

## **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**

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 includes programmers with experience coding for modern computer architectures, including the recent GPU-based implementation of RRTMG. 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. In the initial phase of the project, the NCAR focus has been on profiling the performance of RRTMG as used in their GCM. 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, representatives from a number of different modeling centers have contributed their perspectives on this development effort. This includes John Michalakes (NOAA), Robin Hogan (ECMWF), a number of colleagues at the Max-Planck Institute, and Will Sawyer and Marcus Wetzstein (Swiss Supercomputer Center).

## **WORK COMPLETED**

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 is not yet ready for scientific application, partly because some aspects (e.g. McICA sampling of cloud variability) is not yet implemented but, more importantly, because the underlying spectroscopic information is somewhat out of date, so that the accuracy of our simplified algorithms can not be thoroughly evaluated. RRTMGP\_LW\_v0 has been provided to our NASA GSFC collaborators and NCAR colleagues for evaluation and profiling, and colleagues in the Swiss climate modeling center will adapt this code to run on a GPU for implementation into their GCM (based on the Max Planck Institutes' s ICON model).

A completely new driver has been developed for this version, interfacing with the calling GCM with required (for each atmospheric column) inputs: layer average temperatures, layer average pressures, layer edge pressures, surface skin temperature, and gas concentrations (derived type) for all modeled gases. Optional inputs are the layer column amounts of dry air and layer edge temperatures. A fully functional gas optics module has been developed; in addition to its code, this module contains an object class that specifies the spectral bands, their g-points, all stored coefficients, etc. This module has these same inputs, and its outputs are (per g-point and atmospheric column) gas optical depths, the internal (i.e. Planck) layer source irradiances, the internal source irradiances for increasing (relative to the layer ordering provide by the user) layer edges, the internal source irradiances for decreasing layer edges, and the source irradiances from the surface. The gas optical depth calculation includes contributions from major species, minor species (though not all have stored coefficients yet), and the water vapor foreign and self continua. The interpolation scheme needed to compute absorption coefficients from gas concentrations, temperature, and pressure has been completely redesigned compared to RRTMG. For this development, we increased (compared to RRTMG) the high range of surface pressures to 1100 mb so that we encompass the highest sea level pressure recorded below 750 m (1083.8 mbar). Likewise we've expanded our range of Earth-based temperatures to 160 – 355 K so our absorption coefficients are valid for more extreme cases. Making these changes in RRTMGP required changes to our systems and scripts that generate the stored k-distributions. We've now built flexibility into our updated scripts to facilitate future modifications of the minimum/maximum temperatures/pressures in the code.

A new longwave absorption-emission solver has been developed, with exact treatment of the linear-in-tau approximation. Although there is not yet a solver for performing longwave calculations that

include scattering, all components needed for these calculations ready and the solver can be dropped into place.

Since the solver operates on each g-point independently while the gas optics code operates most efficiently operates with g-point as its inner loop, at the gas optics routine reverses the index order of its input before performing its calculations and then reverses the order of its output after its calculations are performed.

All output from the gas optics module, including the components of the optical depth (e.g. major, continuum), has been validated with respect to the corresponding output from the development code, which has the same coding structure as in RRTMG. This validation exercise was successfully performed for layering that goes from surface to TOA, as well as TOA to surface. A script has been developed that calls the driver using input in netcdf format, allowing validation of the calculated flux and cooling rates.

A new build system has been developed for easier integration into existing projects. It supports various Fortran compilers, automatically determines and displays dependencies, and allows for a parallel build.

In addition, Co-PIs Pincus and Wehe attended the ESPC AOLI meeting in Boulder, CO, in November 2014, which was hosted by Pincus. At this meeting, Pincus presented an overview of our project's goals and status. (PI Mlawer could not attend due to a scheduling conflict with another meeting.)

## **RESULTS**

The release of RRTMGP\_LW\_v0 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. Input classes have been developed for gas concentrations, random number generators (needed for cloud sampling to treat variability), cloud properties, and aerosol properties. Computed fluxes constitute another class. This structure allows simplification of run-time choices, such as the number of streams used in the flux calculation and the spectral integration of the output fluxes. Code efficiency is gained from exposure of fine-grained parallelism and algorithmic simplification, especially a reduction in branching. The code and the stored data it utilizes are independent of each other; the data is provided at run time.

Given the modular nature of this code, it will be relatively straightforward to modify to run in the shortwave region. The shortwave code will reuse most of the longwave components; the main difference will be the data it utilizes.

The build system that has been developed will allow for easier and more flexible integration over a wide range of computing architectures.

### *Development activities at NCAR*

Our NCAR collaborators, led by Brian Eaton, reviewed the proposed RRTMGP design and provided useful feedback. In addition, they ran the RRTMGP build/test framework on NCAR compute platforms and provided feedback. They also began the task of refactoring the top-level radiation interface in CAM to prepare for the inclusion of RRTMGP.

## **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**

The initial version of the high-performance broadband longwave radiation code we are developing under this support, RRTMGP\_LW\_v0, has been completed and distributed to selected colleagues at modeling centers, including NOAA, NCAR, and CSCS. 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**

In addition to their analysis of RRTMGP\_LW\_v0, our colleagues at the Swiss Supercomputer Center (CSCS) in Lugano will be developing a GPU version (OpenACC) of this code for use in the ICON LES model. This version will provide a significant foundation for the GPU version of our code that is a deliverable for this project. Andre Wehe of AER will spend the first week in November in Lugano to both assist Will Sawyer and his team with this development and to be tutored in GPU programming techniques by CSCS experts. This will support our future ability to develop and maintain GPU versions of the high-performance radiation code.

## **REFERENCES**

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## **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>