The Earth radiation budget from a surface perspective

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Content

Part 1: Earth radiation budget mean state
- What is the significance of global energy balance?
- How well can we quantify its components?
- How is it reproduced in climate models?

Part 2: Earth radiation budget temporal changes
- How do the radiative components change over time?
- What are the implications for climate change?
Earth radiation budget

Units: Wm⁻²

Incoming solar TOA: 340 (340, 341)
Solar absorbed atmosphere: 79 (74, 91)
Solar absorbed surface: 185 (179, 189)
Solar reflected TOA: 100 (96, 100)
Solar reflected surface: 24 (22, 26)
Latent heat: 161 (154, 166)
Evaporation: 84 (70, 85)
Sensible heat: 20 (15, 25)
Thermal up surface: 398 (394, 400)
Thermal down surface: 342 (338, 348)

Earth radiation budget

Units: Wm$^{-2}$

Sun: Ultimate energy source

- Solar absorbed atmosphere: 340 Wm$^{-2}$ (341, 340)
- Solar absorbed surface: 185 Wm$^{-2}$ (189, 187)
- Solar reflected TOA: 100 Wm$^{-2}$ (100, 100)
- Solar reflected surface: 24 Wm$^{-2}$ (22, 26)
- Evaporation: 84 Wm$^{-2}$ (85, 85)
- Sensible heat: 20 Wm$^{-2}$ (20, 20)
- Latent heat: 0 Wm$^{-2}$
- Thermal up surface: 398 Wm$^{-2}$ (394, 400)
- Thermal down surface: 342 Wm$^{-2}$ (338, 348)
- Atmospheric window: 239 Wm$^{-2}$ (236, 242)
- Greenhouse gases: 239 Wm$^{-2}$ (236, 242)
- Solar down surface: 161 Wm$^{-2}$ (166, 166)
- Unbalance: 0.6 Wm$^{-2}$ (0.2, 1.0)

Earth radiation budget

Radiation balance at the Top of Atmosphere

Absorbed SW

- Solar absorbed atmosphere: 340 (340, 341)
- Solar down surface: 79 (74, 91)
- Solar absorbed surface: 185 (179, 189)
- Solar reflected surface: 24 (22, 26)
- Latent heat: 84 (70, 85)
- Sensible heat: 20 (15, 25)

Emitted LW

- Thermal up surface: 398 (394, 400)
- Atmospheric window: 239 (236, 242)
- Thermal down surface: 342 (338, 348)

Units: Wm$^{-2}$

Earth radiation budget

Radiation balance at the Top of Atmosphere regulates energy content of the climate system

Absorbed SW

340 (340, 341)

Units: Wm$^{-2}$

79 (74, 91)
solar absorbed atmosphere

185 (179, 189)
solar down surface

161 (154, 166)
solar absorbed surface

24 (22, 26)
solar reflected surface

20 (15, 25)
sensible heat

84 (70, 85)
evaporation

thermal up surface

398 (394, 400)

342 (338, 348)
thermal down surface

Emitting LW

239 (236, 242)

atmospheric window

greenhouse gases

Earth radiation budget

Radiation balance at the surface

Units: Wm$^{-2}$

340 (340, 341)

79 (74, 91)

185 (179, 189)

161 (154, 166)

24 (22, 26)

100 (96, 100)

84 (70, 85)

20 (15, 25)

239 (236, 242)

398 (394, 400)

342 (338, 348)

Radiation balance at the surface determines surface climate and drives the global water cycle.

 Units: Wm$^{-2}$

Estimates of global mean radiation budgets

**Historic estimates:**

**Pre-satellite period**

<table>
<thead>
<tr>
<th>TSI (Wm$^{-2}$)</th>
<th>Planetary Albedo</th>
<th>Absorption by earth/atmosphere in the atmosphere</th>
<th>Absorption in the atmosphere</th>
<th>Emission at TOA (Wm$^{-2}$)</th>
<th>Global radiation (Wm$^{-2}$)</th>
<th>Absorbed global radiation (Wm$^{-2}$)</th>
<th>Surface long-wave in-radiation (Wm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1326</td>
<td>0.33</td>
<td>223 (66)</td>
<td>66 (19)</td>
<td>193</td>
<td>162 (48)</td>
<td>0.10</td>
<td>325</td>
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<tr>
<td>1326</td>
<td>0.37</td>
<td>228 (65)</td>
<td>63 (18)</td>
<td>199</td>
<td>167 (50)</td>
<td>0.14</td>
<td>328</td>
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<tr>
<td>1395</td>
<td>0.38</td>
<td>222 (65)</td>
<td>78 (24)</td>
<td>222</td>
<td>165 (47)</td>
<td>0.12</td>
<td>337</td>
</tr>
</tbody>
</table>

Fig. 2. Heat balance of the atmosphere: (A) radiant energy reaching the atmosphere, part of which is (B) absorbed by the earth, (C) absorbed by the air, and (D) reflected by the earth or air; (E) radiation of the earth, part of which is (M) reflected back, (H) absorbed, and (K) transmitted; (E and F) downward and upward radiation of the air, respectively; and (L) heat passing from the earth to the air other than by radiation [after Dines, 1917].


**TSI:** 1326-1963 Wm$^{-2}$

**Planetary Albedo:** 0.33-0.5

**OLR:** 174-327 Wm$^{-2}$

**London 1957**

Ohmura 2015
Early Satellite Period: Earth Radiation Budget Experiment (ERBE) 1985-1989

Planetary albedo: 0.30
Total SW absorption/ LW emission: 235 Wm$^{-2}$
Estimates of global radiation budgets

“Golden era” of satellite observations: CERES satellite observations in the 2000s

NASA Releases Terra’s First Global 1-Month Composite Images

Loeb et al. 2018
Estimates of global radiation budgets

Units Wm\(^{-2}\)

- incoming solar TOA: 340 (340, 341)
- solar absorbed atmosphere: 79 (74, 91)
- solar down surface: 185 (179, 189)
- solar reflected TOA: 100 (96, 100)
- solar reflected surface: 24 (22, 26)
- latent heat: 84 (70, 85)
- sensible heat: 20 (15, 25)
- thermal up surface: 398 (394, 400)
- thermal outgoing TOA: 239 (236, 242)
- atmospheric window
- greenhouse gases
- thermal down surface: 342 (338, 348)

Wild et al. 2013, Climate Dynamics
Estimates of global radiation budgets

Uncertainties

Units Wm$^{-2}$

Satellite missions
CERES
SORCE

- Solar absorbed atmosphere: 79 (74, 91)
- Solar down surface: 185 (179, 189)
- Solar reflected TOA: 100 (96, 100)
- Solar reflected surface: 24 (22, 26)
- Sensible heat: 20 (15, 25)
- Evaporation: 84 (70, 85)
- Latent heat: 20
- Imbalance: 0.6 (0.2, 1.0)
- Thermal up surface: 398 (394, 400)
- Thermal down surface: 342 (338, 348)
- Atmospheric window: 239 (236, 242)
- Greenhouse gases: 2 (1, 3)

Wild et al. 2013, Climate Dynamics
Estimates of global radiation budgets

Uncertainties remain in the estimation of the energy balance components

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 Wm\(^{-2}\)

Wild et al. 2013, 2018 Climate Dynamics
Longwave radiation budgets in CMIP5 GCMs

Outgoing longwave radiation

top of atmosphere cloud free

Reference Satellite Value (CERES EBAF): 267 Wm$^{-2}$
Multimodel mean: 263 Wm$^{-2}$
Model range: 13 Wm$^{-2}$
Standard dev.: 3.3 Wm$^{-2}$

Global means of 38 models

Wild et al. 2013, 2018 Climate Dynamics
Longwave radiation budgets in CMIP5 GCMs

Outgoing longwave radiation

top of atmosphere cloud free

Reference Satellite Value (CERES EBAF): 267 Wm$^{-2}$

Multimodel mean 263 Wm$^{-2}$
Model range: 13 Wm$^{-2}$
Standard dev.: 3.3 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, 2018 Climate Dynamics
Longwave radiation budgets in CMIP5 GCMs

Outgoing longwave radiation

top of atmosphere cloud free

Multimodel mean: \(263 \text{ Wm}^{-2}\)
Model range: \(13 \text{ Wm}^{-2}\)
Standard dev.: \(3.3 \text{ Wm}^{-2}\)

Reference Satellite Value (CERES EBAF): \(267 \text{ Wm}^{-2}\)

Downward longwave radiation

surface cloud free

Multimodel mean: \(313 \text{ Wm}^{-2}\)
All sky model range: \(27 \text{ Wm}^{-2}\)
Standard dev.: \(5.6 \text{ Wm}^{-2}\)

Wild et al. 2013, 2018 Climate Dynamics
Constraints from surface observations

Baseline Surface Radiation Network
- 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
- 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
Constraints from surface and space

Surface radiation stations with multiyear records

Combing surface and satellite obs to estimate surface, atmosphere and TOA radiation budgets
Large changes in surface and atmospheric energy budgets from IPCC AR4 to AR5

Global Energy Balance in IPCC AR4 and AR5

Wild et al. 2013

IPCC AR3 / AR4

Kiehl & Trenberth (1997)
Global Energy Balance in IPCC AR4 and AR5

Large changes in surface and atmospheric energy budgets from IPCC AR4 to AR5

Wild et al. 2013

IPCC AR3 / AR4
Kiehl & Trenberth (1997)
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IPCC AR4 / AR5

Kiehl & Trenberth (1997)

Large changes in surface and atmospheric energy budgets from IPCC AR4 to AR5

Wild et al. 2013

IPCC AR3 / AR4

Kiehl & Trenberth (1997)
Earth Radiation Budget without clouds

TOA fluxes from CERES satellite obs

Surface clear-sky fluxes from BSRN obs

Wild et al. 2018, Climate Dynamics
Cloud radiative effects (CRE)

All sky


<table>
<thead>
<tr>
<th>Units Wm$^{-2}$</th>
<th>SW CRE</th>
<th>LW CRE</th>
<th>Net CRE</th>
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</thead>
<tbody>
<tr>
<td>TOA</td>
<td>-47</td>
<td>28</td>
<td>-19</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>-54</td>
<td>28</td>
<td>-26</td>
</tr>
<tr>
<td>TOA CMIP5</td>
<td>-49</td>
<td>25</td>
<td>-24</td>
</tr>
</tbody>
</table>

Clear sky


Part 2:
Temporal changes in Energy Balance components
Earth Energy Balance: temporal changes

Units Wm$^{-2}$

- incoming solar TOA: 340 (340, 341)
- solar absorbed atmosphere: 79 (74, 91)
- solar down surface: 185 (179, 189)
- solar absorbed surface: 161 (154, 168)
- solar reflected TOA: 100 (96, 100)
- solar reflected surface: 24 (22, 26)
- atmospheric window: 84 (70, 85)
- thermal up surface: 398 (394, 400)
- thermal down surface: 342 (338, 348)

Anthropogenic Perturbations

- Greenhouse gases

- latent heat: 20 (15, 25)
- sensible heat: 0.6 (0.2, 1.0)

Earth Energy Balance:
- temporal changes
Earth Energy Balance: temporal changes

Units Wm$^{-2}$

Aerosols

- Incoming solar TOA: 340 (340, 341)
- Solar absorbed atmosphere: 185 (179, 189)
- Solar down surface: 161 (154, 168)
- Latent heat: 84 (70, 85)
- Sensible heat: 20 (15, 25)
- Imbalance: 0.6 (0.2, 1.0)

Greenhouse gases

- Thermal up surface: 398 (394, 400)
- Thermal down surface: 342 (338, 348)
- Atmospheric window: 239 (236, 242)

Anthropogenic Perturbations

- Greenhouse gases

Energy flow diagram showing the balance between incoming solar radiation, solar absorbed, reflected, and latent heat, as well as sensible heat, with an imbalance of 0.6 Wm$^{-2}$. Aerosols and greenhouse gases are highlighted, with specific values for each component.
Earth Energy Balance: temporal changes

Anthropogenic Perturbations

Greenhouse gases

Aerosols
Earth Energy Balance: temporal changes

Changes in OLR with increasing CO$_2$

Instantaneous doubling of CO$_2$

Gradual increase of CO$_2$ (1%y$^{-1}$)

CMIP5 Ensemble mean response to 1%CO$_2$ increase

SW absorption

OLR

Conceptual view

CMIP5 model simulations

Donohoe et al. 2014 PNAS
Earth Energy Balance: temporal changes

Changes in TOA radiation with increasing CO2

Scenario A1B, 24 CMIP3 models

Trenberth and Fasullo 2009
Earth Energy Balance: temporal changes

Observed changes in OLR 1985-2016

Dewitte and Clerbaux 2018
Earth Energy Balance: temporal changes

Decadal changes at the Earth’s surface

Greenhouse gases

Aerosols

Increase

Decrease
Decadal changes at the Earth’s surface

Greenhouse gases increase at Earth’s surface.
Changes in downward longwave radiation

- expected to undergo largest change of all energy balance components in coming decades
- CMIP5 models suggest increase of 6 Wm\(^{-2}\) since 1870
- Only monitored since the initiation of BSRN early 1990s
Observed changes downward longwave radiation since 1994

Observed changes at BSRN sites since early 1990s:

25 longest BSRN records (totally 353 years): $+2.0 \text{ Wm}^{-2}\text{dec}^{-1}$

- Philipona et al. (2009): $+2.4-2.7 \text{ Wm}^{-2}\text{dec}^{-1}$ (Europe, 1981-2005)
- Wang and Liang (2009): $+2.2 \text{ Wm}^{-2}\text{dec}^{-1}$ (1973-2008)
- Wild et al. (2008): $+2.6 \text{ Wm}^{-2}\text{dec}^{-1}$ (BSRN sites 1990s)
- Prata (2008): $+1.7 \text{ Wm}^{-2}\text{dec}^{-1}$ (clear sky, 1964-1990)
Future changes in downward longwave radiation

CMIP5 projections 21\textsuperscript{th} century

10 CMIP5 Models

- bcc-csm1-1
- CanESM2
- CNRM-CM5
- HadGEM2-ES
- inmcm41-M
- NorESM1-M
- IPSL-CM5A-LR
- CCSM4-Mk3-6-0
- MRI-CGCM3.1 mean
- CSIRO-Mk3-6-0
- Multimodel mean

Future changes in downward longwave radiation

CMIP5 projections 21st century

2010-2030:
RCP8.5: +2.2 Wm$^{-2}$/dec
RCP4.5: +1.7 Wm$^{-2}$/dec

Observed: +2 Wm$^{-2}$/dec

10 CMIP5 Models

RCP 8.5

RCP 4.5

25 Wm$^{-2}$

10 Wm$^{-2}$

Decadal changes at the Earth’s surface

Earth Energy Balance: temporal changes

- Greenhouse gases: Increase
- Aerosols: Decrease

- Solar absorbed at TOA: 340 (340, 341)
- Solar reflected TOA: 100 (96, 100)
- Latent heat: 24 (22, 26)
- Evaporation: 185 (179, 189)
- Solar absorbed at surface: 161 (154, 168)
- Sensible heat: 84 (70, 85)
- Thermal up surface: 398 (394, 400)
- Thermal down surface: 342 (338, 348)

Units: Wm$^{-2}$
Earth Energy Balance: temporal changes

Decadal changes at the Earth’s surface

Solar radiation at Earth’s surface
Decadal changes in surface solar radiation

Potsdam 1937 - 2014

Wild 2016, WIREs Clim Change
Decadal changes in surface solar radiation

Wild 2016, WIREs Clim Change

“dimming”
Decadal changes in surface solar radiation

Wild 2016, WIREs Clim Change
## Decadal changes in surface solar radiation

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>USA</td>
<td>-6</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Europe</td>
<td>-3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>China/Mongolia</td>
<td>-7</td>
<td>4</td>
<td>-4</td>
</tr>
<tr>
<td>Japan</td>
<td>-5</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>India</td>
<td>-3</td>
<td>-8</td>
<td>-10</td>
</tr>
</tbody>
</table>

Numbers: literature values for changes in Wm⁻²/decade

“dimming” “brightening”

Impact on global warming

Observed temperature Northern Hemisphere

Data source: CRU

Modulations of global warming in line with dimming / brightening

Wild 2012, BAMS
Wild 2016, WIREs Clim Change
Conclusions

- Earth Energy Balance is fundamental to the climate system, and requires a precise quantification.

- Uncertainty of the Outgoing Longwave Radiation at TOA as measured by CERES due to calibration is $3.7 \text{ Wm}^{-2}$ (2-sigma). This may be improved with FORUM.

- Anthropogenic interferences perturb the Earth energy balance.

- Changes are measureable at the TOA, in the oceans and at Earth’s surface.

- Increase in greenhouse gases modulates the LW radiation: leads to an increase in surface downward LW of $2\text{ Wm}^{-2}$/decade, while sign of future change in OLR is less clear.