EARTHQUAKE SYSTEM SCIENCE RESEARCH

Allocation: NSF PRAC/6.3 Mnh
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EXECUTIVE SUMMARY:

SCEC's multi-disciplinary research team is using Blue Waters to develop high-resolution computational models of earthquake processes and to calculate physics-based probabilistic ground motion forecasts for selected urban areas in the United States. The U.S. Geological Survey (USGS), through its National Seismic Hazard Mapping Project (NSHMP), currently uses empirical probabilistic seismic hazard analysis (PSHA) to promote seismic safety engineering and disaster preparedness across the United States, including California. PSHA is the scientific basis for many engineering and social applications including performance-based design, seismic retrofitting, resilience engineering, insurance rate setting, disaster preparation and warning, emergency response, and public education. SCEC's research goal is to develop physics-based models for the urban regions of California that are more accurate than the empirical NSHMP standard. Our long-term goal is to extend the more accurate physics-based PSHA across the full bandwidth needed for seismic building codes, simulating ground motions at frequencies up to 10 Hz. We are working with the USGS to integrate SCEC computational results into NSHMP products that will benefit end-users of earthquake information including scientists, engineers, and the public.

INTRODUCTION

Over the last decade, SCEC's earthquake system science research program has developed detailed earth structural models and HPC software needed to perform realistic, physics-based earthquake simulations. During that time, SCEC has verified the computational readiness and scalability on Blue Waters for dynamic rupture, deterministic earthquake wave propagation, and probabilistic seismic hazard simulation codes.

METHODS & RESULTS

Over the last year, SCEC used Blue Waters to conduct earthquake system science computational research in two main areas. First, we integrated advanced physics into deterministic earthquake wave propagation software. Second, we calculated the first 1 Hz CyberShake hazard model, doubling the maximum frequency of the previous 0.5 Hz CyberShake hazard model completed in 2014.

We integrated more realistic physics into our high-performance earthquake simulation software to model frequency-dependent attenuation [1], free-surface topography [2], and non-linear yielding effects [3]. All of these effects become increasingly important when simulating high-frequency ground motions.

In March 2015, SCEC's GPU-based, CUDA-language, high-performance wave propagation software received the NVIDIA Global Impact Award [4–6]. We integrated this high-performance GPU-based code into our physics-based probabilistic seismic hazard workflows. This enabled SCEC to make use of highly efficient GPUs for our floating-point-intensive processing.

Starting in April 2015, our SCEC team ran the first 1 Hz physics-based Los-Angeles-area seismic hazard model. SCEC used Blue Waters, together with Titan (Oak Ridge Leadership Computing Facility, OLCF), over seven weeks to produce this hazard calculation for scientists and civil engineers. These recent results, called CyberShake Study 15.4, combined the large number of GPU nodes on Titan with both GPU and CPU nodes on Blue Waters to reduce the time-to-solution for a CyberShake model calculation from months to weeks. This CyberShake calculation represents a collaboration that includes the University of Southern California, NSF Track-1 facilities, and Department of Energy Leadership HPC centers working together and with scientists and engineers on socially important, broad-impact, HPC-based research.

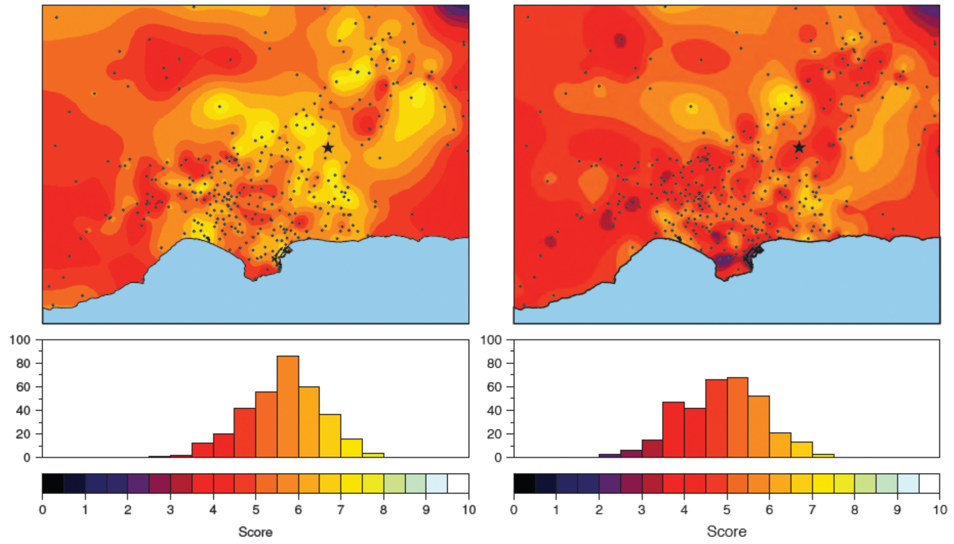

FIGURE 1: Maps of the Los Angeles region that compare SCEC simulated ground motions to observed ground motions using two different 3D Earth structure models as input to the 1 Hz ground motion simulation (left: CVM-S4.26, right: CVM-H). Red/purple indicates a poor match and yellow indicates a good match using a goodness-of-fit method. The star indicates the epicenter of the 2008 M5.4 Chino Hills earthquake and dots show ground motion recordings for the event. [Credit: Ricardo Taborda, University of Memphis; Jacobo Bielak, Carnegie Mellon University]

WHY BLUE WATERS?

SCEC computational research continues to expand in multiple dimensions, including geographical range, higher resolution, and more time steps, so new simulations require more computational, memory, and storage resources.

SCEC computational needs continue to grow because individual earthquake simulations do not "solve" a problem when run once. In many cases, seismic hazard calculations involve use of fault models and earth structure models. When these structural models are updated, simulations need to be run again, with new inputs, in order to produce updated seismic hazard estimates. Re-running simulations with new inputs increases our need for computational time.

Deterministic ground motion simulation techniques work well at 1 Hz and below in many areas. The maximum necessary simulated frequency for global earthquake simulations is about 1 Hz. The maximum necessary simulated frequency for seismic hazard analysis is above 10 Hz. Ground motion modelers must implement improved physics and improved code performance in order to increase the maximum simulated frequency of wave propagation codes to the required higher frequencies. Due to the large node count and significant memory per core on Blue Waters, SCEC researchers were able to perform ground motion simulations on Blue Waters at 4 Hz frequencies using two different computational methods. Validation of these new simulation capabilities will involve simulating well-recorded historic California earthquakes and comparing the simulated ground motions against the recorded ground motions [7].

SCEC's earthquake system science computational research uses a broad range of codes and system capabilities. Blue Waters provides the broad range of system capabilities we need in our computation research including CPUs with a significant amount of RAM as well as many highly efficient GPU nodes. Blue Waters also provides very large online disk storage that is very valuable for storing temporary intermediate files during long-duration calculation. The Blue Waters software stack and computing policies also provide very valuable support for SCEC's large-scale scientific workflows that rely on scientific workflow management tools and remote job submission support.

Blue Waters helps reduce the time-to-solution for SCEC's long-duration CyberShake calculations to manageable levels. SCEC is currently collaborating with a civil engineering group on CyberShake hazard model development. The project requires a six-month update cycle, so scientists and engineers meet every six months to review the updated CyberShake hazard model. Blue Waters enables SCEC to meet this schedule because a full CyberShake simulation can run within one review cycle.

SCEC plans to expand use of its most advanced modeling from southern California to more regions. Several specific goals, including a statewide California CyberShake seismic hazard model, will require the computing capabilities of the next generation of Track-1 systems.

PUBLICATIONS

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SIMULATING CUMULUS ENTRAINMENT: A RESOLUTION PROBLEM, OR CONCEPTUAL?

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EXECUTIVE SUMMARY:

Understanding and predicting the rate at which cumulus clouds deplete their water content by the entrainment of dry air, affecting their development, longevity, and ability to precipitate, has been elusive. Simulations performed on Blue Waters are enabling us to investigate if the problem lies in our ability to represent the smallest scales of turbulence in our models, or if our underlying conceptual models of the physics of entrainment are flawed, or both.

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. Entrainment is the process by which clouds bring dry air from outside the cloud inward. It can initially favor precipitation formation; eventually, it dilutes the cloud and encourages its demise. A long-standing problem in meteorology has been to reproduce how quickly entrainment dilutes a cumulus cloud. Currently, all models fail. This has long been assumed to be a problem of inadequate spatial resolution, where the smallest scales of turbulence must be parameterized and their effects are improperly represented. It could also result from a fundamental problem in our conceptual understanding of the entrainment process. Our goals are to test both possibilities.

METHODS & RESULTS

We've run numerous simulations at relatively coarse (50 m) resolution in order to see how entrainment in a single cumulus cloud differs due to basic physical parameters, such as the strength of the cloud forcing, the size (width) of the cloud, and the amount of wind shear (the change in wind speed with height) in the atmosphere surrounding the cloud. We've also developed tools to quantify the entrainment that is occurring in the simulated clouds as they grow in time. As predicted from laboratory and theoretical models of thermals, narrower clouds are diluted by entrainment more quickly, helping to validate the cloud model results. However, contrary to theoretical models, weaker clouds, i.e. those having weaker updrafts, also appear to be diluted more quickly than stronger clouds. This finding is perplexing, and we continue to explore related parameter spaces to determine if the result is physically viable or due to a computational artifact in cloud models. Future comparison of the simulation results with aircraft observations of real cumulus clouds will also be key to understanding these findings.

WHY BLUE WATERS

Our Blue Waters allocation is essential for testing the resolution-dependency of the entrainment process and in particular for determining the sizes of the eddies that are most critical to represent in simulations of cumulus entrainment. Blue Waters–with its huge number of nodes, its high speed, and its large storage capability for high-resolution model output and analysis–allows us to push the spatial scale limit much farther than in the past. We intend to increase the resolution to as high as 5 m (over domain sizes of 10 km or greater) in order to understand any computational issues related to cumulus entrainment, in addition to improving our knowledge of the underlying physics. The computational demands of these large simulations quickly supersede the limits of most computers

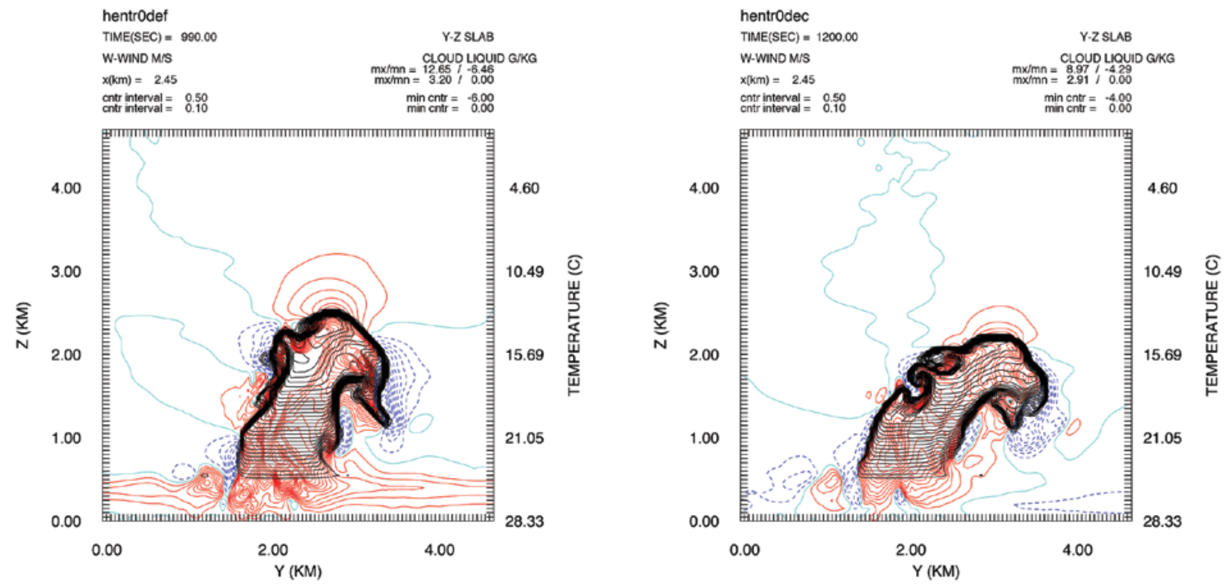

FIGURE 1: Vertical cross-sections through two cloud simulations, showing the difference in vertical configurations of the clouds with respect to initial cloud forcing. Vertical velocities are contoured in increments of 0.5 m s-1, where red indicates upward motion and blue indicates downward motion. Black contours indicate cloud water mass in increments of 0.1 g per kg of air. The left panel shows results for stronger cloud forcing, producing a more upright cloud, and the right panel shows results for weaker cloud forcing, where the cloud is more susceptible to leaning due to the ambient wind flow (not shown). The leaning cloud appears to entrain more dry air than the former, for similar cloud top heights.