing resources and dividing up tasks independently of the batch system.

We have experienced firsthand the usefulness of the *PWE* system as it has been readily applied to different numerical problems and settings. Besides Atmospheric Sciences, it has or is currently planned for use in astronomy and operations research. In addition to idealized research, we have also used the *PWE* system in WRF real-data forecast model experiments.

5. SUMMARY

It is a key consideration in our experimental design that we realistically plan and efficiently manage a large suite of simulations (using a good “first cut” analysis), but also make detailed interrogation of selected cases practical and easy. Our computational approach does so, using the *Parameterized Workflow Engine* to carry out large parameter studies (100s-1000s of runs) while handling the large data and logistical challenges that could otherwise overwhelm such a project. Given a simple specification of the desired input parameters and their variation, a large parameter study can be specified and carried out, in our case using Teragrid resources.

Our work to date has revealed a particularly strong response in the form of distinctly different behavior between control simulations with a single cell vs. those in which another cell develops simultaneously. While our analysis continues, we are currently testing WRF v3.0 and moving toward much higher resolution so we might simulate and understand the impact of storm interaction on mesocyclogenesis and tornadogenesis.

6. ACKNOWLEDGMENTS

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Jewett and Wilhelmson are particularly indebted to *PWE* system developers from the middleware research and advanced application support groups at NCSA, who have worked closely with our group and permitted us to concentrate less on (significant) computational challenges and more on our science.

7. FURTHER INFORMATION

Further information on the Parameterized Workflow Engine is available at < *broker.ncsa.uiuc.edu/mrd* >

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