RRTMGP: A High-Performance Broadband Radiation Code for the Next Decade

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LONG-TERM GOALS

We are developing a high-performance broadband radiation code for the current generation of computational architectures. This code, called RRTMGP, will be a completely restructured and modern version of the accurate RRTMG radiation code (*Mlawer et al., 1997*; *Iacono et al.*, 2008) that has been implemented in many General Circulation Models (GCMs) including the Navy Global Environmental Model (NAVGEM), the NCAR Community Earth System Model (CESM), and NOAA's Global Forecast System (GFS). Our proposed development will significantly lessen a key bottleneck in these highly complex and coupled models, namely the large fraction of computational time currently required for the calculation of radiative fluxes and heating rates.

OBJECTIVES

The radiation calculations needed for climate simulations require many independent and complicated calculations, and are therefore an inviting target for new computing architectures such as Many-Integrated-Cores (MICs) and Graphical Processing Units (GPUs). We are developing RRTMGP ('P' stands for 'parallel'), a modern version of the radiation code (RRTMG) used by many climate models, directed at the current generation of vector- and cache-based computational architectures. This code will retain the high accuracy of RRTMG, but is being developed from scratch to make it more flexible and amenable to optimization across a wide range of platforms. The objective is a single well-maintained, well-documented, and efficient radiation code that can be used by the modeling community for a diverse range of applications across a wide range of computing facilities. RRTMGP will exhibit profound improvements in speed for GPU and vector CPU machines and lesser, but still valuable, speed-ups on other CPU-based platforms relative to the current version of the code.

APPROACH

[technical approach, key individuals at your own or other organizations]

The collaborating team consists of scientists and programmers with detailed knowledge of RRTMG and its use within GCMs, as well as representatives of modeling centers that use RRTMG and plan to upgrade to RRTMGP. Eli Mlawer of AER, the lead developer of RRTMG, is the PI of this project and his team at AER has included programmers with experience coding for modern computer architectures. Team member Robert Pincus of University of Colorado refactored RRTMG to create PSRad, which has served as a prototype for the current development. Drs. Mlawer and Pincus are leading the design and development of RRTMGP. Brian Eaton of NCAR, which has employed RRTMG in its GCM (CESM/CAM) for nearly a decade, leads a group at this modeling center participating in the project. Project collaborators Ming Liu and Tim Whitcomb of NRL represent the interests of the Navy GCM (NAVGEM).

Due to the expected wide impact of this development effort on climate and weather modeling, we have solicited feedback on this development effort from representatives of a number of different modeling centers (in addition to the collaborators on this project). We have provided access to the RRTMGP code repository at AER to John Michalakes (NOAA), Robin Hogan (ECMWF), Leonidas Linarkakis and other colleagues at the Max-Planck Institute, Will Sawyer and Marcus Wetzstein (Swiss Supercomputer Center), V. Balaji (GFDL), Matthew Norman (ORNL), and Hans Johansen (LBNL).

WORK COMPLETED

[tasks completed, technical accomplishments]

Last year we completed a working version of the new longwave code, RRTMGP_LW_v0. This version is capable of computing fluxes and heating rates and has the anticipated final organization and structure of RRTMGP. RRTMGP_LW_v0 was missing some key pieces, but was provided to our NCAR and other colleagues for evaluation and profiling.

In the past year we completed a full implementation of RRTMGP code for both longwave and shortwave radiation. Longwave radiation can be computed assuming no scattering, using up to 4 Gaussian quadrature angles. Shortwave radiation is computed using the two-stream approximation for layer properties and adding to treat transport. The code is capable of including the impacts of cloud and/or aerosols although testing has focused on clear skies. The ability to include scattering in the longwave is nearly complete. Our development to date has used older spectroscopic data in the mapping of atmospheric temperatures, pressures, and gas concentrations to spectrally-resolved optical properties. We are in the process to updating to state-of-the-science spectroscopic information, which can be added simply to RRTMGP by the use of a different input file.

During the course of the last year's development we implemented a systematic testing suite using a standardized netCDF file for convenience. There are three classes of tests: 1) an end-to-end test that compute fluxes given atmospheric and boundary conditions; 2) a series of "unit tests" in which significant computational task is executed in series; and 3) a set of validation tests against known values and/or independent implementations. The end-to-end and unit tests are automated, such that new code can be run against previous versions and any differences reported by executing a single script that makes use of a standardized Python environment. The verification tests include comparisons of two-stream results against a code being developed for ECMWF and comparisons of RRTMGP transport algorithms against the plane-parallel version of the high angular-resolution Spherical Harmonics/Discrete Ordinate Method (SHDOMPP) code developed by Frank Evans. (See Figure 1.) We also have developed validation tests that consist of comparisons between RRTMGP flux and heating rate calculations against those calculated by the benchmark radiation model LBLRTM. These tests consist of a set of scripts we developed to compare the calculations of the two models for numerous atmospheric columns representative of the present atmosphere. Also included are profiles corresponding to pre-industrial and future conditions and gas concentrations, allowing the code's radiative forcing performance to also be validated. This rigorous testing gives us high confidence in the correctness of our code.

The code has been systematically organized into three layers. One layer interacts with users and the host model, managing initialization, user choices, error handling, and especially the translation of the host model's physical description of the atmosphere to the optical description required by the radiative transfer calculation. A lower layer acts as a broker, managing flow control to implement user choices, for example by choosing which low-level routines to call. The foundation of RRTMGP is a set of low-level computational kernels. These are highly-optimized, fully-vectorized routines that do the heavy computational work with sanitized (know-good) inputs. The kernels all have C bindings. This means they may be called by other languages including C, C++, and Python, but also so they may be replaced by other implementations without affecting the interface to the host model. Our initial experiences suggest that this division allows for both flexibility and efficiency, the project's two main goals.

We modestly enhanced the flexibility of the RRTMGP computational ecosystem by modifying two Fortran 2003 "classes" (objects) representing gas concentrations and optical properties (optical thickness, single-scattering albedo, and phase function – the variables used in the radiative transfer equation). Much of RRTMGP's efficiency comes because it is vectorized across the user-settable "column" dimension, so that problems can be optimally sized for a given platform. The column dimensions of the gas concentration and optical properties must be consistent with this size; we have now added a way to extract subsets of these objects along the column dimension, similar to the Fortran ability to extract array sections, so that the objects may conveniently be used in loops over a larger problem.

RESULTS

[Describe meaningful technical results achieved in the report fiscal year. Make the significance clear. Emphasize what was learned, not what was done. This should be a summary of significant results and conclusions, and, especially, any "new capabilities" generated.]

The completion of the current version of RRTMGP represents a significant milestone for the project. The developed code strikes a balance between readability and comprehensibility (for its anticipated scientific user base) and advanced computational features and flexibility (critical for parallelization). RRTMGP_v0 makes extensive use of Fortran 2003 classes and abstract interfaces. Code efficiency is gained from exposure of fine-grained parallelism and algorithmic simplification. The code and the stored data it utilizes are independent of each other; the data is provided at run time.

Development activities at NCAR

The longwave code, which has been mature for longer, has been fully implemented in the NCAR CESM by Brian Eaton, though given the temporary state of the spectroscopic data we have ensured only that results are not unreasonable. Brian provided very valuable feedback to the development team that resulted in several major modifications to the code, including a move from using subroutines and explicit error handling to implementing tasks as functions that return error strings, and a move to having initialization accept arrays rather than read directly from files. These choices should make it easier to use RRTMGP in existing model infrastructures.

IMPACT/APPLICATIONS

The development of RRTMGP should have a significant impact on the ability of GCMs, including NAVGEM and CESM, to perform efficient and accurate simulations of climate and weather.

TRANSITIONS

[An S&T product has sufficiently matured and some organization (acquisition, industry, customer) outside of ONR is doing something with it. "Product" includes equipment, prototypes, original ideas/theories, and equations. Include 'who' that 'organization' is, how they are using it, and when it is expected to be used. It is of special interest if it is already being used or has had acquisition funds committed. Examples are 'products' entering acquisition, being used by industry, or being used by other S&T organizations such as DARPA)]

Access to RRTMGP_LW has been provided to colleagues at a number of modeling centers, including NRL, NCAR, NOAA (including GFDL), CSCS, and DOE (ORNL and LBNL). Our colleagues are analyzing the new code's structure for a number of different compilers, and continue to provide us with useful feedback. They will also be profiling the code's computational performance.

RELATED PROJECTS

[Identify closely related projects and briefly describe the nature of each relationship (include web links as appropriate/available)]

Our colleagues at the Swiss Supercomputer Center (CSCS) in Lugano are continuing to work on developing a GPU version (OpenACC) of this code for use in the ICON LES model. AER programmer Andre Wehe went to Lugano last year to work on a GPU version of RRTMGP with OpenACC. This effort did not result in a functioning GPU version since the the relevant Fortran compilers didn't support a number of the features employed in RRTMGP and, at the time, the computational kernels in the code hadn't been as cleanly isolated as they now are. Our Swiss and German collaborators are now working on an implementation using GridTools, a software framework that allows for optimal computational layouts transparently across a range of platforms.

REFERENCES

Iacono, M.J., J.S. Delamere, E.J. Mlawer, M.W. Shephard, S.A. Clough, and W.D. Collins, Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models, *J. Geophys. Res.*, **113**, D13103, doi:10.1029/2008JD009944, 2008.

Mlawer, E.J., S.J. Taubman, P.D. Brown, M.J. Iacono, and S.A. Clough, Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.,* **102**, 16,663-16,682, 1997.

PUBLICATIONS

Pincus, R., E. J. Mlawer, et al., Radiative flux and forcing parameterization error in aerosol-free clear skies, *Geophys. Res. Lett.*, http://onlinelibrary.wiley.com/doi/10.1002/2015GL064291/pdf

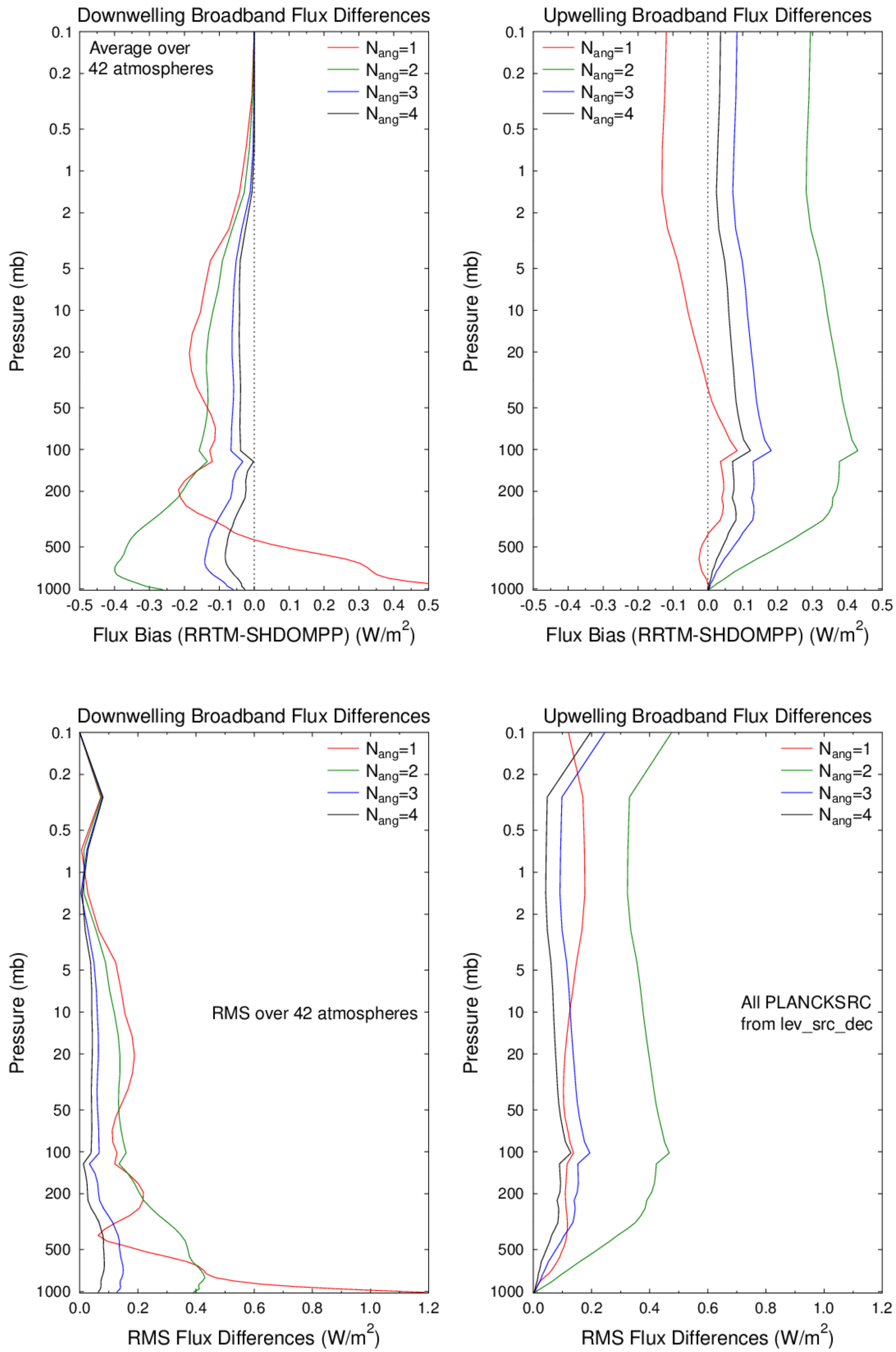

Figure 1. (top) Differences and (bottom) RMS of RRMTGP calculations using 1 through 4 angles with respect to reference calculations by SHDOMPP for downwelling (left) and upwelling (right) flux.