Project Information

Project title: Simulations of Supercells and Tornadoes (ILL_baae)

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Executive summary

Our group has had continuous access to Blue Waters since the friendly user period before its official inception. In previous reports, we discussed research results including a breakthrough simulation of a devastating supercell thunderstorm that produced a long-lived, long-path, extremely violent tornado. Over the yearlong period spanned by this report, additional simulations were conducted that explore the sensitivity to model parameters, visualization and analysis code was further developed and new visualizations created. A significant rewrite of the I/O code described in previous work was completed, making the code much easier to understand and maintain while resolving outstanding bugs in the older code. Further, this I/O code was applied to the version of the model used in previous work, as well as the latest version of the CM1 model. Two manuscripts were published on this work during this time.

Key Challenges: description of the science/engineering problem being addressed

Supercell thunderstorms are responsible for the most damaging tornadoes, including long-path, long-lived tornadoes producing near-ground winds in excess of 300 miles per hour. While these "high-end" supercells are the least common, they create the vast majority of death and destruction of all supercells. We seek to better understand the behavior of such storms, as well as what factors determine whether these rare, but devastating storms occur, versus more common, less devastating storms, including those that produce no tornado or weak, short-lived tornadoes. This is one of the pressing problems in the field of mesoscale meteorology today. In order to address these research questions, supercomputing hardware is required due to the resolution required to capture flow features on the order of 50 to 100 meters that are believed to play an important role in the formation and maintenance of tornadoes.

Why it Matters

Forecasting tornadoes is an extremely difficult task. Only about 20% of supercells produce tornadoes, with less than 1% of supercells producing the most damaging tornadoes that cause the most damage and fatalities. Typically tornado warnings are issued after a tornado is detected on radar or sighted by weather spotters. We desire the ability to forecast the path and strength of a tornado dozens of minutes before it forms. Ideally, we would like to be able to make this forecast even before the supercell forms. In short, a dramatically increased lead time and increased skill in forecasting such tornadoes would results in fewer human fatalities, and this is the ultimate end-game desired result of our research.

One of the outcomes of this work has been the generation of hours of high fidelity videos of simulated cloud, rain, temperature, pressure, vorticity, and parcel paths from key simulations.

These animations are used in scientific and public presentations, with all presentations being uploaded to YouTube where they may be viewed by anyone. Currently 245 people are subscribed to the YouTube channel that contains these talks. Educators (ranging from secondary school to college/grad school) have used these videos in the classroom, and a traveling museum display on "wild weather" including animations of our work is currently active.

Why Blue Waters

CM1 is a cloud model that simulates the three-dimensional time-varying atmosphere. CM1 utilizes non-blocking parallel communication via MPI, and also utilized OpenMP on parallelizing triply nested loops. In its original form CM1 scales very well to hundreds of thousands of cores on Blue Waters, so long as little to no I/O occurs. We need Blue Waters to conduct this work because of the immense scale of these simulations, requiring billions of grid zones in order to obtain adequate resolution. Further, the amount of I/O required to analyze and visualize model results is staggering, with a given simulation creating on the order of 1/2 PB of losslessly compressed HDF5 output.

In order to achieve our results, significant modifications were required to the I/O driver of the CM1 model, and many experiments with compiler options and optimization strategies were conducted. Further, a plugin for the VisIt visualization and analysis tool was developed (this was a couple years ago) which continues to be maintained and tuned, with much help from Blue Waters staff.

Performance of our modified version of CM1 is quite good, and we continue to see linear scaling as we run larger and larger simulations at higher and higher resolution. Prior to our code modifications, I/O was a significant bottleneck. Our new driver utilizes the core driver of HDF5, wherein hundreds to thousands of 3D fields are written to a HDF5 file (one file per node) grown in memory before being flushed to disk. This approach has greatly alleviated the I/O load to the point where saving data at extremely high temporal frequency (i.e., 1 save per model second for thousands of seconds) is possible, and in fact, I/O does not dominate wallclock time.

Results

We have simulated (at 30 meter grid spacing) long-path devastating tornadoes spawned by supercells in the environment sampled adjacent to the 24 May 2011 observed long-path EF5 tornado that occurred near El Reno, OK. To our knowledge, this simulation is the first of its kind, capturing the genesis and nearly two hour long life cycle of the tornado. Subsequent simulations at higher resolution (20 meter grid spacing) have revealed a tornado that bears a striking resemblance to observations, even more so than the 30 meter simulation.

We have only recently begun analyzing these simulations quantitatively, and expect that we will be analyzing already-conducted simulations for several years due to the immense amount of data involved in the simulations. One important discovery is the extreme sensitivity to initial conditions and model parameters of the simulated supercells. Nearly insignificant / arbitrary / small changes to model parameters sometimes result in supercells that do not produce a long track tornado - sometimes producing no tornado at all. Should this result hold and be applicable to the real atmosphere, it has significant implications to the operational forecasting community, since it implies the ability to forecast an individual tornado may not be feasible, and the best we can hope for is a decent probabalistic forecast based upon an ensemble of simulations at comparable resolutions, something not feasible with today's hardware.

The work completed during this allocation was instrumental in the receipt by PI Orf of a two-year PRAC, beginning September 2016, that is currently underway to continue this work.

Next Generation Work

- Run simulations at ∼5 meter isotropic resolution
- Incorporate terrain / bluff bodies (trees, structures) at the model bottom boundary rather than using a free-slip surface or parameterized surface roughness
- Ensembles (30 to 50 simulations) at 20 or 30 meter grid spacing, such that enough variability is included to explore the robustness of the solution and the sensitivity of solutions to environmental and model parameters
- Visualizations/animations at even higher temporal frequency in order to capture the very fast flow in the vicinity of the tornado (say, saving every model time step)
- Incorporation of novel lossy compression into HDF5, reducing the data footprint of simulations
- Simulations in dozens of different environments in which tornadic supercells occurred

List of publications, data sets associated with this work

Orf, L., R. Wilhelmson, and L. Wicker, 2016: Visualization of a simulated long-track EF5 tornado embedded within a supercell thunderstorm. Parallel Comput., 55, 2834.
`http://dx.doi.org/10.1016/j.parco.2015.10.014`

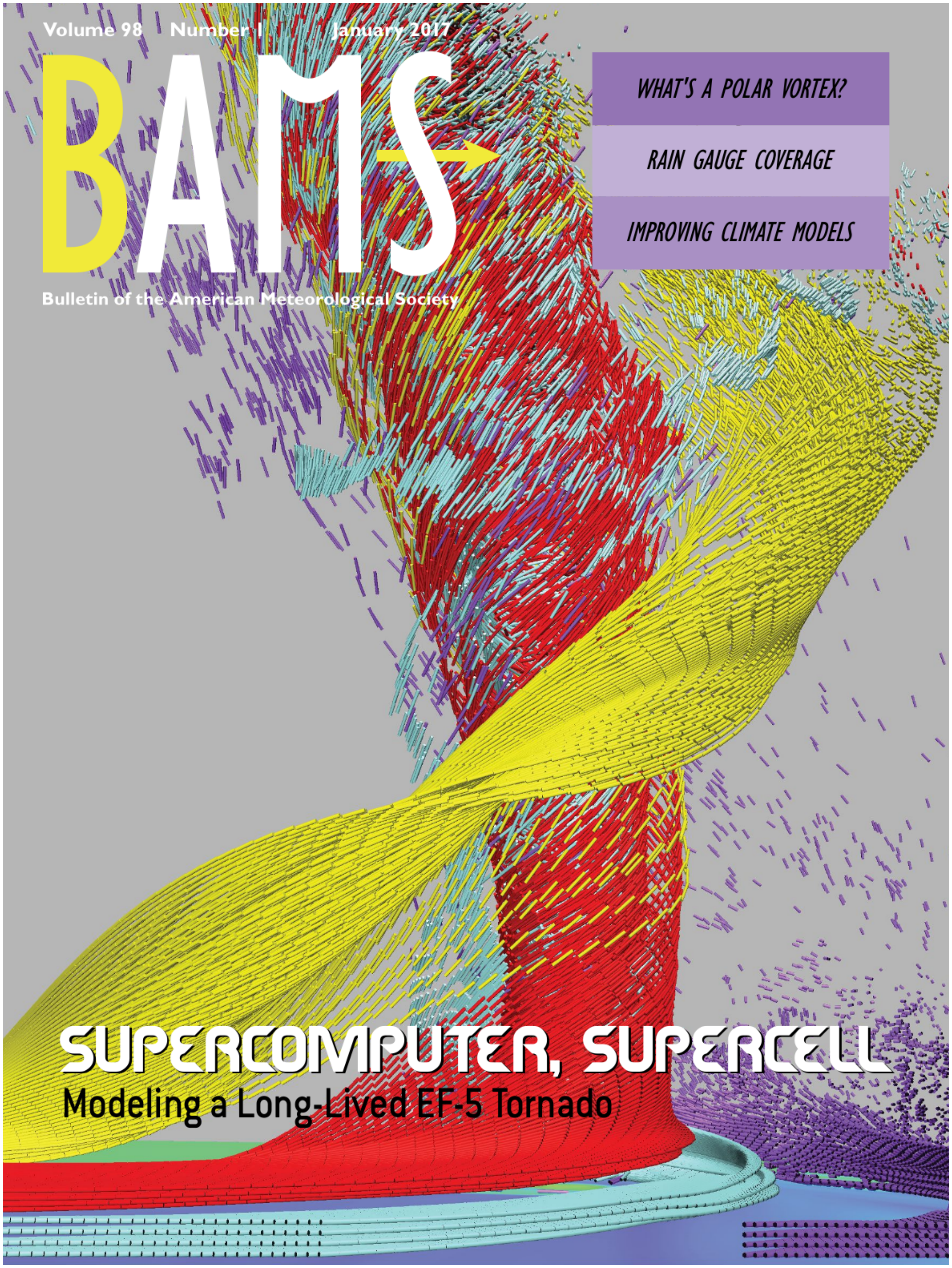
Orf, L., R. Wilhelmson, B. Lee, C. Finley, and A. Houston, 2017: Evolution of a Long-Track Violent Tornado within a Simulated Supercell. Bull. Am. Meteorol. Soc., 98, 4568.
`http://dx.doi.org/10.1175/BAMS-D-15-00073.1`

Supplemental materials to Bull. Am. Meteorol. Soc. article:
`http://dx.doi.org/10.1175/BAMS-D-15-00073.2`

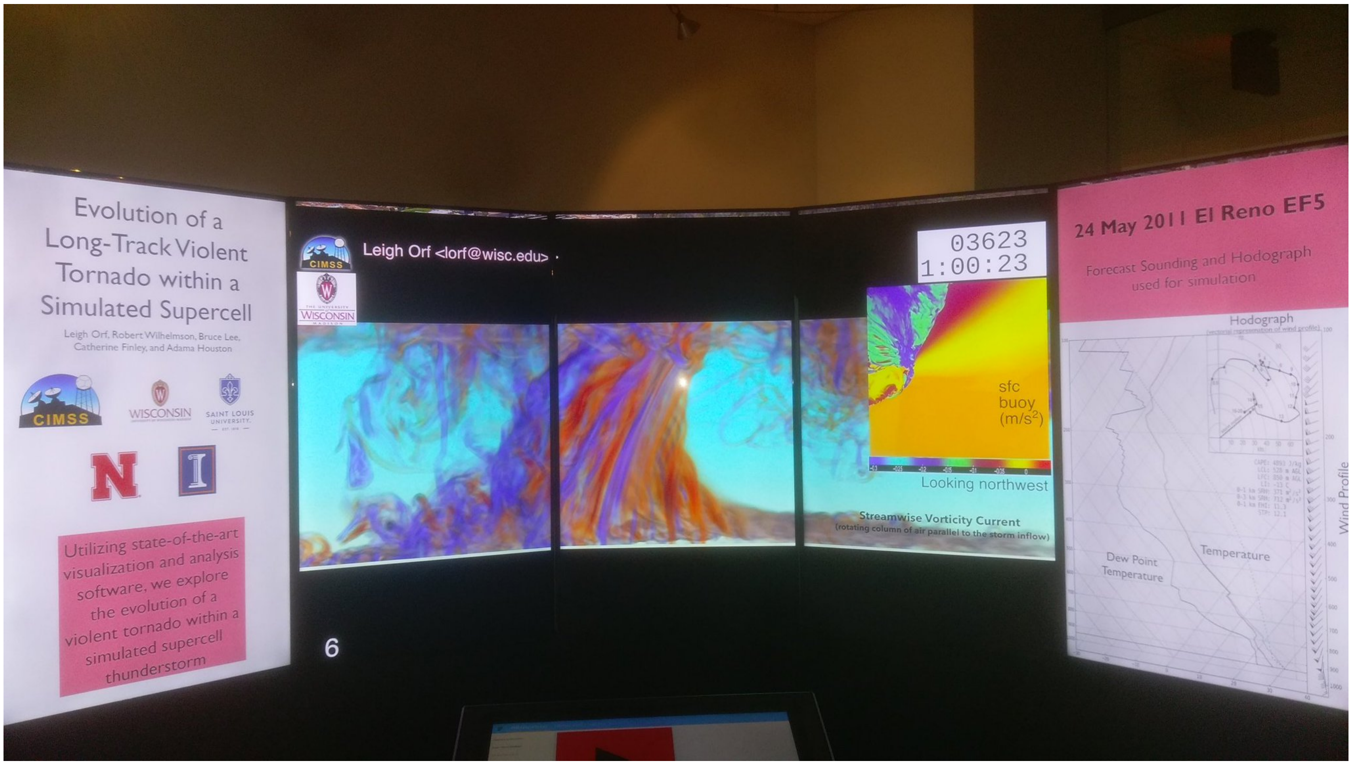
Other publications/products

- ZFP lossy floating point compression algorithm incorporated into HDF5, reducing data load 1-2 orders of magnitude without significant loss of accuracy (hopefully this will be an option for all Blue Waters users once it is less beta)
- NSF-sponsored CADENS videos from this work:
  `http://www.ncsa.illinois.edu/enabling/vis/cadens/documentary/super_tornado`
  `http://avl.ncsa.illinois.edu/documentary-television-film/making-of-super-tornado`
- Web page linking to high quality presentations in video form: `http://orf.media`

- Wilhelmson and Orf both received IDC Innovation Excellence Awards for their work on Blue Waters:
`http://insidehpc.com/2016/11/idc-announces-hpc-innovation-excellence-awards-2`
- Science North (Canada) "Wild Weather" display, which includes animations of this work:
`http://sciencenorth.ca/internationalsales/index.aspx?id=4214`



The January 2017 edition of the Bulletin of the American Meteorological Society, the high impact flagship journal of the AMS, featured our work on the cover.



A video loop of our simulation data is on display at the National Weather Center in Norman, Oklahoma. The display is in the visitors area and is shown to tour groups.