The surface radiation budget as observed and simulated in CMIP5 models

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Part 1: Surface radiation budget mean state

- How well can we quantify its components?
- How is it reproduced in climate models?
- What observational constraints are available?
- How consistent are global energy and water cycles?

Part 2: Surface radiation budget temporal changes

- How do the surface radiative components change over time?
- How consistent are surface and satellite-derived changes?
Satellite missions
CERES
SORCE

Units Wm$^{-2}$

Incoming solar TOA

Solar absorbed atmosphere

Solar down surface

Imbalance

Solar absorbed surface

Evaporation

Sensible heat

Latent heat

Solar reflected surface

TOA

Solar reflected TOA

Thermal outgoing TOA

239 (236, 242) ±3

Surface radiation budget traditionally larger uncertainties than TOA budget

Global Mean Earth Radiation Budget

Uncertainties

Units Wm$^{-2}$

340 (340, 341) ±0.5

100 (96, 100) ±2

239 (236, 242) ±3

Surface radiation budget traditionally larger uncertainties than TOA budget
Estimates of global mean radiation budgets

Large differences in surface and atmospheric radiation budget estimates

Global Energy Balance estimates in the 1990s:
ERBE constrains TOA fluxes

Kiehl and Trenberth (1997) BAMS

Wild et al. 1998 Clim Dyn
TOA Fluxes constrained by CERES / SORCE

Recent Earth Radiation Budget estimates

Discrepancies in surface energy fluxes remain
Shortwave radiation budgets in CMIP5 GCMs

**Absorbed shortwave radiation top of atmosphere**

- Model mean: 239 Wm\(^{-2}\)
- Model range: 11 Wm\(^{-2}\) (4.5%)
- Standard dev.: 3.0 Wm\(^{-2}\)
- Reference Satellite Value (CERES EBAF): 240 Wm\(^{-2}\)

**Absorbed shortwave radiation surface**

- Model mean: 164 Wm\(^{-2}\)
- Model range: 17 Wm\(^{-2}\) (10%)
- Standard dev.: 4.1 Wm\(^{-2}\)

Wild et al. 2013, Climate Dynamics
Longwave radiation budgets in CMIP5 GCMs

Outgoing longwave radiation
top of atmosphere

Multimodel mean: 238 Wm\(^{-2}\)
Model range: 12 Wm\(^{-2}\)
Standard dev.: 2.9 Wm\(^{-2}\)

Reference Satellite Value (CERES EBAF): 239.8 Wm\(^{-2}\)

Downward longwave radiation
surface

Multimodel mean: 339 Wm\(^{-2}\)
All sky model range: 20 Wm\(^{-2}\)
Standard dev.: 4.4 Wm\(^{-2}\)

Wild et al. 2013, Climate Dynamics
Longwave radiation budgets in CMIP5 GCMs

**Outgoing longwave radiation top of atmosphere**

Multimodel mean: 238 Wm$^{-2}$
Model range: 12 Wm$^{-2}$
Standard dev.: 2.9 Wm$^{-2}$

Reference Satellite Value (CERES EBAF): 239.8 Wm$^{-2}$

**Downward longwave radiation surface cloud free**

Multimodel mean: 313 Wm$^{-2}$
All sky model range: 27 Wm$^{-2}$
Standard dev.: 5.6 Wm$^{-2}$

Wild et al. 2013, Climate Dynamics
Land mean surface energy balance in CMIP5 GCMs

Model mean: 302 Wm\(^{-2}\)
Model range: 33 Wm\(^{-2}\)
Standard dev.: 7.2 Wm\(^{-2}\)

Downward longwave radiation surface

Land means of 43 models

Model mean: 192 Wm\(^{-2}\)
Model range: 42 Wm\(^{-2}\) (22%)
Standard dev.: 10 Wm\(^{-2}\)

Downward shortwave radiation surface

Land means of 43 models

=> Large discrepancies in surface radiative fluxes in CMIP5 models

Wild et al. 2015, Clim. Dyn.
Land mean surface energy balance in CMIP5 GCMs

Land mean surface net radiation
- Model mean 73 Wm$^{-2}$
- Model range 29 Wm$^{-2}$ (40%)

Land mean latent heat flux
- Model mean 40 Wm$^{-2}$
- Model range 14 Wm$^{-2}$ (36%)

Land mean sensible heat flux
- Model mean 31 Wm$^{-2}$
- Model range 27 Wm$^{-2}$ (86%)

=> Uncertainties in radiative fluxes in CMIP5 models affects energy available for sensible and latent heat fluxes

Wild et al. 2015, Clim.Dyn.
Implications

Discrepancies in surface energy budget components in different estimates and climate models still (too) large
e.g. land mean downward solar radiation differs by more than 40 Wm$^{-2}$

=> hampers realistic simulation of surface climates and adequate energy exchanges with other climate system components (e.g., oceans, biosphere, cryosphere)

=> Observational references required to better constrain these fluxes:
  • satellite-derived products
  • direct surface observations
Outcome from GEWEX Radiative Flux Assessment (RFA, P. Stackhouse, E. Raschke et al.):

- **Satellite-derived surface downward radiation products** of SRB, CERES, ISCCP (not latest versions!) **differ considerably** (> 10% at many locations)
- Necessity for direct surface observations as anchor sites
Constraints from surface observations

**Baseline Surface Radiation Network (BSRN)**
- WCRP initiative, starting in 1992
- Highest measurement quality at selected sites worldwide (currently 51 anchor sites)
- Minute values
- Ancillary data for radiation interpretation

**Global Energy Balance Archive (GEBA)**
- Worldwide measurements of historic energy fluxes at the surface (2500 sites)
- Solar radiation data at many sites since 1950s, some back to 1930s
- Monthly mean values

Ohmura, Gilgen, Wild 1989

Ohmura et al. 1998

BSRN site Payerne
Constraints from surface observations

Assessment of gridded surface solar radiation products with surface observations
Comparing point observations with gridded data

Challenge: What is the error when comparing point observations and gridded datasets of surface solar radiation?

=> requires knowledge on spatial subgrid variability within gridbox

How representative is a point observation for an entire gridbox?

Use of high resolution (0.03°) CMSAF surface solar radiation product to estimate spatial subgrid variability in coarser grids (e.g. CERES 1° grid)

=> Estimated climatological mean absolute bias (deviation of local point observation from 1° grid mean) is ~3 Wm⁻² (Hakuba et al. 2013, 2014)

Hakuba, Folini, Sanchez-Lorenzo, Wild, 2013: Spatial representativeness of ground-based solar radiation measurements, JGR 118
Hakuba, Folini, Sanchez-Lorenzo, Wild, 2014: Spatial representativeness - Extension to the full Meteosat disk. JGR 119
Validation of satellite-derived SSR products

**CERES-EBAF**

![Map of CERES-EBAF biases](image)

**GEWEX SRB**

![Map of GEWEX SRB biases](image)

**UMD-SRB**

![Map of UMD-SRB biases](image)

**ISCCP-FD**

![Map of ISCCP-FD biases](image)

**Biases of surface solar radiation against surface obs. from GEBA**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Bias (Wm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERES-EBAF</td>
<td>5.0</td>
</tr>
<tr>
<td>GEWEX-SRB V3.0</td>
<td>8.1</td>
</tr>
<tr>
<td>UMD-SRB V3.3.3</td>
<td>10.9</td>
</tr>
<tr>
<td>ISCCP-FD</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Validation of CERES-EBAF Surface

CERES surface solar radiation against different surface networks

<table>
<thead>
<tr>
<th>Observational Network (Number)</th>
<th>Bias (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSRN (34)</td>
<td>2.73(15.47)</td>
</tr>
<tr>
<td>CEOP (40)</td>
<td>-1.10(7.55)</td>
</tr>
<tr>
<td>GEBA(_b) (237)</td>
<td>0.63(11.33)</td>
</tr>
<tr>
<td>GEBA (335)</td>
<td>3.33(14.23)</td>
</tr>
<tr>
<td>BUOY (37)</td>
<td>5.00(5.53)</td>
</tr>
<tr>
<td>ALL(_c) noChina(_b) (348)</td>
<td>1.28(14.62)</td>
</tr>
<tr>
<td>ALL(_d) (446)</td>
<td>2.57(13.93)</td>
</tr>
</tbody>
</table>

Evaluation of CMIP5 surface solar radiation

Constraining surface fluxes with BSRN obs:
Most models overestimate surface SW down

Wild et al. 2013, Climate Dynamics
Constraining surface fluxes with GEBA obs: Most models overestimate surface SW down

Wild et al. 2013, Climate Dynamics
Evaluation of CMIP5 surface solar radiation

CMIP5: SURFACE SOLAR DOWN BIASES

Model bias at 760 GEBA sites
Model bias at 42 BSRN sites

Different CMIP5 models

Wild et al. 2013, Climate Dynamics
Best estimates for land mean surface fluxes

Surface SW down over land
GCM global land means versus their biases averaged over land based GEBA sites

Best estimate surface SW down over land:
184 Wm\(^{-2}\)

Wild et al. 2015, Climate Dynamics
**Best estimates for ocean mean surface fluxes**

**Surface SW down over ocean**

*GCM global ocean means versus their biases averaged over maritime observation sites*

**Best estimate**

*Surface SW down over oceans:*

185 Wm$^{-2}$
### Global mean downward surface solar radiation

#### Best estimates for global mean downward surface solar radiation

<table>
<thead>
<tr>
<th>Source</th>
<th>Method</th>
<th>SW down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild et al. (2013, 2015)</td>
<td>Surface obs + CMIP5 models</td>
<td>185 Wm$^{-2}$</td>
</tr>
<tr>
<td>Ma et al. (2015)</td>
<td>Bias corrected CERES EBAF</td>
<td>185 Wm$^{-2}$</td>
</tr>
<tr>
<td>L’Ecuyer et al. (2015)</td>
<td>Adjusted ISCCP-FD/SRB to close surface energy budget</td>
<td>186 Wm$^{-2}$</td>
</tr>
<tr>
<td>Trenberth et al. (2009, 2012)</td>
<td>ISSCP-FD + correction for water vapor absorption</td>
<td>184 Wm$^{-2}$</td>
</tr>
<tr>
<td>Cox et al. (2016)</td>
<td>SRB release 4.0, near zero overall bias against surface obs.</td>
<td>185 Wm$^{-2}$</td>
</tr>
</tbody>
</table>

**Multiple lines of evidence for a global mean surface downward shortwave radiation near 185 Wm$^{-2}$**
Downward SW of 185 Wm$^{-2}$ in line with observational constraints

Surface flux estimates consistent with direct observations

Surface SW Absorbed: 160 Wm$^{-2}$

Additional albedo estimate (0.13) to derive absorbed SW of ~160 Wm$^{-2}$

Global Mean Earth Radiation Budget

TOA fluxes from CERES EBAF/SORCE

TOA SW Absorbed: 240 Wm$^{-2}$

Surface SW Absorbed: 160 Wm$^{-2}$

Additional albedo estimate (0.13) to derive absorbed SW of ~160 Wm$^{-2}$

Global Mean Earth Radiation Budget

TOA fluxes from CERES EBAF/ SORCE

TOA SW Absorbed: 240 Wm\(^{-2}\)

Surface SW Absorbed: 160 Wm\(^{-2}\)

=> Leaves ~ 80 Wm\(^{-2}\) SW atmospheric absorption

Global Mean Earth Radiation Budget

Assessment of longwave radiation

Surface downward longwave radiation

Evaluation of CMIP5 downward longwave

LW down
41 BSRN sites

Constraining surface fluxes with BSRN observations: CMIP5 models typically underestimate LW down

Wild et al. 2013, Climate Dynamics
Model bias at 41 BSRN sites

Model bias at 45 GEBA/BSRN sites

CMIP5: SURFACE THERMAL DOWN BIASES

Different CMIP5 models

Wild et al. 2013, Climate Dynamics
Best estimates for global mean LW down

Surface LW down global mean
GCM global means versus their biases averaged over 41 BSRN sites

Global means in CMIP5 climate models (Wm\(^{-2}\))

Model biases against surface obs. (Wm\(^{-2}\))

Best estimate surface LW down: 342 Wm\(^{-2}\)

Wild et al. 2013, Climate Dynamics
## Global mean downward longwave radiation

### Best estimates $LW_{\text{down}}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Method</th>
<th>SW down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild et al. (2013, 2015)</td>
<td>Surface obs + CMIP5 models</td>
<td>342 Wm$^{-2}$</td>
</tr>
<tr>
<td>Kato et al. (2013)</td>
<td>CERES EBAF</td>
<td>344 Wm$^{-2}$</td>
</tr>
<tr>
<td>ERA40</td>
<td>Reanalyses</td>
<td>344 Wm$^{-2}$</td>
</tr>
<tr>
<td>ERA Interim</td>
<td></td>
<td>342 Wm$^{-2}$</td>
</tr>
<tr>
<td>Wang and Dickinson (2013)</td>
<td>Surface obs + ERA-I, CERES-SYN, SRB, MERRA</td>
<td>342 Wm$^{-2}$</td>
</tr>
<tr>
<td>L’Ecuyer et al (2015)</td>
<td>Adjusted ISCCP-FD/SRB to close surface energy budget</td>
<td>341 Wm$^{-2}$</td>
</tr>
<tr>
<td>Wild et al. (1998, 2001)</td>
<td>Surface obs + AMIP models</td>
<td>344 Wm$^{-2}$</td>
</tr>
</tbody>
</table>

Cf. IPCC AR3/AR4

Residual of surface energy balance 324 Wm$^{-2}$

Multiple lines of evidence for a global mean surface downward longwave radiation slightly above 340 Wm$^{-2}$
Surface flux estimates consistent with direct observations

Units Wm$^{-2}$

Surface net radiation: 104 Wm$^{-2}$

c.f. Trenberth et al. 98 Wm$^{-2}$  Stephens et al. 113 Wm$^{-2}$

Global mean latent heat flux constrained to about 79-85 Wm^{-2} (82-88 mm/month global mean precipitation equivalent)

=> Consistent representation of global energy and water cycles
Global energy balance without clouds

Wild, Hakuba, Folini, Long 2016 AIP proceedings
Global Mean Energy Balance

Clear sky TOA fluxes from CERES EBAF

Clear sky

CMIP5 clear sky surface fluxes constrained by BSRN obs

Wild, Hakuba, Folini, Long 2016 AIP proceedings
### Global mean Cloud Radiative Effect (CRE)

#### All sky

<table>
<thead>
<tr>
<th>Units Wm(^{-2})</th>
<th>SW CRE</th>
<th>LW CRE</th>
<th>Net CRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOA</td>
<td>-47</td>
<td>27</td>
<td>-20</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>9</td>
<td>-1</td>
<td>8</td>
</tr>
<tr>
<td>Surface</td>
<td>-56</td>
<td>28</td>
<td>-28</td>
</tr>
</tbody>
</table>


Present study

Wild, Hakuba, Folini, Long 2016 AIP proceedings
Part 2: Temporal changes in surface radiative fluxes
Global Energy Balance: temporal changes

Decadal changes at the Earth’s surface

- **Aerosols**
  - Decrease
  - Clouds
  - Increase

- **Greenhouse gases**
  - Decrease
  - Clouds
  - Increase
Decadal changes in surface solar radiation

Potsdam, Germany 1937 – 2014

Surface solar radiation (Wm$^{-2}$)

1940  1960  1980  2000

“dimming”  “brightening”

CM-SAF  SRB  ISCCP  CERES

Wild et al. 2005, Science
Wild 2016, WIREs Clim Change
Trends in CM SAF and GEBA: 1994-2005

CMSAF record is homogeneous after 1993

Trends (1994-2005):  
Composite of 56 sites  
CMSAF $+4.54 \text{ Wm}^{-2}/\text{dec}$  
GEBA $+4.62 \text{ Wm}^{-2}/\text{dec}$

Difference time series stable

Sanchez-Lorenzo, Wild, Trentmann 2013, Remote Sensing of Environment
Figure 15. Linear trends of the mean monthly series obtained using the 47 CM SAF and GEBA series over Europe during the period 1994-2005. The values are expressed as Wm\(^{-2}\) per decade.

Courtesy Arturo Sanchez-Lorenzo
Comparing point observations with gridded data

**Challenge:** How representative is the temporal SSR variability measured at a station for its larger scale surrounding?

=> requires knowledge on spatial coherence of temporal variability

Use of high resolution (0.05°) CMSAF surface solar radiation dataset to estimate correlation between observed station timeseries and CMSAF single pixels

**PhD Matthias Schwarz**

Median correlation map of 140 SSR stations (center point of map) and single 0.05° pixels from CM-SAF
Strong brightening in Spain, after 2000 dominated by decrease of clouds (75%) and decrease of aerosol (25%)
Sanchez Lorenzo et al. 2012

Mateos et al. 2014 JGR

Mateos, Sanchez-Lorenzo, Antón, Cachorro, Calbó, Costa, Torres, Wild (2014), Quantifying the respective roles of aerosols and clouds in the strong brightening since the early 2000s over the Iberian Peninsula, JGR 119, 10,382–10,393
Surface cloud radiative effect in Spain

Comparison CRE CERES EBAF <> obs at 3 sites in Spain

Surface CRE well captured in CERES-EBAF

Mateos et al. 2014 JGR

Mateos, Sanchez-Lorenzo, Antón, Cachorro, Calbó, Costa, Torres, Wild (2014), Quantifying the respective roles of aerosols and clouds in the strong brightening since the early 2000s over the Iberian Peninsula, JGR 119, 10,382–10,393
Surface solar radiation trends in CERES

Period 2003-2012 Units Wm\(^{-2}\)/decade

Data from CERES EBAF-surface (Kato et al. 2013)
Aerosol induced multidecadal changes

Clear/ all sky solar radiation in Italy

- **North Year**
- **All-sky**
- **Clear-sky**

**Global Anthropogenic Sulfur Emissions**

Data source: Stern, 2005

Wild et al, 2005, *Science*

**Manara et al. 2016, ACP**

*Decadal changes in clear sky solar radiation in line with changes in anthropogenic emissions*
Aerosol induced multidecadal changes

Can aerosol explain these radiative changes?

=> sensitivity studies with global climate model ECHAM-HAM with sophisticated treatment of aerosol and cloud microphysics (Stier et al. 2005, Lohmann et al. 2007)

surface solar radiation clear sky in ECHAM-HAM

Transient simulations with constant and historic (variable) aerosol emissions

Folini and Wild 2011, 2015 JGR
Unforced decadal SSR variability

Surface solar radiation variability in unforced control simulations in coupled Earth System model MPI ESM

Annual mean all sky SSR time series for Stockholm (nearest land grid box) from MPI-ESM-LR (left, annual mean data in black, five year running mean in blue) and corresponding histogram (40 bins) of 10 year trends of this time series (right), with 25th and 75th percentile indicated in red.

Substantial decadal variation in unforced model simulations

Folini et al. (submitted)

Conclusions (I): surface radiation budget mean state

- **Accurate knowledge of TOA radiation components, but large discrepancies in various estimates of the surface energy balance components and their representation in climate models**
  - Surface radiation observations and well evaluated satellite-derived products can provide some constraints

- **CMIP5 models tend to overestimate downward SW and underestimate downward LW radiation**
  - Long standing issue in climate models (AMIP-I, II, CMIP3), biases generally reduced compared to earlier model generations, but not completely removed.

- **Increased confidence in recent estimates of global surface radiation budget, as independent surface and satellite based approaches converge to within a few Wm^{-2}**
  - Enable a consistent representation of global energy and water cycles
  - Uncertainties remain in surface albedo and partitioning of sensible and latent heat fluxes
Conclusions (II): surface radiation budget changes

- **Significant decadal changes in both surface downward LW and SW observational records**
  - Observations indicate increase of downward LW of ~ 2 Wm\(^{-2}\) per decade, in line with CMIP5 simulations and expectations from an increasing greenhouse effect
  - Surface shortwave radiation also undergoes strong decadal changes (“dimming/brightening“) > not adequately represented in CMIP5 climate models
  - Forced versus unforced variability in surface shortwave radiation still debated
  - Satellite-derived products of surface shortwave radiation may capture cloud-induced surface solar radiation trends and surfac cloud radiative effects well. Longer term aerosol dominated trends might be more challenging

- **Implications for climate change**
  - Dimming/brightening may induce modulations of global warming, asymmetric hemispheric warming rates, and affects DTR, hydrological cycle, cryosphere, terrestrial carbon uptake/plant growth, solar power production