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Supporting Information for

[Errors in Calculating Solar Heating of the Climate System]

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Methods

The Solar-J (SJ) module has been adapted to match as closely as possible the RRTMG (RR) spectral data. SJ has a long history of modeling and testing photolysis rates (e.g., Olson et al, 1997; Photo Comp, 2010) for wavelengths 180-400 nm and thus have confidence in our results for stratospheric heating rates over those of RR (see H2017). For wavelengths > 778 nm SJ simply takes the RR model. Since v7.5, SJ has shifted a wavelength boundary, 345-412-778 nm to 345-485-778 nm, to better separate the Rayleigh scattering region (345-485 nm) from the Chappuis ozone absorption (485-778 nm). In some test cases using alternative spectral models LLNL and CLIRAD, we have further reduced this latter band to 485-700 nm to better constrain the ozone absorption region.

The solar heating codes Solar-J and RRTMG-SW are included as modules within the UC Irvine chemistry-transport model (UCI CTM, Prather et al., 2017). The UCI CTM is coupled with meteorological fields from the European Centre Integrated Forecast System, open IFS cycle 38r1 run at T159N80L60 using the native Gaussian grid for atmospheric physics (about 1.1° horizontal with 60 layers). We take the archived 3-hour averages of the atmospheric column data: pressure on the layer edges; temperature, water vapor, cloud fraction, cloud liquid water content, cloud ice water content in each layer. A standard ozone climatology is used. Cloud effective radii (liquid and ice) and scattering phase function are as specified in the CTM photolysis code Cloud-J (Neu et al., 2007;

Prather, 2015). The heating rates reported here are calculated for the IFS fields of January 2015. Cloud fields change every 3 hours, and the solar zenith changes every hour, giving 744 hourly data for January. The OSA code generously provided by Séférian was modified slightly: the diffuse albedo was not used as Solar-J calculates albedos specifically for each scattered stream; the albedo goes to a constant for SZA > 90° in spherical atmospheres; and the parameter table for the white-cap variable 'XRWC' was reset from 0.0 to 0.2 for wavelengths <400 nm.

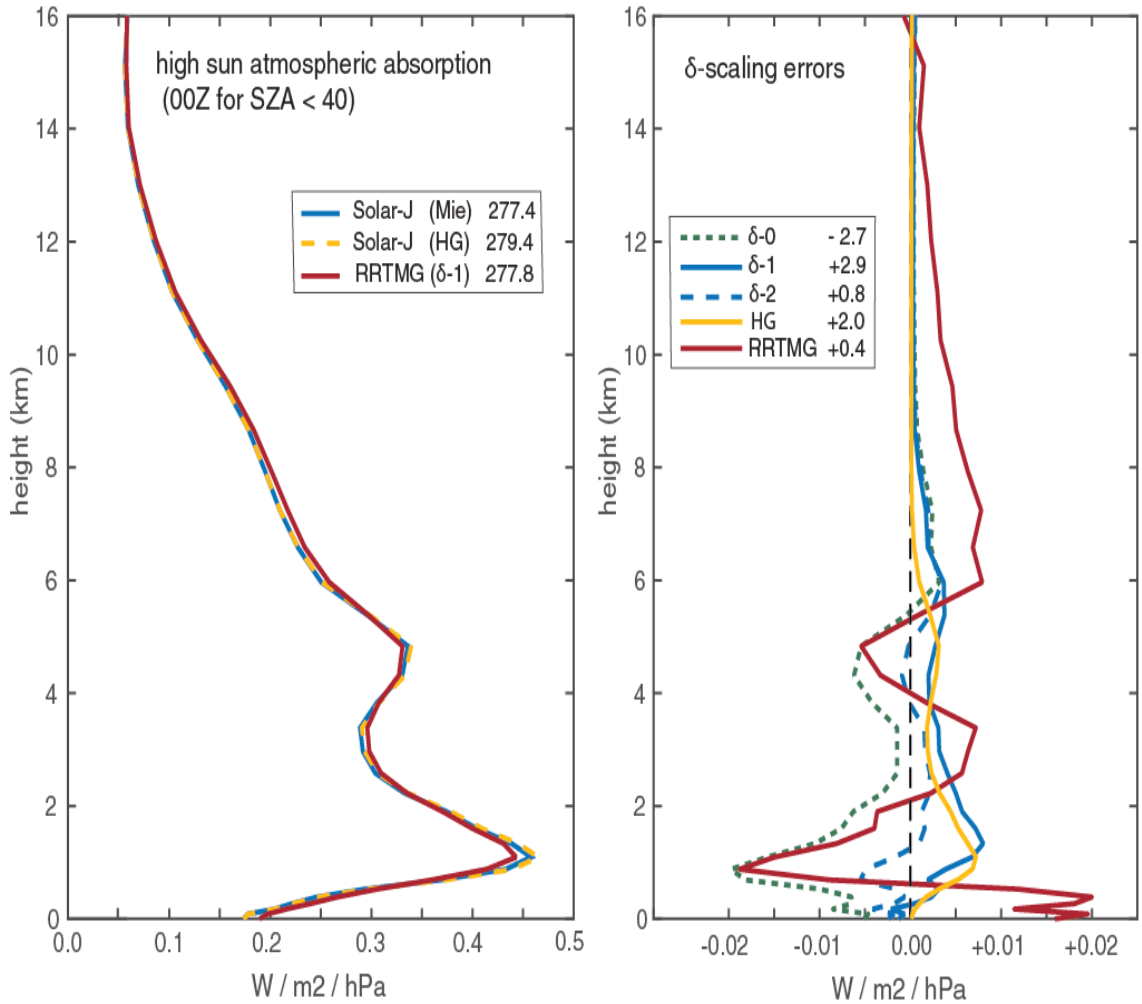

Figure S1. (a) January atmospheric absorption profiles (W m^{-2} hPa^{-1}) over the Pacific Ocean at high sun (SZA > 40° at 00Z, area within green oval in Figure 3). Liquid-water, but not ice-water clouds are included. The total heating rates (W m^{-2}) for Solar-J with standard Mie phase function, Solar-J using a Henyey-Greenstein (HG) phase function, and RRTMG (standard δ-1 scaling) are shown in the legend. These values are only averaged over high sun. (b) Profiles of the errors in atmospheric absorption caused by δ-scaling (0, 1, 2) and HG phase function for liquid-water clouds. Same conditions as for left panel and the total heating-rate differences are given in the legend. Also shown is the difference, RRTMG (δ-1) minus Solar-J (Mie).

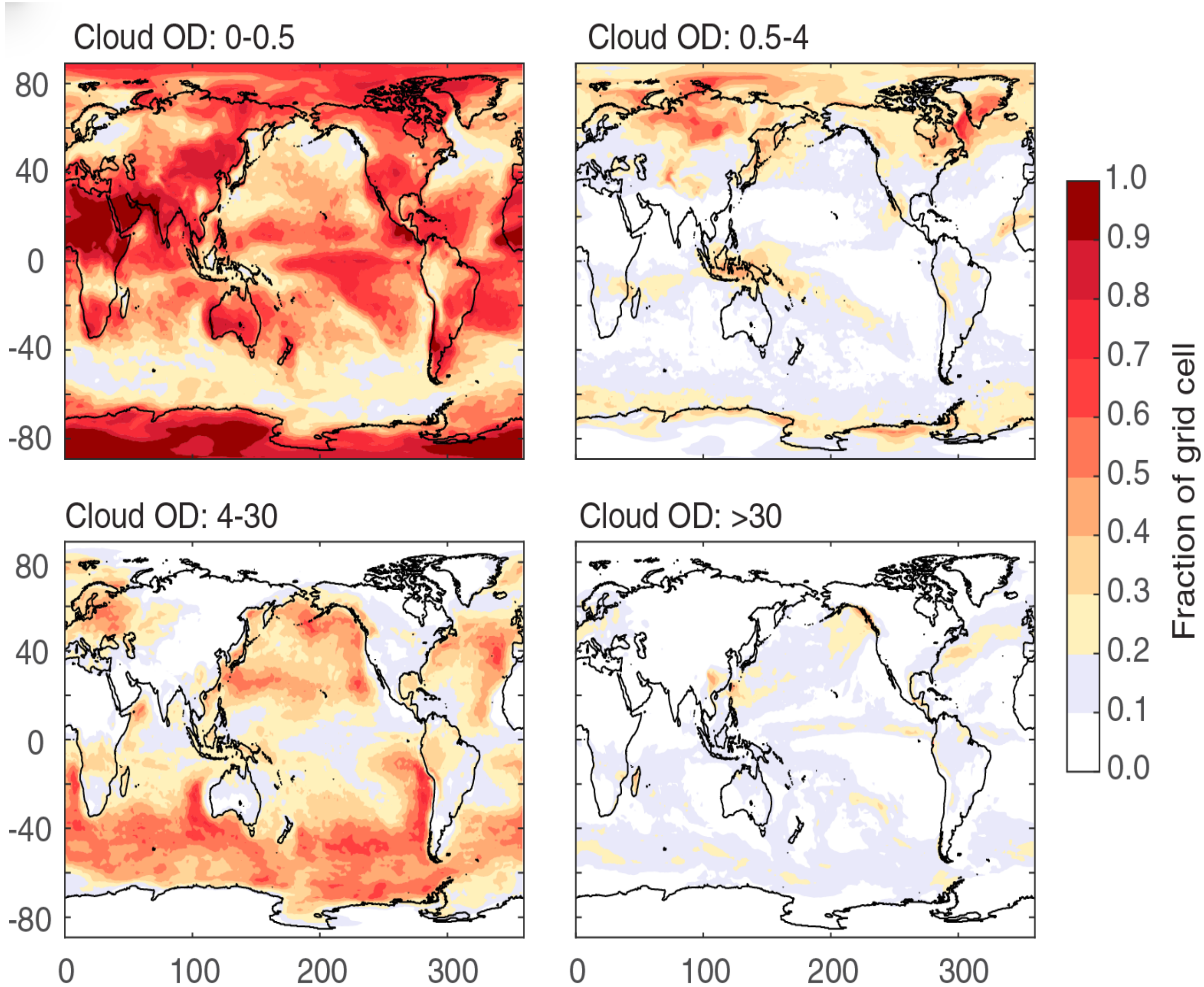

Figure S2. Fractional area in each of the four QCA bins using MAX-COR overlap for the January 2015 case study here. The QCAs are binned by 600 nm total cloud optical depth (liquid + ice water): 0 – ½; ½ – 4; 4 – 30; >30.

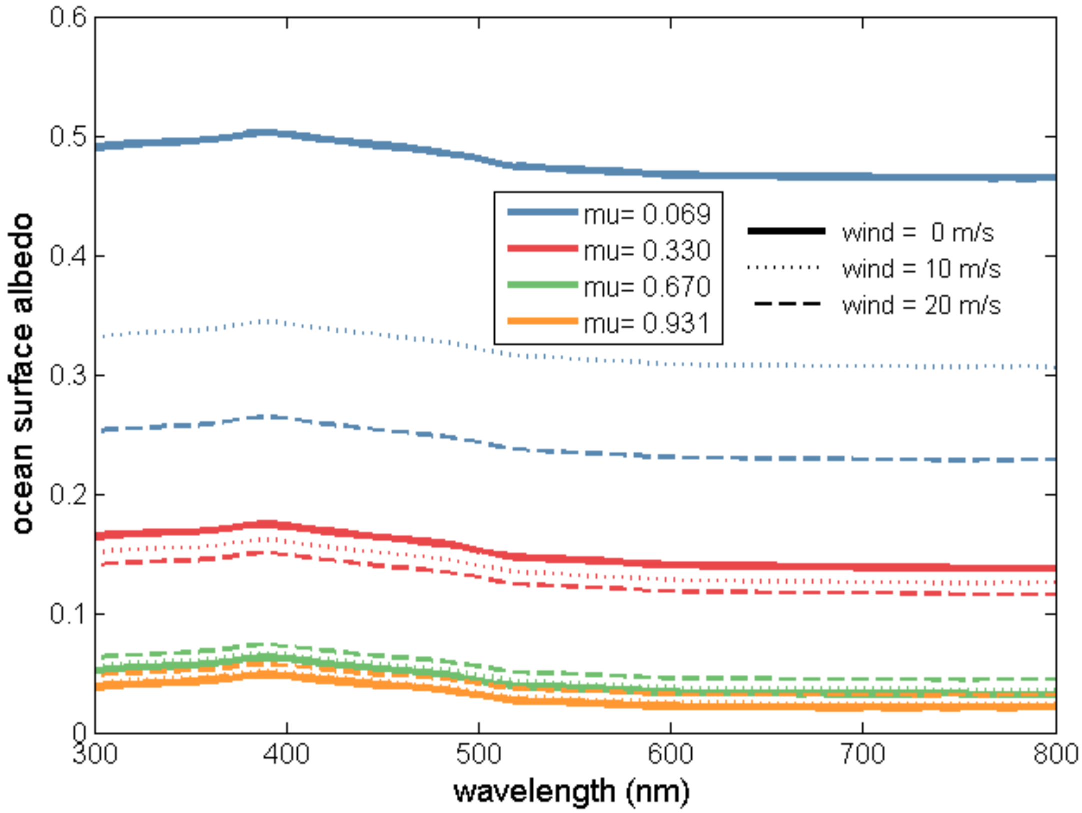

Figure S3. Ocean surface albedo (OSA, dimensionless) as a function of wavelength, shown for different incident angles (colors) and different wind speeds (dashed or dotted. Four different incident zenith angles are identified by their cosine values (mu, color coded) and are those used in Solar-J's 8-stream scattering code: 0.931 (orange), 0.670 (green), 0.330 (red), 0.069 (blue). Three different wind speeds are shown: 0 m/s (solid), 10 m/s (dotted), 20 m/s (dashed).

Table S1	
notation	code description
SJ	The standard version of Solar-J version 7.6d as published here. It is a minor update of 7.6c published in Prather and Hsu (2019, doi.org/10.7280/D1096P) to make the MAX-RAN consistent with 7.6c changes. Solar-J uses Cloud-J data tables for heating by O_2 (bins 1:11, <291 nm) & O_3 (bins 1:18, <778 nm) and RRTMG-SW tables for other gas-phase absorption (H_2O, CO_2, CH_4, O_2) in IR bins 18:27 (83 sub bins with 5 in visible and 78 in IR). Full cloud treatment includes vertical decorrelation length for cloud overlap (MAX-COR) to generate independent column atmospheres (ICAs) and then 4 cloud quadrature atmospheres (QCAs) to average over the ICAs. SJ can also be run with clear-sky or averaged cloud (full cloud cover in each cell as the average of cloudy and clear fractions), which does not invoke cloud-overlap and ICAs. SJ can be run in flat, spherical, refractive, and geometric options. SJ by default uses a constant ocean surface

	albedo (OSA = 0.06) but can invoke OSA to be of function of wavelength, incident angle (including scattered light) and surface wind.
SJ/RAN	SJ run with MAX-RAN cloud overlap.
SJ/RRX	The 78 IR sub-bins are replaced with the RRTM-SW benchmark code's 144 sub-bins.
SJ/CLIRAD	Solar-J with IR bins replaced with CLIRAD model: 0.70-1.22, 1.22-2.27, and 2.27-10.0 µm, each with 10 absorption sub-bins for each bin (Chou and Lee, 1996; Chou et al., 1999). The edge of the IR transition is shifted from 778 to 700 nm and cross section in bin 18 are adjusted. Only water vapor is included in the IR bins.
SJ/LLNL	The IR bins are replaced by the 3 large LLNL bins: 0.69–0.86, 0.86–2.27, and 2.27–3.85 µm, which include a total of 21 sub-bins. The edge of the IR transition is shifted from 778 to 700 nm and cross section in bin 18 are adjusted. Only water vapor is included in the IR bins. (Chou, 1992; Grant & Grossman, 1998).
SJ/66b	SJ with a very high wavelength resolution in the IR used to resolve ice- and liquid-water cloud absorption. It is constructed using 0.05 to 0.10 µm wide bins, yielding 66 IR bins instead of the 9 in SJ. Without sub-bins, it cannot calculate any IR gas absorption.
SJ/Ray	SJ with the standard Rayleigh gas scattering phase function ($1 + \cos^2(\Theta)$) changed to isotropic.
SJ/δ0	SJ with all cloud optical depths and phase functions changed to δ-0 scaling, see text and Table 2.
SJ/δ1	SJ with all cloud optical depths and phase functions changed to δ-1 scaling, see text and Table 2.
SJ/δ2	SJ with all cloud optical depths and phase functions changed to δ-2 scaling, see text and Table 2.
SJ/HG	SJ with all cloud phase functions changed to Henyey-Greenstein, see text and Table 2.
SJ/OSA	SJ with OSA a function of wavelength, incident angle (including scattered light) and surface wind.
RRTMG-SW	The standard RRTMG-SW version 4.0 code. If there are fractional clouds, this code uses MAX-RAN cloud overlap and McICA sampling of the ICAs,

Table S1. Versions of Solar-J and RRTMG-SW codes used here.

Table S2.

name	Table 1 row	code version	conditions.	Incident	Reflected	Atmos.	Surface
B0	1-5	SJ	flat-atmosphere, clear sky	351.37	49.92	70.71	230.74
B1	1	SJ/CLIRAD	flat-atmosphere, clear sky	351.37	50.86	65.03	235.47
B2	2	SJ/LLNL	flat-atmosphere, clear sky	351.37	50.46	63.05	237.87
B3	3	SJ/RRX	flat-atmosphere, clear sky	351.37	49.95	70.47	230.95
MR	5	SJ/Ray	flat-atmosphere, clear sky	351.37	49.91	70.72	230.74
C0	6-7	SJ/66b	sphere, QCA, no IR gases	352.85	127.37	28.96	196.53
C1	6	SJ/CLIRAD	sphere, QCA, no IR gases	352.86	125.23	32.80	194.83
C2	7	SJ	sphere, QCA, no IR gases	352.89	126.23	30.64	196.02
Mh	8	SJ/HG	flat-atmosphere, averaged clouds, no ice clouds	351.45	127.26	78.31	145.88
M0	8-11	SJ	flat-atmosphere, averaged clouds, no ice clouds	351.45	127.31	78.17	145.97
M1	9	SJ/δ0	flat-atmosphere, averaged clouds, no ice clouds	351.41	127.04	77.95	146.41
M2	10	SJ/δ1	flat-atmosphere, averaged clouds, no ice clouds	351.42	126.98	78.40	146.04

M3	11	SJ/δ2	flat-atmosphere, averaged clouds, no ice clouds	351.42	126.99	78.22	146.20
M4	15	SJ	flat-atmosphere, averaged clouds	351.46	131.19	78.49	141.77
D0	14	SJ	flat-atmosphere, QCA/MAX-COR cloud overlap	351.43	111.59	76.87	162.97
D1	14	SJ/RAN	flat-atmosphere, QCA/MAX-RAN cloud overlap	351.43	110.24	76.81	164.38
O0	17	SJ/OSA	sphere, varied OSA	352.98	111.72	76.77	164.49
O1	17	SJ	sphere, fixed OSA at 0.06	352.98	112.40	76.93	163.65
R0	4	RRTMG-SW v4.0	clear sky	351.38	51.22	70.24	229.92
R1	15	RRTMG-SW v4.0	averaged clouds	351.38	130.82	75.82	144.74
R2	12	RRTMG-SW v4.0	averaged clouds, no ice clouds	351.38	126.17	77.35	147.86
R3	16	RRTMG SW v4.0	McICA	351.38	108.14	74.45	168.79

Table S2. Description of model simulations and global-mean area-weighted fluxes averaged over January 2015 (744 hourly data) using the UCI CTM and the T159L60 (~1.1º x 1.1º) ECMWF forecast fields developed by U. Oslo from the Open-IFS system (Søvde et al., 2012; Prather et al., 2017). Solar constant =1360.8 W/m2 for all runs.