GEOS-Chem - RRTMG (GCRT) Documentation

This documentation serves as a 'how-to' guide for getting started with producing online radiative properties from GEOS-Chem as well as more in depth description of the interfacing of the two models (which will be on the GEOS-Chem wiki at some point). If you want to get started running the model then read 'Running GCRT'. If you are interested in the underlying assumptions for aerosol, clouds and surface properties then skip to the next section 'Aerosol, Clouds and Surface properties'. This is a work in progress - if you have any questions or have trouble running GCRT please email David Ridley (daridley@mit.edu).

Contents

Running GCRT

Quick start checklist

- Install NetCDF libraries for GEOS-Chem v9 onwards
- Ensure RRTMG optics look-up table (LUT) files for each species are in the run directory
- Ensure modis_surf_201210/ and the required surface property files exist in data directories
- Ensure species_clim_profiles.bpch is available in the GEOS-Chem directory i.e. /GEOS_2x2.5/
- Set switches in input.geos.rad for the Radiation Menu
- Set the ND71 output diagnostics required (generally this is set to 1 in the menu)

- Compile code with 'make RRTMG=yes' (this takes 15-20mins during the first compile)
- Run the model
- Copy the model output tracerinfo.dat and diaginfo.dat to the directory where IDL is run

Required auxiliary files

To perform the radiative transfer calculations extra optical and surface property information is required. The original jv_spec_aod.dat has been replaced with six LUT files, one for each aerosol type in the original jv_spec_aod.dat (dust.dat, so4.dat, soot.dat, org.dat, ssa.dat, ssc.dat), that should be placed in the run directory (and are included in the run directory in this beta release). See **aerosol optics** for more information on how these are created. Furthermore, the jv_spec.dat file contained aerosol properties at 300, 400, 600 and 999 nm (for the Fast-J calculations) that are no longer necessary with the new spectrally resolved optics files. Therefore these have been removed from jv_spec.dat and are now read from the individual species files (jv_spec.dat is still used for non-aerosol data that Fast-J requires).

The albedo and emissivity of the surface have been processed from multi-wavelength, broadband MODIS data. These are 8-day composites considered to be climatological means, calculated from 2002 – 2007 and are expected in /modis_surf_201210/ within the GEOS-Chem data directories (e.g. GEOS_4x5/). The data is in the BPCH format with each file containing four broadband albedos and emissivity interpolated to the 16 wavelengths for LW RRTMG calculations. See **surface emissivity and albedo** below for specific information on how these files are processed. These data files are stored in the /aux_files/surface/ folder of this release. Create the /modis_surf_201210/ directory within the GEOS-Chem data directory (i.e. /GEOS_2x2.5/) and move the files to that location.

The climatologies of CH_4, N_2O, CFC-11, CFC-12, CFC-22 and CCl4 for troposphere and stratosphere are stored in an external BPCH file (species_clim_profiles.bpch) which is stored in the /aux_files/spec_climatology/ folder of the release. This file should be moved to the GEOS-Chem data directory i.e. /GEOS_2x2.5/.

Version 9 of GEOS-Chem requires the NetCDF libraries to be installed. Downloading and installation instructions are available on the GEOS-Chem website:

http://wiki.seas.harvard.edu/geos-chem/index.php/Installing_HDF5_and_netCDF4

In addition, the following lines should be added to the .cshrc file to provide environmental variables for the GEOS-Chem makefiles (with the path corrected for your own library installation location).

```
# set NETCDF_ROOT = '/usr/local/netcdf-3.5.0_pgi32'
set NETCDF_ROOT = '/home/user/GEOS/GEOS-Chem-Libraries/opt/ifort'
setenv PATH ${NETCDF_ROOT}/bin:${PATH}
setenv NETCDF_LIB $NETCDF_ROOT/lib
setenv NETCDF_INC $NETCDF_ROOT/include
setenv NETCDF_MOD $NETCDF_ROOT/includeset

setenv ROOT_LIBRARY_DIR '/home/user/GEOS/GEOS-Chem-Libraries'
```

```
setenv GC_BIN        $ROOT_LIBRARY_DIR/bin
setenv GC_INCLUDE    $ROOT_LIBRARY_DIR/include
setenv GC_LIB        $ROOT_LIBRARY_DIR/lib
```

input.geos.rad menu

Running online radiative calculations is computationally expensive so several switches have been introduced to minimize run time. These can be found in the modified input.geos file (now called input.geos.rad) after the chemistry menu (and also an extra diagnostic line at the end of the BPCH output section). The following is a breakdown of what each switch represents.

AOD Wavelength (nm): There is now an option to choose the wavelengths at which the aerosol optical properties are required. Up to 3 wavelengths can be output at once and should be entered in nm with a space between each. This works independently of whether RRTMG is switched on and is included above the RRTMG switch. the LUT contains optics at 11 commonly used wavelengths prior to the RRTMG wavelengths. The requested wavelength is selected from the common wavelengths (out of 300, 400, 440, 500, 550, 600, 675, 800, 870, 1000 and 1020 nm) or interpolated to the requested wavelength (using the angstrom exponent for AOD and linear interpolation for the SSA and asymmetry parameter).

Turn on RRTMG? This must be switched on to run RRTMG. The selection of AOD wavelength is still active even when this is off. The model must have been compiled with 'make RRTMG=yes' to be able to turn on this switch.

Calculate LW fluxes? Switches on LW calculations.

Calculate SW fluxes? Switches on SW calculations.

Clear-sky flux? Performs radiative calculations without clouds.

All-sky flux? Performs radiative calculations with clouds (see Section XX for description of MCICA cloud algorithm). Both clear-sky and all-sky can be turned on at the same time without a significant increase in run time.

Radiation Timestep [min]: This is the frequency at which calls to RRTMG are made and currently must be a multiple of the dynamical time step (30 min for 4x5 simulations and 15 min for 2x2.5 simulations). The RRTMG calculation is instantaneous (i.e. not an average over the period selected) and is set to occur first at 00H + half of the radiation timestep. We recommend calling RRTMG no more frequently than every 180 min for a standard run (producing RRTMG calls at 1H30M, 4H30M etc.).

Species fluxes: These are the available species for which radiative properties can be calculated. The legend is included on the following line of the input file (see Table 1). Setting a value to 1 means that the radiative effect will be calculated for that species, zero means that it will be omitted from any calculation. The baseline run contains all species switched on and each requested species involves calling RRTMG with that species omitted so that the difference can be calculated (this 'omission' rather than 'addition' method takes into account the interaction with other aerosol and gases). Note that the number of calls to RRTMG

will be equal to the total sum of this line plus one (for the 'baseline' case) so this can substantially increase model run time. Currently, one call to RRTMG takes 42% longer than the standard model and switching on all outputs doubles the total run time.

Abbreviation	Species
O3	Ozone
ME	Methane
SU	Sulfate
NI	Nitrate
AM	Ammonium
BC	Black carbon
OA	Organic aerosol
SS	Sea salt
DU	Mineral dust
PM	All particulate matter
BA	Baseline flux

Table 1 – Species available for output from the flux calculations

As a rough guide, for a typical setup requiring the radiative effect of all aerosols combined (i.e. one call to RRTMG with aerosols and one call without), 20% of the time is spent on LW calculations, 75% of the time spent on SW calculations, and the remainder on initialization of clouds and aerosol and writing output.

N.B in input.geos.rad the size of the fine and coarse sea-salt aerosol can be assigned for use in the deposition code, however please be aware that this will not affect the optical properties assumed for the fine and coarse aerosol, which are fixed (see the r-eff column of the ssa.dat and ssc.dat LUT files in the run directory).

The gases radiative flux have been included for completeness but are relatively untested compared with the aerosol species and should therefore be treated with caution.

Default profiles for important gases
The RT calculations require profiles of CO2, CH_4, N_2O, O_3 and CFC-11, CFC-12, CFC-22 and CCl4 throughout the atmosphere, including the stratosphere. GEOS-Chem now reads in default profiles for most of the listed species, excluding CO2 and O3, which will be discussed below. The N_2O profile is the July 2012 zonal mean profile derived from the climatological database built for the NASA AURA TES instrument. The CH_4 profile is the July zonal mean profile from the same database. Since GEOS-Chem does provide tropospheric CH_4 values (in the CSPEC variable), the default profile is used only in the stratosphere, after being scaled to match the GEOS-Chem CH4 at the tropopause. The default profiles for CFC-11, CFC-12 and CCl4 are the climatologies generated for the UARS instrument, while the F22 profile was generated for the MIPAS instrument. Due to the Montreal protocol the concentrations of these species have been changing; since these are older climatologies the profiles have been scaled to match the surface values provided in the IPCC AR4 WG1 Table 2.1.

CO_2 has been set to a constant value of 390 ppmv, consistent with current (2012) observations. Tropospheric O_3 comes directly from the GEOS-Chem CSPEC variable, while stratospheric O3 is calculated with the same algorithm used by the FAST-J module.

The stratospheric CH_4, N_2O, CFC-11, CFC-12, CFC-22 and CCl4 profiles have been consolidated into a single bpch file that contains the profiles interpolated to the GEOS-Chem vertical grid and replicated over all latitudes and longitudes (i.e. onto the standard GEOS-Chem grid). This file is currently stored in the data directory for GEOS-Chem (e.g. GEOS_2x2.5/species_clim_profiles.2x25). These profiles are read in once, by READ_STRAT_CLIM (called by main.F and stored in rrtmg_rad_transfer.F) during model start-up.

Output fields available

A new BPCH diagnostic, ND71, has been created to store the radiative output fields. There are 11 fields (8 fluxes and 3 aerosol optical properties) available for each species and currently 101 output species (plus the baseline flux) giving a grand total of 118 tracers within the RADMAP-$ gamap category (plus another 60 if all 3 wavelength outputs are selected). The user simply has to switch this output on (set to 1) and the model will only produce output for those conditions set in the Radiation Menu. For the flux fields, 1 to 8 in table 2, output is the **change in flux caused by the presence of the species, or the Direct Radiative Effect (DRE, Wm^{-2})**. The baseline flux is also output by default so that the total flux can be calculated from the change in flux if required. To be consistent with the literature downwards is considered a positive flux (giving a negative Δflux at surface and TOA for purely scattering aerosol over dark surface). The optical properties are output for each species selected in the menu, e.g. if all aerosol (PM) and sulfate (SU) are selected in the 'species fluxes' menu and 550 nm selected in 'AOD wavelength' then the AOD, SSA and asymmetry parameter will be output for all aerosol (e.g. AODPM550, SSTPM550 and ASMPM550) and for sulfate alone (e.g. AODSU550, SSASU550 and ASMPM550).

Index	RADMAP-$ tracer	GAMAP name*
1	TOA SW (All-sky)	FSWXXTA
2	Surface SW (All-sky)	FSWXXSA
3	TOA LW (All-sky)	FLWXXTA
4	Surface LW (All-sky)	FLWXXSA
5	TOA SW (Clear-sky)	FSWXXTC
6	Surface SW (Clear-sky)	FSWXXSC
7	TOA LW (Clear-sky)	FLWXXTC
8	Surface LW (Clear-sky)	FLWXXSC
9	Total AOD (at wavelength YYY nm)	AODXXYYY**
10	AOD-weighted column Single Scattering Albedo (at YYY nm)	SSAXXYYY
11	AOD*SSA weighted asymmetry parameter (at YYY nm)	ASMXXYYY

*XX is replaced with the selected species abbreviation (listed above) or BA for the baseline flux case,
**YYY is the wavelength selected by the user in the input.geos.rad

Table 2 – output fields and naming for the ND71 diagnostic

Aerosol, Clouds and Surface Properties

Aerosol optics

Source

Aerosol optics have been calculated using the GADS database of aerosol properties (Hess et al., 1998) and the standard Mie code previously used to generate the jv_spec_aod.dat (Mishchenko et al., 1996). The GADS database is getting old so some updates have been made to the optics, including previous changes from (Drury et al., 2010); (Jaegle et al., 2010) and (Ridley et al., 2012), treatment of sulfate as ammonium sulfate rather than H_2SO_4, reduction of OC hygroscopicity, and updating of the dust SW refractive indices to more recent (and considerably different) values (Sinyuk et al., 2003) derived from AERONET and TOMS and generally accepted as an improvement (Balkanski et al., 2007; Ghan et al., 2012).

Processing

To save interpolation within the model, the LUT generated at GADS wavelengths has been interpolated to the RRTMG wavelengths. GADS contains aerosol properties at 61 wavelengths between from 250nm to 40,000nm, whereas RRTMG requires 30 wavelengths ranging from 229.8nm to 55555.6nm (see Table 3). Spline interpolation is used to translate from GADS to RRTMG wavelengths for each spectrally-dependent parameter (mass extinction efficiency, SSA, phase function etc.) and has been checked to ensure good agreement. For the two RRTMG wavelengths out of the range of the GADS data the properties at the longest and shortest wavelengths are simply copied (i.e. the data for 229.8nm and 55555.6nm is the same as for 250nm and 40,000nm). While spline interpolation give the best fit to the resonances in the spectral properties it sometimes overshoots to slightly negative values when GADS values were approximately zero for mass extinction efficiency and phase function, therefore checks were in place to set these to zero.

Implementation in GEOS-Chem

In the LUTs read in to GEOS-Chem there are 11 'standard' wavelengths included before the 30 RRTMG wavelengths (see Table 4). The purpose of these is to provide the aerosol properties at common wavelengths so that no interpolation is required for output when RRTMG is switched off. When RRTMG is switched on, these are still used for the calculation of aerosol AOD, SSA and asymmetry parameter to preserve consistency.

Wavenumber (cm^{-1})	Wavelength (nm)
180	55555.6
425	23529.4
565	17699.1

665	15037.6
760	13157.9
900	11111.1
1030	9708.7
1130	8849.6
1285	7782.1
1435	6968.6
1640	6097.6
1940	5154.6
2165	4618.9
2315	4319.7
2490	4016.1
2925	3418.8
2903	3444.7
3601	2777.0
4310	2320.2
4892	2044.2
5623	1778.4
6872	1455.2
7872	1270.3
10590	944.3
14420	693.5
18970	527.1
25015	399.8
30390	329.1
43507	229.8
1412	7082.2

Table 3 - RRTMG wavenumbers and the corresponding wavelengths

Wavelength (nm)
300
400
440
500
550
600
675
800
870
1020
1000

Table 4 - Standard wavelengths (used when RRTMG is switched off)

The lookup tables are stored per species as ASCII files. A NetCDF version has also been created and will be read in with future versions of GEOS-Chem (e.g. the grid independent version). These tables are read in using a modified version of RD_AOD.F, also containing a subroutine for calculating the coefficients required to interpolate to the user requested wavelength (CALC_AOD) using the angstrom exponent for optical depth and linear interpolation for SSA and asymmetry parameter.

How to generate new optics

This process is slightly convoluted and may be updated once sensitivity tests begin. First, the optical properties (mass extinction efficiency, single scattering albedo, phase functions) are generated from the GADS aerosol properties at 61 wavelengths between 0.25µm and 40µm. GADS properties are stored at 7 different relative humidities (0, 50, 70, 80, 90, 95 and 99%) for all but dust, which has properties for 7 different dry aerosol sizes. [Note: the GEOS-Chem model does not use the 95 and 99% values]. GADS contains dust properties separated into fine, accumulation, coarse and aged (transported). We currently just use the aged dust properties for all sizes, but with the updated refractive indices from (Sinyuk et al., 2003) as mentioned above. The Mie calculations are performed for each GEOS-Chem aerosol species separately – SO4, BC, OA, SS (accumulation), SS (coarse) and dust, producing 6 ASCII files in a similar format to the previous jv_spec_aod.dat but with spectrally resolved properties. These must then be interpolated to the RRTMG wavelengths. Below are the details of the procedure.

1. The Fortran code to calculate the optics for each species is stored locally in /home/dar/Mie_to_distrib/Mie_code/ or email daridley@mit.edu for access (calc_so4.dat, calc_soot.dat, calc_org.dat, calc_ssa.dat, calc_ssc.dat, calc_dust_all.dat). Compile each of these with ifort filename –o outname.x
2. There is a script to push the job to the servers (some can take a while) stored in /home/dar/Mie/run_mie.sh. Edit the name of the .x file in the script and submit this for each species. The .dat files will be output ready to be compiled into the format read in by GEOS-Chem.
3. Compile 'compile_jv_spec.pro' IDL code (stored in /home/dar/IDL/ and run INTERP_LUT) to read these ASCII files, interpolate from GADS wavelengths to RRTMG wavelengths and output as ASCII files for each species. This expects the optics files to be in /home/dar/GEOS/v9-01-01/jv_spec_gads/ and also requires rtwv.sav containing the RRTMG wavelengths to interpolate to (that can be found in /home/dar/IDL/).

If the NetCDF version is required then run COMPILE_JV_SPEC (in the same compile_jv_spec.pro) to read in the individual ASCII files produced from the Fortran Mie code (this will be required for use with future versions of GEOS-Chem).

For the IDL code please contact: daridley@mit.edu

Treatment of clouds

Cloud optical properties required by RRTMG are calculated within the RT code itself.

The liquid water optical properties are computed following equations 13-15 along with Tables 1 through 6 from Hu and Stamnes (1993). These equations are parameterizations derived from Mie theory. The equations are reproduced here:

$$b_{ext} = LWC * (a_1 r_{eff}^{b1} + c_1)$$
$$1 - W = a_2 r_{eff}^{b2} + c_2$$
$$g = a_3 r_{eff}^{b3} + c_3$$

where LWC is the liquid water content in g/m^3, β_{ext} is the extinction in m^{-1}, ω is the single scattering albedo, g is the asymmetry parameter, r_{eff} is the effective radius in microns, and a, b and c are fitting parameters listed as a function of wavelength in the tables. Note that in the longwave RRTMG does not model scattering and thus only the extinction is calculated, while all three parameters are calculated and used in the shortwave. The liquid water optical properties are calculated at the wavelengths provided in the tables for a range of particle sizes, interpolated to a fine spectral grid and averaged over each band. The actual values used by RRTMG in the longwave can be found in the rrtmg_lw_init.f90 routine in the absliq1 variable; the values for the shortwave are in rrtmg_sw_init.f90 in the extliq1, ssaliq1 and asyliq1 variables.

The ice optical properties for the shortwave are calculated following equations 3.8 and 3.9 (a, b, c and d) along with Tables 3a through 3d from Fu (1996). These equations are parameterizations derived from the output of a geometric ray tracing program, which assumes that the ice cloud particles are randomly oriented hexagonal ice crystals. The equations are as follows:

$$f = \frac{1}{2W} + f_d$$
$$b = IWC * (a_0 + a_1 / DGE)$$
$$1 - W = b_0 + b_1 DGE + b_2 DGE^2 + b_3 DGE^3$$
$$g = c_0 + c_1 DGE + c_2 DGE^2 + c_3 DGE^3$$
$$f_d = d_0 + d_1 DGE + d_2 DGE^2 + d_3 DGE^3$$

where f is the fraction of the scattered energy in the forward peak, IWC is the ice water content in g/m^3, and a, b, c and d are fitting parameters listed in the tables. DGE is the generalized effective size in microns, as defined in Fu, equation 2.3, and is basically a ratio of the total volume to the total area of all the ice particles in the layer; f_δ represents the contribution of the δ-function peak of scattered energy residing in the forward peak. The parameters actually used in RRTMG are obtained using the same process as for the

liquid optical properties and are stored in rrtmg_sw_init.f90 in the extice3, ssaice3, asyice3 and fdlice3 variables.

The absorption due to ice particles for the longwave is calculated following equation 3.2 and Table 1b from Fu et al. (1998). This equation is a parameterizations derived from the output of the combination of a geometric ray tracing program and Mie calculations, which assume that the ice cloud particles are randomly oriented hexagonal ice crystals. The equation is reproduced here:

$$b_a = \frac{IWC}{DGE}(b_0 + b_1 DGE + b_2 DGE^2 + b_3 DGE^3)$$

where β_a is the absorption in m^{-1} and the b values are fitting parameters from the table. The RRTMG values are stored in "rrtmg_lw_init.f90 in the absice3 variable.

Sub-grid variability can be modeled by constructing MULTIPLE sub-columns for each grid box; all sub-columns have the same profile information (i.e. temperature, water vapor) and vertical extent as the original grid box. They differ only in the distribution of the cloudy layers. This is done in the Independent Column Approximation (ICA) -- in each sub-column clear layers in the profile are set to clear, while cloudy layers are set to either clear or completely cloudy by a method that is statistically consistent with the individual layer cloud fractions and the assumed overlap of the cloudy layers. In a traditional ICA the RT code is run over all pseudo-spectral calculation points (g-points) for every sub-column. RRTMG utilizes the Monte Carlo Independent Column Approximation (McICA) (Pincus, 2003), in which each g-point is matched to a single sub-column, reducing the number of RT calculations required by a factor equal to the number of g-points with respect to an ICA implementation. The default vertical cloud overlap relationship is maximum overlap between clouds in adjacent layers and random overlap if cloudy layers are separated by clear layers (i.e. maximum-random overlap). This makes the assumption that clouds in adjacent layers are part of the same cloud column and should therefore be stacked on top of one another, whereas those separated by a clear layer are different clouds and therefore randomly positioned relative to one another. When averaged over a reasonable interval in time or space the mean fluxes calculated with the McICA approach are unbiased with respect to the fluxes obtained from the more computationally expensive ICA calculations. However, this does mean that runs will not necessarily produce identical results each time. The cloud fields are held constant for all RT calculations at a single RT time step, but the Monte-Carlo set up will force the cloud properties to vary randomly between time steps.

Implementation in GEOS-Chem

The required inputs for the cloud optical properties calculations are the cloud liquid effective radius, the cloud ice generalized effective size (DGE) (in microns) and liquid (LWP) and ice water paths (IWP) (in g/m^2)

for each layer. GEOS5 currently does not output any of these variables. $_\tau$Since there is a great deal of uncertainty in the values of cloud particle sizes, we chose representative values of effective radii derived from a near-10-year average of MODIS-Aqua data, provided by L. Oreopoulos (personal communication): 14.2 microns for water and 24.8 microns for ice. In order to obtain DGE for ice particles we used equation 3.12 from Fu (1996):

$$DGE = \frac{8r_e}{3\sqrt{3}}$$

r_e is related to r_{eff}, but the relationship varies with ice crystal habit and shape. Given that that the objective here is merely to derive a reasonable value for the DGE, we chose to assume r_{eff} equal to r_e and obtained a value of 38.182 microns for DGE.

The liquid water path is calculated from the liquid visible optical depths provided by GEOS5, using the effective radius just cited, in the following equation valid in the shortwave for liquid cloud droplets (Thomas and Stamnes, 2002):

$$LWP = \frac{2}{3} t_l r_l r_{eff}$$
where τ_l is the visible optical depth for liquid clouds, ρ_l is the density of water (in g/cm³), r_{eff} is the effective radius (in microns) and LWP is the liquid water path in g/m².

Similarly, the ice water path is calculated from the ice visible optical depths provided by GEOS5, using the DGE cited above, in the following equation valid in the shortwave for ice cloud particles (Fu, 1996). This equation is equivalent to Fu's equation 3.3, integrated over a layer:

$$IWP = \frac{\sqrt{3}}{4} t_i r_i DGE$$

where τ_l is the visible optical depth for ice clouds, ρ_i is the density of ice (in g/cm³), DGE is the generalized effective size (in microns) and IWP is the ice water path in g/m².

In this way the visible optical depths calculated by RRTMG are consistent with those provided by GEOS-5.

Surface emissivity and albedo
Source

The MODIS 'filled surface albedo' product has not been used owing to the removal of snow coverage to estimate the albedo of the underlying surface in that product. Here we use the raw albedo and emissivity products, but there is considerable uncertainty linked with the surface albedo used and this is an area of on-going research.

RRTMG requires spectrally resolved emissivity for the 16 LW wavelengths used. The MODIS MOD11C2 product contains land emissivity at 6 wavelengths between 3.75 µm and 12.0 µm at a resolution of 0.05 degrees, on global maps over 8-day periods. RRTMG wavelengths extend beyond this range (3.4 µm to 55.6 µm) therefore the MODIS emissivity must be interpolated to the RRTMG values within the range and fixed for the values outside of this range to the 3.75 µm and 12.03 µm MODIS emissivity. This appears to be the best solution at this time given that GMAO GEOS-5 output only contains broadband emissivity.

The albedos required in RRTMG are the direct and diffuse (also known as black-sky and white-sky) components for the UV-visible and visible-IR range. The MODIS MCD43C3.5 product provides direct and diffuse land albedo data at 8-day frequency over 7 wavelengths and also broadband for the UV-visible and visible-IR range (see Table 5). We use the broadband albedos from MODIS (0.3-0.7 µm for UV-visible and 0.7-5.0 µm for visible-IR).The ocean is currently assumed to have an albedo of 0.07 across all wavelengths (Roeckner et al., 2003; Stier et al., 2007) however more research is required to determine if assuming a spectral dependence is considered a significant improvement. The emissivity of the ocean is set to 0.98. From (Sidran, 1981) this appears to be relatively constant between 0.2µm and 12µm, after which it decreases slightly to 0.95 until beyond 40µm. Again, this is an approximation and may require improvement in the future.

Surface Property	RRTMG requirements (µm)	MODIS products (µm)
Albedo (UV-vis)	0.200 – 0.625	0.3 – 0.7
Albedo (NIR)	0.625 – 12.2	0.7 – 5.0
Emissivity	3.42 – 55.6	3.75 – 12.0

Table 5 – surface properties and the required wavebands by RRTMG and the MODIS data available

Processing

The MODIS data is processed from the native resolution and wavelengths to those required by GEOS-Chem and RRTMG, with the temporal resolution remaining at 8-days.

There is often missing data in the MODIS files, even after re-gridding to a coarser resolution (the MODIS data is regridded from 0.05 degree to 0.5 degree initially to speed up processing). At certain times of year MODIS does not retrieve albedo at high latitudes (due to no sunlight during overpass) therefore data is only available for certain seasons, leading to discontinuities. However, those high latitude areas are in darkness for periods of the year and so the surface albedo will become less important (i.e. when calculating the radiative transfer in regions of darkness there will be no need for the albedo anyway). To prevent non-physical discontinuities in the albedo the current solution is to fill in the blanks with the average albedo and emissivity created from the five 8-day files before and after. Any remaining missing data is then filled in with the climatological average. This can occur at high latitudes where no MODIS data is available and leads to some discontinuity in the albedo fields. However, these generally occur in locations and times with minimal solar incidence (the reason for poor data coverage) and therefore a minimal impact on the radiative properties.

Once ocean and missing values have been filled the MODIS data is then interpolated to the required GEOS-Chem spatial resolution and the direct albedo, diffuse albedo and emissivity all interpolated to the required wavelengths. Emissivity is required at several wavelengths outside the range of the MODIS observations and, as mentioned above, the current solution to this is to repeat the highest and lowest MODIS emissivity values for those outside of the range.

The data is written as a BPCH file for each 8-day composite containing both albedos and the emissivity. The tracers are named ALBDIR1, ALBDIF1, ALBDIR2, ALBDIF2, and EMIS and stored under the MODAVG-$ diagnostic. The current version of the code expects the climatological averages to be located in /GEOS_2x2.5/modis_surf_201210/.

Implementation in GEOS-Chem

Reading of the surface fields is triggered from within main.F by READ_INITIAL_MET_FIELDS at the start of the model run and then when ITS_TIME_FOR_SURFACE_RAD() is true during READ_MET_FIELDS. Met fields are read every few hours therefore a check is employed to ensure we don't read a surface file more than once.

READ_SURFACE_RAD within rrtmg_transfer_mod.F reads in the BPCH files from the modis_surf_201210/ and stores the variables as ALBDIR(IIPAR,JJPAR,NALBD), ALBDIF(IIPAR,JJPAR,NALBD) and EMISS(IIPAR,JJPAR,NEMISS), where NALBD=2 and NEMISS=16, allocated in the rrtmg_transfer_mod.F module and made public.

INIT_SURFACE_RAD and CLEANUP_SURFACE_RAD perform the usual array creation and destruction.

How to generate new surface fields

The code required to process the MODIS HDF files and output BPCH files is stored in the modis_surf.pro routine (in /home/dar/IDL/, contact daridley@mit.edu).

1. Call REGRID_SURF,yyyy – this takes the raw MODIS files, regrids them to a more manageable 0.5 degree resolution and saves them out to /home/data/obs/MODIS/compiled/
2. Call PROCESS_SURF_CLIM,res=res – this reads in the regridded files for 2002 - 2007, fills missing values, converts to the GEOS-Chem grid specified (res=2 or 4 for 2x2.5 or 4x5, respectively), interpolates the emissivity wavelengths, and calls WRITE_SURF_BPCH to save the files in the format modis_surf_02-07_DDD.4x5 locally.
3. Transfer the modis_surf_02-07_DDD.4x5 files to the GEOS_2x2.5/modis_surf_201210/ directory.

Specific GEOS-Chem changes

Here is a breakdown of the chain of events involved in producing the radiative flux output:

- Read radiation selection from user (once)
- Read spectral aerosol properties (once)
- Read surface emissivity and albedo (every 8 days)
- Calculate aerosol optics over RRTMG wavelengths (at chemistry timestep)
- Prepare cloud and aerosol fields for RRTMG (at radiation timestep)
- Calculate fluxes with and without each requested species (at radiation timestep)
- Calculate with and without clouds if requested (at radiation timestep)
- Output required radiative effects and optical diagnostics (at radiation timestep)

Below is a list of the GEOS-Chem modules modified to provide the interface with RRTMG.

JV_CMN_MOD.F (most of the new variables are stored in here within a pre-processor clause)

CMN_DIAG.F (number of diagnostics updated within a pre-processor clause)

TIME_MOD.F (extra radiation timestep function and counters added)

NDXX_SETUP.F (ND71 diagnostic set up if requested)

CLEANUP_MOD.F

DIAG3.F (BPCH output added for ND71 radiation diagnostics)

DIAG_MOD.F (Diagnostic memory allocated within pre-processor clause)

DIAG48_MOD.F (Alterations because of shape change of ODAER and wavelength interpolation)

DIAG49_MOD.F (Alterations because of shape change of ODAER and wavelength interpolation)

DIAG50_MOD.F (Alterations because of shape change of ODAER and wavelength interpolation)

DIAG51_MOD.F (Alterations because of shape change of ODAER and wavelength interpolation)

DIAG51b_MOD.F (Alterations because of shape change of ODAER and wavelength interpolation)

PLANEFLIGHT_MOD.F (Alterations because of shape change of ODAER and wavelength interpolation)

LOGICAL_MOD.F

INPUT_MOD.F (Addition of new radiation input variables)

INITIALIZE.F

GAMAP.F (section to create the correct tracer outputs depending on user selected inputs)

RRTMG_TRANSFER_MOD.F (New - the RRTMG calling procedure)

RD_AOD.F (rewritten to take the new optics files and determine interpolation to user wavelength)

MAIN.F (initialization and call to RRTMG and setting up of surface albedo and emissivity fields and stratospheric gas profiles)

FAST_J.F (mapping new ODAER onto Fast-J OPTAER)

OPMIE.F (modification to use variables from new optics tables rather than jv_spec.dat)

SET_AER.F (removal of aerosol type indices from jv_spec.dat)

AEROSOL_MOD.F (RDAER rewritten for multi-wavelength calculation and to accumulate RT variables, stored in pre-processor clauses)

DUST_MOD.F (modified for multi-wavelength calculation and accumulation of RT variables, stored in pre-processor clauses)

SET_PROF_O3.F (New – loads O3 profile)

For more information on specific changes please contact David Ridley (daridley@mit.edu)

References

Balkanski, Y., Schulz, M., Claquin, T., Guibert, S., 2007. Reevaluation of Mineral aerosol radiative forcings suggests a better agreement with satellite and AERONET data. Atmospheric Chemistry and Physics 7, 81–95.

Drury, E., Jacob, D.J., Spurr, R.J.., Wang, J., Shinozuka, Y., Anderson, B.E., Clarke, A.D., Dibb, J., McNaughton, C., Weber, R., 2010. Synthesis of satellite (MODIS), aircraft (ICARTT), and surface (IMPROVE, EPA-AQS, AERONET) aerosol observations over eastern North America to improve MODIS aerosol retrievals and constrain surface aerosol concentrations and sources. Journal of Geophysical Research 115, D14204.

Fu, Q., 1996. An Accurate Parameterization of the Solar Radiative Properties of Cirrus Clouds for Climate Models. J. Climate 9, 2058–2082.

Fu, Q., Yang, P., Sun, W.B., 1998. An accurate parameterization of the infrared radiative properties of cirrus clouds for climate models. Journal of climate 11, 2223–2237.

Ghan, S.J., Liu, X., Easter, R.C., Zaveri, R., Rasch, P.J., Yoon, J.-H., Eaton, B., 2012. Toward a Minimal Representation of Aerosols in Climate Models: Comparative Decomposition of Aerosol Direct, Semidirect, and Indirect Radiative Forcing. Journal of Climate 25, 6461–6476.

Hess, M., Koepke, P., Schult, I., 1998. Optical propeties of aerosol and clouds: The software package OPAC. Bull. Am. Meteorol. Soc. 79, 831–844.

Hu, Y.X., Stamnes, K., 1993. An Accurate Parameterization of the Radiative Properties of Water Clouds Suitable for Use in Climate Models. J. Climate 6, 728–742.

Jaegle, L., Quinn, P.K., Bates, T.S., Alexander, B., Lin, J.-T., 2010. Global distribution of sea salt aerosols: new constraints from in situ and remote sensing observations. Atmos. Chem. Phys. Discuss. 10, 25687–25742.

Mishchenko, M.I., Travis, L.D., Macke, A., 1996. Scattering of light by polydisperse, randomly oriented, finite circular cylinders. Appl. Optics 35, 4927–4940.

Pincus, R., 2003. A fast, flexible, approximate technique for computing radiative transfer in inhomogeneous cloud fields. Journal of Geophysical Research 108.

Ridley, D.A., Heald, C.L., Ford, B., 2012. North African dust export and deposition: A satellite and model perspective. Journal of Geophysical Research 117.

Roeckner, E., Bäuml, G., Bonventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., 2003. The atmospheric general circulation model ECHAM5. PART I: Model description, Report 349, Max Planck Institute for Meteorology, Hamburg, Germany.

Sidran, M., 1981. Broadband reflectance and emissivity of specular and rough water surfaces. Applied Optics 20, 3176–3183.

Sinyuk, A., Torres, O., Dubovik, O., 2003. Combined use of satellite and surface observations to infer the imaginary part of refractive index of Saharan dust. Geophysical Research Letters 30.

Stier, P., Seinfeld, J.H., Kinne, S., Boucher, O., 2007. Aerosol absorption and radiative forcing. Atmospheric Chemistry and Physics 7, 5237–5261.

Thomas, G.E., Stamnes, K., 2002. Radiative transfer in the atmosphere and ocean. Cambridge University Press.