SIMULATIONS OF VIOLENTLY TORNADIC SUPERCELLS AND DAMAGING THUNDERSTORMS

Allocations: NSF PRAC/3,630 Knh (bagm)
NSF PRAC/21,000 Knh (baye)
GLCPC/360 Knh (baro)

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EXECUTIVE SUMMARY

Three projects on Blue Waters carried out by PI Leigh G. Orf have led to a better understanding of violently tornadic supercells (bagm and baye) as well as thunderstorms that produce damaging straight-line winds (baro).

Breakthrough simulations of violently tornadic supercells previously conducted on Blue Waters brought to light new features in these simulated storms that directly challenge long-held conceptual models of supercell morphology and tornado formation. A feature the research team dubbed the streamwise vorticity current that occurs in a part of the storm that has been long ignored by field meteorologists has been identified as playing a key role in tornado genesis and maintenance.

In new work (baye), the research team conducted a simulation study of a violently tornadic supercell, run at unprecedented scale and resolution. The simulation, requiring 20,000 Blue Waters nodes and one-quarter of a trillion grid zones, contains the genesis and maintenance of a long-track EF5-strength tornado exhibiting a multiple-vortex structure. Novel techniques of visualization recently developed by the team combine volume-rendered imagery of vorticity and cloud field with the track of the tornado as manifest by ground-relative traces of the vorticity, velocity, and pressure fields. These tracks bear a striking resemblance to damage swaths found in nature, clearly showing the cycloidal paths of rapidly moving suction vortices embedded within the wide, wedge-shaped tornado.

RESEARCH CHALLENGE

Tornadoes are common in the United States, and the strongest tornadoes cause devastating damage and severe loss of life. Understanding the nature of the strongest tornadoes (rated EF4/EF5 on the Enhanced Fujita Scale) is of great societal interest. A better understanding of these storms will help improve forecasting of the events and provide accurate, targeted warnings, thereby reducing the false alarm rate of the National Weather Service.

Thunderstorms that produce downbursts are also of interest to atmospheric scientists. While "dry" downbursts are relatively understood to be forced by the evaporation of rain in a deep, dry atmospheric boundary layer, "wet" downbursts, which are believed to be forced primarily by drag induced by falling rain and hail, are less understood.

METHODS & CODES

The team used the CM1 model, developed at the National Center for Atmospheric Research, for all three projects. One of the PIs, Leigh Orf, has written an I/O driver for CM1 and a set of tools to read data, called LOFS or the "lack of file system." LOFS is so named because it is a file-based file system that sits upon Lustre. Crucially, LOFS allows very high throughput of saved data; organizes it in an efficient, logical manner; and allows for the use of lossy compression on floating point data using ZFP. In addition, LOFS has a simple application programming interface for reading LOFS data directly as well as for converting it to the popular netCDF format, which can be used to share the data with colleagues or as input for visualization tools.

RESULTS & IMPACT

Simulations of violently tornadic supercells (bagm). These simulations and the hours of high-definition animated video shared in near real time on YouTube have shaken up the field of mesoscale meteorology, directly challenging long-established conceptual models of supercells and tornadoes. The processes the research team has identified are novel, with one direct outcome of this work being a $2.3-million National Science Foundation-sponsored program (TORUS) to search for evidence of these features in the real atmosphere.

Quarter-trillion-zone tornadic supercell simulation (baye). As this simulation is not yet complete and was only recently integrated to its current state, results are preliminary. Video sequences showing high-definition animations of cloud and vorticity fields from a recent talk, shared on social media, have been viewed hundreds of thousands of times. The severe storms community is very aware of this work on Blue Waters, primarily through less highly resolved simulations covered in another Blue Waters allocation.

This new 10-meter simulation and the features that are resolved will be of significant interest to scientists and to the general public. Owing to its sheer size, it will take years to analyze these data; however, without Blue Waters, the simulation simply could not have been performed. The PI's efforts in data management and compression enable the data to be saved at very high temporal resolution; data will be analyzed using new techniques on GPUs on the next-generation Frontera machine and in-house GPUs.

Damaging thunderstorms (baro). Both simulations produced complexes of downbursts as well as surface instantaneous winds exceeding 80 miles per hour. Studying the forcing that results in these strong surface winds will help scientists understand the interplay between falling precipitation and thermodynamic effects involving phase changes of water substance that lead to strong downdrafts and subsequent damaging near-surface horizontal winds.

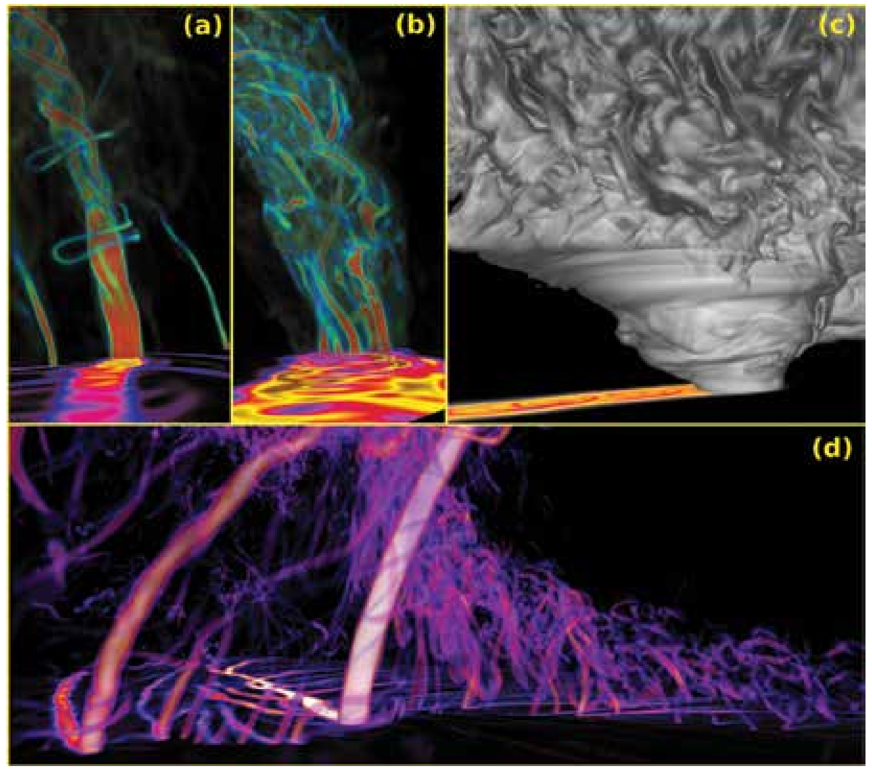

Figure 1: (a) Vertical vorticity field and vorticity tracks of the EF5 tornado shortly following tornadogenesis. (b) As in (a) but during the maintenance phase of the tornado. (c) The cloud field and negative pressure perturbation track during the maintenance phase. (d) A wide-angle view of the tornado shortly following tornadogenesis.

WHY BLUE WATERS

No other nonclassified machine available to U.S. scientists has Blue Waters' capacity. In addition, NCSA has been exceptional in terms of staff support, helping the team over seemingly insurmountable hurdles and keeping the machine in a healthy state.

PUBLICATIONS & DATA SETS

L. Orf, "The role of the streamwise vorticity current in tornado genesis and maintenance," presented at the 29th Conf. Severe Local Storms, Stowe, VT, U.S.A., Oct. 22–26, 2018.

K. T. Halbert, "Cold pool horizontal streamwise vorticity during tornadogenesis and maintenance in a simulated supercell thunderstorm," presented at the 29th Conf. Severe Local Storms, Stowe, VT, U.S.A., Oct. 22–26, 2018.

C. A. Finley, L. Orf, B. D. Lee, and R. Wilhelmson, 2018: "High-resolution simulation of a violent tornado in the 27 April 2011 outbreak environment," presented at the 29th Conf. Severe Local Storms, Stowe, VT, U.S.A., Oct. 22–26, 2018.

M. A. Elmore, "Sensitivity of tornado evolution to changes in 0–500 m wind shear in high-resolution simulations," presented at the 29th Conf. Severe Local Storms, Stowe, VT, U.S.A., Oct. 22–26, 2018.

L. Orf, "The use of ZFP lossy floating point data compression in tornado-resolving thunderstorm simulations," presented at the 2017 AGU Fall Meeting; New Orleans, LA, U.S.A., Dec. 11–15, 2017. [Online]. Available: https://agu.confex.com/agu/fm17/meetingapp.cgi/Paper/209055.

L. Orf, "Petascale supercell thunderstorm simulations, and a new hypothesis for tornado formation and maintenance," presented at the Joint Congress of the Canadian Society for Mechanical Engineering and the CFD Society of Canada (CSME-CFDSC Congress 2019), Western University, London, ON, Canada, June 2-5, 2019. [Online], available: https://youtu.be/5cel1fLxR04?t=2291.

S. Li, S. Jaroszynski, S. Pearse, L. Orf , and J. Clyne, "VAPOR: A visualization package tailored to analyze simulation data in earth system science," *Atmosphere*, vol. 10, no. 9, p. 488, 2019.

L. Orf, "A violently tornadic supercell thunderstorm simulation spanning a quarter-trillion grid volumes: Computational challenges, I/O framework, and visualizations of tornadogenesis," *Atmosphere*, vol. 10, no. 10, p. 578, 2019.