Development of the CERES Flux-by-cloud type simulator

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What is the Flux-by-cloud type product?

- Assigns a flux to each observed ISCCP cloud type within a region.
- For each 1°x1° region between 60° S and 60° N, each daytime footprint is placed into 1-3 $p_c$-$\tau$ ISCCP-like categories (3 categories would be the case of a footprint with two cloud levels as well as clear pixels).
- For the footprints with a single cloud type, the standard SSF flux is added to that $p_c$-$\tau$ category.
- For footprints with multiple cloud levels, narrowband-to-broadband radiance conversions are performed for each cloud level.
- Broadband radiances are converted to fluxes using ADMs.
Here, Terra passed over the SE Pacific on Jan 1 2008, and there were two $p_c$-$\tau$ cloud types ($p_c$=800-1000 hPa, $\tau$=3.6-9.4 and $\tau$=9.4-23). The optically thicker part of the region has more outgoing SW, and slightly less OLR.
What is a simulator?

- Put simply, a simulator is meant to replicate what a space-based instrument would measure if it flew above a GCM or other model on the temporal and spatial scales of the measurements.
Motivation for flux-by-cloud type simulator

- Cloud properties and fluxes/albedos will be matched within 1.5 hours to the closest CERES overpass, which is important because of the large diurnal cycles in cloud fraction, $\tau$, and $p_c$ in many areas.
- Breaking out the flux by cloud type can help isolate physical parameterizations that are problematic (e.g., convective clouds, boundary-layer parameterizations, or processes involving surface albedo), and provide a test for new parameterizations.
- Diagnoses using flux-by-cloud type combined with frequency of occurrence can also help determine whether an unrealistically small or large occurrence of a given cloud type has an important radiative impact for a given region.
Outline of Simulator Approach

1. Read in data at GCM grid size
2. Run cloud generator and cloud property simulator to produce atmospheric subcolumns
3. Classify subcolumns into $p_c\tau$ cloud types
4. Perform radiative transfer on a subset of subcolumns in each type
Cloud Generator

• GCM grid cells are much larger (~1°×1°, or ~10000 km²) than MODIS pixels (~8 km² spacing), so the grid cells are first split into enough “pseudo-pixel” subcolumns so that they represent a comparable area.

• The subcolumns are assigned a binary (0 or 1) cloud fraction at each vertical level using a cloud generator (Klein and Jakob 1999; Webb et al. 2001) with the maximum-random overlap assumption.
Langley Fu-Liou Model

- Fu-Liou radiative transfer model is run for at least 5 profiles for each $p_c-\tau$ cloud type, obtaining mean broadband LW and SW fluxes, $F_{LW}(5)$, $F_{SW}(5)$.

- Meteorological conditions (temperature, ozone concentration, water vapor mixing ratio, surface albedo, solar zenith angle) are considered horizontally homogeneous over each GCM grid cell.

- Computationally expensive to calculate radiative transfer on every column, so it is performed on additional profiles until mean flux $F(n+1)$ does not change much relative to $F(n)$.

![Graph showing mean F (W m$^{-2}$) vs iteration number]

- Initial fluctuations in mean F stabilizes after 15 iterations.
TOA Radiation test

- Meant to verify that RT model produces similar TOA LW and SW fluxes as CMIP5 GCMs for simple cases.
- Pick cases where there is a single, overcast layer of liquid water cloud over ocean, and apply the Fu-Liou model to them.
- Profile inputs: $p$, $T$, $q_v$, $O_3$.
- Surface inputs: skin temperature, albedo, and emissivity.
- Cloud-layer inputs: top and base pressure, effective radius, optical depth
- I found and ran several cases for both the CNRM-CM5 and UKMO-HadGEM2A models.
Single-Layer overcast water cloud: CNRM-CM5 Case 1

- Located over Southern Ocean (62.3 S, 135 E)
- $r_e$ derived from Benedetti and Janiskova: 10.9 µm
- $\tau$ derived from same equation used in Fu-Liou code: 24.1
- $p_{\text{base}} = 983$ hPa, $p_{\text{top}} = 880$ hPa
- Albedo derived from surface ($SW_{\text{up}}/SW_{\text{down}}$): 0.061
- Surface emissivity from ($LW_{\text{up}}/\sigma_{sb}T^4$): 0.994
- Cosine of SZA: 0.193
Single-Layer overcast water cloud: CNRM-CM5 Case 1

TOA Flux (W/m²)

- SW
- LW

TOA SW Albedo

- Fu-Liou
- CNRM-CM5
Single-Layer overcast water cloud: CNRM-CM5 Case 2

- Located over Southern Ocean (53.9 S, 118.1 E)
- $r_e$: 11.9 $\mu$m
- $\tau$: 19.3
- $p_{\text{base}} = 983$ hPa, $p_{\text{top}} = 920$ hPa
- Surface albedo: 0.061
- Surface emissivity: 0.997
- Cosine of SZA: 0.658
Single-Layer overcast water cloud: CNRM-CM5 Case 2

![Graphs showing TOA flux and TOA SW albedo for SW and LW bands. The graphs compare Fu-Liou and CNRM-CM5 models.]
Single-Layer overcast water cloud: CNRM-CM5 Case 2 (t+3hr)

- Same inputs as previous Case 2, but using radiation fields at 3 hours past the time stamp of the clouds, since downward TOA solar radiation is an average of 3 hours previous to time stamp.
- Cosine of SZA: 0.272
Single-Layer overcast water cloud: CNRM-CM5 Case 2 (t+3hr)
Single-Layer overcast water cloud: Case 1 (UKMO-HadGEM2A)

- Located over Southern Indian Ocean (36.3 S, 99.4 E)
- $r_e$ from model output: 15.9 $\mu$m
- $\tau$ from model output: 14.3
- $p_{\text{base}} = 969$ hPa, $p_{\text{top}} = 928$ hPa
- SW albedo derived from surface ($SW_{\text{up}}/Sw_{\text{down}}$): 0.062
- Surface emissivity from ($LW_{\text{up}}/\sigma_{sb}T^4$): 0.9998
- Cosine of SZA: 0.933
Single-Layer overcast water cloud: Case 1 (UKMO-HadGEM2A)

TOA Flux (W/m^2)

- SW
- LW

TOA SW Albedo

- Fu-Liou
- UKMO-HadGEM2A
Single-Layer overcast water cloud: Case 2 (UKMO-HadGEM2A)

- Located over Western Pacific Ocean (25 N, 138.75 E)
- $r_e$ from model output: 14.1 \( \mu \text{m} \)
- $\tau$ from model output: 19.0
- $p_{\text{base}} = 936$ hPa, $p_{\text{top}} = 884$ hPa
- SW albedo derived from surface ($SW_{\text{up}}/Sw_{\text{down}}$): 0.064
- Surface emissivity from ($LW_{\text{up}}/\sigma_{sb}T^4$): 0.9998
- Cosine of SZA: 0.569
Single-Layer overcast water cloud: Case 2 (UKMO-HadGEM2A)
Summary

- The CERES flux-by-cloud type data product assigns fluxes to ISCCP ($p_c$, $\tau$) cloud categories.
- As a first step towards building a simulator, the TOA fluxes associated with single-layer water clouds were compared between the Langley Fu-Liou RT model and CNRM-CM5 and UKMO-HadGEM-2A GCM output.
- Fu-Liou OLR is close to that of CNRM-CM5 output, but TOA shortwave albedo tends to be significantly higher, perhaps because of incorrect conversion of LWC to $\tau$, or timestamp issues.
- Fu-Liou TOA shortwave albedo is close to that of UKMO-HadGEM2A output, but OLR tends to be lower, by as much as 5%.
Extra slides
Future Work

• Apply simulator to models with 3-hourly IPCC CFMIP (Cloud Feedback Model Intercomparison Project) output.
• We will compare flux-by-cloud type output on monthly or greater timescales, since fluctuations associated with weather are impossible for climate models to reproduce.
• Use albedo rather than flux for SW because up to 1.5 hours of temporal mismatch will cause significant flux differences.
• Will run the simulator a limited number of times with radiative transfer applied to all subcolumns in order to verify that the limited number used will be a good approximation.
Surface Albedo and Emissivity

- Neither quantity is provided in the model output.
- For albedo, use ratio of $SW_{up}/SW_{down}$ at the surface.
- For surface emissivity, use ratio of $LW_{down}/\sigma T_s^4$ at the surface.
Surface Albedo

CNRM Jan 2008 surface albedo from surface fluxes

CERES/SARB Mar 2000 surface albedo from Rutan et al. (2006)
Surface Emissivity

CNRM Jan 2008 surface albedo from surface LW up, skin temp.

Surface broadband emissivity from Wilber et al. (1999)

CNRM LW emissivities seem higher than those from Wilber et al. (1999), especially over the Sahara desert and East Antarctica. Some values over the Americas are actually over 1.0.
Cloud Property Simulator

• The MODIS simulator from the CFMIP Observational Simulator Package (COSP) is used to derive cloud properties.

• Each cloudy subcolumn is assigned to one of the 42 $p_c$-$\tau$ cloud types based on the $p_c$ and $\tau$ values obtained from the MODIS simulator, with clear columns representing a 43rd type.
3 parts but one total flux for a footprint:

- Upper layer
- Lower layer
- Clear

After processing, we will assign a flux value to each part.
Steps involved with offline Flux-by-cloud type Simulator

- Read in required variables: profiles of temperature, water vapor, cloud fraction, etc.
- For those grid cells that match the FBCT product (daytime, 60°S-60°N, closest model output time to Terra/Aqua overpass), use MODIS cloud property simulator at fine (~8km²) resolution to produce ~1000 cloudy columns.
- These columns are grouped into $p_c-\tau$ categories.
Note on RT calculations

• When assigning the flux to a CTP-$\tau$ bin, we use the retrieved CTP and $\tau$ from the MODIS simulator, but the flux is based on the actual cloud profile.

• For example, a column with a very thin cloud could be counted as “clear”, but its retrieved fluxes would take the cloud into account.
Benefits of this approach

• Cloud properties and fluxes/albedos are matched within 1.5 hours to the closest CERES overpass, which is important because of the large diurnal cycles in cloud fraction, $\tau$, and $p_c$ in many areas.

• Breaking out flux by cloud type can help isolate physical parameterizations that are problematic, and provide a test for new parameterizations.
What’s in the CFMIP archive

- 7 participating modeling centers: CCCMA (Canada), CNRM (France), LASG (China), MRI (Japan), MPI-M (Germany), MOHC (UK), and NCAR.

- Only three of the models have 3-hourly profile data of air temperature, cloud amount, mass fraction of water/ice: CNRM, MRI, and MOHC. MRI doesn’t seem to have stratiform cloud amount?

- Water vapor profiles are included at a six-hourly interval for all three models.

- Effective radii of water/ice, tau profiles and emissivity are included for MRI, MOHC only.

- 3-hourly land and sea ice skin temperature seems to only be included for CNRM, MRI only. Only MRI has 3-hourly SST, but all models have monthly mean skin temperature, which should be OK for SST.
### Single-Layer overcast water cloud: CNRM-CM5 Case 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>CNRM output</th>
<th>Fu-Liou output</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOA SW down</td>
<td>270.9 W m(^{-2})</td>
<td>270.9 W m(^{-2})</td>
</tr>
<tr>
<td>TOA SW up</td>
<td>156.9 W m(^{-2})</td>
<td>161.6 W m(^{-2})</td>
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<tr>
<td>TOA SW albedo</td>
<td>0.579</td>
<td>0.597</td>
</tr>
<tr>
<td>TOA OLR</td>
<td>242.6 W m(^{-2})</td>
<td>240.3 W m(^{-2})</td>
</tr>
<tr>
<td>SFC SW down</td>
<td>35.0 W m(^{-2})</td>
<td>37.1 W m(^{-2})</td>
</tr>
<tr>
<td>SFC SW up</td>
<td>2.1 W m(^{-2})</td>
<td>2.3 W m(^{-2})</td>
</tr>
<tr>
<td>SFC LW up</td>
<td>323.5 W m(^{-2})</td>
<td>325.3 W m(^{-2})</td>
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# Single-Layer overcast water cloud: CNRM-CM5 Case 2

<table>
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<th>Variable</th>
<th>CNRM output</th>
<th>Fu-Liou output</th>
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<tbody>
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<td>924.9 W m$^{-2}$</td>
<td>924.9 W m$^{-2}$</td>
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<td>TOA SW up</td>
<td>369.2 W m$^{-2}$</td>
<td>475.8 W m$^{-2}$</td>
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<tr>
<td>TOA SW albedo</td>
<td>0.399</td>
<td>0.515</td>
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<tr>
<td>TOA OLR</td>
<td>243.6 W m$^{-2}$</td>
<td>246.5 W m$^{-2}$</td>
</tr>
<tr>
<td>SFC SW down</td>
<td>369.4 W m$^{-2}$</td>
<td>240.6 W m$^{-2}$</td>
</tr>
<tr>
<td>SFC SW up</td>
<td>22.5 W m$^{-2}$</td>
<td>14.6 W m$^{-2}$</td>
</tr>
<tr>
<td>SFC LW up</td>
<td>335.5 W m$^{-2}$</td>
<td>336.4 W m$^{-2}$</td>
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Single-Layer overcast water cloud: Case 2 (CNRM, t+3hr)

<table>
<thead>
<tr>
<th>Variable</th>
<th>CNRM output</th>
<th>Fu-Liou output</th>
</tr>
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<tbody>
<tr>
<td>TOA SW down</td>
<td>382.7 W m⁻²</td>
<td>382.7 W m⁻²</td>
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<tr>
<td>TOA SW up</td>
<td>203.9 W m⁻²</td>
<td>217.5 W m⁻²</td>
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<td>TOA SW albedo</td>
<td>0.533</td>
<td>0.568</td>
</tr>
<tr>
<td>TOA OLR</td>
<td>248.2 W m⁻²</td>
<td>246.5 W m⁻²</td>
</tr>
<tr>
<td>SFC SW down</td>
<td>74.5 W m⁻²</td>
<td>67.3 W m⁻²</td>
</tr>
<tr>
<td>SFC SW up</td>
<td>4.5 W m⁻²</td>
<td>4.1 W m⁻²</td>
</tr>
<tr>
<td>SFC LW up</td>
<td>335.5 W m⁻²</td>
<td>336.4 W m⁻²</td>
</tr>
</tbody>
</table>
Single-Layer overcast water cloud: Case 3

- Located over Southern Ocean (52.5 S, 118.1 E)
- $r_e$: 11.6 µm
- $\tau$: 23.0
- $p_{\text{base}} = 1005$ hPa, $p_{\text{top}} = 922$ hPa
- SW albedo: 0.061
- Surface emissivity: 0.998
- Cosine of SZA: 0.265
## Single-Layer overcast water cloud: Case 3

<table>
<thead>
<tr>
<th>Variable</th>
<th>CNRM output</th>
<th>Fu-Liou output</th>
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</thead>
<tbody>
<tr>
<td>TOA SW down</td>
<td>372.5 W m(^{-2})</td>
<td>372.5 W m(^{-2})</td>
</tr>
<tr>
<td>TOA SW up</td>
<td>197.1 W m(^{-2})</td>
<td>215.9 W m(^{-2})</td>
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<tr>
<td>TOA SW albedo</td>
<td>0.529</td>
<td>0.579</td>
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<tr>
<td>TOA OLR</td>
<td>251.1 W m(^{-2})</td>
<td>248.0 W m(^{-2})</td>
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<tr>
<td>SFC SW down</td>
<td>69.4 W m(^{-2})</td>
<td>57.5 W m(^{-2})</td>
</tr>
<tr>
<td>SFC SW up</td>
<td>4.2 W m(^{-2})</td>
<td>3.5 W m(^{-2})</td>
</tr>
<tr>
<td>SFC LW up</td>
<td>337.7 W m(^{-2})</td>
<td>338.3 W m(^{-2})</td>
</tr>
</tbody>
</table>
Single-Layer overcast water cloud: CNRM Case 4 (t+1)

- Located over Southern Ocean (52.3 S, 123.8 E)
- $r_e$: 11.6 $\mu$m
- $\tau$: 33.3
- $p_{\text{base}} = 1004$ hPa, $p_{\text{top}} = 881$ hPa
- SW albedo: 0.061
- Surface emissivity: 0.998
- Cosine of SZA: 0.409
Single-Layer overcast water cloud: CNRM (Case 4, t+1)

<table>
<thead>
<tr>
<th>Variable</th>
<th>CNRM output</th>
<th>Fu-Liou output</th>
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</thead>
<tbody>
<tr>
<td>TOA SW down</td>
<td>574.7 W m⁻²</td>
<td>574.7 W m⁻²</td>
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<tr>
<td>TOA SW up</td>
<td>317.1 W m⁻²</td>
<td>349.8 W m⁻²</td>
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<tr>
<td>TOA SW albedo</td>
<td>0.552</td>
<td>0.609</td>
</tr>
<tr>
<td>TOA OLR</td>
<td>255.4 W m⁻²</td>
<td>251.7 W m⁻²</td>
</tr>
<tr>
<td>SFC SW down</td>
<td>110.2 W m⁻²</td>
<td>81.0 W m⁻²</td>
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<tr>
<td>SFC SW up</td>
<td>6.8 W m⁻²</td>
<td>4.9 W m⁻²</td>
</tr>
<tr>
<td>SFC LW up</td>
<td>342.6 W m⁻²</td>
<td>342.8 W m⁻²</td>
</tr>
</tbody>
</table>
Met Office Hadley Centre Model

- Profile inputs: $p$, $T$ (3hr), $q_v$ (6hr) are present, $O_3$ does not appear to be (could use standard atmosphere?)
- Surface inputs: Skin temperature available every 3hr, albedo and emissivity derivable from (3-hourly) surface fluxes.
- Cloud inputs: Stratiform and convective cloud cover, stratiform and convective water and ice content, stratiform and convective optical depth, stratiform and convective effective radius for water and ice.
### Single-Layer overcast water cloud: Case 1 (UKMO-HadGEM2A)

<table>
<thead>
<tr>
<th>Variable</th>
<th>UKMO output</th>
<th>Fu-Liou output</th>
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<tbody>
<tr>
<td>TOA SW down</td>
<td>1317.9 W m(^{-2})</td>
<td>1317.9 W m(^{-2})</td>
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<td>TOA SW up</td>
<td>524.3 W m(^{-2})</td>
<td>521.5 W m(^{-2})</td>
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<tr>
<td>TOA SW albedo</td>
<td>0.398</td>
<td>0.396</td>
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<tr>
<td>TOA OLR</td>
<td>266.5 W m(^{-2})</td>
<td>258.2 W m(^{-2})</td>
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<td>SFC SW down</td>
<td>508.7 W m(^{-2})</td>
<td>497.5 W m(^{-2})</td>
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<td>SFC SW up</td>
<td>31.3 W m(^{-2})</td>
<td>30.9 W m(^{-2})</td>
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<tr>
<td>SFC LW up</td>
<td>400.5 W m(^{-2})</td>
<td>400.4 W m(^{-2})</td>
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Single-Layer overcast water cloud: Case 2 (UKMO-HadGEM2A)

<table>
<thead>
<tr>
<th>Variable</th>
<th>UKMO output</th>
<th>Fu-Liou output</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOA SW down</td>
<td>802.8 W m(^{-2})</td>
<td>802.8 W m(^{-2})</td>
</tr>
<tr>
<td>TOA SW up</td>
<td>441.4 W m(^{-2})</td>
<td>425.6 W m(^{-2})</td>
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<tr>
<td>TOA SW albedo</td>
<td>0.550</td>
<td>0.530</td>
</tr>
<tr>
<td>TOA OLR</td>
<td>263.7 W m(^{-2})</td>
<td>250.4 W m(^{-2})</td>
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<tr>
<td>SFC SW down</td>
<td>195.6 W m(^{-2})</td>
<td>195.7 W m(^{-2})</td>
</tr>
<tr>
<td>SFC SW up</td>
<td>12.5 W m(^{-2})</td>
<td>12.5 W m(^{-2})</td>
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<tr>
<td>SFC LW up</td>
<td>442.8 W m(^{-2})</td>
<td>442.6 W m(^{-2})</td>
</tr>
</tbody>
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Single-Layer overcast water cloud: Case 3 (UKMO)

- Located over Southern Ocean (41.25 S, 120 E)
- $r_e$ from model output: 17.1 $\mu$m
- $\tau$ from model output: 4.5
- $p_{\text{base}} = 958$ hPa, $p_{\text{top}} = 935$ hPa
- SW albedo derived from surface ($SW_{\text{up}}/Sw_{\text{down}}$): 0.049
- Surface emissivity from ($LW_{\text{up}}/\sigma_{sb} T^4$): 0.9999
- Cosine of SZA: 0.928
# Single-Layer overcast water cloud: Case 3 (UKMO)

<table>
<thead>
<tr>
<th>Variable</th>
<th>UKMO output</th>
<th>Fu-Liou output</th>
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<tbody>
<tr>
<td>TOA SW down</td>
<td>1309.8 W m(^{-2})</td>
<td>1309.8 W m(^{-2})</td>
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<tr>
<td>TOA SW up</td>
<td>284.1 W m(^{-2})</td>
<td>297.2 W m(^{-2})</td>
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<tr>
<td>TOA SW albedo</td>
<td>0.217</td>
<td>0.227</td>
</tr>
<tr>
<td>TOA OLR</td>
<td>256.9 W m(^{-2})</td>
<td>249.0 W m(^{-2})</td>
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<td>SFC SW down</td>
<td>823.3 W m(^{-2})</td>
<td>793.8 W m(^{-2})</td>
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<td>SFC SW up</td>
<td>40.3 W m(^{-2})</td>
<td>38.9 W m(^{-2})</td>
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<tr>
<td>SFC LW up</td>
<td>381.0 W m(^{-2})</td>
<td>380.9 W m(^{-2})</td>
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