WCRP Open Science Conference, Denver, Oct. 26, 2011

Decadal changes in surface radiative fluxes – overview and update

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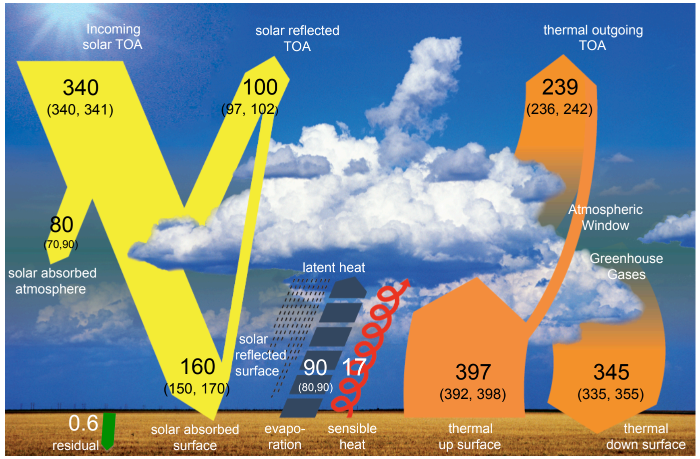
Global Mean Radiation Budget

Units Wm^{-2}



Global Mean Radiation Budget

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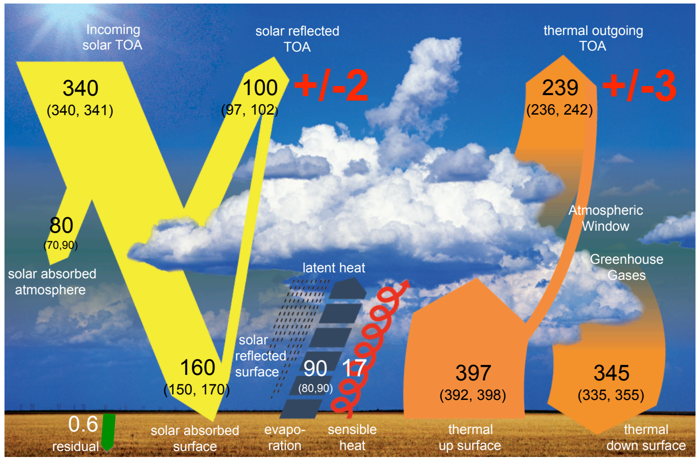

Global Mean Radiation Budget

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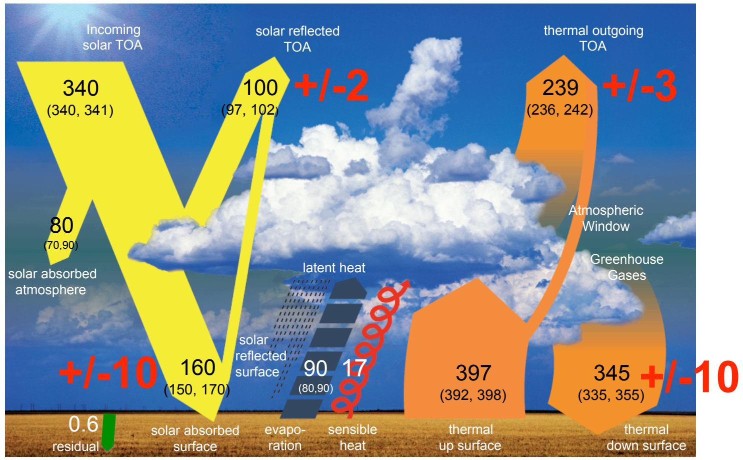

Surface radiation budget less well constrained than TOA budget

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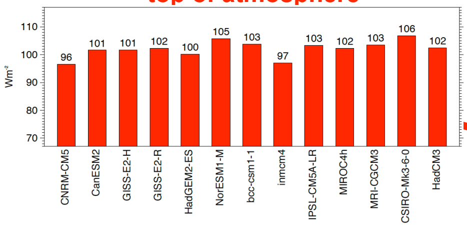
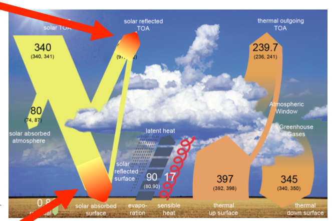
Shortwave radiation budgets in CMIP5 GCMs

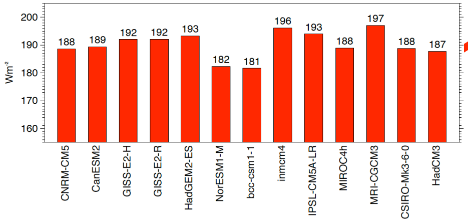
Reflected shortwave radiation
top of atmosphere



Model mean: 102 Wm^{-2}
Model range: 10 Wm^{-2}
Standard dev.: 3.0 Wm^{-2}
Reference Satellite Value
(CERES EBAF): 99.9 Wm^{-2}



Downward shortwave radiation
surface



Model mean: 189 Wm^{-2}
Model range: 16 Wm^{-2}
Standard dev.: 4.7 Wm^{-2}

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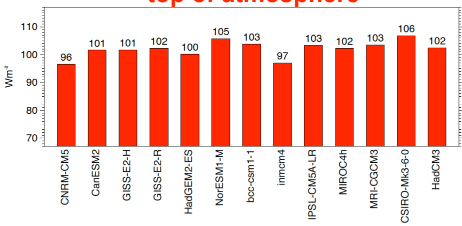
Shortwave radiation budgets in CMIP5 GCMs

Reflected shortwave radiation
top of atmosphere



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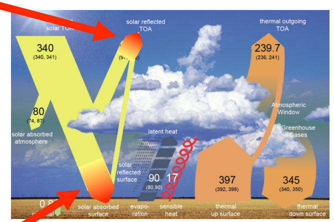
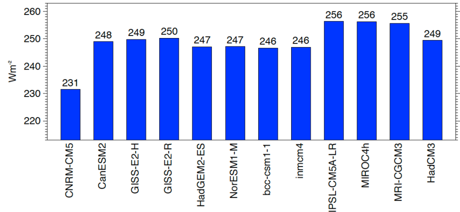


Downward shortwave radiation
surface cloud free



Model mean: 248 Wm^{-2}
Model range: 25 Wm^{-2}
Standard dev.: 6.5 Wm^{-2}

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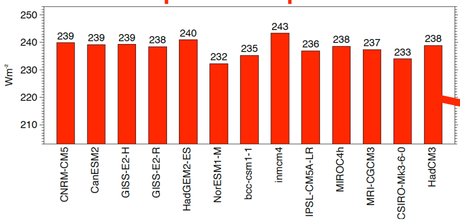
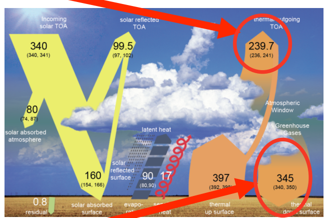
Longwave radiation budgets in CMIP5 GCMs

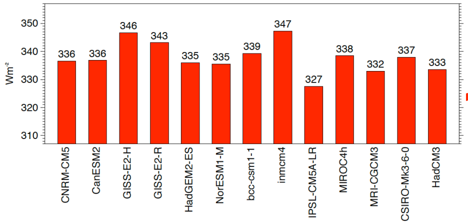
Outgoing longwave radiation
top of atmosphere



Multimodel mean 238.5 Wm^{-2}
Model range: 11 Wm^{-2}
Standard dev.: 2.9 Wm^{-2}
Reference Satellite Value
(CERES EBAF): 239.8 Wm^{-2}



Downward longwave radiation
surface



Multimodel mean 338 Wm^{-2}
All sky model range: 20 Wm^{-2}
Standard dev.: 5.4 Wm^{-2}

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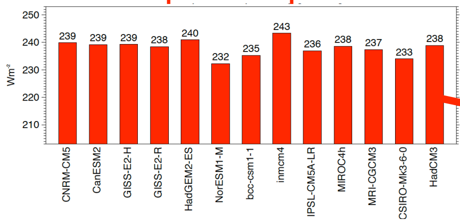
Longwave radiation budgets in CMIP5 GCMs

Outgoing longwave radiation
top of atmosphere



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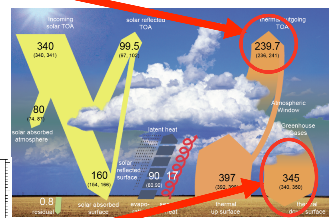
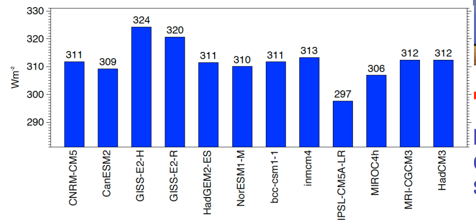


Downward longwave radiation
surface cloud free



Multimodel mean 312 Wm^{-2}
Clearsky model range:27 Wm^{-2}
Standard dev.: 6.5 Wm^{-2}

=>Large model uncertainties particularly at the Earth Surface

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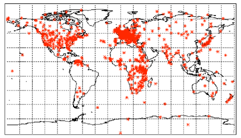
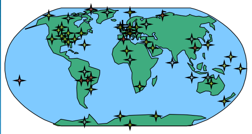
Constraints from surface observations



Ohmura, Gilgen, Wild 1989

GEBA Global Energy Balance Archive

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



Ohmura et al. 1998

BSRN 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

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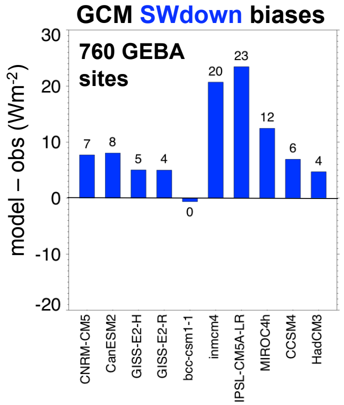
Evaluation of CMIP5 surface radiation balance



Mean model bias SWdown at 760 GEBA sites: +9.3 Wm^{-2}

Multimodel mean SWdown: 189 Wm^{-2}

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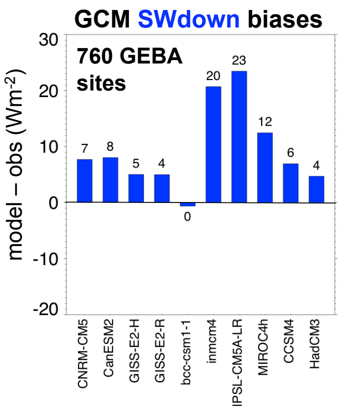
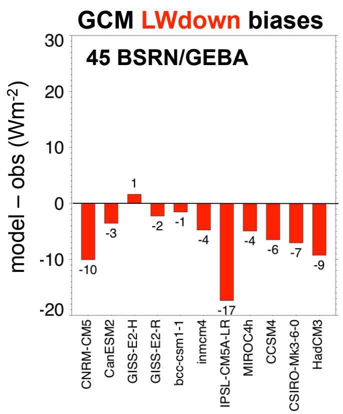
Evaluation of CMIP5 surface radiation balance





Mean model bias SWdown at 760 GEBA sites: +9.3 Wm^{-2}

Multimodel mean SWdown: 189 Wm^{-2}

Mean model bias LWdown at 45 BSRN/GEBA sites: -6 Wm^{-2}

Multimodel mean LWdown: 338 Wm^{-2}

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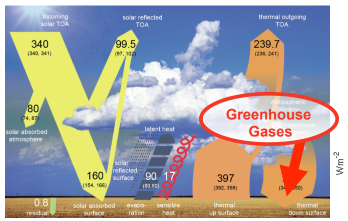
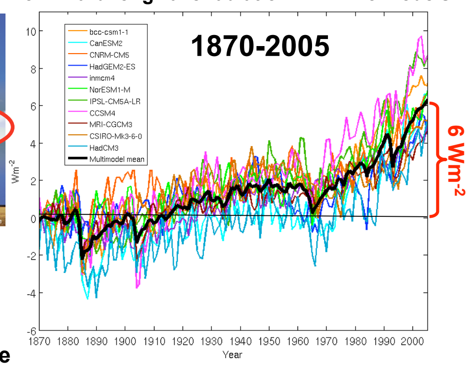
Changes in downward longwave radiation



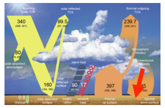
- **most directly affected by changes in atmospheric greenhouse gases**
- **GCMs suggest increase since 1870 of 6 Wm^{-2}**
- **expected to undergo largest change of all energy balance components in coming decades**

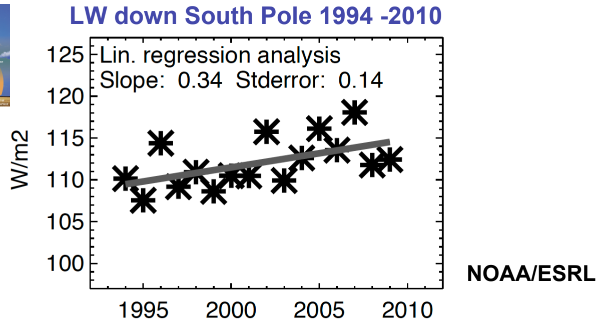
Downward longwave radiation in CMIP5 models



Wild et al. 1997 J. Climate
Wild et al. 2001 J. Climate
Wild et al. 2005 Gewex News

Observed changes downward longwave



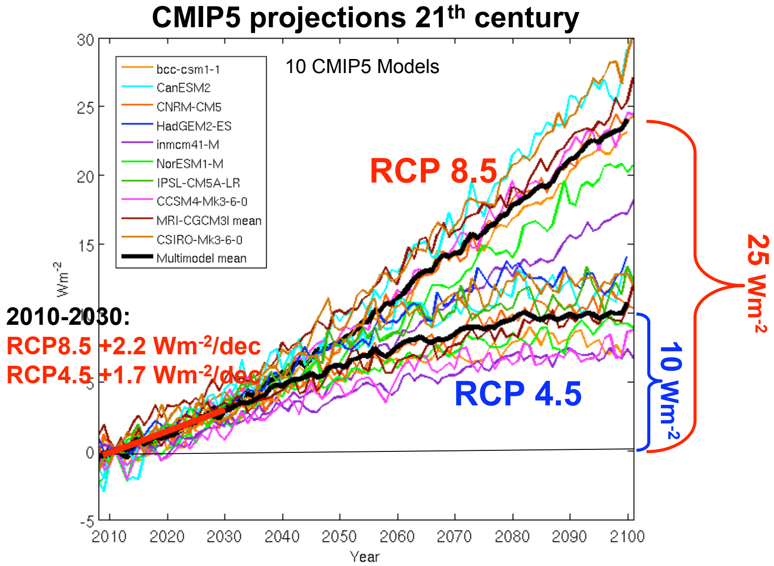


Observed changes at BSRN sites since early 1990s:

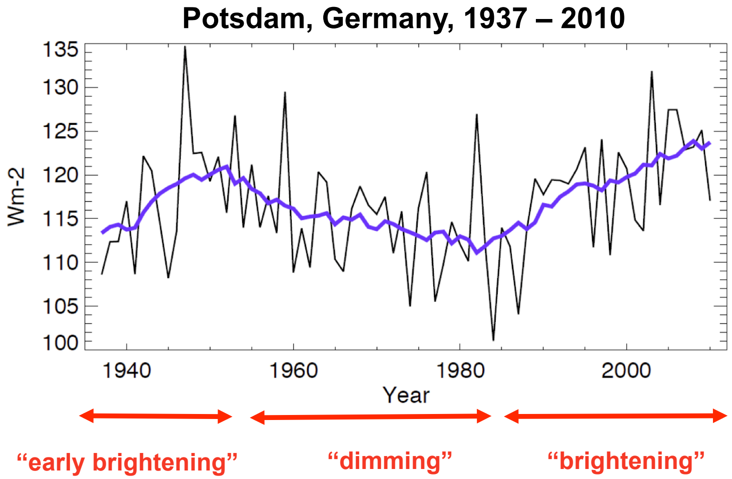
24 longest BSRN records (totally 324 years) covering period 1992-2010

- **18 stations (75%) with increase** in LW down (10 significant)
- **6 stations (25%) with decrease** in LW down (4 significant)
- **Average change all sites: +2.0 $Wm^{-2}dec^{-1}$**

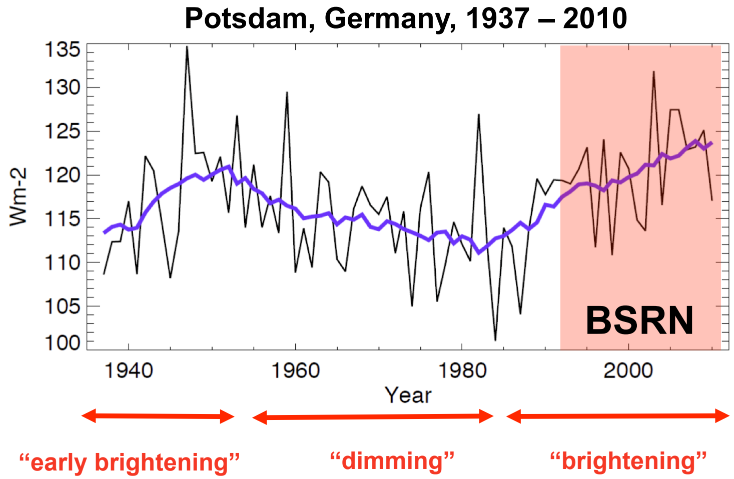
Downward longwave in RCP scenarios



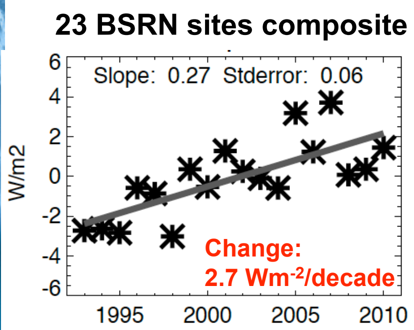
Decadal changes in surface SW radiation



Decadal changes in surface SW radiation



BSRN SW down 1993-2010



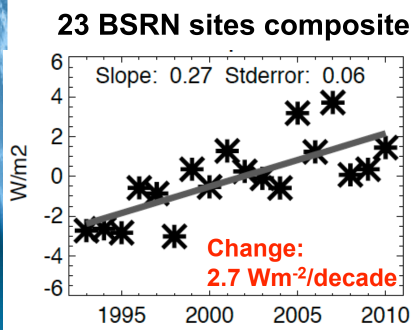
Observed changes at 23 BSRN sites since early 1990s:

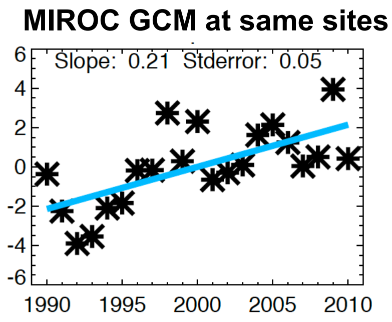
23 longest BSRN records (totally 306 years) covering period 1993-2010:

20 stations with increase (11 significant)

3 stations with decrease (0 significant)

BSRN SW down 1993-2010





Observed changes at 23 BSRN sites since early 1990s:

23 longest BSRN records (totally 306 years) covering period 1993-2010:

20 stations with increase (11 significant)

3 stations with decrease (0 significant)

CMIP5-simulated changes at 23 BSRN sites since early 1990s:

Mean model slope: 0.5 Wm^{-2}/decade

Maximum model slope (MIROC): 2.1 Wm^{-2}/decade

Minimum model slope: -2.7 Wm^{-2}

BSRN observed SW clear– vs. all-sky changes

Table 3. All-Sky and Clear-Sky Changes in Annual Mean Surface Solar Radiation Determined at the Longest Records Available From BSRN[a]

Station	Years	Period	All-Sky	Clear-Sky
Ny Alesund/Spitzbergen, Norway	11	1993–2003	0.80 (0.39)	0.86 (0.21)
Barrow, Alaska	10	1993–2002	0.18 (0.27)	0.85 (0.22)
Lindenberg, Germany	8	1995–2002	–0.71 (0.68)	0.27 (0.36)
Fort Peck, Montana	10	1996–2005	0.33 (0.48)	0.53 (0.51)
Payerne, Switzerland	11	1993–2003	1.08 (0.54)	0.10 (0.13)
Rock Springs, Wyoming	7	1999–2005	–0.75 (1.40)	0.39 (0.26)
Table Mountain, Colorado	10	1996–2005	0.55 (0.38)	0.60 (0.21)
Boulder, Colorado	12	1992–2003	0.96 (0.26)	0.63 (0.13)
Bondville, Illinois	11	1995–2005	1.45 (0.42)	0.55 (0.29)
Desert Rock, Nevada	7	1999–2005	0.53 (0.89)	0.92 (0.75)
South Great Plain, USA	9	1996–2004	0.75 (0.48)	0.43 (0.24)
Goodwin Creek, USA	11	1995–2005	0.48 (0.52)	0.14 (0.41)
Bermuda	12	1992–2003	0.53 (0.34)	0.12 (0.13)
Kwajalein	11	1993–2003	0.54 (0.67)	0.59 (0.11)
Syowa, Antarctica	9	1994–2002	0.20 (0.37)	0.13 (0.11)
Georg von Neumayer, Antarctica	13	1993–2005	1.34 (0.32)	0.67 (0.16)
South Pole	13	1992–2004	0.41 (0.15)	0.54 (0.14)
Average over 17 sites			0.51	0.49

[a]Clear-sky detection based on the algorithm from *Long and Ackerman* [2000]. Changes expressed as linear regressions with 1σ uncertainty estimates given in parentheses. Stations ordered by latitude from north to south. Units are given in $Wm^{-2}a^{-1}$.

175 years of data
17 sites
1992-2005

All sky change:
0.51 $Wm^{-2}y^{-1}$
Clear sky change:
0.49 $Wm^{-2}y^{-1}$

Similar changes under all-skys and clear-skys

Long and Ackermann (2000) clear sky detection algorithm

Wild, Trussel, Ohmura, Long, König-Langlo, Dutton, Tsvetkov (2009) J. Geophys. Res., 114

Regional tendencies in surface solar radiation

Observed tendencies in surface solar radiation

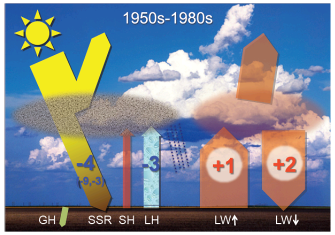
	1950s-1980s	1980s-2000	after 2000
USA	-6	5	8
Europe	-3	2	3
China/Mongolia	-7	4	-4
Japan	-5	8	0
India	-3	-8	-10

Numbers: literature values for changes in Wm^{-2}/decade

Wild BAMS, in press

Schematic view of dimming/brightening

DIMMING



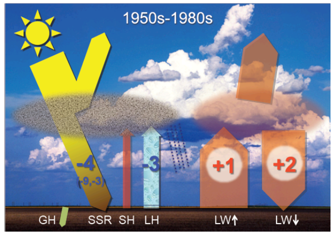
1950s to 1980s

- **Shortwave dimming overcompensates increasing longwave downward radiation**
- **Surface radiative energy decreases**

Wild et al. (2004) GRL 32
Wild (2011) BAMS

Schematic view of dimming/brightening

DIMMING



1950s to 1980s

- **Shortwave dimming overcompensates increasing longwave downward radiation**
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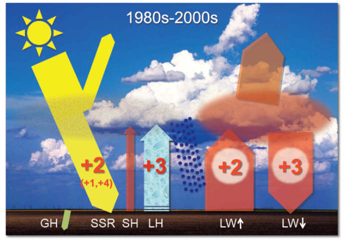
Wild et al. (2004) GRL 32
Wild (2011) BAMS

BRIGHTENING



since 1980s

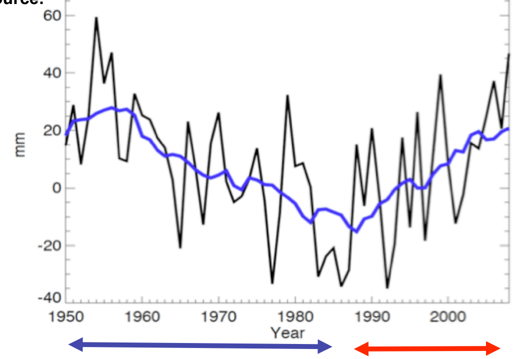
- **Absence of shortwave dimming > no longer masks longwave greenhouse effect**
- **Surface radiative energy increases**

Wild et al. (2005) Science 308
Wild et al. (2007) GRL
Wild (2011) BAMS

Observed precipitation changes 1950-2010

Observed precipitation NH mean land

Data source: GHCN



Wild, BAMS (in press)

Negative surface net radiation

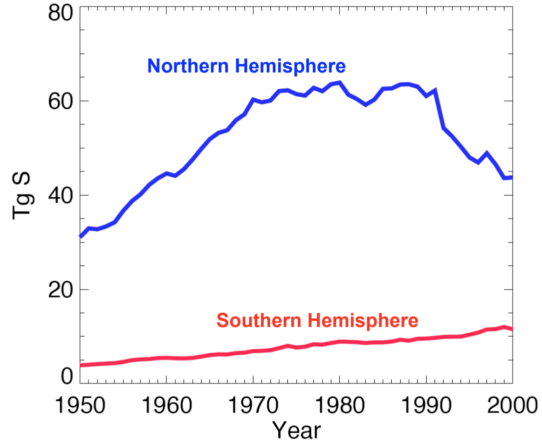
Positive surface net radiation

Variations in precipitation in line with with variations in surface net radiation

climate

Asymmetric hemispheric pollution

Anthropogenic sulfur emission 1950-2000



Source: IPCC AR4, based on Stern (2005)

Emissions show trend reversal in NH, but not in SH

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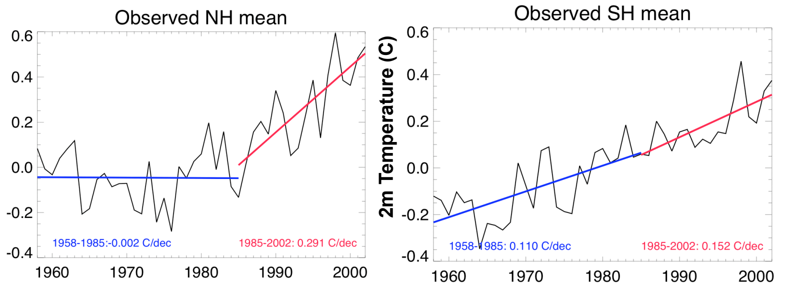
Asymmetric hemispheric warming



Linear regression slopes observed 2m T

Obsdata: CRU

Units °C/ decade	1958-2002	1958-1985 "dimming"	1985-2002 "brightening"
NH	+0.10	-0.002	+0.29
SH	+0.12	0.11	+0.15

Wild BAMS, in press

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Conclusions

- Still considerable uncertainties in global mean radiation budget particularly at the surface. Surface observations can provide some constraints.
- CMIP5 models tend to overestimate downward shortwave and underestimate downward longwave radiation at Earth's surface compared to direct observations from GEBA and BSRN.
- Significant decadal changes observed in both surface shortwave and longwave fluxes.
- CMIP5 models simulate a current increase of downward longwave radiation of 2 Wm^{-2} per decade, in line with indications from BSRN observations.
- Surface shortwave radiation undergoes strong decadal changes ("dimming/brightening"), not well simulated in climate models, with potential implications for decadal warming and the hydrological cycle.

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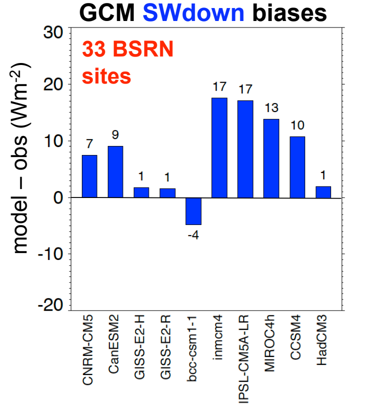
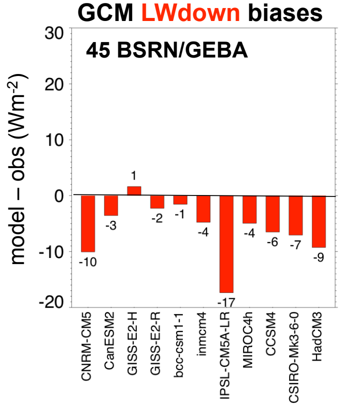
Evaluation of CMIP5 surface radiation balance





Mean model bias SWdown at 33 BSRN sites: +7.6 Wm^{-2}

Multimodel mean SWdown: 189 Wm^{-2}

Mean model bias LWdown at 45 BSRN/GEBA sites: -6 Wm^{-2}

Multimodel mean LWdown: 338 Wm^{-2}

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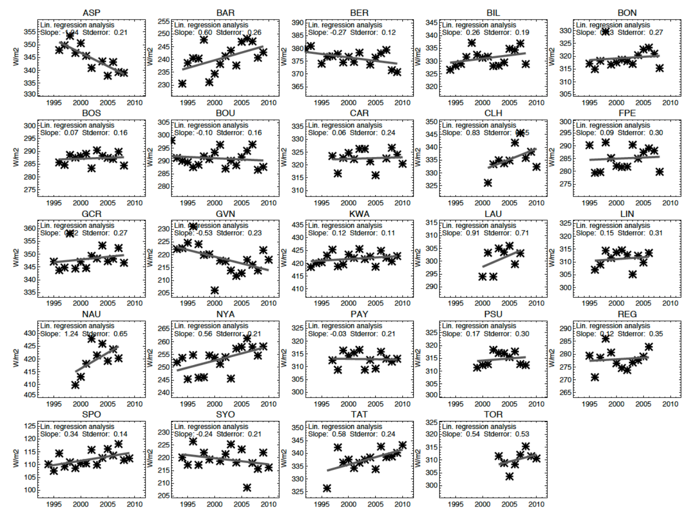
BSRN LW down trends 1992 -2010

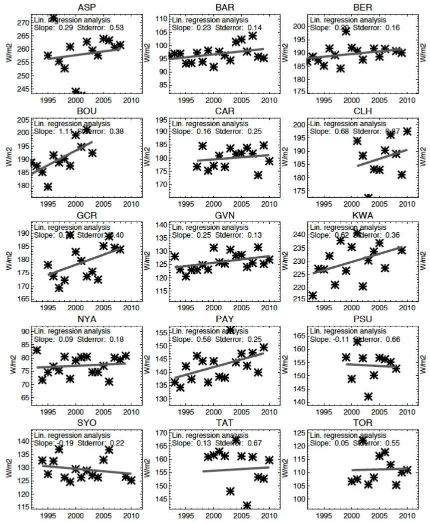
24 longest BSRN records, totally 324 years, 18 (10) pos., 6 (4) neg.

Average change: 0.20 $Wm^{-2}y^{-1}$ (c.f. CMIP5 average 0.25 $Wm^{-2}y^{-1}$)



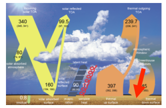
BSRN SW down 1992-2010

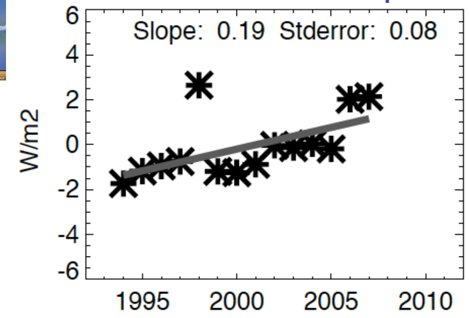
23 stations (min.8 years), 306 years totally, 20(11) pos, 3(0) neg. slopes



All sky change: $0.37\ Wm^{-2}y^{-1}$

Observed changes downward thermal radiation





Observed changes at BSRN sites since early 1990s:

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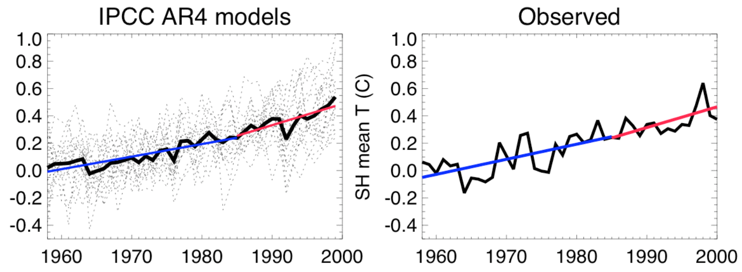
- 18 stations with increase (10 significant)
- 6 stations with decrease (4 significant)
- **Average change: $+2.0\ Wm^{-2}dec^{-1}$**

Southern hemisphere warming

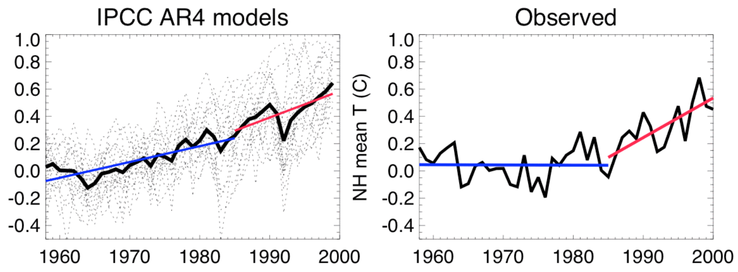


Linear regression slopes NH 2m T

Units °C per decade	dimming phase 1958-85	brightening phase 1985-99	Change dimming > brightening
Model mean (18 GCMs)	**+0.09**	**+0.15**	**+0.06**
Observed	**0.11**	**+0.15**	**+0.04**

Decadal warming in unpolluted SH more realistic than in polluted NH

Northern hemisphere warming

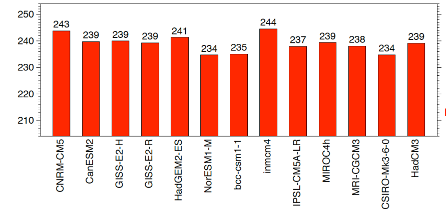


Linear regression slopes NH 2m T

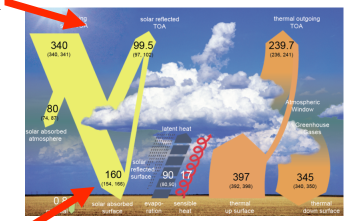
Units °C per decade	dimming phase 1958-85	brightening phase 1985-99	Change dimming > brightening
Model mean (18 GCMs)	**+0.12**	**+0.19**	**+0.07**
Observed	**-0.002**	**+0.29**	**+0.31**

Solar radiation budgets in CMIP5 GCMs

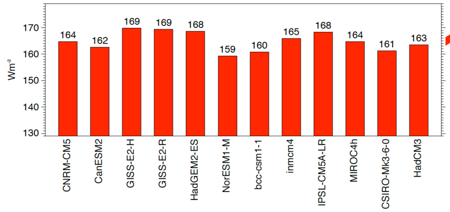
Absorbed solar radiation
top of atmosphere



Model mean: 239 Wm^{-2}
Model range: 10 Wm^{-2}
Standard dev.: 3.1 Wm $^{-2}$
Reference Satellite Value (CERES EBAF): 240 Wm^{-2}



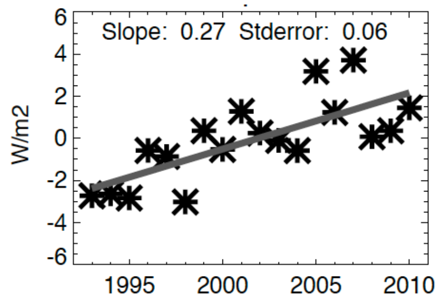
Absorbed solar radiation
surface



Model mean: 165 Wm^{-2}
Model range: 10 Wm^{-2}
Standard dev.: 3.6 Wm $^{-2}$

BSRN SW down 1993-2010

23 BSRN sites composite



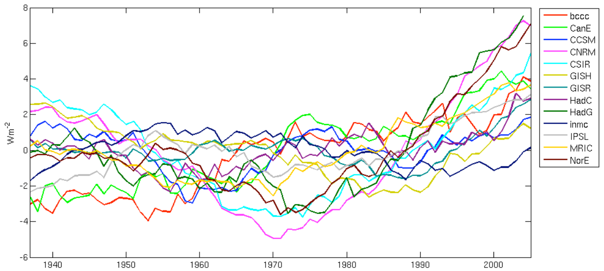
Change:
2.7 Wm^{-2}/decade

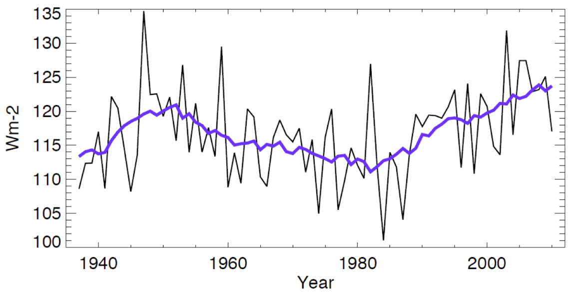
Observed changes at BSRN sites since early 1990s:

23 longest BSRN records (totally 306 years) covering period 1993-2010

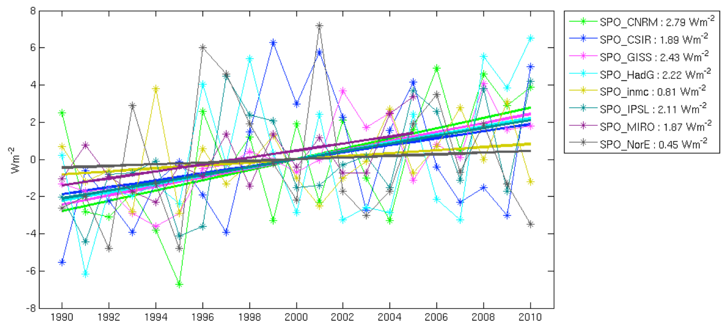
- 20 stations with increase (11 significant)
- 3 stations with decrease (0 significant)

SW down at Potsdam in CMIP5

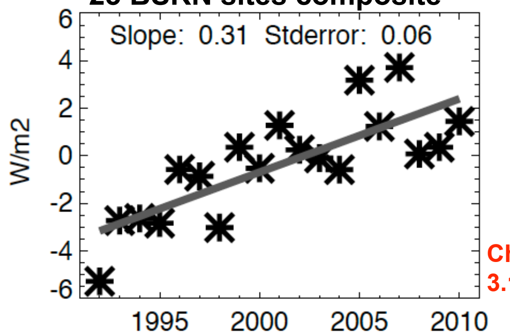




Simulation of LW down in CMIP5



BSRN surface solar radiation 1992-2010



Change:
3.1 Wm^{-2}/decade

Observed changes at BSRN sites:

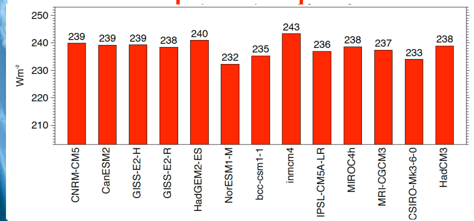
23 longest BSRN records (totally 306 years) covering period 1992-2010

- 20 stations with pos. change (11 significant),
- 3 stations with negative change (0 significant)

Thermal radiation budgets in CMIP5 GCMs

Wild 2005, Geophys. Res. Lett. 32

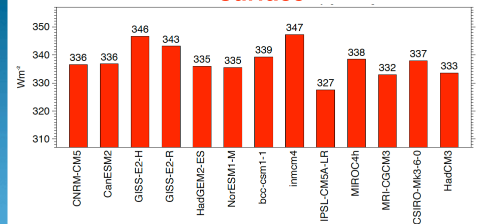
Outgoing thermal radiation
top of atmosphere



Multimodel mean 238.5 Wm^{-2}
Model range: 11 Wm^{-2}
Standard dev.: 2.9 Wm $^{-2}$

Rlut mean 238.5
All sky Model Range: Wm^{-2}
Standard dev.: 2.9 Wm $^{-2}$
Clear sky 3.3

Downward thermal radiation
surface



Clear sky Model Range: Wm^{-2}
Mean 312
Standard dev.: 6.5 Wm $^{-2}$

All sky Model Range: 20 Wm^{-2}
Standard dev.: 5.4 Wm $^{-2}$

=>Large model uncertainties particularly at the Earth Surface

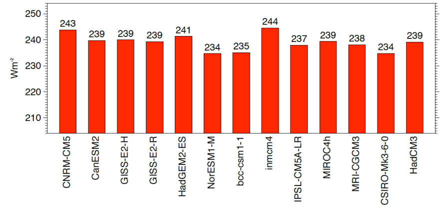
Conclusions

- Still considerable uncertainties in global mean radiation budget at the surface.
- CMIP5 models still tend to overestimate downwoard solar and underestimate downward thermal radiation
- Strong decadal chages observed in both surface solar and thermal fluxes.
- CMIP 5 models suggest an current increase rate of downward thermal radiation of 2 Wm-2 per decade in line with indications from BSRN observations.
- Surface solar radiation undergoes strong decadal changes (“dimming/brightening“) with potential implications for global warming and the hydrological cycle.
- BSRN stations indicate a similar brightening under clear- and all sky conditions.

Solar radiation budgets in CMIP5 GCMs

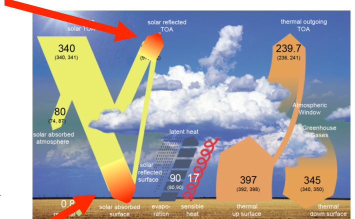
Wild 2005, Geophys. Res. Lett. 32

Absorbed solar radiation
top of atmosphere

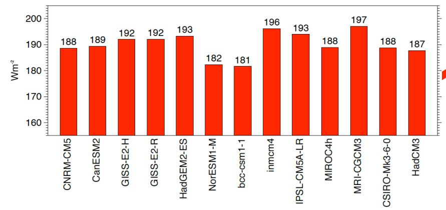


Model mean: 239 Wm^{-2}
Standard dev.: 3.1 Wm $^{-2}$

Reference Satellite Value (): 240 Wm^{-2}



Downwelling solar radiation
surface

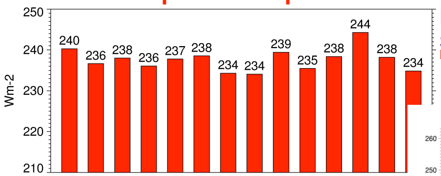


Model Mean: 165 Wm^{-2}
Standard dev.: 3.6 Wm $^{-2}$

Solar radiation budgets in IPCC AR4 GCMs

Wild 2005, Geophys. Res. Lett. 32

Absorbed solar radiation top of atmosphere



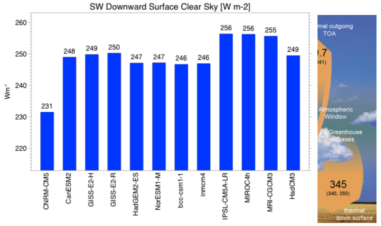
Global means of 14 state-of-the-art climate models

Rsut Model range: 10 Wm^{-2}

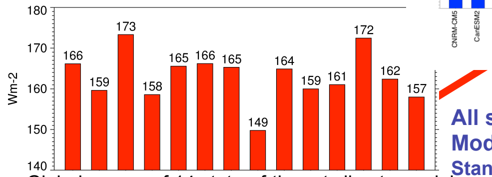
Standard dev.: 2.9 Wm^{-2}

Rsutcs stdev 2.0

Reference Satellite Value (ERBE): 240 Wm^{-2}



Absorbed solar radiation surface



Global means of 14 state-of-the-art climate models

All sky

Model Range: Wm^{-2}

Standard dev.: 4.7 Wm^{-2}

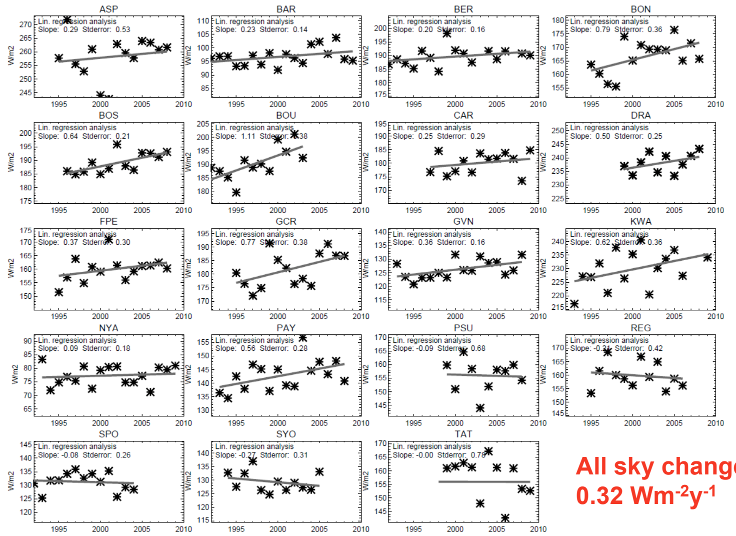
Clear sky

Model Range: Wm^{-2}

Standard dev.: 6.6 Wm^{-2}

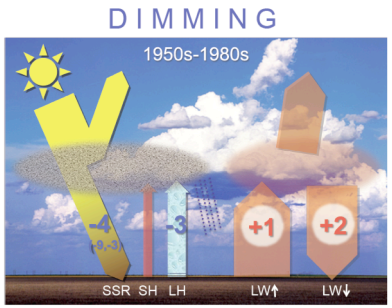
BSRN SW down 1992-2010

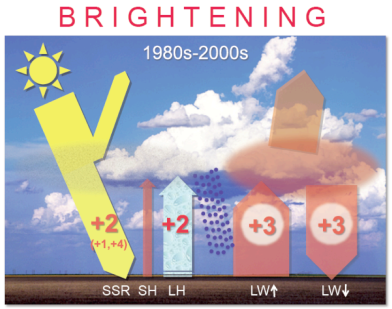
24 stations (min.10 years), 271 years totally, 14(11) pos, 5(0) neg. slopes



All sky change: 0.32 Wm^{-2}y^{-1}

Schematic view of dimming/brightening





Wild 2011, BAMS

Surface radiation balance controls global water cycle

Regional tendencies from GEBA

Wild et al. 2009 JGR

Observed tendencies in surface solar radiation

	1990s	after 2000
USA	↗	↗
Central America	→	↘
Europe	↗	↗
China/Mongolia	↗	→
Japan	↗	→
Korea	↗	↗
India	↘	↘
Antarctica	↗	→

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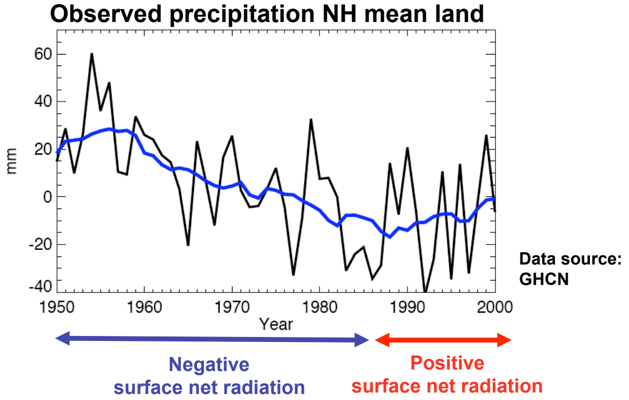
Impact on the global water cycle



Variations in precipitation quantitatively consistent with variations in surface net radiation

Wild, Grieser Schaer GRL 2008
Wild 2009 JGR

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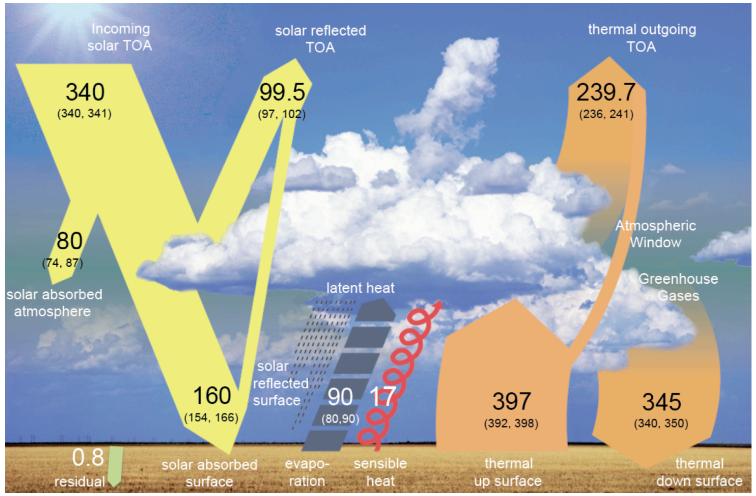
Global Mean Radiation Budget

Units Wm^{-2}



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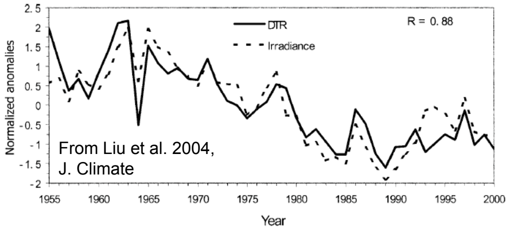
DTR as proxy for surface insolation changes

DTR:

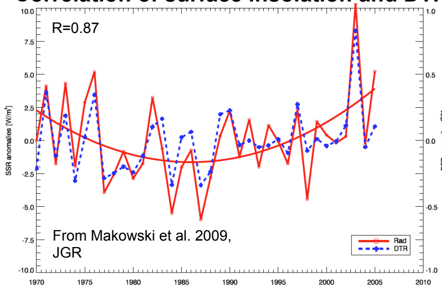
Diurnal Temperature Range

=T max – T min

Correlation of surface insolation and DTR in China



Correlation of surface insolation and DTR in Europe



Daily maximum temperature dominated by surface solar radiation

Daily minimum temperature dominated by thermal radiation

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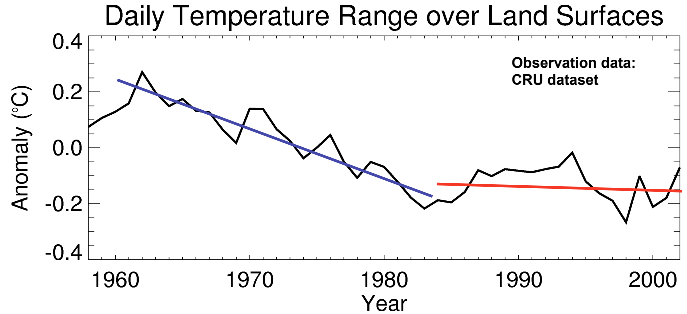
Observed DTR Land Mean 1958-2000

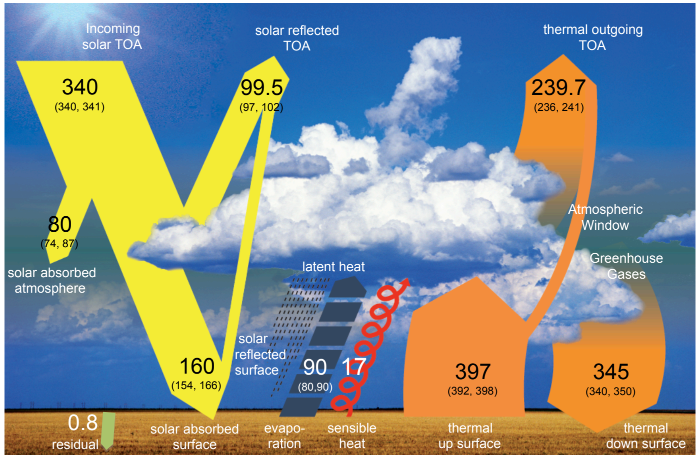


Linear regression slopes land mean DTR

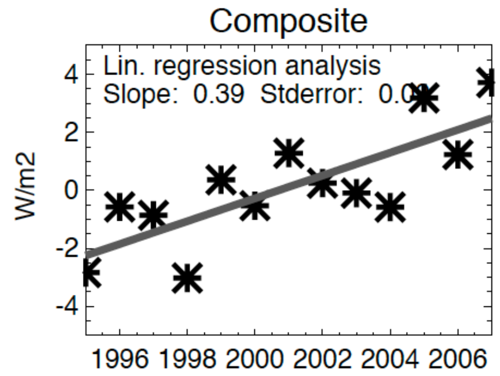
Units °C/ decade	1958-1985 "dimming"	1985-2002 "brightening"
T max	-0.04	+0.37
T min	0.11	+0.40
DTR	-0.15	-0.03

Evidence for large scale change in surface radiative forcings

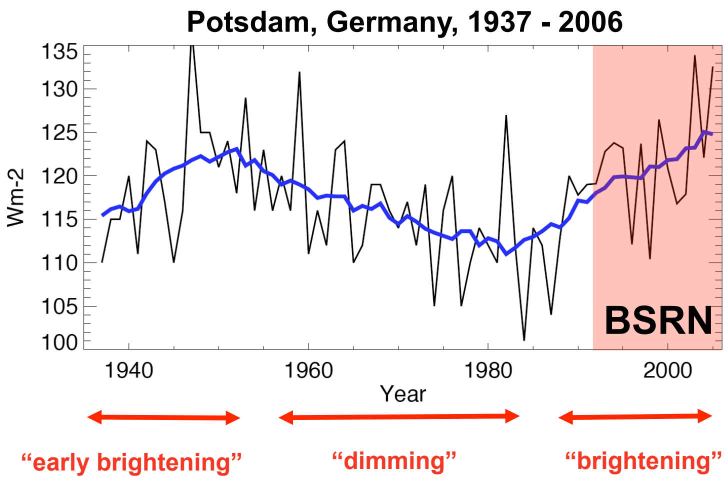
Wild et al. 2007, Geophys. Res. Lett.



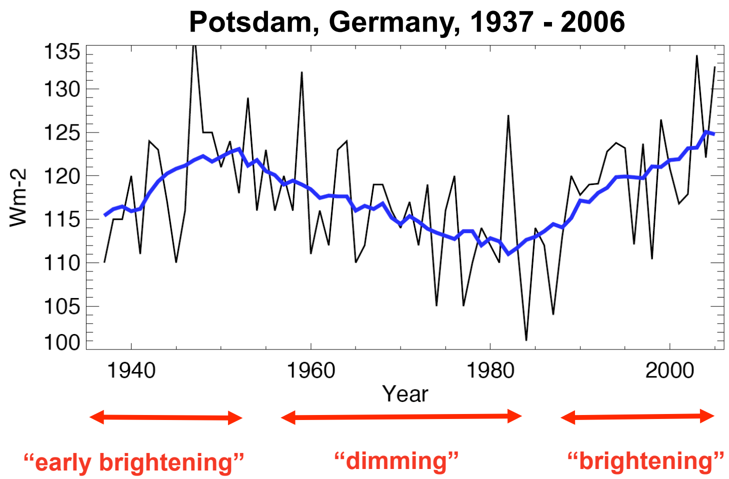
BSRN SW down 1995-2007



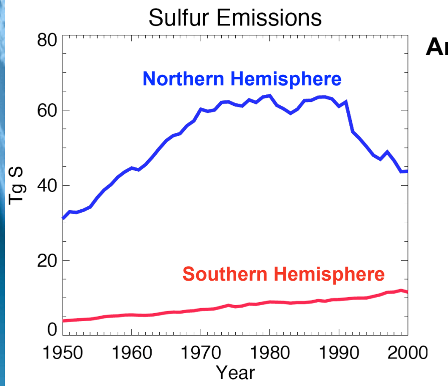
Decadal changes in surface solar radiation



Decadal changes in surface solar radiation



Asymmetric hemispheric pollution



Anthropogenic sulfur emission 1980 versus 2000 (Tg S y^{-1})

	1980	2000	
NH	64	43	- 21
SH	9	11	+ 2

Source: IPCC AR4, based on Stern (2005)

- **Emissions much larger in SH than NH**
- **Emissions substantially reduced since 1980s in NH but not in SH**

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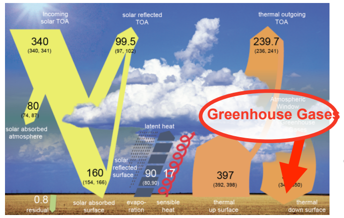
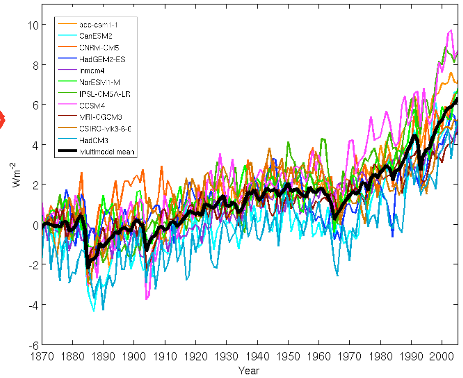
Changes in downward thermal radiation



- most directly affected by changes in atmospheric greenhouse gases
- GCMs suggest increase since 1870 of 6 Wm^{-2} (most of it since 1960s)
- expected to undergo largest change of all radiative fluxes in coming decades

Downward thermal radiation in CMIP5 models 1870-2005



Current increase in CMIP5 models: 2.5 Wm^{-2}/decade

Wild et al. 1997 J. Climate
Wild et al. 2001 J. Climate
Wild et al. 2005 Gewex News

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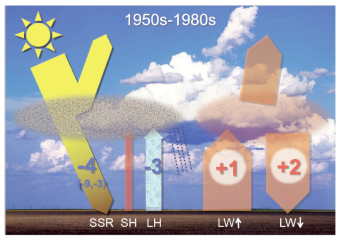
Schematic view of dimming/brightening

DIMMING

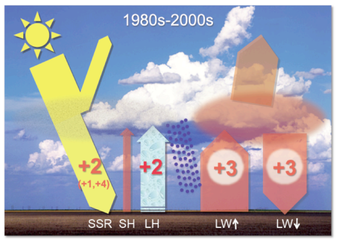


1950s to 1980s

- **Solar dimming overcompensates increasing thermal downward radiation**
- **Surface radiative energy decreases**

Wild et al. (2004) GRL 32

BRIGHTENING



since 1980s

- **Absence of solar dimming no longer masks thermal greenhouse effect**
- **Surface radiative energy increases**

Wild et al. (2005) Science 308
Wild et al. (2007) GRL

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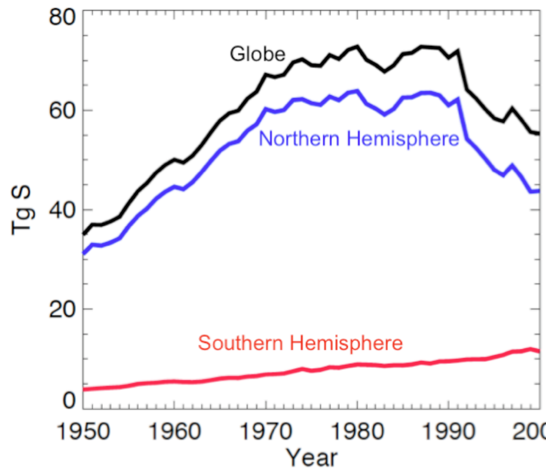
Asymmetric hemispheric pollution

Anthropogenic sulfur emission 1950-2000



Source: IPCC AR4, based on Stern (2005)

Emissions show trend reversal in NH, but not in SH

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Fehleranalyse Globalstrahlung (SW down)

Representativität eines einzelnen Jahresmittelwertes für mittlere Klimatiologie einer 2.5° Gitterbox:

Mittlerer Fehler: 7 %

zusammengesetzt aus:

- Zufälliger Messfehler (2%)

- Vernachlässigung Trends (3%)

- Vernachlässigung interanuelle Variabilität (4%)

- Subgrid Variabiltät (5%)

GCM Analysen:

- **zufällige Messfehler, Trend, interannuelle Variabilität: minimiert, da nur langjährige Messreihen**
- **Subgrid Variabilität reduziert bei T106 (1.1°) Analysen**

Mittlerer Fehler der Obswerte in GCM Vergleichen << 7 %

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Identification of clear sky periods

Long and Ackerman (2002), JGR 105 (D12), 15609-15626

- **Based on 1 minute data of downwelling total and diffuse shortwave irradiance**
- **4 tests applied:**

A) Normalized total shortwave magnitude test Normalized with solar zenit angle, nominal range of values for clear sky

B) Maximum diffuse shortwave test
clear sky diffuse irradiance below a certain threshold

C) Change in magnitude with time test
compares temporal change in total irradiance, small for clear periods compared to cloudy periods over short timescales

D) Normalized diffuse ratio vatiability test
diffuse divided by total irradiance,smooth timeseries for clear skies, variability below threshold

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Measurement uncertainty: single measurement

Kurzwellig:

- Pyranometer:
  2% (Ohmura and Gilgen 1993)
  4 Wm^{-2} bei guter Wartung der Instrumente (Konzelmann und Ohmura 1995)

Langwellig:

- Pyrgeometer: +/- 2 Wm^{-2} (R. Phillipona, Pers. Mitteilung)
- Pyrradiometer:
  Belüftet, mit Schattenscheibe: +/- 10 Wm^{-2}

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BSRN Measurement Accuracy Target

- **Direct SW radiation: 1% or 2 Wm-2 (normal incidence pyrheliometer)**
- **Diffuse radiation: 4 % or 5 Wm-2 (ventilated pyranometer)**
- **Global Radiation 2% or 5 Wm-2 (ventilated pyranometer)**
- **Reflected SW radiation: 5% (ventilated pyranometer)**
- **Downwelling longwave radiation +/ - 2 Wm-2 (pyrgeometer)**