Annual Report for Blue Waters Allocation: Sonia Lasher-Trapp, Oct 2016

- **Project Information**
  - ***Simulating Cumulus Entrainment: A Resolution Problem, or Conceptual?***

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- **Executive summary (150 words)**

Deep cumulus clouds produce the majority of the earth's precipitation, but their strength, longevity and ability to precipitate are affected greatly by *entrainment*. Entrainment is the process by which clouds introduce dry air from outside the cloud inward, decreasing their buoyancy and their water content (i.e., *dilution*). For decades it has been argued that numerical simulations underpredict the dilution of cumulus clouds due to inadequate model resolution limiting entrainment. Using 3D cloud simulations on Blue Waters at increasingly higher resolution, and our new entrainment and dilution quantification algorithms, we have not only quantified the increase in simulated entrainment that was expected, but also have conceptually clarified a limit at which further grid refinement is unproductive in diluting the cloud core. This limit appears near a grid spacing of 10 m, although simulations of cumuli in other environments are yet needed to establish the generality of this result.

Description of research activities and results

- *Key Challenges:* The original model we intended to use for this project was determined to be insufficient to run at the high resolutions with many processors on the BW system. Thus, we had to move to a completely new model with a more modern architecture and better community support, CM1, which other BW users have run successfully.
  - In order to quantify the entrainment and the resulting cloud dilution, clouds on the scale of several kilometers must be simulated with grid spacing down to the 10 m scale. Some of these runs required more than 10,000 processors. An issue related to the time step in the CM1 model was discovered that delayed progress in producing simulations at the smaller grid spacings for over two months, but was finally isolated and corrected. (The issue has now been documented with the BW team and the CM1 lead author to assist other users in the future.)
  - These simulations must output the results frequently (every 4-6 seconds) in order for our entrainment and dilution algorithms (run outside of the CM1 model) to capture their evolution accurately, requiring significant amounts of storage on local disks with direct access needed by these analysis programs. The algorithms had to be adapted from the former model to run on the output of the CM1 model.

    - As model resolution increased, the quantification algorithms could not handle the full variable output arrays from the model, and thus they had to be adapted to perform upon smaller subsets of the model domain.
- *Why it Matters*: Large-scale weather and climate models have inadequate spatial and temporal resolution to model cumulus entrainment, and thus rely on parameterizations that assume a particular underlying conceptual model of entrainment. Our work is helping to determine what resolution finer-scale models must use in order to represent the process faithfully, so that their results can form the basis for improved parameterizations used in larger scale models. In addition, we have determined that dilution, i.e., the decrease in cloud buoyancy and water inside the core of the cloud, converges faster than the entrainment values themselves, as the model resolution is increased. This is good news, as in general the dilution effects are more important to the larger-scale models themselves than the exact amount of entrainment.
- *Why Blue Waters:* Our Blue Waters allocation was essential for testing the resolution-dependency of the entrainment process, and in particular for determining the sizes of the eddies that were most critical to represent in simulations to converge upon a solution of the cloud dilution. The Blue Waters supercomputer allowed us to push the spatial scale limit much farther than in the past, with its huge number of nodes, its high speed, and its large storage capability for high-resolution model output and analysis. The hardware needed to run these kinds of simulations quickly supersedes the limits of most computers.
- *Accomplishments:* We've run cloud simulations with grid spacing of 200, 100, 50, 30, 15, and 10 m to understand how and why the values of entrainment do not, but the results of entrainment (i.e. dilution) eventually do, converge. This is an important result with far-reaching implications across the atmospheric science community that is concerned with cumulus parameterization at larger scales, as well as those members of the community concerned with the details of the amount of liquid water inside the clouds available for producing precipitation. This work was presented at the International Conference on Clouds and Precipitation in July 2016 and fueled significant enthusiasm and discussion.

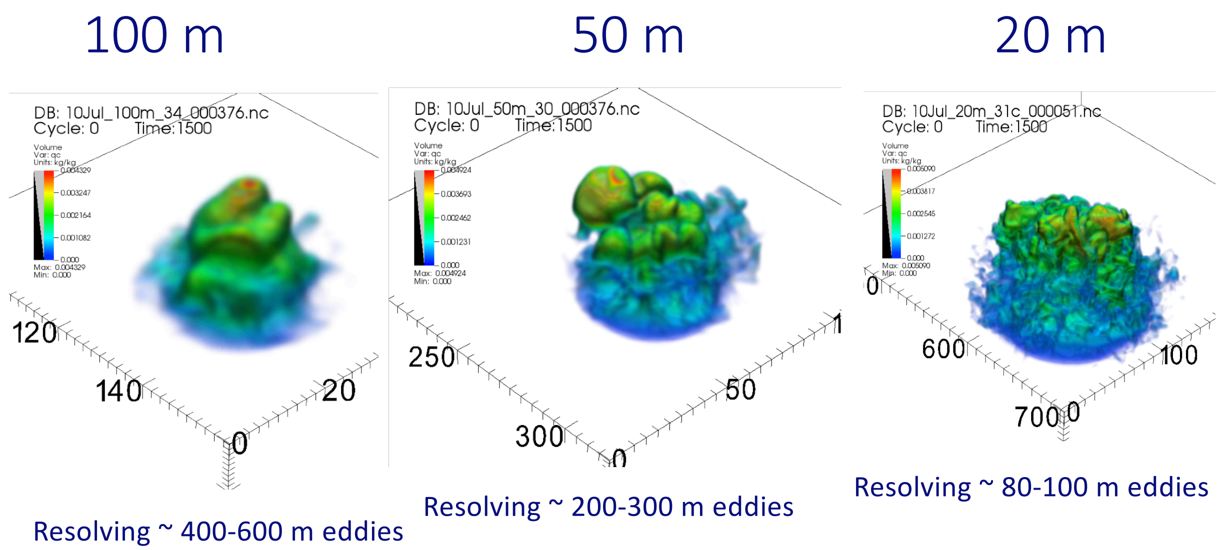

Figure 1: Snapshots of clouds simulated at different grid spacings (noted at top) and the sizes of turbulent eddies that are well-resolved in each.

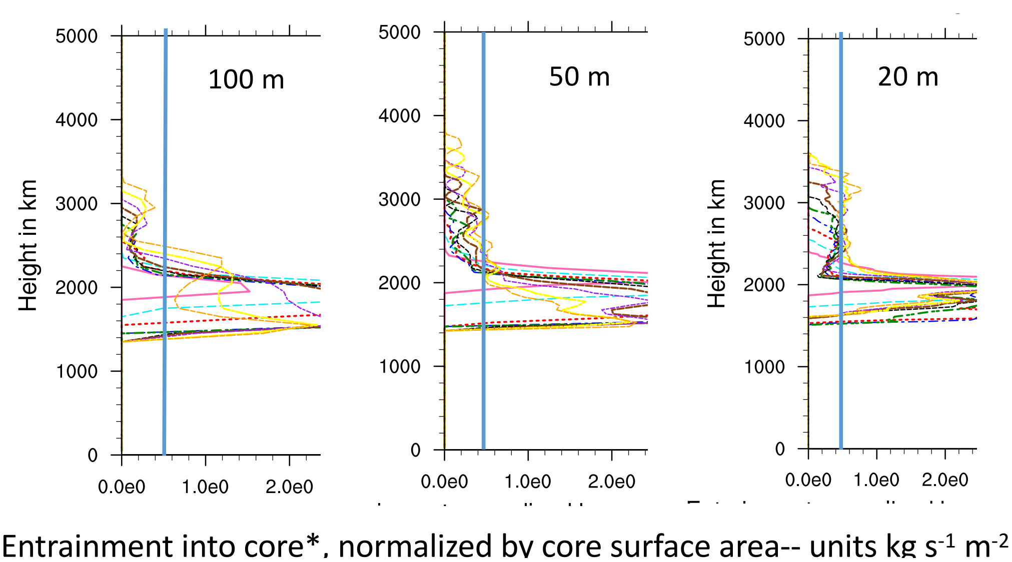

Figure 2: Vertical profiles of entrainment (horizontal mass fluxes) into the core of the clouds, as a function of time (different curves in each plot) and grid spacing used for the simulation (noted at top of each plot). Entrainment values continue to increase as the simulations used a grid spacing as small as 10 m (not shown).

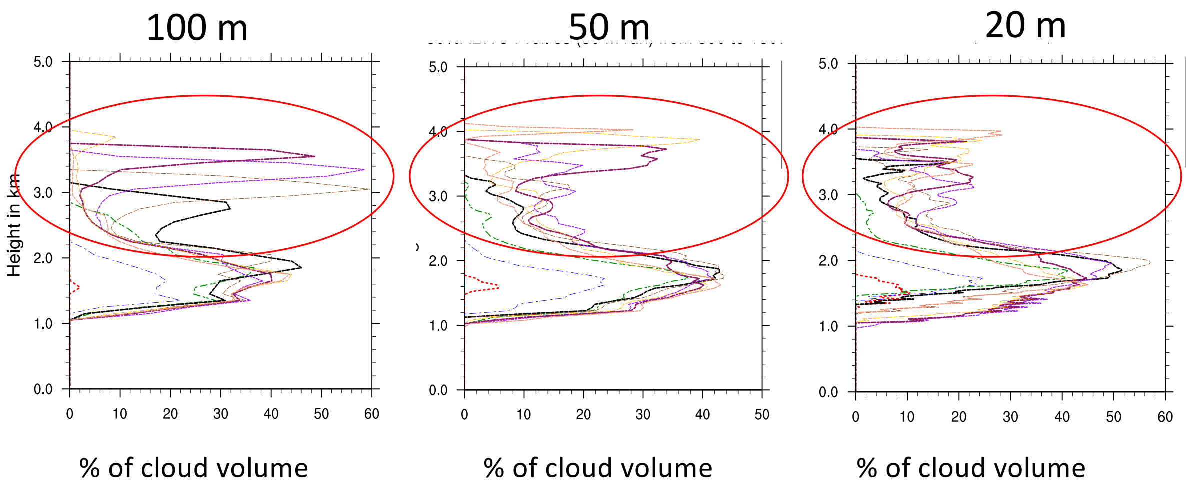

Figure 3: Vertical profiles of cloud core dilution, i.e., the percent of the cloud volume at each height that contains 80% or more of its theoretical maximum liquid water amount in the absence of entrainment, versus time (different curves) and for different simulation grid spacing (noted at top of each plot). Dilution values eventually converged as the simulations used a grid spacing as small as 10 m (not shown).

- **List of publications and presentations associated with this work**

Presentations:

Simulating Cumulus Entrainment: A Resolution Problem, or Conceptual? BW Users Conference, Oregon, June 2016 (presented some preliminary results)

High-Resolution Simulations of Cumulus Entrainment. International Conference on Clouds and Precipitation, Manchester, England, July 2016

Publications:

Lasher-Trapp, S., G., D. M. Moser, and D. Leon, 2016: High-Resolution Simulations of Cumulus Entrainment and Dilution, in prep.

Other products:

A new proposal to the NSF to extend this work to the effects of entrainment on severe storm generation and precipitation is also in preparation.

These simulations are also being used in Prof. Lasher-Trapp's courses on Clouds and Precipitation.

- **Plan for next year**

I am requesting a similar allocation to that received last year: 250,000 node-hours on Blue Waters for our new project: ***Untangling Entrainment Effects on Hail and Rain in Deep Convective Clouds***

Executive Summary: *Entrainment* describes how clouds bring dry air from outside the cloud inward, by their own motions. Its effects can limit storm development, longevity, and various interdependent microphysical processes that ultimately govern the precipitation produced. Our understanding of the connections between entrainment and precipitation has been limited by inadequate model resolution in past studies. Our previous work utilizing Blue Waters showed that the resulting effects of entrainment didn't converge until the grid spacing approached 10 m for a cumulus cloud. We will investigate if those results can be scaled for coarser model resolution used when simulating severe thunderstorms. New high-resolution 3D simulations of convective storms run on Blue Waters, along with our entrainment quantification algorithms, will be used to *untangle the intricate web of connections* between entrainment and its effects upon excessive rainfall and hailfall, with the ultimate goal of improving forecasts of these events.

Scaling the runs conducted on BW over the past year to those planned for this project (to be run using the same CM1 model, with slightly lower resolution but over a much wider domain, and with more sophisticated microphysics which means more equations to be marched forward in the model) the few, highest resolution runs will require nearly 20,000 node-hours to run. But these highest resolution runs will be limited in number, less than ten. The majority of the runs will require on the order of hundreds of node-hours to a few thousand. This allocation will be split among 3 graduate student projects and my own, to study the details of how entrainment of dry air into the cloud alters the microphysical processes within it, ultimately affecting rain and/or hail at the ground.

The default storage quotas should be sufficient. I will scale the anticipated usage schedule according to the timeframe in which some students anticipate finishing their degrees at UIUC, and others "ramp up" in our research group. Expressing this per quarter as a percent of the requested allocation, we anticipate the following usage: Q1: 10%, Q2: 25%, Q3: 35%, Q4: 30%.