HIGH-RESOLUTION SIMULATIONS OF CUMULUS ENTRAINMENT

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EXECUTIVE SUMMARY

Understanding and predicting the rate at which liquid and ice are depleted in cumulus clouds by the entrainment of dry air, which affects their vertical development, longevity, and ability to precipitate, has been elusive. Observations alone are not sufficiently comprehensive to determine the key scales and motions involved. Simulations performed on Blue Waters are enabling us to address this problem numerically to determine (a) physically the most important scales of turbulence and (b) the minimum model resolution required for predicting the bulk cloud properties resulting from entrainment. A new approach for direct calculation of entrainment in a single simulated cloud has been applied for this purpose. The simulation results are consistent with new observational quantification of eddy sizes at the cloud edge, as detected by airborne cloud LIDAR.

INTRODUCTION

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, and/or become severe thunderstorms. Entrainment is the term for the process by which clouds bring dry air from outside the cloud inward. In time, entrainment not only reduces the cloud buoyancy, limiting its vertical development, but also depletes its liquid water by evaporation, limiting precipitation formation. A long-standing problem in meteorological models has been to reproduce how quickly entrainment accomplishes these results. This problem affects a broad range of atmospheric science problems, ranging from short-term weather forecasts in numerical weather prediction models to climate forecasts in regional and global climate models.

METHODS & RESULTS

Using a thermodynamic atmospheric profile collected from an observational study of real cumuli as input to the CM1 cloud-resolving model, we continually decreased the model grid spacing from 200 m down to 20 m to represent increasingly smaller "eddies" in a single cumulus cloud (Fig. 1). We applied a recently developed numerical technique [1] to find the edge of the high liquid water core within the cloud, and then at this edge directly calculated the air inflow and outflow from the core surface to quantify the net entrainment as a function of space, and of time. We then created one-minute averaged vertical profiles of the entrainment to compare among different simulations, and to compare to the amount of liquid water in the core of the cloud versus time.

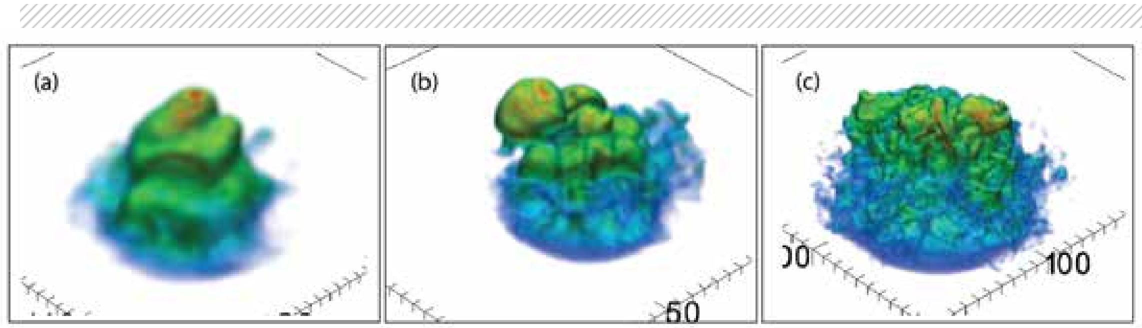

FIGURE 1: Cloud water shown at 1500 s for simulations run with (a) 100 m, (b) 50 m, and (c) 20 m grid spacing. The representation of increasingly smaller entraining eddies results from smaller grid spacing, and leads to fewer and weaker areas of high values of cloud water (red).

The results show that as the model grid spacing is decreased, more entrainment occurs in the simulated clouds. The entrainment at 20 m grid spacing is nearly double that at 100 m, and about 1 ½ times that at 50 m grid spacing. The increased entrainment depletes the cloud core more quickly (Fig. 2), in closer agreement to airborne observations of multiple clouds on this day. It is not yet clear that the model results have converged at 20 m grid spacing, and so runs with smaller grid spacing are yet being conducted to resolve even smaller eddies. New wavelet analysis of airborne cloud LIDAR data suggests that eddies at the cloud tops on the order of 30-50 m wide are prevalent (Figure 3), and thus will likely need to be represented in our simulations to attain the most realistic computational results.

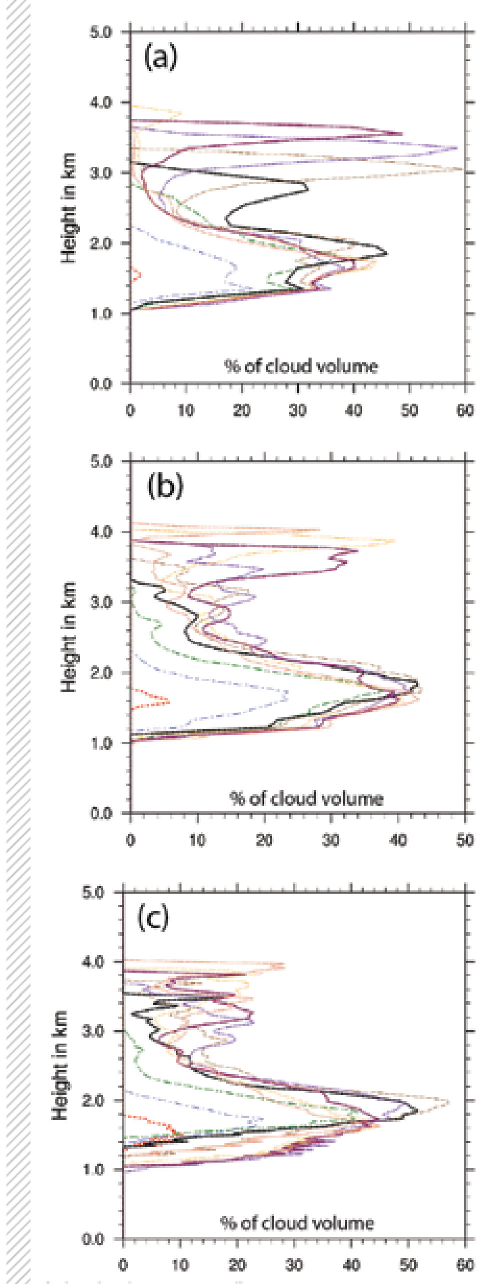

FIGURE 2: Vertical profiles of the percentage of the cloud volume at the given altitude that contains high values of cloud water (i.e. exceeding 80% of the maximum theoretical upper limit). The results are most important above 2 km height, where local areas of high liquid water can promote precipitation. As more entrainment is represented at smaller grid spacing (a) 100 m, (b) 50 m, (c) 20 m, less of the cloud volume contains regions of high cloud water.

WHY BLUE WATERS

Our Blue Waters allocation is essential for testing the resolution-dependency of the entrainment process, in particular for determining the sizes of the eddies that are most critical to represent in these and future simulations of cumulus entrainment. Blue Waters allows 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.

NEXT GENERATION WORK

Our work over the past couple of years has focused on understanding what spatial and temporal scales must be considered in high-resolution simulations of cumulus clouds. This helps to accurately capture the most important cloud motions for evolution of the bulk properties (like total cloud water mass) in space and time. As we complete that investigation over the next year, including running ensembles to assess the generality of the results heretofore performed with single cloud simulations, we will also begin pursuing the question of how an accurate representation of cumulus entrainment in model simulations can affect the development, longevity, and severity of thunderstorms and the rain and/or hail that they produce. Such simulations will need to be run over a larger domain and for longer periods of time, and require detailed information on the cloud particles (water droplets, ice, raindrops, hail). By the time the Track-1 system is in place in 2019/2020, we will have some initial simulations performed, but the new system will allow us to run ensembles of simulations to assess the generality of the results for better understanding and prediction of flash floods and hail storms.

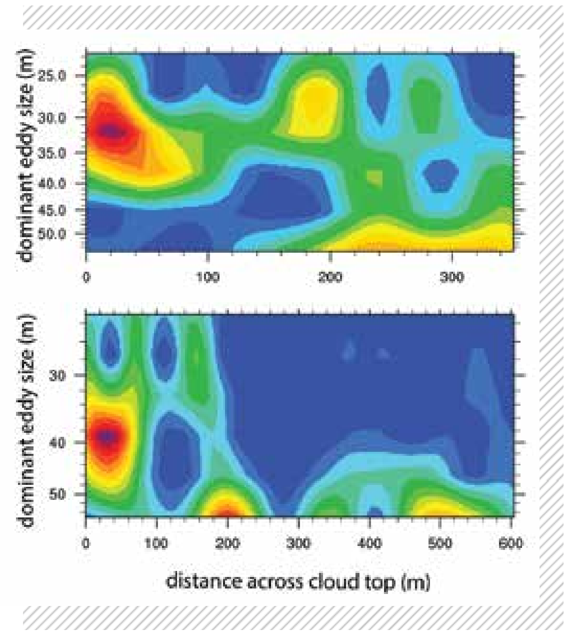

FIGURE 3: Examples of wavelet analysis performed from scans across the tops of two real cumulus clouds with an airborne cloud lidar. "Hot spots" (red) show areas where cloud top eddies of the size shown on the vertical axis are prevalent. This observational evidence thus warrants additional simulations at higher resolution to investigate if these smaller eddies contribute significantly to entrainment.

PUBLICATIONS AND DATA SETS

Lasher-Trapp, S., D. H. Moser, D. C. Leon, J. French, and A. M. Blyth, High Resolution Simulations of Cumulus Entrainment. *17th International Conference on Clouds and Precipitation*, Manchester, England, July 25-29, 2016.

FORECASTING GLOBAL CROP PRODUCTIVITY USING NOVEL SATELLITE DATA AND PROCESS-BASED MODELS

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EXECUTIVE SUMMARY

The ultimate goal of this project is to improve predictability for global crop yield by integrating site measurements, advanced remote sensing observation, and process-based modeling. We took our first step forward by focusing on the high-temperature impacts on corn/soybean yield in the U.S. Corn Belt. Different pathways of high-temperature impacts on crop yield are considered in our newly developed CLM-APSIM modeling framework, which combines the strengths of earth system model and agronomy crop models. We are conducting parameter sensitivity analysis and optimization as well as a set of historical simulation experiments aimed at disentangling the contribution of different mechanisms to high-temperature impacts on crop yield. Projection runs will also be conducted shortly to explore the impact of high temperatures on crop yield under various climate change scenarios.

INTRODUCTION

Temperatures over the terrestrial areas of the planet are expected to increase at least twice the global average, with specific regions experiencing increases of between 3-4°C by the mid-2000s. With this expected climate change scenario, high temperature can severely affect crop productivity through different pathways. Individual processes have been well studied, but mostly in isolation, prompting a need for a holistic approach to quantify different processes at one time and in actual environments. Furthermore, when projecting future high-temperature impact on crop productivity under climate change, instead of lumping all effects into a single regression coefficient as done in most previous statistical studies, we should explicitly simulate different processes in a process-based manner which makes designing detailed climate change adaptation strategies for agriculture systems achievable.

Corn and soybean are the two most widely planted crops in the U.S., with planted acreage of 92.9 and 74.8 million acres in 2012. The U.S. produces about 40% of the global corn and soybean crops. Understanding the mechanisms of corn/soybean response to abiotic stresses and providing possible breeding priority for improved varieties has critical significance for the U.S. agricultural economy and also for individual farmers.

METHODS & RESULTS

In this study, we aim to quantify various processes of high-temperature impacts on corn/soybean yield at various scales. Specifically, we consider the following major processes: (1) direct temperature effects on photosynthesis and respiration; (2) sped-up growth rate and the shortening of growing season; (3) heat stress during reproductive stage (flowering and grain-filling); (4) high-temperature-induced increase of atmospheric water demands. By combing the strength of the Community Land Model (CLM) in modeling surface hydrology and photosynthesis and that of the Agricultural Production Systems sIMulator (APSIM) in modeling crop phenology, the newly developed CLM-APSIM crop modeling framework enables us diagnose the effect of high temperature stress through different processes on various crop phonology stages.

First, ground measurements obtained from the advanced SoyFACE facility at the University of Illinois at Urbana-Champaign are used to validate, tune, and improve the CLM-APSIM modeling framework at the site level. Second, parameter screening and sensitivity analysis (SA) experiments are conducted at the local site scale. We use the Sobol sensitivity analysis, which is a global SA method that decomposes the variance of the model output into contributions from each parameter. It's interactions with other parameters through tens of thousands of ensemble simulations of the CLM-APSIM model following the improved Monte Carlo scheme. Third, we calibrate the CLM-APSIM model at grid scale across U.S. through model-data fusion or data assimilation techniques. Novel satellite data, such as fluorescence from OCO-2, soil moisture from SMAP, backscattering information from RapidSCAT, will be used to constrain the CLM-APSIM model at grid scale. We finally use the CLM-APSIM modeling framework to project crop yield for the whole U.S. Corn Belt under different baseline climate scenarios (efficient versus business-as-usual ones).

WHY BLUE WATERS

The computational demand of our satellite data interpretation and modeling effort is huge (~5PB storage for satellite/model inputs and outputs) and the Blue Waters facility offers us the best solution for large processing element demands, high-frequency I/O, and output post-processing and visualization. Interactions with the system staff and those in NCSA lead to a strong technical support for our project.

NEXT GENERATION WORK

As described above, the ultimate goal of this project is to improve the forecasting skill of global crop yield under climate change, though we just focused on U.S. Corn Belt at present. We plan to extend our modeling work to the whole globe on a possible next-generation Track-1 system in the 2019-2020 timeframe. The global scale research is essential as climate change-induced temperature increasing has been diagnosed everywhere across the global terrestrial areas. Understanding the high-temperature impacts on crop yield at the global scale will be helpful to the world's food security and agriculture economy.