3D RADIATIVE TRANSFER MODEL COUPLED TO THE WEATHER RESEARCH AND FORECASTING MODEL

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Executive Summary:

Our goal is to improve Numerical Weather Prediction models and Remote Sensing algorithms for Earth's atmosphere through greatly improved treatment of radiative transfer (RT). Our starting point is to produce a highly accurate 3D Monte Carlo RT model that can better handle the atmosphere's complexity. Our first applications have been in studying biases in cloud products derived from NASA satellite instruments. In tandem, model development has advanced our capabilities from monochromatic simulations to broadband, spectrally integrated, simulations. Future directions include coupling the standalone RT model with a dynamic model of the atmosphere to quantify time-integrated impacts of 3D RT on cloud properties and evolution.

Description of Research Activities and Results:

Recent events such as the typhoon in the Philippines and Hurricane Sandy point to the importance of understanding and predicting Earth's weather and climate. Research in weather and climate has massive societal benefits, and indeed has been one of the leading drivers for advancing supercomputing infrastructures. The least understood aspect of the weather and climate system are Earth's clouds, particularly as they interact with solar radiation. Clouds play an exceptionally important role in the atmosphere, redistributing radiative energy from the sun as well as that emitted from the Earth and atmosphere. Currently, radiative transfer (RT) in atmospheric models is represented in a primitive manner (mostly in a single dimension-up/down) because of the exceptional computational expense. Computational resources have always been a constraint on how radiation can be explicitly represented in dynamic models of the atmosphere such as the Weather Research and Forecasting Model (WRF), especially at LES (large eddy simulation) scales with grid spacing ranging from 10m-100m. As the numerical representation of other physical processes have advanced (e.g. cloud microphysical processes), the representation of radiative processes have remained markedly unsophisticated. This is true even at the finest LES resolutions where the approximations that allow for computationally inexpensive treatments break down even further.

These crude representations of radiative transfer can result in localized orders-of-magnitude error in radiative heating in the presence of clouds with complex morphology. The resulting errors, when allowed to feedback on cloud dynamics, feedback as errors in cloud size, lifetime, and physical properties. These changes in turn may impact weather and climate by, for example, affecting rainfall, surface atmospheric heating, and photolysis rates. While 3D radiative transfer is a solved problem (e.g., by way of a Monte Carlo solution), albeit a computationally expensive one, *a full 3D RT model has never before been coupled to a cloud dynamics model*. Here we propose to do just that. This coupled model, for the first time, will allow us to study and understand how errors from the crude RT approximations used in the past feedback on cloud properties and their evolution. We anticipate that the contributions from radiative cooling at cloud edge and other radiative effects could close the current gap between numerical results and observations, not only of dynamical properties but of micro- and macro-physical cloud properties. In carrying out this project, we will address longstanding significant computational challenges inherent in solving the radiative transfer problem in cloudy atmospheres.

Simulating 3D RT coupled to WRF is a Blue Waters-class computational problem that far exceeds traditional XSEDE resources. As a result of this research, a new tool will be developed and made available to the research community– an LES model with a full 3D radiative physics package. This will provide a solid foundation for testing future hypotheses involving the two-way interaction of cloud systems and radiation. This model will also become a test-bed for the development of practical RT parameterizations that capture the most important 3D RT effects at lower resolution and lower computational cost, which will benefit the broader modeling community striving to improve weather and climate predictions. Our new model will also address other unresolved issues related to the role of 3D RT in the interpretation of aircraft and satellite observations of clouds and aerosols, which is a key component of Prof. Di Girolamo's NASA-sponsored research program.

During this first year we have used the RT model to address problems in cloud products derived from NASA satellite instruments. One of the largest experiments conducted involved simulating light intensity observed by satellite during a tornado outbreak across central Illinois. The simulation consisted of tracing the paths of approximately 2 billion bundles of monochromatic light through a 655x895x167 domain, with a 400m horizontal resolution and 75m vertical resolution. This was largest domain ever simulated with a 3D radiative transfer model applied to the atmosphere. Images from this simulation were included in the Blue Waters 2014 Annual Report. Simulations comprising this experiment were at one point occupying one third of the available nodes on Blue Waters. This experiment revealed potential memory limitations for future experiments involving large domains and many bundles, which limit the scalability of the model. However, due to the independent nature of the computations, assuming an appropriate random number generator and unique seed value are used, individual instances of the model can be run at peak efficiency, and results combined in post-processing to achieve the total number of bundles desired.

Additional experiments highlighted the bias caused by neglecting 3D radiative transfer in the models used to invert satellite observations of light intensity into low-cloud properties. For example the determination of low-cloud height shows a bias of about 30-400m, strongly dependent on the 3D distribution of the cloud liquid and ice water content and on sun-view geometry. When cloud height trends of 40m are significant enough to imply enhanced negative feedbacks of clouds in the climate system a bias of 30-400m calls into question the actual magnitude of that feedback. Another example involved highlighting deficiencies in the standard technique utilized to derive cloud effective radius and optical depth simultaneously from satellite observations of light intensity. When 3D radiative transfer is taken into account, cloud side leakage of radiation results in a bias in the effective radius towards larger values, while the optical depth inversion remains relatively unaffected. This calls into question commonly used effective radius products from satellite instruments such as MODIS.

In addition to these high impact experiments large advances in model development have been made. The previously monochromatic radiative transfer model has been extended to allow for broadband integration. This involved a re-working of the MPI communication set up to manage the competing goals of load balance and communication efficiency. To conduct the first simulations of a non-idealized atmosphere also required constructing tables of scattering properties of atmosphere's gasses, a sizable undertaking itself. Currently work is continuing on improving the communication efficiency, and constructing a table of cloud scattering properties, the final step in developing a stand-alone broadband radiative transfer model for the atmosphere.

List of Associated Publications:

Di Girolamo, L., A. L. Jones, D. Jackson, B. Jewett, and B. Chapman, (2014), Blue Waters Applications of a 3-D Monte Carlo Atmospheric Radiative Transfer Model, Blue Waters Annual Report, University of Illinois Press, Urbana, IL.

Di Girolamo, L. 2014: Blue Waters applications of 3D Monte Carlo atmospheric radiative transfer. Blue Waters Symposium, May 13 - 15, Urbana, IL.

Larry Di Girolamo, University of Illinois, Urbana, IL; and C. O. Haney, G. Zhao, L. Liang, A. Jones, R. M. Rauber, A. Manaster, and S. Platnick, Cloud drop effective radius as observed from aircraft, MODIS and MISR. A. L. Jones, and L. Di Girolamo, A New Spectrally Integrating 3D Monte Carlo Radiative Transfer Model, paper presented at 14th Conference on Atmospheric Radiation, American Meteorological Society, Boston, MA, July 7-11, 2014.

A. L. Jones, and L. Di Girolamo, A New Spectrally Integrating 3D Monte Carlo Radiative Transfer Model, paper presented at 14th Conference on Atmospheric Radiation, American Meteorological Society, Boston, MA, July 7-11, 2014.(with video)

A. L. Jones, Development of a Highly Accurate 3D Radiative Transfer Model, presented as part of the University of Illinois Atmospheric Sciences Colloquia Series, Urbana, IL, April 1, 2015.

Jones, A. L., (2015 anticipated), Radiative Heating Rates in a heterogeneous Cloudy Atmosphere from a New Spectrally Integrating 3D Monte Carlo Atmospheric Radiative Transfer Model, Ph.D. Dissertation, University of Illinois, Urbana, IL.

Di Girolamo, L., et al., An evaluation of the MODIS liquid cloud drop effective radius product for tradewind cumulus clouds: implications for data interpretation and building climatologies. (in preparation)

Plan for next year:

Next year work will continue on completing the stand-alone radiative transfer model. It will then be utilized to provide highly accurate standards of comparison for other radiative transfer models. This contribution will allow for inclusion of parameterizations of 3D effects in the simpler, less expensive, more commonly used radiative transfer models that are either coupled to climate and weather models, or used to invert satellite observations, for example. Additional experiments, highlighting the bias in satellite products due to 3D effects will be conducted. Finally, work will begin on coupling the stand-alone model to a high resolution dynamic model of the atmosphere to finally quantify the time-integrated impact of radiative heating on cloud properties and evolution.

We request 240,000 node hours for next year. Alexandra Jones has been supported with a Blue Waters Graduate Fellowship allocation since September 2014 that will expire at the end of August 2015. Therefore her utilization of the Blue Waters professor allocation will greatly increase. The timing will correspond with the completion of the development of the stand-alone model which will then be utilized to demonstrate the importance of 3D radiative transfer in the high accuracy benchmark simulations mentioned above. Once the model is coupled to a high resolution dynamic model of the atmosphere, high utilization of the allocation will then occur. Therefore we expect the usage break down by quarter to be the following:

Q1: 25% Q2: 20% Q3: 15% Q4: 40%

The storage requirement is not anticipated to be large relative to Blue Waters capacity. Tables of scattering properties will need to be retained for each unique atmospheric domain, however total storage for those tables and the corresponding output should not exceed 50 TB. The model requires only two input files and produces one output file, so there is no anticipated taxing of the file system expected due to large numbers of files. The radiative transfer model is comprised mainly of logical operations to determine the fate of the bundle of light, i.e. comparisons of random numbers to cumulative distribution functions and simple arithmetic calculations to tally the contribution of each bundle as it travels through the domain. Memory usage will depend on domain size. At this time domain sizes as large as used for the tornado outbreak simulation are not expected.