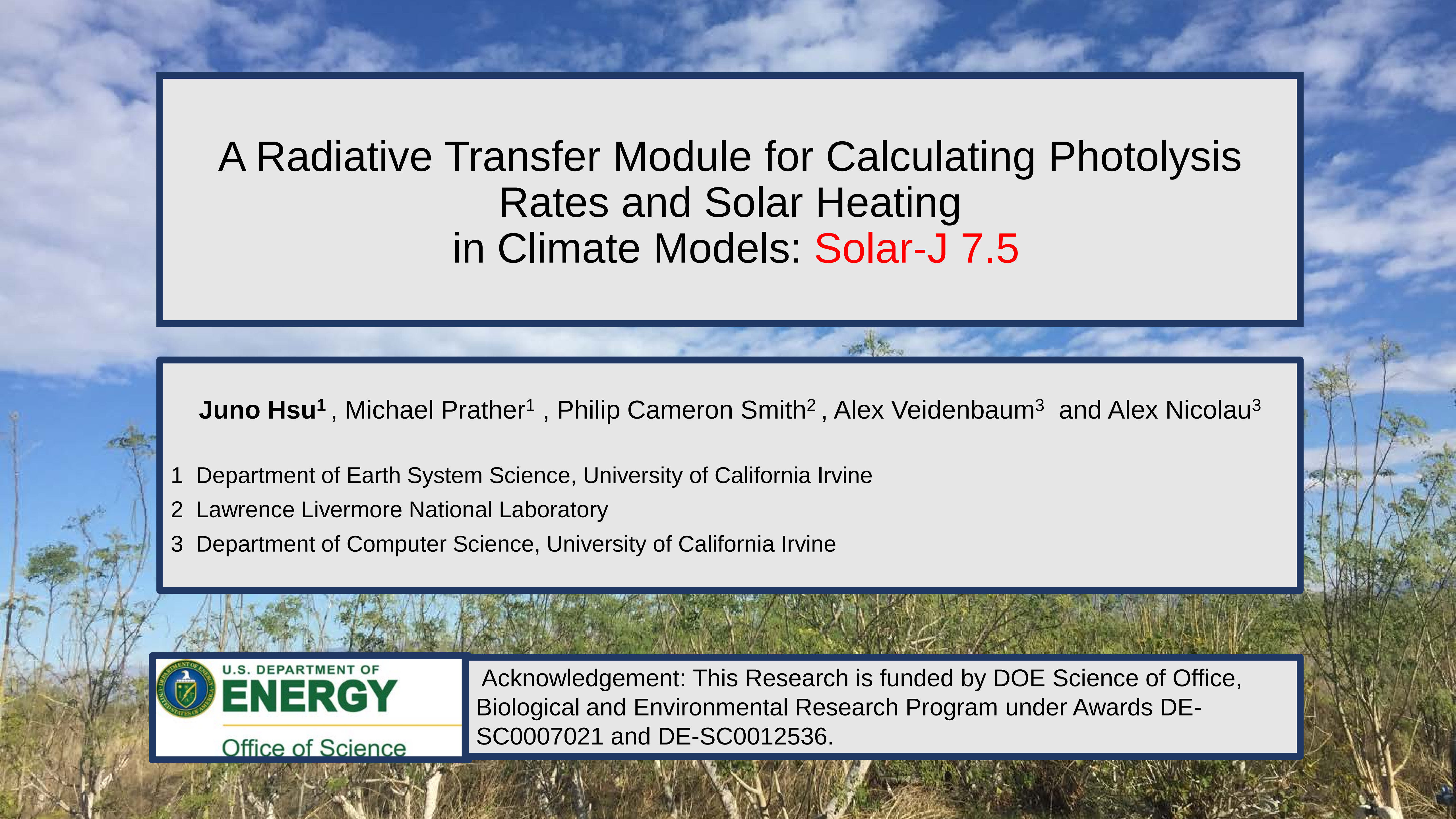

A Radiative Transfer Module for Calculating Photolysis Rates and Solar Heating in Climate Models: Solar-J 7.5

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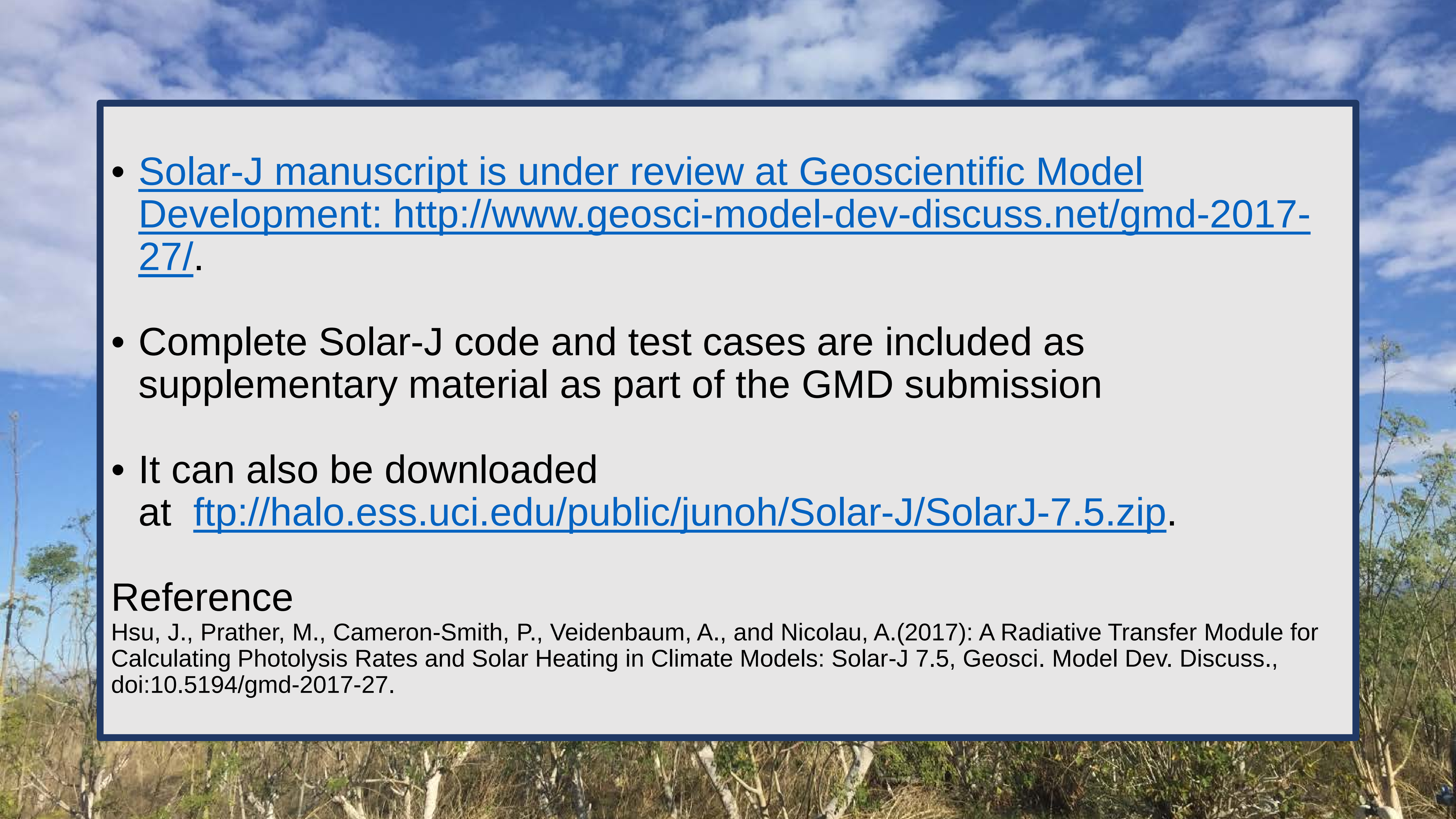


- Solar-J manuscript is under review at Geoscientific Model Development: http://www.geosci-model-dev-discuss.net/gmd-2017-27/.

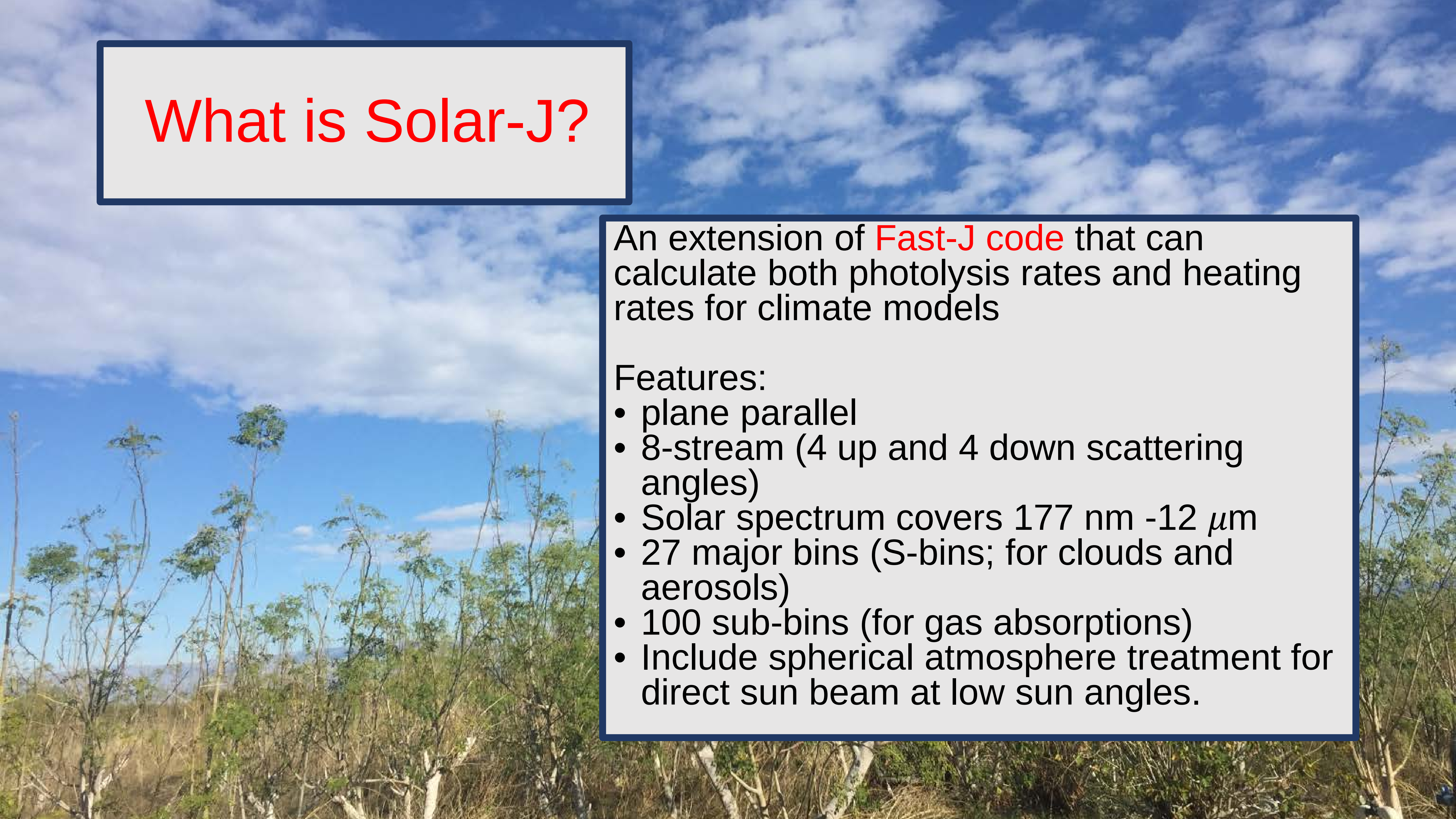
- Complete Solar-J code and test cases are included as supplementary material as part of the GMD submission

- It can also be downloaded at ftp://halo.ess.uci.edu/public/junoh/Solar-J/SolarJ-7.5.zip.

Reference

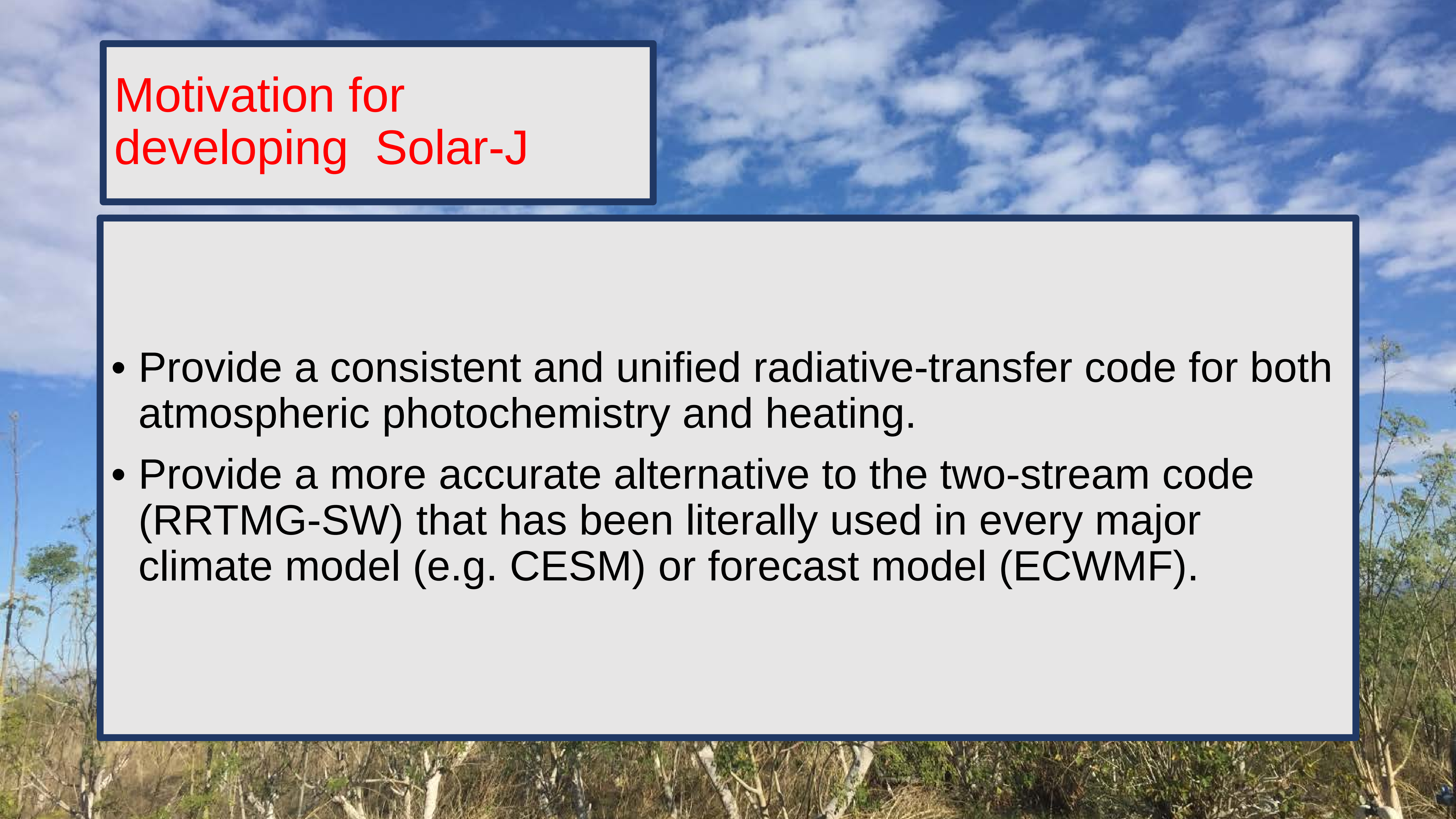
Hsu, J., Prather, M., Cameron-Smith, P., Veidenbaum, A., and Nicolau, A.(2017): A Radiative Transfer Module for Calculating Photolysis Rates and Solar Heating in Climate Models: Solar-J 7.5, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2017-27.

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.

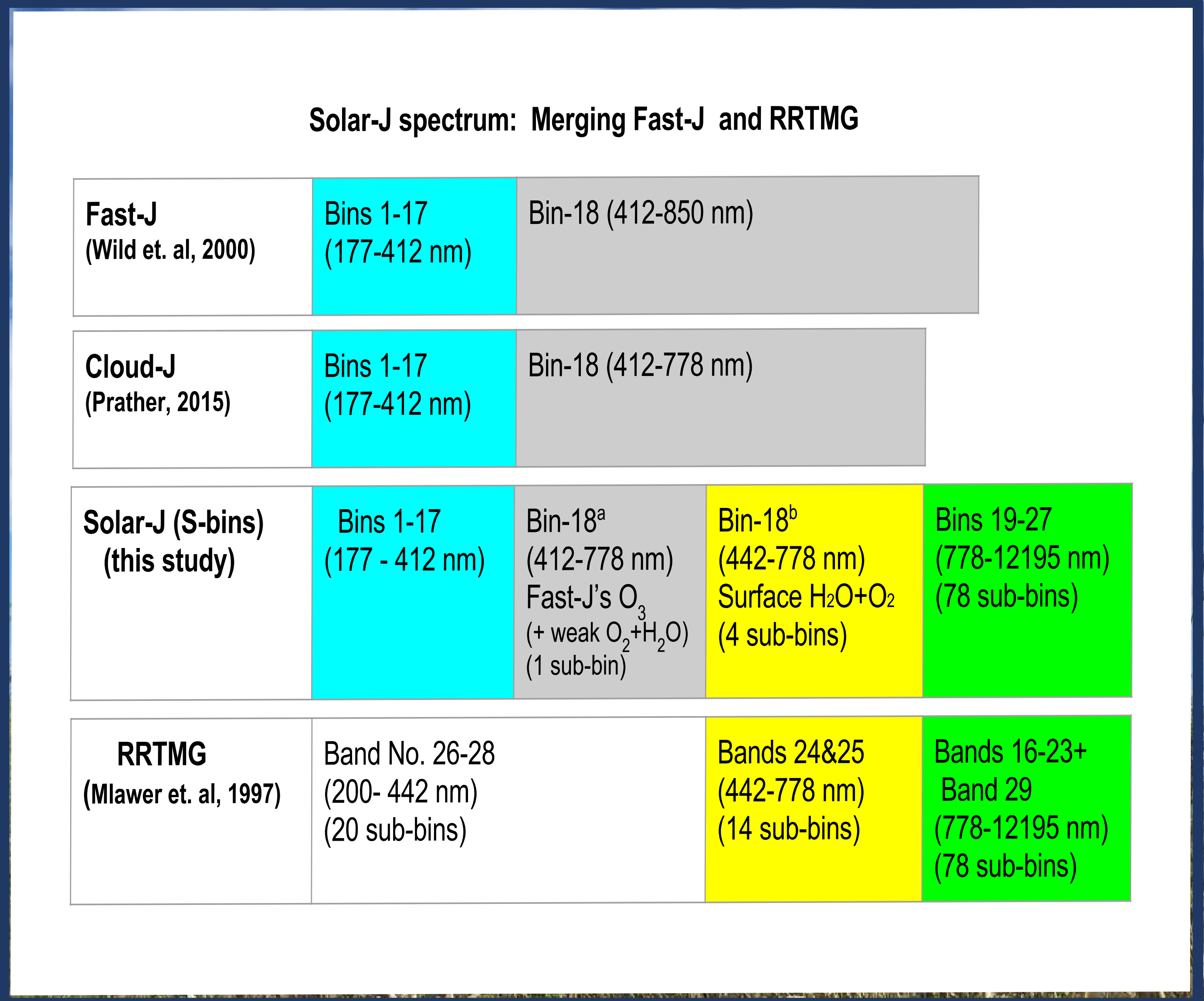


Motivation for developing Solar-J

- 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 H_2O and O_2 absorption in the visible range (yellow box)
- Adopt the RRTMG's gas absorption as it is for wavelength > 778 nm (green box)



Solar-J spectrum: Merging Fast-J and RRTMG

Fast-J (Wild et. al, 2000)	Bins 1-17 (177-412 nm)	Bin-18 (412-850 nm)		
Cloud-J (Prather, 2015)	Bins 1-17 (177-412 nm)	Bin-18 (412-778 nm)		
Solar-J (S-bins) (this study)	Bins 1-17 (177 - 412 nm)	Bin-18^a (412-778 nm) Fast-J's O_3 (+ weak O_2+H_2O) (1 sub-bin)	Bin-18^b (442-778 nm) Surface H_2O+O_2 (4 sub-bins)	Bins 19-27 (778-12195 nm) (78 sub-bins)
RRTMG (Mlawer et. al, 1997)	Band No. 26-28 (200- 442 nm) (20 sub-bins)		Bands 24&25 (442-778 nm) (14 sub-bins)	Bands 16-23+ Band 29 (778-12195 nm) (78 sub-bins)

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

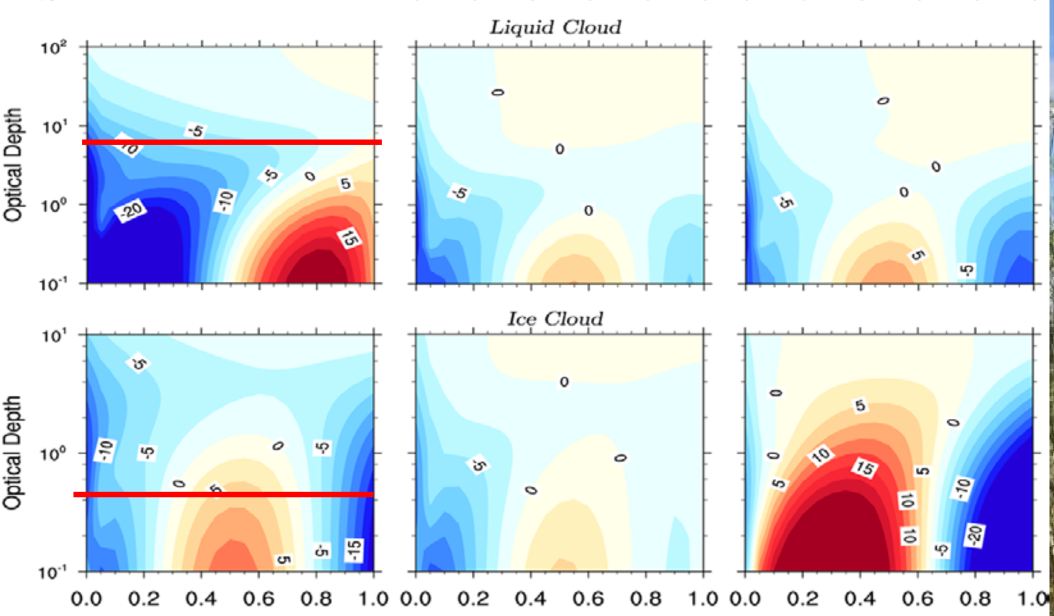
1. 8 discrete directions for diffusive radiance

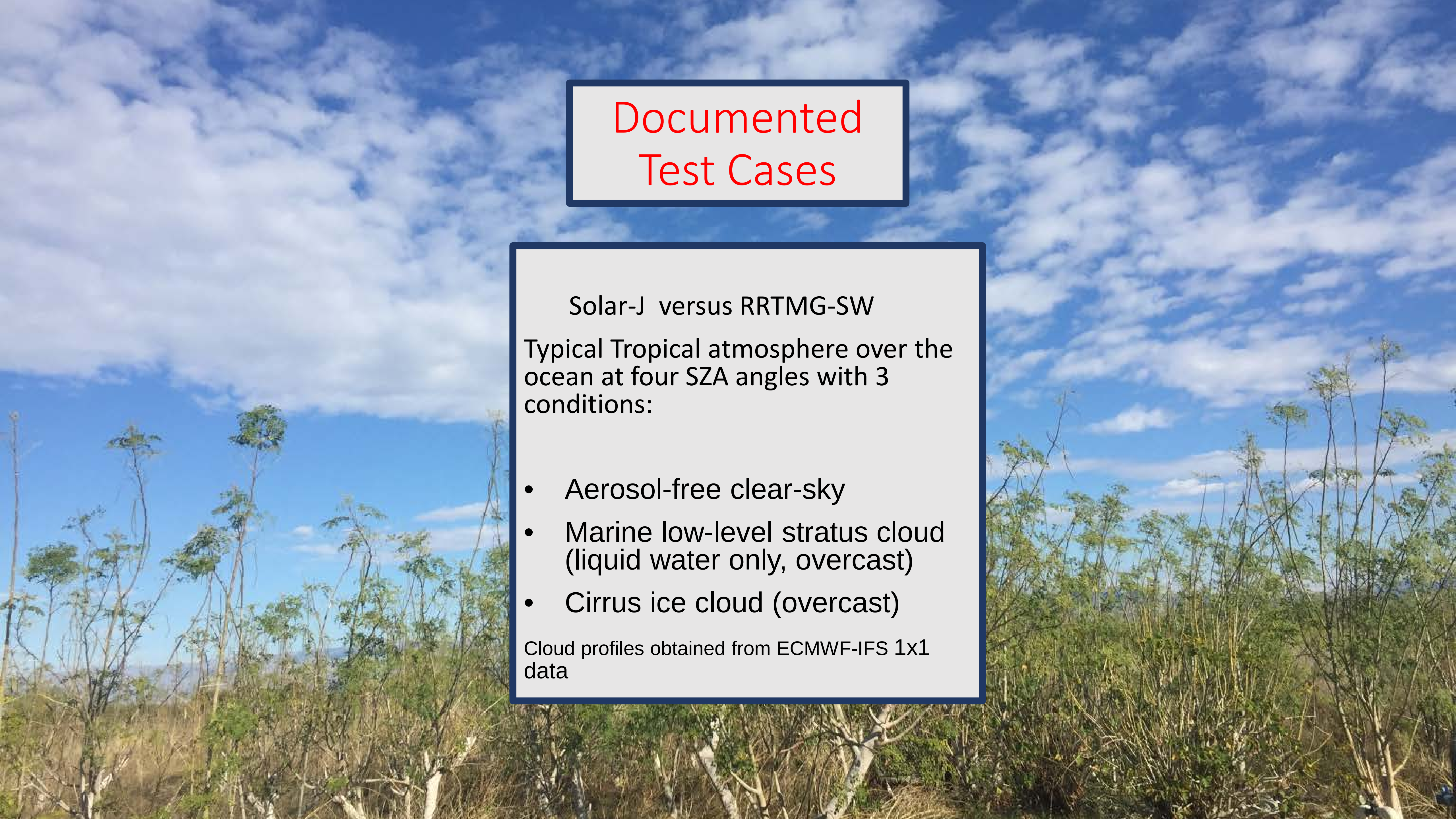
2. Phase functions of clouds and aerosols are realistically represented without arbitrary scaling.

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-tream; 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

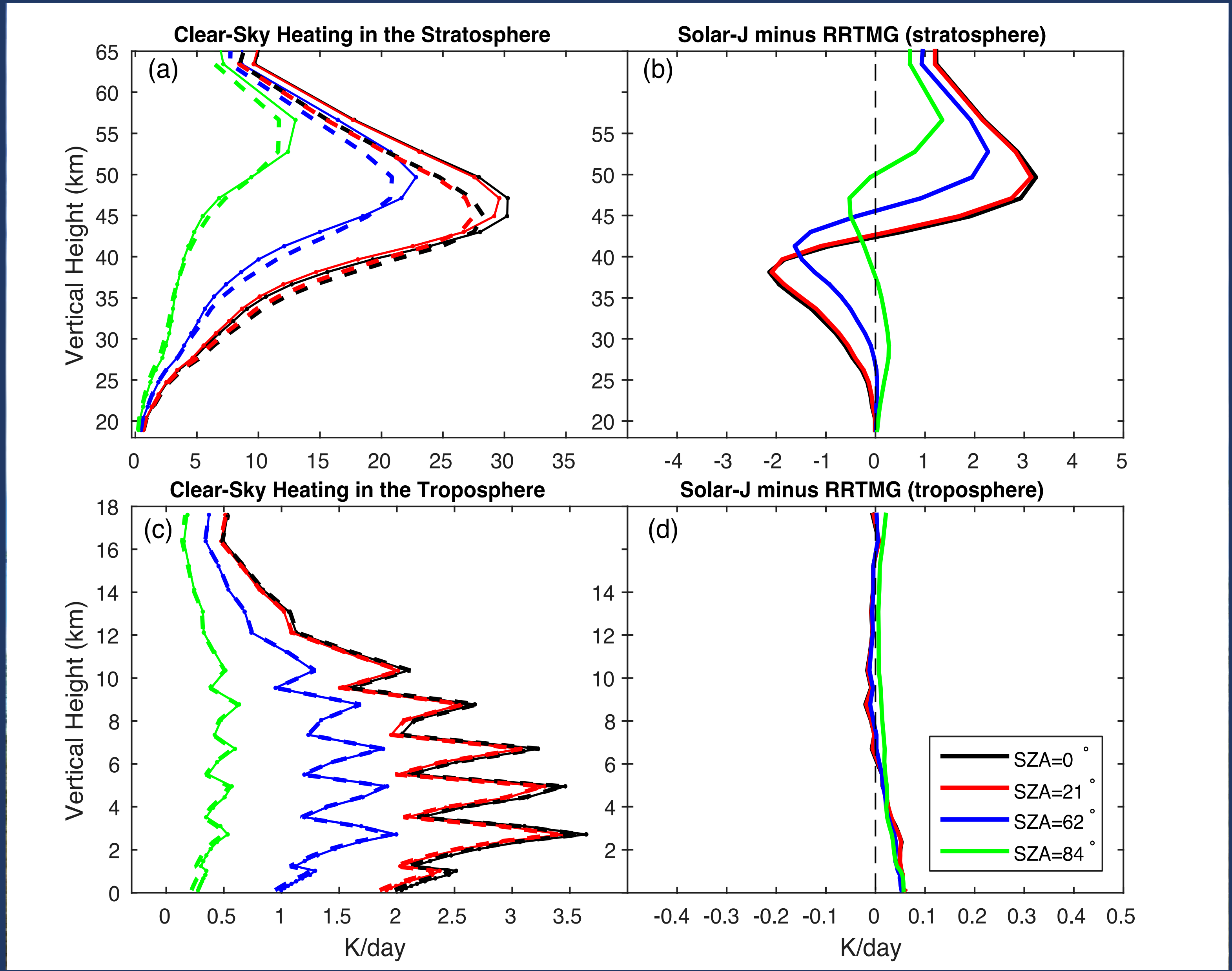
Solar-J - RRTMG

- Stratospheric Heating (top panels)

  -2 K/day - 3K/day

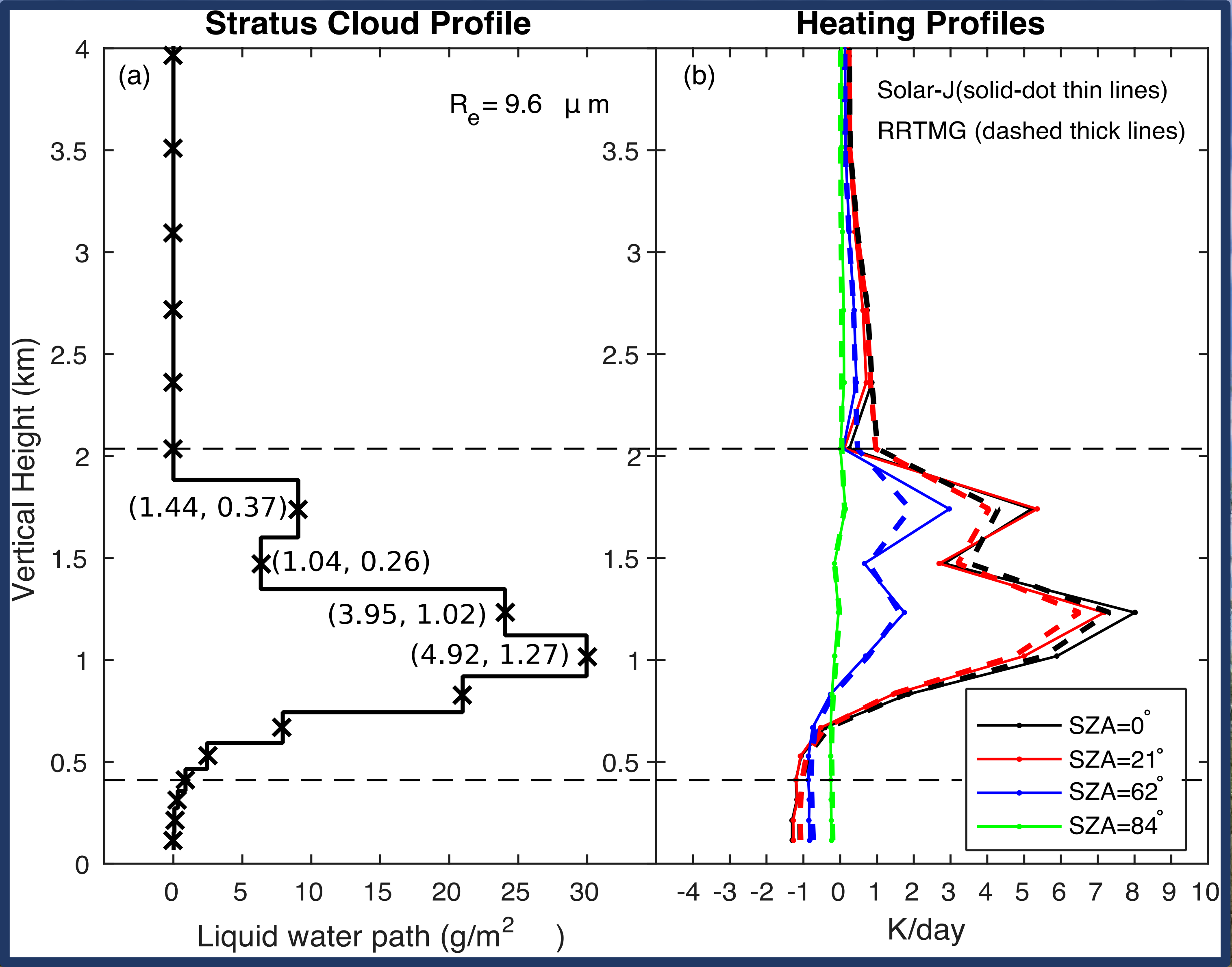
- Tropospheric Heating (bottom panels)

  <0.1 K/day



Marine low-level stratus cloud

- Radiation from S25-S27 (2.5-12 μm) completely absorbed near cloud optical depth τ ~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 τ ~4.
- RRTMG's in-cloud heating is consistently smaller by 5% and 20% for SZA=0º and SZA=62º 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.

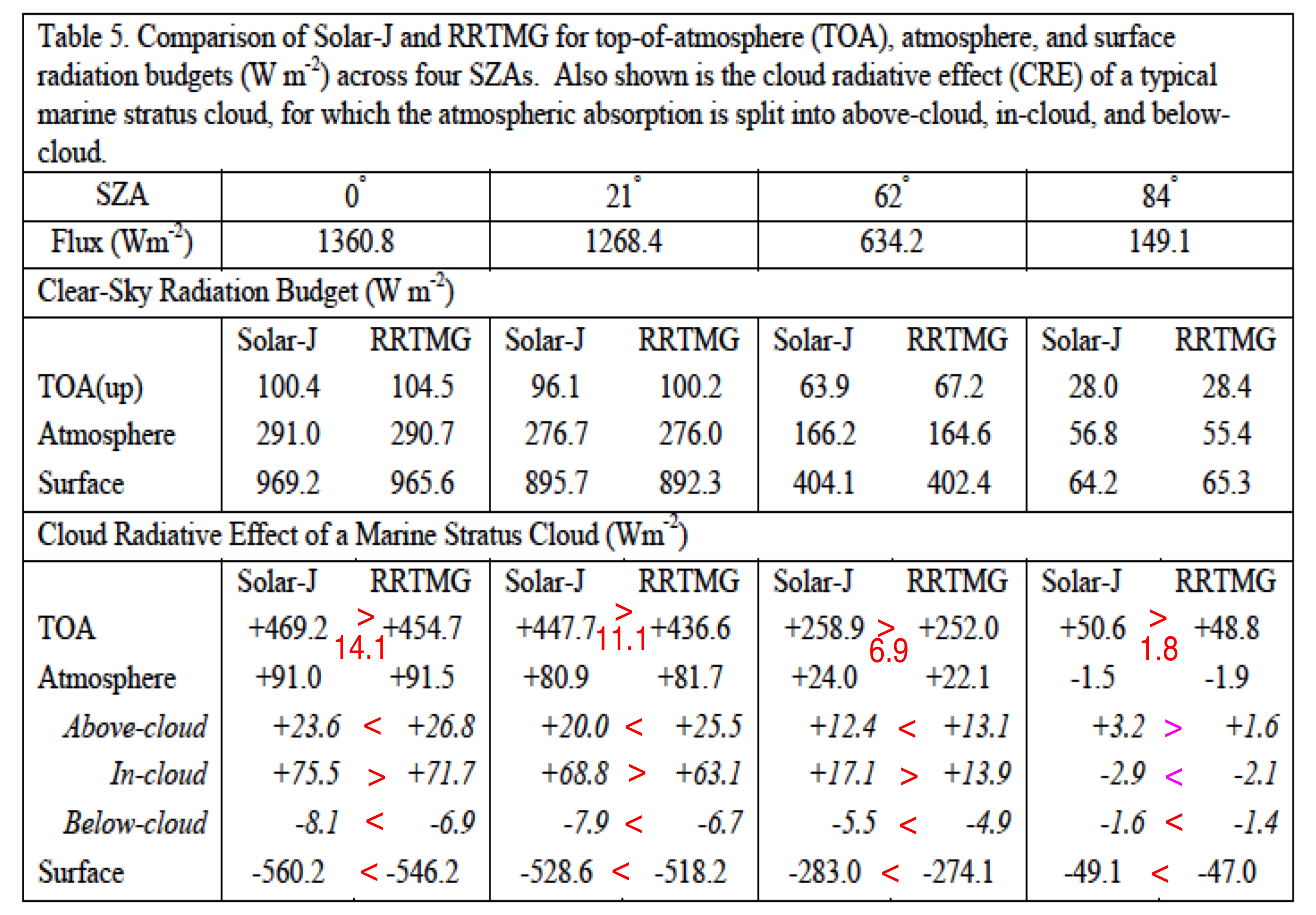


Table 5. Comparison of Solar-J and RRTMG for top-of-atmosphere (TOA), atmosphere, and surface radiation budgets ($W\ m^{-2}$) across four SZAs. Also shown is the cloud radiative effect (CRE) of a typical marine stratus cloud, for which the atmospheric absorption is split into above-cloud, in-cloud, and below-cloud.

SZA	0°			21°			62°			84°		
Flux (Wm^{-2})	1360.8			1268.4			634.2			149.1		
Clear-Sky Radiation Budget ($W\ m^{-2}$)												
	Solar-J		RRTMG	Solar-J		RRTMG	Solar-J		RRTMG	Solar-J		RRTMG
TOA(up)	100.4		104.5	96.1		100.2	63.9		67.2	28.0		28.4
Atmosphere	291.0		290.7	276.7		276.0	166.2		164.6	56.8		55.4
Surface	969.2		965.6	895.7		892.3	404.1		402.4	64.2		65.3
Cloud Radiative Effect of a Marine Stratus Cloud (Wm^{-2})												
	Solar-J		RRTMG	Solar-J		RRTMG	Solar-J		RRTMG	Solar-J		RRTMG
TOA	+469.2	> 14.1	+454.7	+447.7	> 11.1	+436.6	+258.9	> 6.9	+252.0	+50.6	> 1.8	+48.8
Atmosphere	+91.0		+91.5	+80.9		+81.7	+24.0		+22.1	-1.5		-1.9
Above-cloud	*+23.6*	<	*+26.8*	*+20.0*	<	*+25.5*	*+12.4*	<	*+13.1*	*+3.2*	>	*+1.6*
In-cloud	*+75.5*	>	*+71.7*	*+68.8*	>	*+63.1*	*+17.1*	>	*+13.9*	*-2.9*	<	*-2.1*
Below-cloud	*-8.1*	<	*-6.9*	*-7.9*	<	*-6.7*	*-5.5*	<	*-4.9*	*-1.6*	<	*-1.4*
Surface	-560.2	<	-546.2	-528.6	<	-518.2	-283.0	<	-274.1	-49.1	<	-47.0

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)

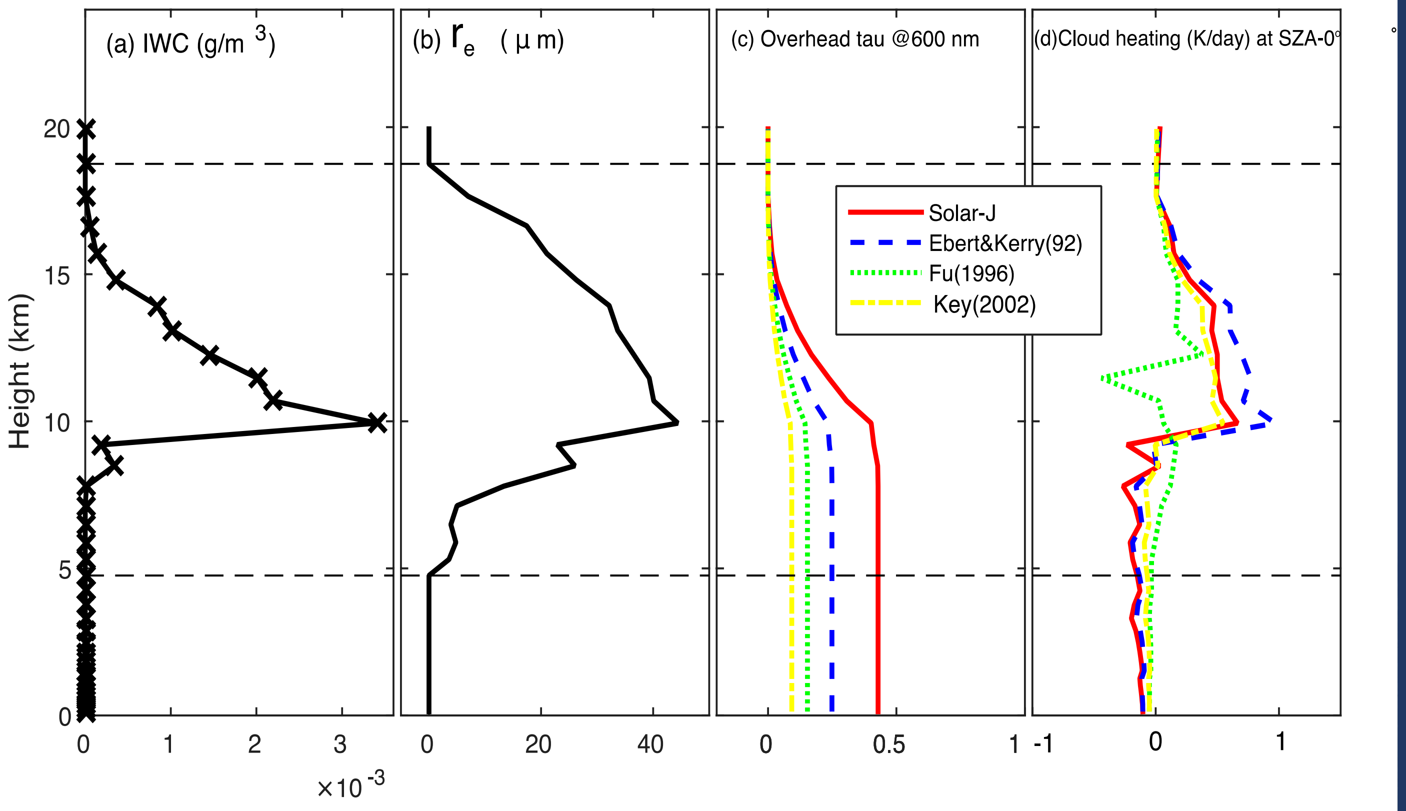
-- CAM 4 and prior versions

Fu (1996)

-- irregular ice crystals wrt De

Key (2002)

--spherical ice from STREAMER package



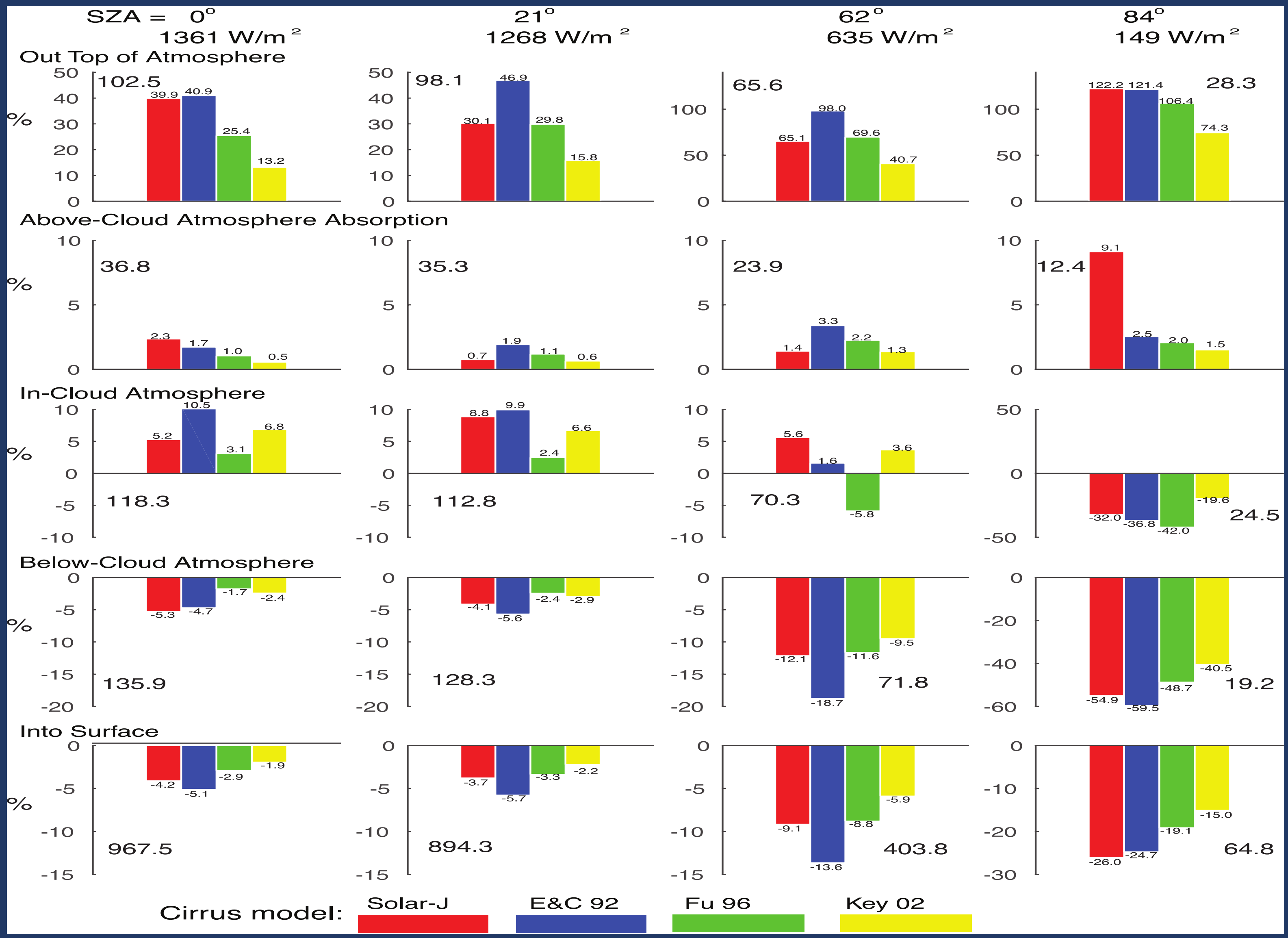
Cirrus Cloud

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 funciton of solar zenith angle)

RRTMG’s 3 schemes:Simiar behaviors but with magnitudes proportional to optical depth



Spherical atmosphere treatment (SZA>90^{o})

Solar-J includes correction for sphericity for direct sunlight. RRTMG-SW doesn't.

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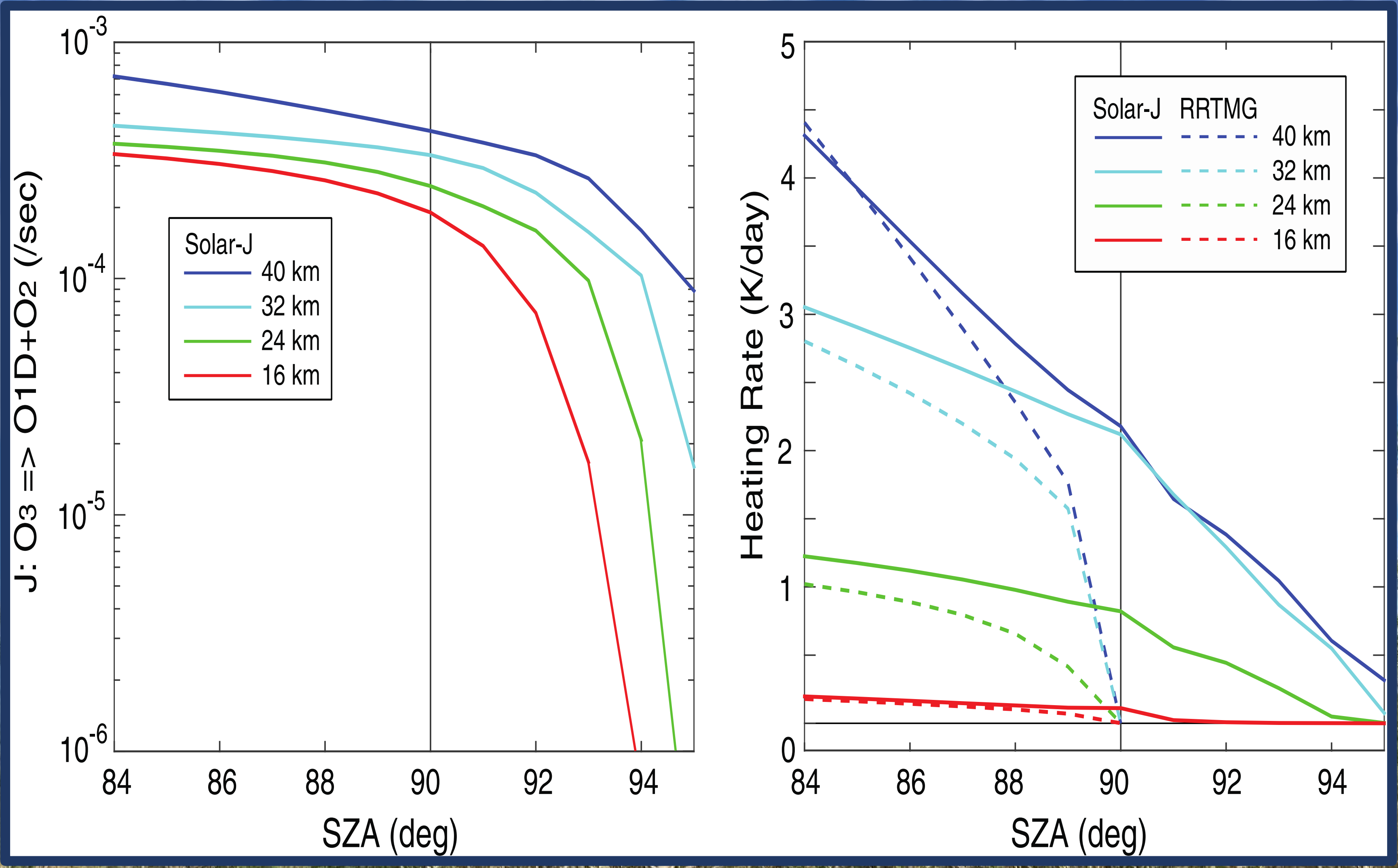
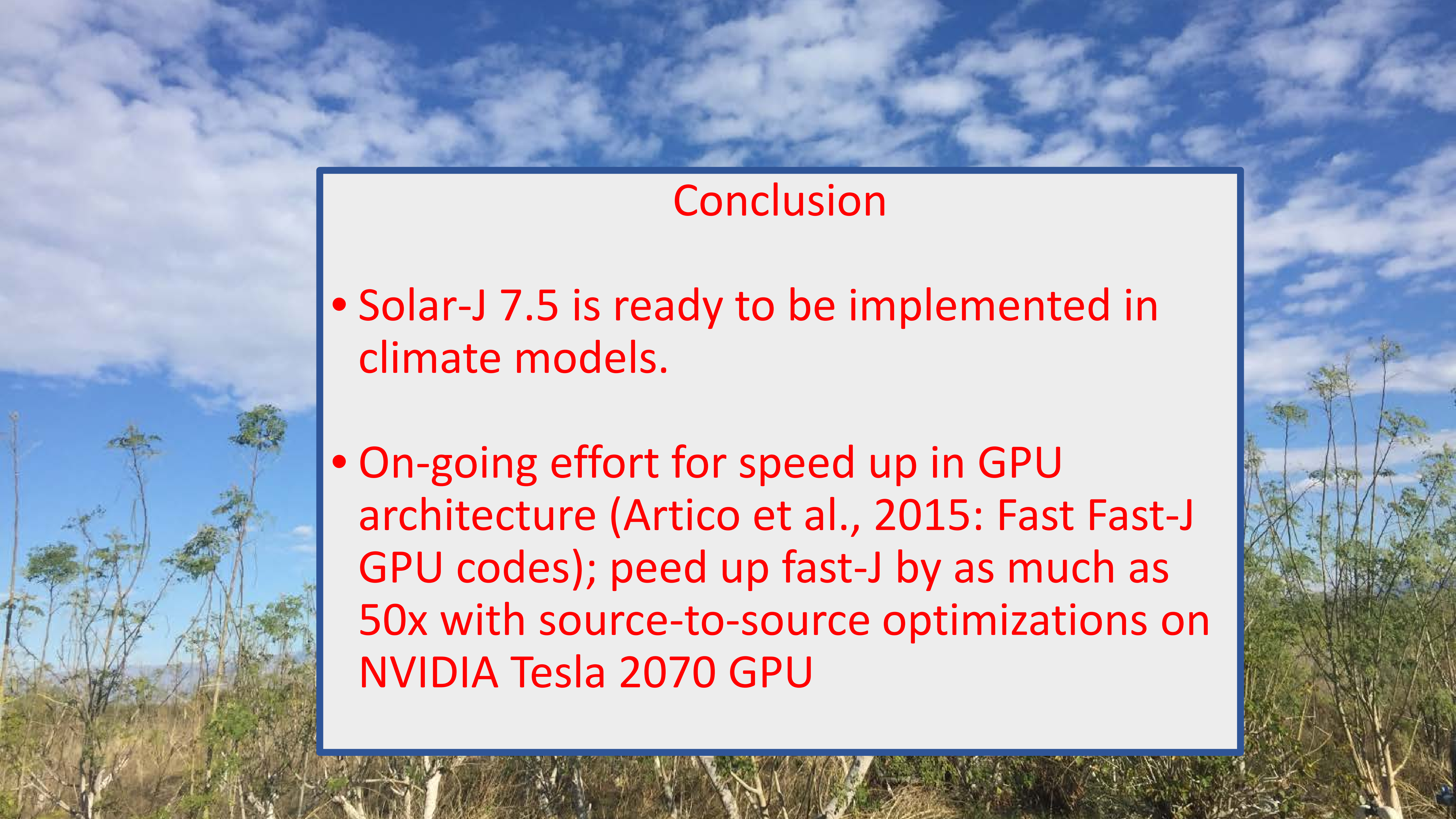


How fast is Solar-J 7.5?

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.

	Fast-J	Solar-J	FRRTMG	Fast-J/RRTMG	Solar-J/RRTMG
Clear-Sky	155	545	109	1.42	5.0
Average Cloud	169	598	118	1.43	5.1



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); peed up fast-J by as much as 50x with source-to-source optimizations on NVIDIA Tesla 2070 GPU