Annual Report for Blue Waters Allocation: Sonia Lasher-Trapp, Oct 2017

- **Project Information:** ***Untangling Entrainment Effects on Hail and Rain in Deep Convective Clouds***
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- **Executive summary (150 words)**

New high-resolution 3D simulations of convective storms run on Blue Waters have been used to begin to untangle the intricate web of connections between entrainment (the introduction of dry air from outside the cloud inward by its own motions) and excessive rainfall and hailfall, and the associated storm outflow that can force new storm generation. High resolution is required to study the interactions of the small-scale turbulent motions (responsible for entrainment) and precipitation processes.

Results over the past year have shown that: (a) a line of closely-spaced storms can limit entrainment and be optimal for producing heavy rainfall, but in unexpected ways; (b) a more detailed analysis of the precipitation-related forcing for thunderstorm outflows suggests that the dominant terms are time-dependent; and (c) the entrainment characteristics and amount in the early stages of storms depends upon the mechanism of storm initiation used in the model.

Description of research activities and results

- *Key Challenges:* As our work has evolved from studying entrainment in single cumulus clouds, to now in individual storms or groups of storms, we have had to expand our model domains to much larger sizes, while trying to keep grid spacing small (200 m and less) to properly represent the smaller turbulent eddies in the cloud motions responsible for entrainment. Thousands of processors are required to divide up the calculations into manageable segments. These deeper storms also have more competing precipitation processes that must be represented in greater detail, thus requiring more memory to store these additional variables while the model is run, and more disk space to output and analyze the high-frequency model data output.
- *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 acquire fundamental knowledge to improve this conceptual model of how entrainment operates in storms, and its effects upon the precipitation they produce, and their ability to generate new storms. Our results can then form the basis for improved parameterizations used in larger scale models to predict weather and climate.
- *Why Blue Waters:* The Blue Waters architecture, speed, and storage is essential for resolving and analyzing the turbulence and precipitation processes at the heart of

these fundamental problems. Blue Waters is allowing us to push the spatial and temporal scale limits much farther than in the past studies, 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 simulations quickly supersedes the limits of most computers. A variety of data analysis tools for the large data sets we create are available and easy to use with Blue Waters, and the support staff is quickly responsive and supportive of users having any issues with their computational work on Blue Waters.

- ***Accomplishments***:
  - We have simulated lines of shallow storms to study how their entrainment differs as the spacing between them is increased or decreased. Similar to a set of observed storms in Southwestern England that caused heavy rainfall, the line of closely-spaced storms ultimately produced far more precipitation, due to a second generation of storms that was more shielded from the drying effects of entrainment. These results are being written for publication in the peer-reviewed literature, and have implications for understanding flash flood events of this nature. The graduate student performing these simulations will complete his Ph.D. in December 2017, and has already secured a job based upon his experience with high-performance scientific computing.

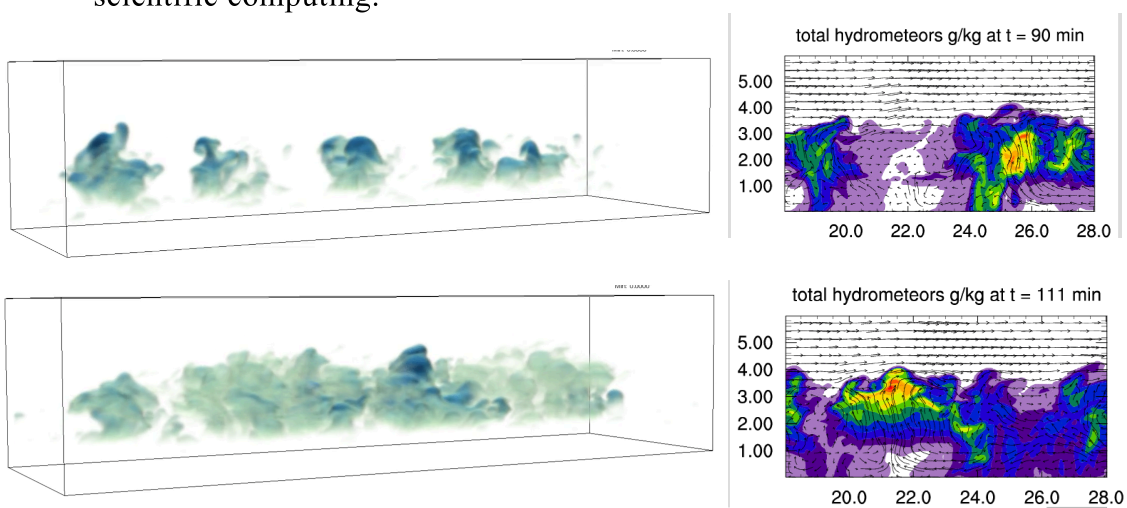

Figure 1. The original closer-spaced clouds (top left; only cloud plotted but not rain) produce some rainfall reaching the ground (top right; both cloud and rain plotted) like other cases with farther-spaced clouds, but the outflows from the falling rain from the closer-spaced clouds collide and produce a second generation of clouds that fill in the line (bottom left and bottom right) that eventually create far more precipitation than in the other cases due to their protection from the drying effects of entrainment.

  - We have also simulated isolated thunderstorms to investigate what latent cooling process (e.g. evaporation of rain, melting of graupel and/or hail, and sublimation of graupel and/or hail) contribute most to the thunderstorm outflows that generate "pools" of cold air that can promote new generations of thunderstorms. As opposed to other studies that have found that one of these terms dominates in an absolute sense (but different studies have found different terms to be dominant), our high temporal and spatial resolution analysis suggests that the dominant terms change in time. These results are also being written for publication in the peer-reviewed literature, and have implications for understanding longer-period outbreaks of thunderstorms. The graduate student performing these simulations will complete her M.S. in Summer 2018, and has already decided to stay at the University and pursue a Ph.D. to follow up on related topics and increase her experience with high-performance scientific computing.

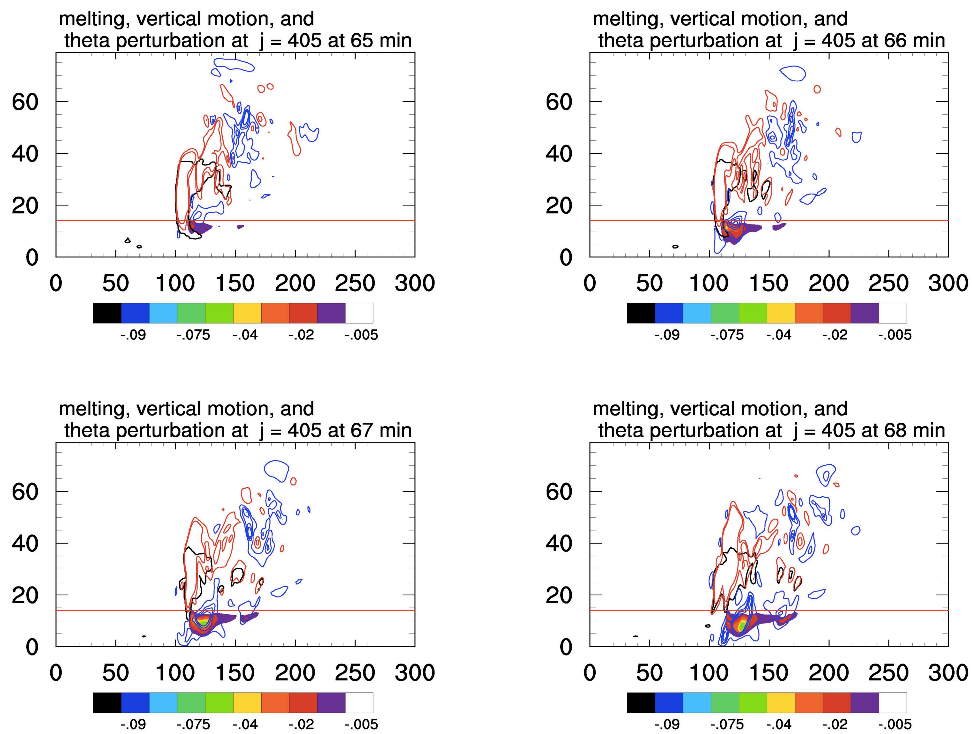

Figure 2a. Vertical cross-sections of the storm occurring within a subset of the model domain, with the cloud water (black contours) in relation to updrafts (red contours) and downdrafts (blue contours). The shading represents the latent cooling due to melting in Kelvin per second. The horizontal red line indicates the melting level. The axis scales are grid points. Through this time series we are able to take a cross-section through the storm's primary downdraft to see what process is contributing most to the downdraft that forms a 2 degree cold pool, in this case melting (vs. evaporation or sublimation). This run has a domain of 250 km x 250 km x 20 km, a resolution of 250 meters and outputs data every 30 seconds for analysis.

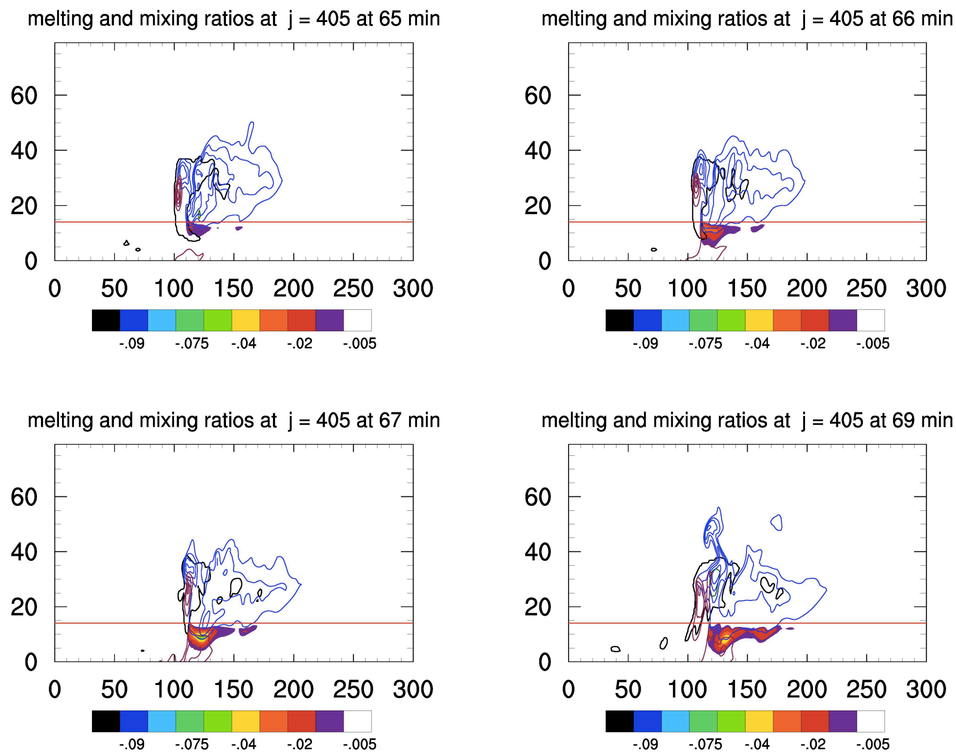

Figure 2b. As the likely contributor to the cold pool in this case and at this time from Fig. 2a appears to be melting, these vertical cross-sections at the same times illustrate what hydrometeors are contributing to this term. The cloud outline is shown (black contour) along with mass (per unit kg of air) for rain (pink), graupel (blue), and hail (green). Melting in Kelvin per second is the shaded values. A persistently large amount of graupel (blue) is located above the strongest region of melting, which cools the air and contributes to the cold pool in the outflow of the storm.

- We have also used high-resolution simulations of the early stages of isolated thunderstorms to understand if the rate of entrainment of dry air into the storm is dependent not only upon the stage of development (a physical cause) but also how the storm is initiated in the model (a numerical artifact). At the early stages, the entrainment differs based upon the storm initialization method. If the storm is initiated with a large buoyant bubble as has often been done historically, entrainment is delayed by the slowness of the large overturning circulation and lack of smaller-scale turbulent eddies. If the storm is initiated with a surface heat flux (a "hot spot" at the bottom of the model make to mimic solar heating of the air near the ground), small thermals develop and build into larger thermals, continually entraining air as found in the ultra-high resolution (down to 10 m grid spacing) that we have performed in earlier studies using Blue Waters. These results are also being written for publication in the peer-reviewed literature, and have implications for understanding how to make thunderstorm simulations more realistic in their earlier stages. Often researchers ignore or discard the early stages of the storms because they suffer these problems, and we are showing the implications of these difficulties upon entrainment and thunderstorm development in numerical models. The graduate student performing these simulations will complete his M.S. in Summer 2018, and is pursuing jobs where he can market his experience with high-performance scientific computing in private companies tackling applied problems in atmospheric science.

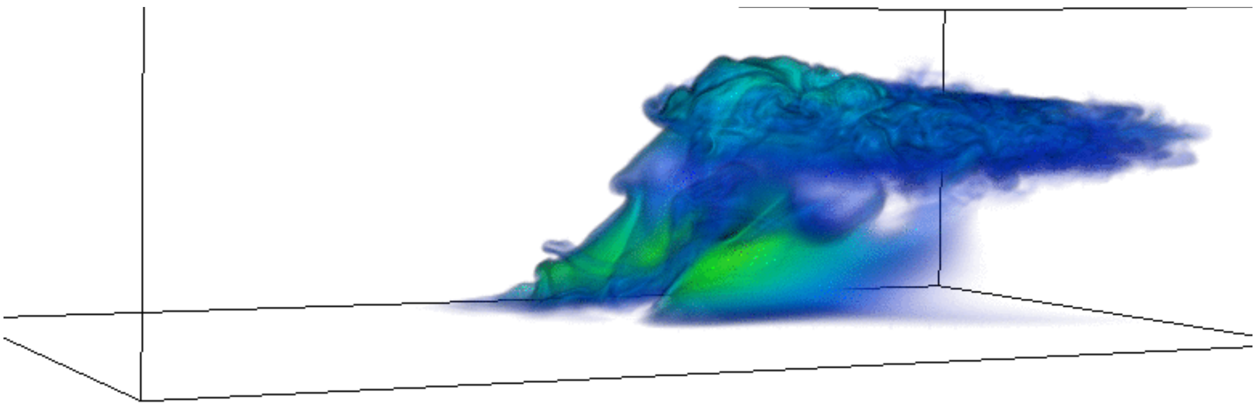

Figure 3. A 3D snapshot of a supercell thunderstorm simulated on Blue Waters. Entrainment is computed at the developing stages of the storm, and quantitative comparisons are being made based on the initialization procedure for the storm in the model. The mathematical equations that govern the behavior of this storm are calculated every fifth of a second and output every 6 seconds, but must then be further analyzed with entrainment diagnostic algorithms.

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

Presentations:

The COnvective Precipitation Experiment (COPE). Department of Marine, Earth, and Atmospheric Science, North Carolina State University, Rayleigh, NC, Oct 2017

An Investigation of Entrainment in Developing Thunderstorms with High Resolution Numerical Simulations. Midwest Student Conference on Atmospheric Research, Urbana, IL Oct 2017

Microphysical Influences on Cold Pool Properties. Midwest Student Conference on Atmospheric Research, Urbana, IL, Oct 2017

Cumulus Entrainment in Convective Clouds and Storms. BW Users Conference, Oregon, May 2017

The Influence of Successive Thermals and Cloud Separation Distance on Entrainment during the Convective Precipitation Experiment. Department of Atmospheric Sciences, University of Illinois, Urbana, IL, Feb 2017

Publications (in prep):

Lasher-Trapp, S., D. M. Moser, and D. Leon: *High-Resolution Simulations of Cumulus Entrainment and Dilution*.

Moser, D. M., and S. Lasher-Trapp: *Cloud Spacing Effects on Entrainment*.

Lasher-Trapp, S., and B. Engelsen: *Simulating the Entrainment in Developing Thunderstorms*.

Mallinson, H., and S. Lasher-Trapp: *Microphysical Influences upon Cold Pools*.

Other products:

NSF Award: *Quantifying Entrainment and its Effects in Isolated, Sheared Cumuli and Thunderstorms,* 2017-2020, S. Lasher-Trapp is Principle Investigator.

The results of our Blue Waters simulations are also being used in Prof. Lasher-Trapp's undergraduate and graduate courses on Clouds and Precipitation Physics.

- **Plan for next year**

I am requesting a 10% larger allocation to that received last year: 275,000 node-hours on Blue Waters, due to an increased number of runs needed to explore a larger parameter space for our new project: ***Untangling Entrainment-Precipitation Interactions 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. New high-resolution 3D simulations of convective storms in environments *spanning a range of thermodynamic and wind conditions* will be run on Blue Waters, along with our entrainment quantification algorithms, to untangle the interactions between entrainment and precipitation processes, with the ultimate goal of increasing our fundamental knowledge of this interaction that can be used to improve forecast models of thunderstorms and the precipitation they produce. We have just been awarded a new NSF grant to study this topic using Blue Waters, and reviewers remarked that our work there is novel and a computer like Blue Waters is necessary to conduct this work and exploration of this large parameter space.

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 similar resolution but over a much wider parameter space thus necessitating many more simulations), we anticipate needing a 10% higher allocation than last year. The few (less than 10), highest resolution runs will require over 10,000 node-hours to run, but the majority of the runs will require on the order of 5000 node hours or less. This allocation will be split among 2 graduate students, a postdoc and myself, 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 for now, but we may have to request additional space before the end of the allocation, depending upon how much of the raw data needs to be saved for each simulation. I will scale the anticipated usage schedule according to the timeframe in which students and a postdoc will be entering/leaving my research group. Expressing this per quarter as a percent of the requested allocation, we anticipate the following usage: Q1: 15%, Q2: 25%, Q3: 35%, Q4: 25%.