A Radiative Transfer Module for Calculating Photolysis Rates and Solar Heating in Climate Models: \textit{Solar-J 7.5}

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• **Solar-J manuscript is under review at Geoscientific Model Development: http://www.geosci-model-dev-discuss.net/gmd-2017-27/**.

• Complete Solar-J code and test cases are included as supplementary material as part of the GMD submission


Reference

What is Solar-J?

An extension of Fast-J code that can calculate both photolysis rates and heating rates for climate models

Features:
• plane parallel
• 8-stream (4 up and 4 down scattering angles)
• Solar spectrum covers 177 nm -12 μm
• 27 major bins (S-bins; for clouds and aerosols)
• 100 sub-bins (for gas absorptions)
• Include spherical atmosphere treatment for direct sun beam at low sun angles.
Motivation for developing Solar-J

- Provide a consistent and unified radiative-transfer code for both atmospheric photochemistry and heating.
- Provide a more accurate alternative to the two-stream code (RRTMG-SW) that has been literally used in every major climate model (e.g. CESM) or forecast model (ECWMF).
Spectral bins/bands configuration

- Retain the high spectral resolution of Fast-J in the shorter wavelength (<778 nm) (blue box)
- Shorten fast-J’s bin 18 (grey box)
- Modify and adopt RRTMG’s H₂O and O₂ absorption in the visible range (yellow box)
- Adopt the RRTMG’s gas absorption as it is for wavelength > 778 nm (green box)
What is wrong with the 2-stream code (e.g. RRTM-G)?

1. Diffuse radiances in all directions represented by only 2 discrete directions
2. Details of the phase functions represented by one number, the asymmetry factor (first moment/3)
3. Atmosphere within a model grid box is horizontally infinite and homogeneous (1D)

Solar-J improves problems 1 & 2 above

1. 8 discrete directions for diffusive radiance
2. Phase functions of clouds and aerosols are realistically represented without arbitrary scaling.

Solar-J is also 1D radiative-transfer solver

Example: relative errors in reflection at 0.55 μm for liquid cloud and ice cloud (Li et al., 2015)

Left: the δ-Eddington approximation (2-stream)
Middle: δ-4SHE (4-stream; real phase function)
Right: δ-4SHE (4-stream; Henyey-Greenstein phase function)
Documented Test Cases

Solar-J versus RRTMG-SW
Typical Tropical atmosphere over the ocean at four SZA angles with 3 conditions:

- Aerosol-free clear-sky
- Marine low-level stratus cloud (liquid water only, overcast)
- Cirrus ice cloud (overcast)

Cloud profiles obtained from ECMWF-IFS 1x1 data
Clear Sky

Solar-J - RRTMG

- Stratospheric Heating (top panels)  
  -2 K/day - 3K/day

- Tropospheric Heating (bottom panels)  
  <0.1 K/day
Marine low-level stratus cloud

- Radiation from S25-S27 (2.5-12 μm) completely absorbed near cloud optical depth $\tau \sim 1$.
- Shorter wavelengths S19 (0.78-1.24 μm), S21 (1.30-1.63 μm), S22 (1.63-1.94 μm), S23 (1.94-2.15 μm), S24 (2.15-2.50 μm) responsible for maximum heating at $\tau \sim 4$.
- RRTMG’s in-cloud heating is consistently smaller by 5% and 20% for SZA=0° and SZA=62° respectively.
Marine Low-level Cloud

- Solar-J’s clear sky reflects 4 W/m² less sunlight back to the space at TOA because of the spectral configuration for Bin 18 (starts at 412 nm rather than 442 nm).
- Solar-J’s stratus cloud reflects about 3% more solar flux at TOA.
- Solar-J has larger in-cloud heating but less above-cloud heating for the first three SZA angles.
Cirrus Cloud

Solar-J vs three built-in ice cloud parameterizations in RRTMG-SW v. 3.9

Solar-J -- use irregular and hexagon ice crystal phase function provided by Mischenko (19 -- other properties (single scattering albedo, refractive indices are derived with Mie-code (Spherical ice) with a range of effective radius

Ebert and Curry (1992) -- CAM 4 and prior versions

Fu (1996) -- irregular ice crystals wrt De

Key (2002) -- spherical ice from STREAMER package
Colar bars-- percentage change relative to the clear sky references

Reflection: TOP ROW

Solar-J: using Mischcheko’s ice phase functions (show large curvature as a function of solar zenith angle)

RRTMG’s 3 schemes: Similar behaviors but with magnitudes proportional to optical depth
Solar-J includes correction for sphericity for direct sunlight. RRTMG-SW doesn’t.
How fast is Solar-J 7.5?

On Intel(R) Xeon(R) CPU E5-2680 v2 @ 2.80GHz, 1-CPU, 100, 000 columns in seconds. Unit for the first three columns: seconds. print-out being completely disabled.

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Conclusion

• Solar-J 7.5 is ready to be implemented in climate models.

• On-going effort for speed up in GPU architecture (Artico et al., 2015: Fast Fast-J GPU codes); speed up fast-J by as much as 50x with source-to-source optimizations on NVIDIA Tesla 2070 GPU