Surface radiative fluxes: key elements in the climate system

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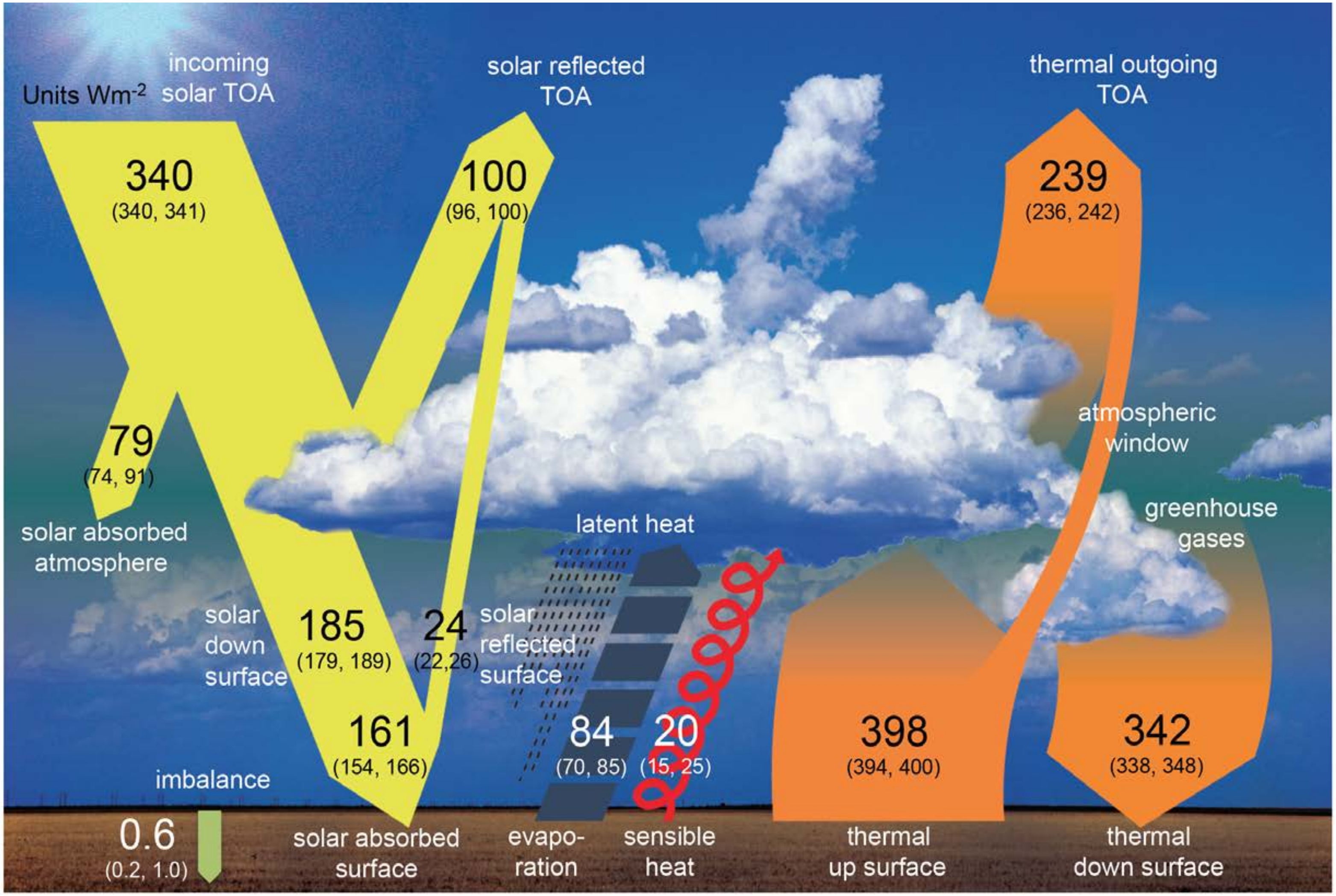
Content

- ***Why are the surface radiative fluxes important in the climate system?***
- ***How well are they represented in satellite-derived products and global climate models?***
- ***What do we know about changes in the radiative fluxes over time?***

Global Mean Energy Balance

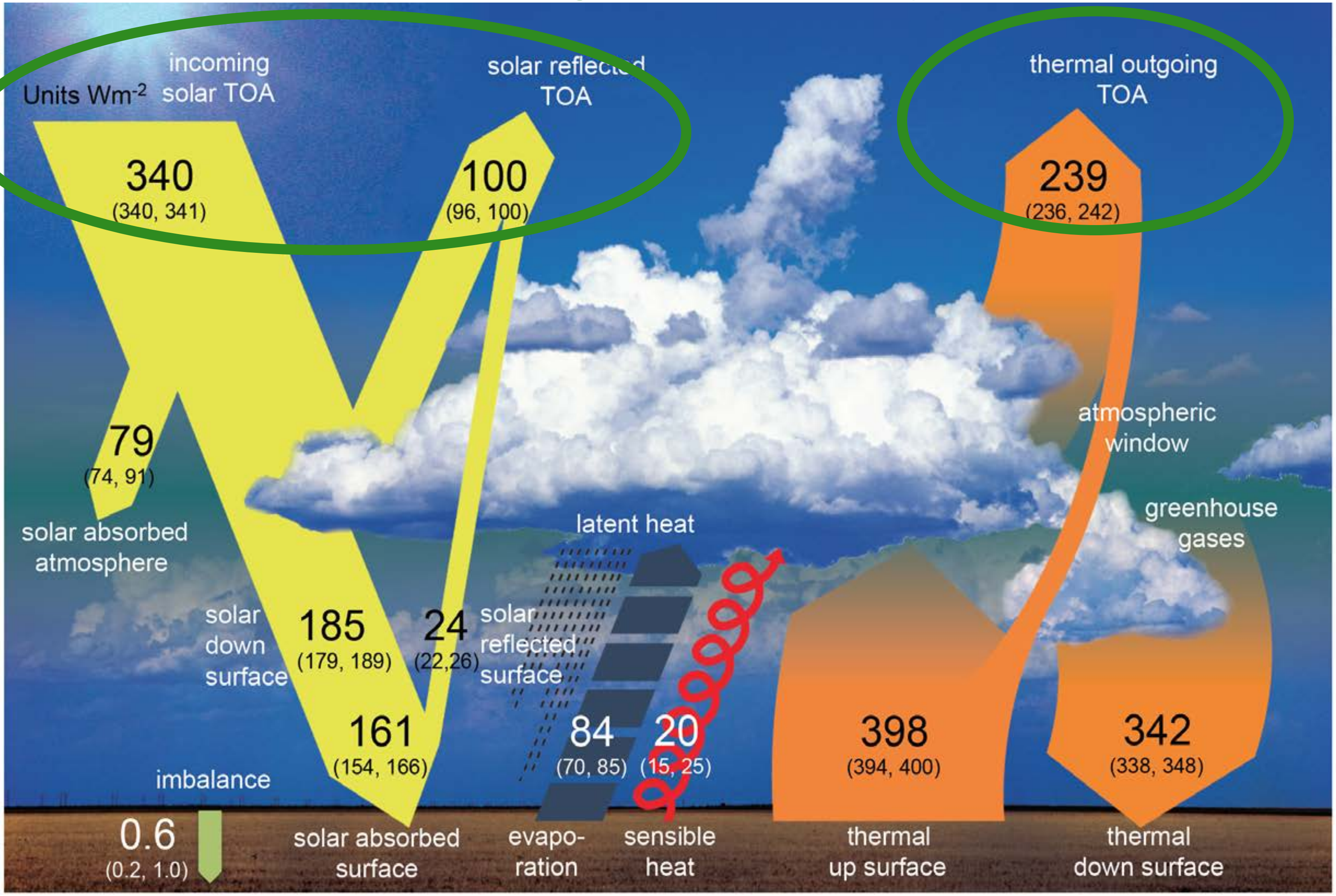
Units Wm^{-2}



Global Mean Energy Balance

TOA radiation balance controls energy content of the global climate system

Units Wm^{-2}



Global Mean Energy Balance

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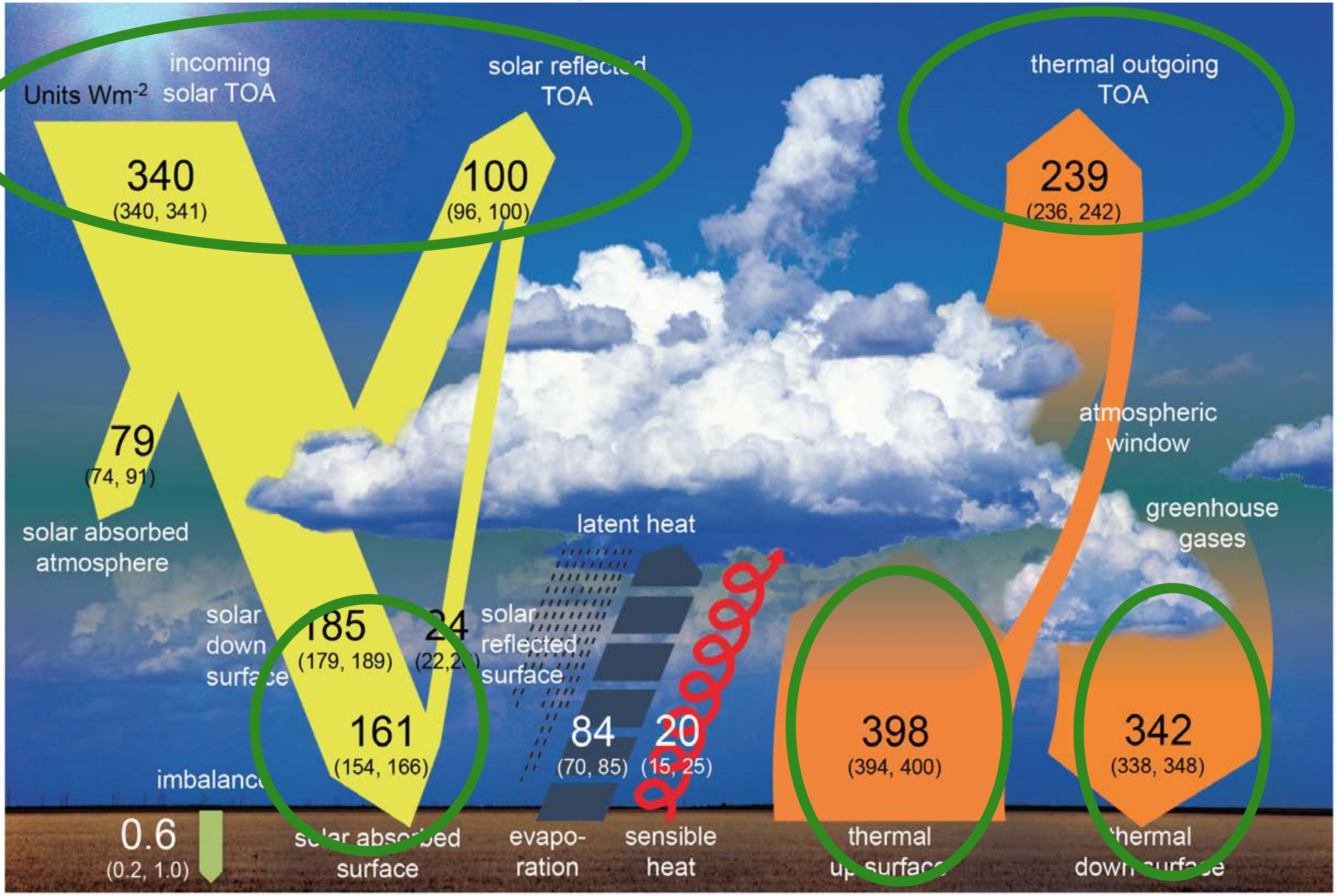

Surface radiation balance

Global Mean Energy Balance

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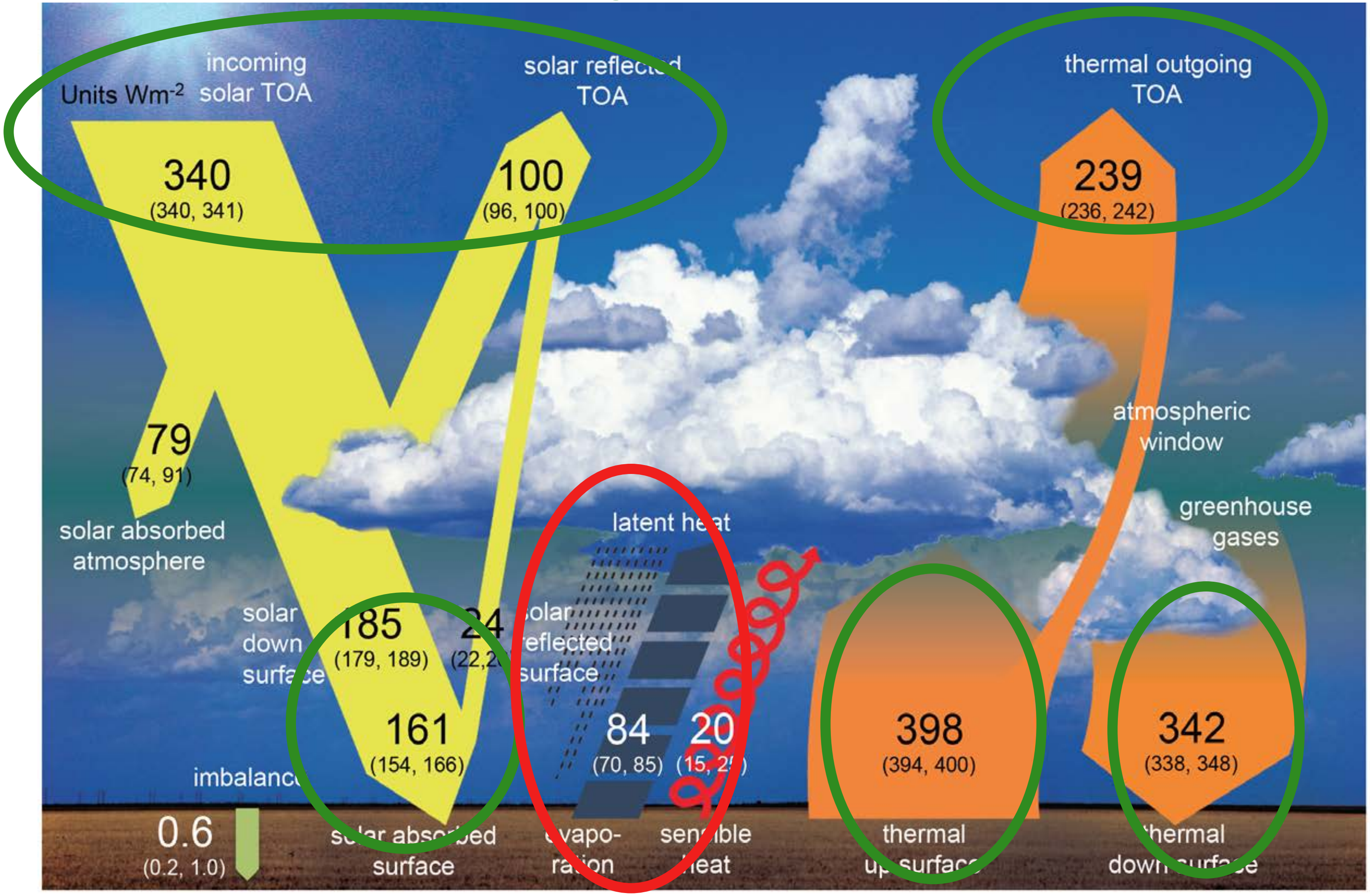
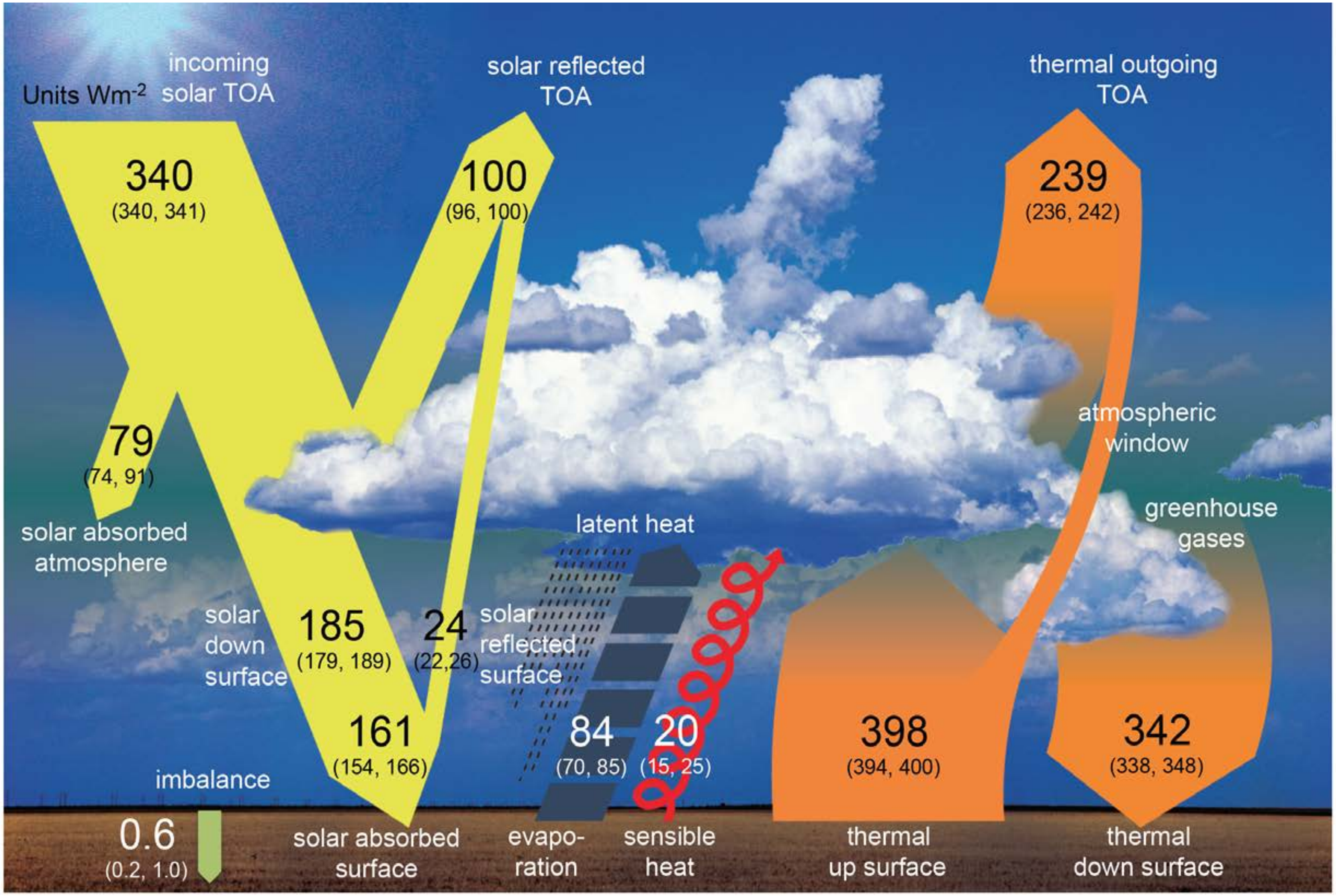
Units Wm^{-2}



Surface radiation balance controls global water cycle

Global Mean Energy Balance

Units Wm-2 ***Uncertainties***



Energy Balance

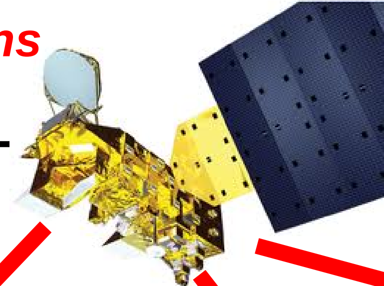
Satellite missions

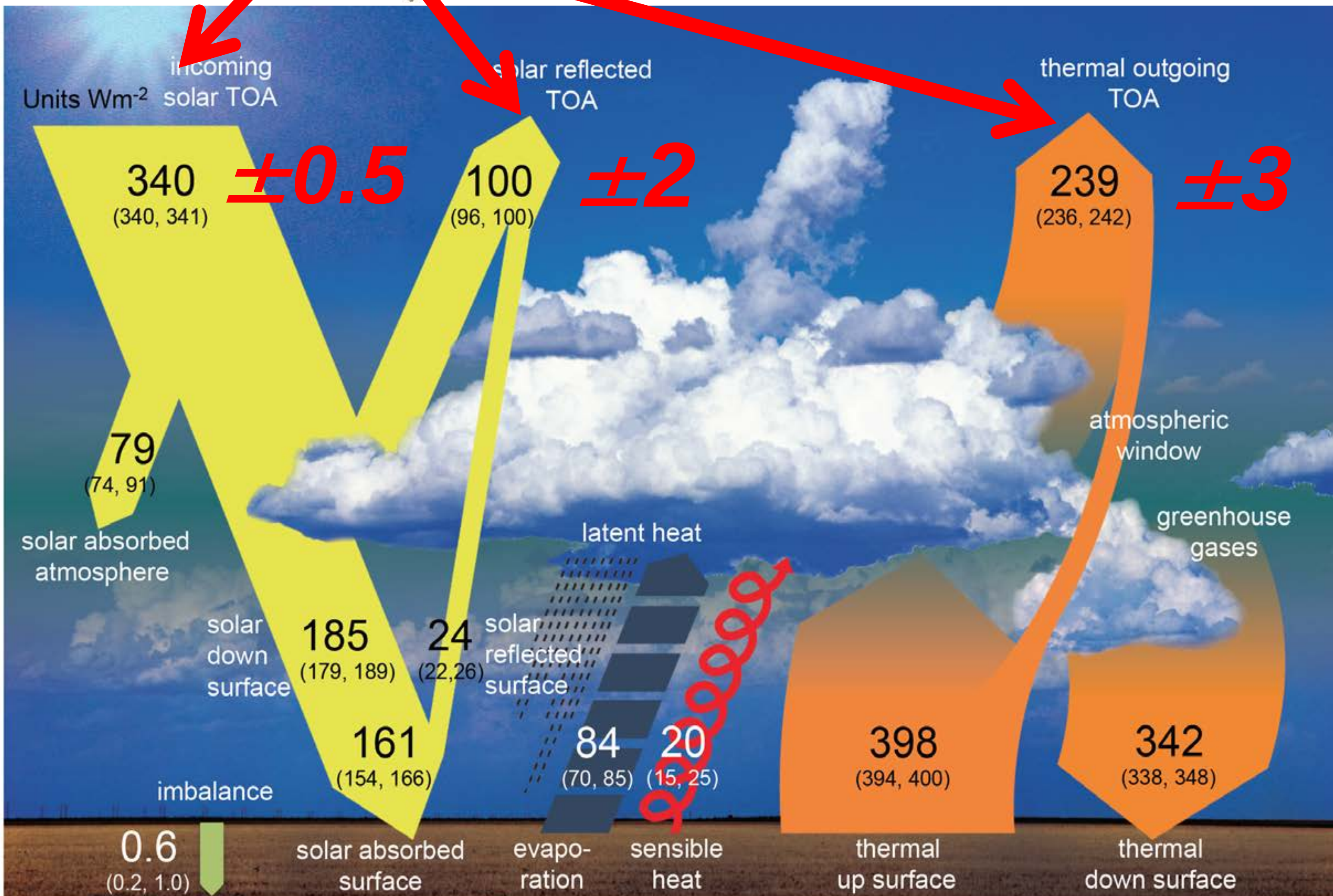
CERES

SORCE

Units Wm^{-2}

Uncertainties





Energy Balance

Satellite missions

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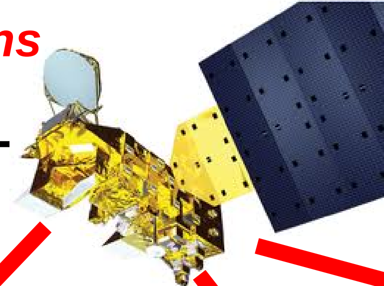
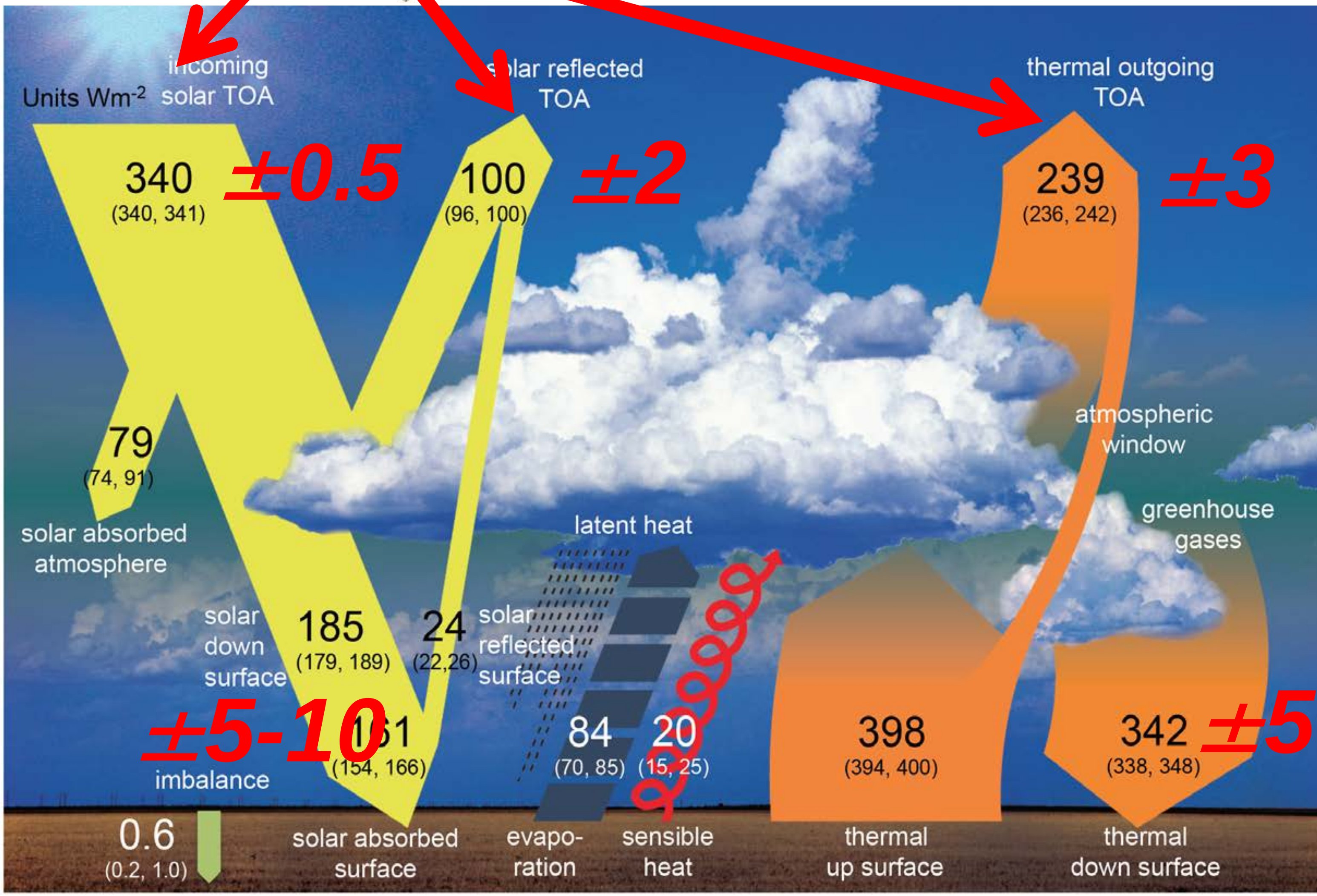
Units Wm^{-2}

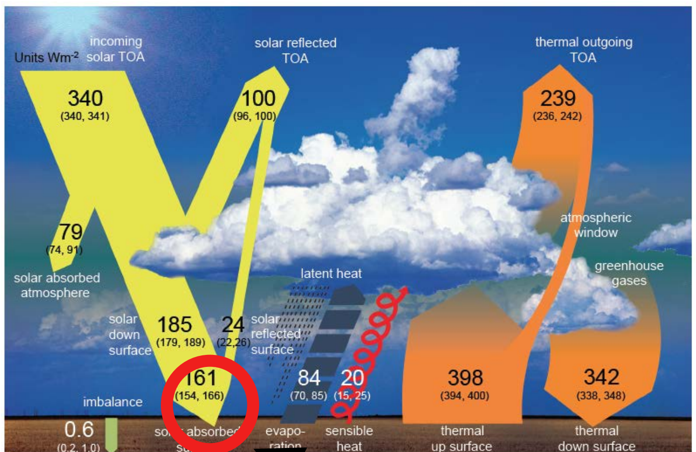
Uncertainties



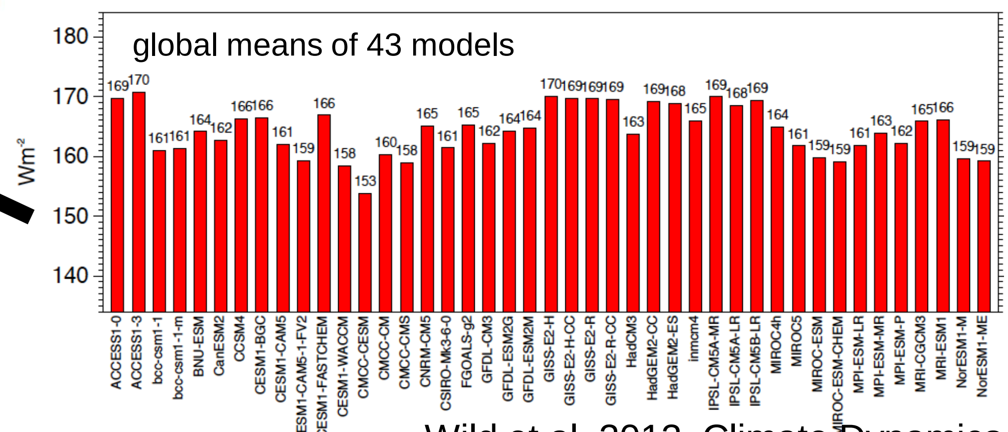


Surface radiation budget has larger uncertainties than TOA budget

Surface radiation budgets in IPCC AR5 climate models



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

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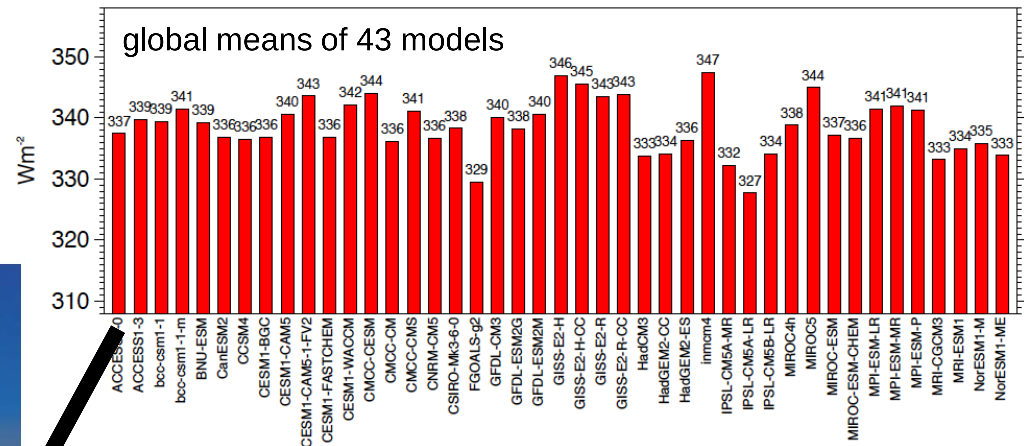
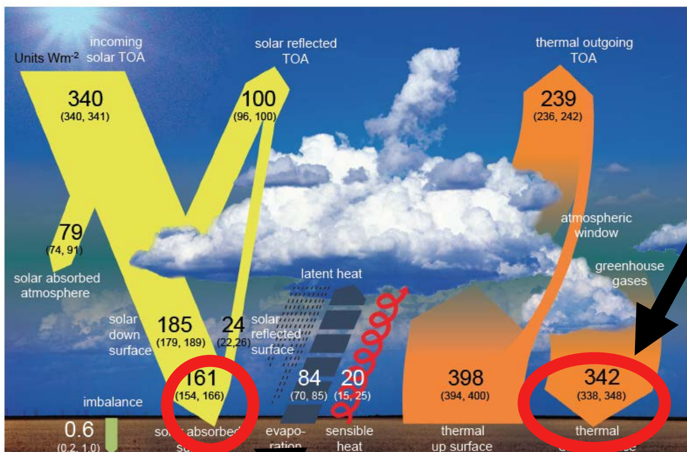
Surface radiation budgets in IPCC AR5 climate models

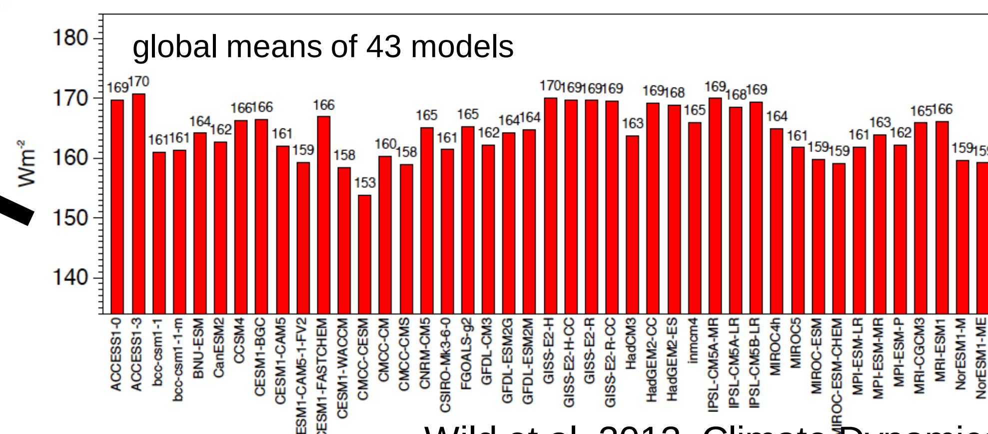
Model mean 339 Wm^{-2}
Model range: 20 Wm^{-2}
Standard dev.: 4.4 Wm^{-2}

Downward longwave radiation surface





Absorbed shortwave radiation surface



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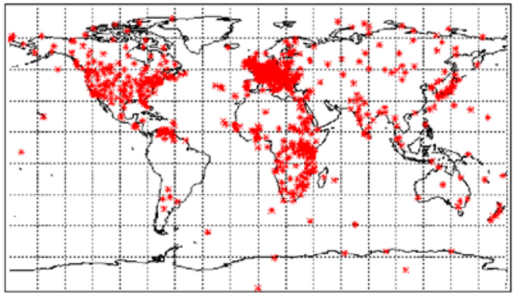
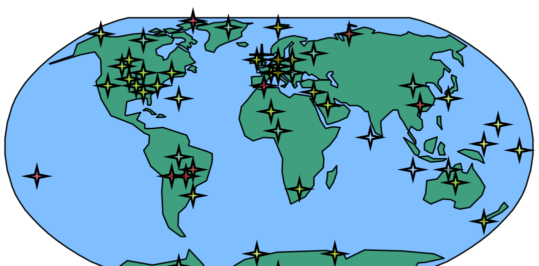
Constraints from surface observations



Ohmura, Gilgen, Wild 1989

BSRN site Payerne



Ohmura et al. 1998

GEBA
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

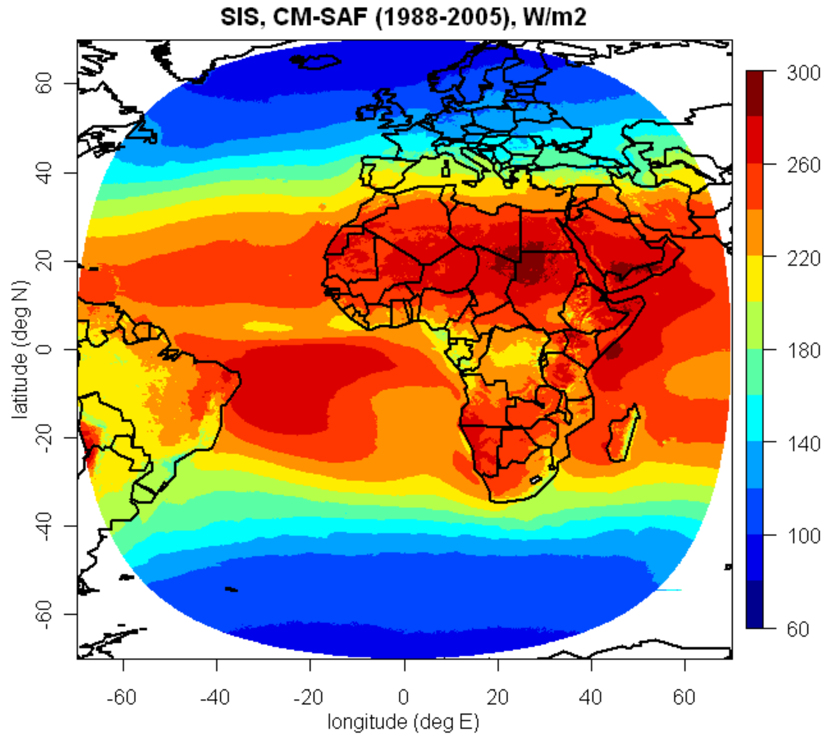
BSRN
Baseline Surface Radiation Network

- WCRP initiative, starting in 1992
- Highest measurement quality at selected sites worldwide (currently 52 anchor sites)
- Minute values
- Ancillary data for radiation interpretation

Validation of satellite products and climate models using surface observations

Validation of CM SAF MFG surface radiation

- 23 year (1983–2005) dataset of surface solar radiation generated by the Satellite Application Facility on Climate Monitoring (CM SAF) based on the Meteosat First Generation (MFG) satellites.
- Validation using homogeneous surface solar radiation records from GEBA (Sanchez-Lorenzo et al. 2013)
- High spatial resolution (0.03° x 0.03°) > facilitates comparison with point observations



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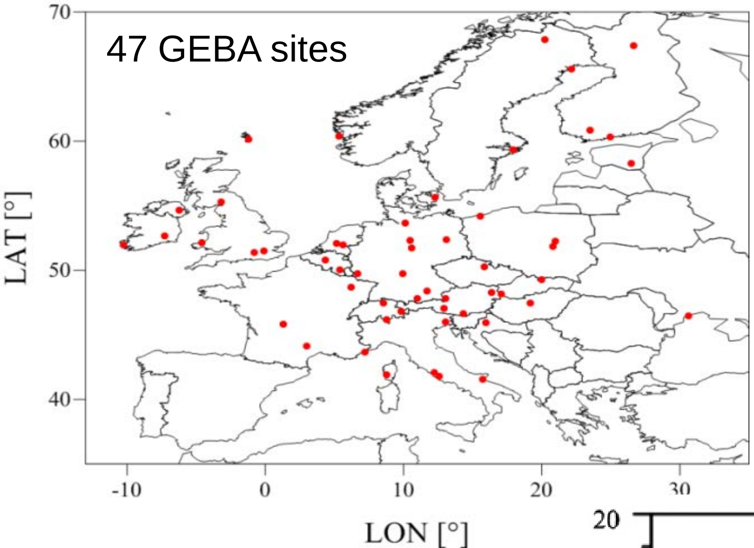
Validation of CM SAF MFG surface radiation

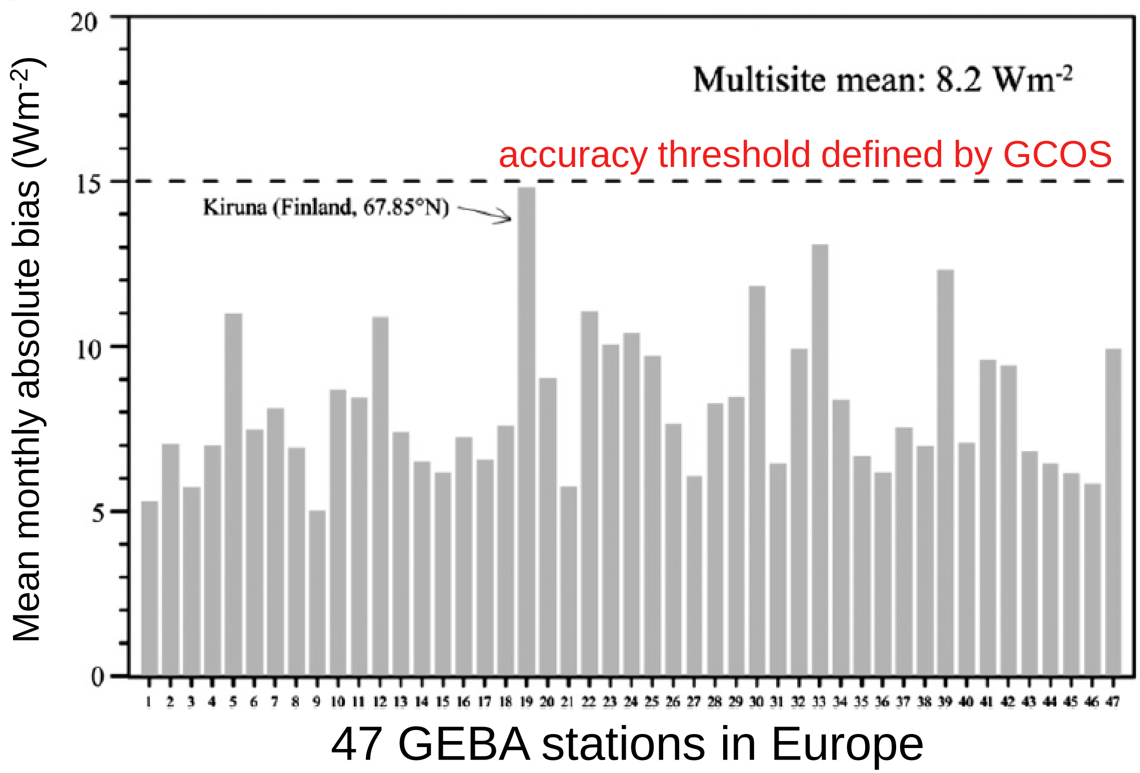


CM SAF surface solar radiation against GEBA observations

CMSAF high 0.03° resolution facilitates validation

Sanchez-Lorenzo, Wild, Trentmann 2013, Remote Sensing of Environment

Absolute biases below accuracy threshold (15Wm^{-2})



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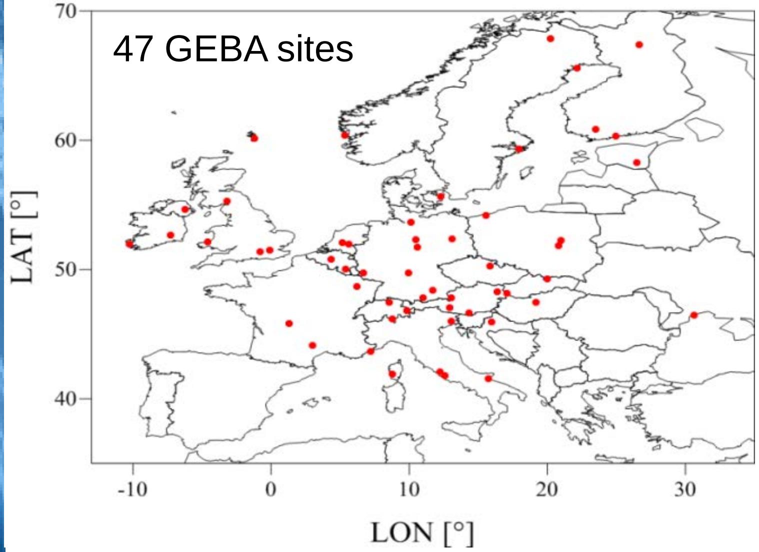
Validation of CM SAF MFG surface radiation



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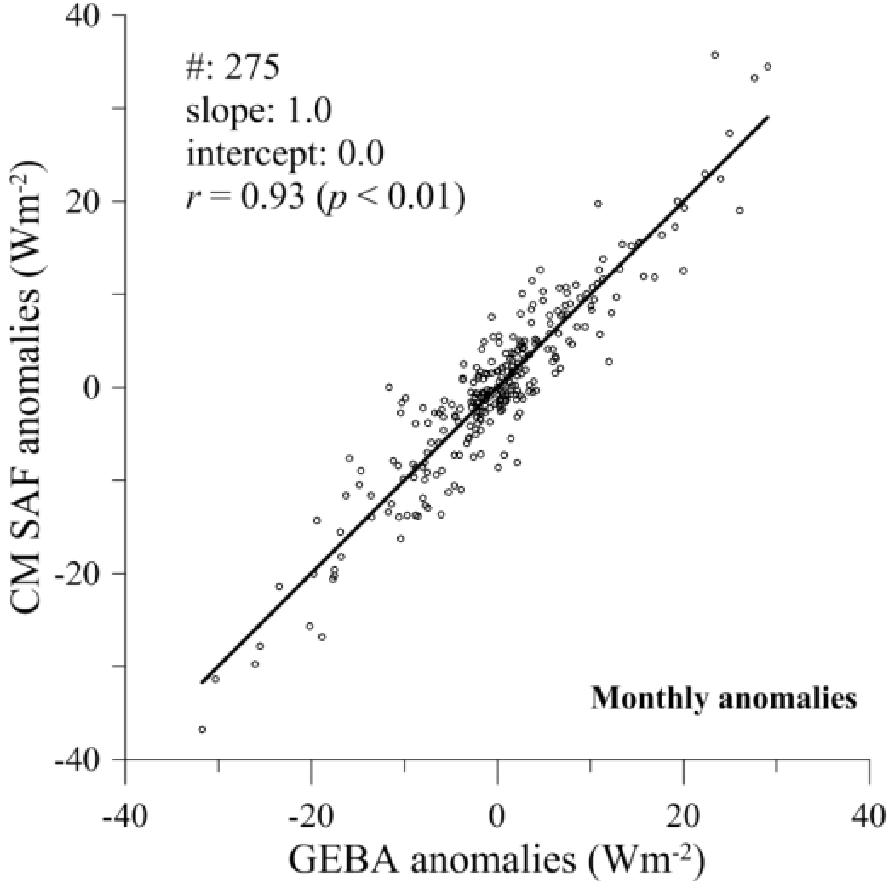
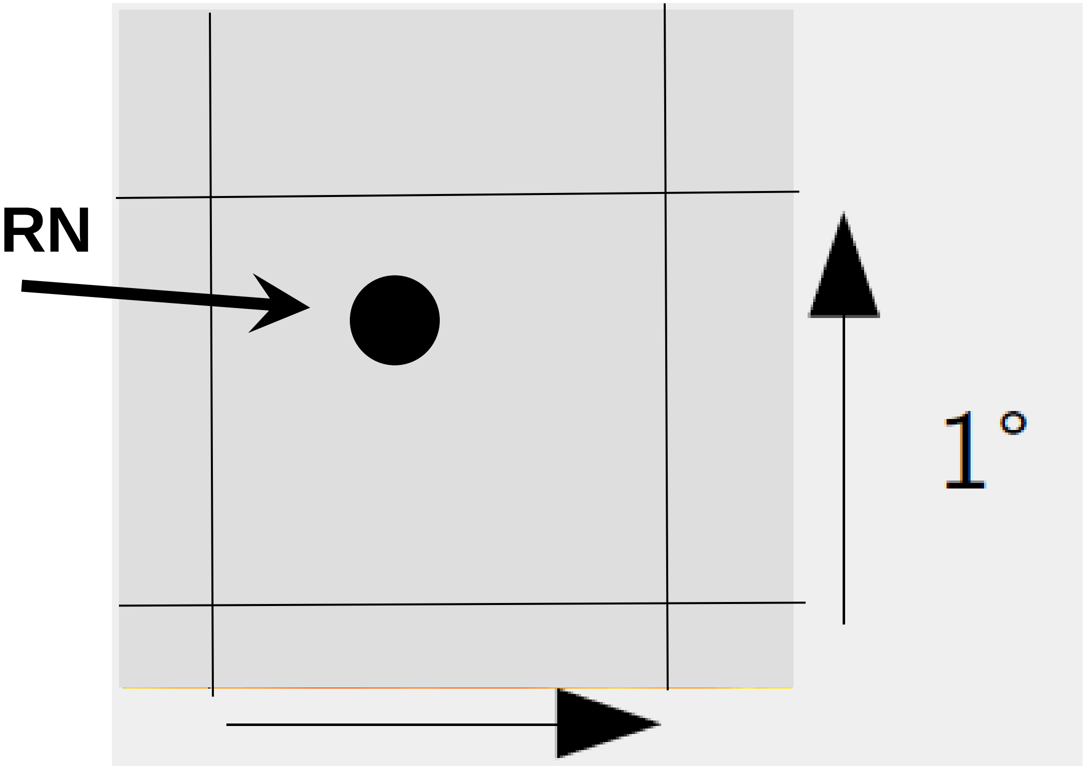


Monthly anomalies well reproduced in CMSAF

Validation of coarser gridded datasets

Global climate models and global satellite products have typically grids of ≥ 1°

GEBA /BSRN station



Hakuba et al. 2013 JGR

Subgrid variability of surface solar radiation estimated from CMSAF 0.03° dataset **See poster Maria Hakuba**

Validation of coarser gridded datasets

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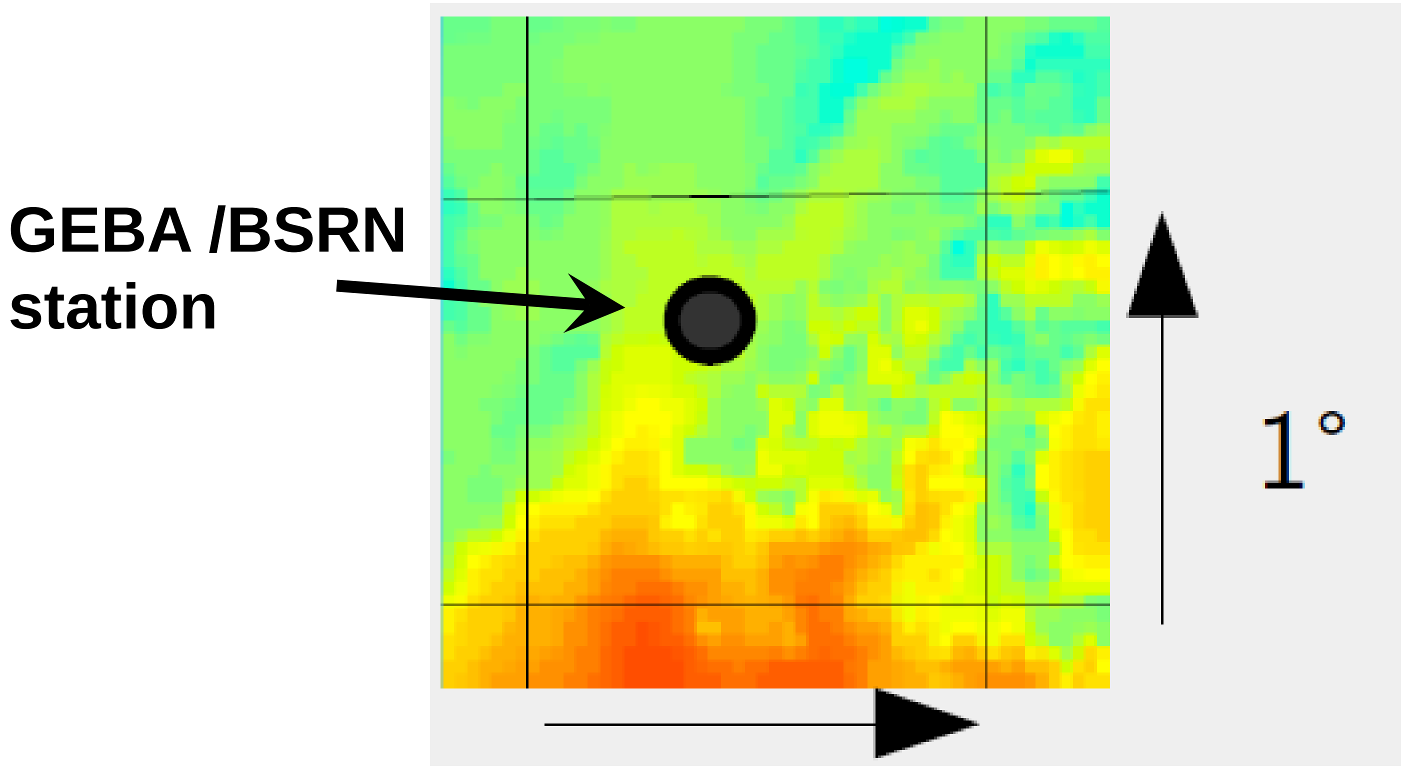


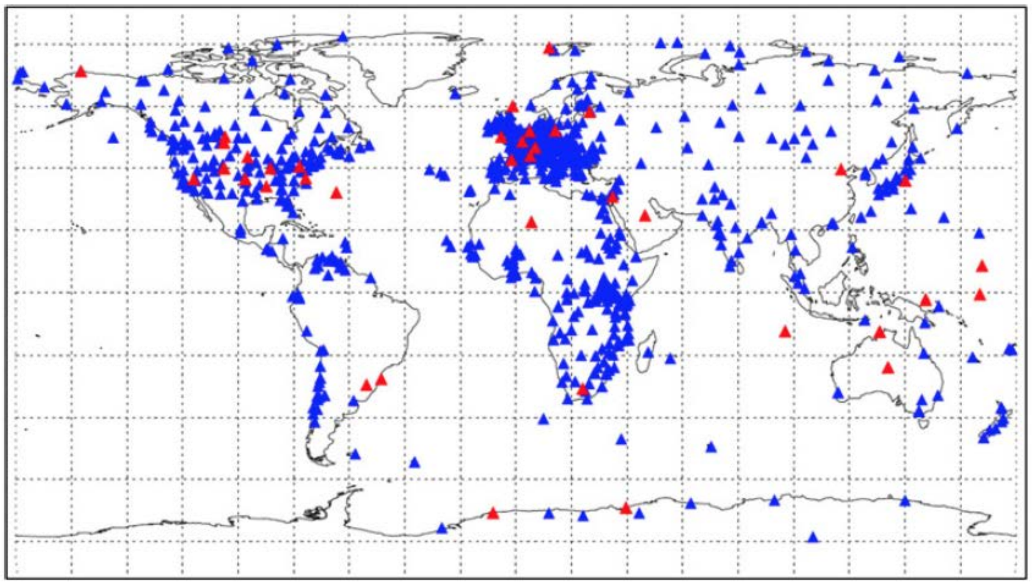
Hakuba et al. 2013 JGR

Subgrid variability of surface solar radiation estimated from CMSAF 0.03° dataset **See poster Maria Hakuba**

Validation of global climate models

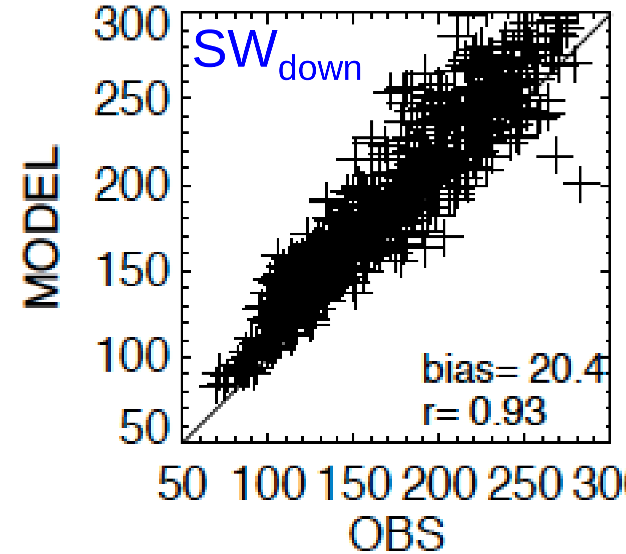
SW_{down} against 760 GEBA sites

Worldwide stations from GEBA and BSRN

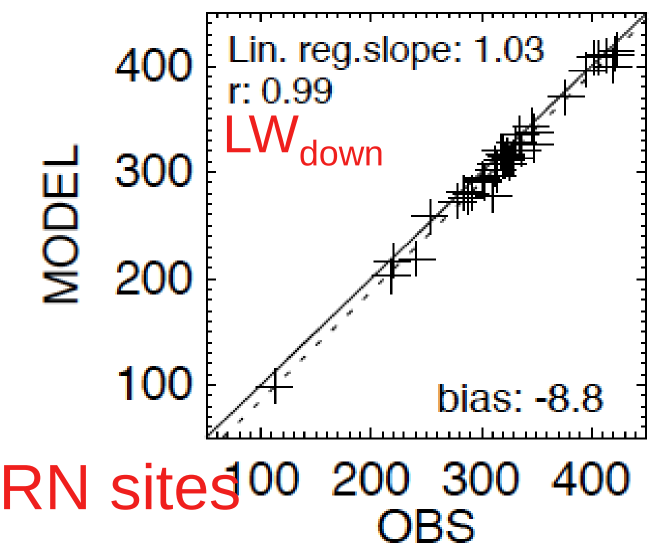


State-of-the art models from IPCC AR5

MRI-CGCM3

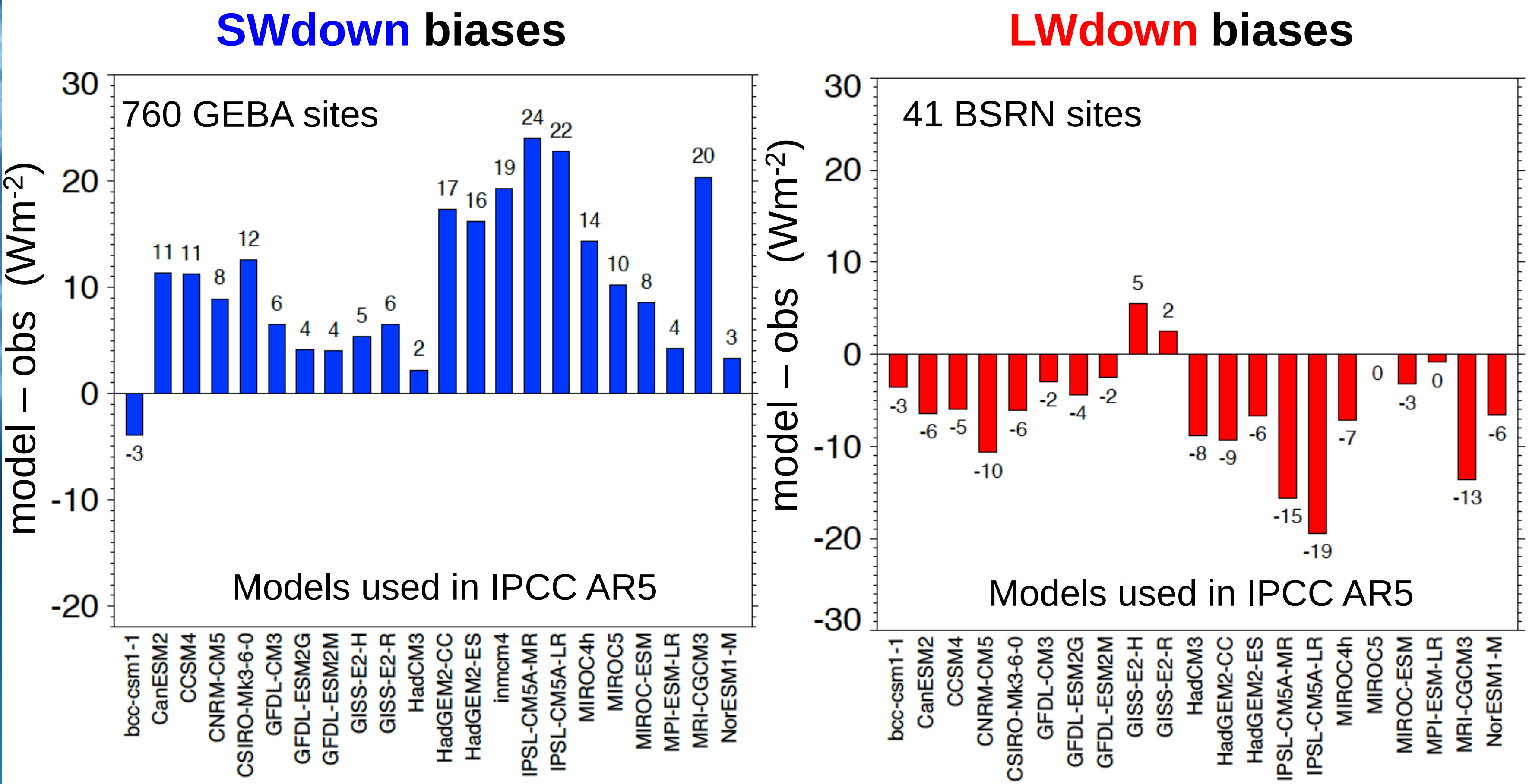


HadCM3



LW_{down} against 41 BSRN sites

Validation of global climate models



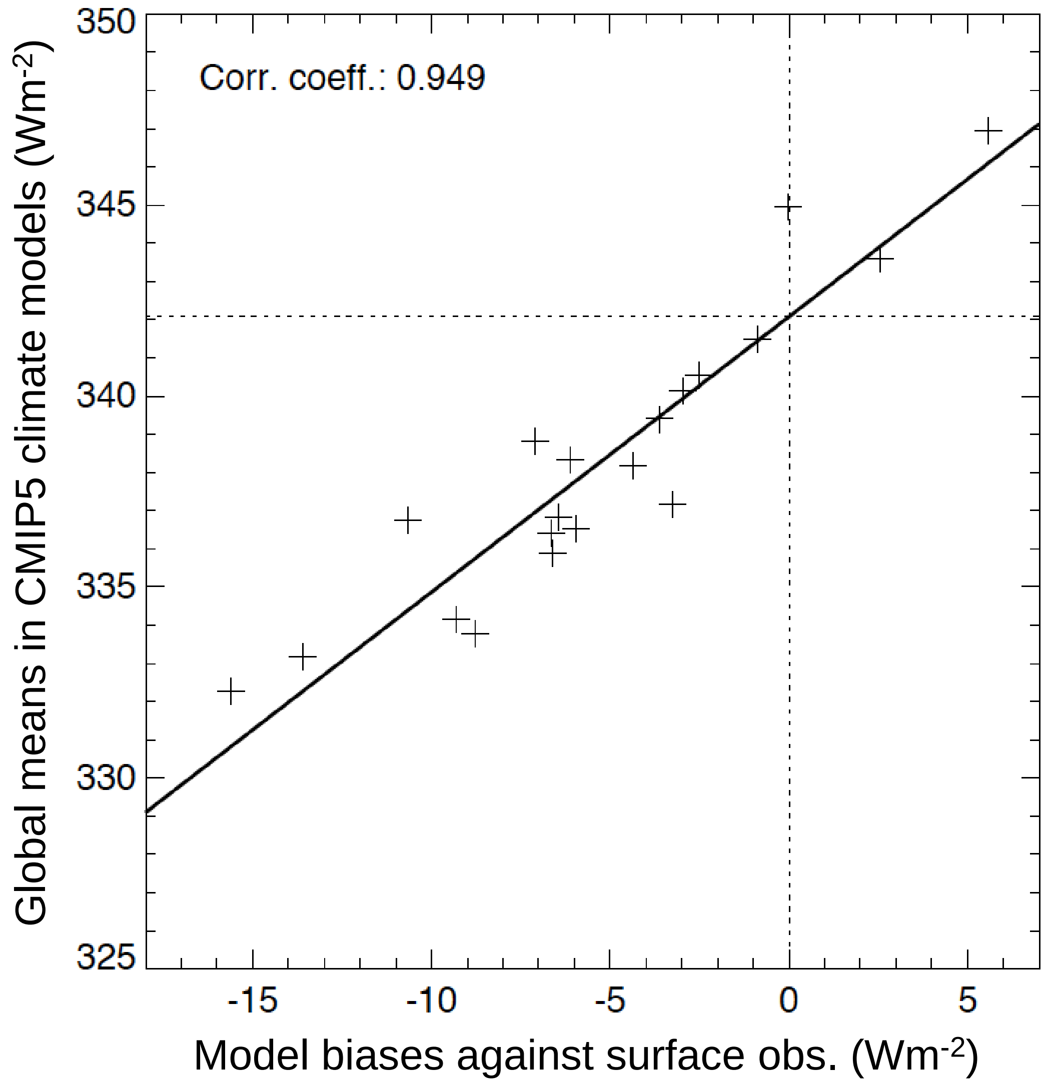
IPCC AR5 models tend to overestimate downward shortwave and underestimate downward longwave radiation at Earth ‘s surface

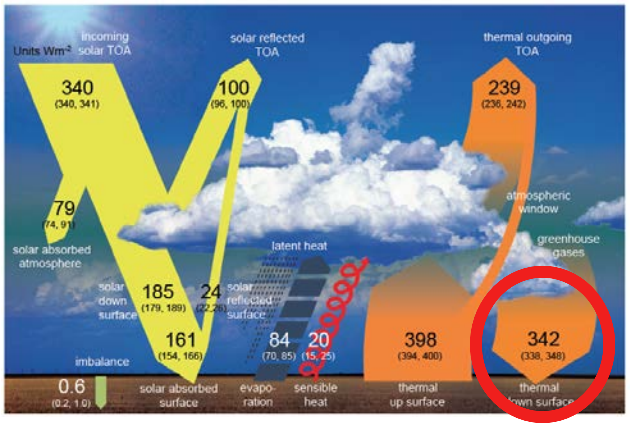
Wild et al. 2013, Climate Dynamics

Best estimates for global mean surface fluxes

Surface Longwave down

GCM global means versus their biases averaged over 41 BSRN sites





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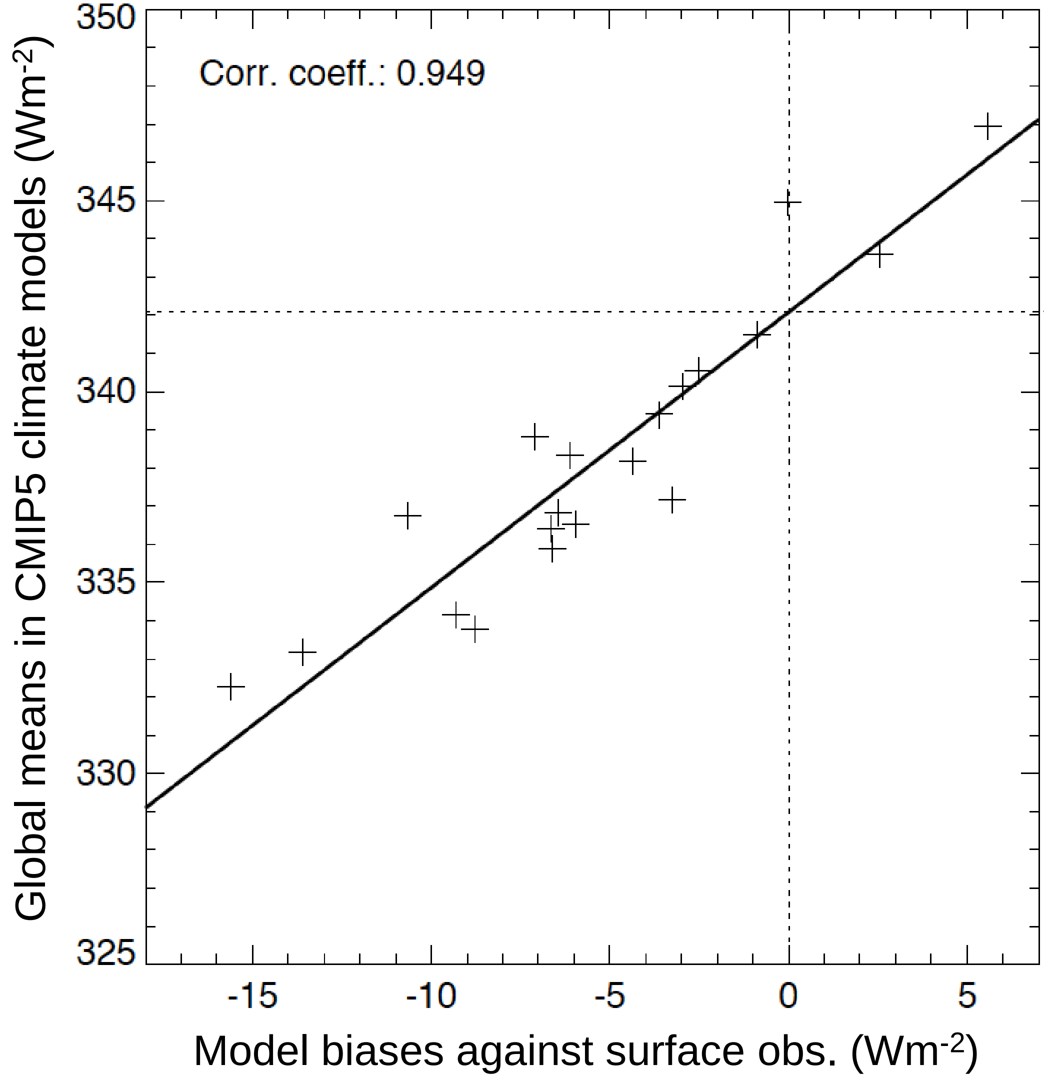
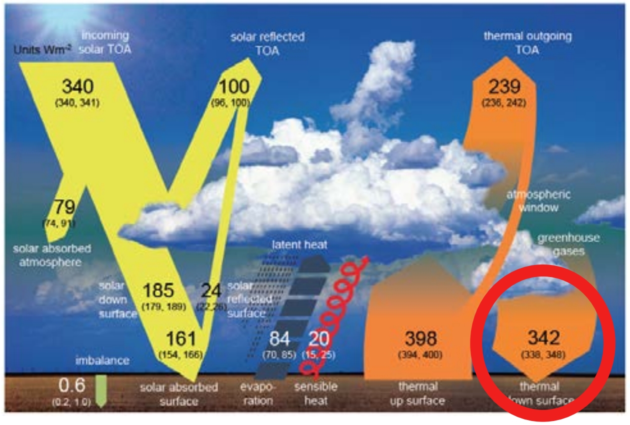


Best estimate surface LW down: ***342 Wm^{-2}***



Wild et al. 2013, Climate Dynamics

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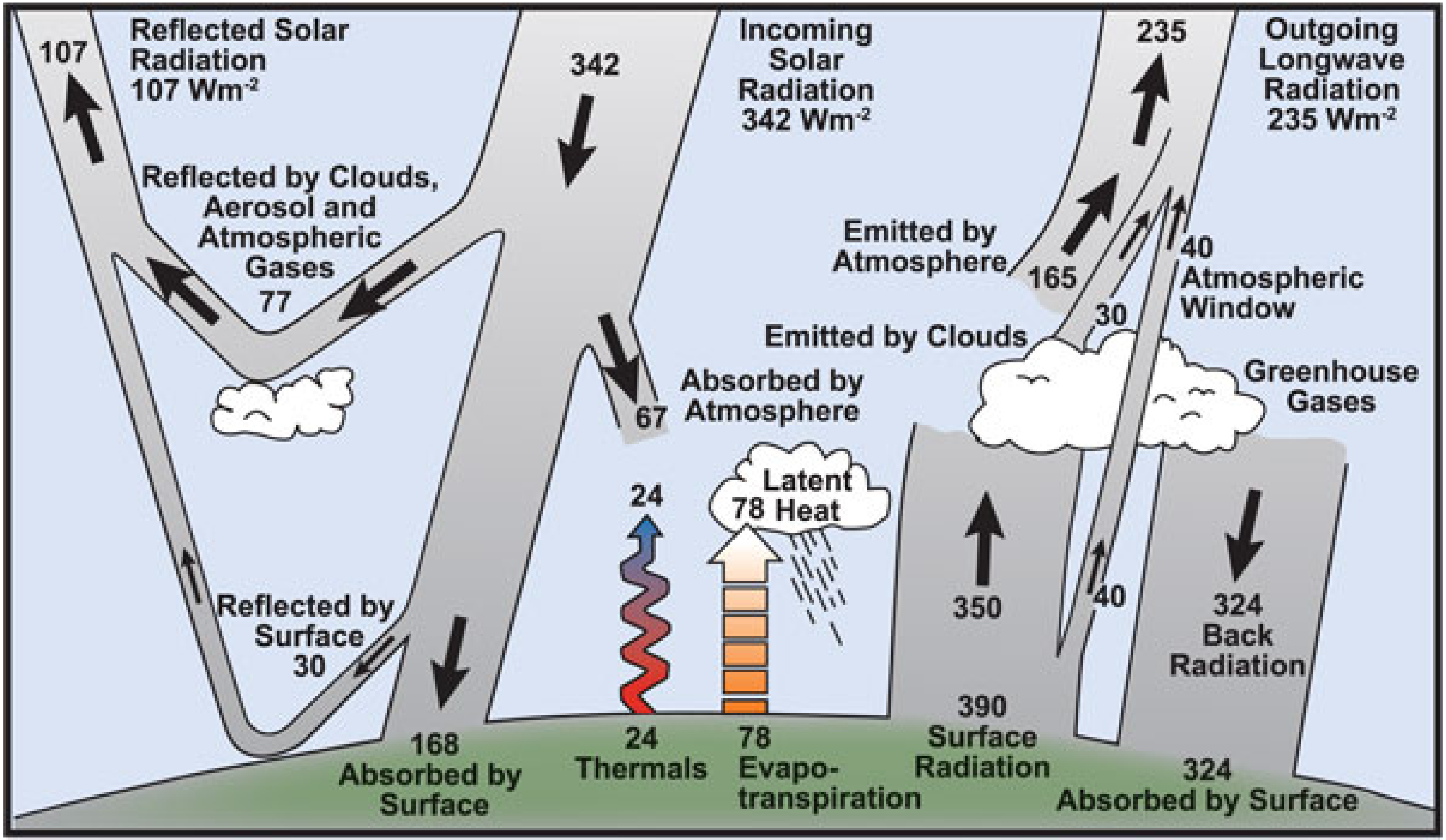
Revision of IPCC AR4 Energy Balance Figure

Units Wm^{-2}



IPCC AR4, based on Kiehl and Trenberth

Wild 2012: A facelift for the picture of the global energy balance, *Atmos. Environ.* **55**

Revision of IPCC AR4 Energy Balance Figure

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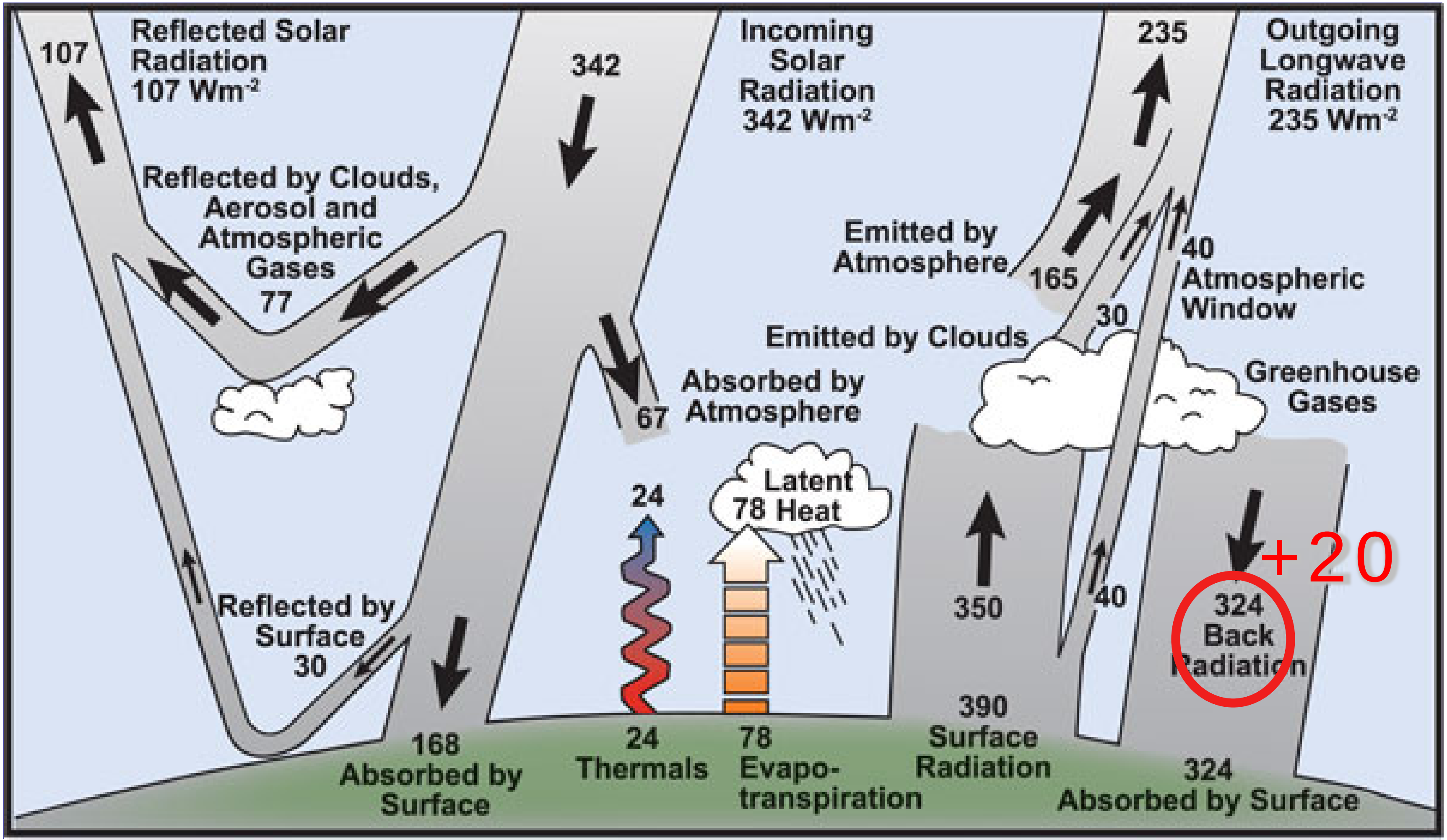

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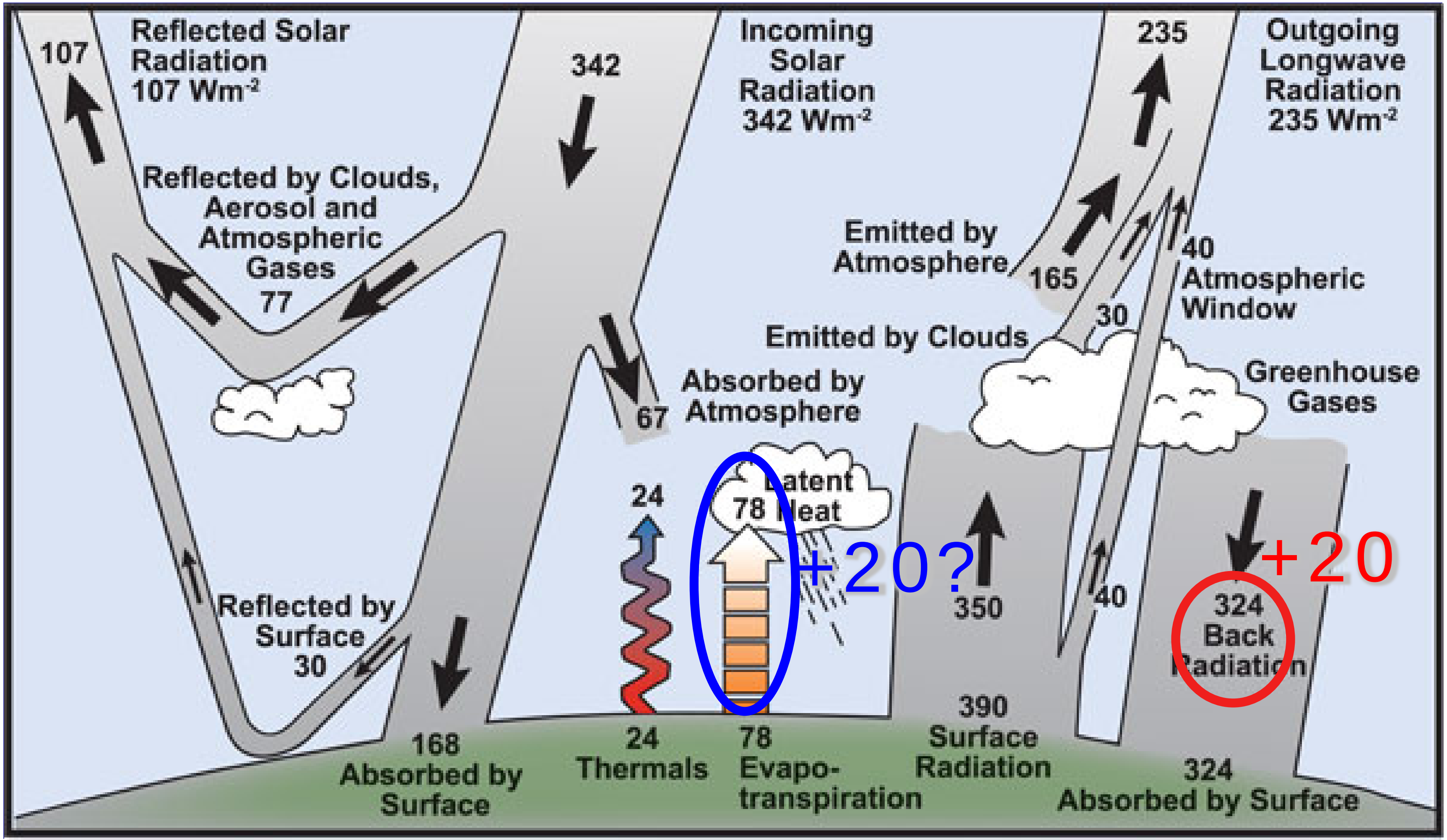

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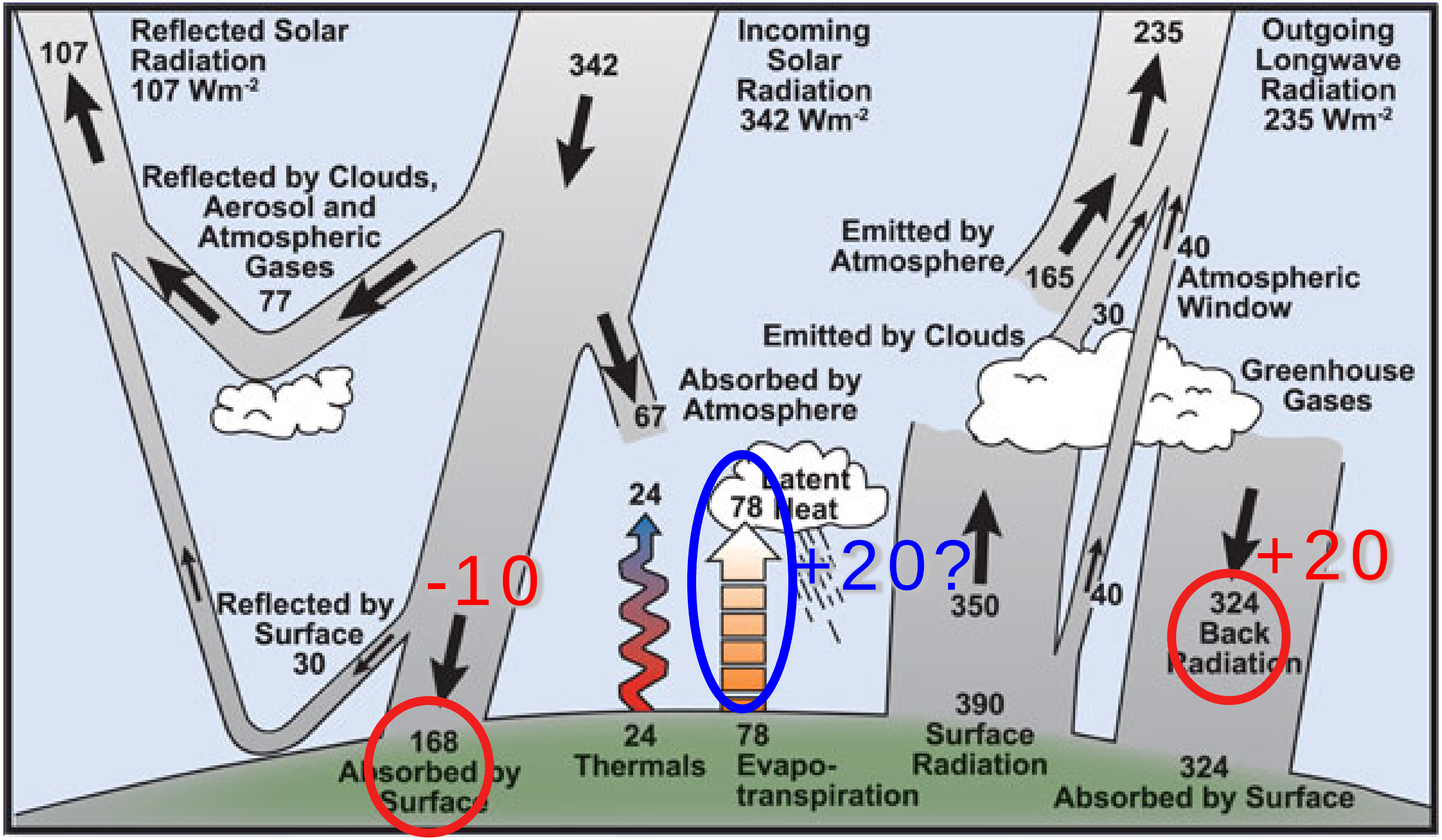

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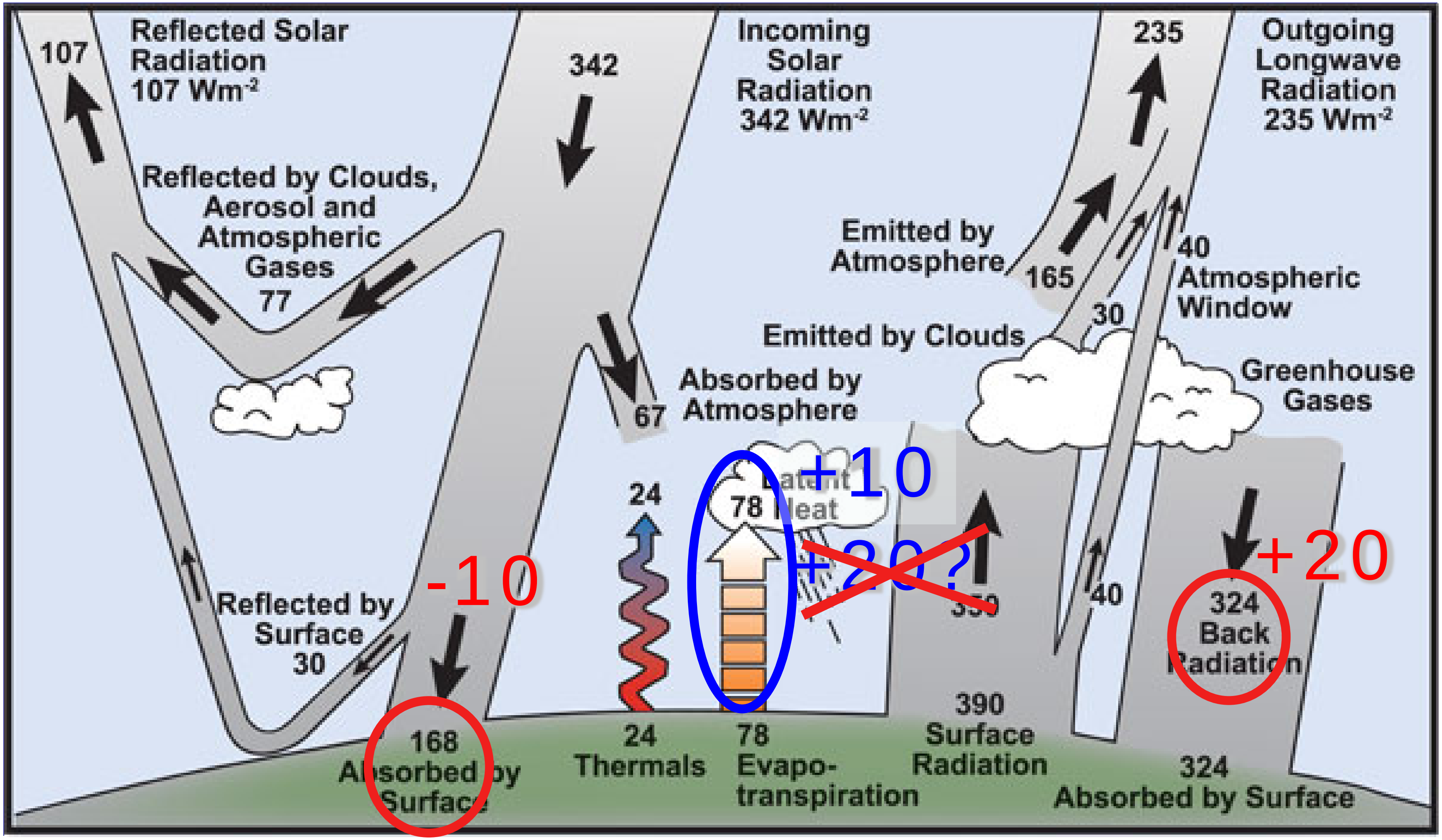

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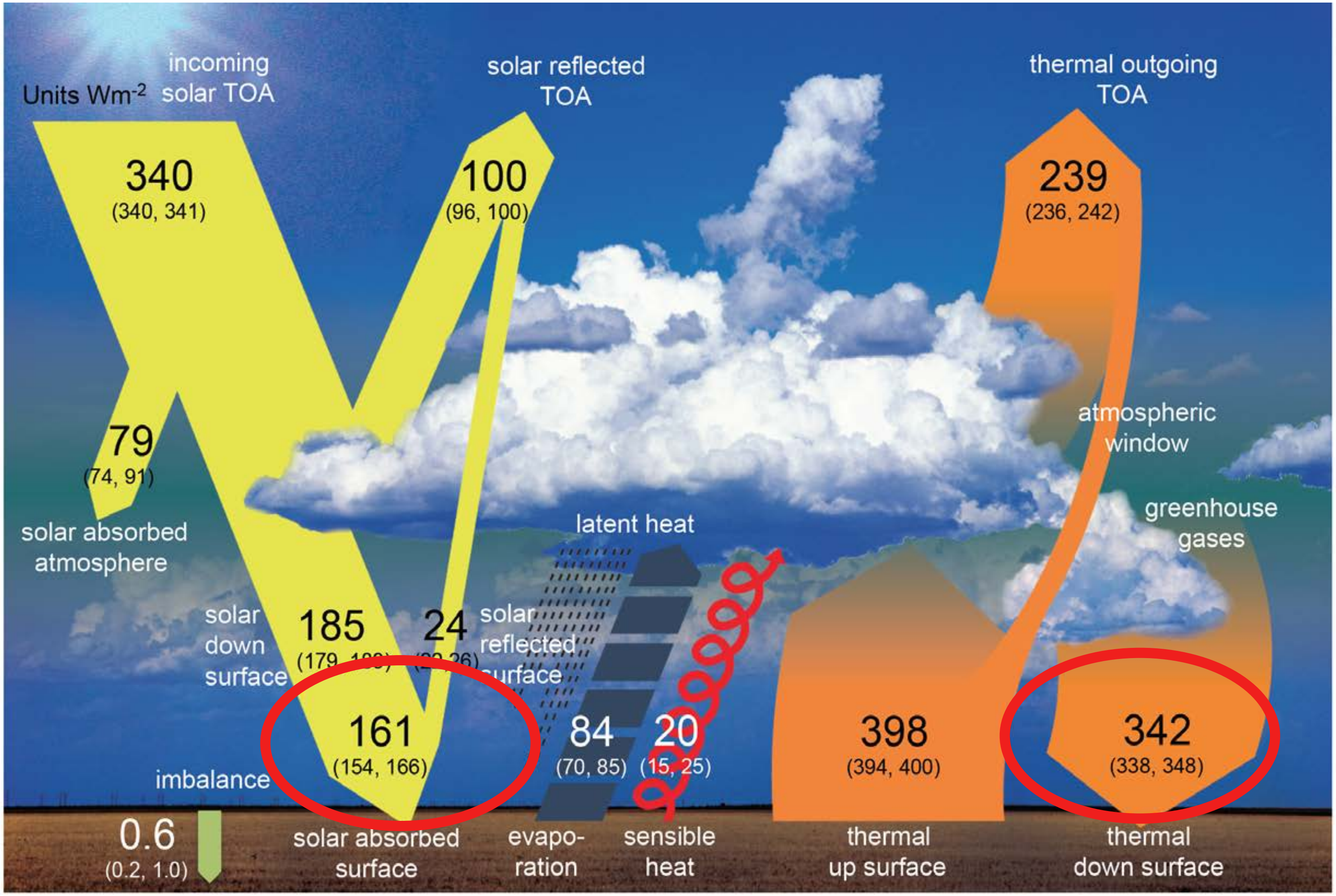
Global Energy Balance in IPCC AR5

Revised estimates consistent with direct observations

Units Wm^{-2}

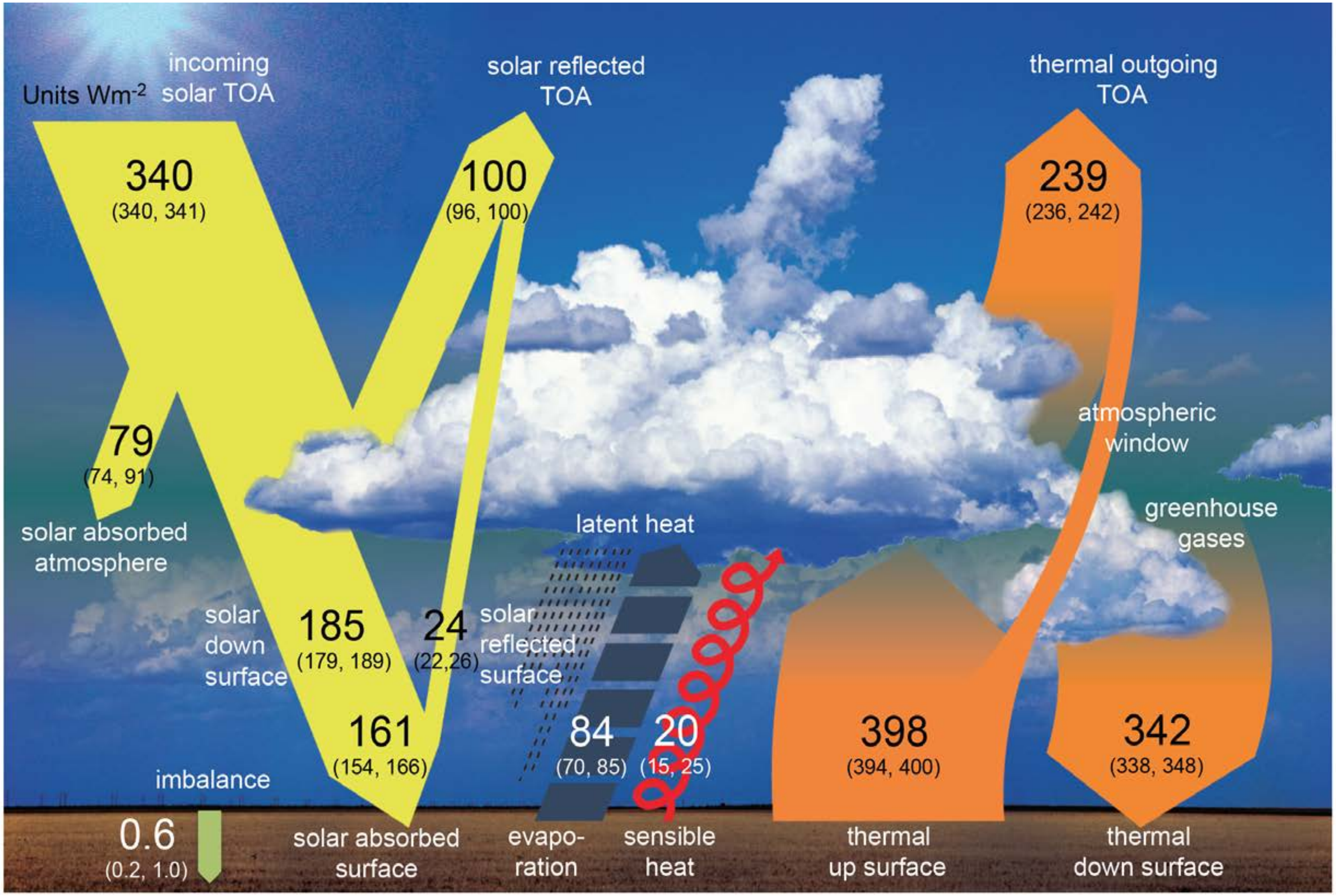


IPCC AR5 / Wild et al. 2013 Climate Dynamics

Global Energy Balance in IPCC AR5

Anthropogenic Perturbations

Units Wm^{-2}



IPCC AR5 / Wild et al. 2013 Climate Dynamics

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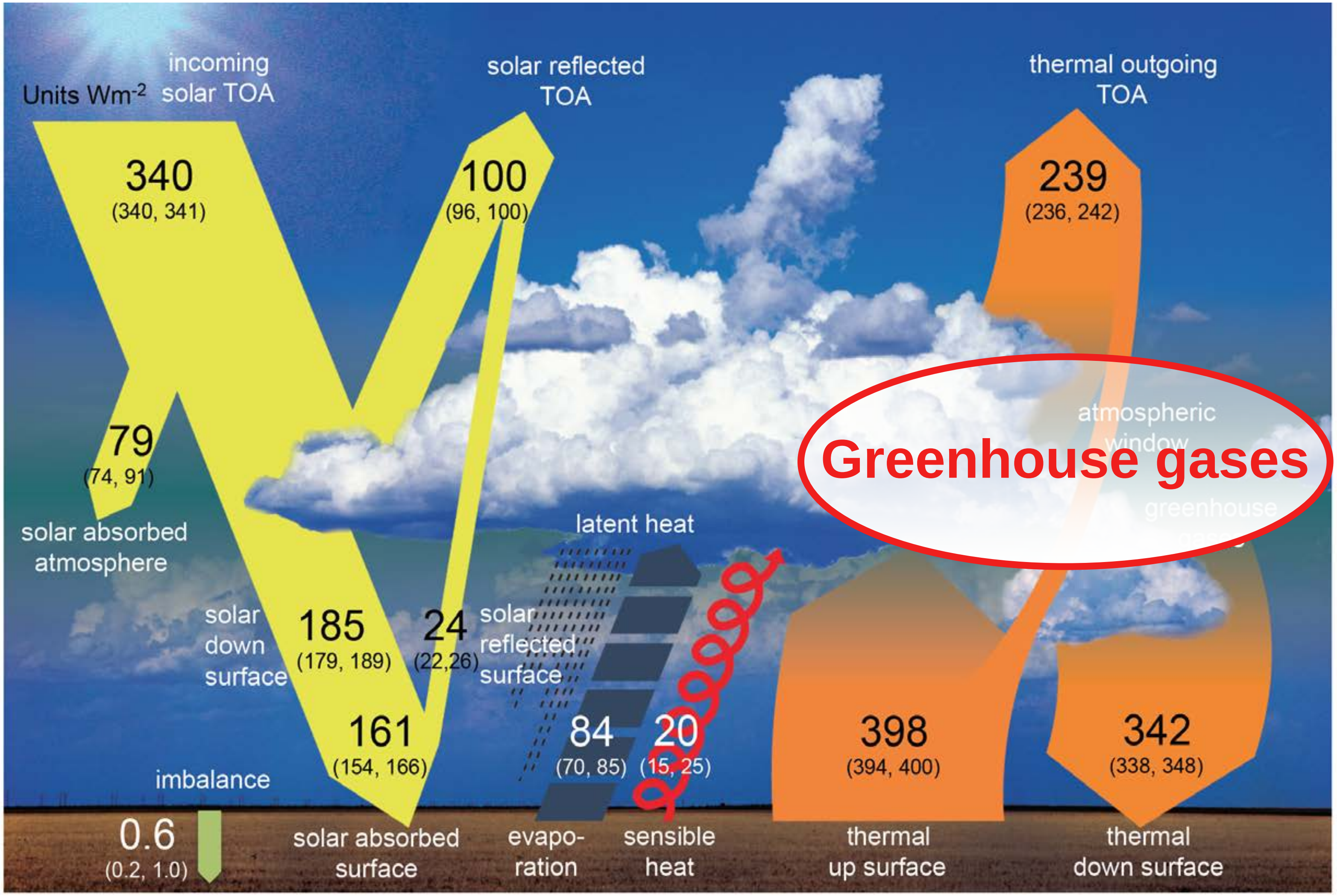

IPCC AR5 / Wild et al. 2013 Climate Dynamics

Global Energy Balance in IPCC AR5

Anthropogenic Perturbations

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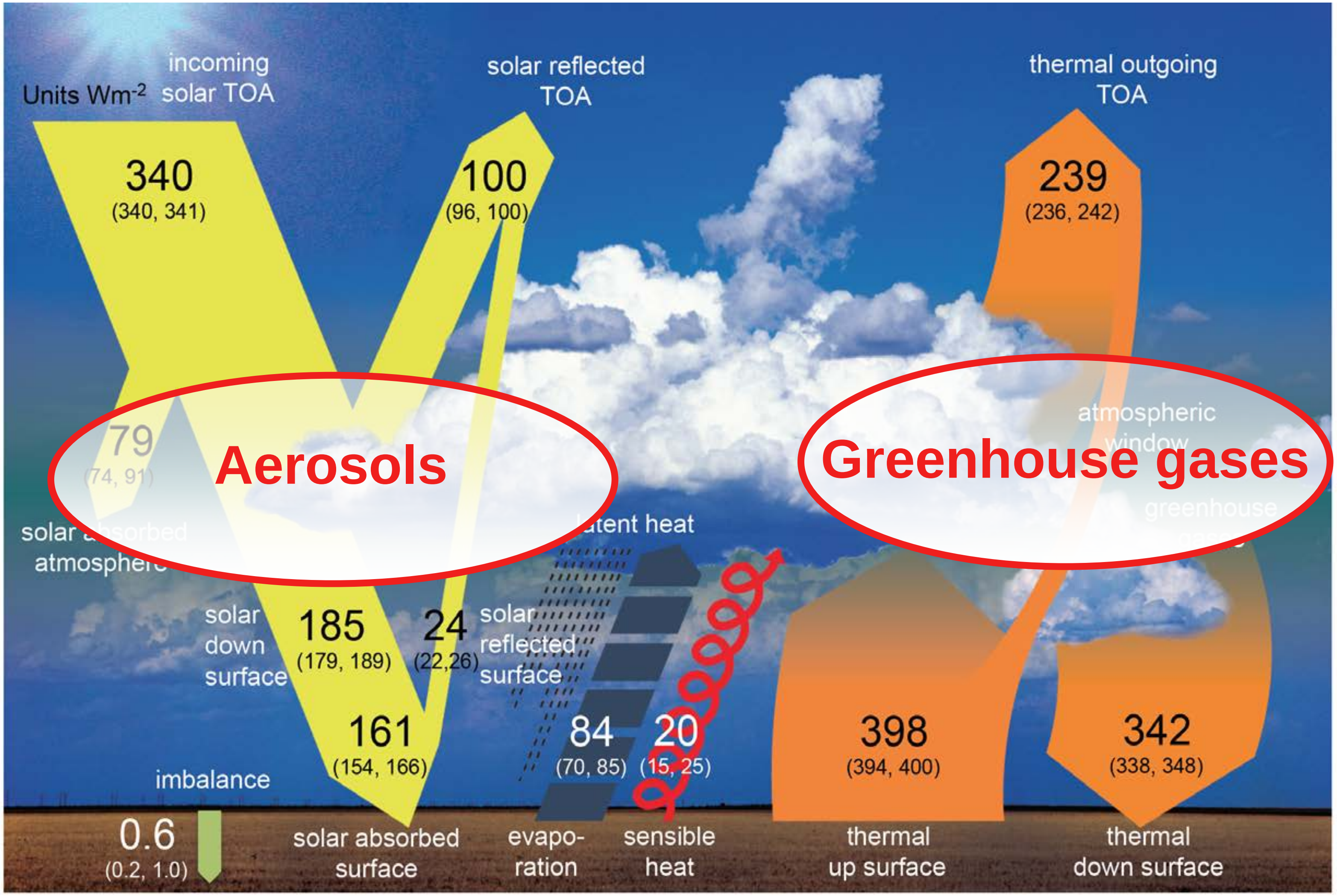

IPCC AR5 / Wild et al. 2013 Climate Dynamics

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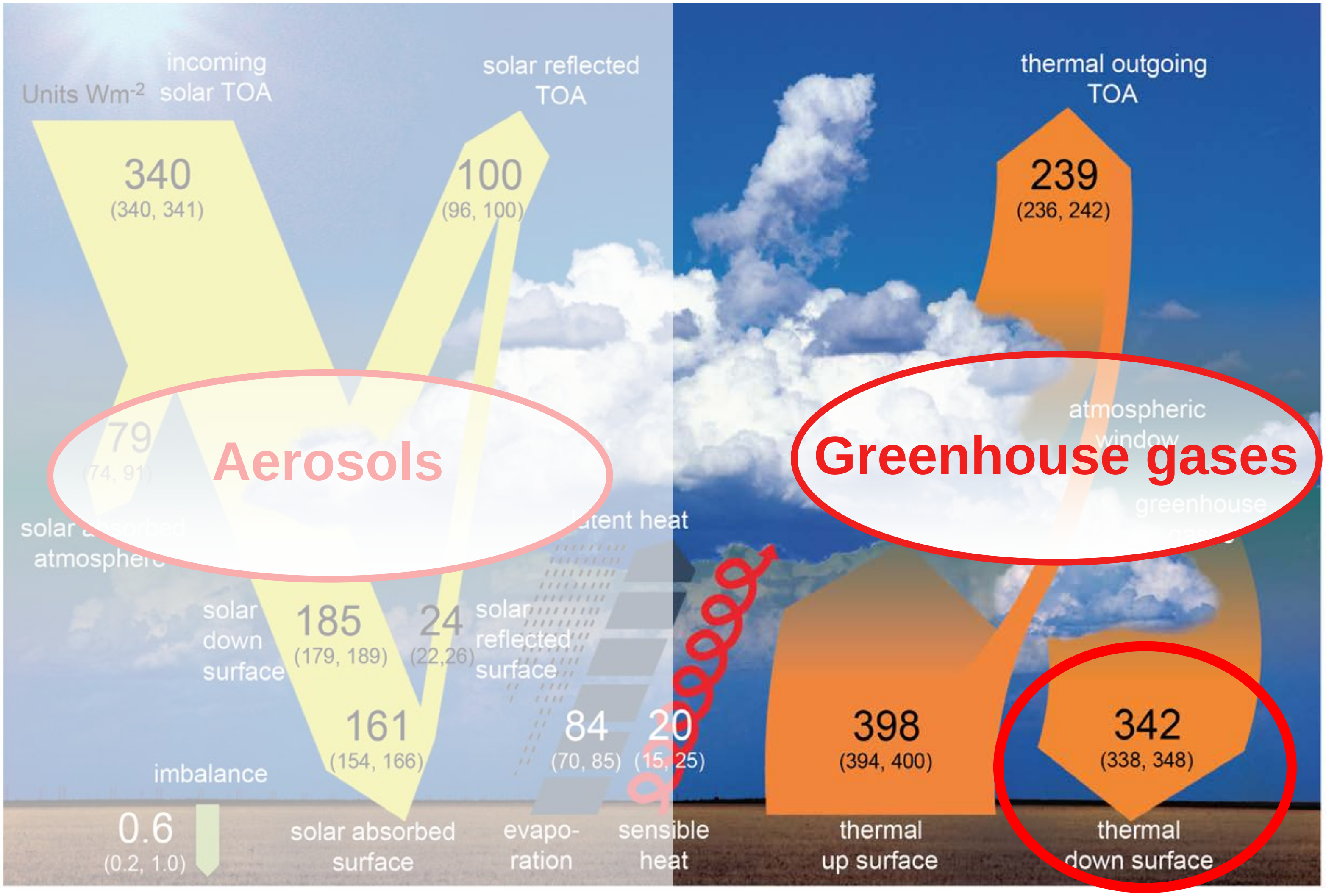
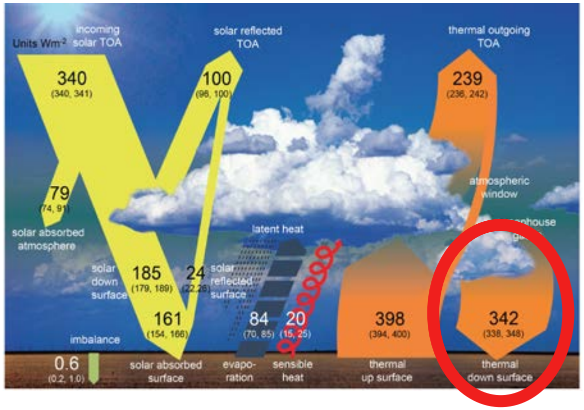
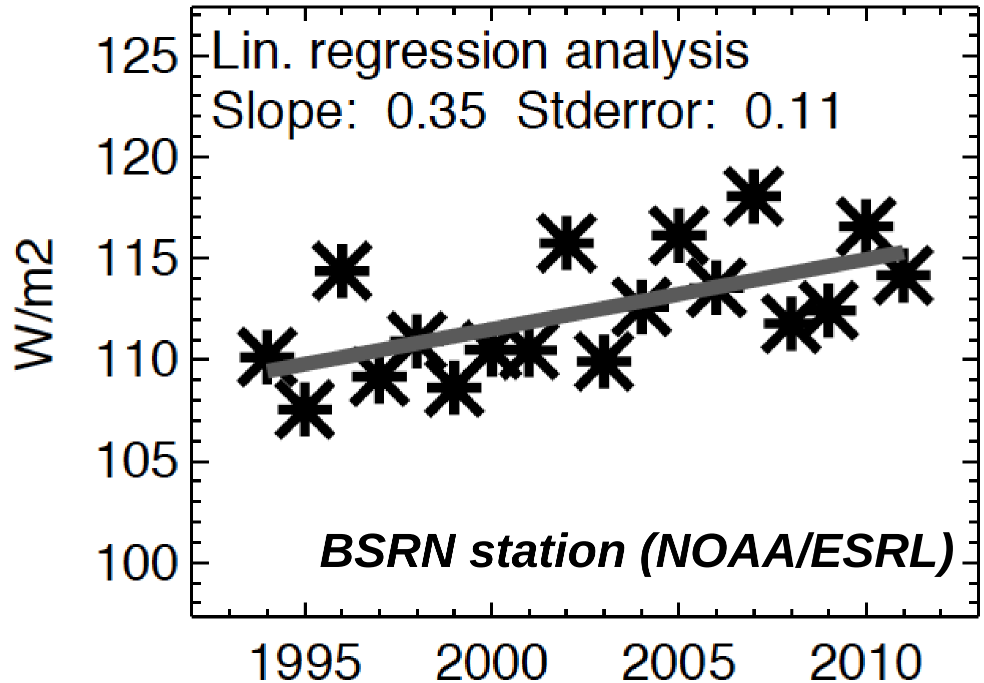


IPCC AR5 / Wild et al. 2013 Climate Dynamics

Observed changes downward longwave radiation

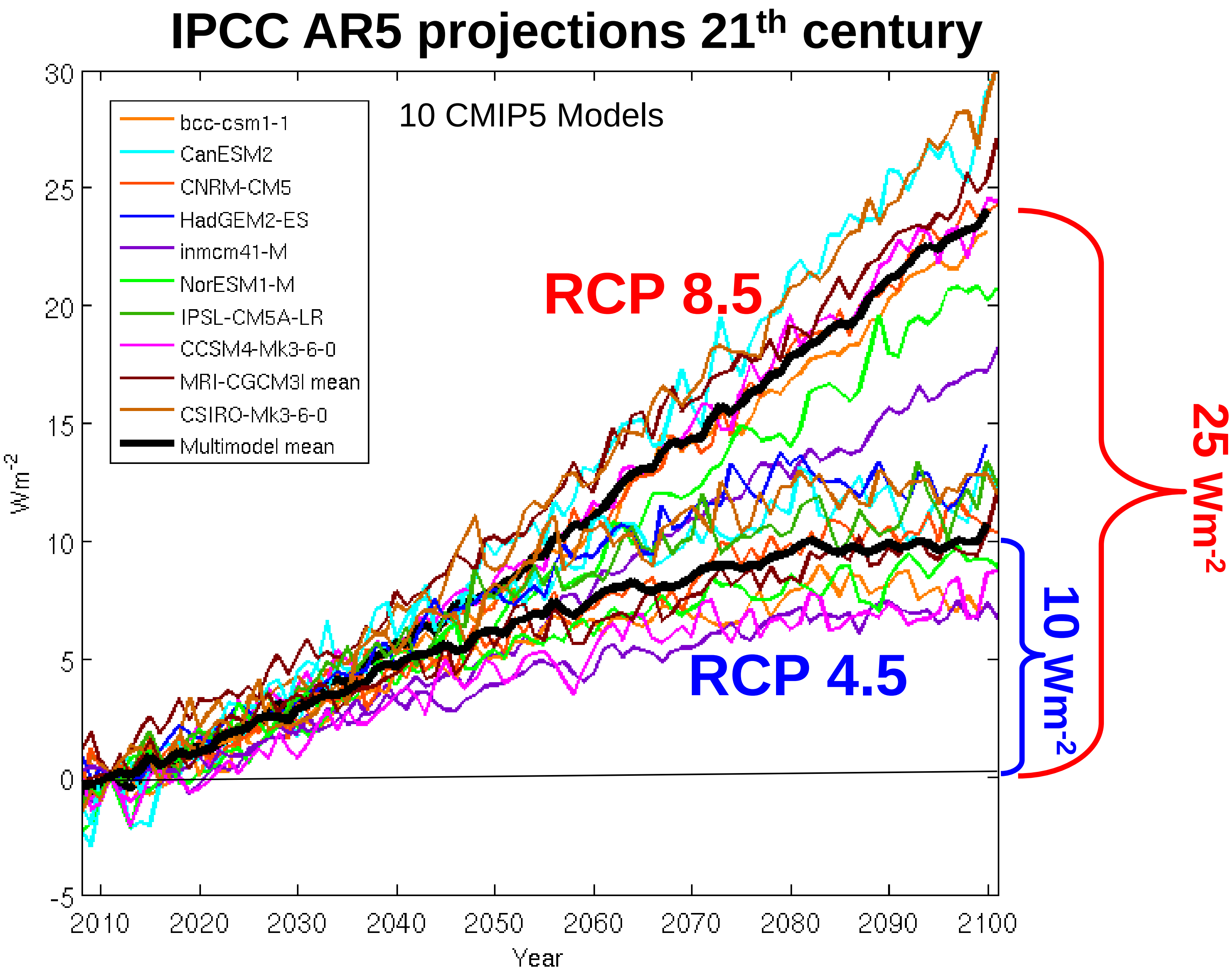


LW down South Pole 1994-2011



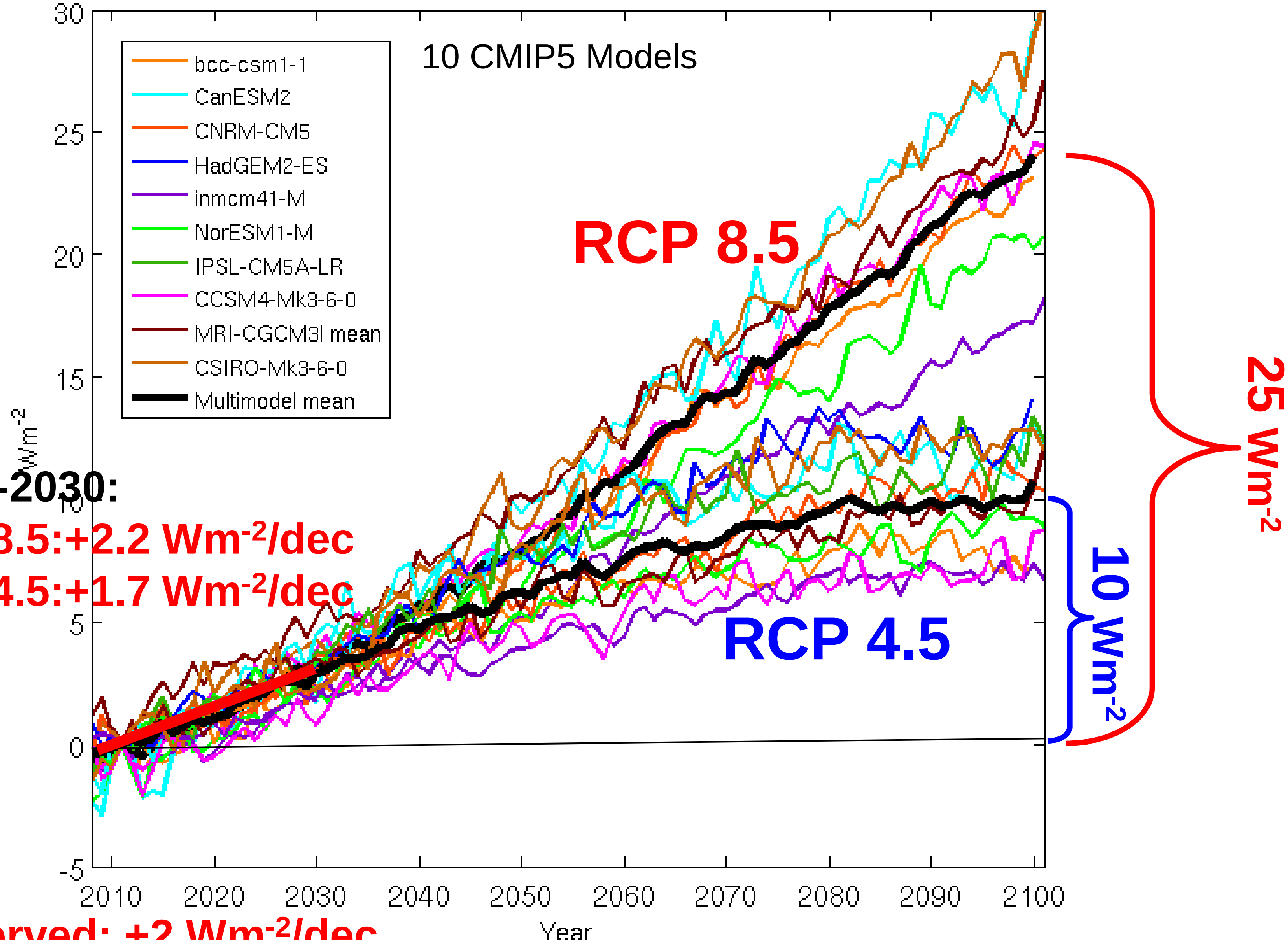
- ***“Greenhouse effect at the surface“:*** *most directly affected by changes in atmospheric greenhouse gases*
- ***Average change at BSRN sites: +2 $Wm^{-2}dec^{-1}$***
- *Expected to undergo largest changes of all energy balance components in coming decades*

Downward longwave in IPCC AR5 scenarios



Downward longwave in IPCC AR5 scenarios

IPCC AR5 projections 21th century



2010-2030:

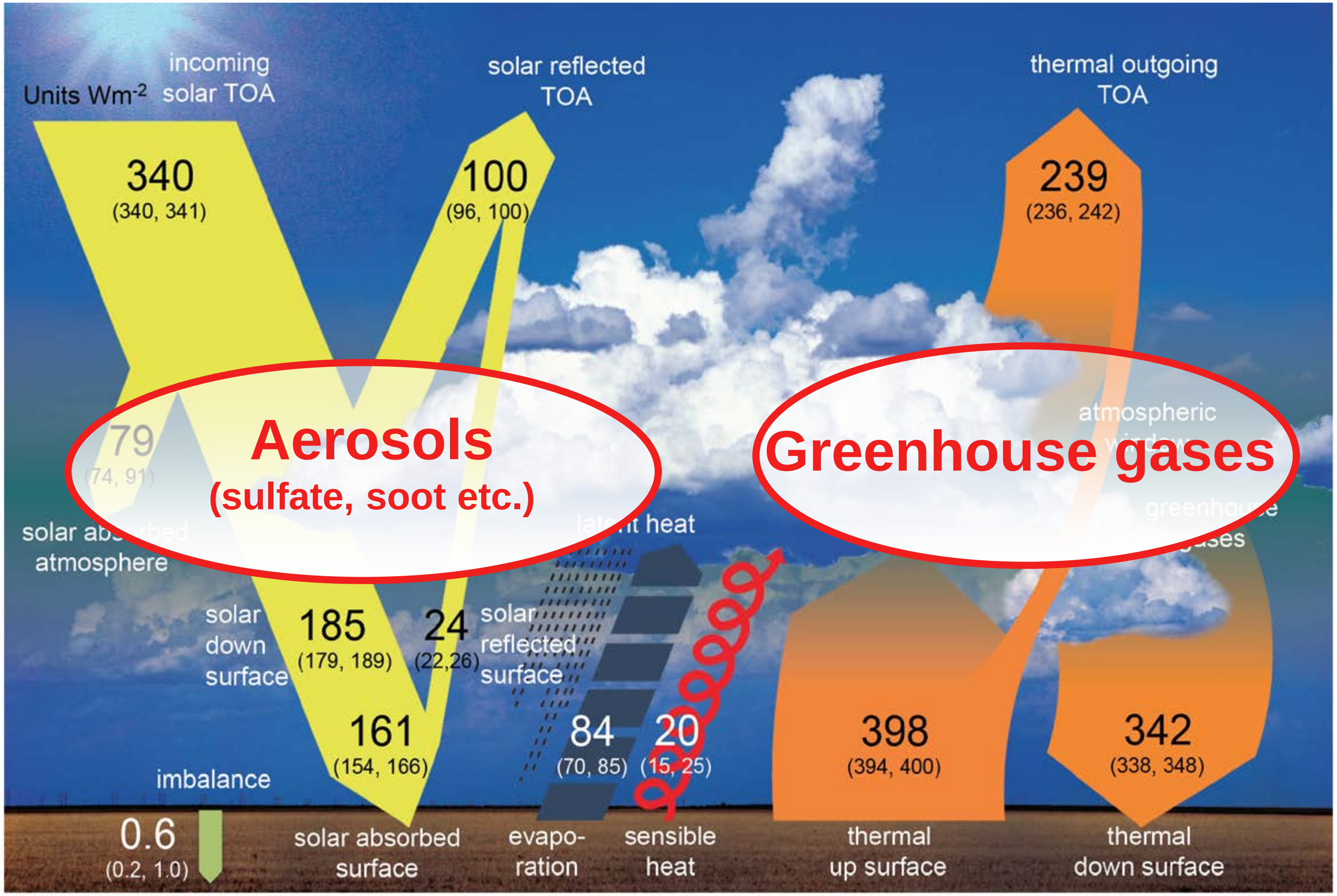
RCP8.5:+2.2 Wm^{-2}/dec

RCP4.5:+1.7 Wm^{-2}/dec

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

Global Mean Energy Balance in IPCC AR5

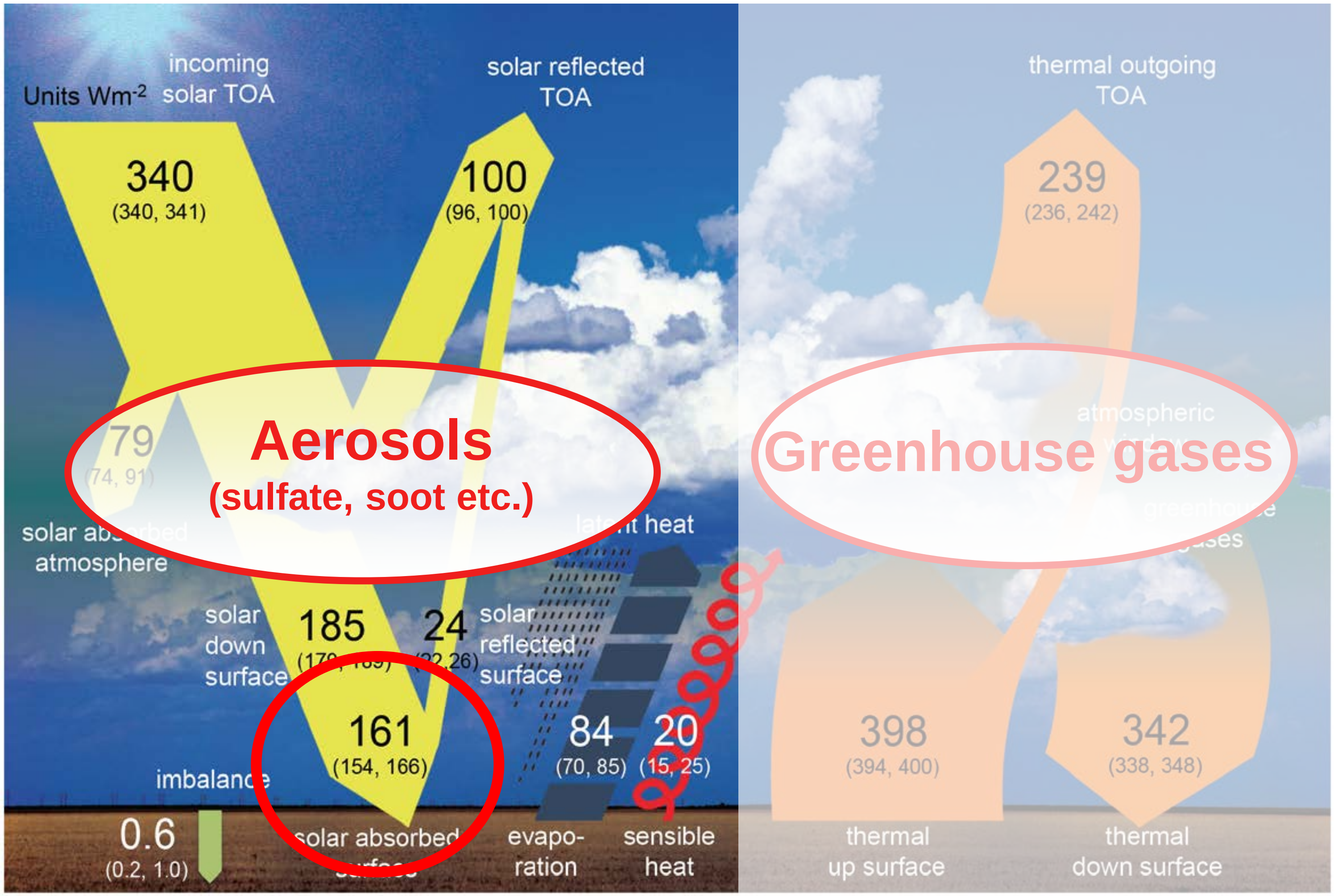
Anthropogenic interference with the climate system



IPCC AR5 / Wild et al. 2013 Climate Dynamics

Global Mean Energy Balance in IPCC AR5

Anthropogenic interference with the climate system

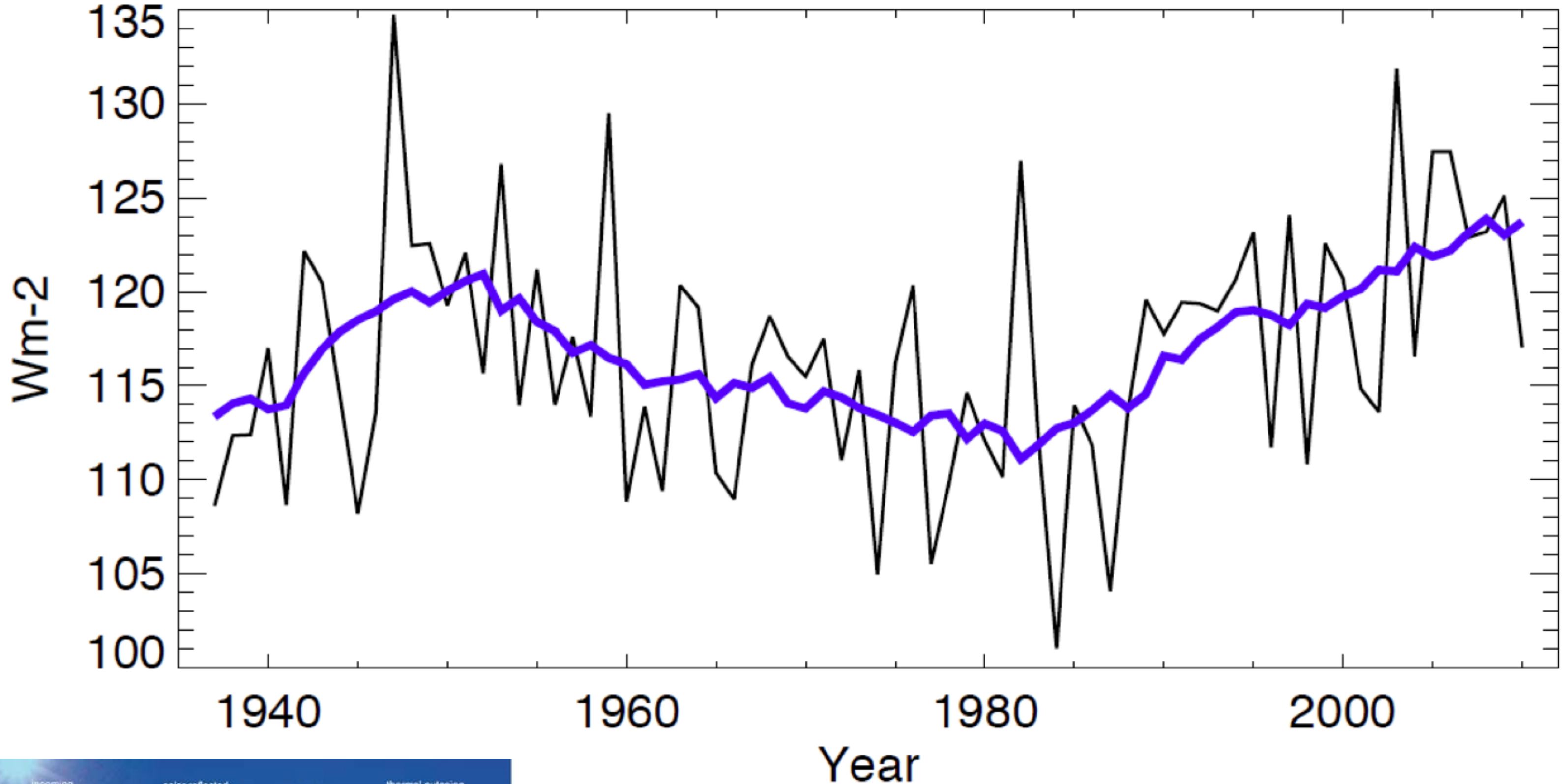


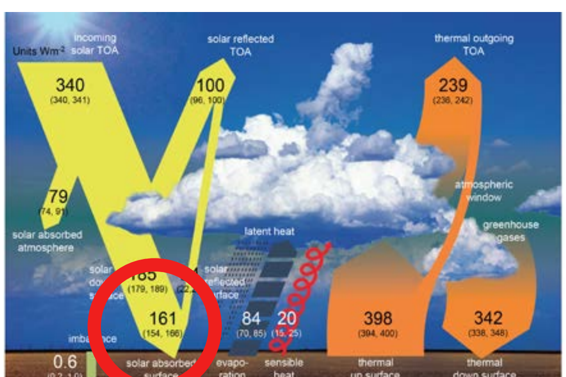
Surface solar radiation

IPCC AR5 / Wild et al. 2013 Climate Dynamics

Decadal changes in surface solar radiation

Potsdam, Germany, 1937 – 2010



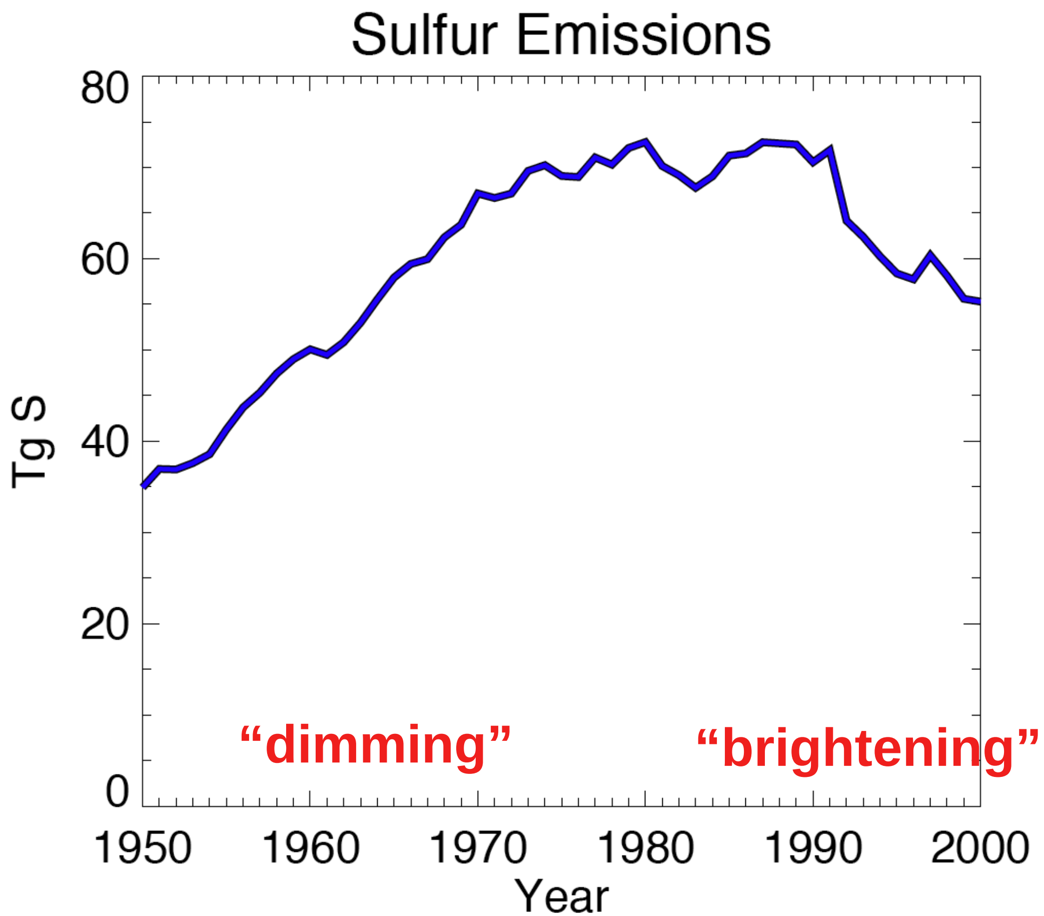


"dimming"

"brightening"

Wild et al. 2005 Science
Wild 2012, BAMS

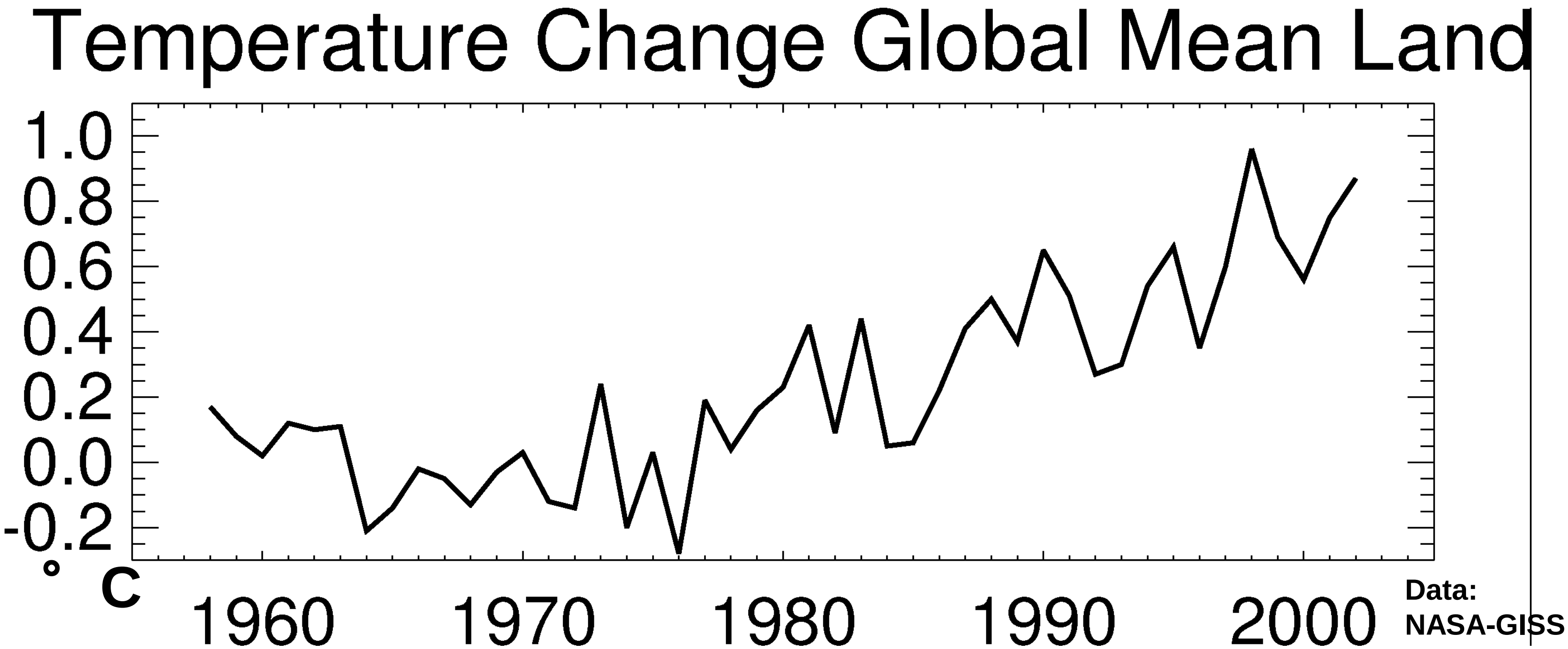
From dimming to brightening: Causes



Global Anthropogenic Sulfur Emissions
1950 - 2000

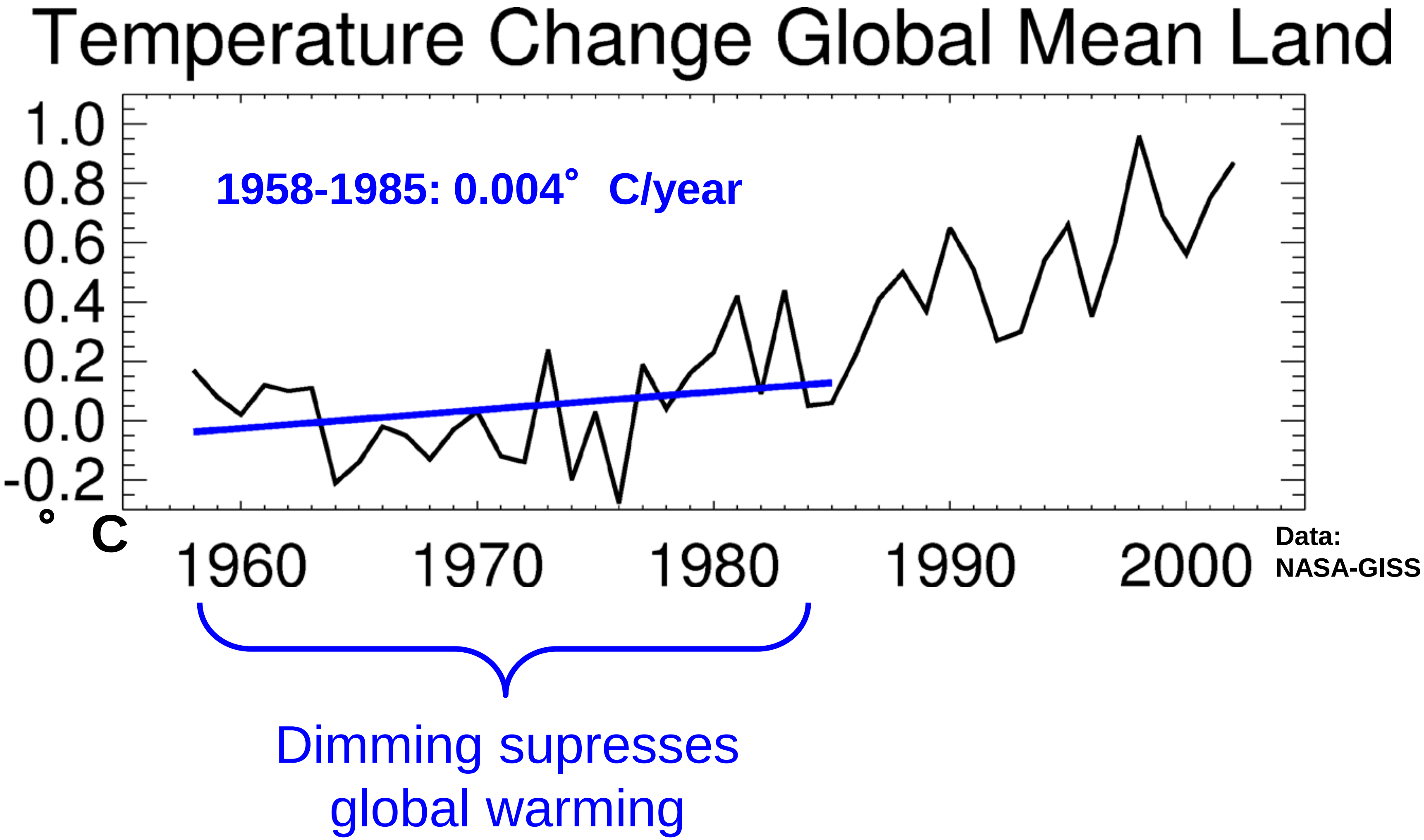
Wild et al. 2005 Science
Wild 2012, BAMS

Solar dimming and greenhouse warming



Wild et al. 2007 Geophys. Res. Lett.

Solar dimming and greenhouse warming



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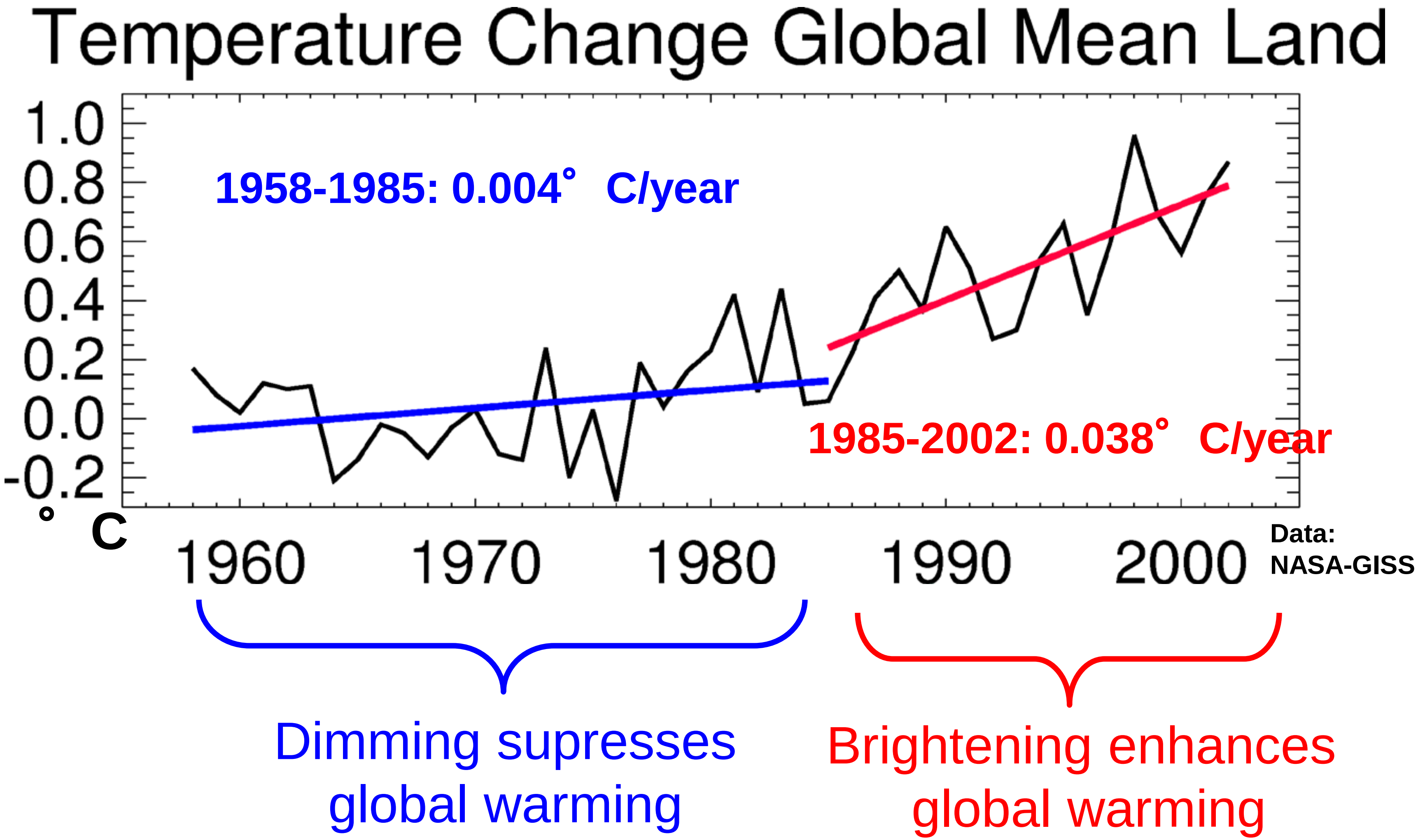

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Decadal changes in surface solar radiation

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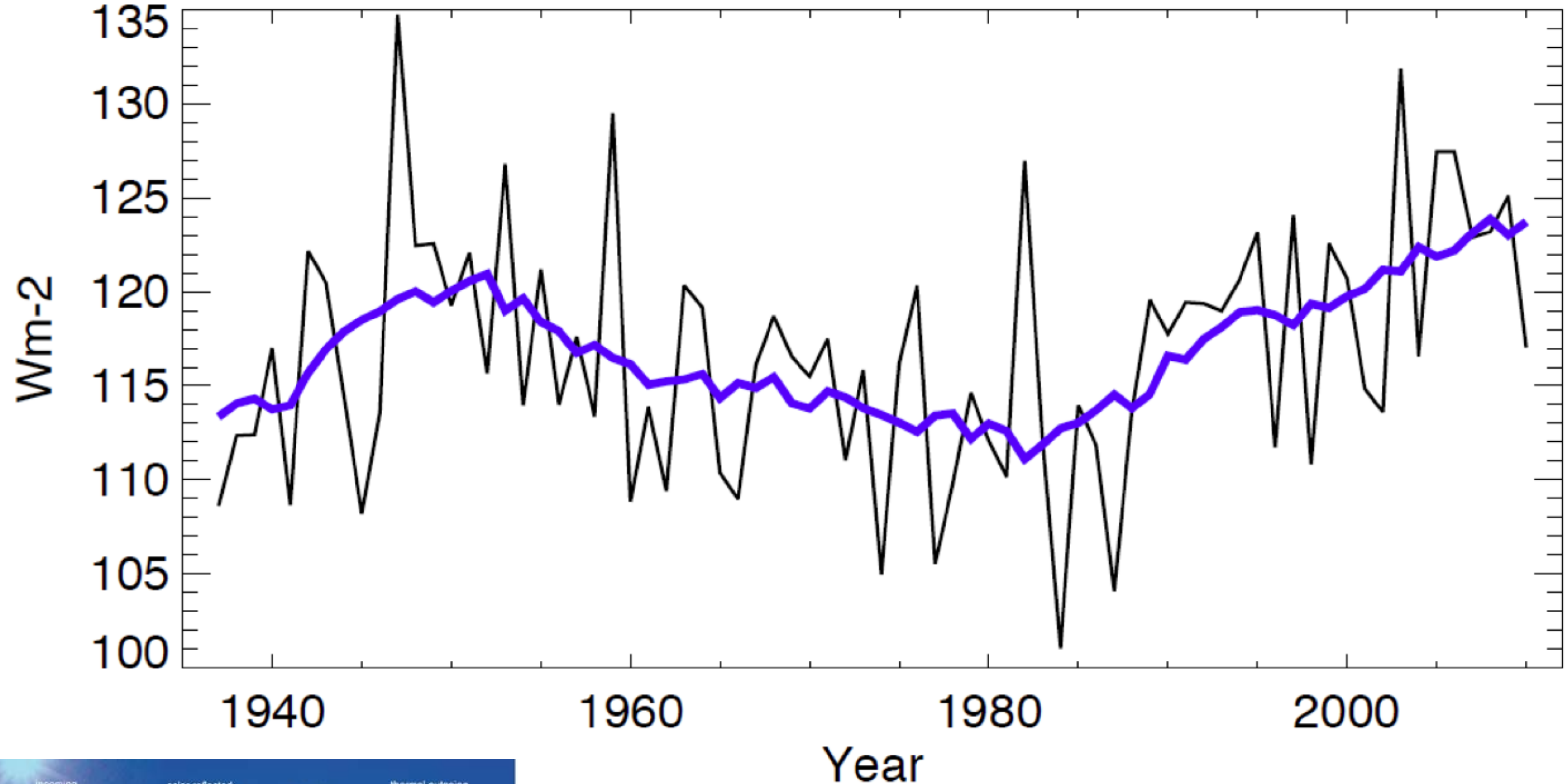

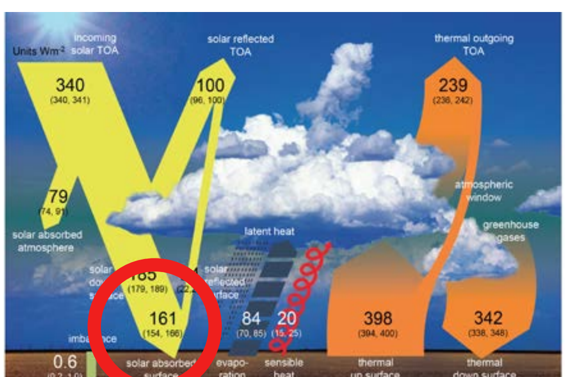

"dimming"

"brightening"

Spatial trend patterns from satellites

Wild 2009, JGR

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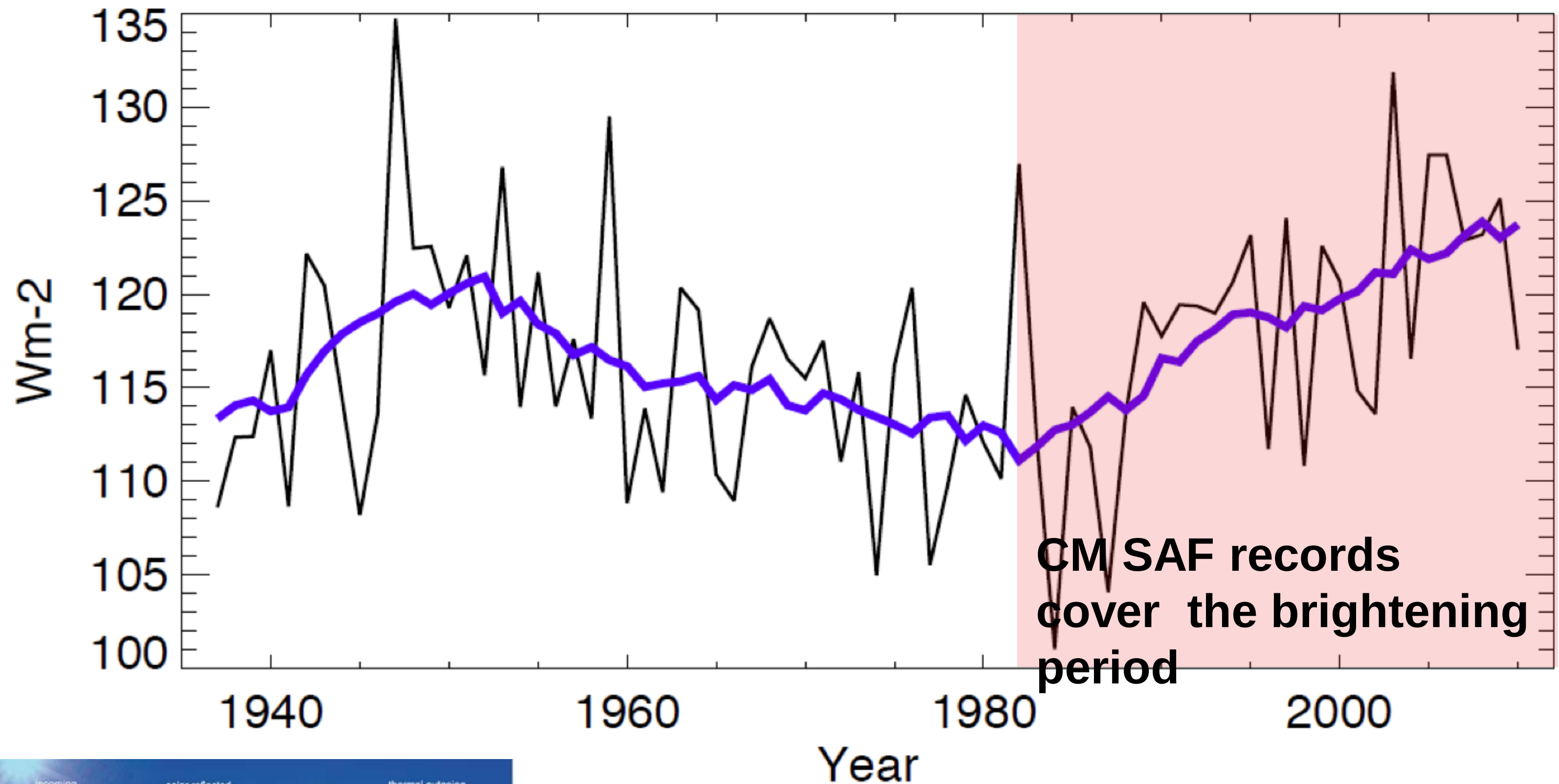
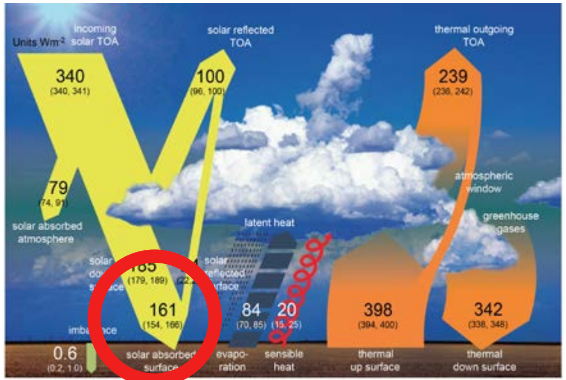
Decadal changes in surface solar radiation

Potsdam, Germany, 1937 – 2010





“dimming”

“brightening”

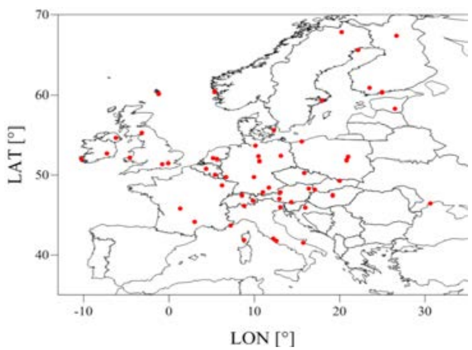
Spatial trend patterns from satellites

Wild 2009, JGR

Solar brightening in CM SAF MFG and GEBA

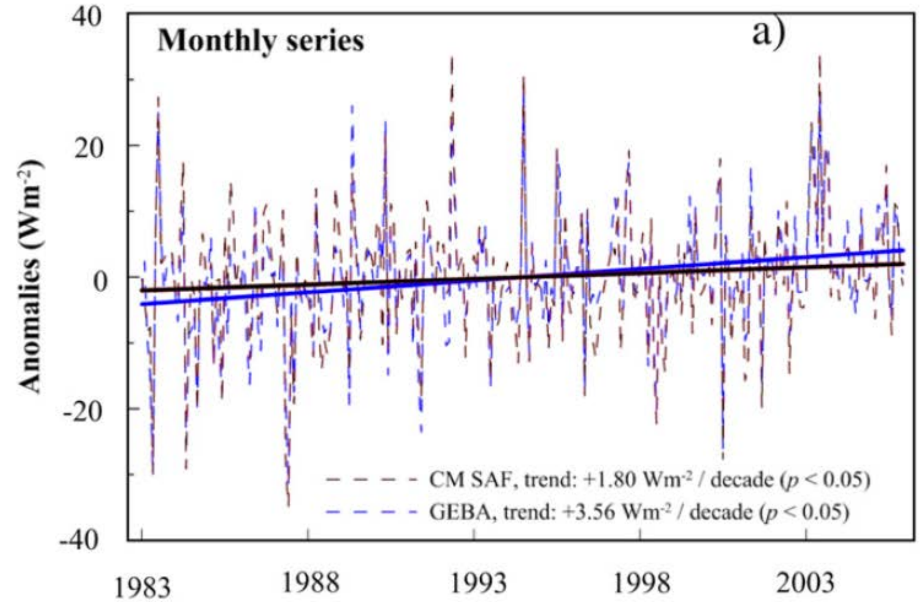
Trends in CMSAF and GEBA at 47 GEBA sites

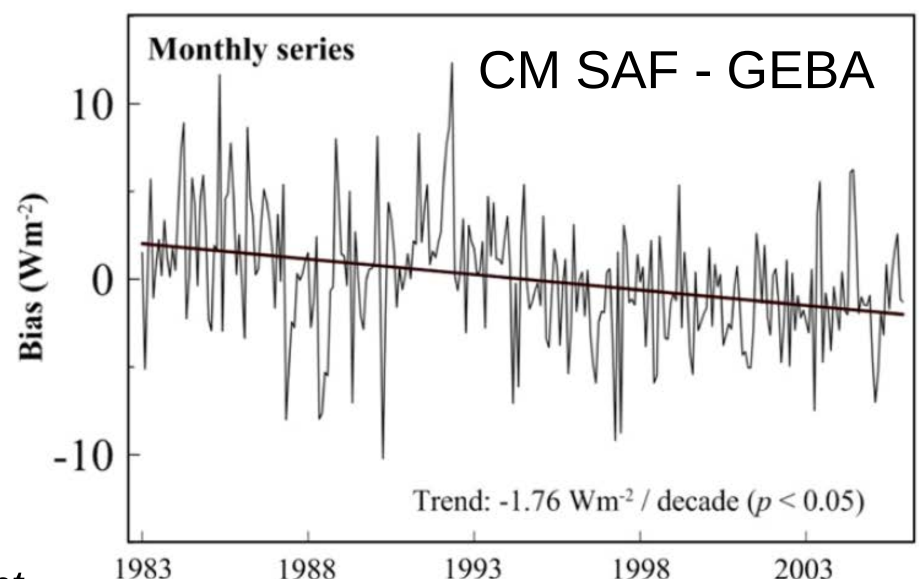
Trend (1983-2005):
CMSAF +1.8 Wm^{-2}/dec
GEBA +3.6 Wm^{-2}/dec



Difference time series not stable

Sanchez-Lorenzo, Wild, Trentmann 2013, Remote Sensing of Environment

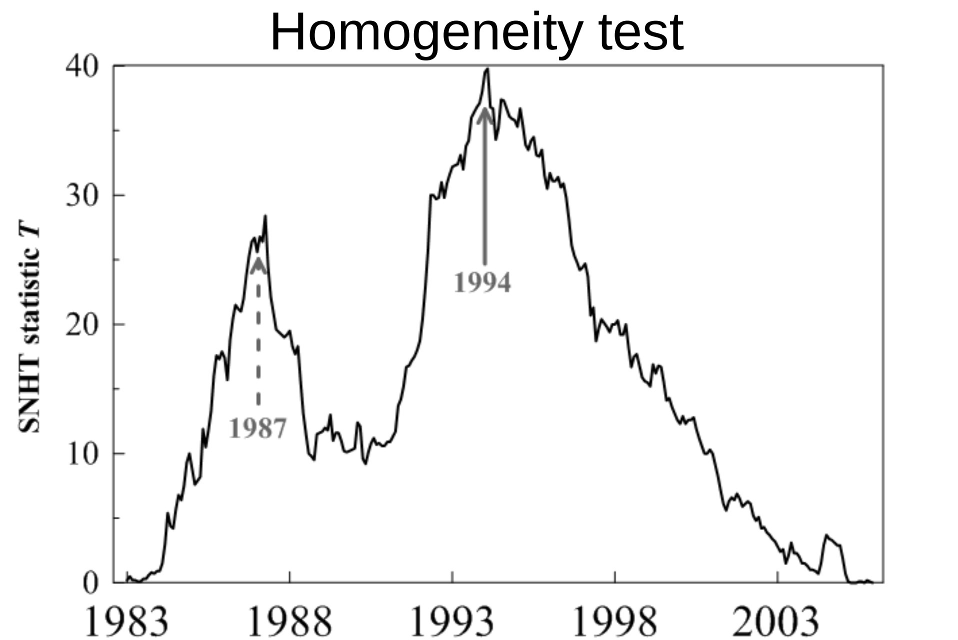


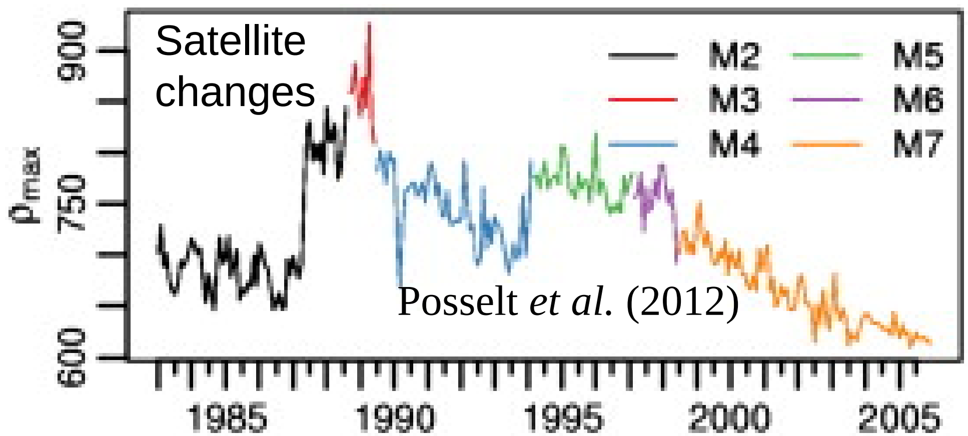


Inhomogeneities in the CM SAF Record

Homogeneity test identifies strong inhomogeneity in CMSAF record in 1994 (transition M4-M5 satellite)

No inhomogeneity after 1994





Inhomogeneities possibly due to the changes in Meteosat satellites

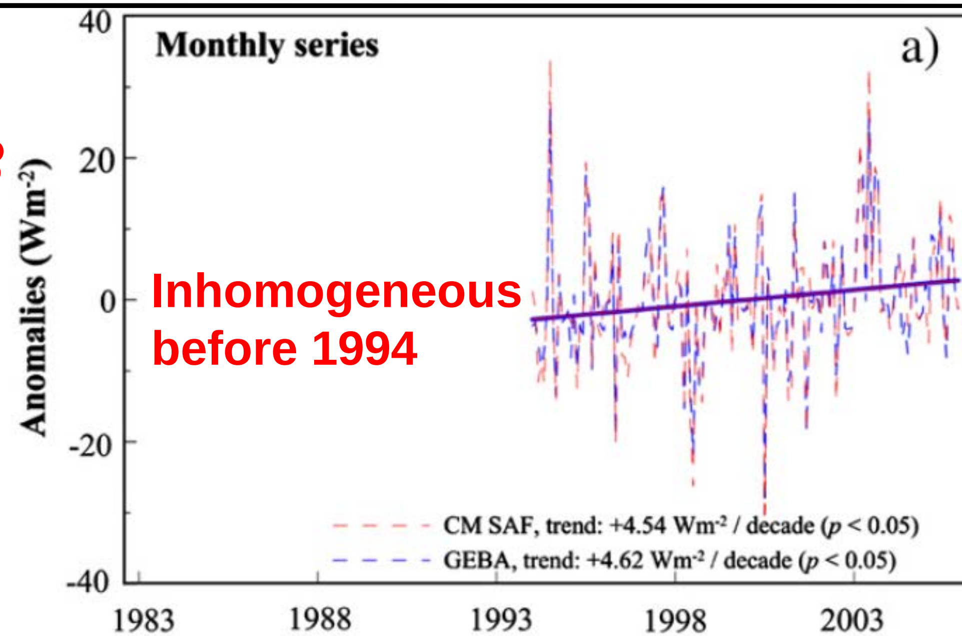
Sanchez-Lorenzo, Wild,Trentmann 2013, Remote Sensing of Environment

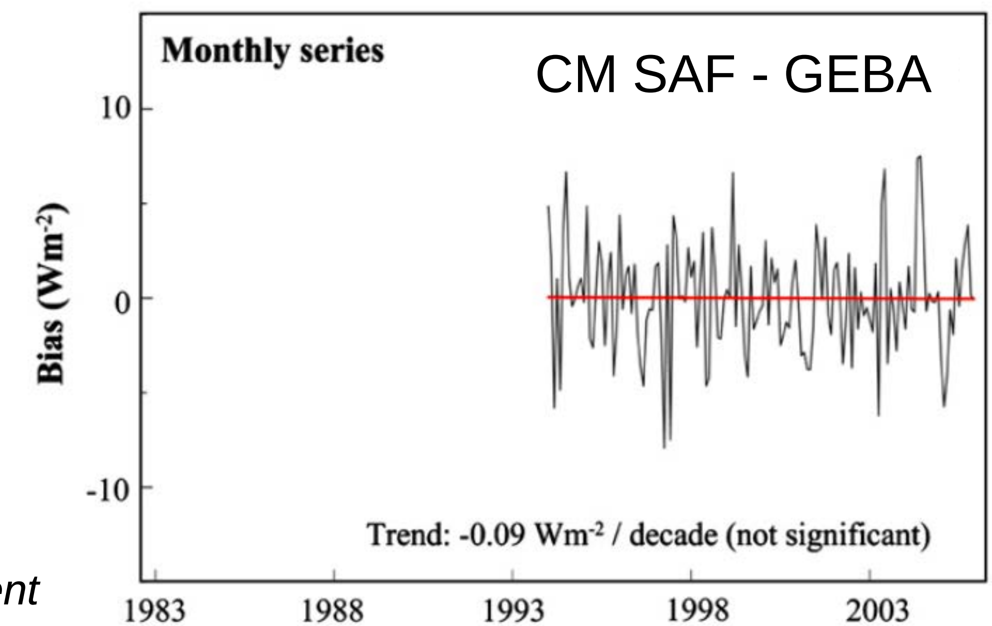
Trends in CM SAF and GEBA: 1994-2005

CMSAF record is homogeneous after 1993

Trends (1994-2005):
CMSAF +4.54 Wm^{-2}/dec
GEBA +4.62 Wm^{-2}/dec

Difference time series stable





Sanchez-Lorenzo, Wild, Trentmann 2013, Remote Sensing of Environment

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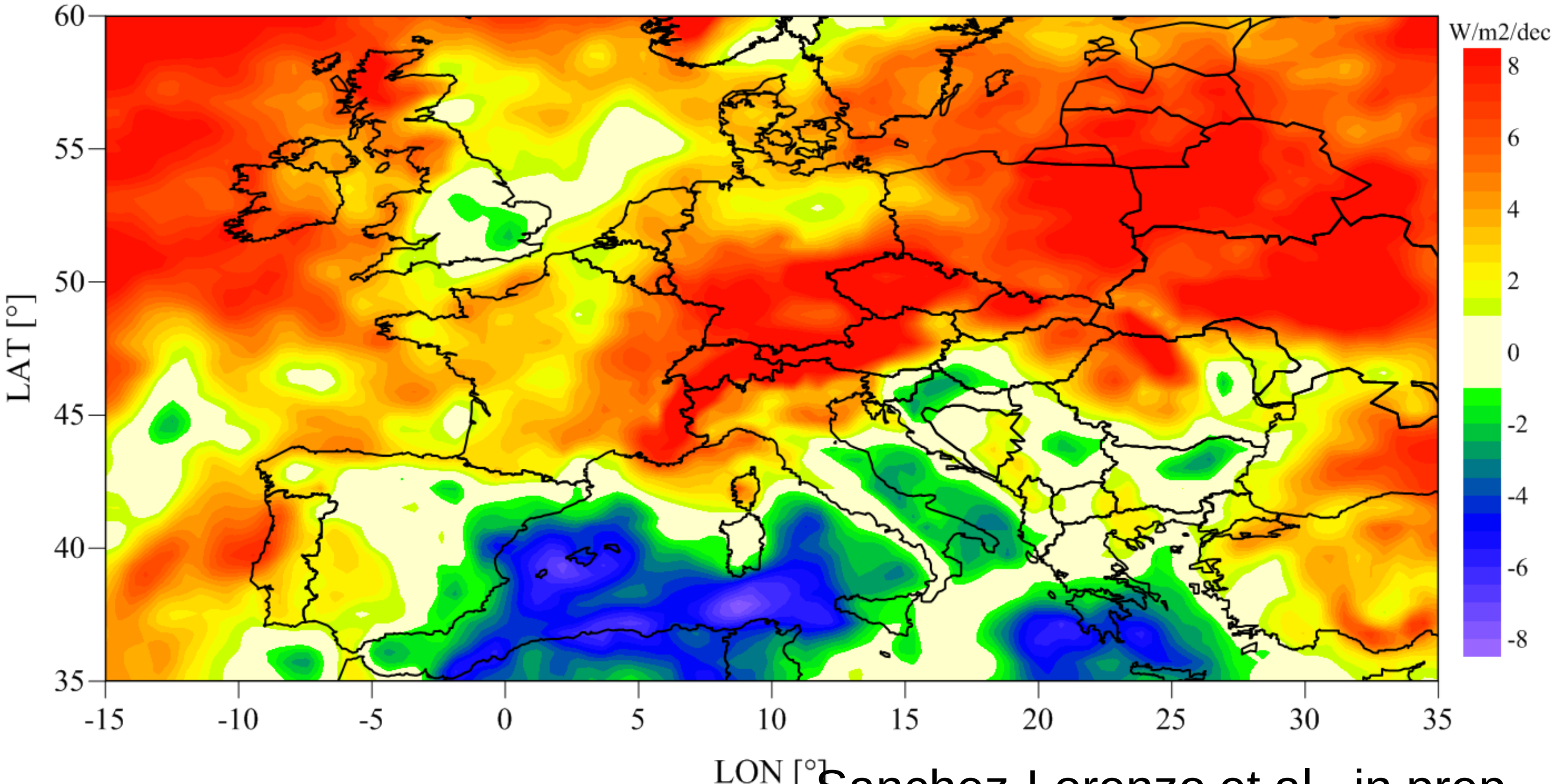
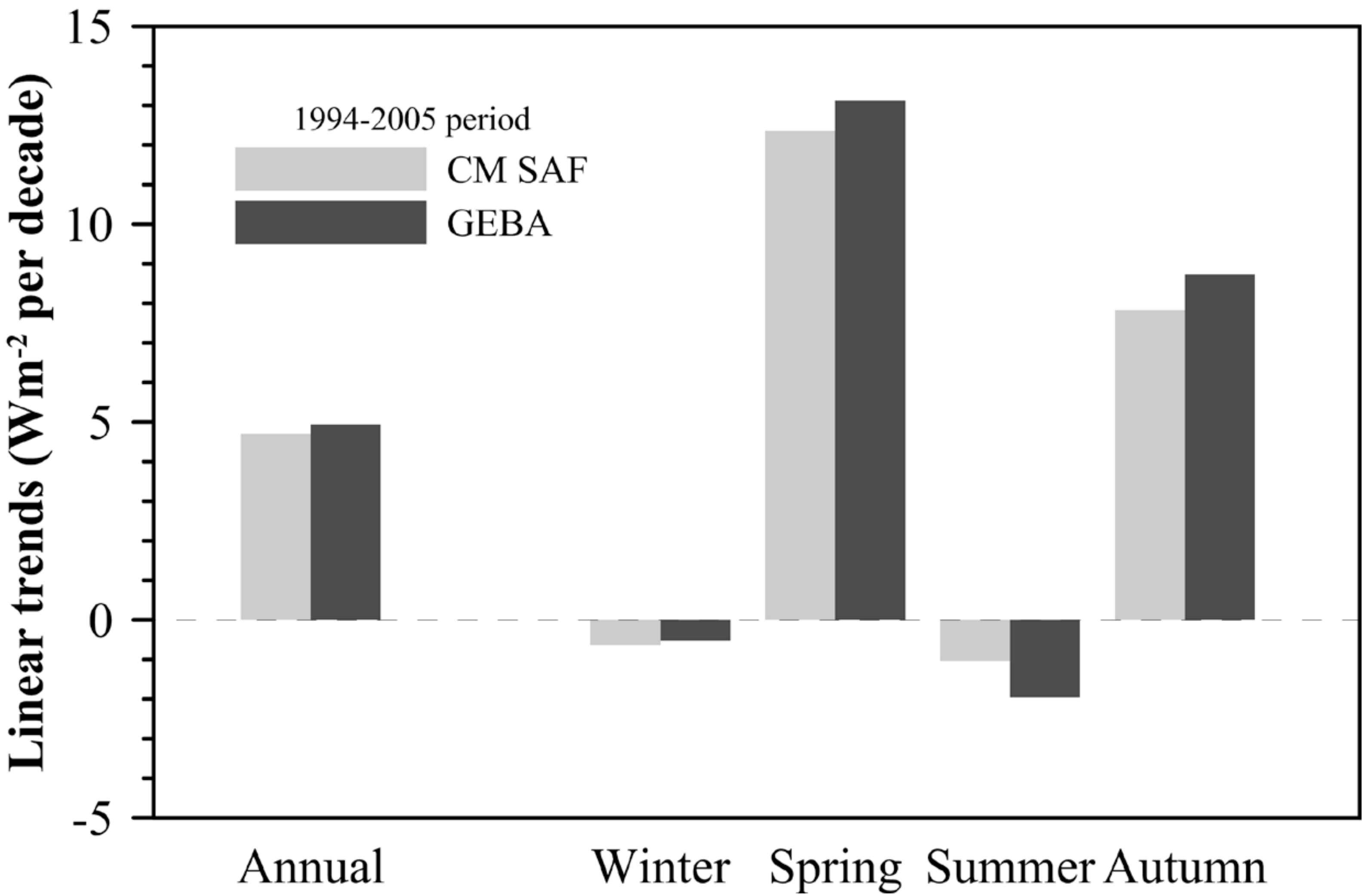
Annual trend patterns in CM SAF 1994-2005

- Annual linear trends in surface solar radiation in Europe (below 60° N)
- Overall trend: +3.12 Wm^{-2} per decade
- Substantial regional differences



Sanchez-Lorenzo et al., in prep.

Seasonal trends in GEBA and CMSAF 1994-2005



Sanchez-Lorenzo et al., in prep.

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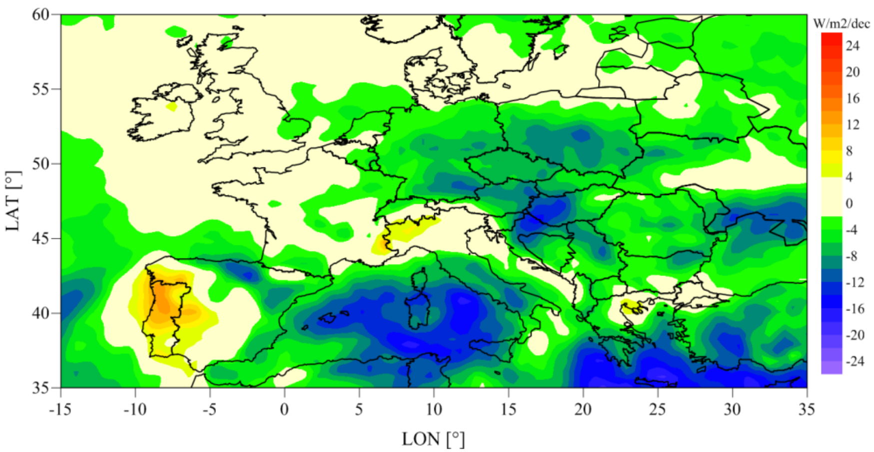
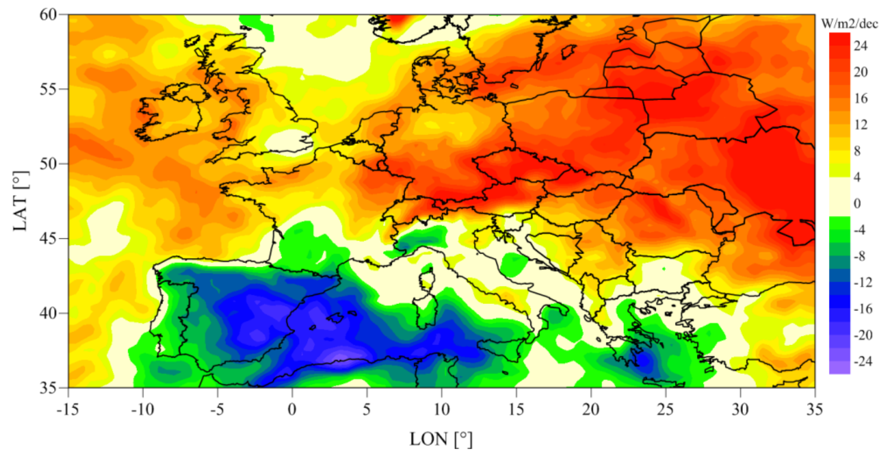
Seasonal trend patterns in CM SAF 1994-2005

Trend patterns of surface solar radiation strongly vary through the seasons

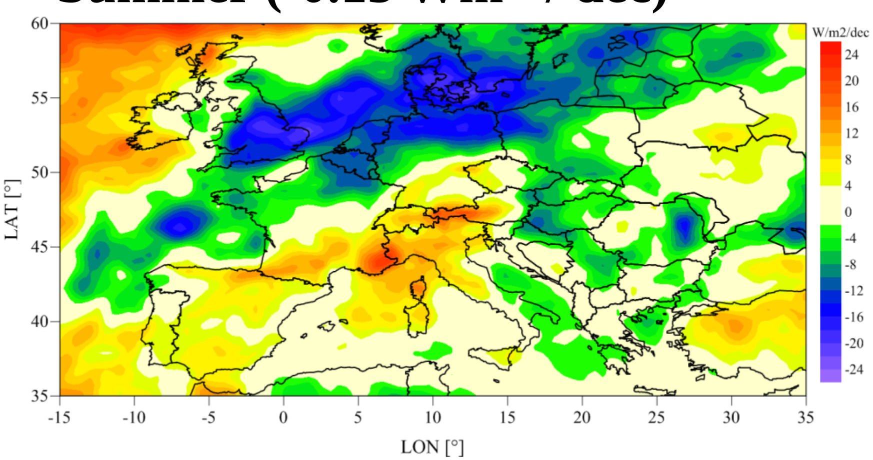
Winter (-3.52 Wm^{-2} / dec)



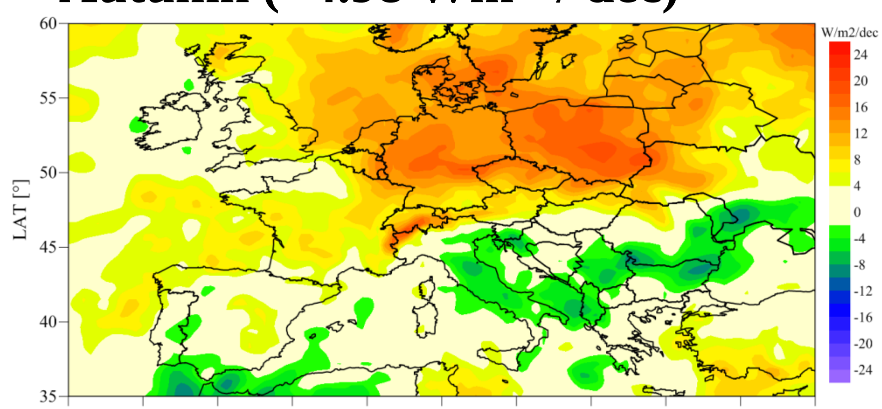
Spring (+7.79 Wm^{-2} / dec)



Summer (-0.15 Wm^{-2} / dec)



Autumn (+4.98 Wm^{-2} / dec)



Sanchez-Lorenzo et al, in prep.

Conclusions

- Surface radiative fluxes play a crucial role for the determination of surface climate and the intensity of the water cycle
- Changes in thermal (“greenhouse effect”) and solar (“dimming /brightening”) surface fluxes largely govern decadal climate change
- Better knowledge of the spatio-temporal patterns of surface radiative fluxes is required > satellite data essential
- CM SAF MFG surface surface solar radiation compares well with homogeneous surface observations
- CM SAF MFG surface solar radiation shows realistic annual and seasonal trends over Europe from 1994 onward > will allow for improved knowledge of spatial patterns of dimming and brightening
- CM SAF CLARA (global dataset 0.25° based on AVHRR, 1982-2009) may allow global scale assessment of dimming and brightening trends

Conclusions

- **Surface radiative fluxes play a crucial role for the determination of surface climate and the intenisity of the water cycle**
- **CMSAF surface compares well with surface observations from GEBA**
- **Realistic annual and seasonal trends over Europe in CMSAF**
- **Towards improved estimates of spatial patterns of dimming and brightening trends**
-
- **Extension of validation to 2010 over europe using CMSAF meteosat Secend generation dats**
- **Global assessment of trends using CMSAF CLARA, based on**

- Figure 11 to 2010

- CMSAF compares well with surface observations in GEBA, also
-
- Realistic annual and seasonal trends over Europe in CMSAF
- Towards improved estimates of spatial patterns of dimming and brightening trends
-
- Extension of validation to 2010 over europe using CMSAF meteosat Secend generation dats
- Global assessment of trends using CMSAF CLARA, based on

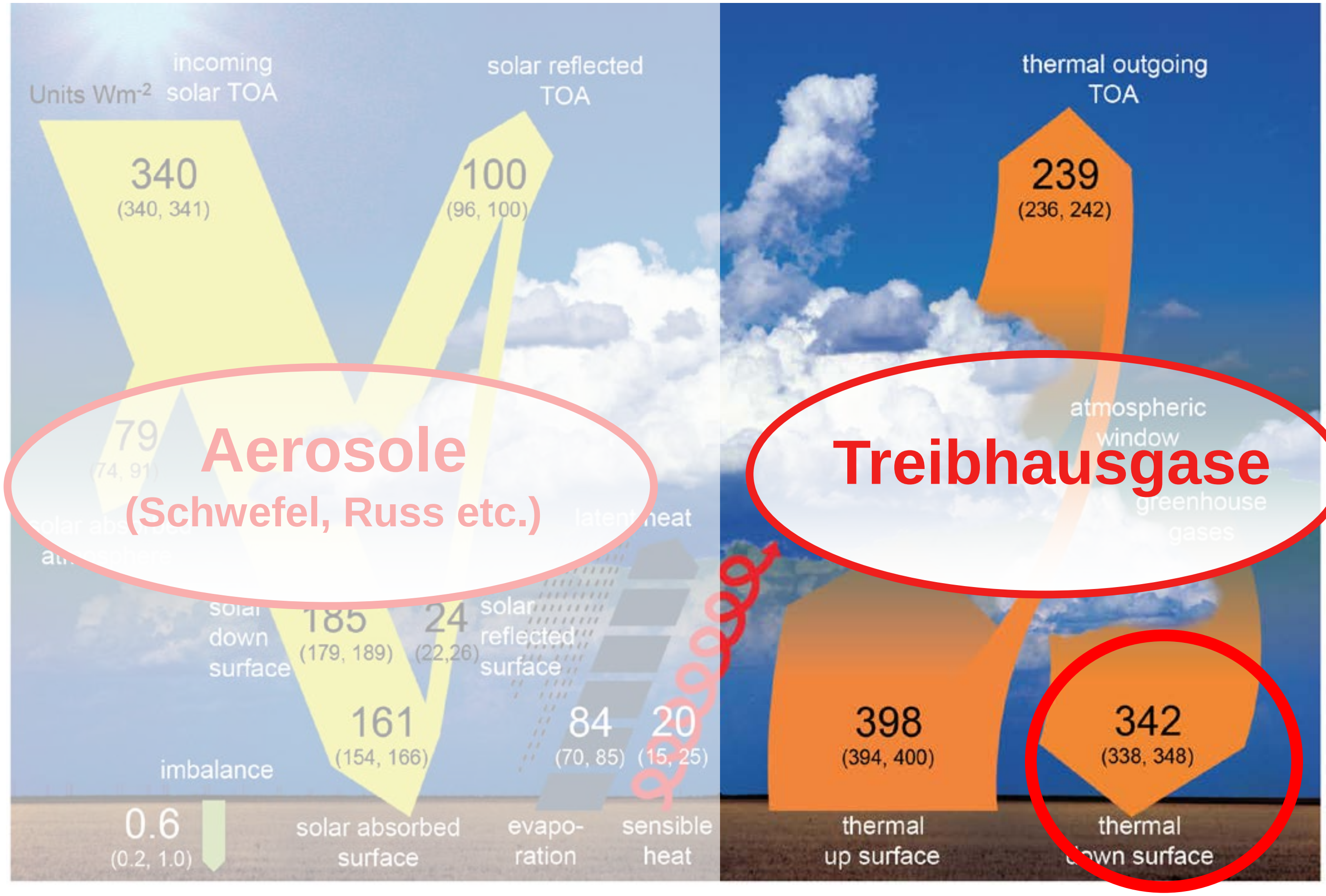
- Figure 11 to 2010

Future steps CMSAF radiation assessment

- Extension of validation to 2010 over Europe using CMSAF meteosat Second generation data
- Global assessment of trends using CMSAF CLARA, based on NOAA/AVHRR satellites
- Figure 11 to 2010

Energiebilanz der Erde

Messbare Änderungen an der Erdoberfläche



Thermische Rückstrahlung

"Treibhauseffekt am Erdboden"

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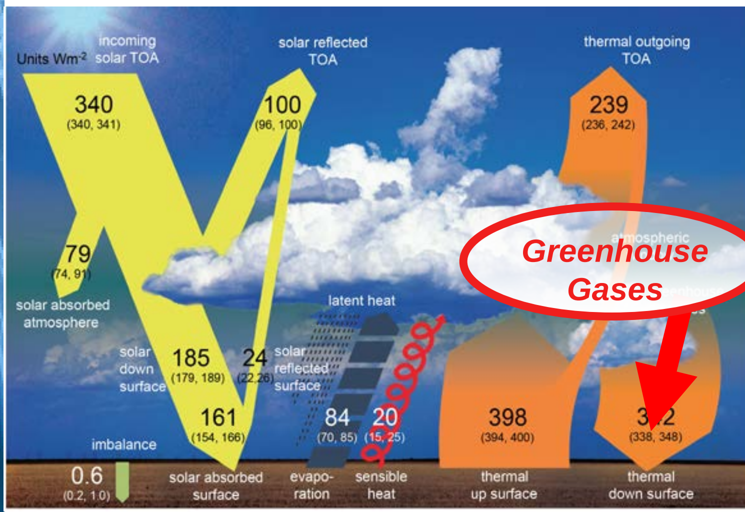
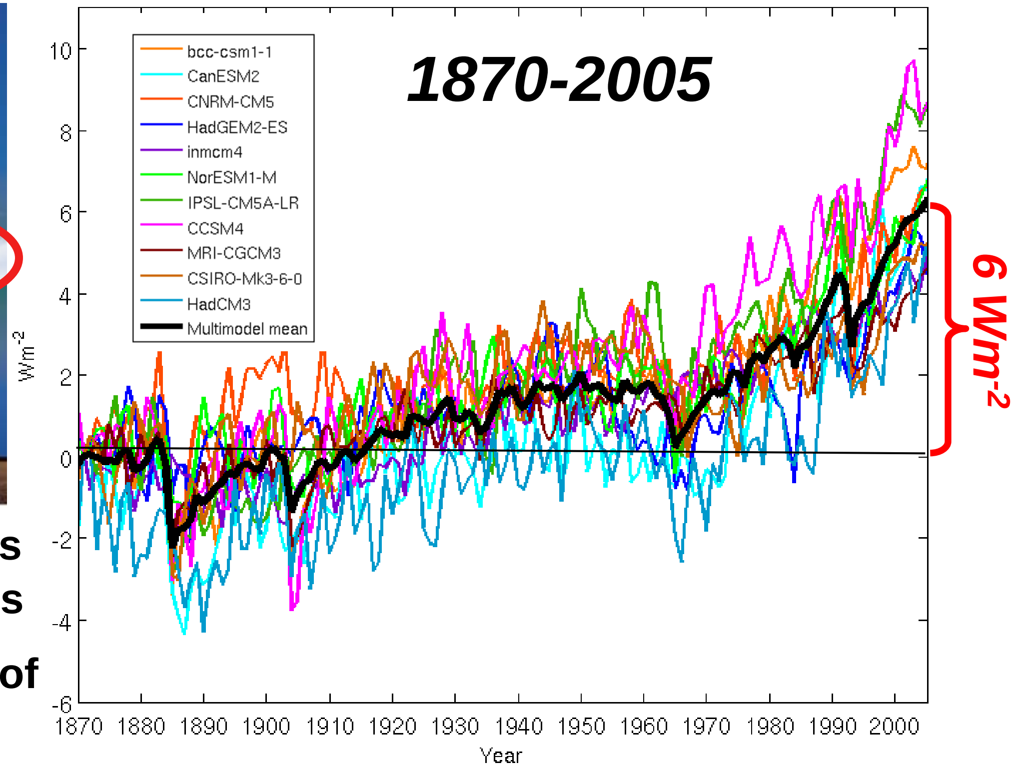
Changes in downward longwave radiation

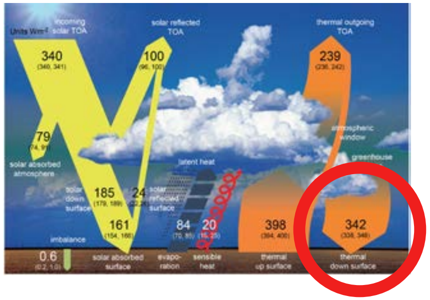


- **most directly affected by changes in atmospheric greenhouse gases**
- **CMIP5 models suggest increase of 6 Wm^{-2} since 1870**
- **expected to undergo largest change of all energy balance components in coming decades**
- **Only monitored since the initiation of BSRN early 1990s**

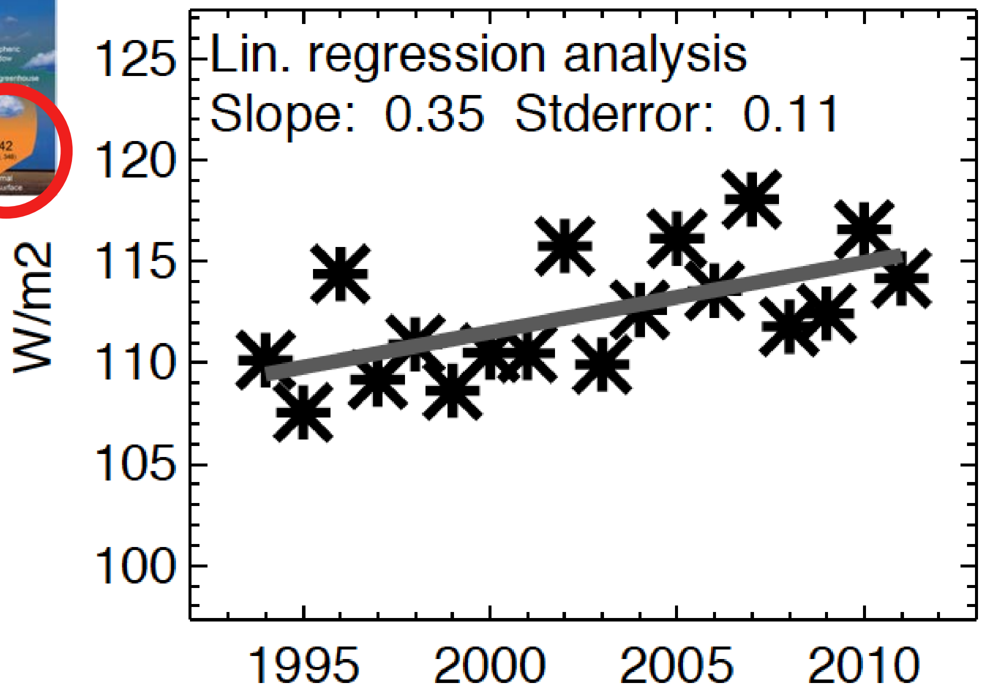
Downward longwave radiation in CMIP5 models



Observed changes downward longwave radiation



LW down South Pole 1994-2011



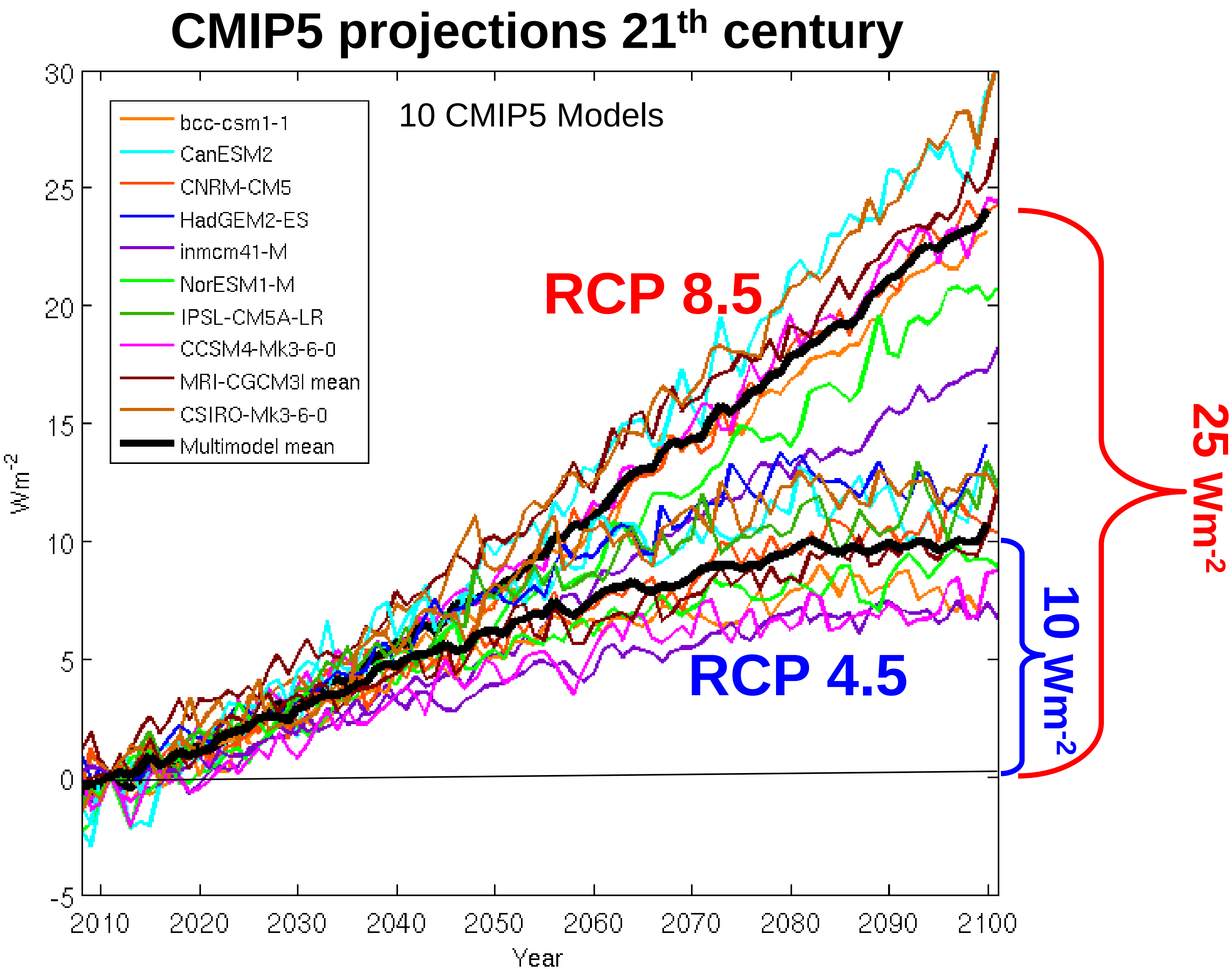
NOAA/ESRL

Observed changes at BSRN sites since early 1990s:

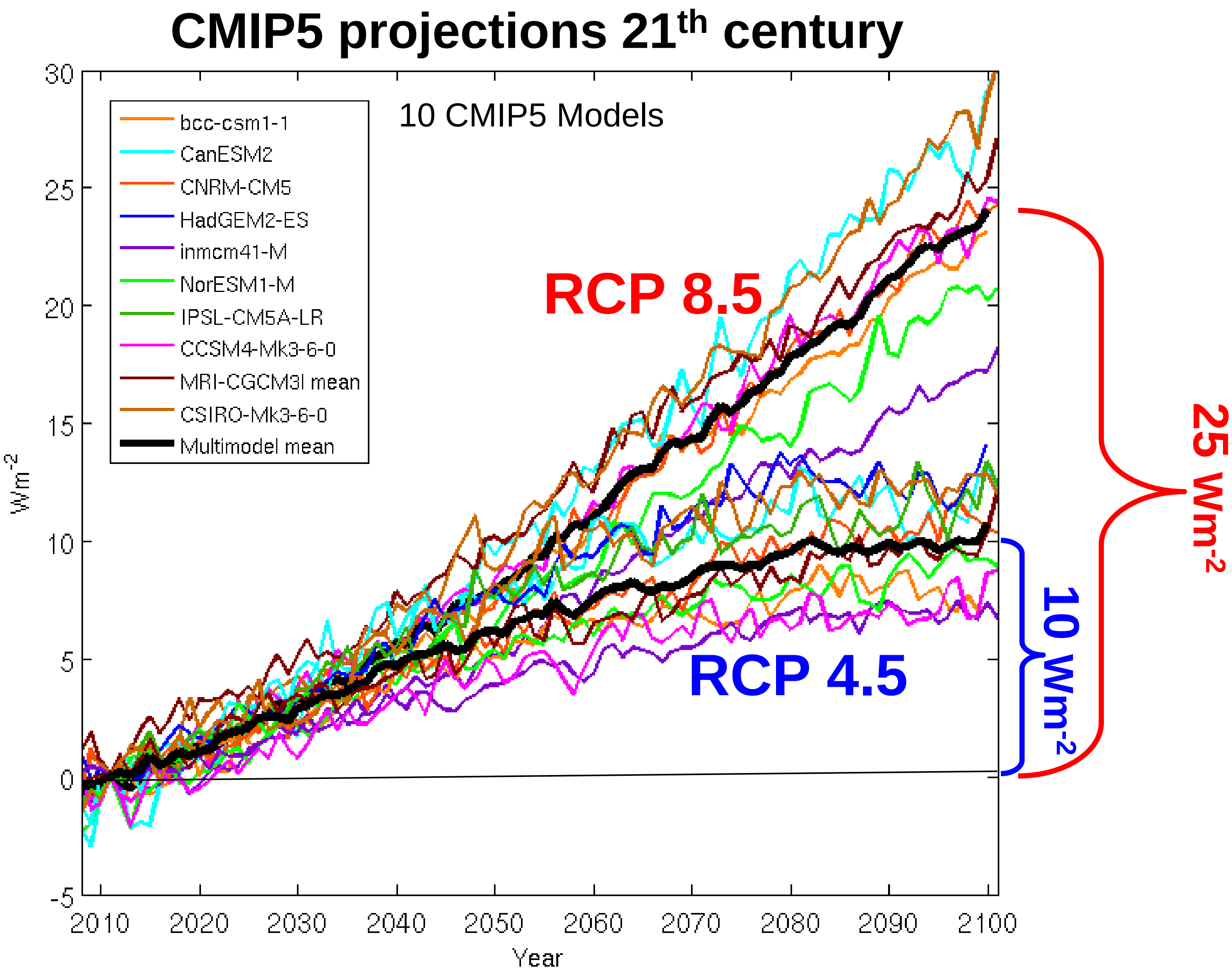
25 longest BSRN records (totally 353 years) covering period 1992-2011

- ***19 stations (76%) with increase*** *in LW down (9 significant)*
- ***6 stations (24%) with decrease*** *in LW down (3 significant)*
- ***Average change all sites: +2.0 $Wm^{-2}dec^{-1}$***

Downward longwave in RCP scenarios

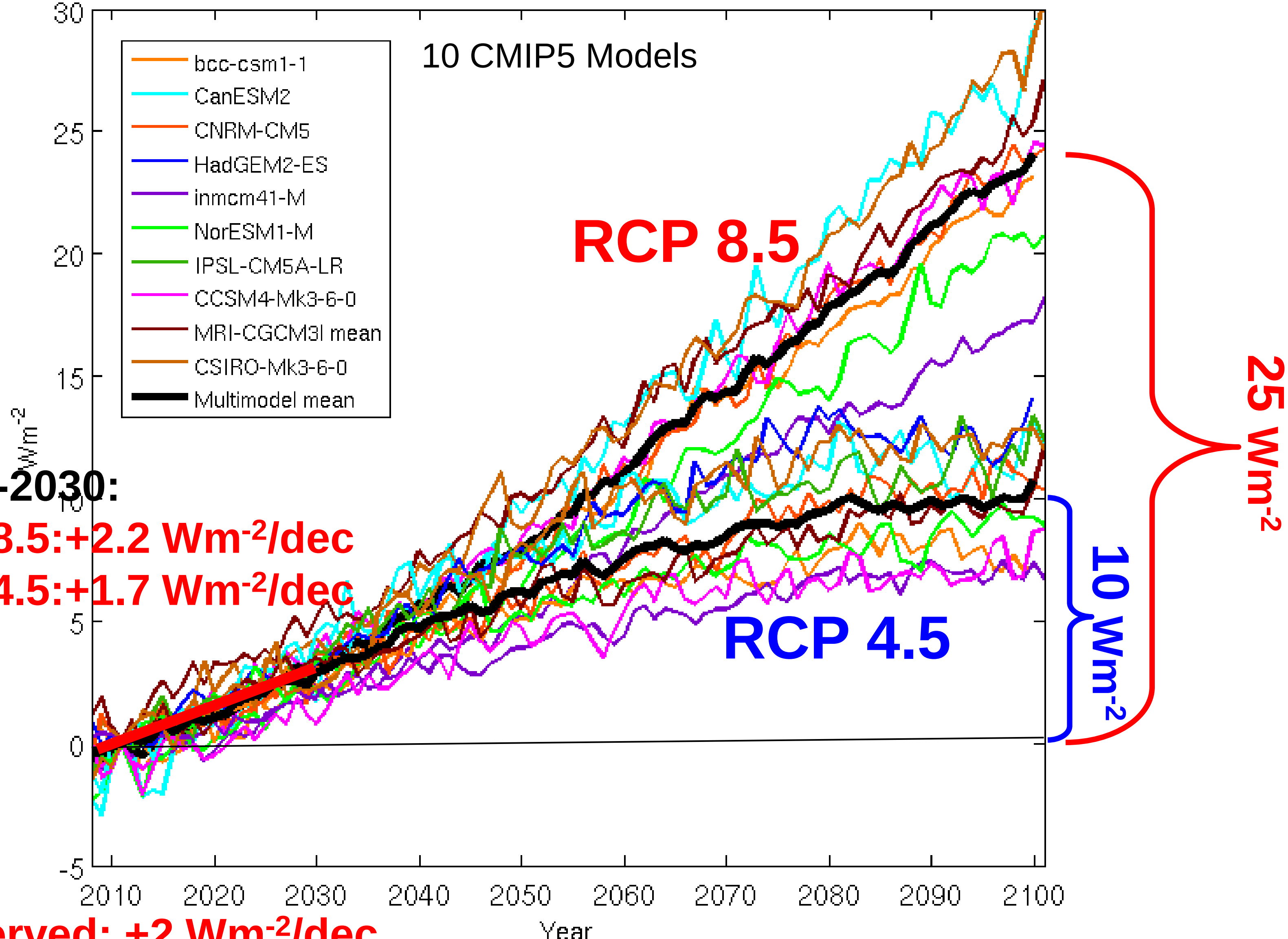


Downward longwave in RCP scenarios



Downward longwave in RCP scenarios

CMIP5 projections 21th century



2010-2030:

RCP8.5:+2.2 Wm^{-2}/dec

RCP4.5:+1.7 Wm^{-2}/dec

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

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Future steps CMSAF radiation assessment

- Extension of validation to 2010 over Europe using CMSAF meteosat Second generation data
- Global assessment of trends using CMSAF CLARA, based on
- Figure 11 to 2010

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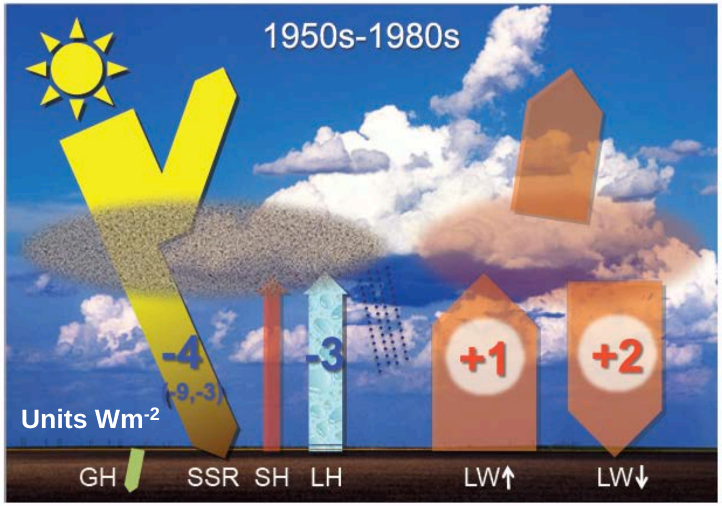
Combined surface solar and thermal (greenhouse) forcing

Schematic view of dimming/brightening

DIMMING



1950s to 1980s

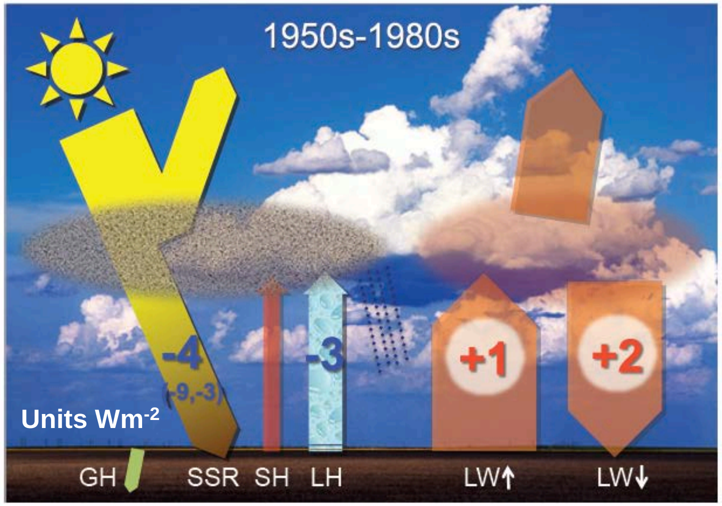
- **Shortwave dimming overcompensates increasing longwave greenhouse effect**
- **Surface radiative energy decreases**

=> Attenuation of water cycle expected

Wild 2012 BAMS

Schematic view of dimming/brightening

DIMMING

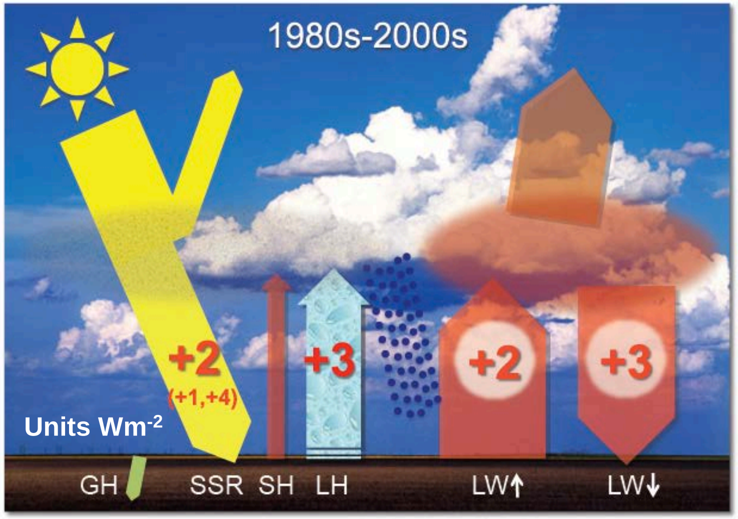


1950s to 1980s

- **Shortwave dimming overcompensates increasing longwave greenhouse effect**
- **Surface radiative energy decreases**

=> Attenuation of water cycle expected

BRIGHTENING



since 1980s

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

=> Acceleration of water cycle expected

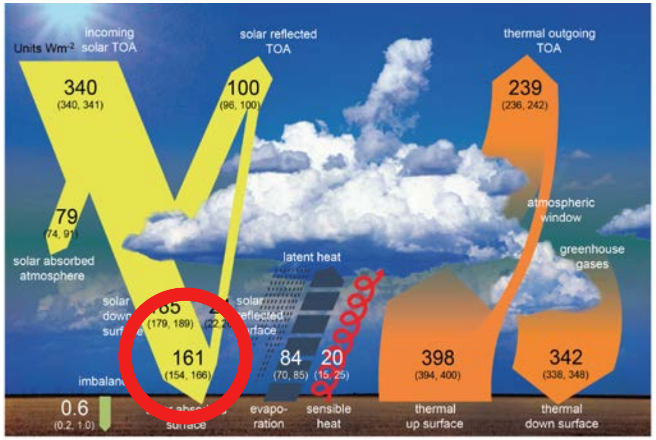
Wild 2012 BAMS

What are the consequences of the surface radiation changes for global warming?

Summary

- Surface and satellite-based observations suggest significant decadal changes in surface radiation, in line with anthropogenic emission pathways.
- Surface shortwave radiation has decreased from the from 1950s to 1980s (“dimming”) and partially recovered thereafter up to 2000 (“brightening”), with mixed tendencies after 2000.
- Indication for an increase in downward longwave radiation in line with model projections and greenhouse theory.
- The monitoring of surface radiation is essential to understand the evolution of global warming and various other aspects of climate change (e.g., intensity of the hydrological cycle, snow and glacier retreat, biospheric growth)

Changes in surface solar radiation 1950s - 1980s



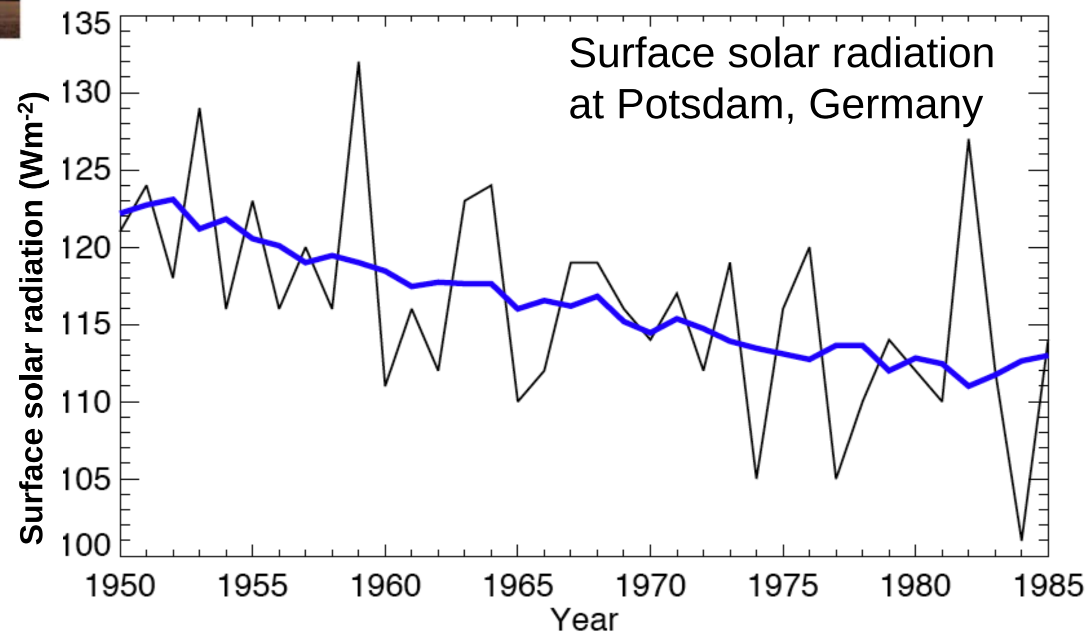
Decrease in surface insolation 1950s-80s:

Ohmura Lang (1989): Decrease in Europe

Gilgen Wild Ohmura (1998): -9 Wm^{-2}

Stanhill Cohen (2001): -10 Wm^{-2}

Widespread measurements of surface solar radiation since the 1950s



Substantial decline in solar radiation at Earth surface:

"global dimming"

Table 1. Estimated Linear Changes in Surface Solar Radiation Over the Period of Roughly 1960s to 1980s Based on Surface Observations[a]

Region	Reference	Number of Sites	Period	Absolute Trend (W m^{-2} $decade^{-1}$)	Relative Trend (% $decade^{-1}$)
		Global Focus			
Global land sites	*Gilgen et al.* [1998]	400	1960–1990	−3.5[b]	−2
Global land sites	*Stanhill and Cohen* [2001]	145	1958–1992	−5.1	−2.7
Global land sites	*Liepert* [2002]	295	1961–1990	−2.3	−1.3
Global urban sites	*Alpert et al.* [2005]	144	1964–1989	−4.1	−2.3[b]
Global rural sites	*Alpert et al.* [2005]	174	1964–1989	−1.6	−0.9[b]
Global remote sites	*Stanhill and Moreshet* [1994]	7	1953–1991	−4.8	−3.3
Global remote sites	*Dutton et al.* [2006]	5	1977–1990	decrease	decrease
		Europe			
Europe	*Ohmura and Lang* [1989]	13	1959–1988	−2.7	−2.0[b]
Europe	*Norris and Wild* [2007]	75	1971–1986	−3.1	−2.3[b]
Zurich (Switzerland)	*Ohmura and Lang* [1989]	1	[illegible]	−10	−7[b]
Baltic	*Russak* [1990]	3	1964–1986	−5.5[b]	−5
Toravere (Estonia)	*Russak* [1990]	1	[illegible]	−2.5[b]	−2.2
Germany	*Liepert et al.* [1994]	8	1964–1990	−6	[illegible]
European part of FSU	*Abakumova et al.* [1996]	diverse	1960–1987	−2.5 to −8[b]	−2 to −6
Moscow	*Abakumova et al.* [1996]	1	[illegible]	[illegible]	−2
Turkey	*Aksoy* [1997]	34[c]	1960–1994	−2[b,c]	−1[c]
Israel	*Stanhill and Ianetz* [1997]	2	1954–1994	−8.8	−5
Ireland	*Stanhill* [1998a]	8	[illegible]	[illegible]	−5[b]
Iberian Peninsula	*Sanchez-Lorenzo et al.* [2007]	72	1950–1980	−3[c]	−1.5[b,c]
Northern Europe	*Stjern et al.* [2009]	11	1955–2003	−4.3	−3.7
		North America			
United States	*Liepert* [2002]	43	1961–1990	−6	−3
Canada	*Cutforth and Judiesch* [2007]	7	1958–1999	−2.6[b]	−1.7
		Central America			
Wider Caribbean	J. C. Antuna et al. (submitted manuscript 2009)	30	1961–1990	−10	−4.5[b]
		Asia			
Hong Kong	*Stanhill and Kalma* [1995]	1	1958–1992	−18	−10.6
Former Soviet Union	*Abakumova et al.* [1996]	160	1960–1987	−1 to −8	−1 to −7
China	*Che et al.* [2005]	64	1961–2000	−4.5	−3[b]
China	*Liang and Xia* [2005]	42	1960–2000	−4.9[b]	[illegible]
China	*Qian et al.* [2007]	85	1955–2000	−3.2	[illegible]

40+ studies show a decrease of observed surface solar radiation between the 1950s and 1980s.

No study with increase.

JGR 2009

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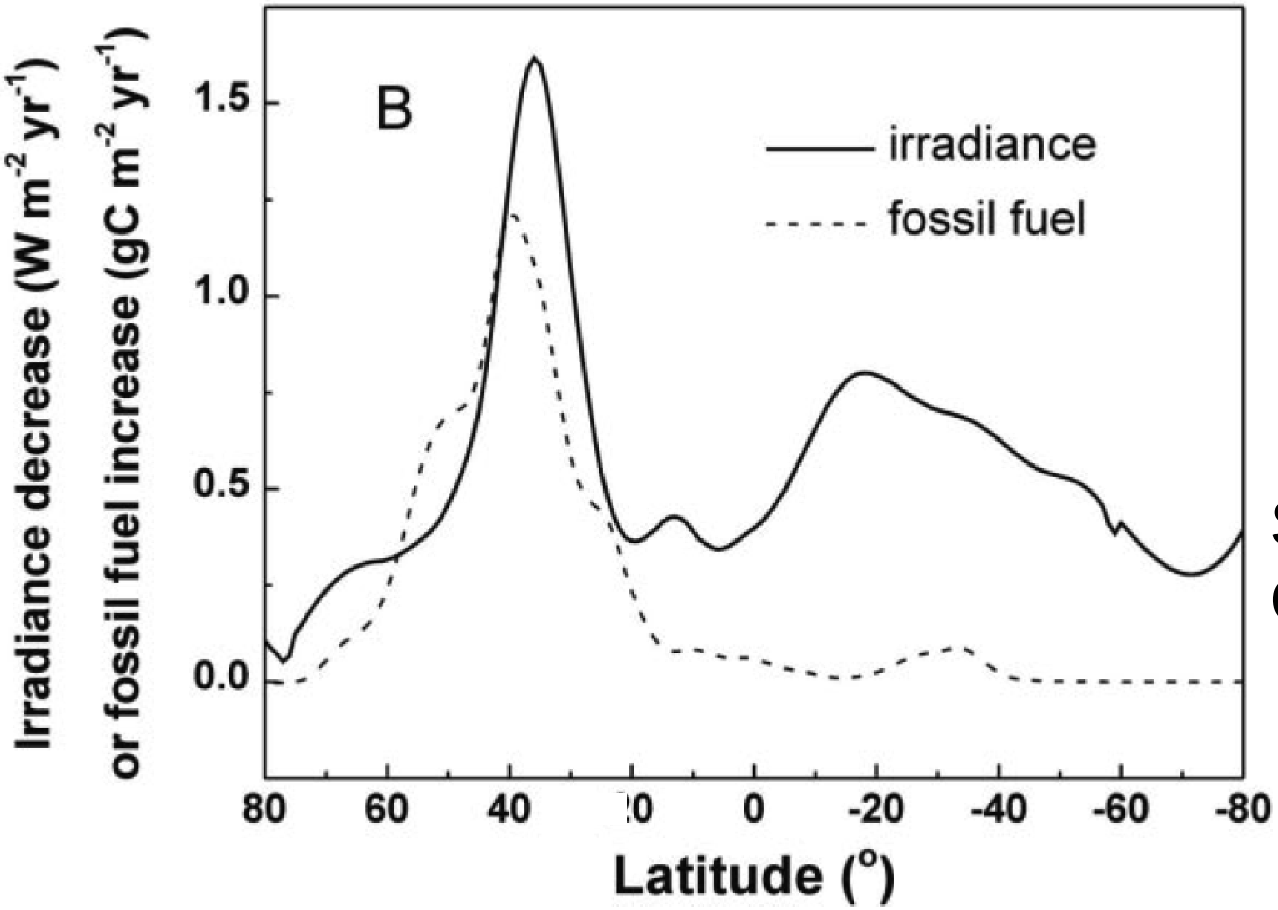
Global dimming: potential causes

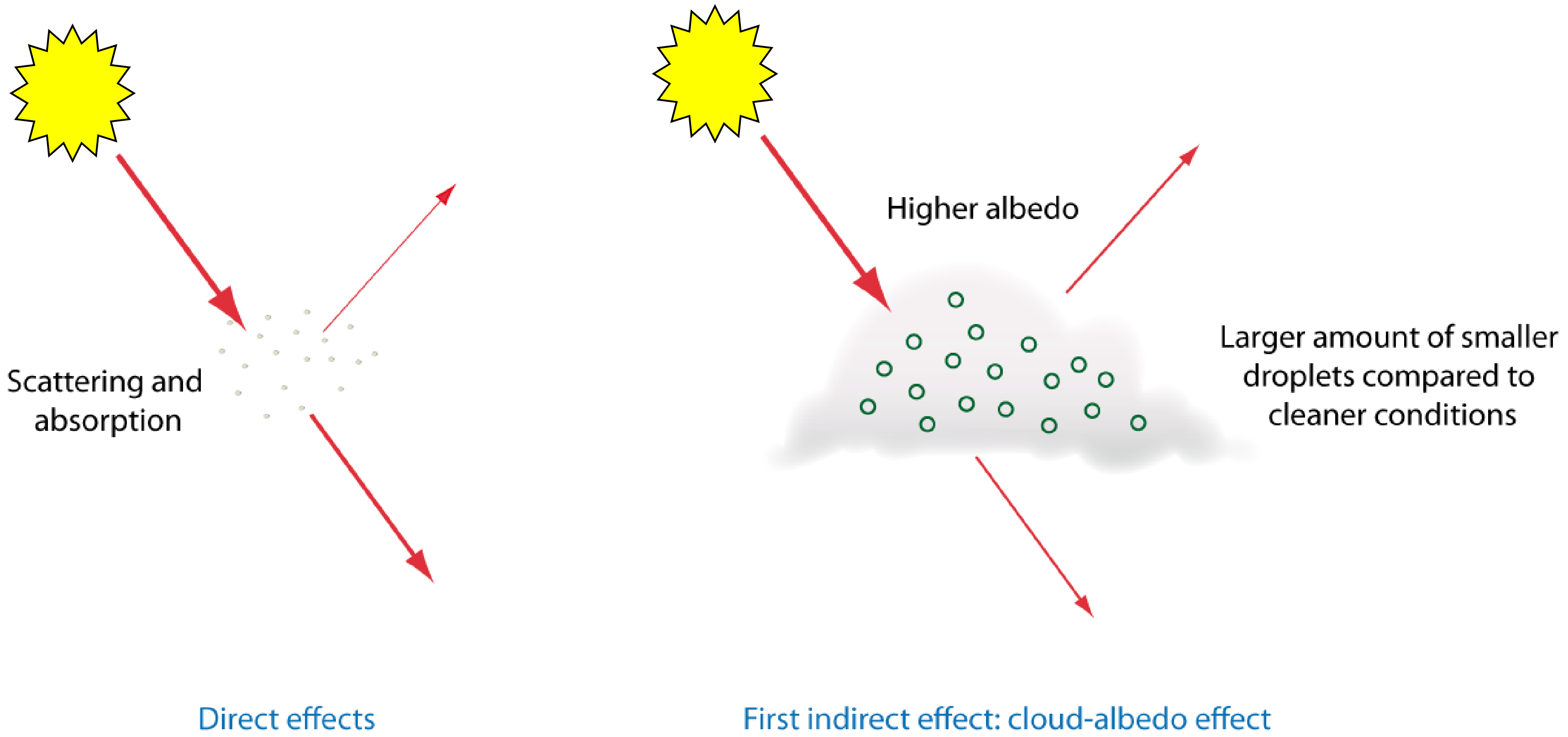


Stanhill and Cohen (2001)

Increase in fossil fuel emissions between 1960 - 1990, In line with decrease in solar radiation at the surface

Global dimming: potential causes

Direct and indirect aerosol effects

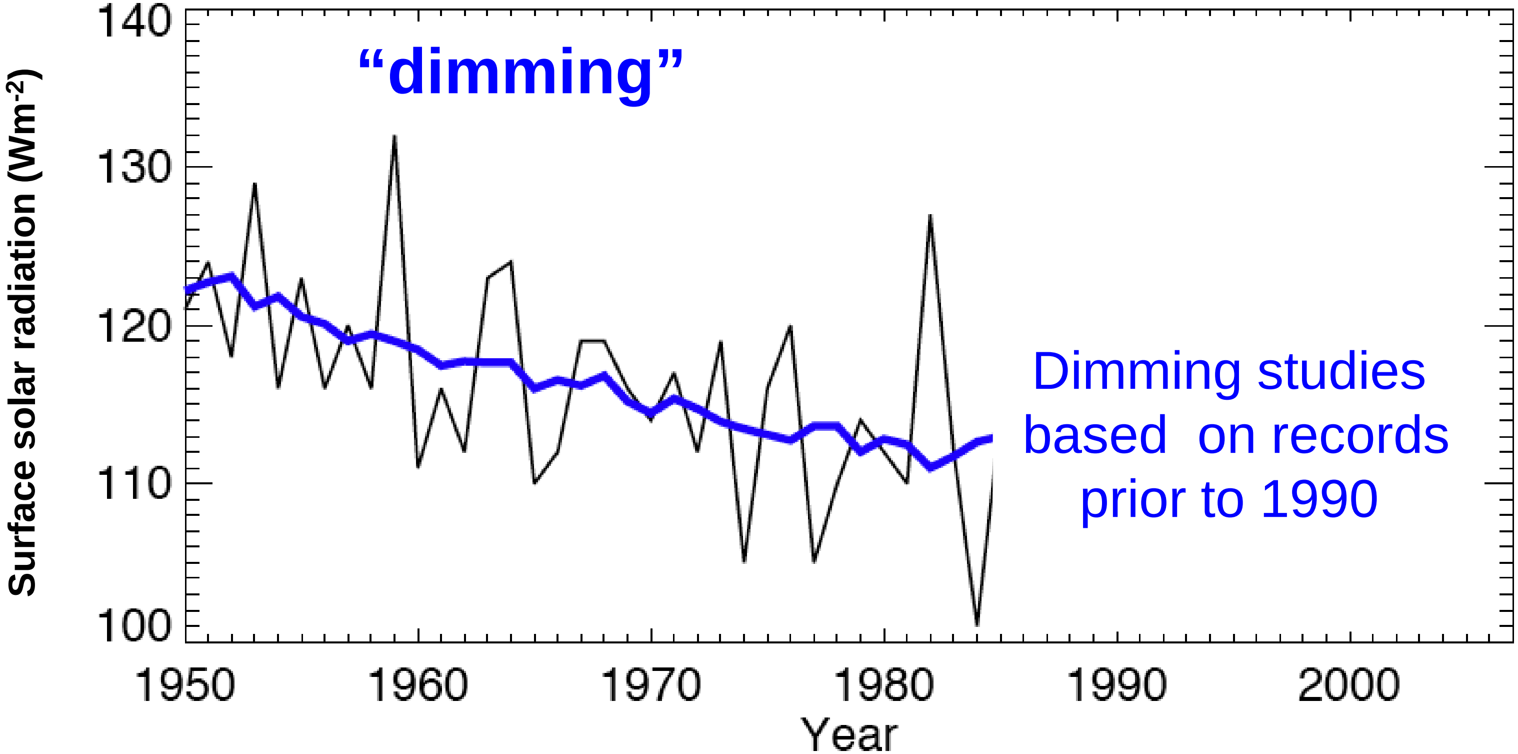


Both direct and indirect aerosol effects (cloud albedo/cloud lifetime) reduce the amount of solar radiation reaching the ground

Extending the records beyond the 1980s

Studies on global dimming used data only prior to 1990

=> Extend observational records from 1980s to present



Surface Solar Radiation at Potsdam

Wild et al. 2005: From dimming to brightening: Decadal changes in solar radiation at the Earth's surface. *Science* 308

Extending the records beyond the 1980s

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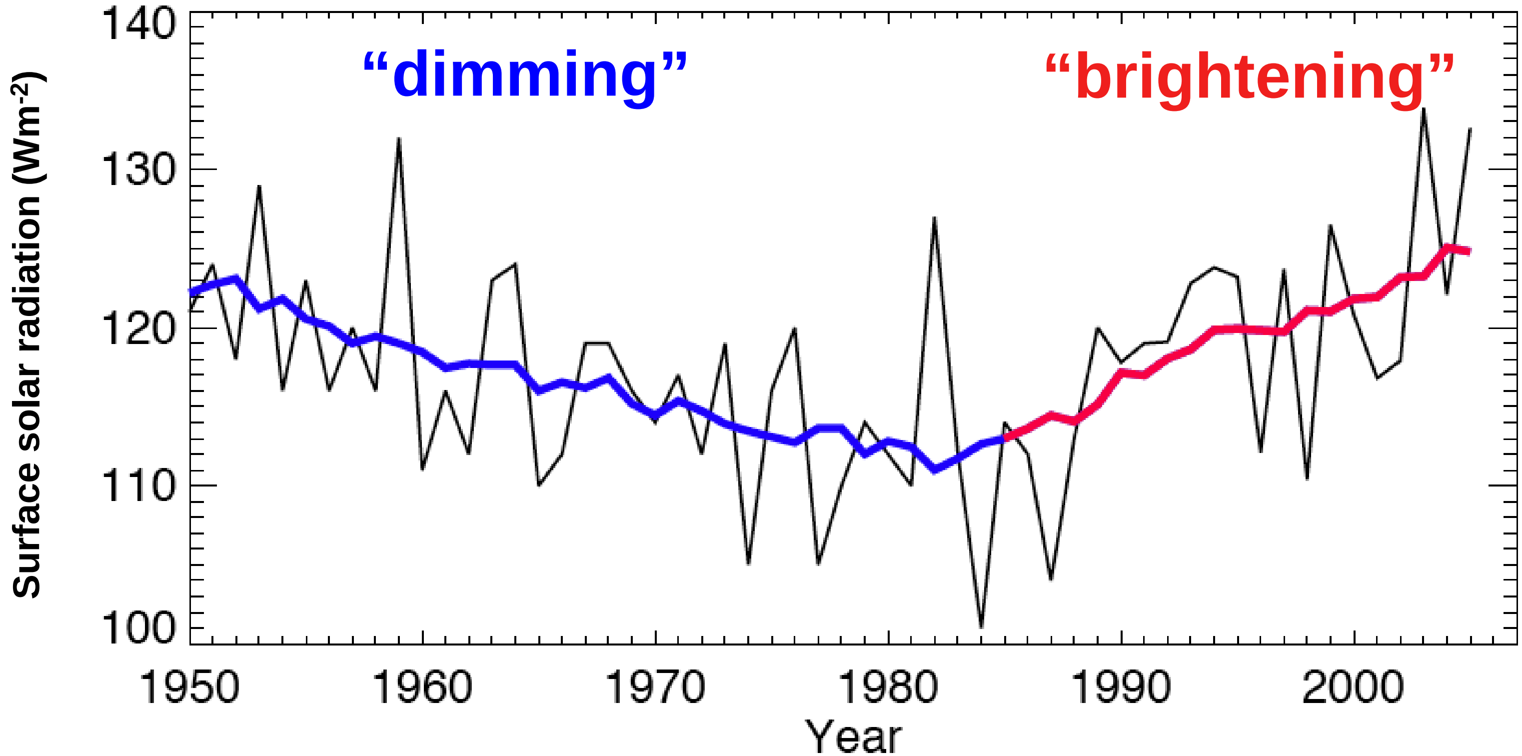
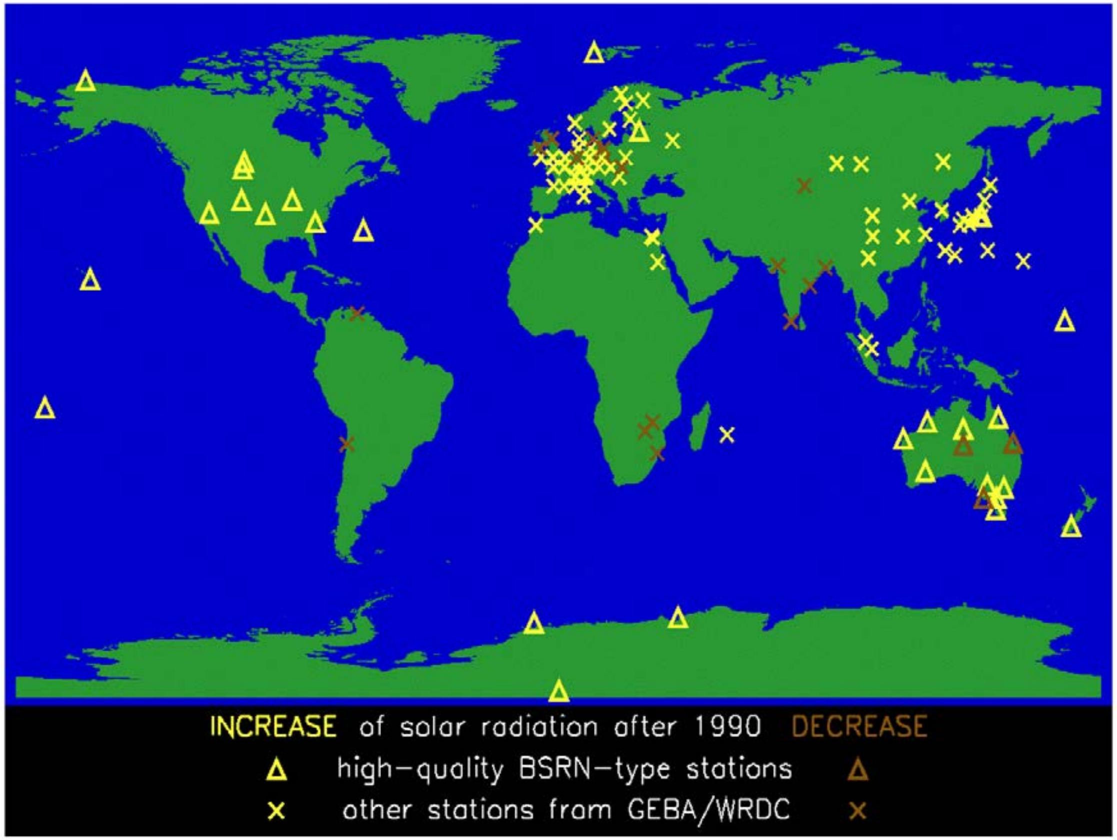


Surface Solar Radiation at Potsdam

Wild et al. 2005: From dimming to brightening: Decadal changes in solar radiation at the Earth’s surface. *Science* 308

Changes in surface solar radiation after 1980s

Observed at BSRN and GEBA sites since 1990



Yellow: Increase

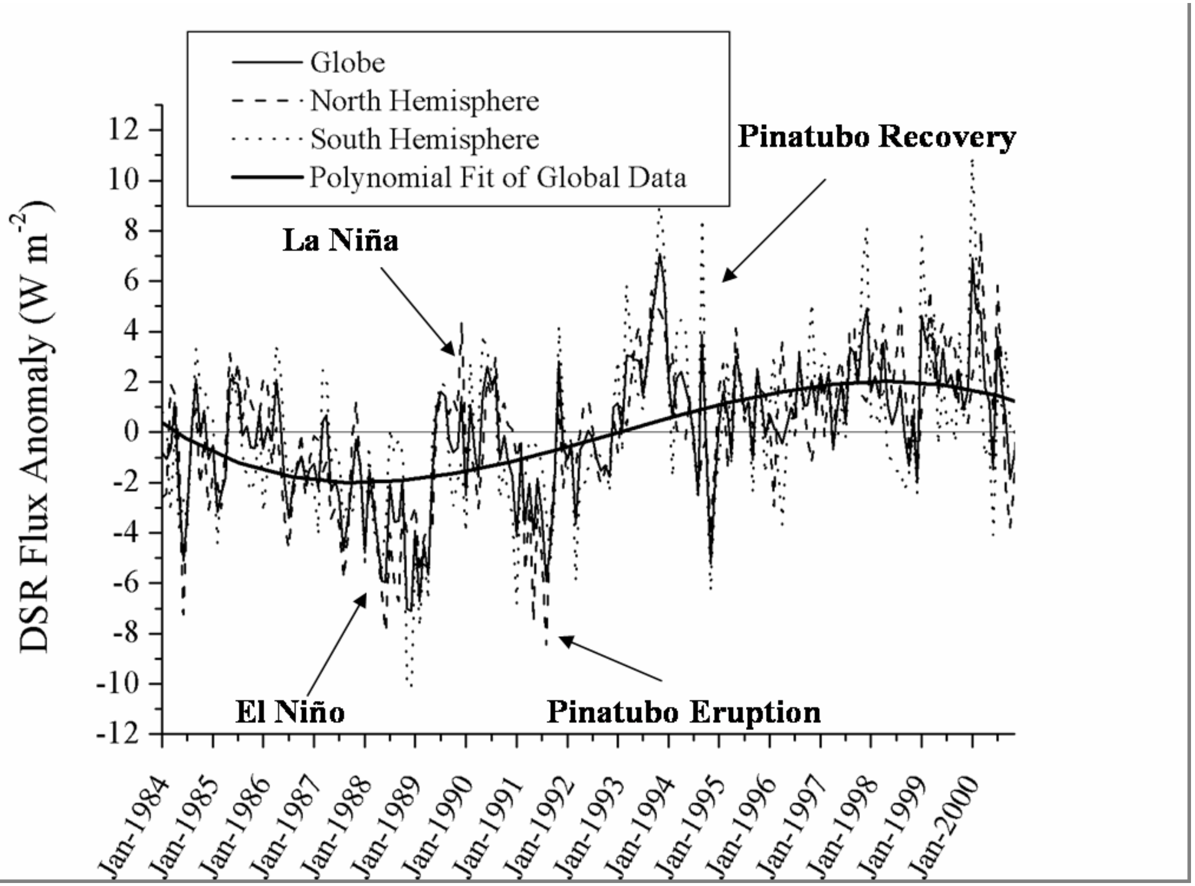
Brown: Decrease

Wild et al. 2005, *Science* 308

No more evidence for "global dimming" after 1980s

Satellite-derived products show brightening

Surface solar radiation 1984- 2000

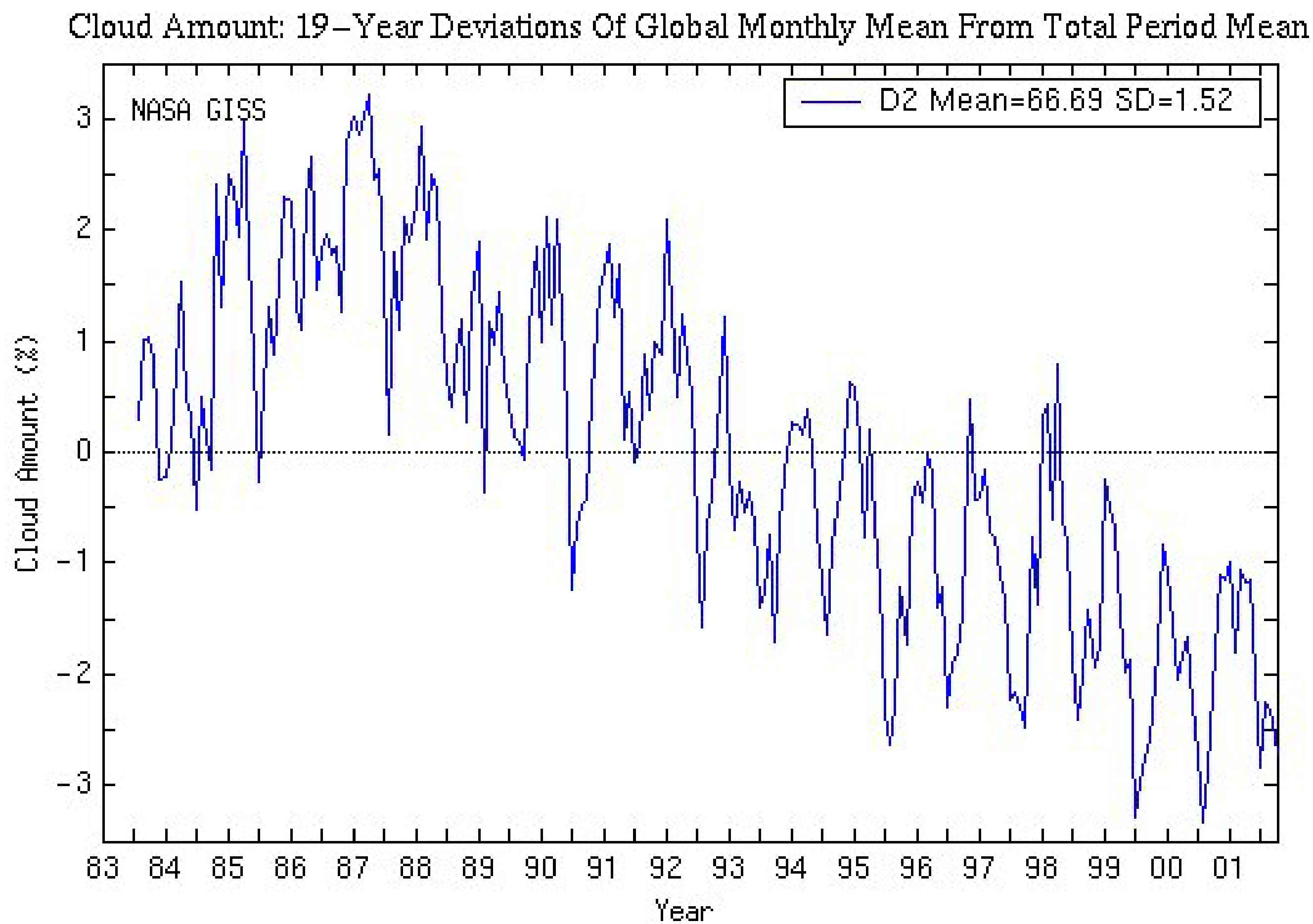


Input from on ISCCP-D2 (Clouds), NCEP/ERA (Humidity), GADS (Aerosol), TOVS (O3)

Hatzianastassiou et al. 2005, ACP

Changes in cloud amount 1983 - 2002

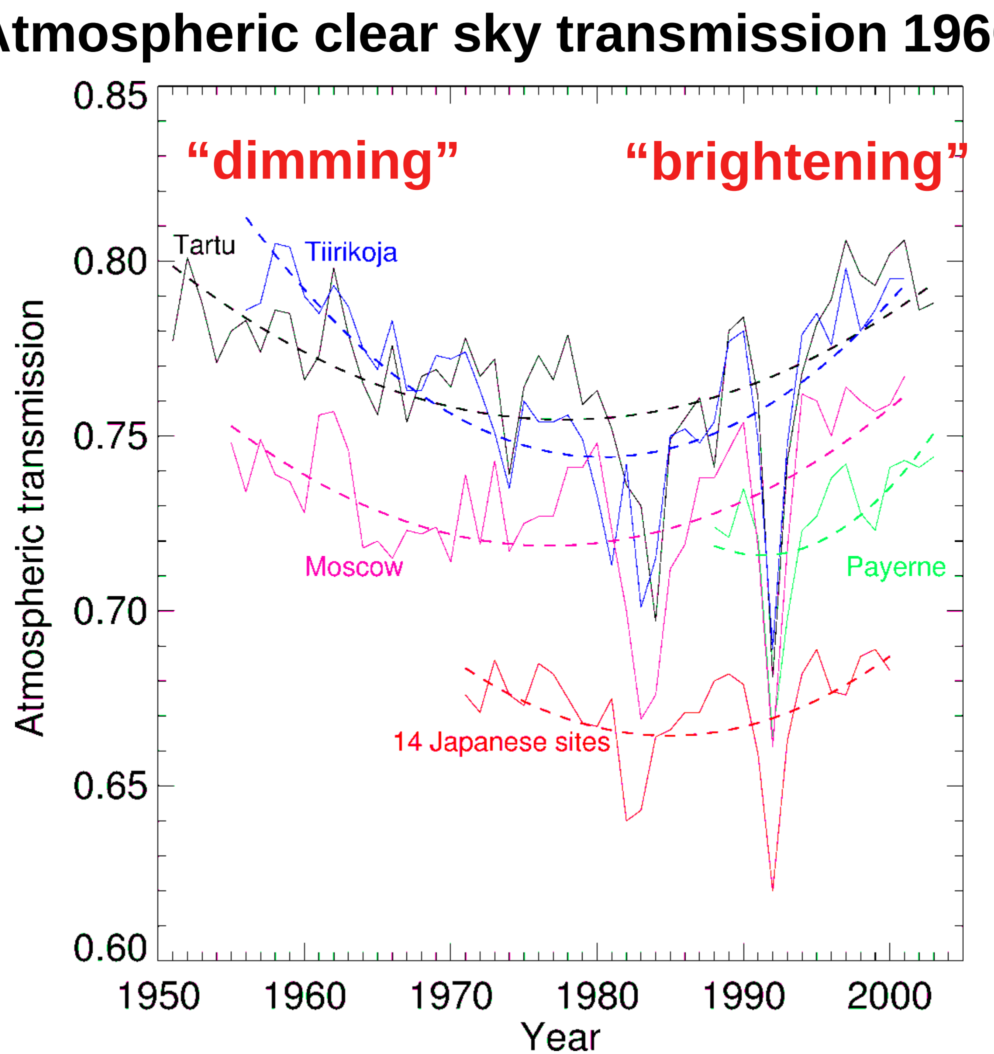
Observed from satellites



Decrease in cloud amout during 1990s?

From ISCCP (NASA/ Bill Rossow)
International Satellite Cloud Climatology Project

Changes in cloud-free atmosphere 1960-2000



Recent recovery in atmospheric transmittance

Wild et al., 2005, *Science 308*

From dimming to brightening: Causes

Aerosol optical depth 1981 - 2005 over oceans from satellites

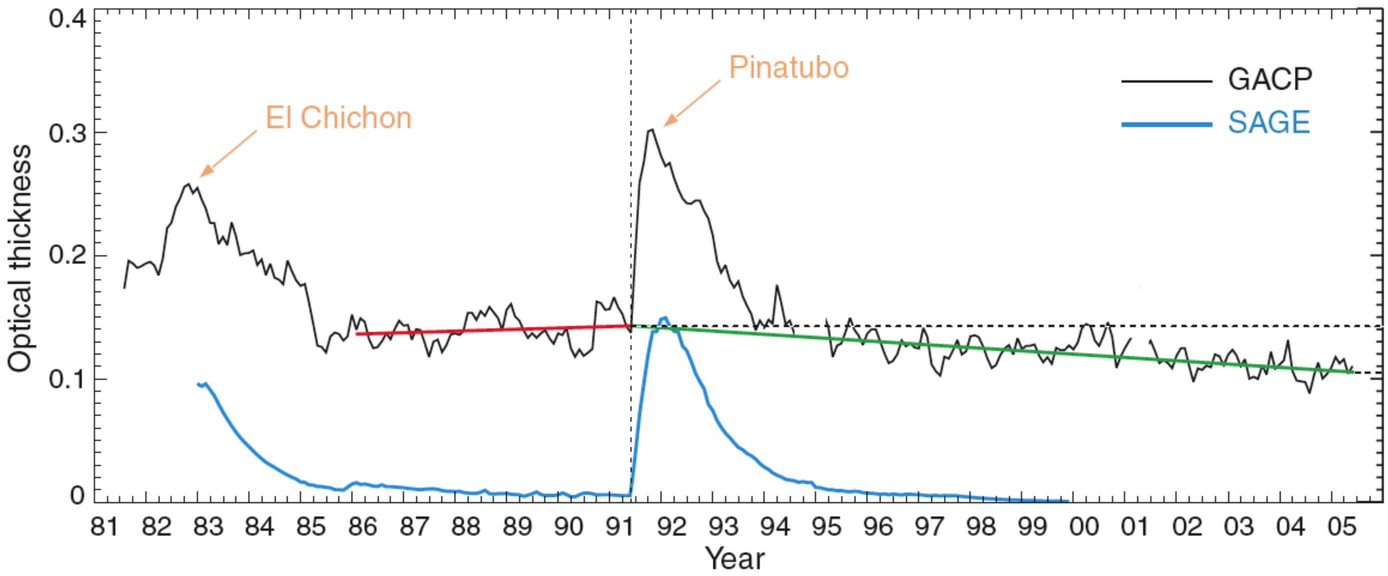
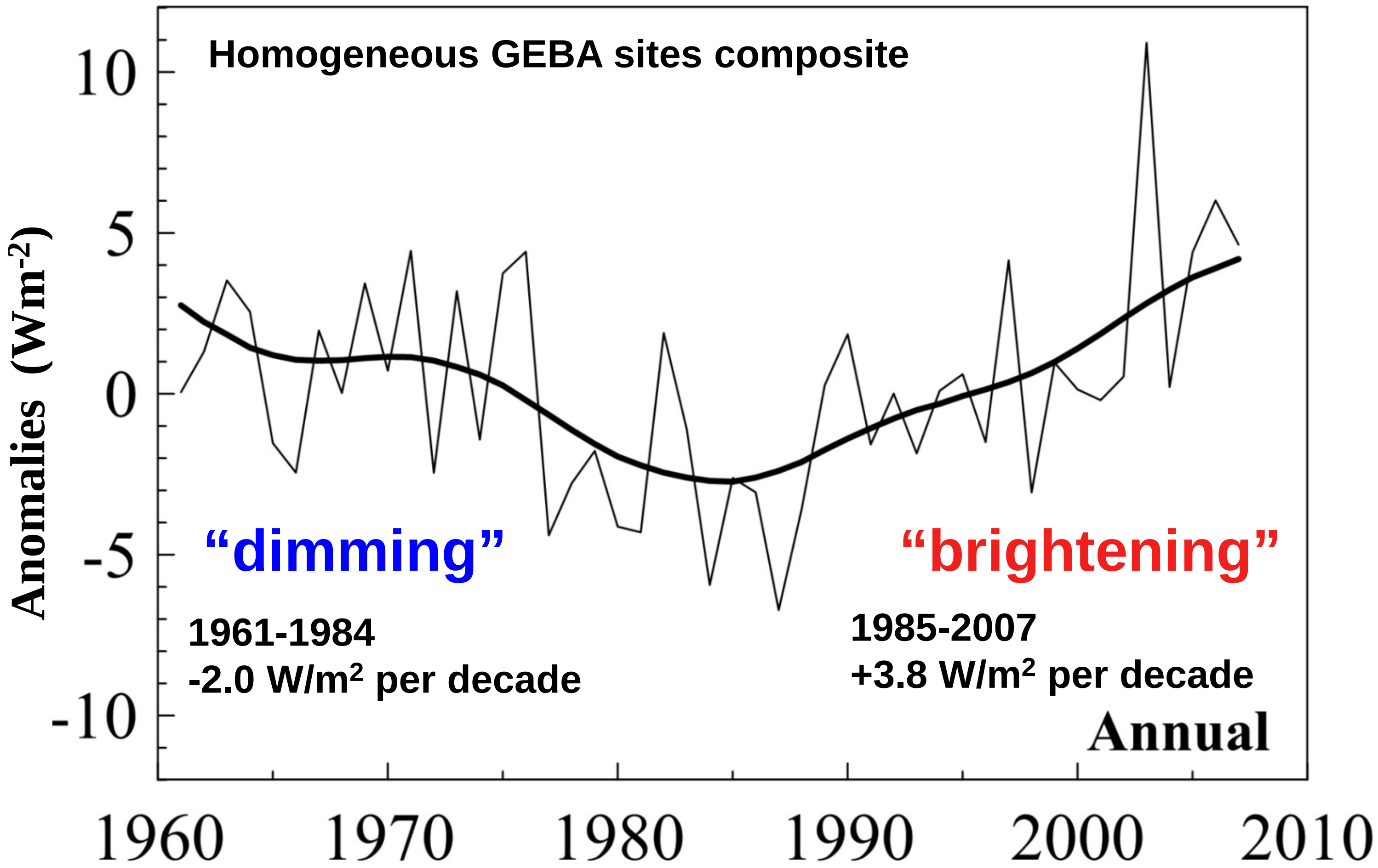


Fig. 1. GACP record of the globally averaged column AOT over the oceans and SAGE record of the globally averaged stratospheric AOT.

Mishchenko et al. Science 2007

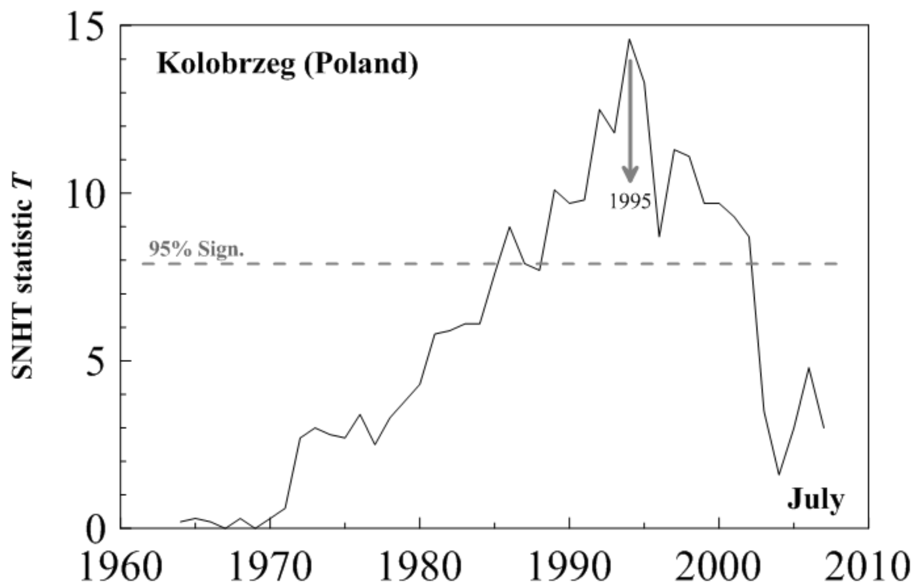
GEBA trends in Europe

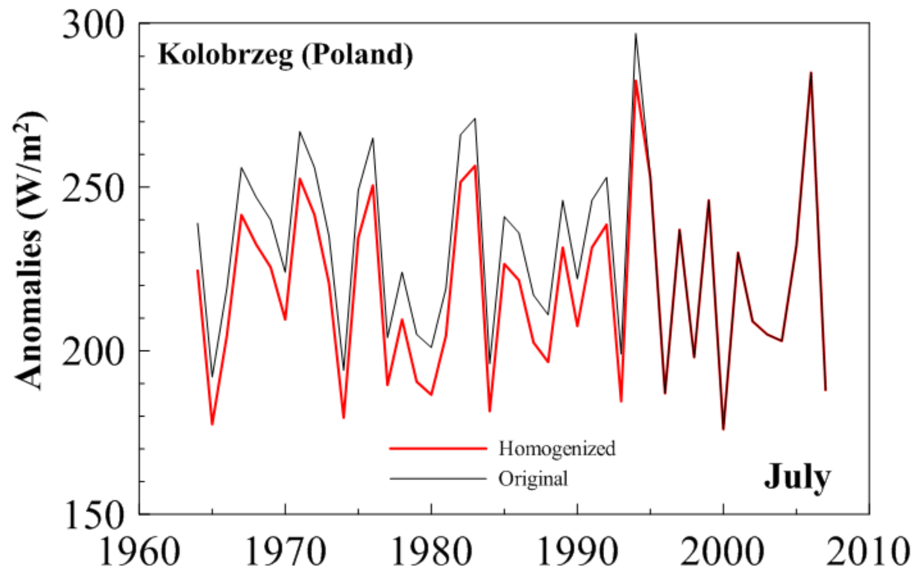


Sanchez-Lorenzo *et al*. (2012, submitted)

INSTITUTE FOR ATMOSPHERIC AND CLIMATE SCIENCE

GEBA trends in Europe





Sanchez-Lorenzo *et al*. (2013, in prep.)

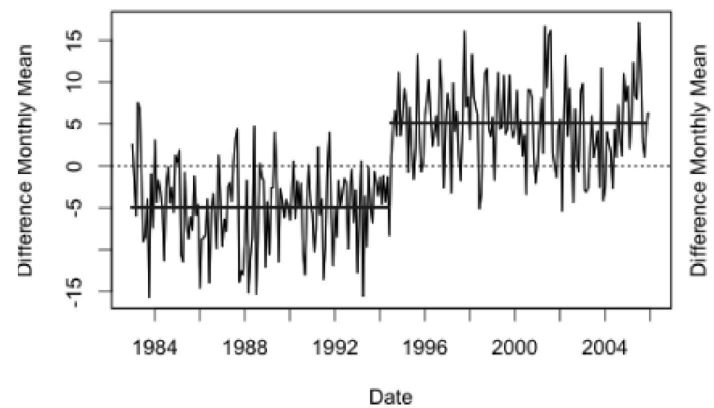
GEBA trends in Europe

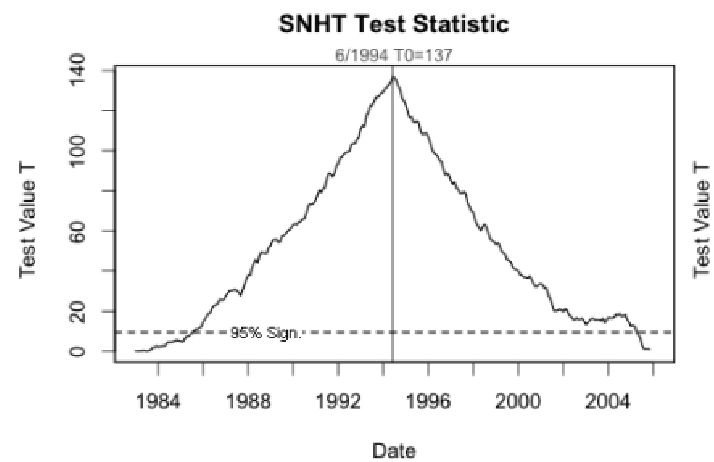
- The series has been homogenized by means of the standard normal homogeneity test (SNHT) – relative approach

$$T(k) = k\bar{z}_1^2 + (n-k)\bar{z}_2^2 \quad k = 1, \ldots, n$$

where

$$\bar{z}_1 = \frac{1}{k}\sum_{i=1}^{k}(Y_i - \bar{Y})/s \quad \text{and} \quad \bar{z}_2 = \frac{1}{n-k}\sum_{i=k+1}^{n}(Y_i - \bar{Y})/s$$





Brinckmann *et al*. (2012)

- 16 of the 56 series show at least one break (≈ 30%)
- Monthly adjustement have been applied