1st workshop on the FORUM Mission, Firenze, October 23-25, 2018

# The Earth radiation budget from a surface perspective

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# Content

## Part 1: Earth radiation budget mean state

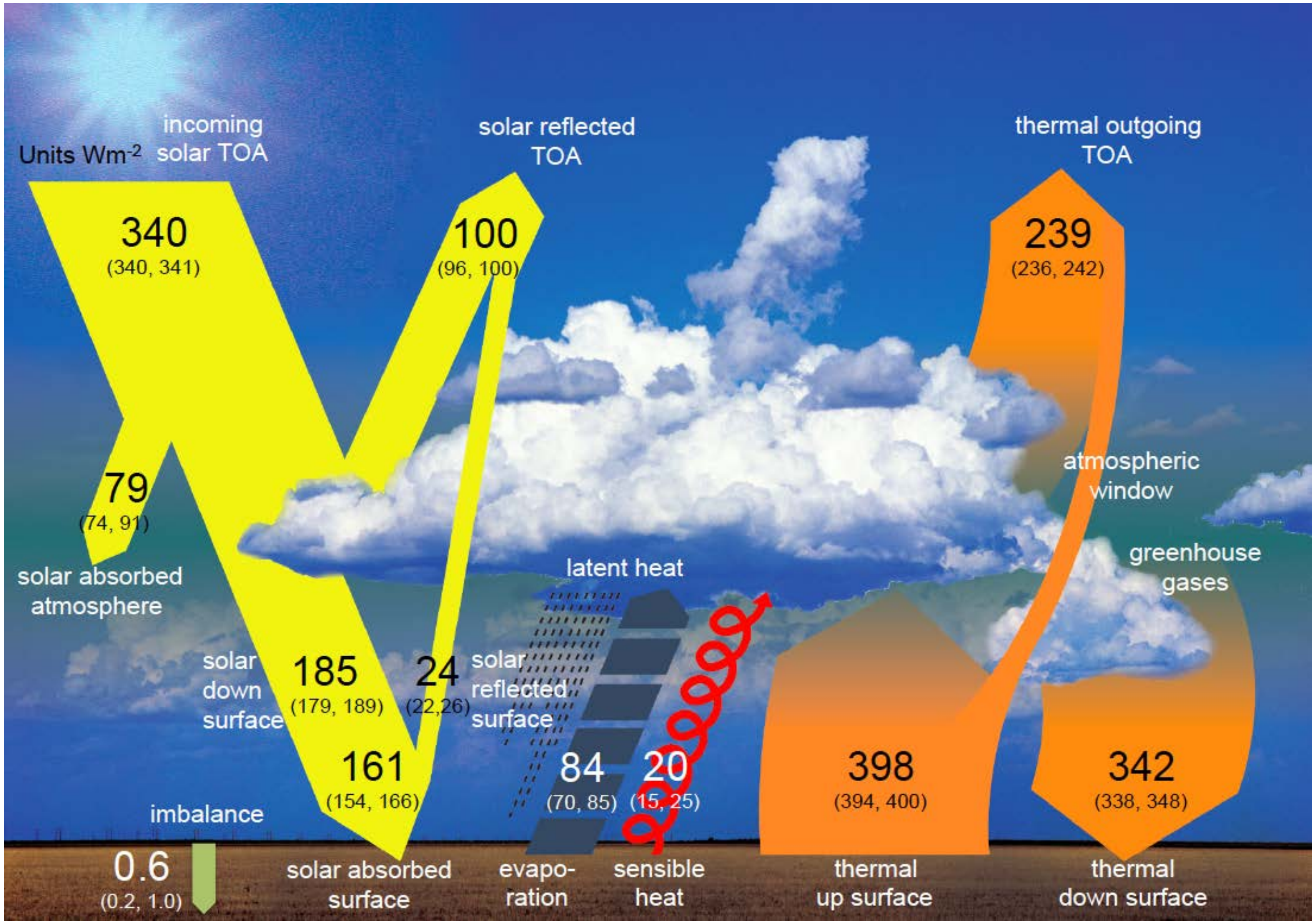
- What is the significance of global energy balance?
- How well can we quantify its components?
- How is it reproduced in climate models?

## 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: $Wm^{-2}$




Wild et al. 2013 Clim.Dyn. / IPCC AR5

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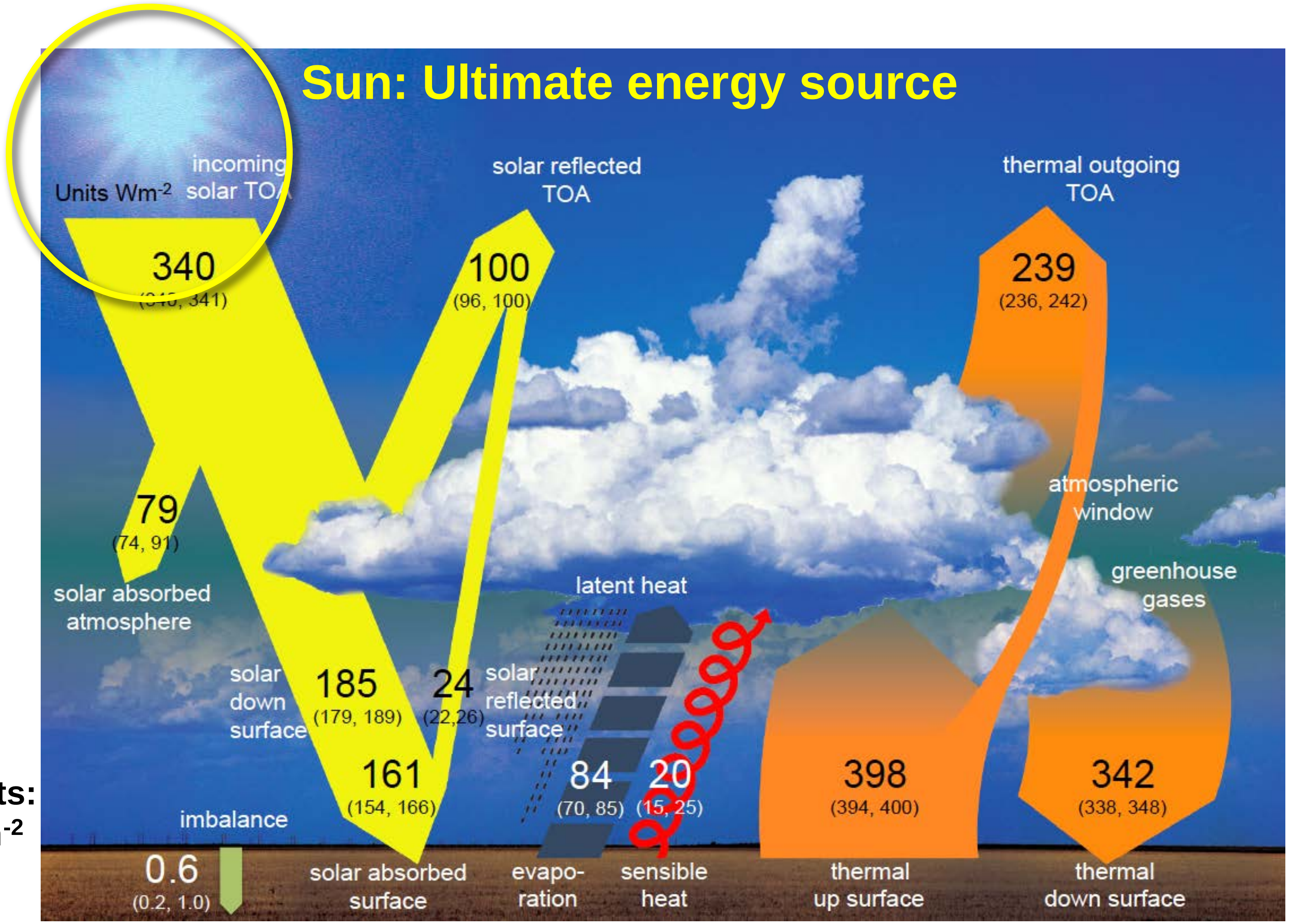
# Earth radiation budget



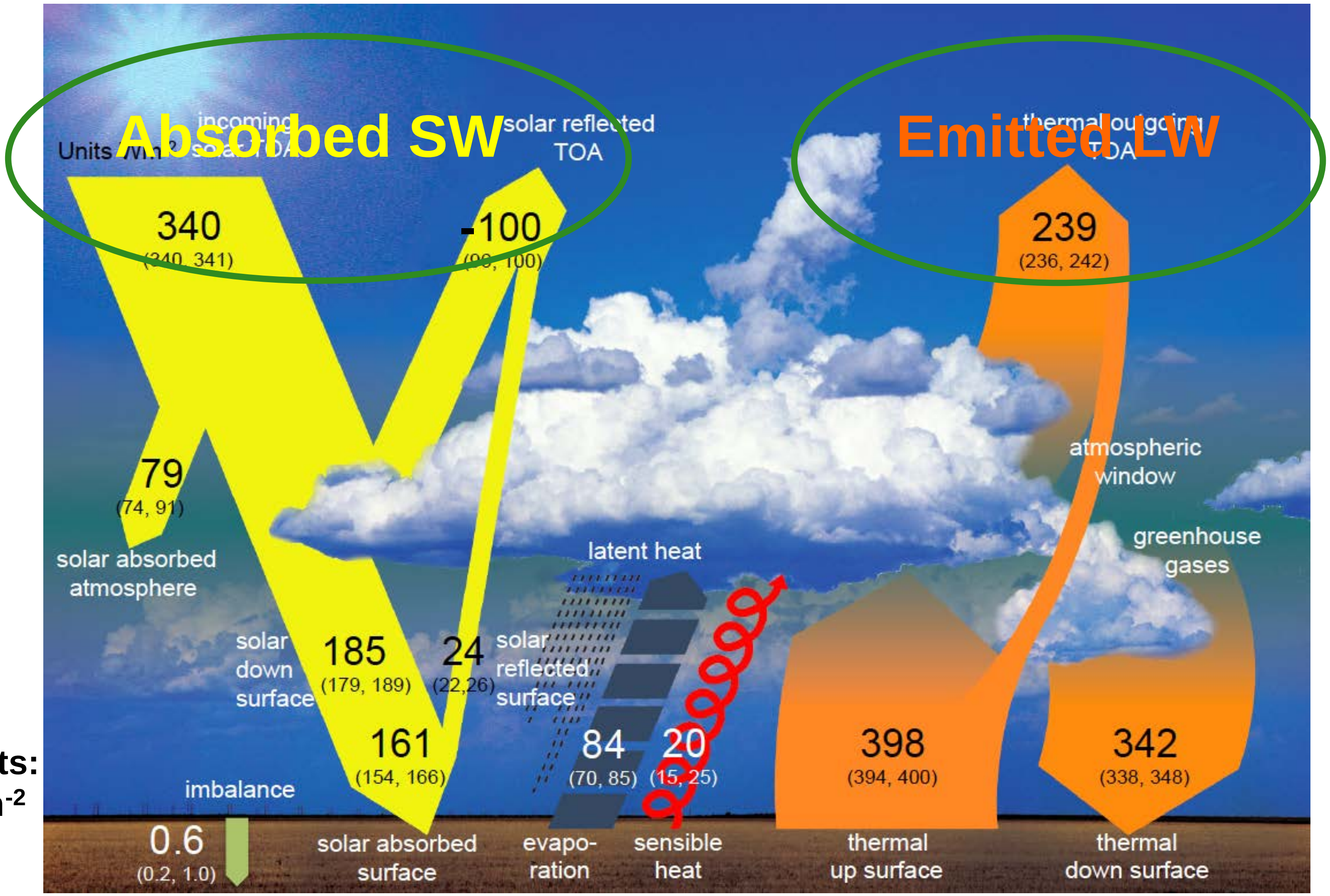



**Units: Wm$^{-2}$**

Wild et al. 2013 Clim.Dyn. / IPCC AR5

# Earth radiation budget

## Radiation balance at the Top of Atmosphere




Units: $Wm^{-2}$

Wild et al. 2013 Clim.Dyn. / IPCC AR5

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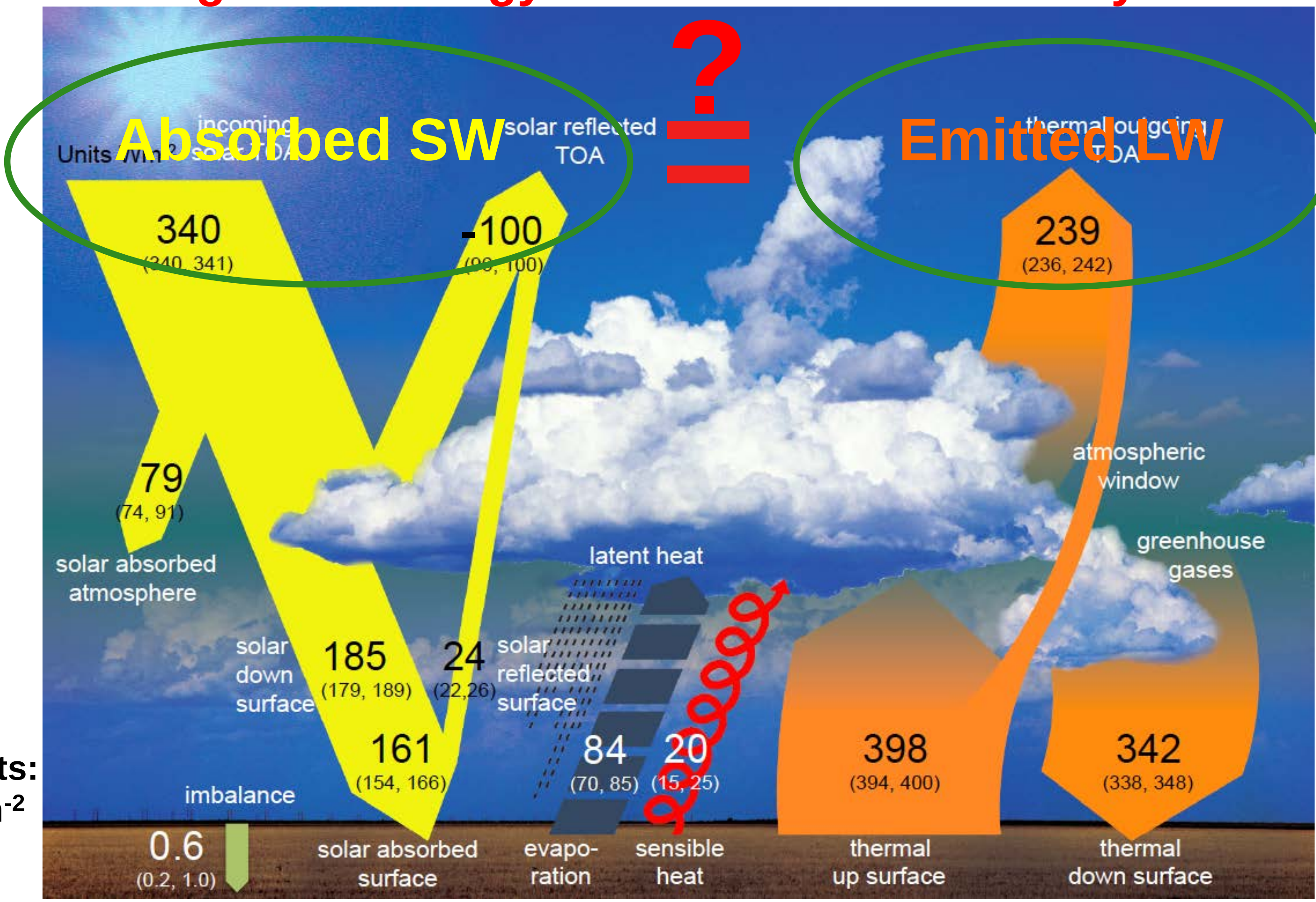
# Earth radiation budget

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

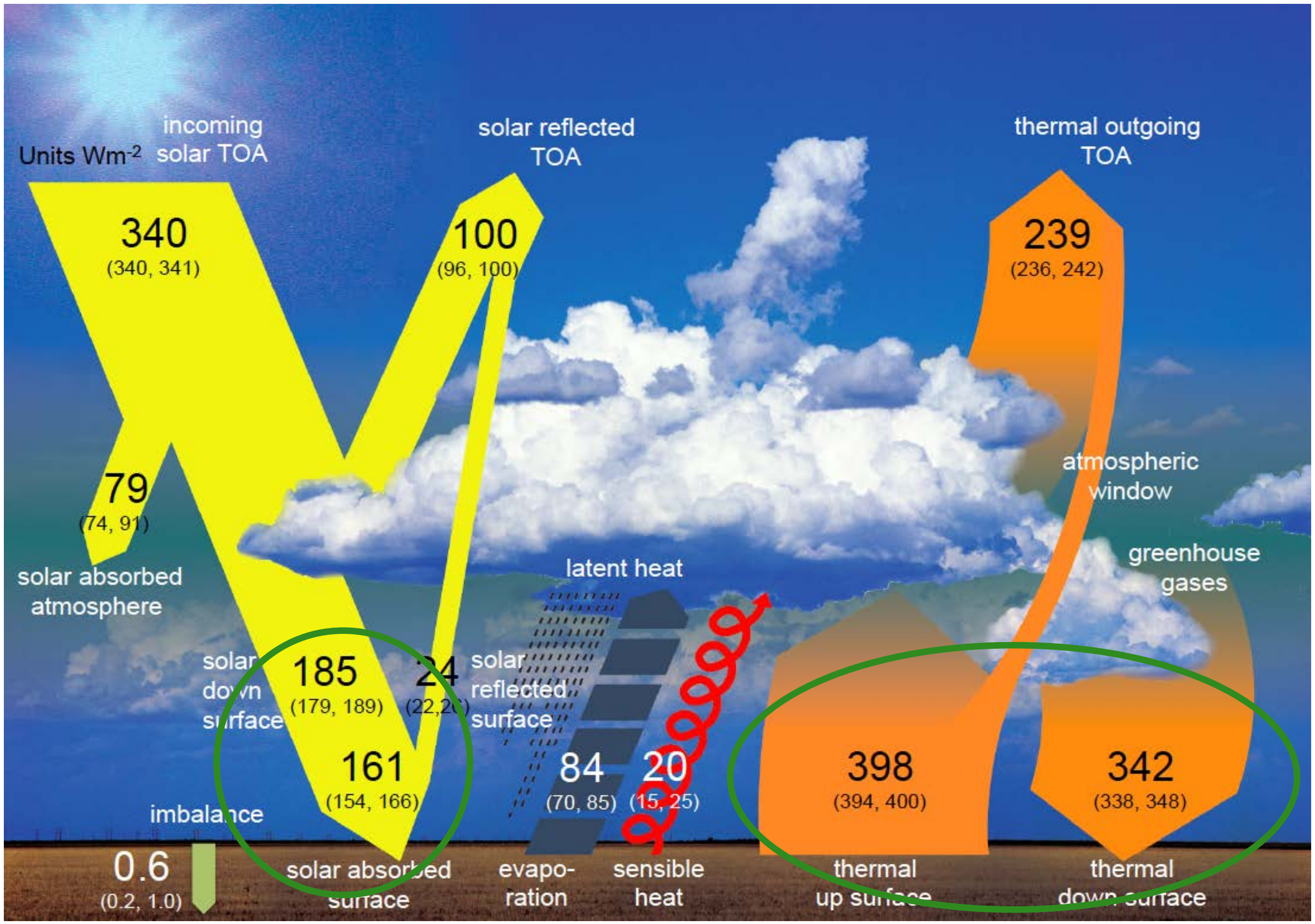



Units: $Wm^{-2}$

Wild et al. 2013 Clim.Dyn. / IPCC AR5

# Earth radiation budget

Units:
Wm-2




**Radiation balance at the surface**

Wild et al. 2013 Clim.Dyn. / IPCC AR5

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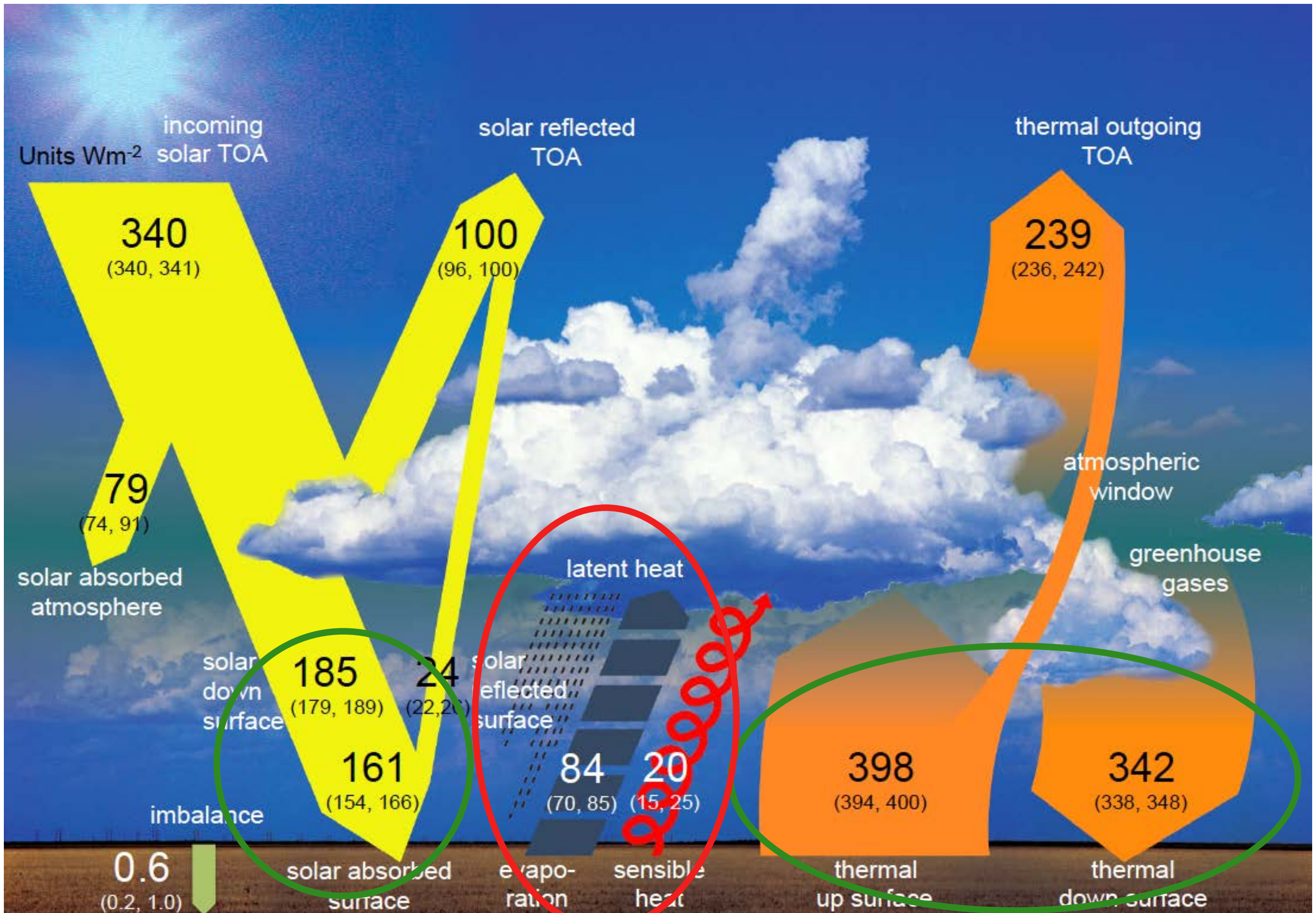
# Earth radiation budget

Units: $Wm^{-2}$




**Radiation balance at the surface**

**determines surface climate and drives the global water cycle**

Wild et al. 2013 Clim.Dyn. / IPCC AR5

# Estimates of global mean radiation budgets

## Historic estimates:
## Pre-satellite period

**TSI: 1326-1963** Wm$^{-2}$
**Planetary Albedo 0.33-0.5**
**OLR 174-327** Wm$^{-2}$

Dines 1917

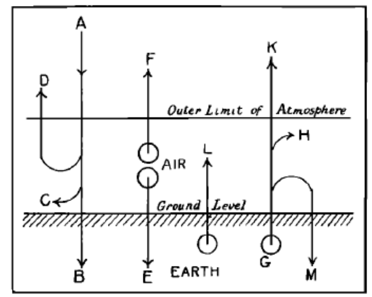



Fig. 2. Heat balance of the atmosphere: (A) radiant energy reaching the atmosphere, part of which is (B) absorbed by the earth, (C) absorbed by the air, and (D) reflected by the earth or air; (G) radiation of the earth, part of which is (M) reflected back, (H) absorbed, and (K) transmitted; (E and F) 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].

London 1957

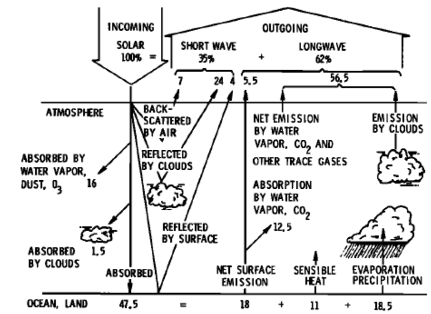



Fig. 3. Same as Figure 2, estimated by *London* [1957].

Source: Hunt et al. 1986 Rev. Geophys.

| | TSI Solar constant Wm$^{-2}$ | Planetary Albedo | Absorption by earth/atmosphere Wm$^{-2}$ | Absorption in the atmoasphere Wm$^{-2}$ | Emissior at TOA Wm$^{-2}$ | Global radiatio Wm$^{-2}$ | Absorbed global radiation Wm$^{-2}$ | Surface Albedo | long-wave in-radiation Wm$^{-2}$ | Long-wave out-radiation Wm$^{-2}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 35) | 1963 | 0.33 | 327 (67) | 81 (17) | 327 | 245 (75 | | | | |
| owle (1908) | 1465 | 0.37 | 231 (63) | 66 (18) | 231 | 179 (49 | 165 (45) | 0.08 | | 388 (14.5) |
| 17) | 1395 | 0.50 | 174 (50) | 29 (8) | 174 | | 145(42) | | 194 | 242 (−17.6) |
| 919) | | 0.43 | | | | | | | | |
| 1928) | 1362 | 0.43 | 194 (57) | | 189 | | | | | |
| ) | 1395 | 0.43 | 199 (57) | 49 (14) | 199 | | 150 (43) | | 307 | 401 (16.9) |
| 936) | | 0.39 | | | | | | | | |
| ilipps (1934) | 1353 | 0.43 | 193 (57) | 52 (16) | 193 | 162 (48 | 145 (43) | 0.10 | 325 | 406 (17.7) |
| 1949) | 1353 | 0.45 | 186 (55) | 44(13) | 186 | 156 (46 | 140 (42) | 0.10 | 328 | 389 (14.7) |
| 9) | | 0.35 | | | | | | | | |
| (1954) | 1353 | 0.34 | 223 (66) | 66 (19) | 223 | 175 (52 | 157 (47) | 0.10 | 355 | 403 (17.2) |
| 956) | 1326 | 0.40 | 199 (60) | 52 (16) | 199 | 171 (52 | 147 (44) | 0.14 | 328 | 385 (14.0) |
| 957) | 1395 | 0.35 | 227 (65) | 61 (17.5) | 227 | 181 (52 | 166 (47.5) | 0.12 | 337 | 400 (16.7) |
| (1962) | | 0.38 | | | | | | | | |
| 963) | 1326 | 0.33 | 222 (67) | 78 (24) | 222 | 167 (50 | 144 (43) | 0.14 | 342 | 390 (15.0) |
| : Strickler (1964) | 1395 | 0.35 | 228 (65) | 63 (18) | 228 | 184 (53 | 165 (47) | 0.10 | 330 | 390 (15.0) |
| 965) | 1395 | 0.36 | 224 (64) | 59 (17) | 224 | 185 (53 | 164 (47) | 0.11 | 273 | 342 (5.5) |

**Ohmura 2015**

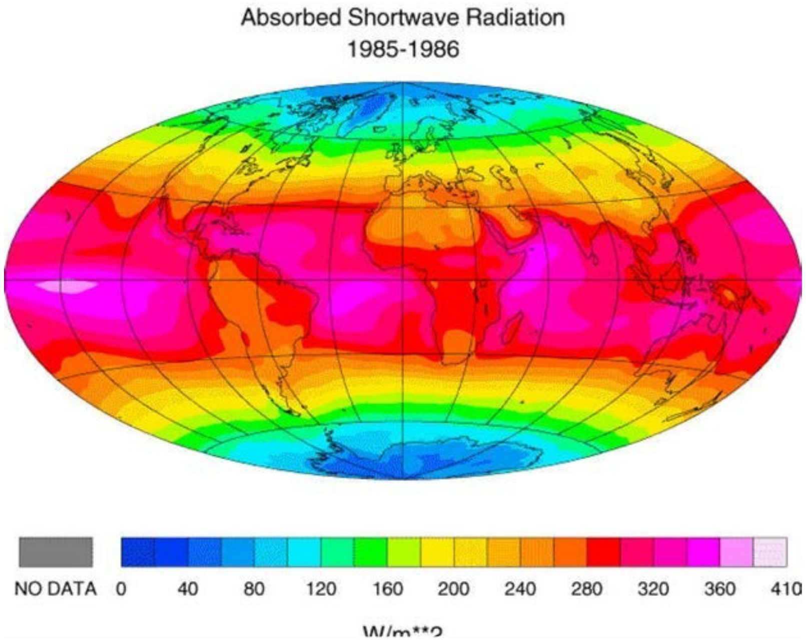
# Estimates of global radiation budgets

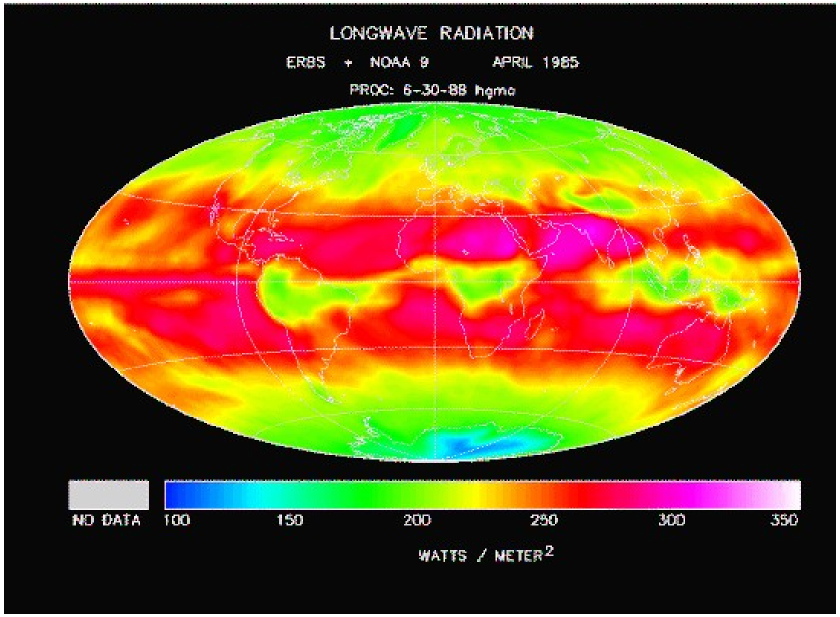
## Early Satellite Period:

### Earth Radiation Budget Experiment (ERBE) 1985-1989

Planetary albedo: **0.30**

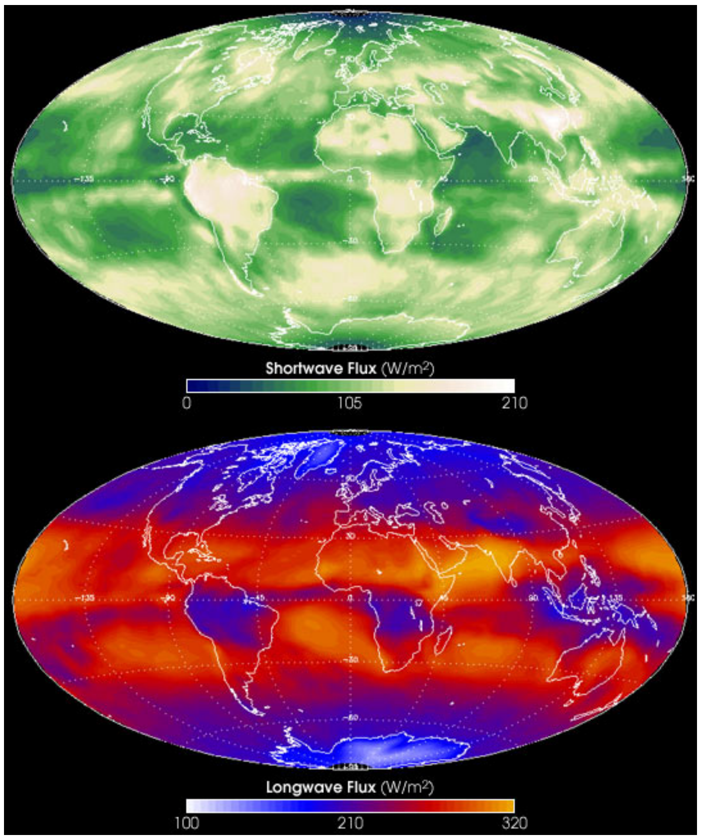
Total SW absorption/ LW emission: **235** $Wm^{-2}$



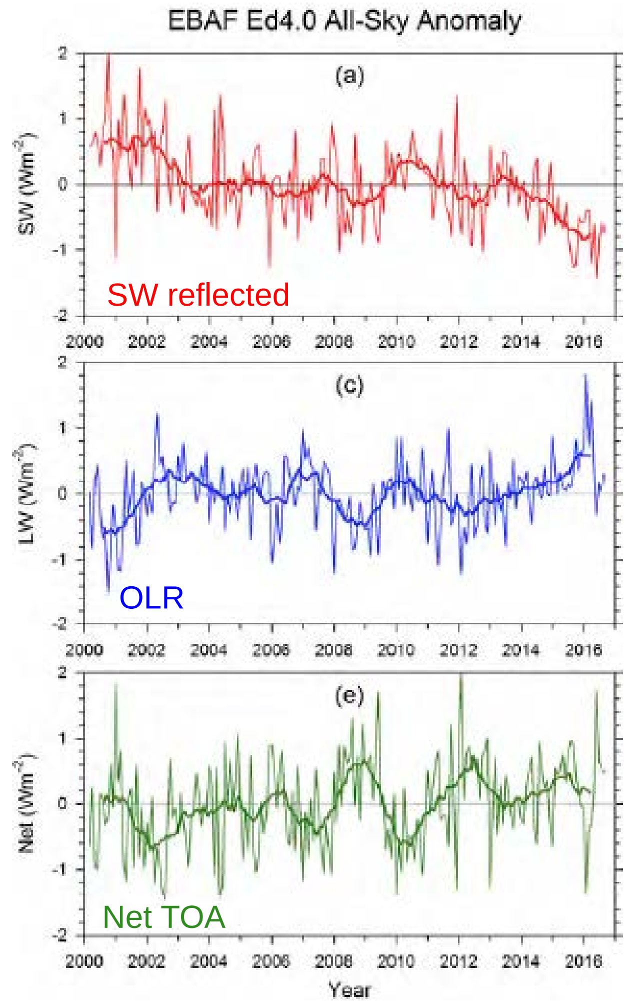



# Estimates of global radiation budgets

## “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

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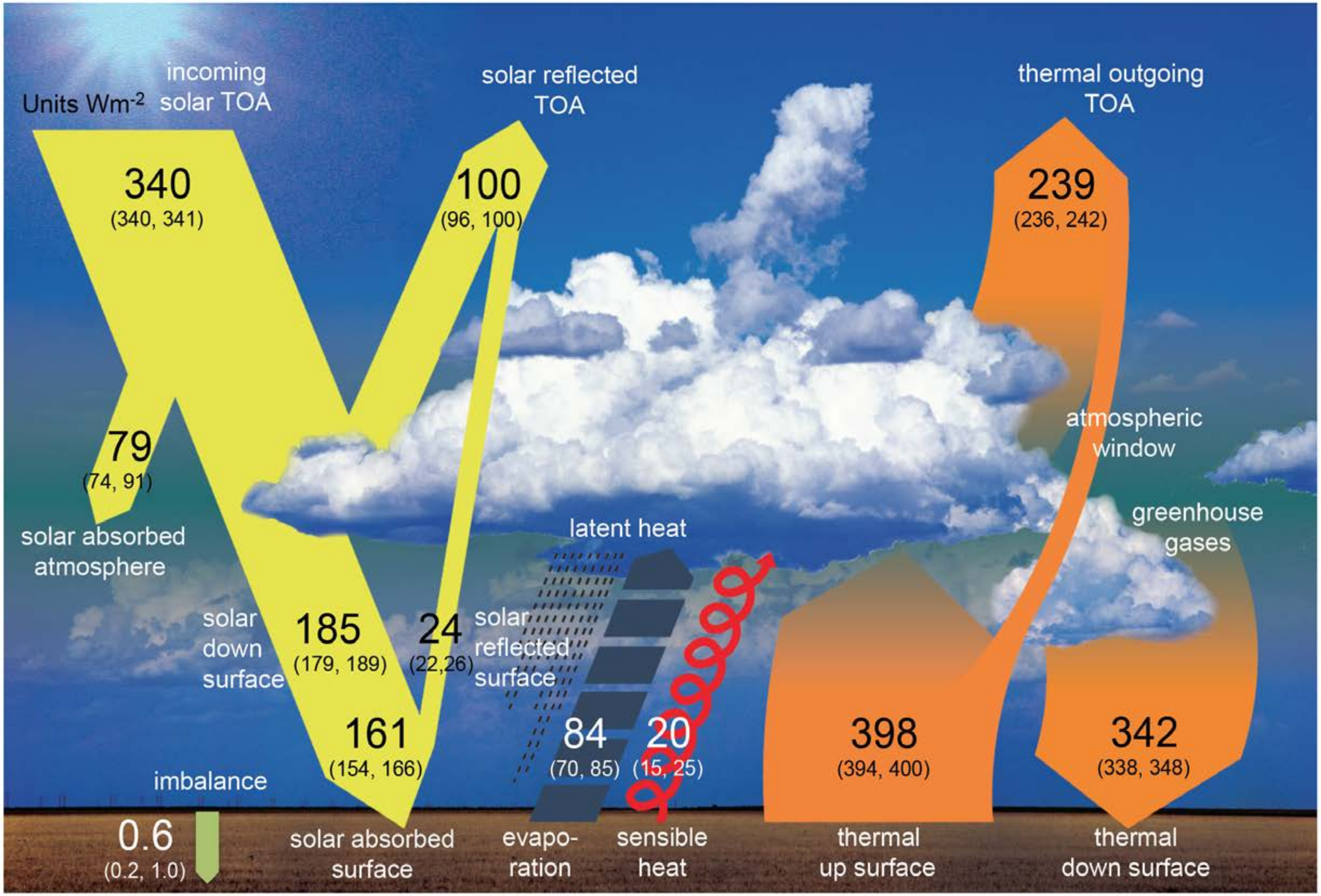
# Estimates of global radiation budgets

## Uncertainties

**Units Wm$^{-2}$**




Wild et al. 2013, Climate Dynamics

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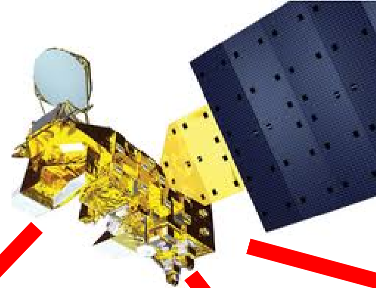
# bal radiation budgets

**Satellite missions**

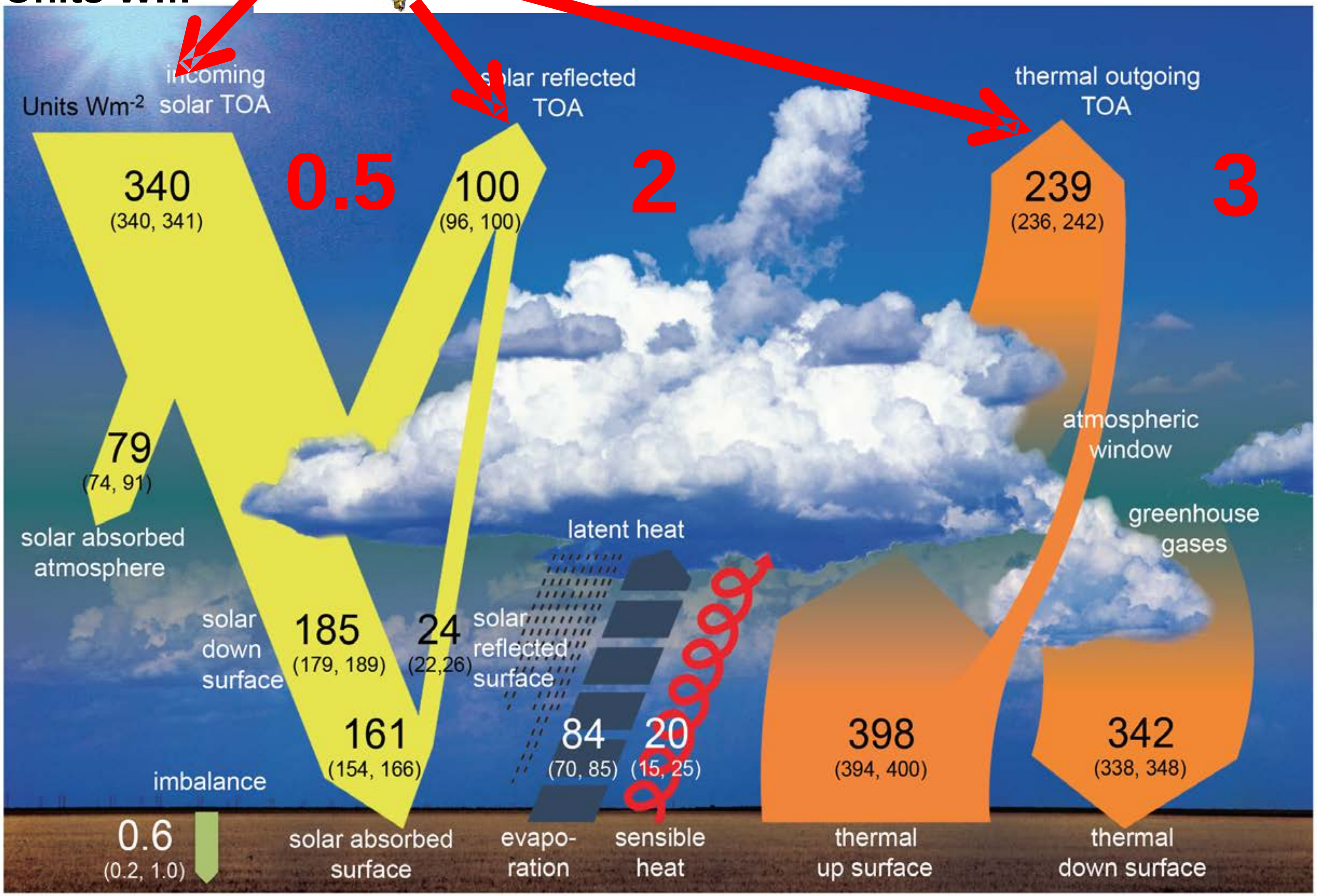
**CERES**

**SORCE**



**Units Wm$^{-2}$**

**Uncertainties**




Wild et al. 2013, Climate Dynamics

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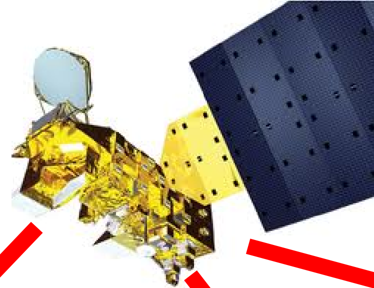
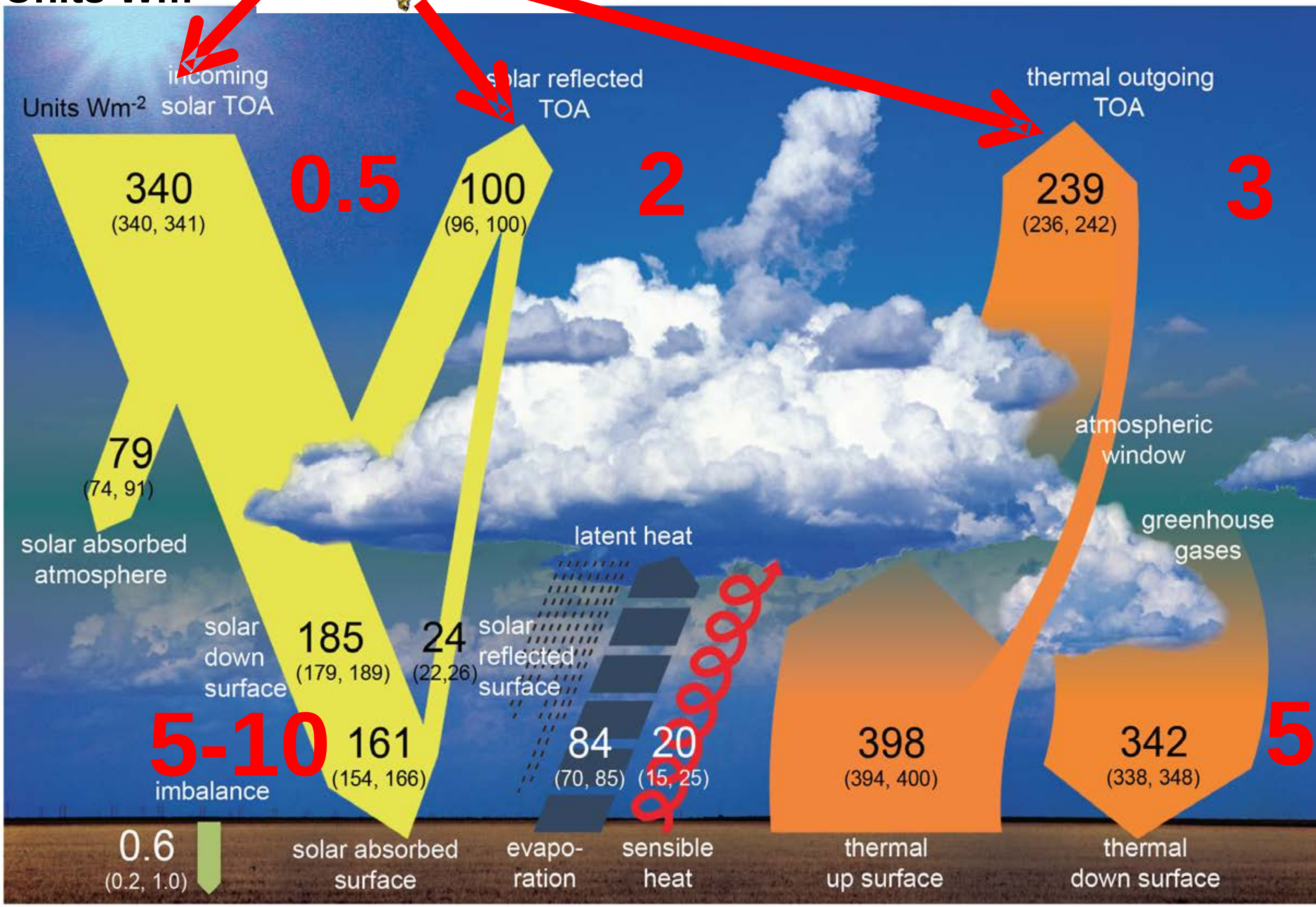
# …bal radiation budgets

**Satellite missions**
**CERES**
**SORCE**



**Units Wm$^{-2}$**

**Uncertainties**

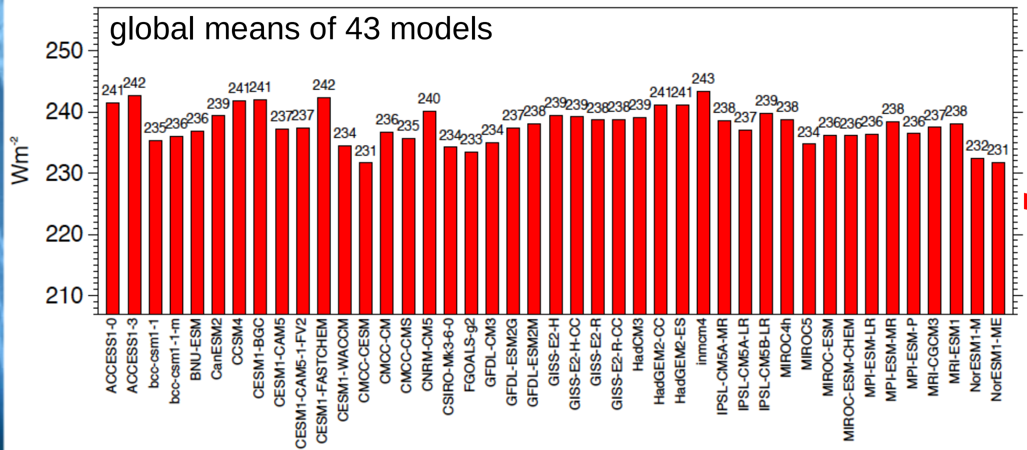



**Uncertainties remain in the estimation of the energy balance components**

Wild et al. 2013, Climate Dynamics

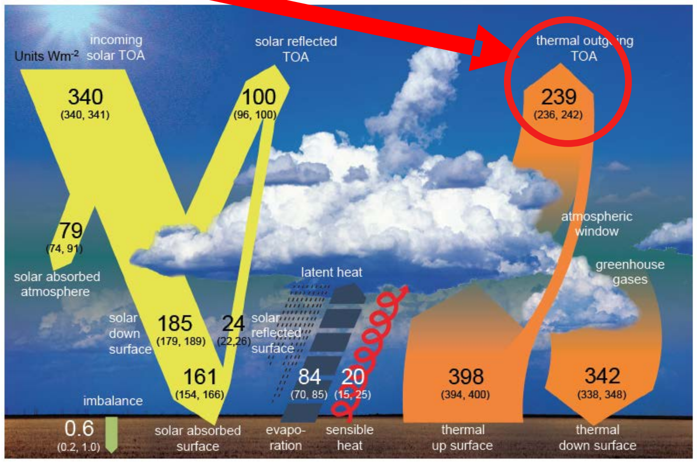
# Longwave radiation budgets in CMIP5 GCMs

## Outgoing longwave radiation
## top of atmosphere




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

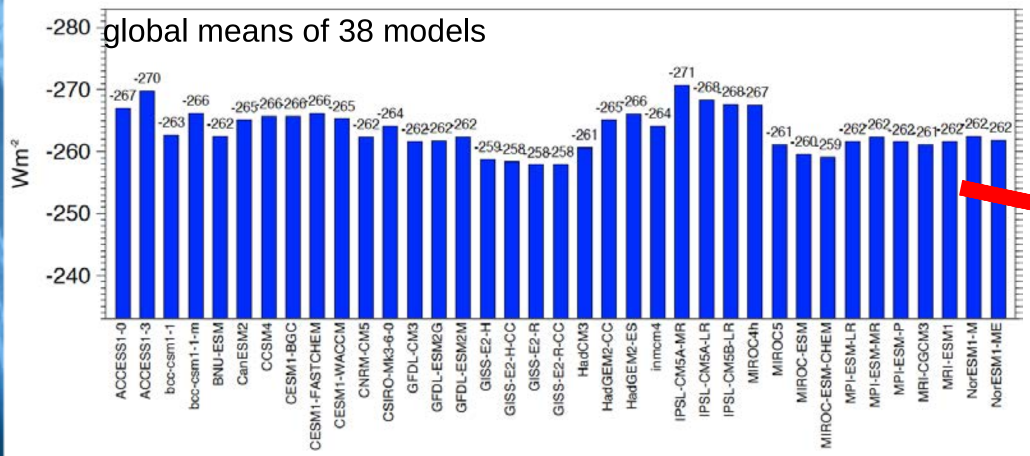
**Reference Satellite Value (CERES EBAF): 239 $Wm^{-2}$**




Wild et al. 2013, 2018 Climate Dynamics

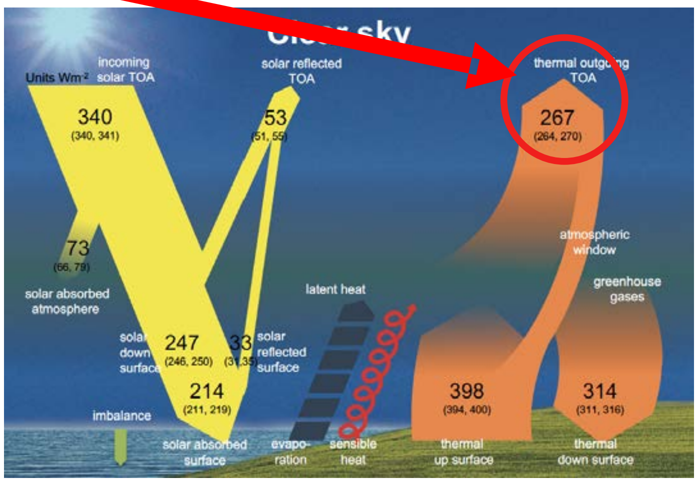
# Longwave radiation budgets in CMIP5 GCMs

**Outgoing longwave radiation**
**top of atmosphere cloud free**




**Multimodel mean 263 Wm$^{-2}$**
**Model range: 13 Wm$^{-2}$**
**Standard dev.: 3.3 Wm$^{-2}$**

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




Wild et al. 2013, 2018 Climate Dynamics

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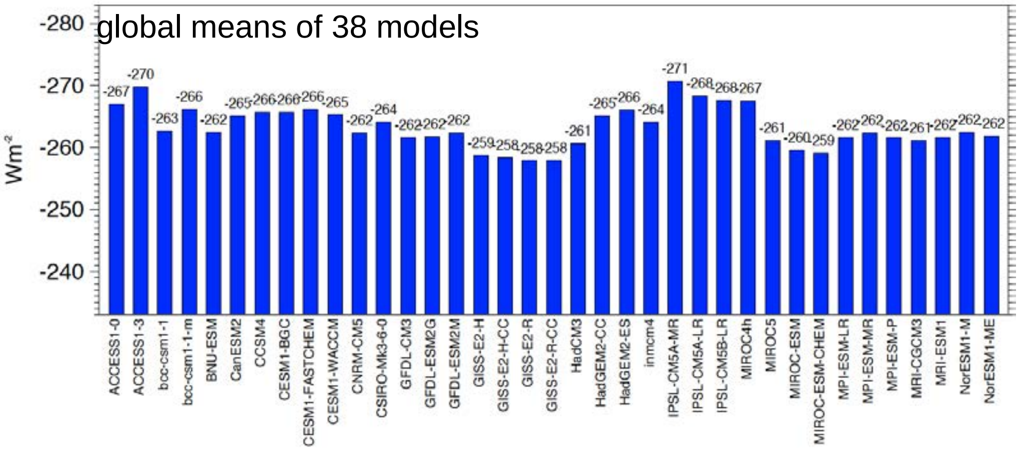
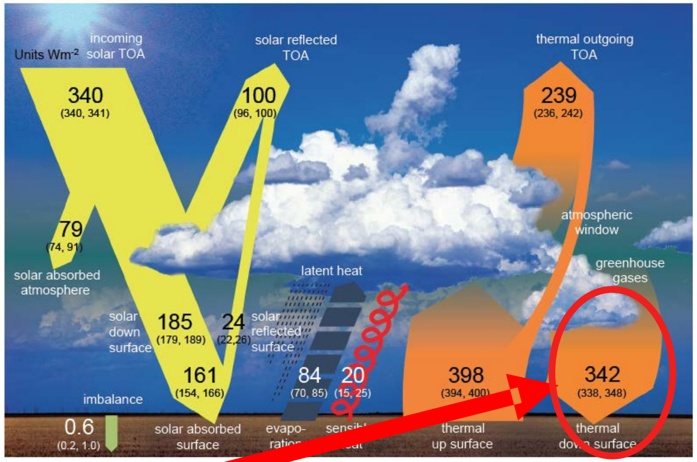
# Longwave radiation budgets in CMIP5 GCMs

## Outgoing longwave radiation
## top of atmosphere cloud free

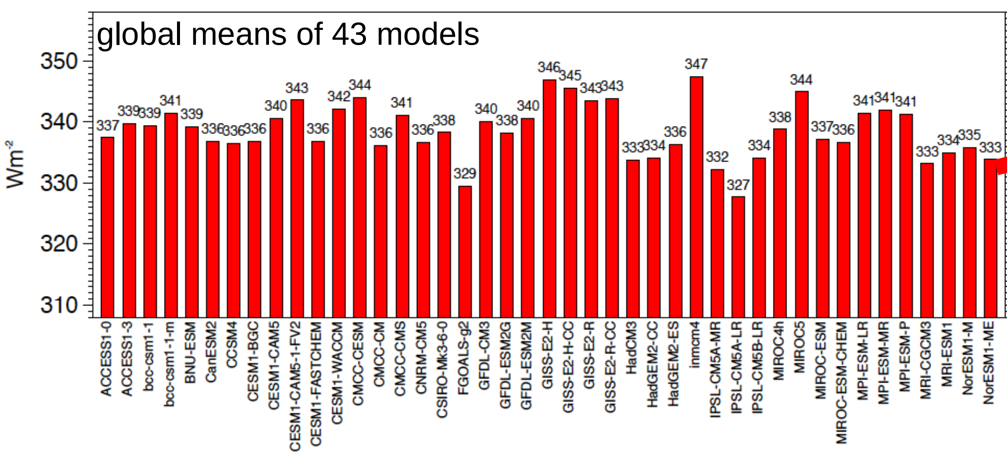



**Multimodel mean 263 $Wm^{-2}$**
**Model range: 13 $Wm^{-2}$**
**Standard dev.: 3.3 $Wm^{-2}$**

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




## 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

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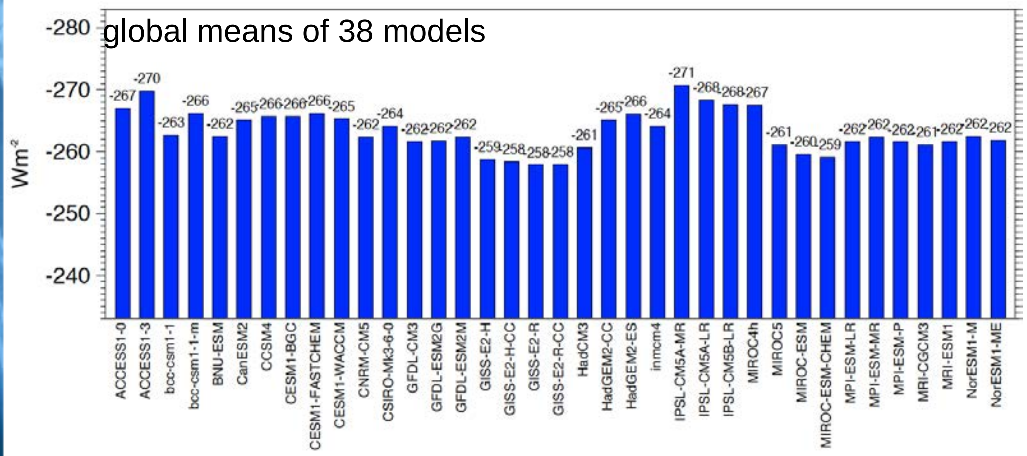
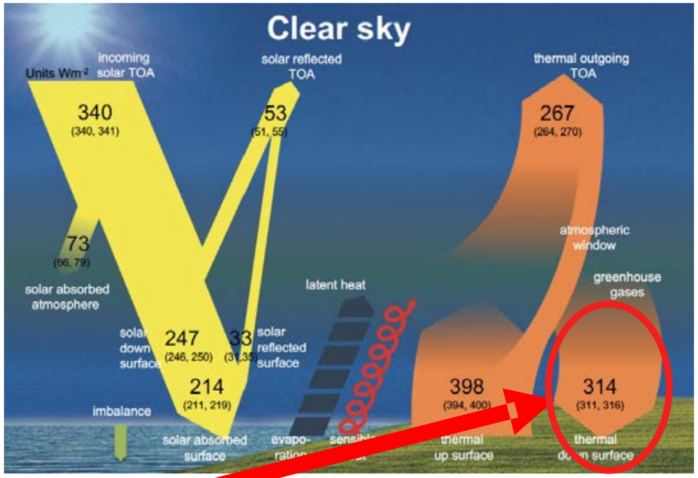
# Longwave radiation budgets in CMIP5 GCMs

## Outgoing longwave radiation top of atmosphere cloud free

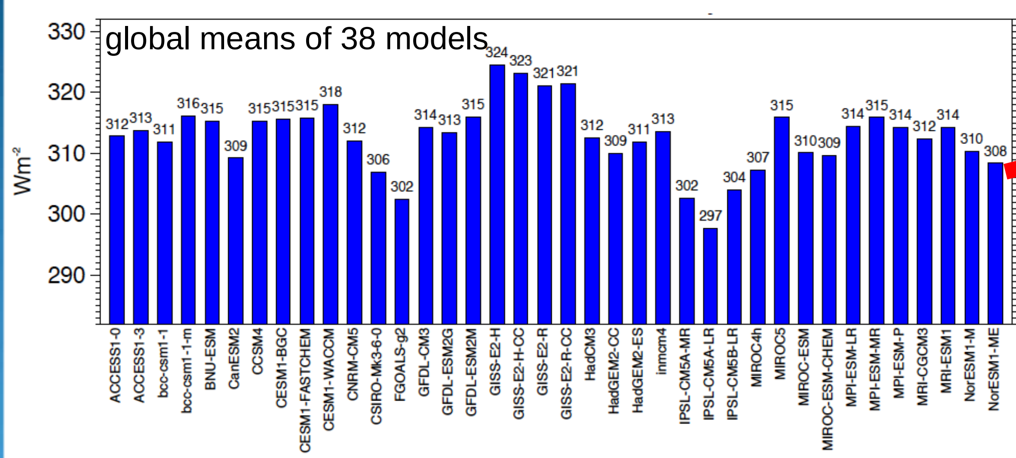



**Multimodel mean 263 $Wm^{-2}$**
**Model range: 13 $Wm^{-2}$**
**Standard dev.: 3.3 $Wm^{-2}$**

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



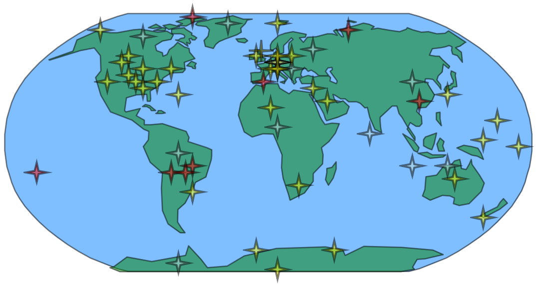

## Downward longwave radiation surface cloud free




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

Wild et al. 2013, 2018 Climate Dynamics

# Constraints from surface observations



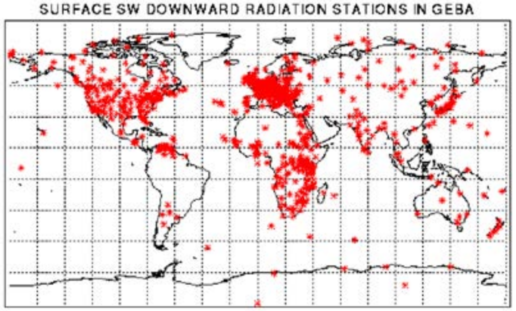
Ohmura et al. 1998

BSRN site Payerne

ets in

GEBA

at more




Ohmura, Gilgen, Wild 1989

=> allows assessment of the absorption of solar radiation at the surface, within the atmosphere and at the TOA in GCMs .

**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

**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

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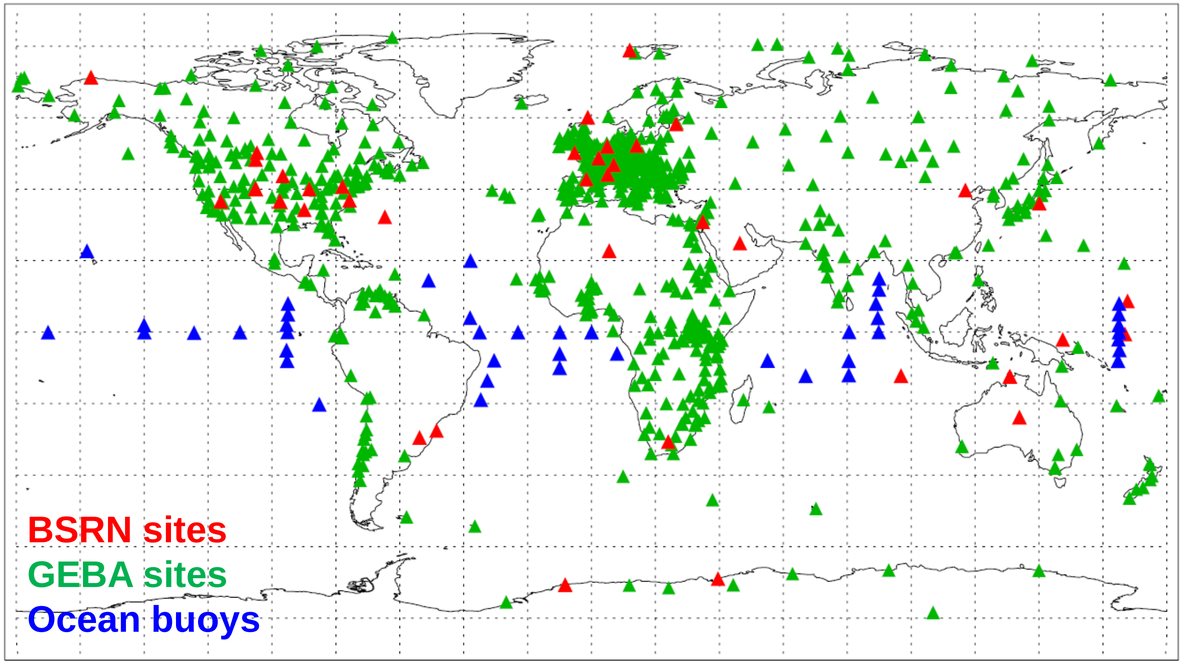
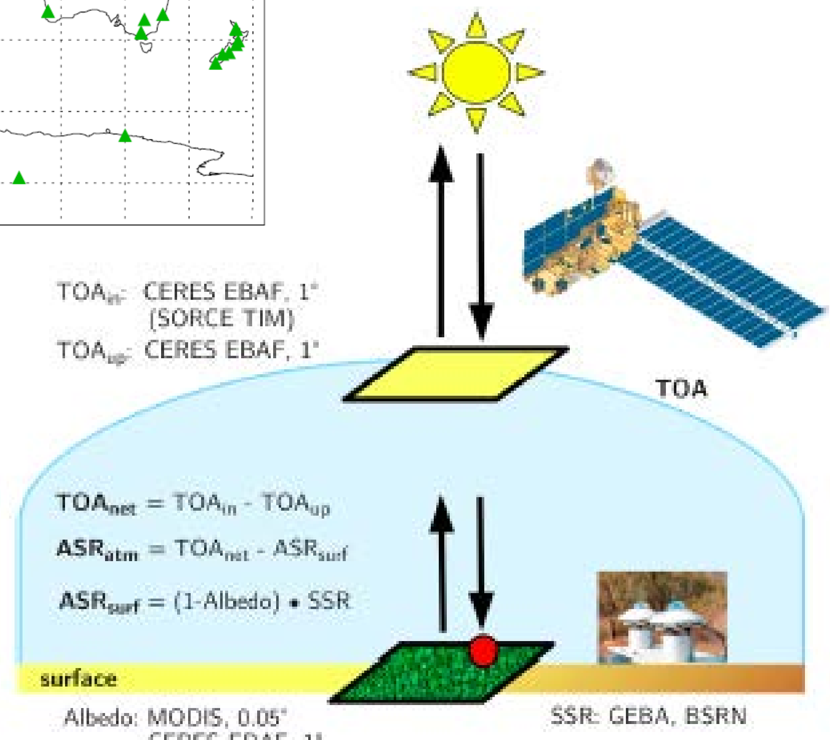
# Constraints from surface and space

Surface radiation stations with multiyear records




**Combing surface and satellite obs to estimate surface, atmosphere and TOA radiation budgets**

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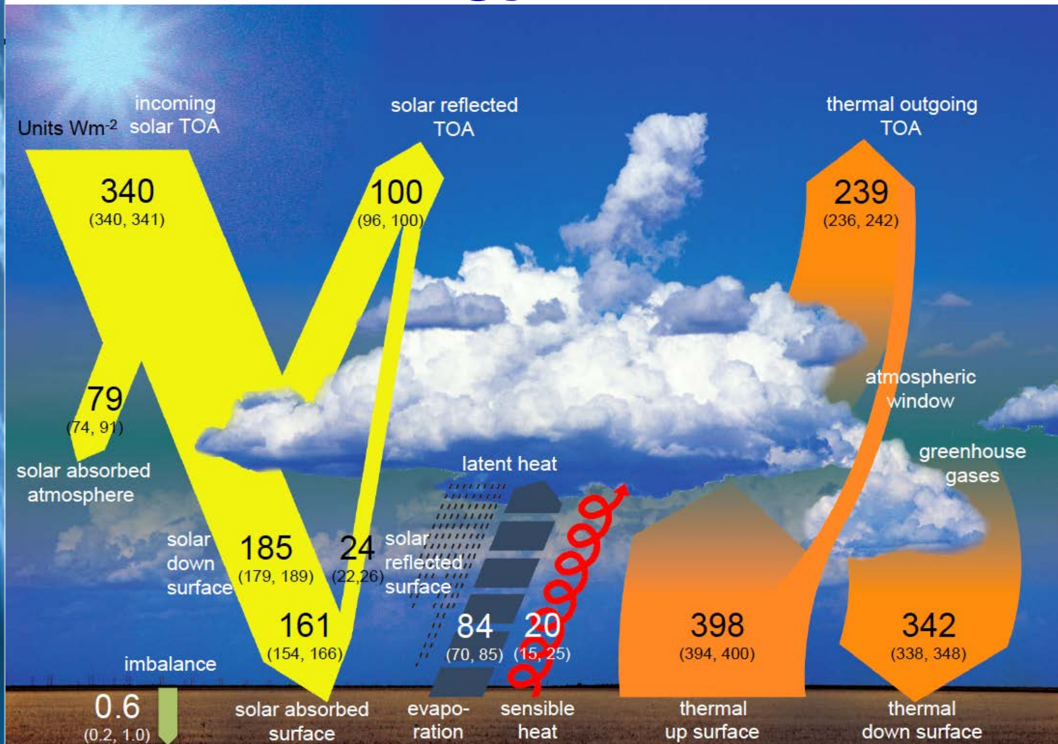
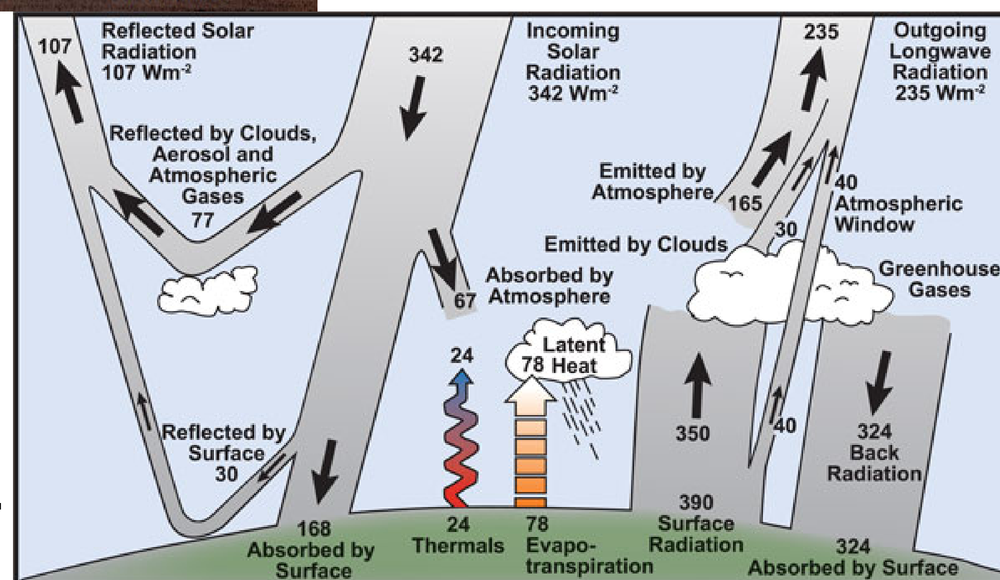
# Global Energy Balance in IPCC AR4 and AR5




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

348

**IPCC AR5**
Wild et al. 2013




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

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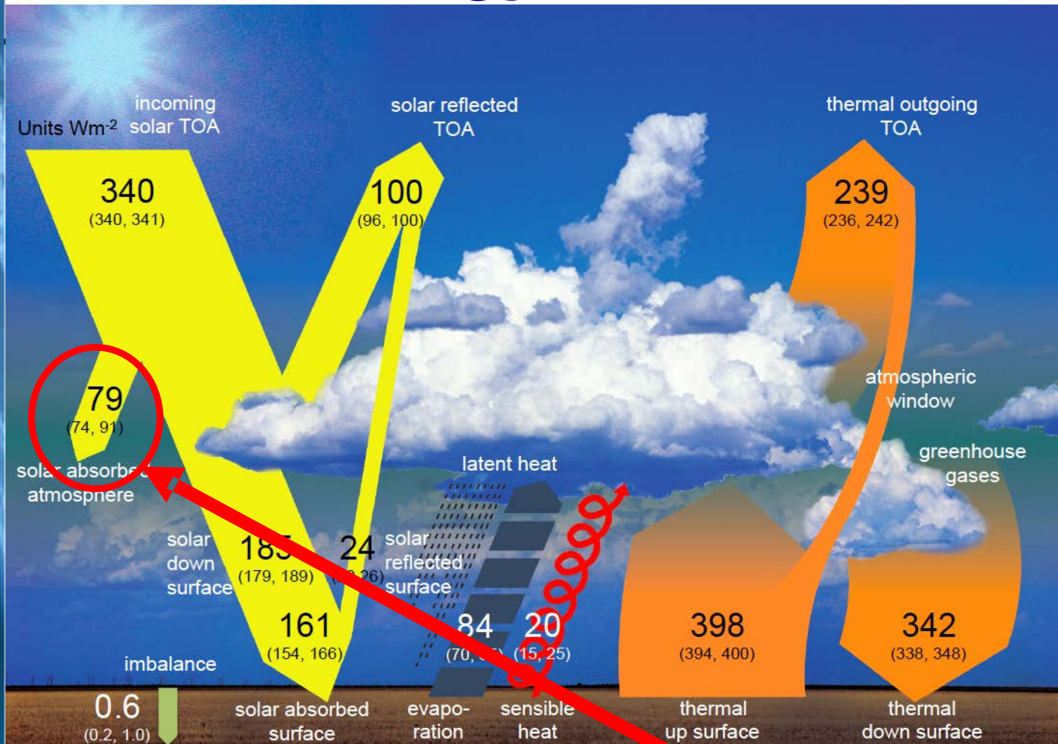
# Global Energy Balance in IPCC AR4 and AR5

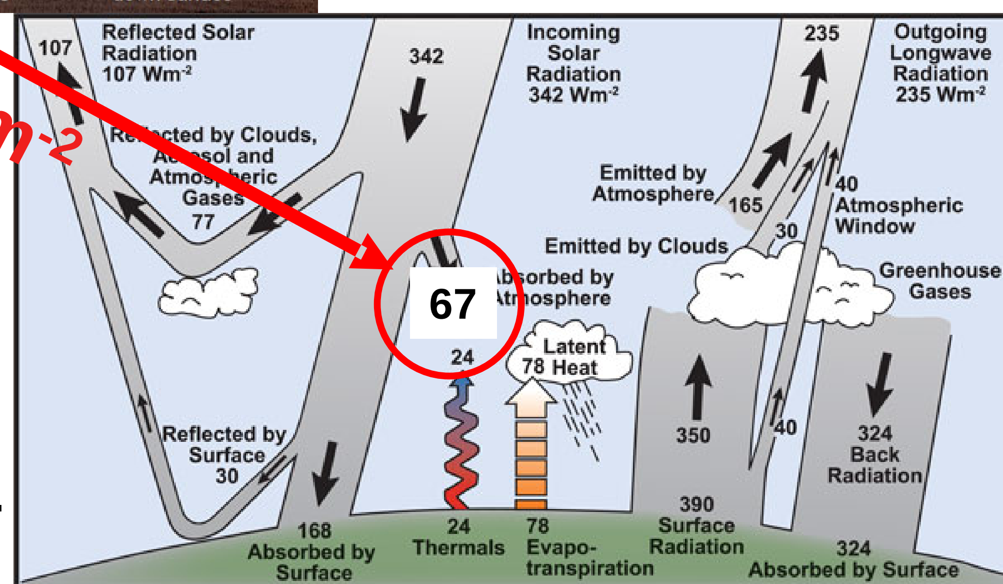



**IPCC AR5**
Wild et al. 2013

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

348

12 Wm$^{-2}$




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

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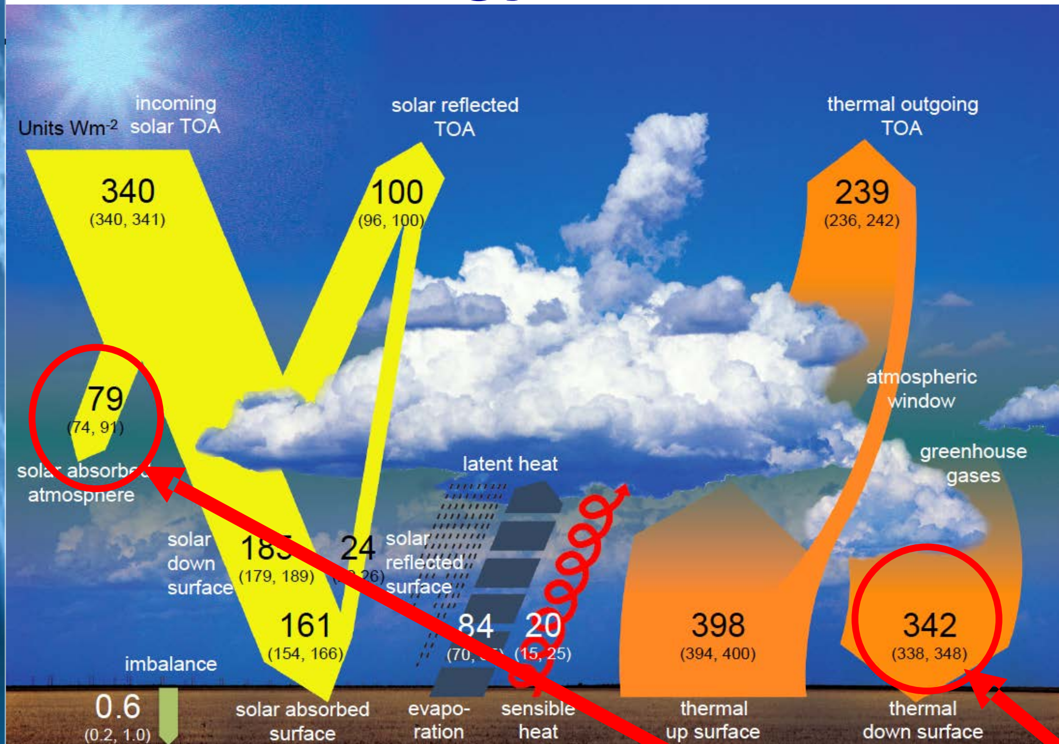
# Global Energy Balance in IPCC AR4 and AR5




**IPCC AR5**

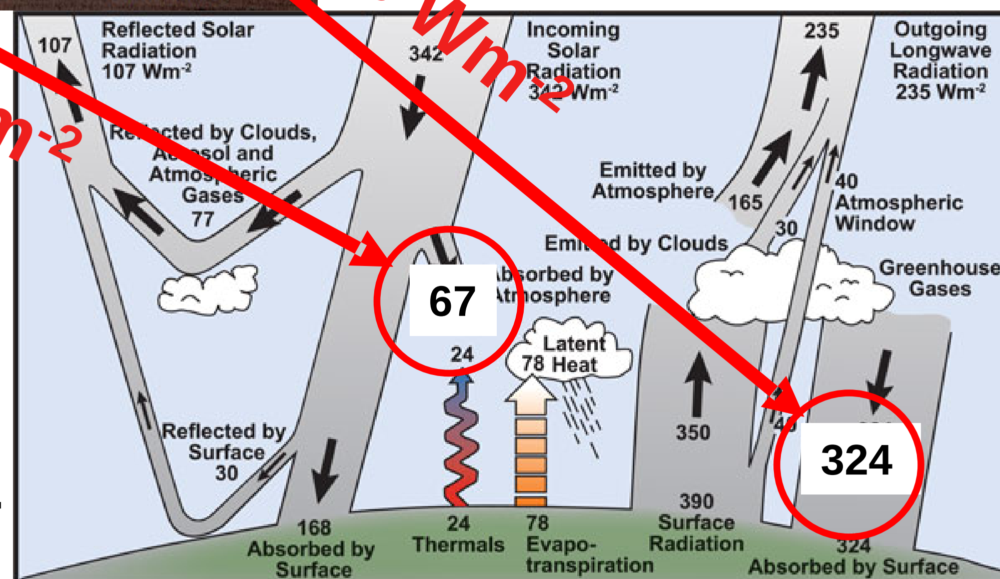
Wild et al. 2013

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

348

12 Wm-2

18 Wm-2




**IPCC AR3 / AR4**

Kiehl & Trenberth (1997)

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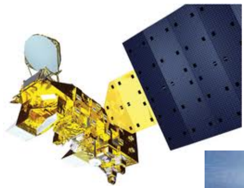
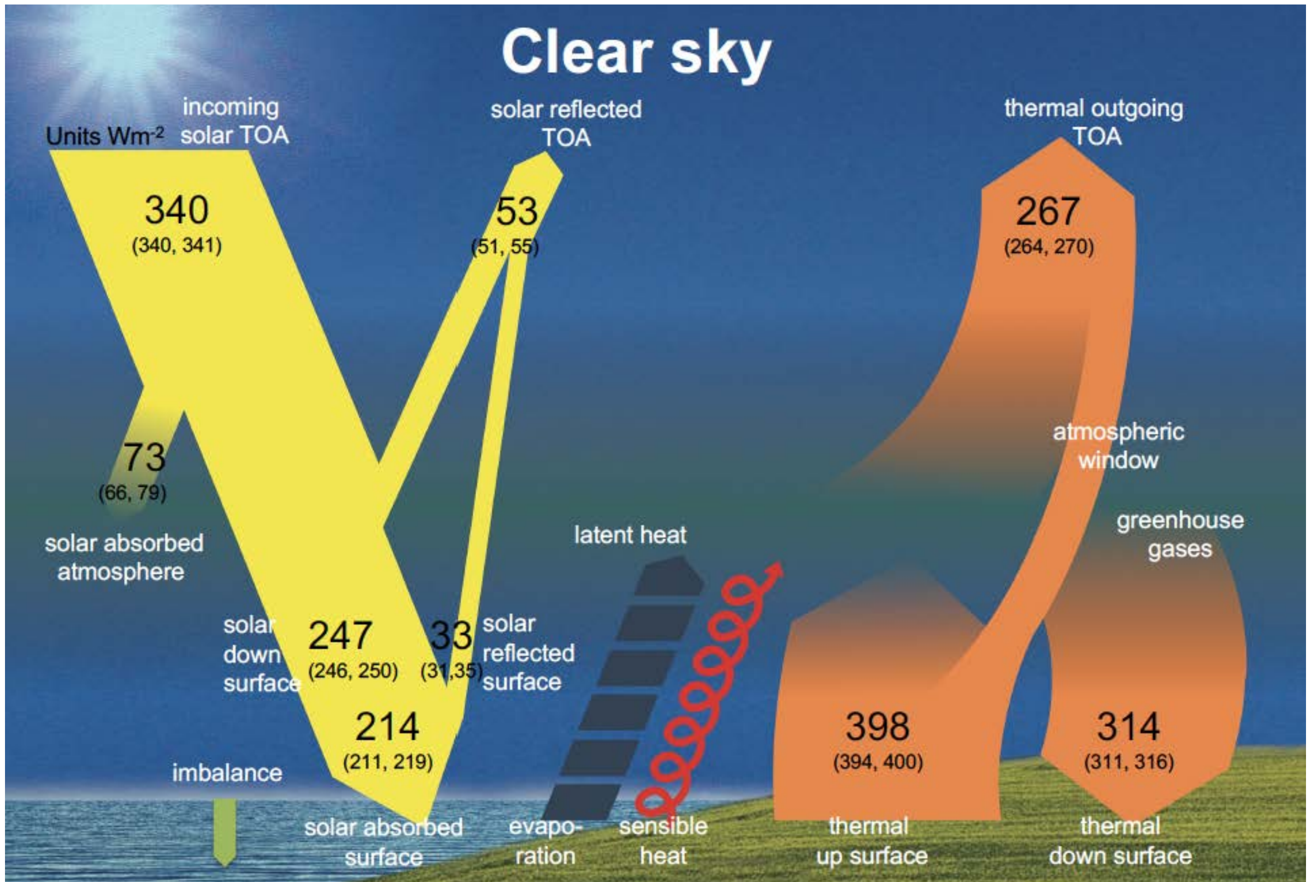
# Earth Radiation Budget without clouds



## TOA fluxes from CERES satellite obs

Units $Wm^{-2}$

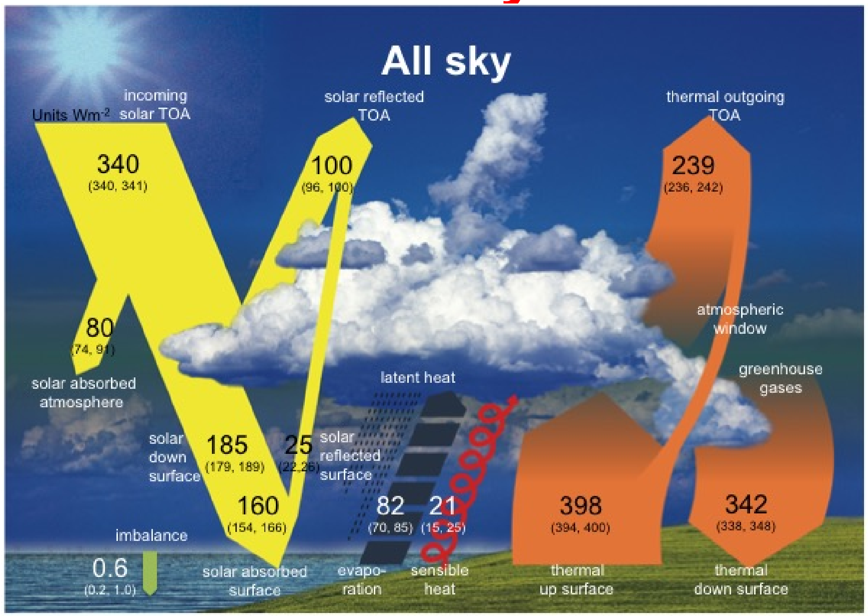



## Surface clear-sky fluxes from BSRN obs

Wild et al. 2018, Climate Dynamics

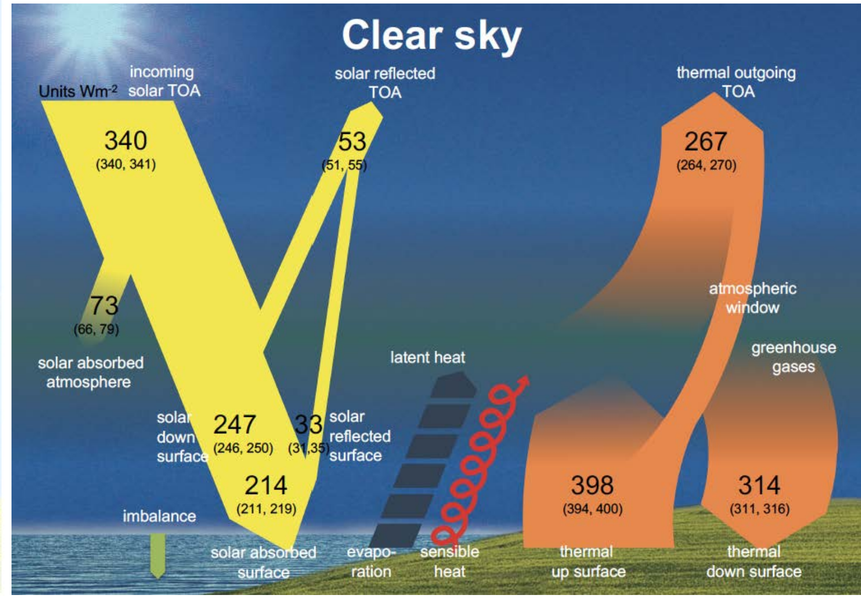
# Cloud radiative effects (CRE)

## All sky




Wild et al 2015 Clim. Dyn.

## Clear sky




Wild et al 2018 Clim. Dyn.

| Units $Wm^{-2}$ | SW CRE | LW CRE | Net CRE |
|---|---|---|---|
| TOA | -47 | 28 | -19 |
| Atmosphere | 7 | 0 | 7 |
| Surface | -54 | 28 | -26 |
| TOA CMIP5 | -49 | 25 | -24 |

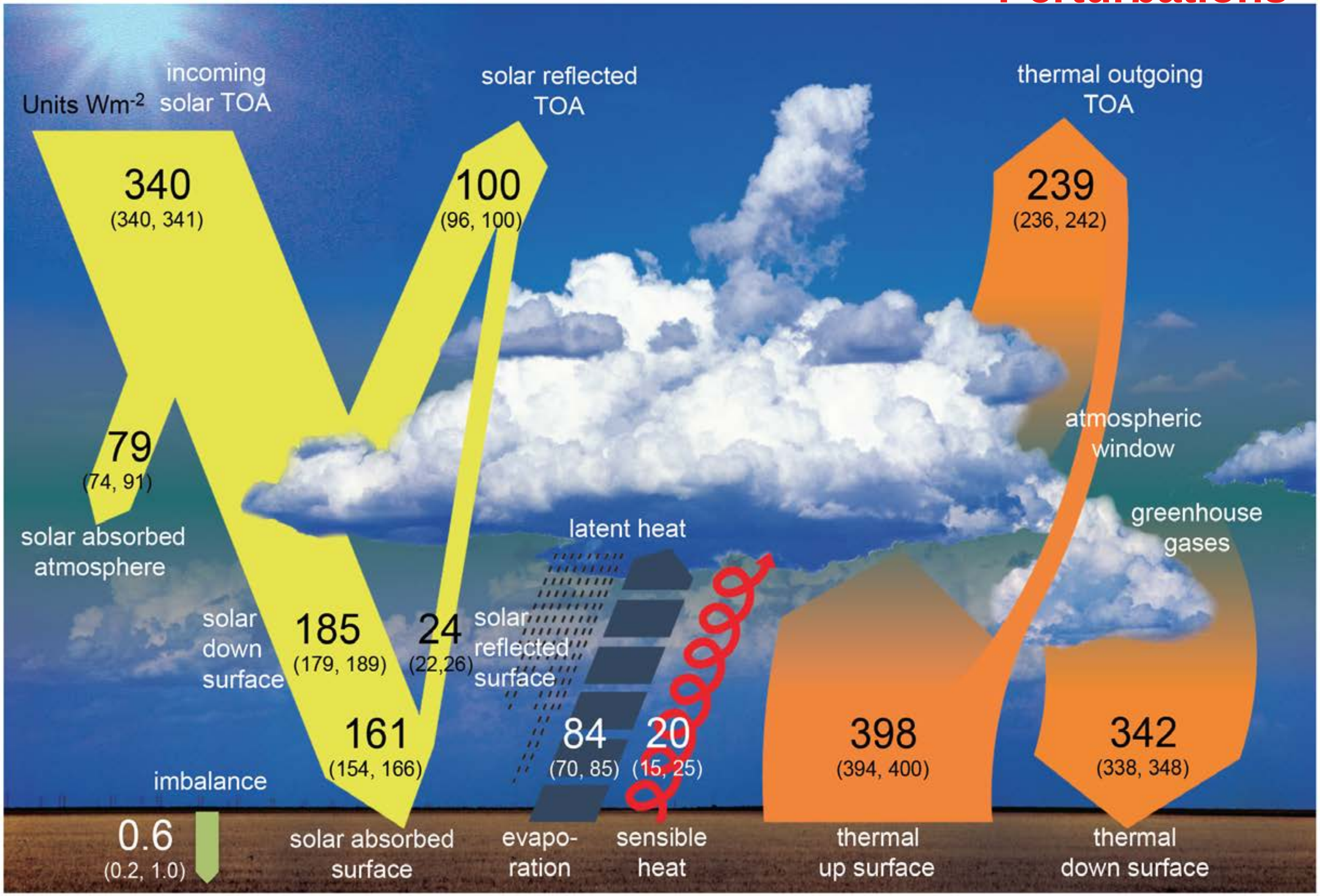
Wild et al. 2018, Clim. Dyn.

# Part 2:
# Temporal changes in Energy Balance components

# Earth Energy Balance: temporal changes

Units Wm$^{-2}$

**Anthropogenic Perturbations**

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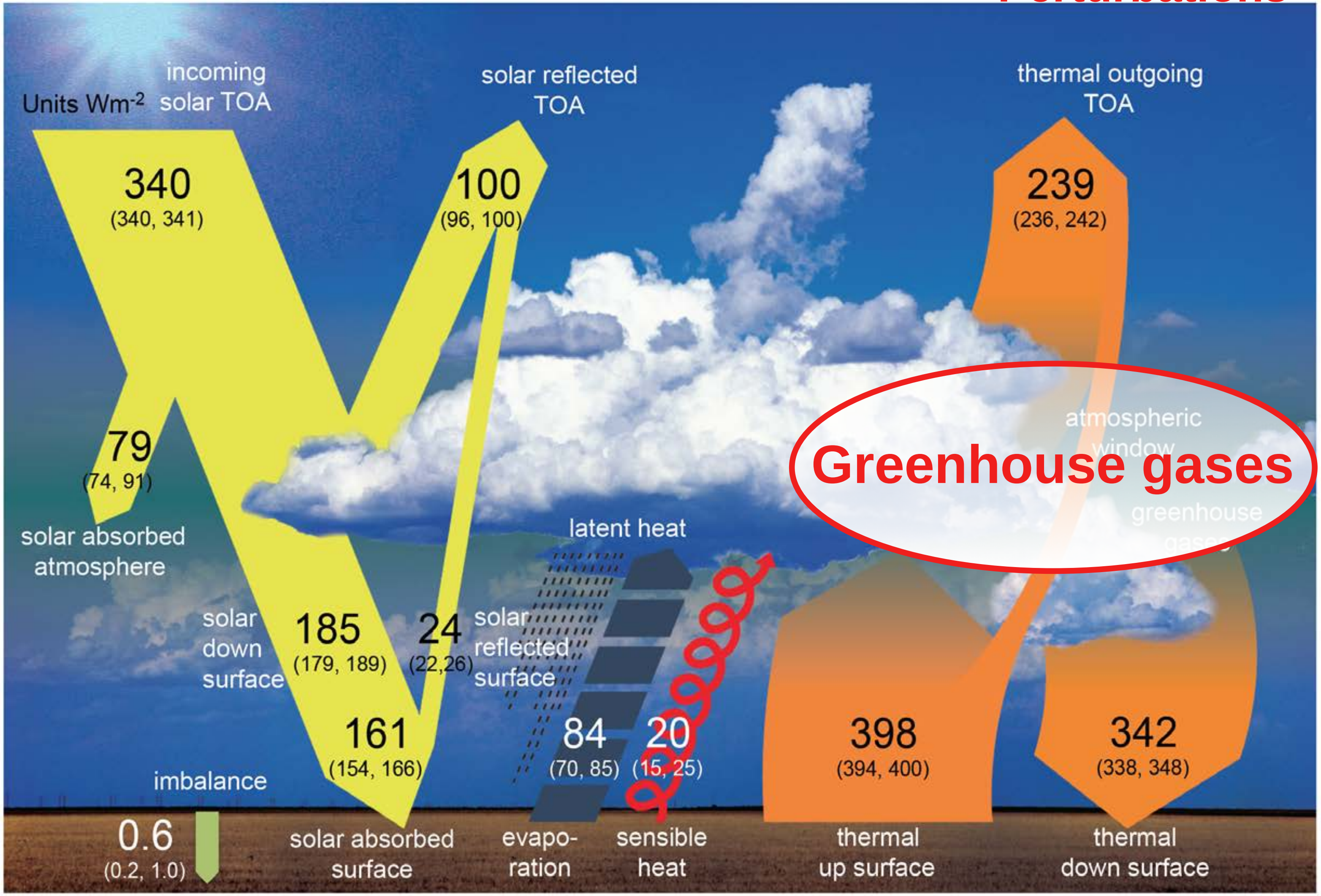
# Earth Energy Balance: temporal changes

**Anthropogenic Perturbations**

**Units $Wm^{-2}$**

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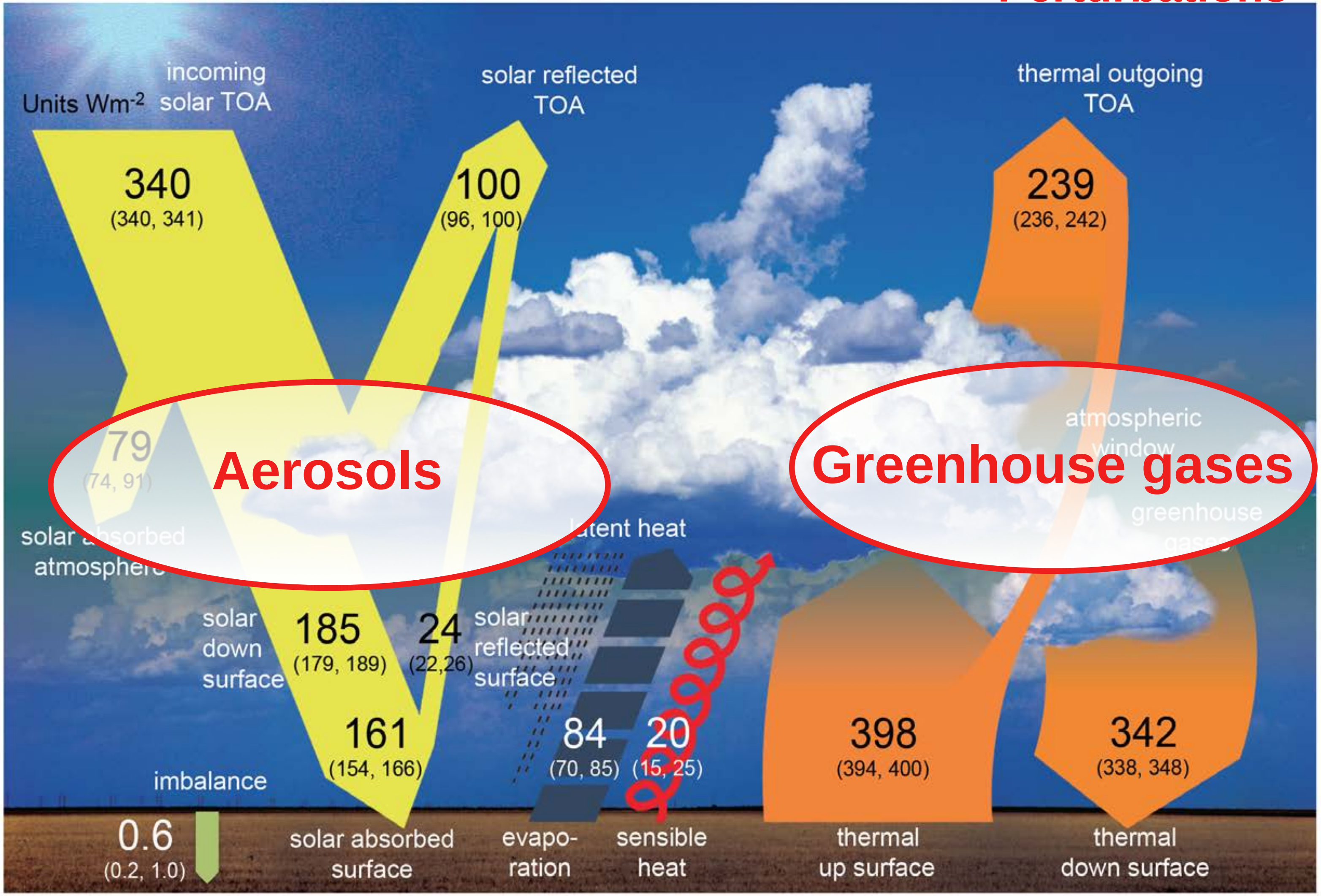
# Earth Energy Balance: temporal changes

Units $Wm^{-2}$

Anthropogenic Perturbations

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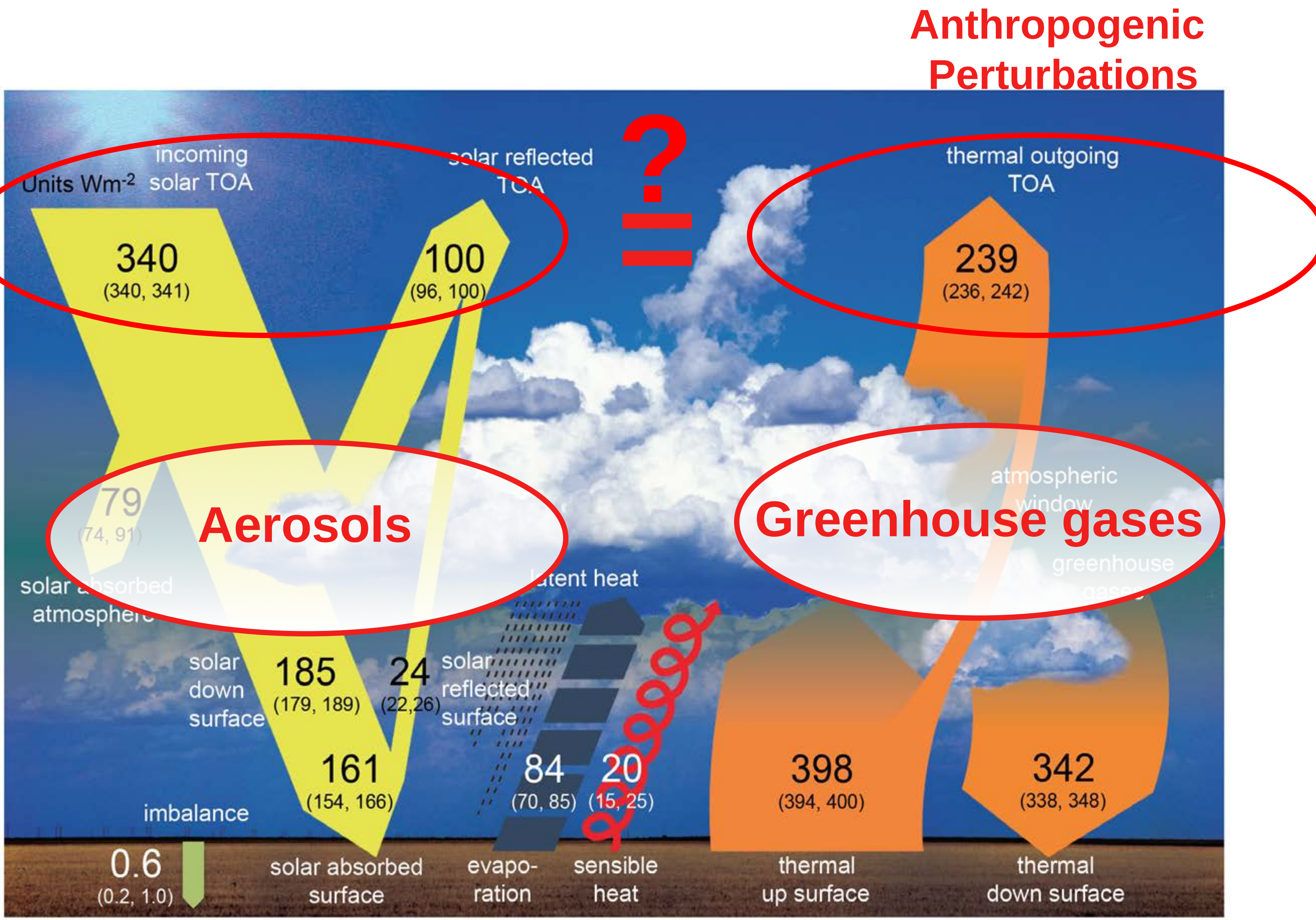
# Earth Energy Balance: temporal changes

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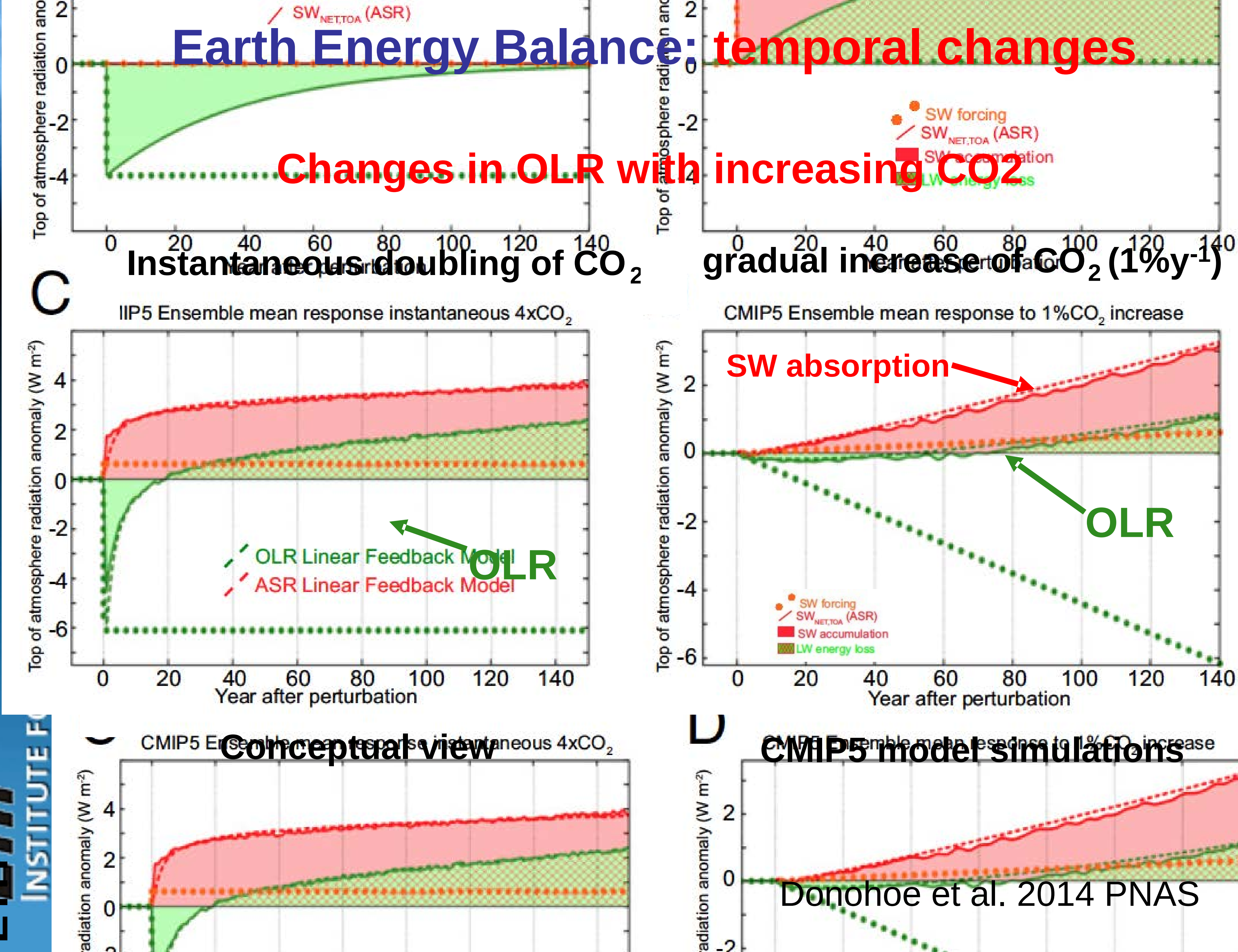
# Earth Energy Balance: temporal changes

## Changes in OLR with increasing CO2

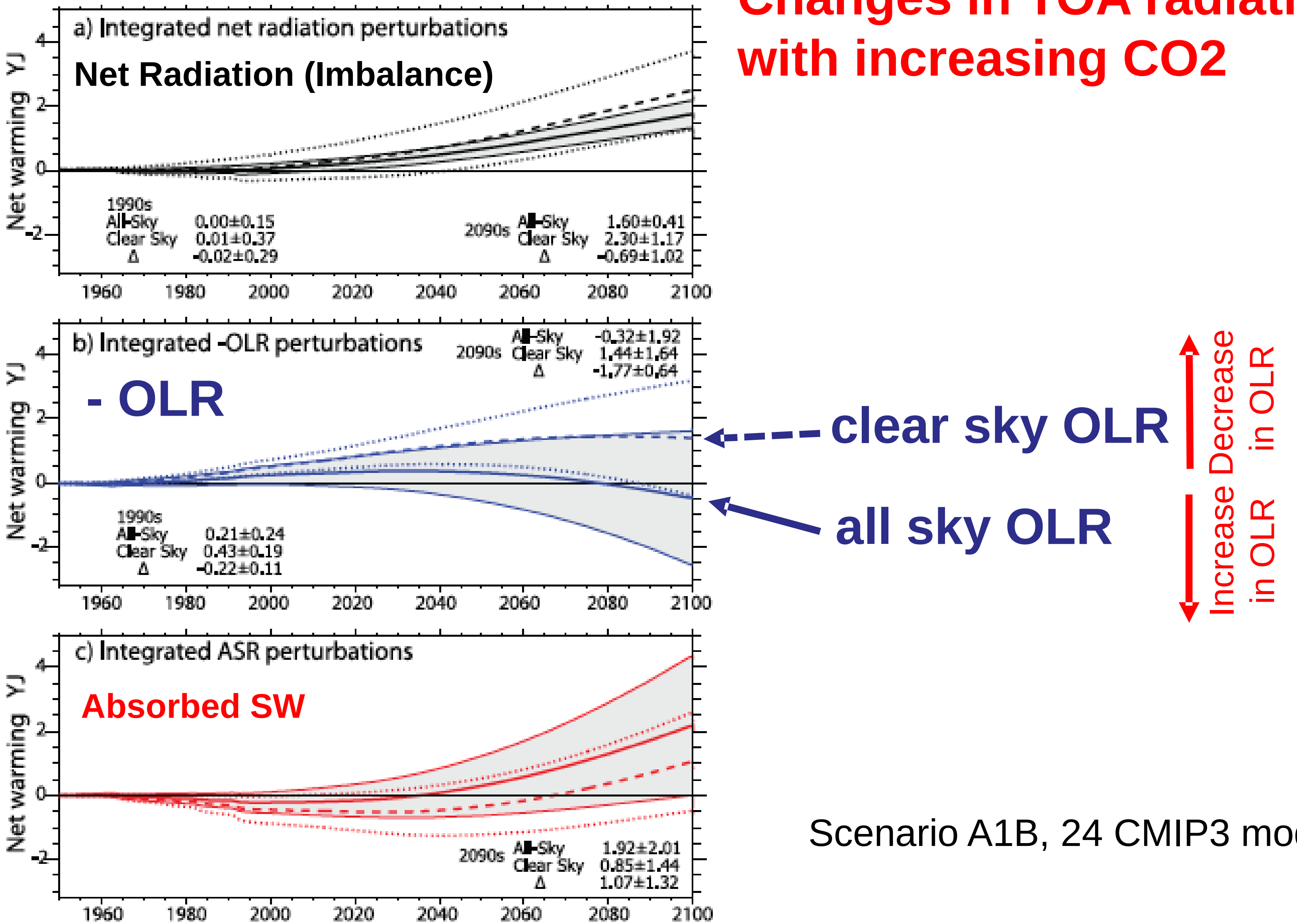
**Instantaneous doubling of $CO_2$** | **gradual increase of $CO_2$ ($1\%y^{-1}$)**




**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

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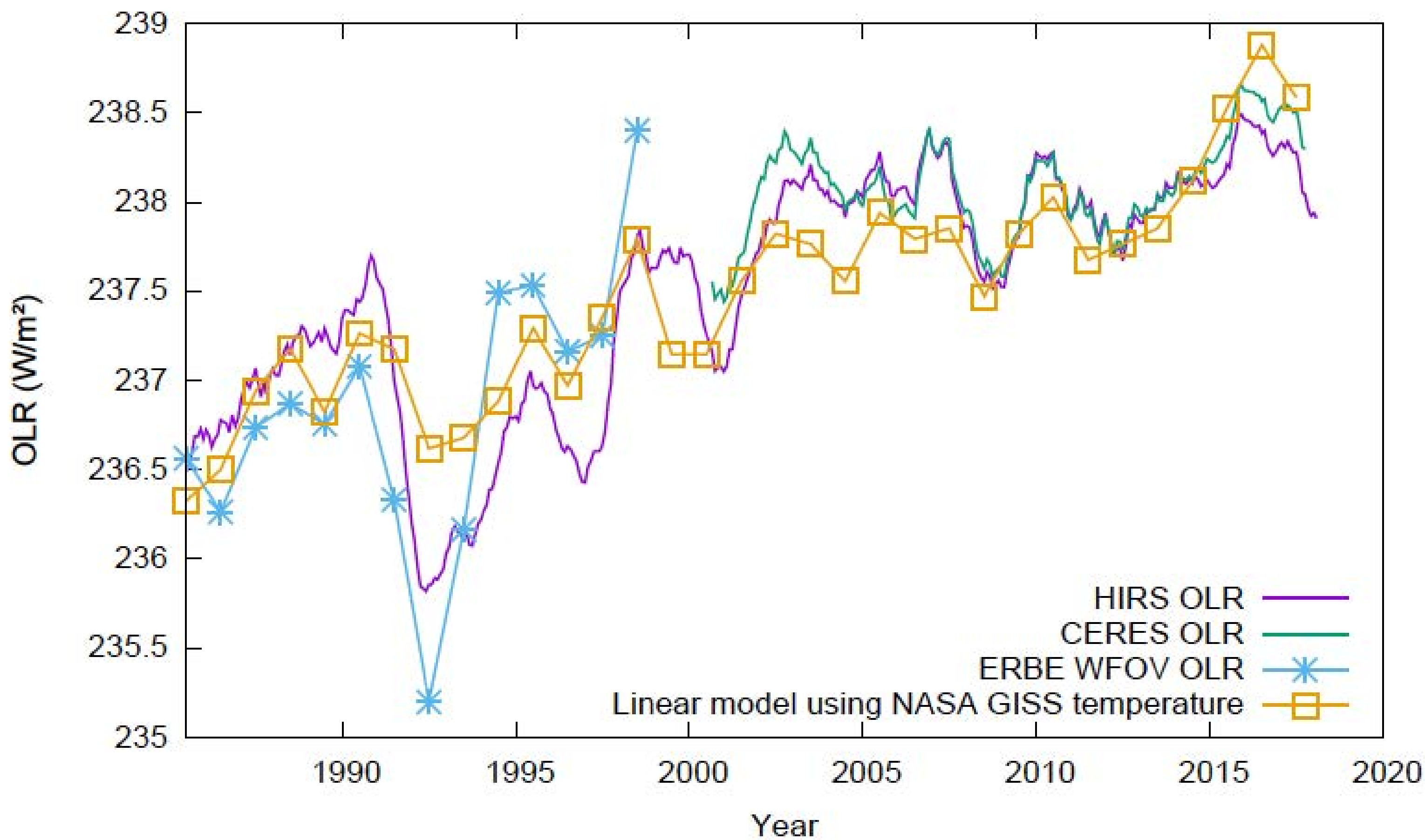
# Earth Energy Balance: temporal changes

## Observed changes in OLR 1985-2016




Dewitte and Clerbaux 2018

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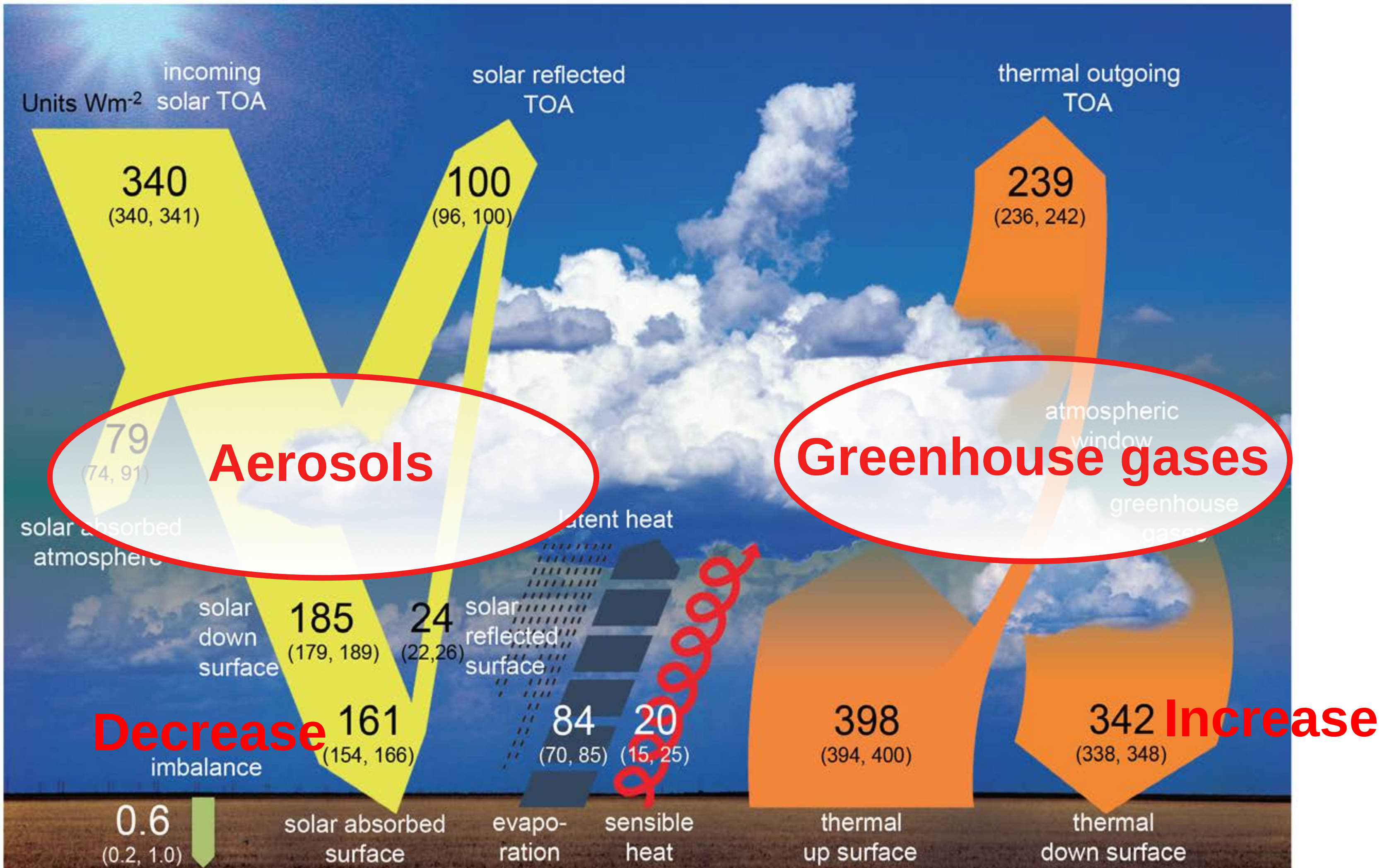
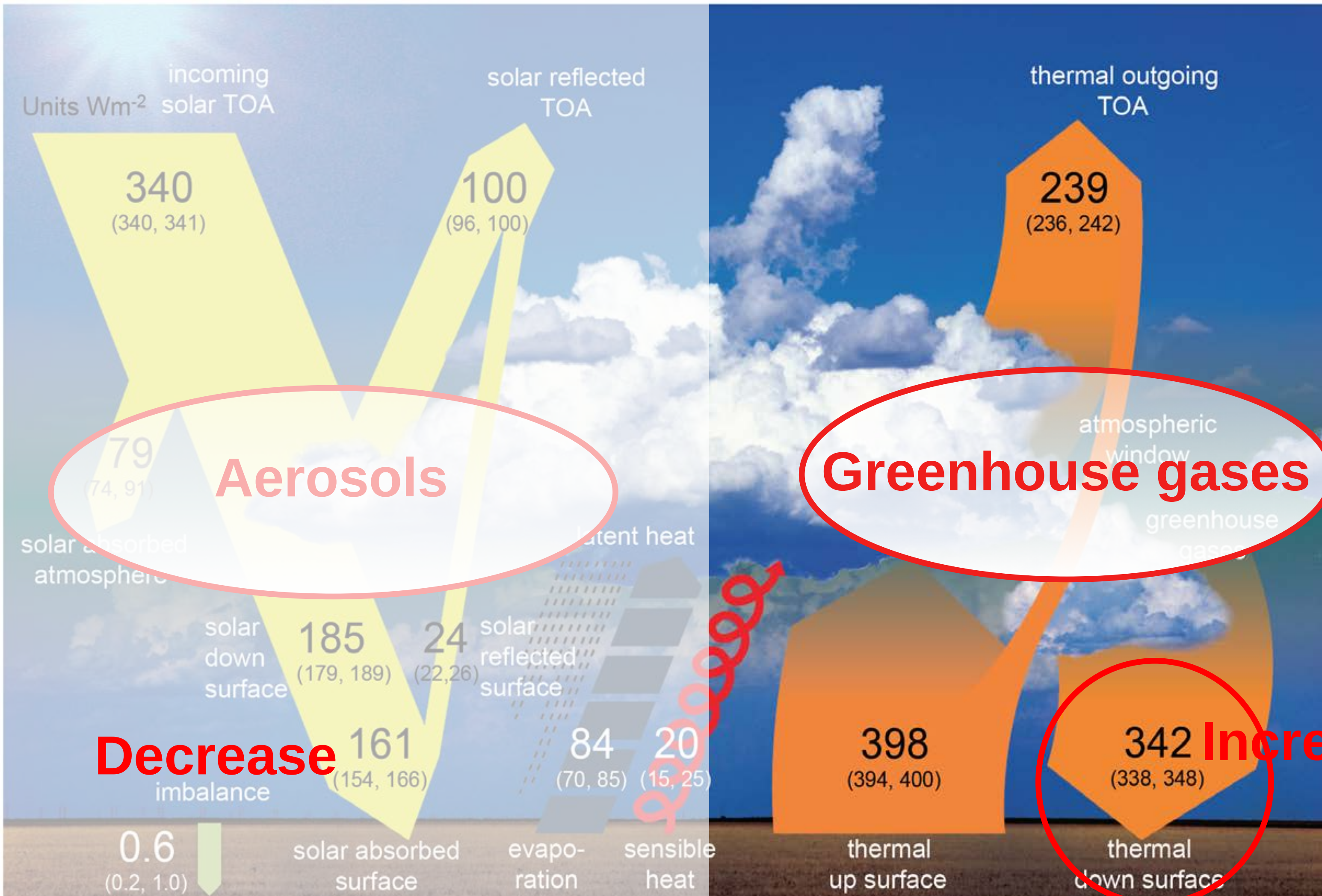
# Earth Energy Balance: temporal changes

## Decadal changes at the Earth’s surface



# Earth Energy Balance: temporal changes

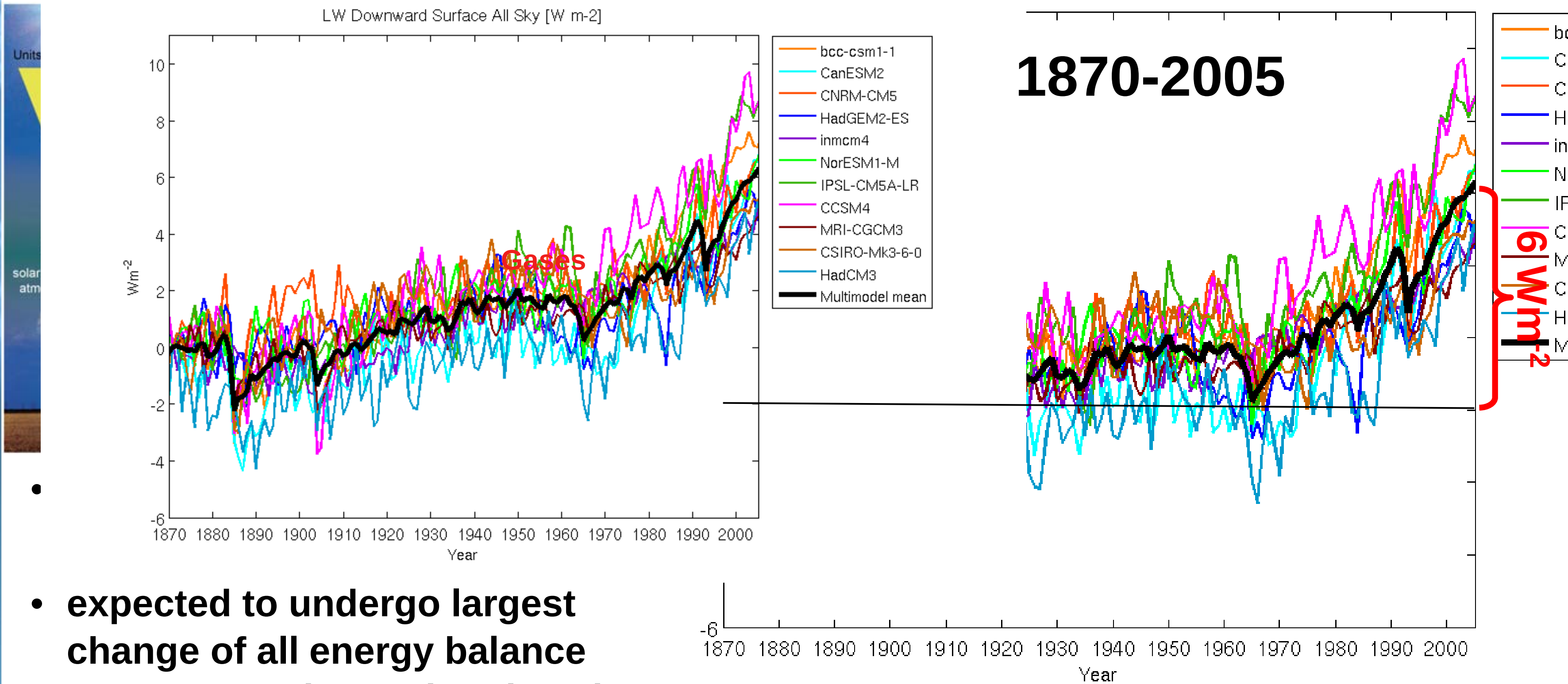
## Decadal changes at the Earth's surface




Greenhouse effect at Earth's surface

# Changes in downward longwave radiation

**Downward longwave radiation in CMIP5 models**




- 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

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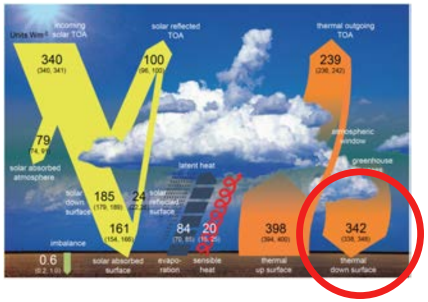
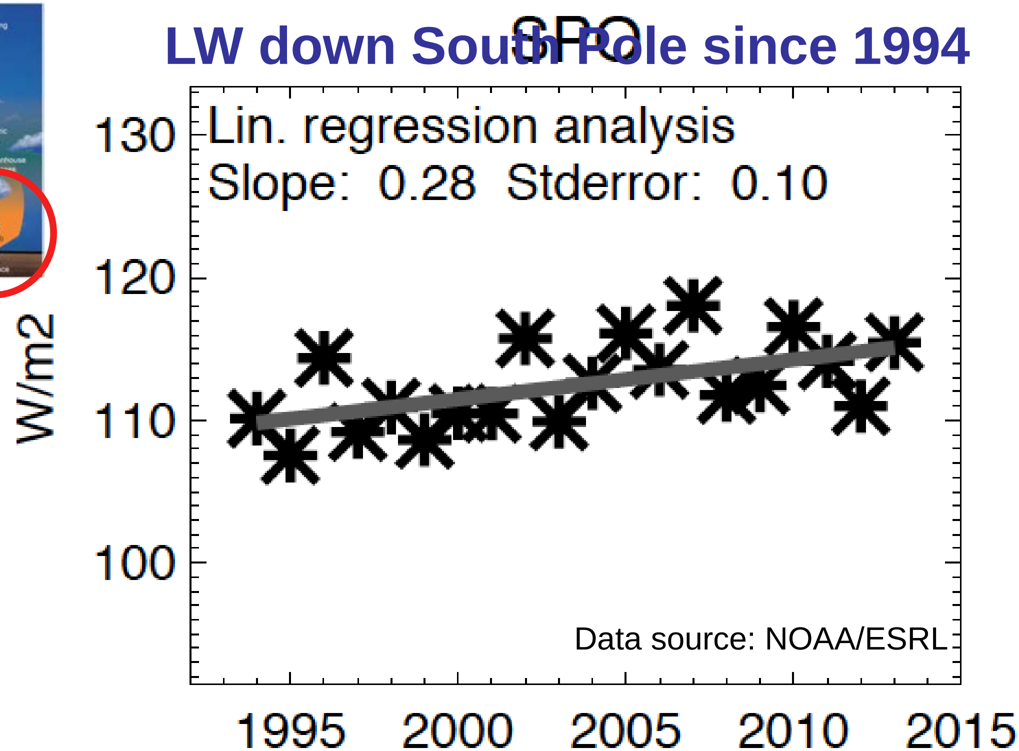
# Observed changes downward longwave radiation




## Observed changes at BSRN sites since early 1990s:

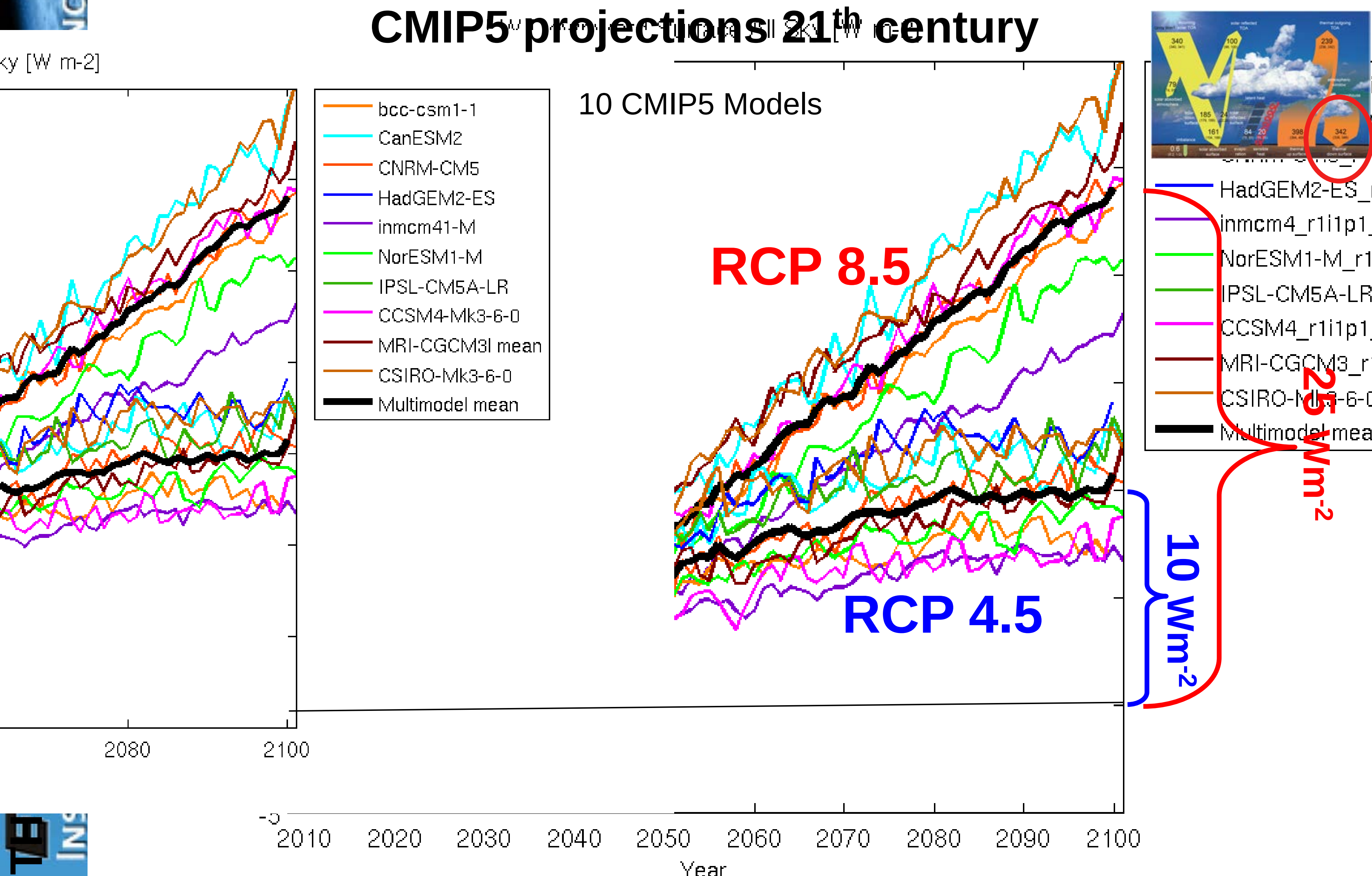
25 longest BSRN records (totally 353 years): **+2.0 $Wm^{-2}dec^{-1}$**

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

Wild 2016, WIREs Clim Change

# Future changes in downward longwave radiation

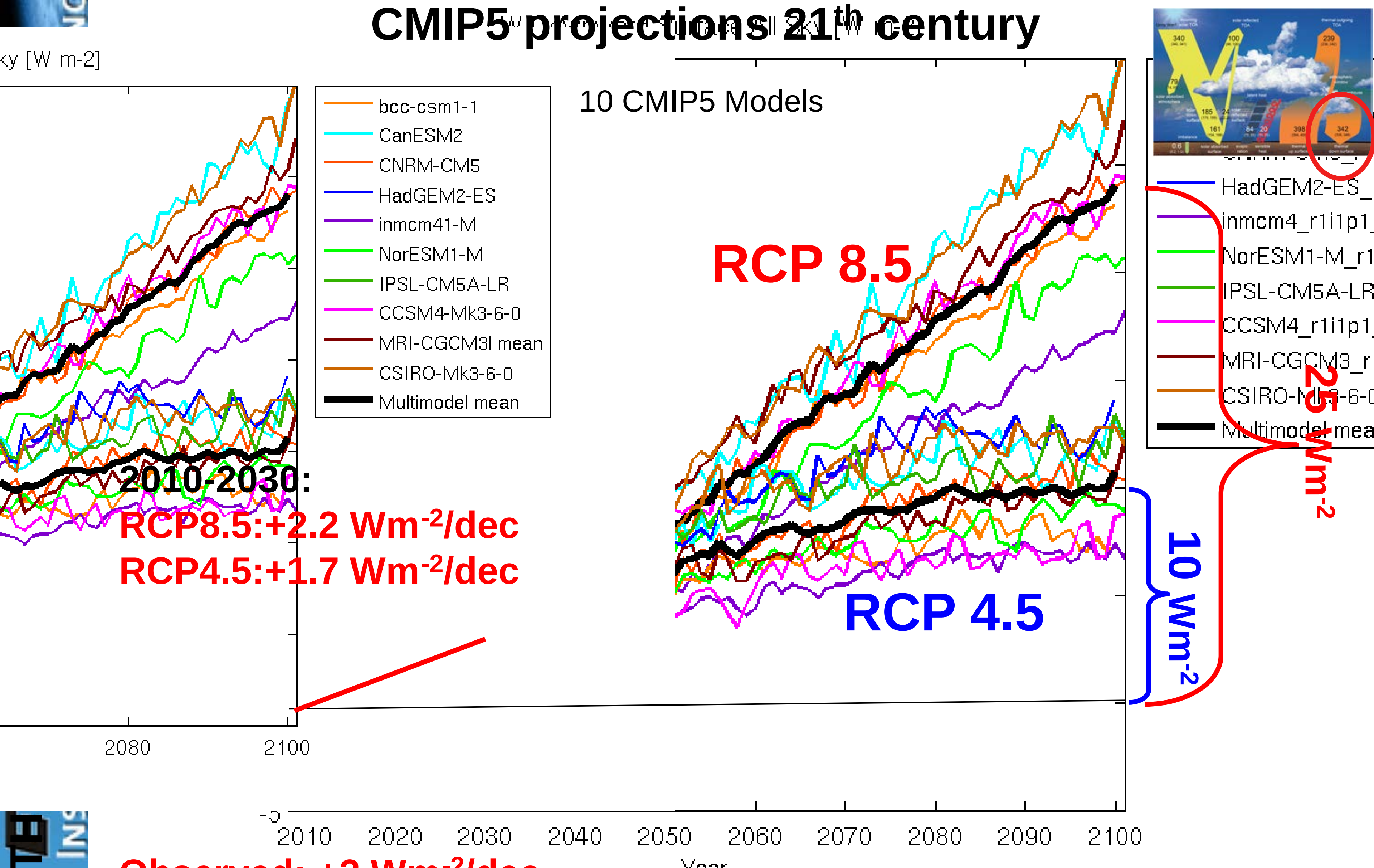
## CMIP5 projections 21th century




Wild et al. 1997 J. Climate / Wild 2016, AIP proc.

# Future changes in downward longwave radiation

## CMIP5 projections 21th century

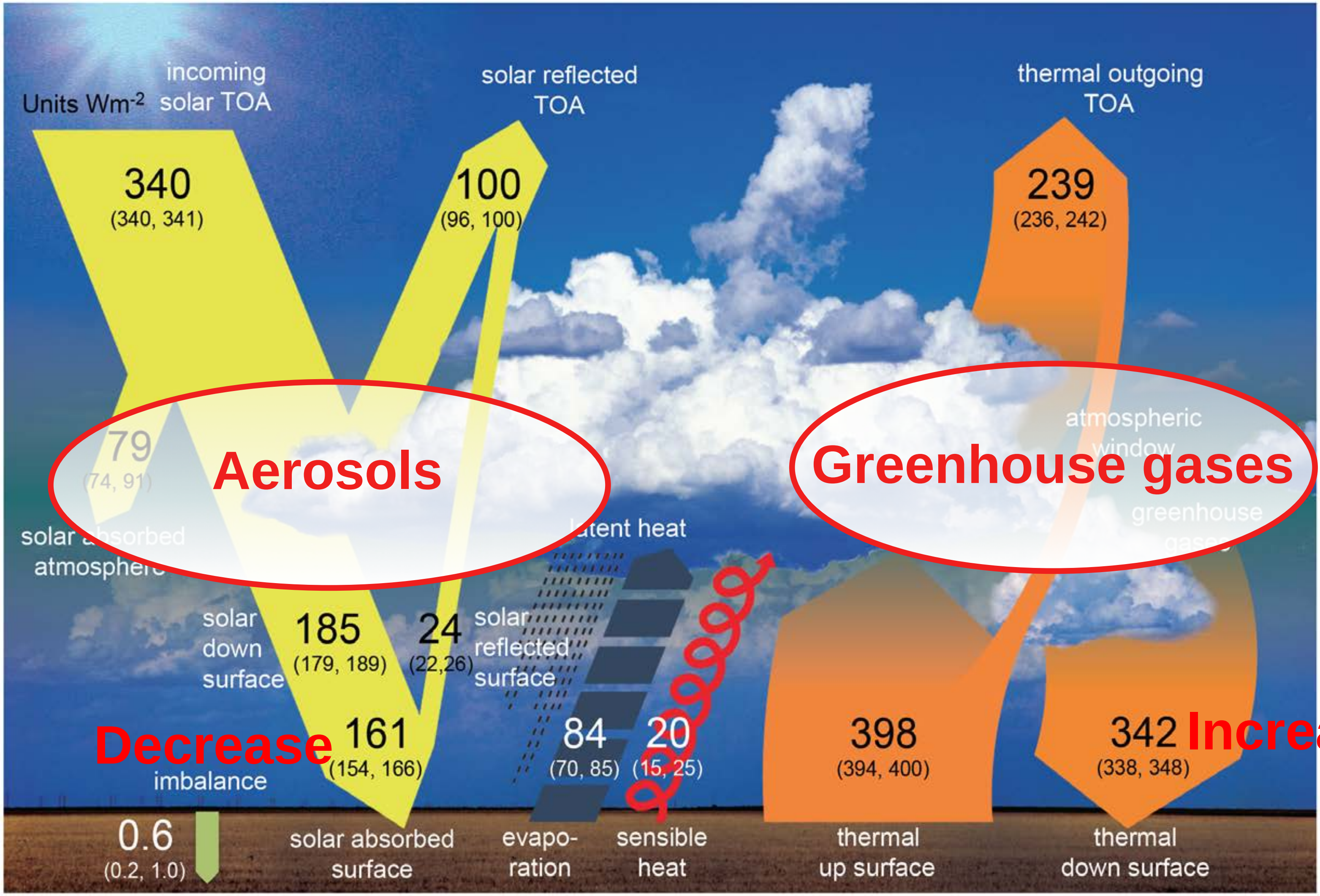



**Observed: +2 $Wm^{-2}$/dec**

Wild et al. 1997 J. Climate / Wild 2016, AIP proc.

# Earth Energy Balance: temporal changes

## Decadal changes at the Earth's surface

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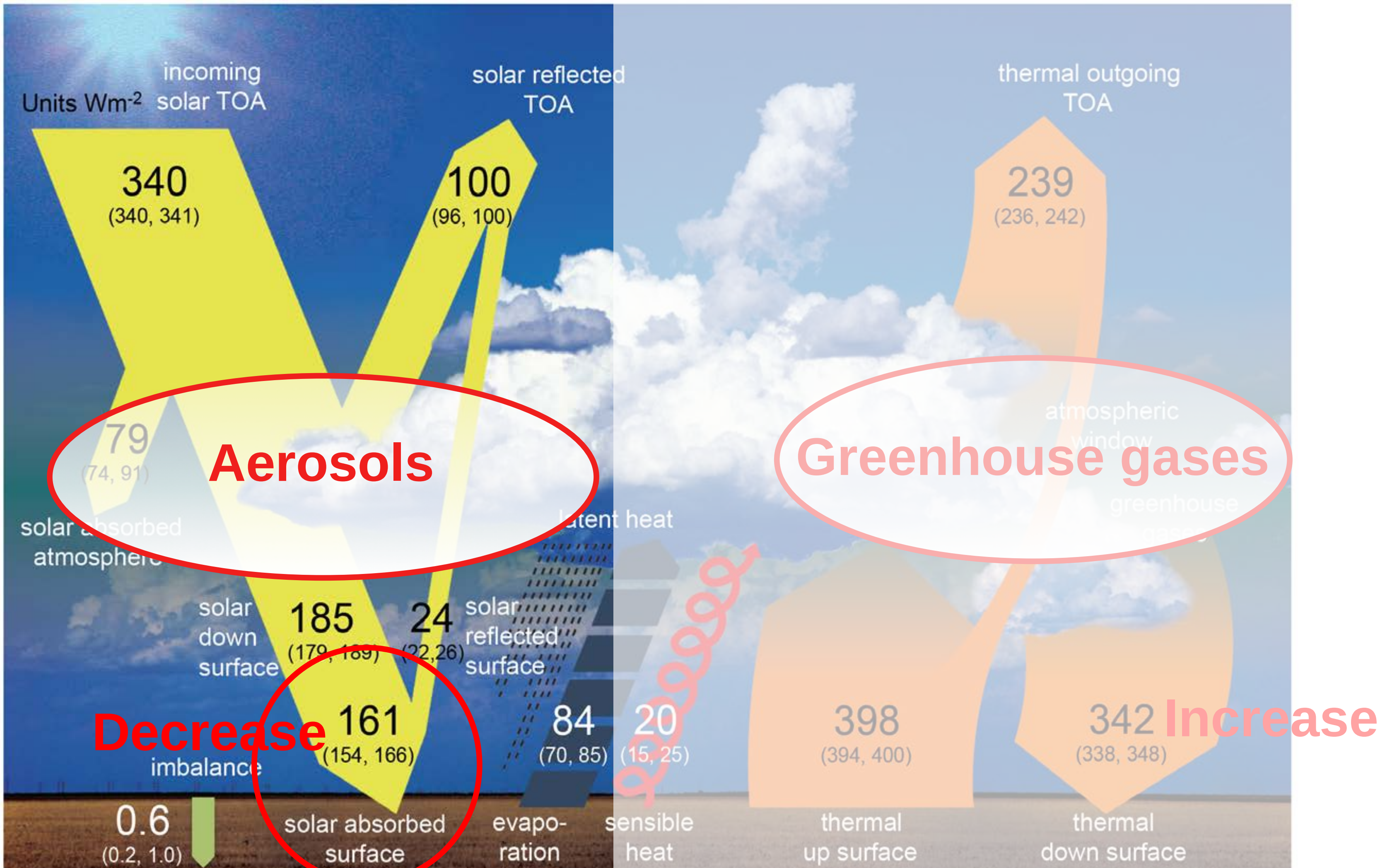
# Earth Energy Balance: temporal changes

## Decadal changes at the Earth's surface




## Solar radiation at Earth's surface

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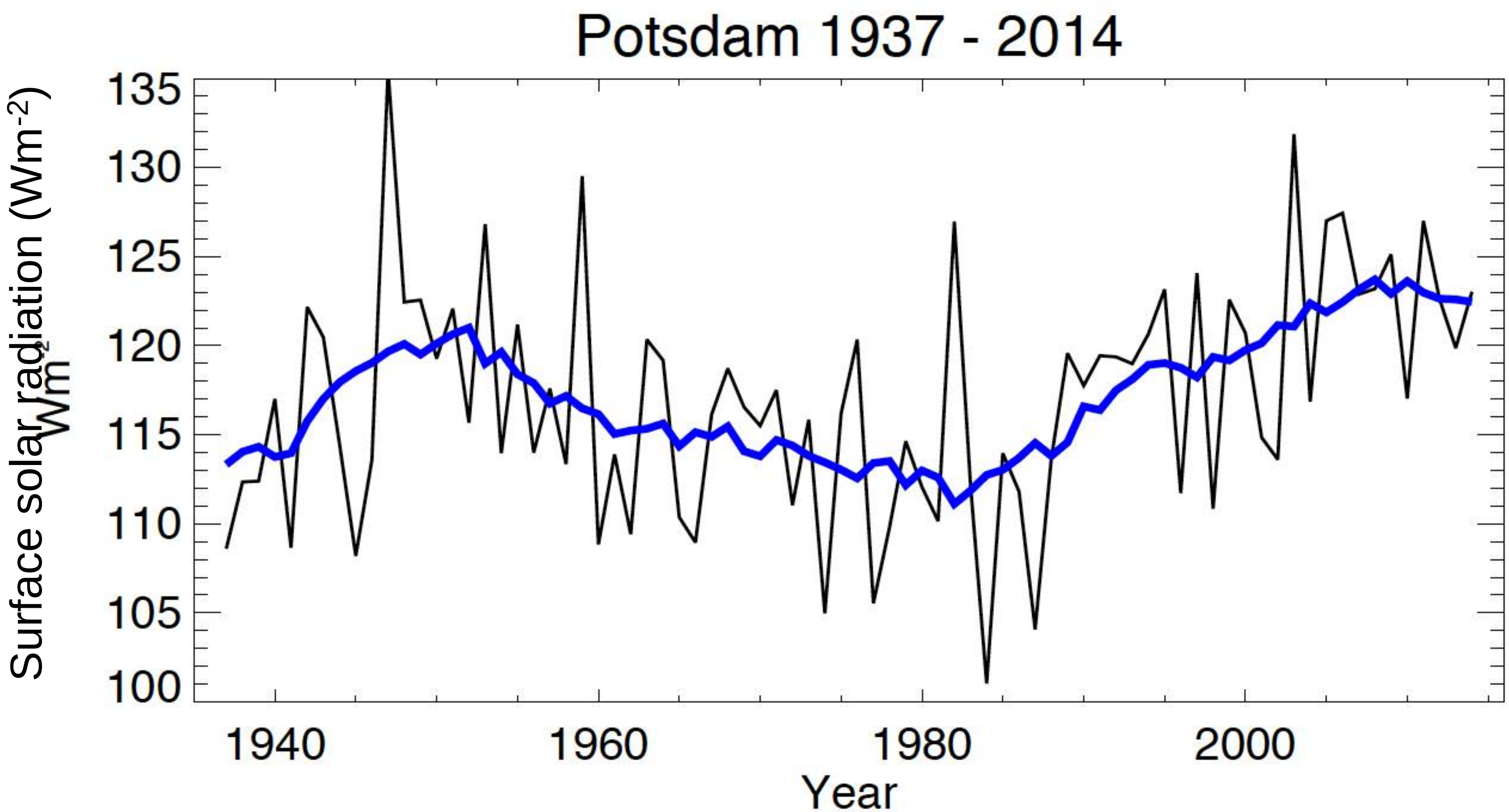
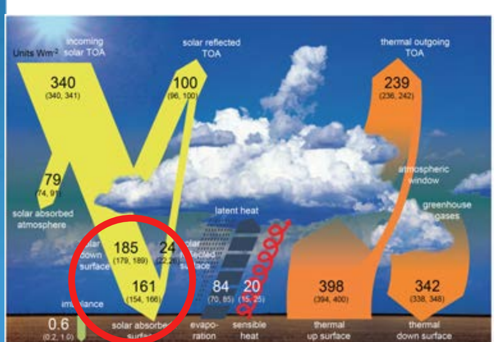
# Decadal changes in surface solar radiation




Wild 2016, WIREs Clim Change

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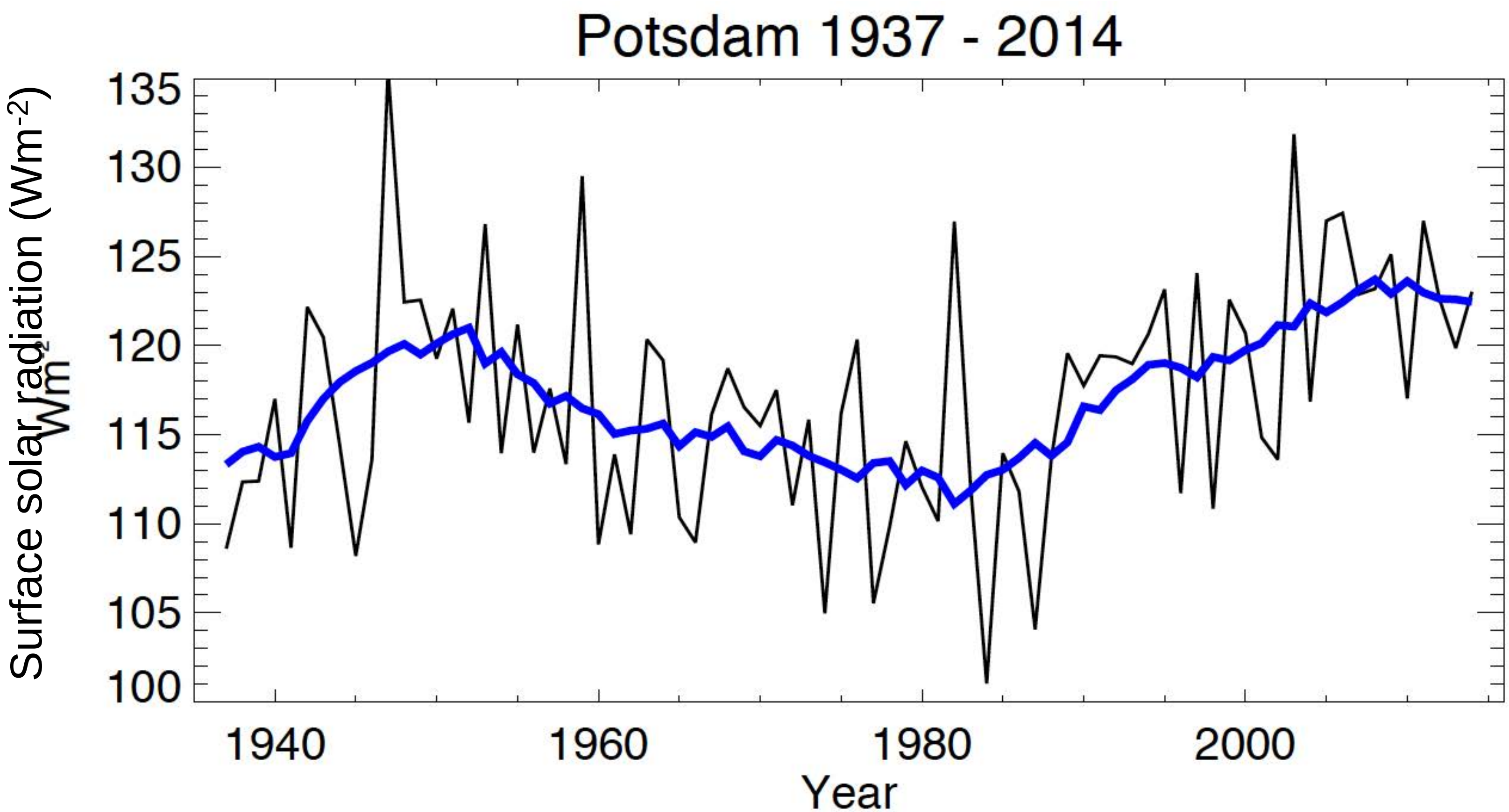
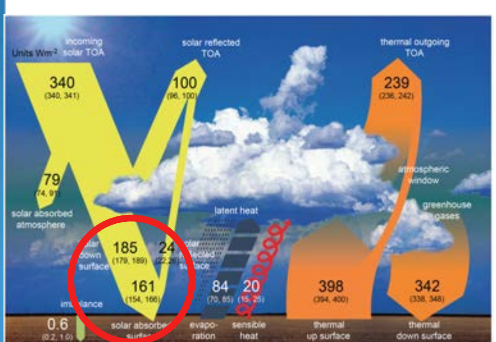
# Decadal changes in surface solar radiation




"dimming"




Wild 2016, WIREs Clim Change

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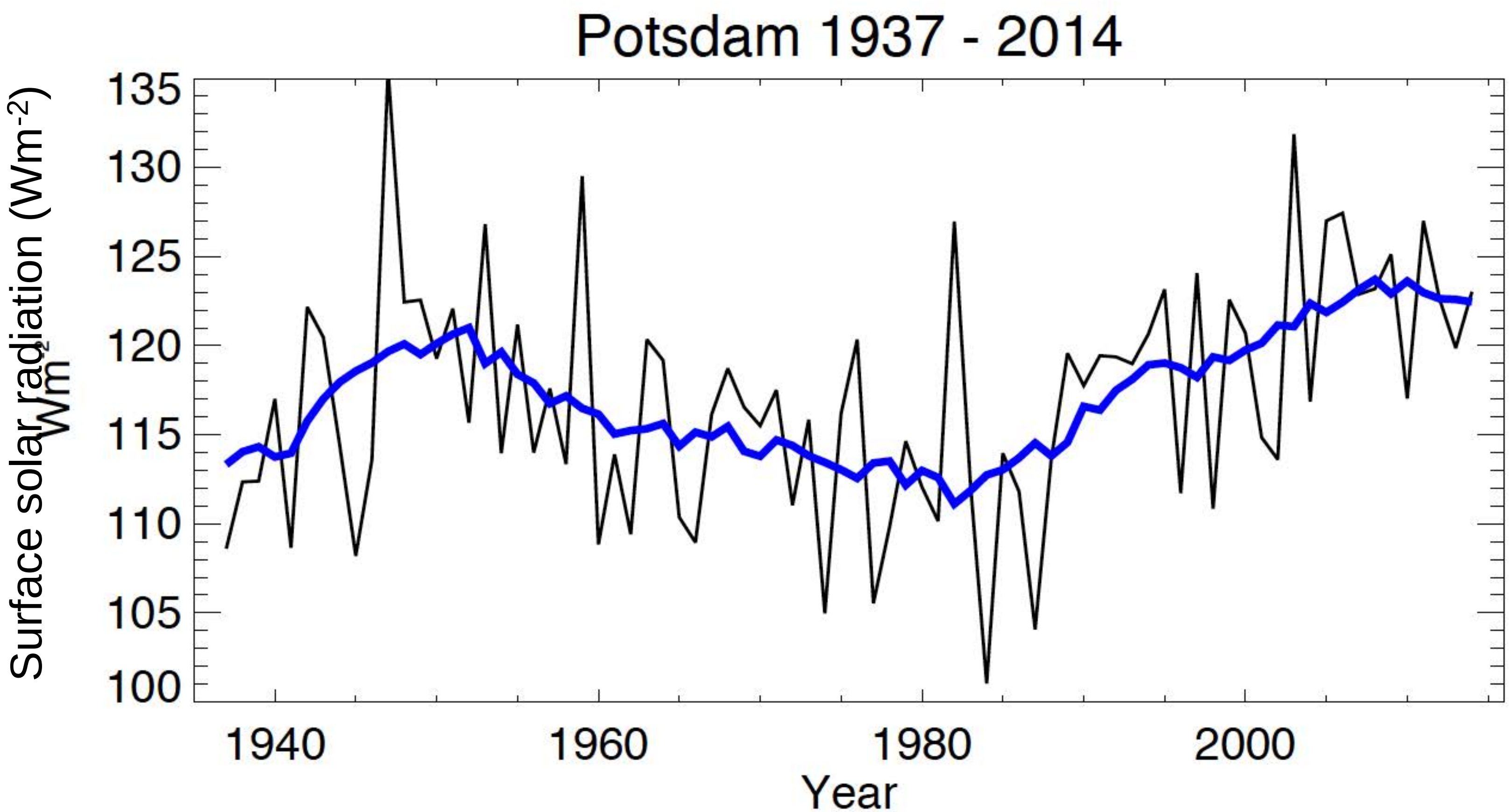
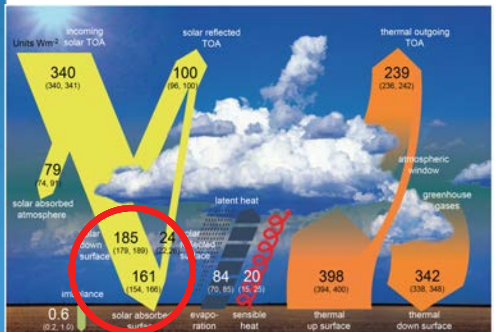
# Decadal changes in surface solar radiation




“dimming”

“brightening”




Wild 2016, WIREs Clim Change

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# Decadal changes 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

**"dimming"** **"brightening"**

Wild, M. 2012: Enlightening Global Dimming and Brightening. Bull. Amer. Meteor. Soc., 93

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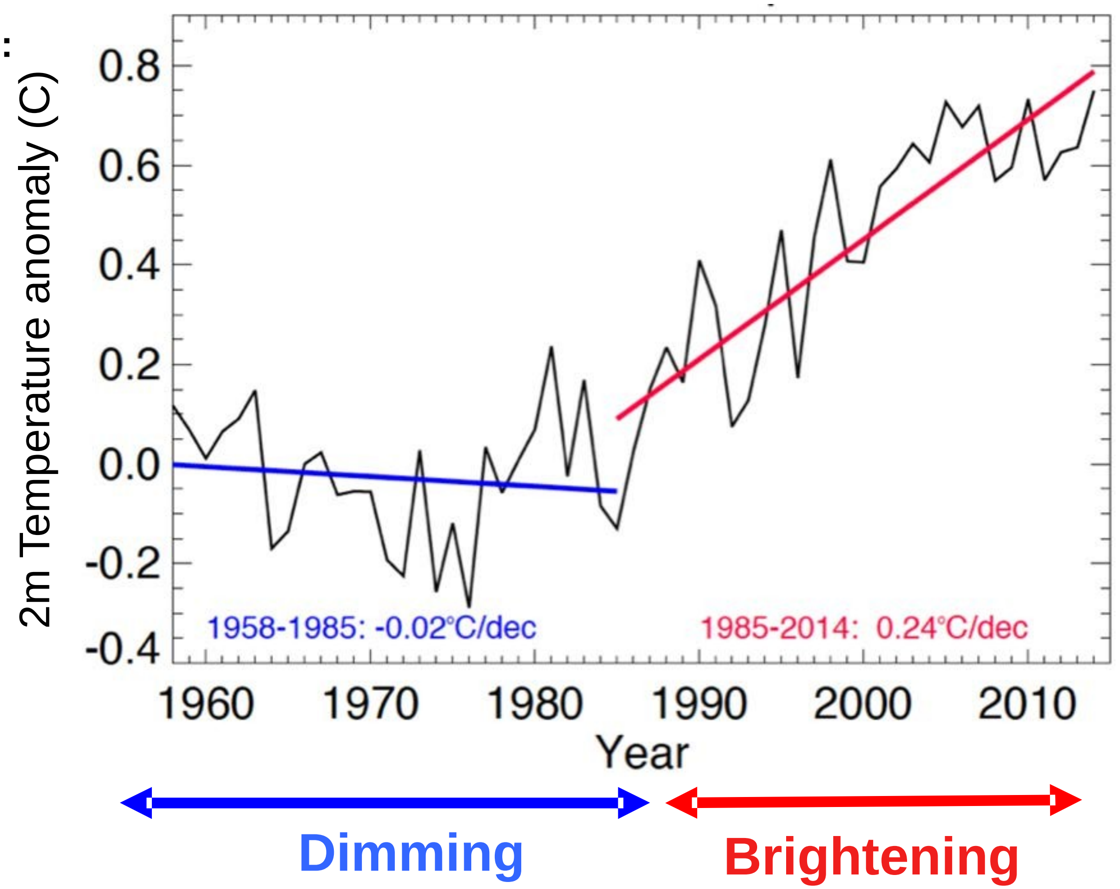
# Impact on global warming

## 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 $Wm^{-2}$ (2-sigma).
  > 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$Wm^{-2}$/decade, while sign of future change in OLR is less clear.

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