Novel Radiation Tool Including Application to GPUs

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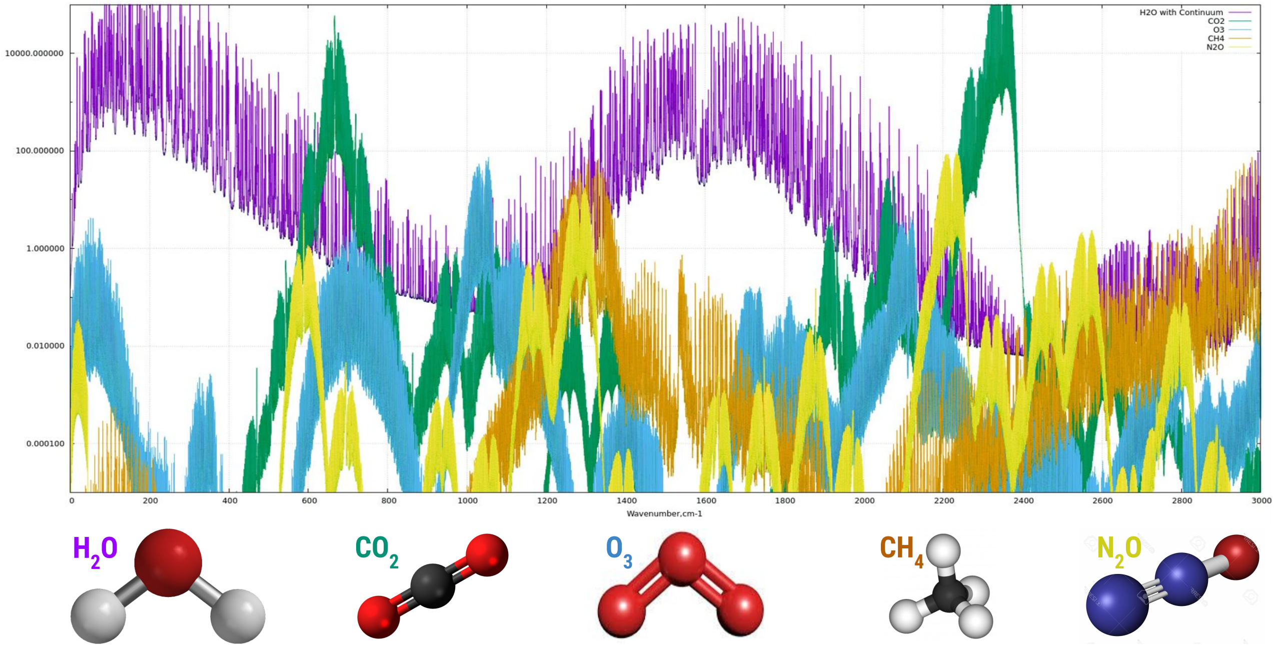
Q3: How can GFDL research and modeling be further utilized to meet NOAA stakeholder needs and enhance research partnerships to ensure GFDL's success?

NOAA
GEOPHYSICAL FLUID DYNAMICS LABORATORY

Why Are Line-by-line (LBL) Calculations Important?

- A line-by-line code connects the micro-scale quantum mechanics of molecules (spectral lines) to the macro-scale radiative fluxes observed on Earth.
- Allows us to model how each gas in the atmosphere impacts the greenhouse effect.
- Requires accurately treating millions of molecular lines.



The spectral lines of the 5 main greenhouse gases

A Brief History of Line-by-line Modeling At GFDL

Solar radiative line-by-line determination of water vapor absorption and water cloud extinction in inhomogeneous atmospheres

Ramaswamy, V, & Freidenreich, S., 1991
JGR 96(D5), 9133-9157

Variations in water vapor continuum radiative transfer with atmospheric conditions

Paynter, D. J. & Ramaswamy, V., 2012
JGR: Atmospheres, 117 D16310

A New Paradigm for Diagnosing Contributions to Model Aerosol Forcing Error

Jones, A. L., et. al., 2017
Geophysical Research Letters, 44(23),

An investigation into biases in instantaneous aerosol radiative effects calculated by shortwave parameterizations in two Earth system models

Freidenreich, S., et. al., 2021
JGR Atmospheres, 126(11)

How a stable greenhouse effect on Earth is maintained under global warming *

Feng, J., Paynter, D., & Menzel, R., 2023
JGR: Atmospheres, *128*(9), e2022JD038124

Greenhouse gas forcing and climate feedback signatures identified in hyperspectral infrared satellite observations *

Raghuraman, S. P., et. al., 2023
Geophysical Research Letters, 50, e2023GL103947

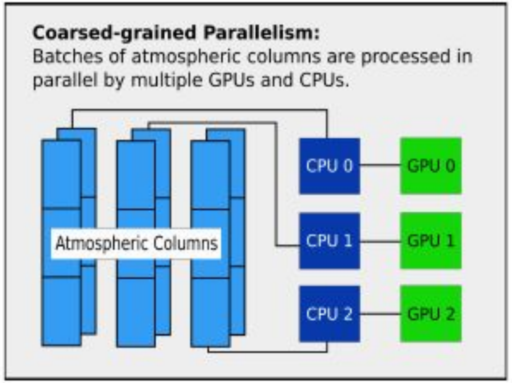
* Used the GFDL GRTcode LBL model

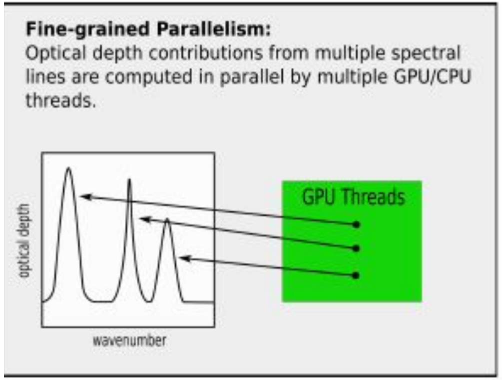
GRTcode: Line-by-line Calculations using GPUs

GRTCODE is designed to be a flexible, modular Line-by-Line (LBL) radiative transfer code for a range of applications. It was written specifically to exploit the massive data parallelism provided by GPUs.

Features:

- Supports the ability to calculate spectra (lines, continuua, CIA and cross sections) between 0-50,000 cm-1 of all major atmospheric gases.
- Flexible implementation, can be used as a subroutine or as standalone command line driven program.
- Written in C/Cuda C, but can be used with Python and FORTRAN bindings.
- Can be easily scaled from single column to GCM resolution.
- Flexible compile options for either CPU or GPU applications.





Present Limitations:

- Simplistic application of CFC, O_2, O_3 cross sections.
- Does not include CO_2 line-mixing.
- Does not support advanced lineshapes

Available at https://github.com/NOAA-GFDL/GRTCODE

Running GRTcode On A Global Scale

Typical steps in a calculation

1) Input pressure, temperature, and atmospheric gas amounts

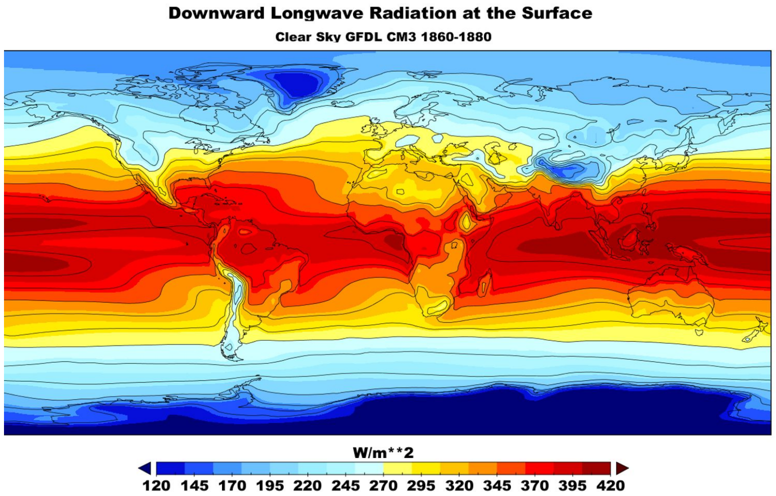
2) Import data associated with molecular lines from a spectral database (HITRAN)

3) Use a line shape function to calculate each spectral line. At each frequency sum all lines.

4) Calculate how the spectra impacts the solar and thermal energy in the atmosphere using a radiation solver code.

Scaling required for global calculations

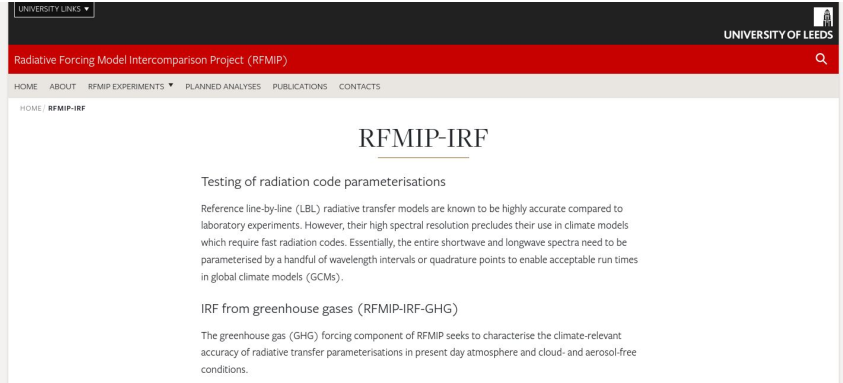
- Atmospheric molecules have ~ **4 million** spectral lines
- Resolving each spectral line requires ~ **5000** spectral calculations
- Resolving a typical atmospheric column on Earth requires ~ **50** vertical layers
- A global calculation (see below) requires ~ **50,000** atmospheric columns



Stakeholder Need: Evaluating Current GCM Biases

- The CMIP6 RFMIP RAD-IRF experiments were designed for line-by-line models to provide accurate, global reference forcing estimates under a variety of scenarios.

- These benchmark values are needed to evaluate the biases of radiation parameterizations employed by global climate models.


UNIVERSITY LINKS ▾
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Radiative Forcing Model Intercomparison Project (RFMIP)
HOME ABOUT RFMIP EXPERIMENTS ▾ PLANNED ANALYSES PUBLICATIONS CONTACTS
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RFMIP-IRF

Testing of radiation code parameterisations

Reference line-by-line (LBL) radiative transfer models are known to be highly accurate compared to laboratory experiments. However, their high spectral resolution precludes their use in climate models which require fast radiation codes. Essentially, the entire shortwave and longwave spectra need to be parameterised by a handful of wavelength intervals or quadrature points to enable acceptable run times in global climate models (GCMs).

IRF from greenhouse gases (RFMIP-IRF-GHG)

The greenhouse gas (GHG) forcing component of RFMIP seeks to characterise the climate-relevant accuracy of radiative transfer parameterisations in present day atmosphere and cloud- and aerosol-free conditions.

Credit: https://rfmip.leeds.ac.uk/rfmip-irf

CMIP6 RFMIP RAD-IRF: Benchmark Radiative Forcing on GPUs

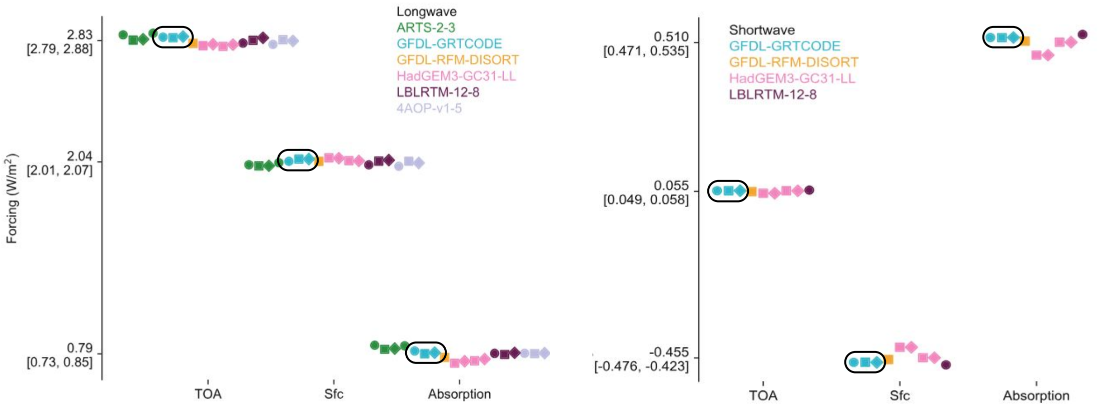


Table 4
Ratio of Adjustment Due to Stratospheric Temperature Equilibration Under the Fixed Dynamical Heating Assumption to Instantaneous Clear-Sky Longwave Radiative Forcing at the Top of Atmosphere and the Surface for a Range of Forcing Agents

Experiment	TOA	SFC
Present day	0.31	−0.03
Present-day CO_2	0.57	−0.05
Present-day CH_4	−0.05	0.01
Present-day N_2O	0.03	−0.01
Present-day O_3	1.90	−0.06
Present-day halocarbons	−0.11	0.01

Note. Both forcing and stratospheric adjustment are computed using GFDL GRTCODE line-by-line model. Shortwave adjustments are all essentially zero.

GRTCODE compares well with established line-by-line codes. It was also **the only model used to calculated benchmark stratospheric temperature adjustment** due to different gases (1800*240 individual column calculations performed on HERA's GPU fine-grained expansion cluster).

Pincus, R., Buehler, S. A., Brath, M., Crevoisier, C., Jamil, O., Franklin Evans, K., et al. (2020) Benchmark calculations of radiative forcing by greenhouse gases. *Journal of Geophysical Research: Atmospheres*, 125, e2020JD033483. https://doi.org/10.1029/2020JD033483

Stakeholder Need: Understanding Recent Spectral Observations

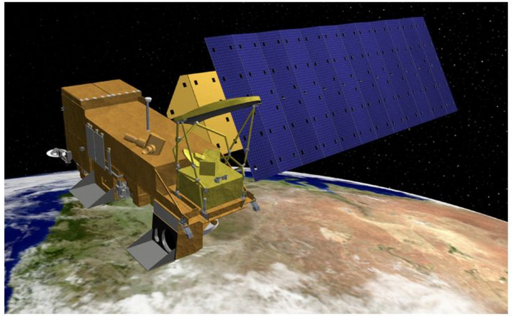
- Recently observed hyperspectral infrared flux trends over the last 20 years show evidence of:
    - An increasing greenhouse effect
    - Stratospheric cooling
    - Surface-tropospheric warming

- Global line-by-line radiation models are needed to evaluate the contributions of greenhouse gases

- NOAA/NESDIS satellite mission planning requires multi-decade anticipation of future observational needs, accompanied by spectral information for instrument and product development.
    - GFDL LBL capabilities can inform this process via e.g. Climate Observing System Simulation Experiments (Climate OSSEs)

MISSION

Overview



Artist rendering of the Aqua satellite, part of NASA's Earth Observing System. Credit: NASA

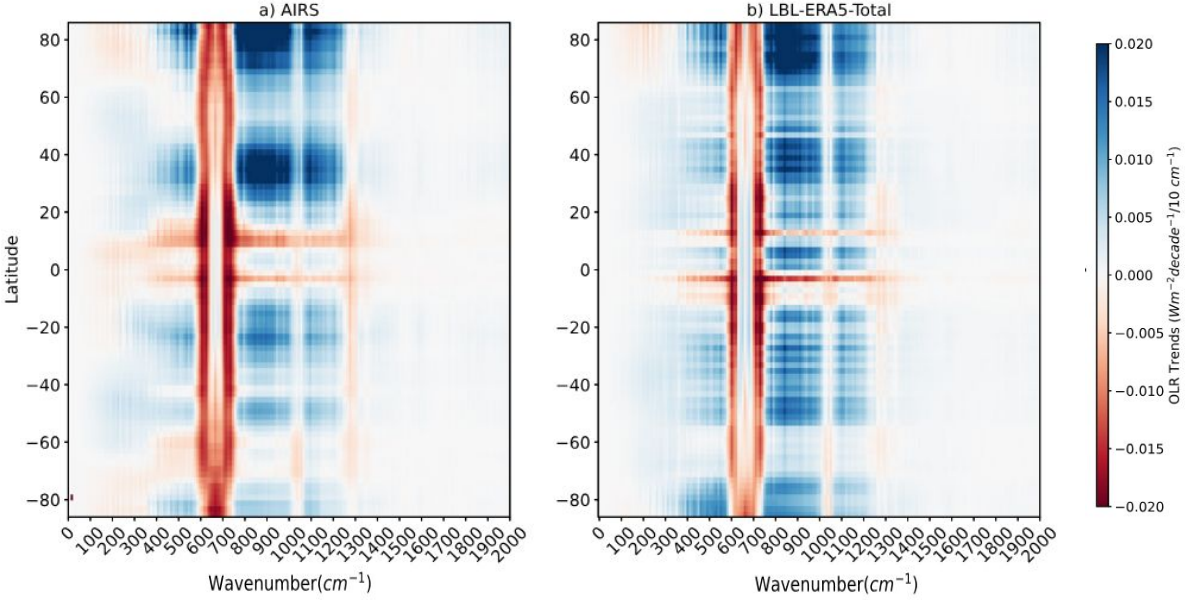
The Atmospheric Infrared Sounder on NASA's Aqua Satellite

AIRS is a facility instrument whose goal is to support climate research and improve weather forecasting

Launched into Earth-orbit on May 4, 2002 aboard NASA's Aqua satellite, the Atmospheric Infrared Sounder, AIRS, provides data critical to the monitoring of Earth's atmosphere. AIRS data are improving weather forecasts and advancing our understanding of Earth's climate. AIRS is one of six instruments aboard Aqua, a satellite that is part of NASA's Earth Observing System. AIRS along with its partner microwave instrument the Advanced Microwave Sounding Unit, AMSU-A, represents the most advanced atmospheric sounding system ever deployed in space. Together these instruments observe the global water and energy cycles, climate variation and trends, and the response of the climate system to increased greenhouse gases.

Credit: NASA

Comparison to Global Hyperspectral Satellite Observations



Using ERA5 global monthly mean reanalysis input, GRTCODE was able to accurately predict zonal-mean spectral outgoing longwave radiation trends from 2003 - 2021, as compared to observations from the Atmospheric Infrared Sounder (AIRS) instrument on NASA's Aqua Satellite.

Raghuraman, S. P., Paynter, D., Ramaswamy, V., Menzel, R., & Huang, X. (2023). Greenhouse gas forcing and climate feedback signatures identified in hyperspectral infrared satellite observations. *Geophysical Research Letters*, 50, e2023GL103947. https://doi.org/10.1029/2023GL103947

Current Challenges

Hardware	• Lack of access to modern GPUs for development and testing • GFDL lacks GPU computing resources for production work
Software	• Programming for GPUs requires using more modern programming models • Compilers/profiling/debugging tools are needed
Human Resources	• Many GFDL developers and users lack experience with GPUs • This global line-by-line model does not have a devoted team or official support for outside users

Enhancing Stakeholder Engagement And Research Collaborations

Over the past 5+ years, GRTcode has been an internal GFDL tool, but has contributed to:

- CMIP6 RFMIP RAD-IRF
- “A Flexible Framework for Radiation Parameterizations Traceable to Benchmarks” - A CPT led by LDEO and the University of Hamburg

With more resources, we hope to engage in new collaborations. Possible targets include:

- Detection/Attribution community ("Climate Projections" project - CPO and NCEI)
- USGCRP Indicators Interagency Working Group (IndIWG)
- NESDIS and OAR/QOSAP for OSSEs
- OAR/Global Monitoring Lab for supporting their Radiation Forcing and AGGI calculations
- IPCC, NCA and other climate assessments including:
    - NOAA's State of the Climate Report (monthly)
    - NOAA-led AMS Annual State of the Climate Report