"BREATHING" CLOUDS AND STORMS: INFLOW AND ENTRAINMENT, PRECIPITATION AND OUTFLOW

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EXECUTIVE SUMMARY

"Entrainment" describes how clouds/storms bring dry air from outside the cloud inward by their own turbulent motions. Its effects can limit storm development, longevity, and precipitation. Our understanding of entrainment has been limited by inadequate model resolution in past studies. Now, we are running high-resolution 3D storm simulations on Blue Waters to quantify the interactions among entrainment, precipitation, and the generation of new storms.

Our latest results suggest that: (1) Storms growing in an environment where the winds increase strongly with height entrain three to five times more dry air than storms growing in a less windy environment; (2) storms that develop closer together may precipitate less initially but can produce outflows (strong winds) capable of forcing new storms that precipitate much more; and (3) the strength of these outflows appears to be most dependent upon the amount of large ice particles, called "graupel," that fall from the storm.

RESEARCH CHALLENGE

Deep convective clouds produce the majority of the earth's precipitation, and yet it is difficult to predict if developing cumulus clouds will attain the depth and longevity required to produce heavy rainfall that can generate flooding in some cases. In addition, strong winds (outflows) from some storms are capable of forcing new storms, leading to thunderstorm outbreaks that can affect large geographical areas. "Entrainment" is the term for the process by which the turbulent motions within clouds bring dry air from outside the cloud inward. In time, entrainment can limit storm development and precipitation but is not always effective in doing so. Long-standing problems in meteorological models have been to understand why they tend to predict rain formation too early, and/or in excessive amounts, and why models often miss predicting outbreaks of storms. Our approach here is to investigate if these deficiencies in past models are related to poor representation of entrainment, and of the types of precipitation that produce the strongest storm outflows that may generate new storms. This problem affects a broad range of atmospheric science problems, ranging from short-term weather forecasts from numerical weather-prediction models to climate forecasts from regional and global climate models.

METHODS & CODES

We used NCAR's CM1 model [1] to simulate convective clouds and storms at high resolution by employing its MPI capabilities on the many nodes available on Blue Waters. We utilized the NSSL microphysical scheme [2] within CM1 to model the details of precipitation formation. We conducted these simulations in both idealized and realistic environments. We evaluated entrainment with our own code [3] that calculates mass fluxes into the core of the storm as it evolves, and related it to the amount of precipitation the storm produces. We also used our own code that calculates the most important melting/evaporation factors that can strengthen storm outflows and potentially produce outbreaks of thunderstorms.

RESULTS & IMPACT

Our latest results are providing new quantitative information that can assist atmospheric scientists researching ways to represent thunderstorm entrainment, precipitation, and outflows in larger-scale weather and climate prediction models. They will also be of use to weather forecasters. Our results suggest that:

- Developing thunderstorms growing in an environment where the winds increase strongly with height (Fig. 1) initially entrain three to five times more dry air than storms developing in a less windy environment. These quantitative guidelines help establish how thunderstorm initiation can be suppressed in very windy environments.
- Storms that develop closer together may precipitate less initially due to their interference with the inflow of air into the neighboring storm bases that fuel them. However, if they do eventually precipitate, their outflows (strong winds) can meet and force new storms that precipitate much more.
- Calculations of the contribution of different kinds of precipitation to the strength of the storm outflows (Fig. 2) have revealed that the amount of large ice particles that fall from the storm appears to be most important rather than the evaporation of rain, as is sometimes assumed. This suggests that certain aspects of precipitation production in storms may be critical to thunderstorm outbreaks.

WHY BLUE WATERS

Our Blue Waters allocation has been essential for achieving the high resolution required within a given simulation to properly represent the smaller cloud motions that are important for entrainment and precipitation development over the larger spatial and temporal domains required for thunderstorms and their outflows. As a result of its huge number of nodes, its high speed, large memory, and its large storage capability for high-resolution model output and analysis, Blue Waters enables us to conduct our detailed calculations over millions of grid points. The hardware needed to run these kinds of simulations quickly supersedes the limits of most computers.

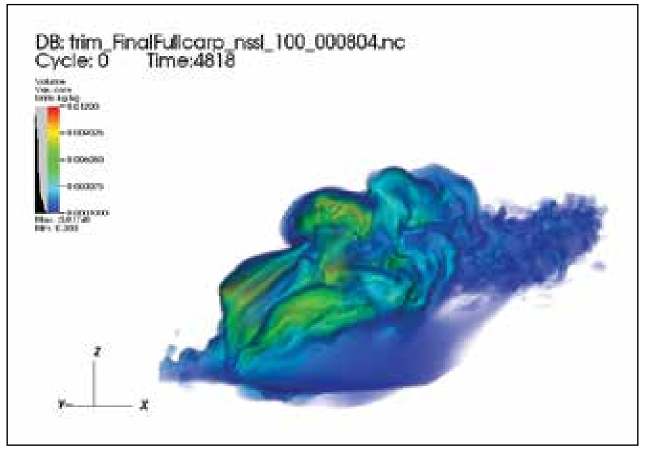

Figure 1: Precipitation mass in a thunderstorm developing in an environment where the wind speed increases greatly with height. Much of the mass from the older part of the cloud (blue colors on right side) was depleted by entrainment.

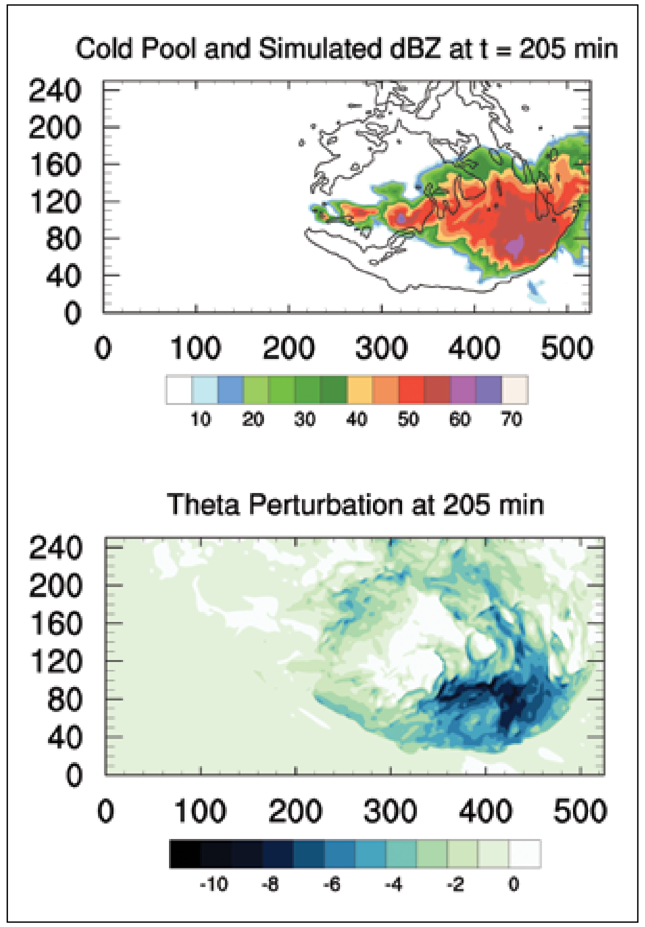

Figure 2: (Top) Simulated radar reflectivity for a system of thunderstorms, with cold outflow outlined in black. (Bottom) Associated temperature deficit (in degrees C) due to the cold precipitation outflow at this time. As this outflow propagates away from the storm, it can force new thunderstorms at its edge.