Radiative Forcing of Earth's Climate in the 20th and 21st Centuries: Theory, Modeling and Observations

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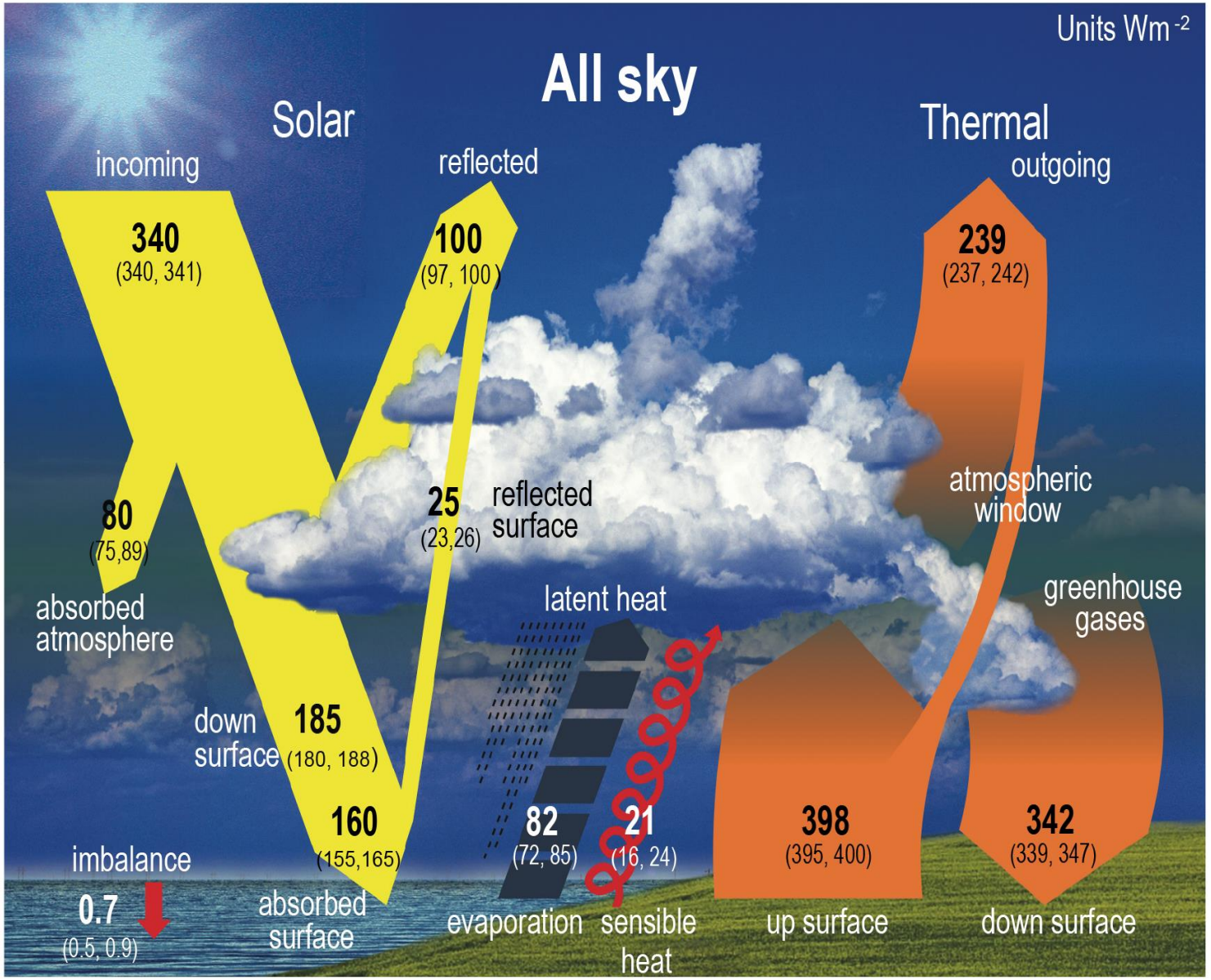
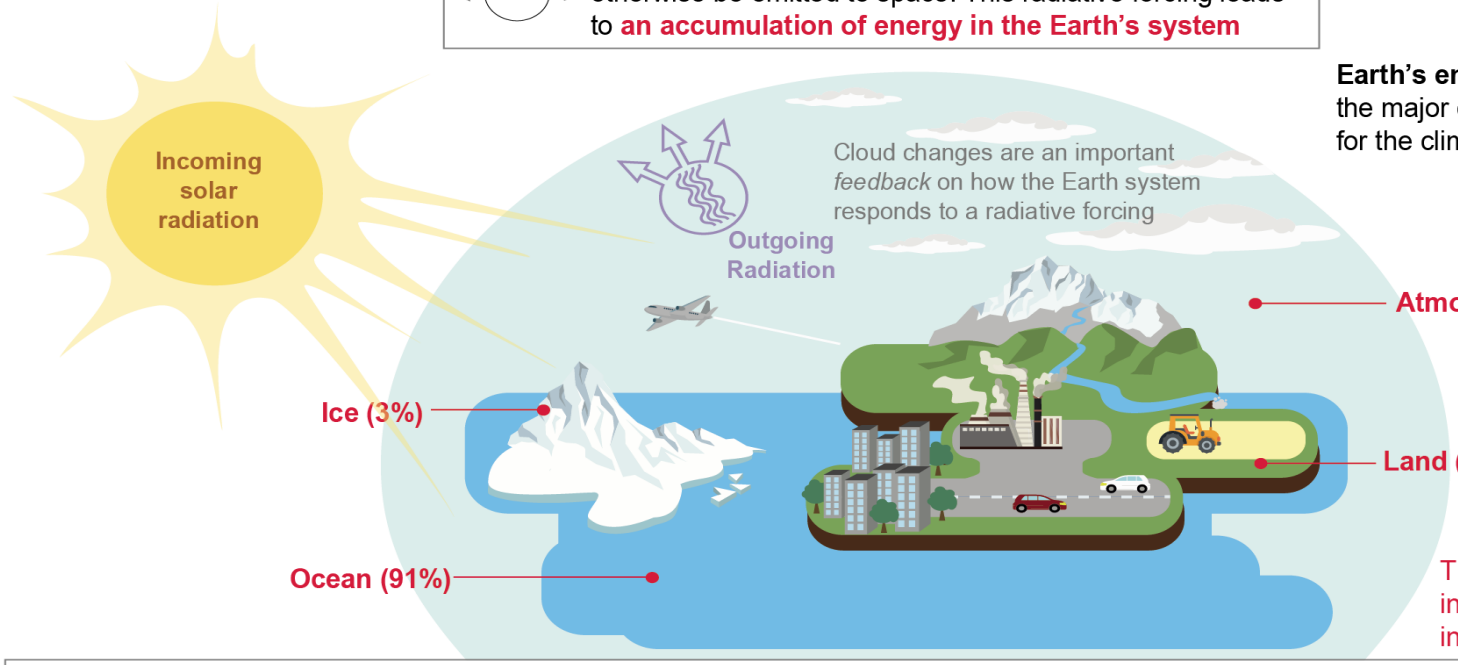

Units Wm -2
All sky
Solar
Thermal
incoming
340
(340, 341)
reflected
100
(97, 100)
outgoing
239
(237, 242)
80
(75,89)
absorbed
atmosphere
25
(23,26)
reflected
surface
atmospheric
window
greenhouse
gases
latent heat
down
surface
185
(180, 188)
160
(155,165)
absorbed
surface
82
(72, 85)
evaporation
21
(16, 24)
sensible
heat
398
(395, 400)
up surface
342
(339, 347)
down surface
imbalance
0.7
(0.5, 0.9)

Earth's energy imbalance results from increases in greenhouse gases absorbing thermal radiation that would otherwise be emitted to space. This radiative forcing leads to **an accumulation of energy in the Earth's system**

Earth's energy budget encompasses the major energy flows of relevance for the climate system *Section* ***7.2***



The contribution to the increase in Earth's energy inventory is shown by %

Earth's energy budget is influenced by:

Radiative forcing
Section ***7.3***

Quantification of effective radiative forcing for human and natural forcing agents:

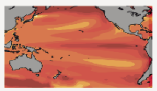
Volcanoes

GHGs and aerosols from agriculture, industry and fossil-fuel combustion

Climate feedbacks
Key Improvements
Section ***7.4***

Key processes explored:

Cloud changes (feedback)

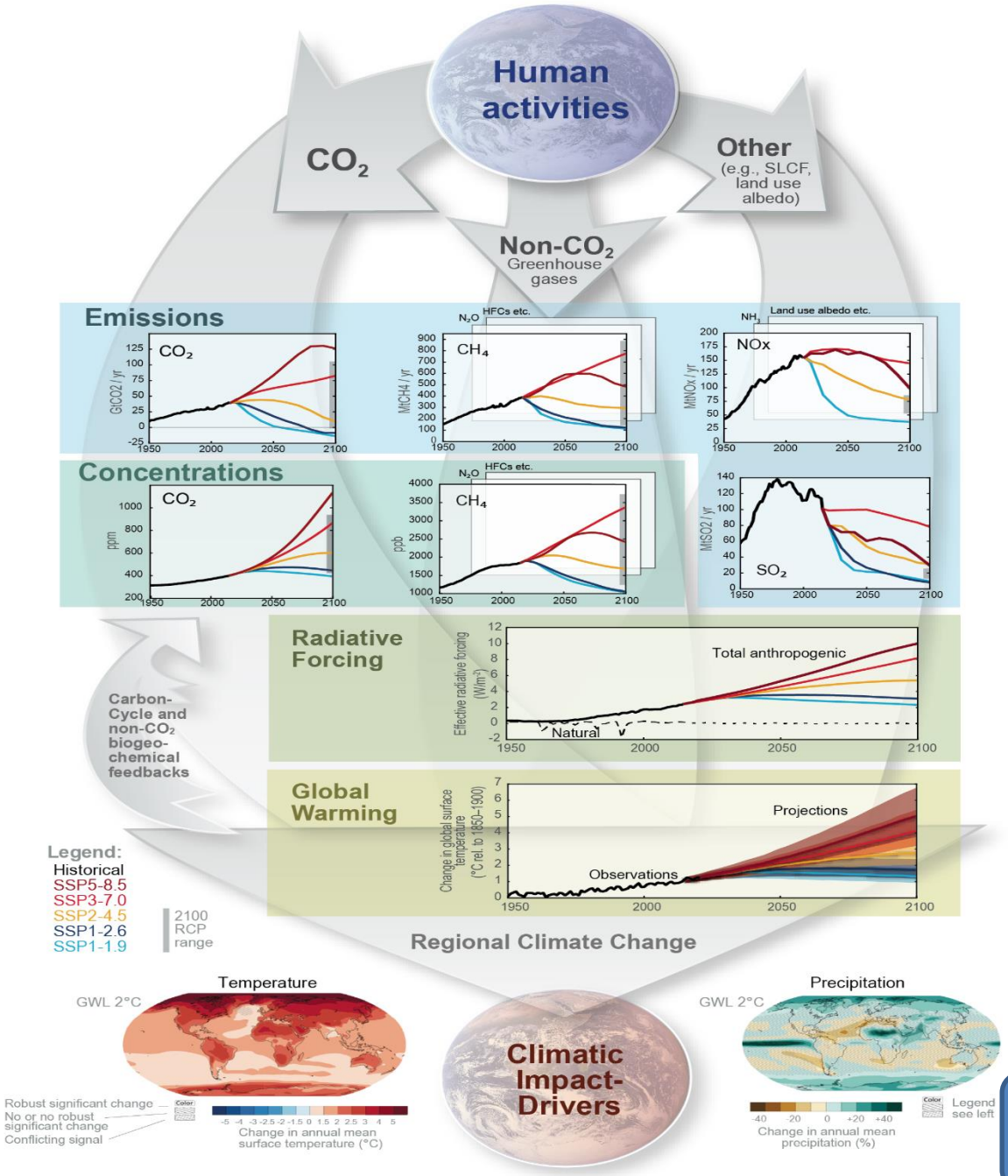


Ocean warming coupled with atmospheric feedbacks

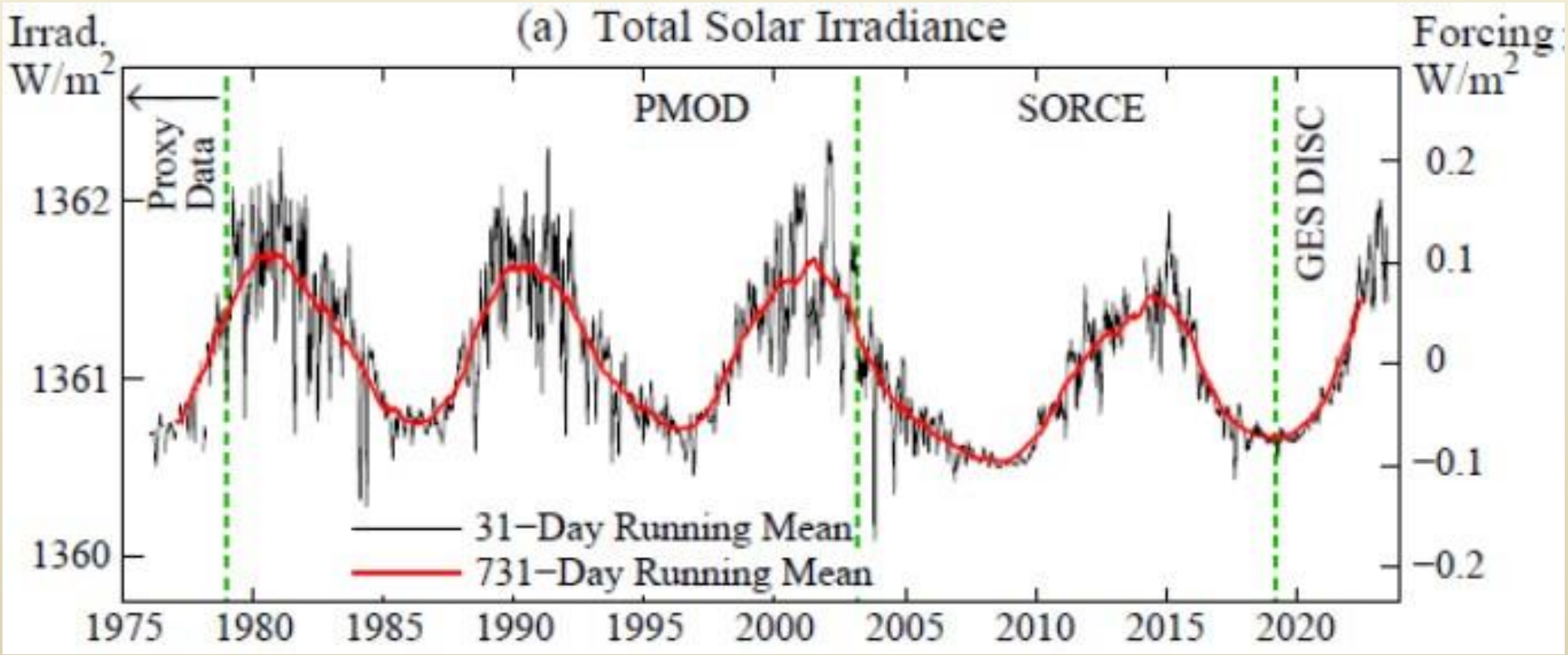
Climate sensitivity
Section ***7.5***

Evidence from: process understanding, historical warming, paleoclimates, and emergent constraints

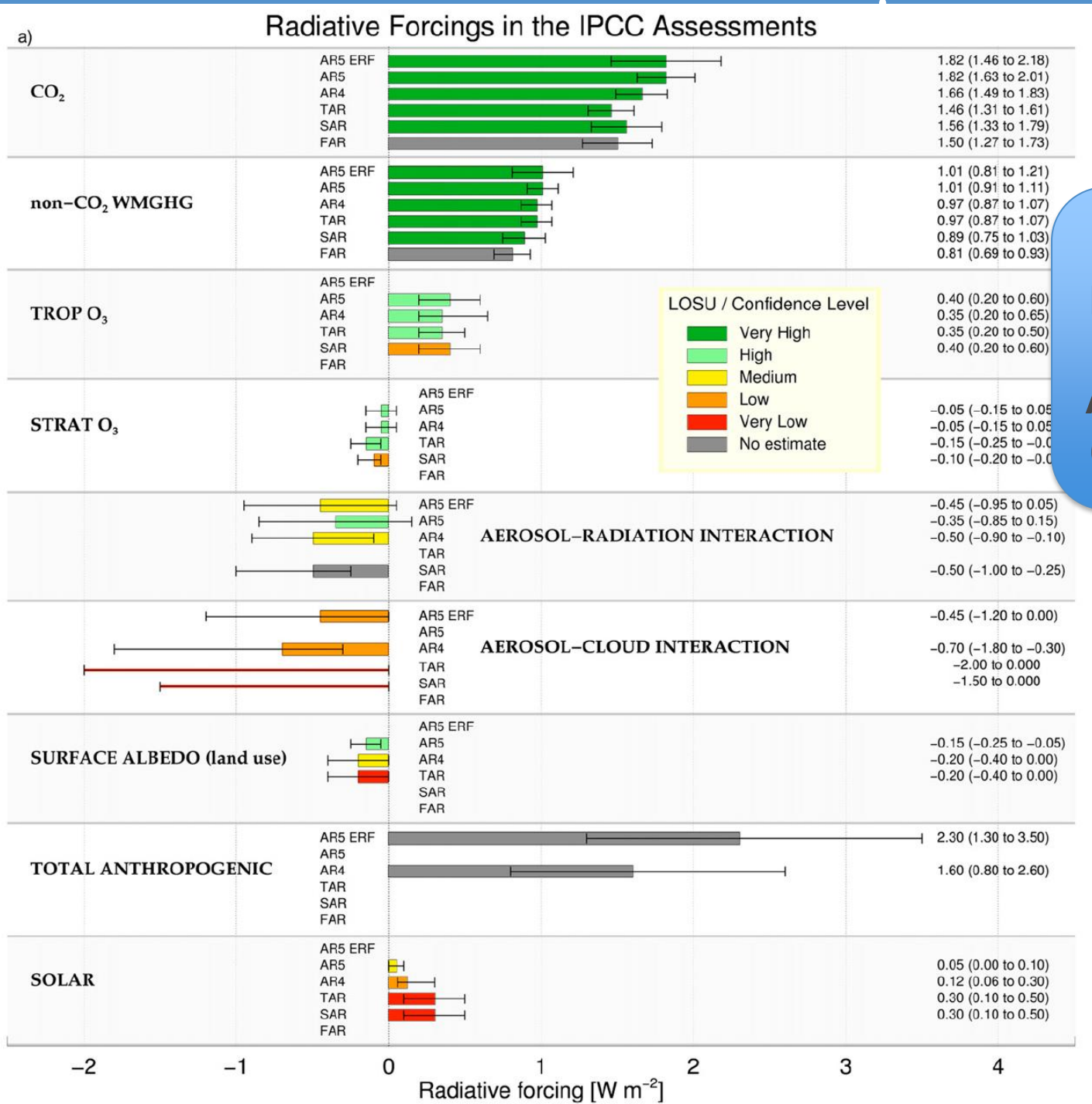
IPCC AR6


Human activities
CO_2
Other (e.g., SLCF, land use albedo)
Non-CO_2 Greenhouse gases
Emissions
CO_2
CH_4
N_2O
HFCs etc.
NOx
NH_3
Land use albedo etc.
SO_2
Concentrations
CO_2
CH_4
N_2O
HFCs etc.
SO_2
Radiative Forcing
Total anthropogenic
Natural
Effective radiative forcing (W/m²)
Carbon-Cycle and non-CO_2 biogeo-chemical feedbacks
Global Warming
Projections
Observations
Change in global surface temperature (°C rel. to 1850–1900)
Legend:
Historical
SSP5-8.5
SSP3-7.0
SSP2-4.5
SSP1-2.6
SSP1-1.9
2100 RCP range
Regional Climate Change
Temperature
GWL 2°C
Robust significant change
No or no robust significant change
Conflicting signal
Change in annual mean surface temperature (°C)
Climatic Impact-Drivers
Precipitation
GWL 2°C
Change in annual mean precipitation (%)
Legend see left

IPCC AR6

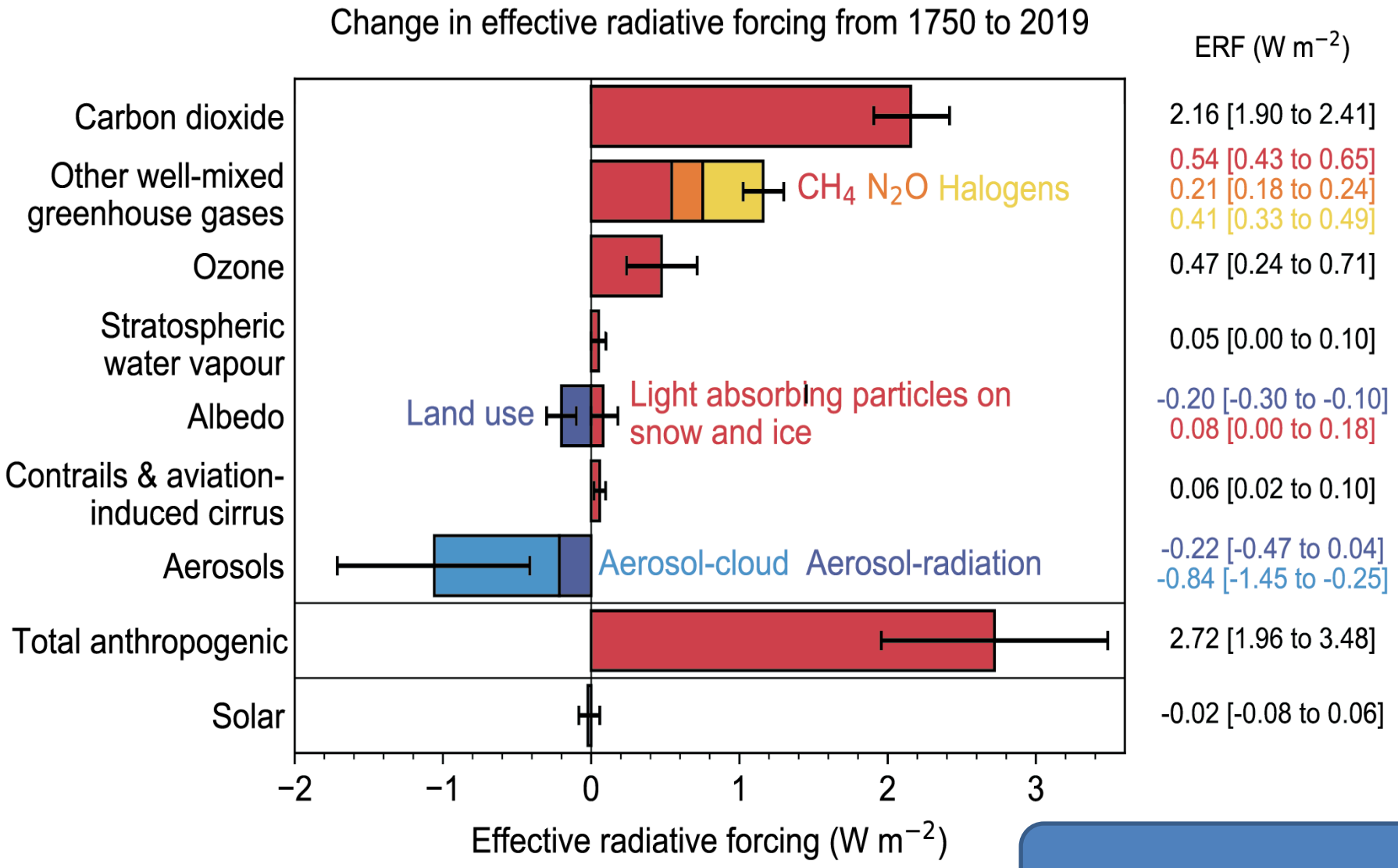


Courtesy:
J. Hansen (2023)



Evolution of RF estimates in the IPCC Assessments (1990 – 2013)

Ramaswamy et al. (2019)


Change in effective radiative forcing from 1750 to 2019
ERF (W m^{-2})
Carbon dioxide
2.16 [1.90 to 2.41]
Other well-mixed greenhouse gases
CH$_4$ N$_2$O Halogens
0.54 [0.43 to 0.65]
0.21 [0.18 to 0.24]
0.41 [0.33 to 0.49]
Ozone
0.47 [0.24 to 0.71]
Stratospheric water vapour
0.05 [0.00 to 0.10]
Albedo
Land use
Light absorbing particles on snow and ice
-0.20 [-0.30 to -0.10]
0.08 [0.00 to 0.18]
Contrails & aviation-induced cirrus
0.06 [0.02 to 0.10]
Aerosols
Aerosol-cloud
Aerosol-radiation
-0.22 [-0.47 to 0.04]
-0.84 [-1.45 to -0.25]
Total anthropogenic
2.72 [1.96 to 3.48]
Solar
-0.02 [-0.08 to 0.06]
−2
−1
0
1
2
3
Effective radiative forcing (W m^{-2})

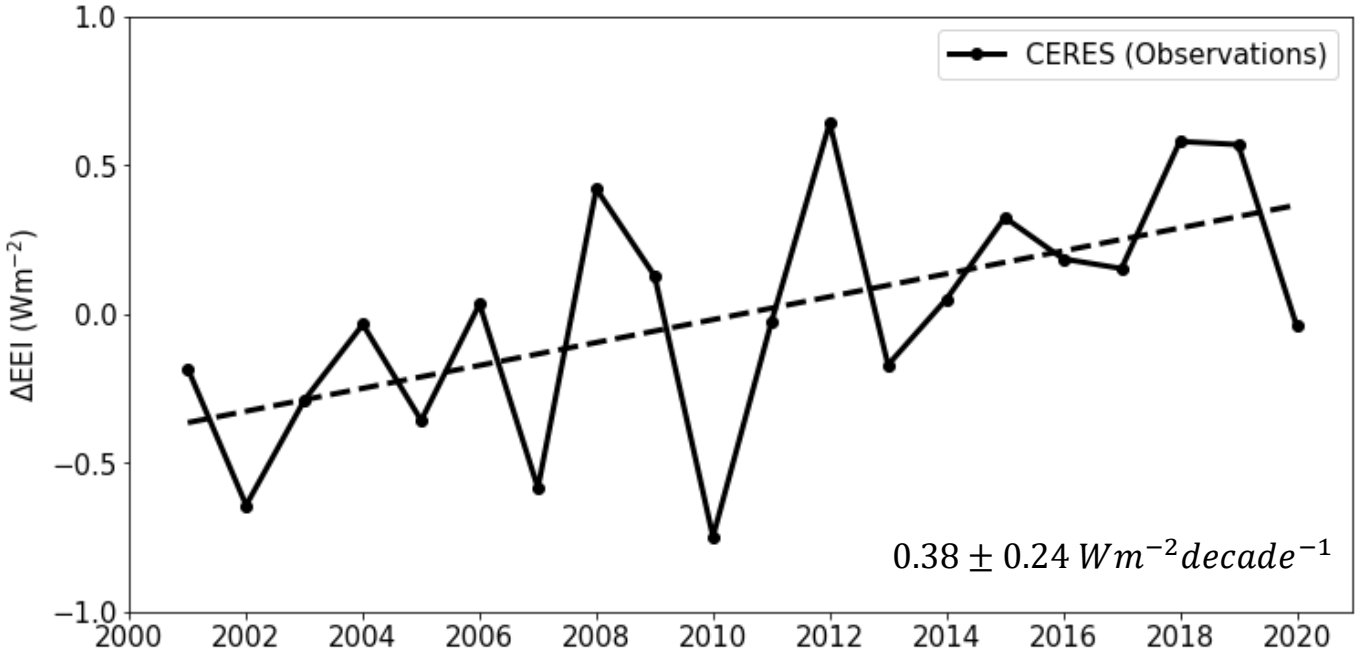
IPCC AR6

Earth's Energy Imbalance:

Greenhouse Gas and Aerosol signatures in the Satellite-Observed Radiation Budget

[Raghuraman et al., Nature Communications, 2021]

Satellite-observed trend in EEI (past 20 years)



See also:

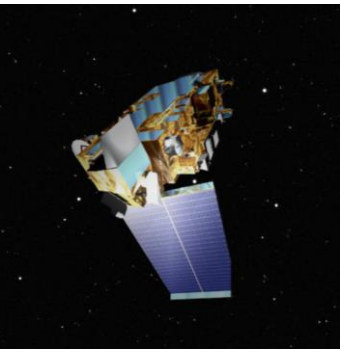
- Hakuba et al., 2021
- Bagnell & DeVries, 2021
- Loeb et al., 2021
- Kramer et al., 2021

- For reference, mean EEI over this period is nearly $1\ \mathrm{Wm^{-2}}$.
- Why is Earth's energy imbalance increasing? Is it just due to internal variability (null hypothesis)?
- $\Delta\mathrm{EEI} = \Delta\mathrm{ERF} + \lambda\Delta\mathrm{T_s} + \epsilon$

Methodology

Modeled Earth's energy imbalance
- CMIP6 Historical
- AM4 PSST+ERF (Prescribed SSTs, sea ice, and forcing)
- 2001-2020 Forcing
- 6 models, 162 realizations

Internal variability
- CMIP6 Control
- AM4 Control
- Pre-industrial Forcing
- 48 models, 1,393 realizations



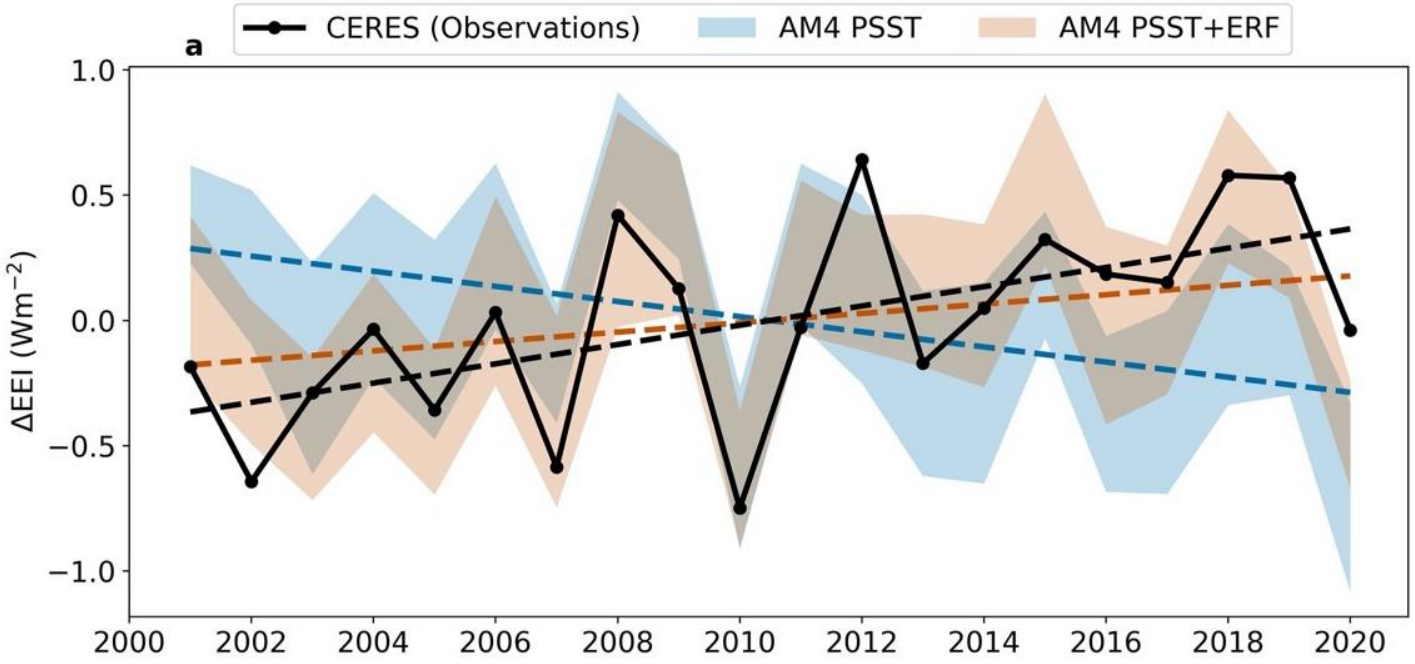
CERES EBAF satellite observations

$$\Delta EEI = \Delta ERF + \lambda \Delta T_s + \epsilon$$

Effective Radiative Forcing
- AM4 PSST+ERF -AM4 PSST
- 2001-2020 Forcing

Response
- AM4 PSST (Prescribed SSTs and sea ice)
- Fixed Forcing
- 20 realizations

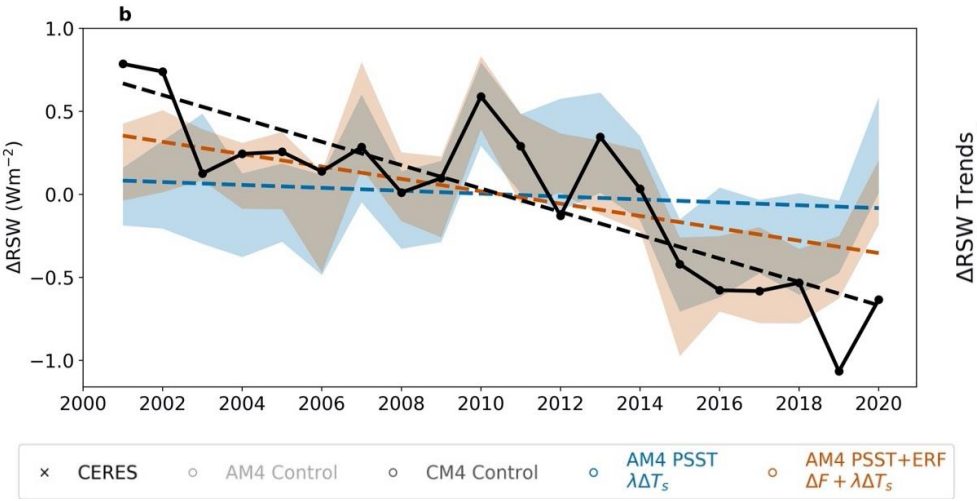
Anthropogenic forcing & feedback yields a god estimate of the observed TEEI

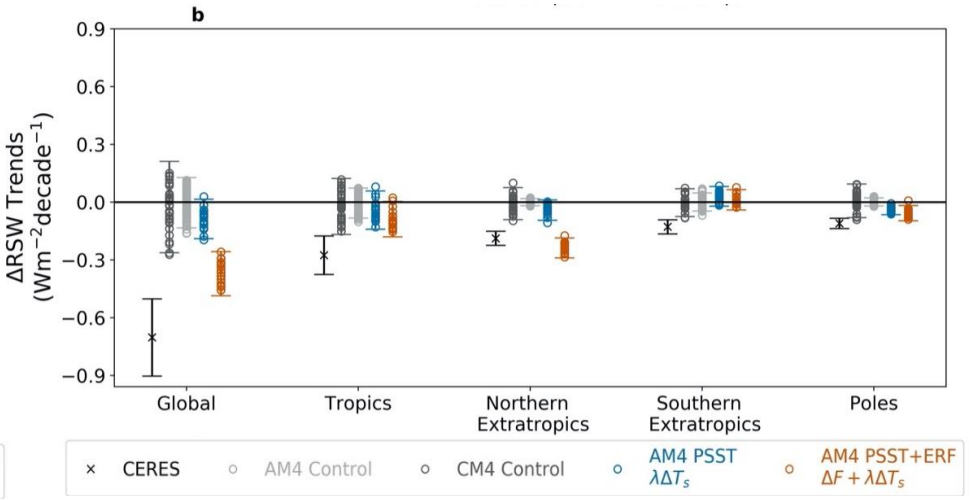


Raghuraman et al. (2021).
Also, Kramer et al. (2021)

Large decrease in reflected sunlight

$$EEI = S_0 - (\mathbf{RSW} + OLR)$$





- Reduction in reflection observed across the globe
- Forcing dominates this reduction in reflection: aerosol decrease and greenhouse gas rapid cloud adjustments
- Feedbacks supplement this reduction in reflection: sea-ice decreases

Climate Response to Radiative Forcings

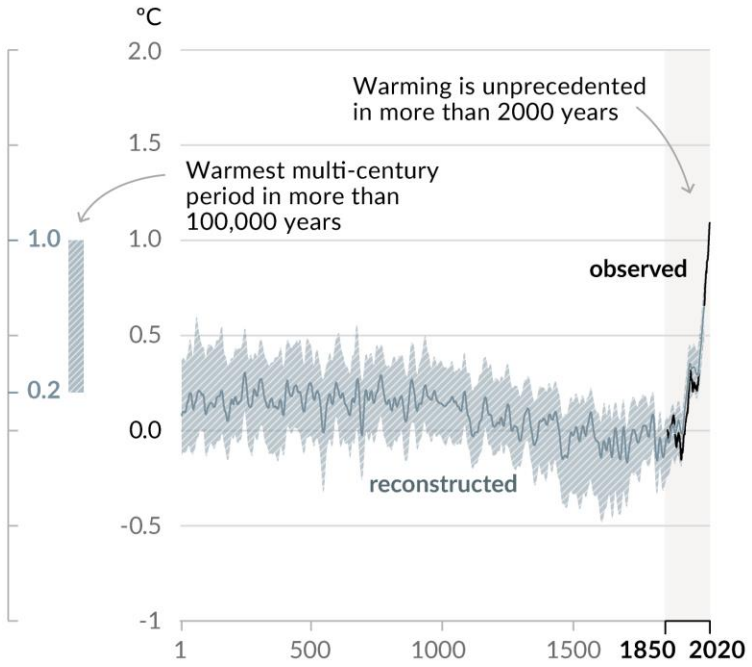
IPCC AR6

Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

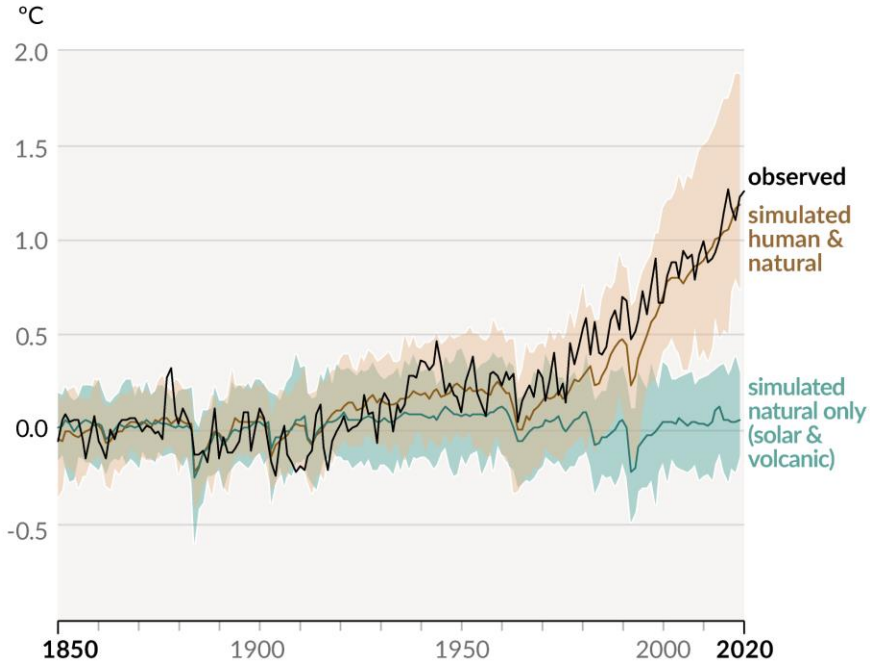
Figure SPM.1

Changes in global surface temperature relative to 1850-1900

a) Change in global surface temperature (decadal average) as reconstructed (1-2000) and **observed** (1850-2020)

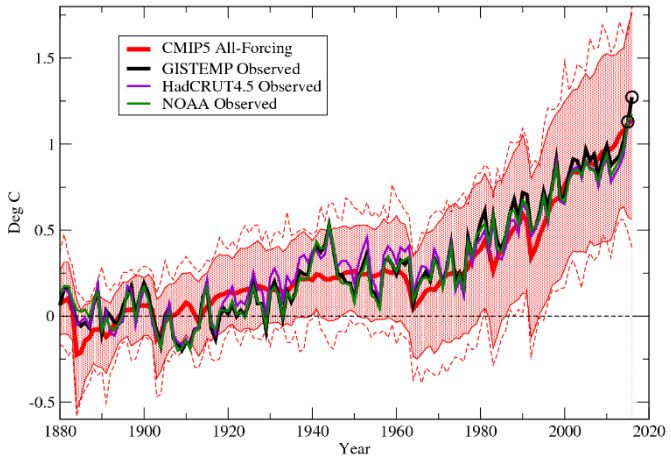


b) Change in global surface temperature (annual average) as **observed** and simulated using human & natural and only natural factors (both 1850-2020)

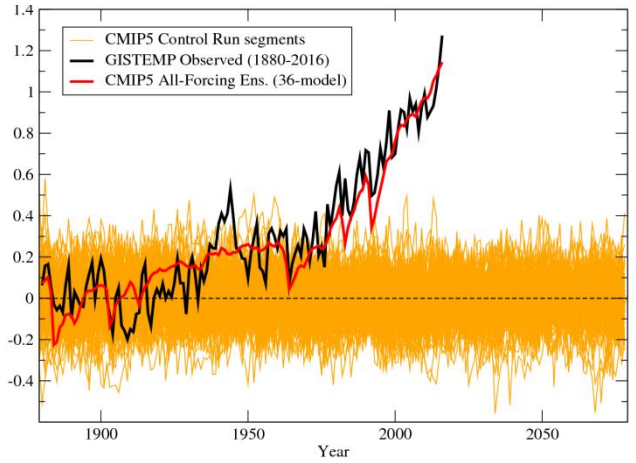


Comparing 2016's record observed global temperatures with CMIP5 models

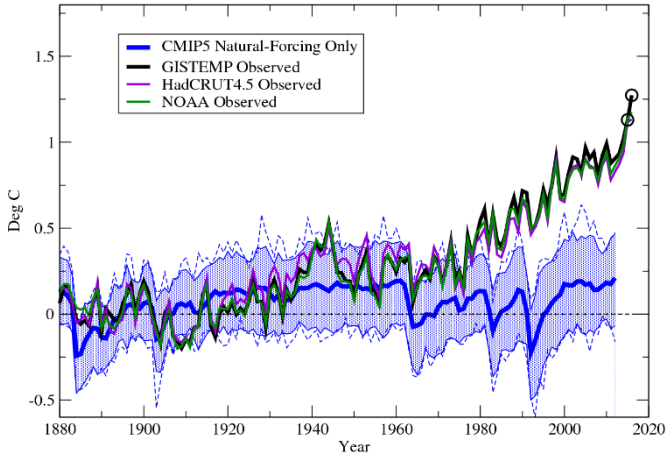
a) Observed vs. Natural + Anthropogenic Forcing



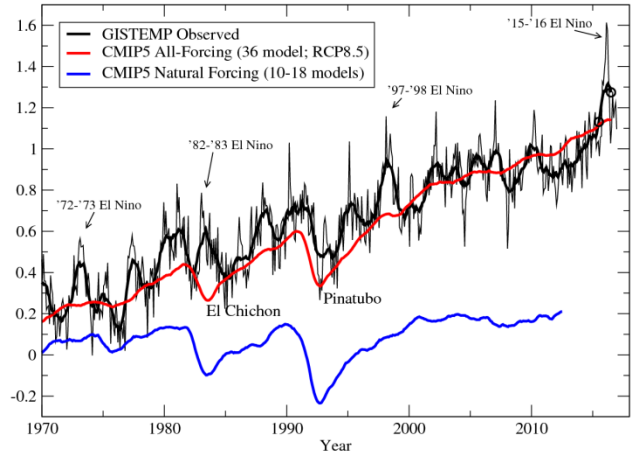
c) Observed vs. Internal Climate Variability



b) Observed vs. Natural Forcing Only



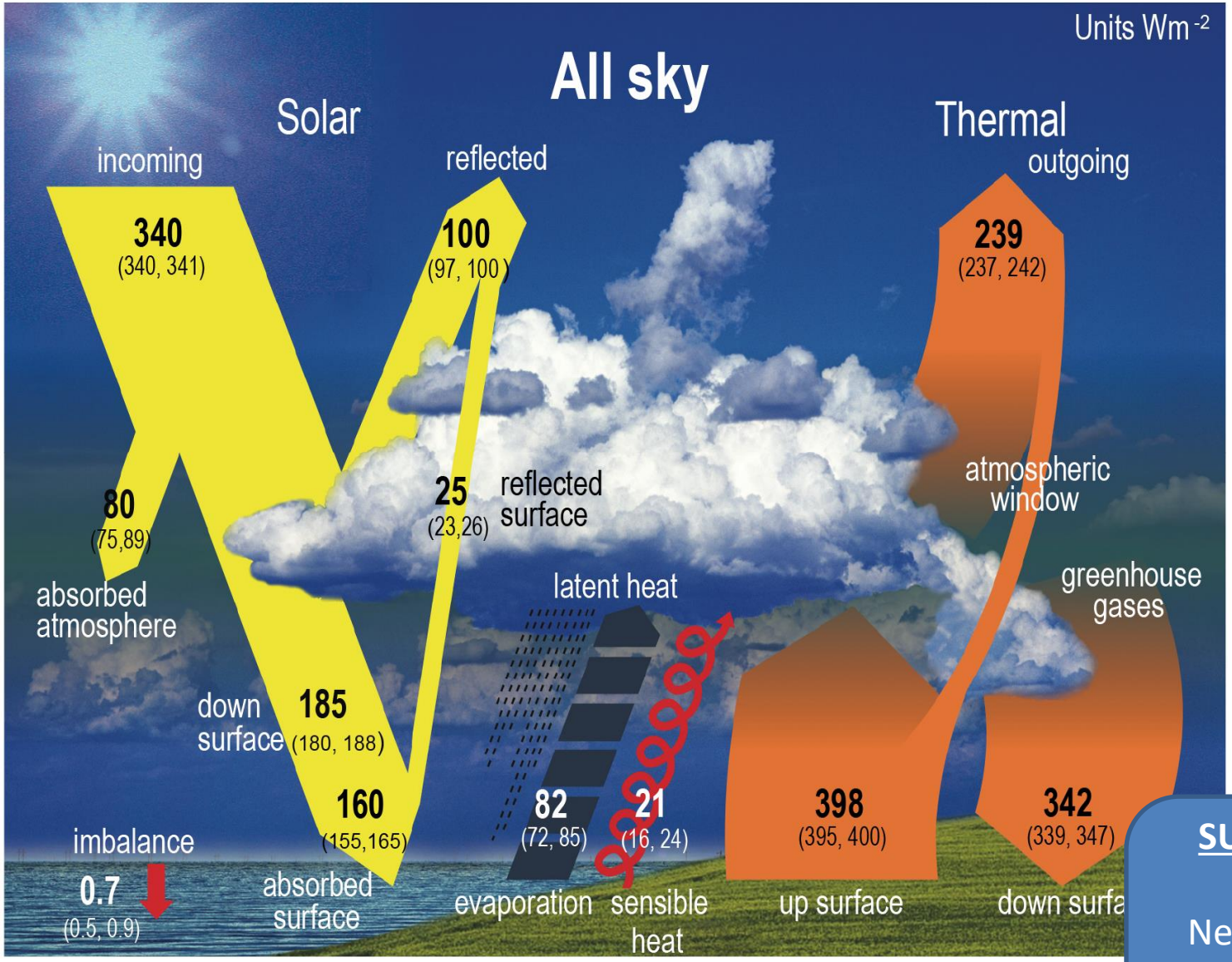
d) Recent Global Temperature Variability



Source: Knutson et al., BAMS (2018)

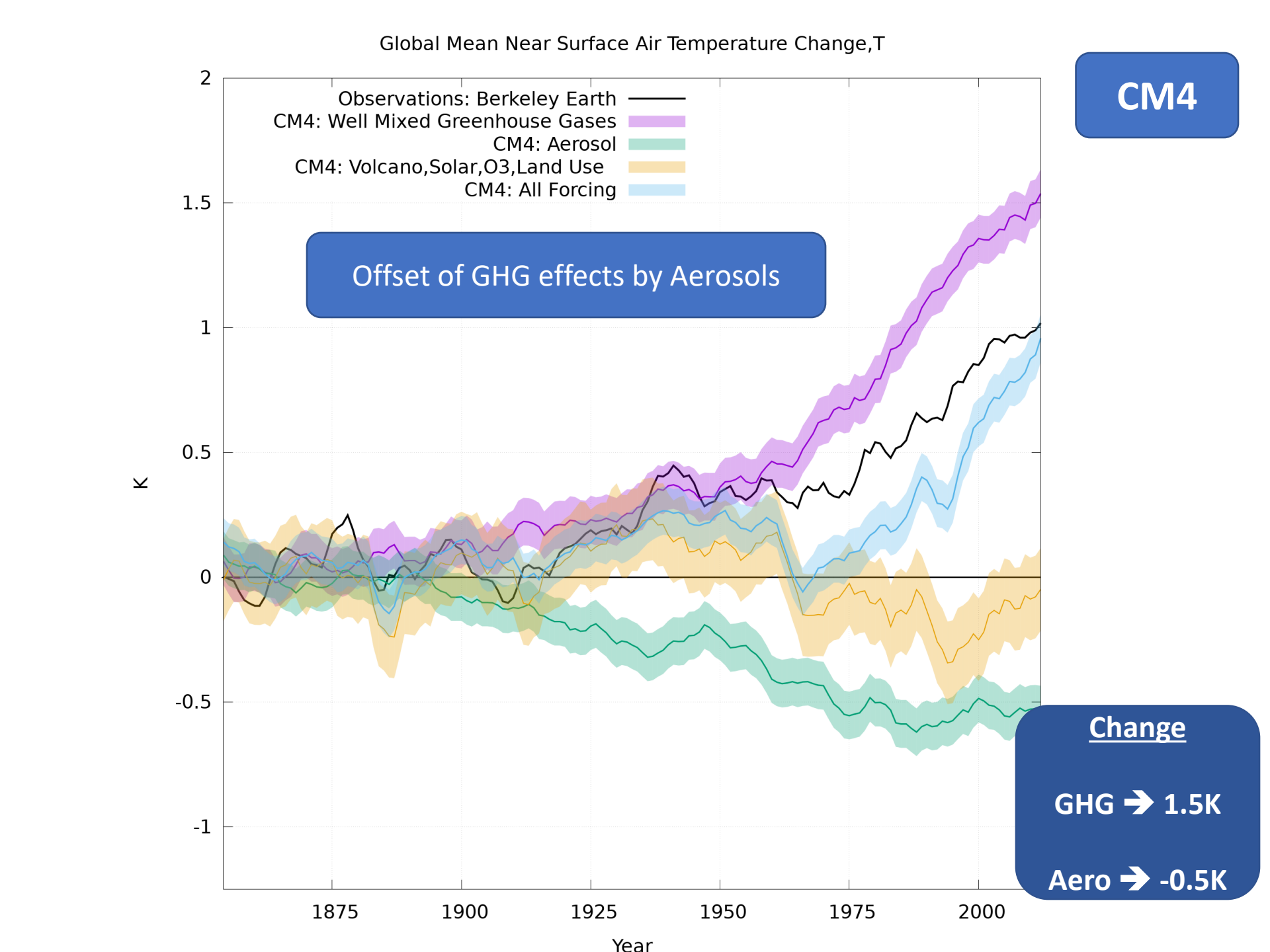
Surface budgets, and Energy-Water nexus

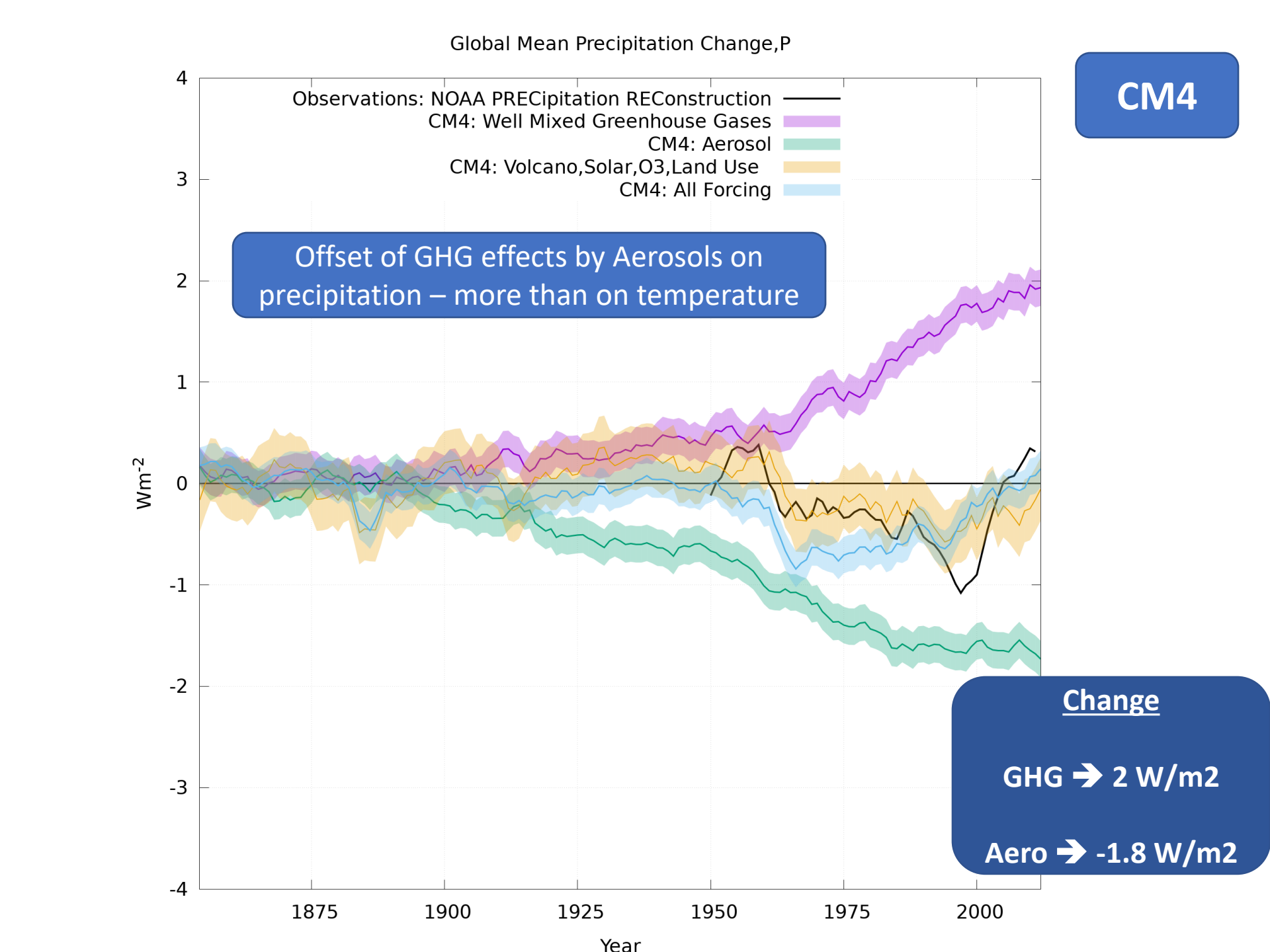
GHGs vs Aerosols



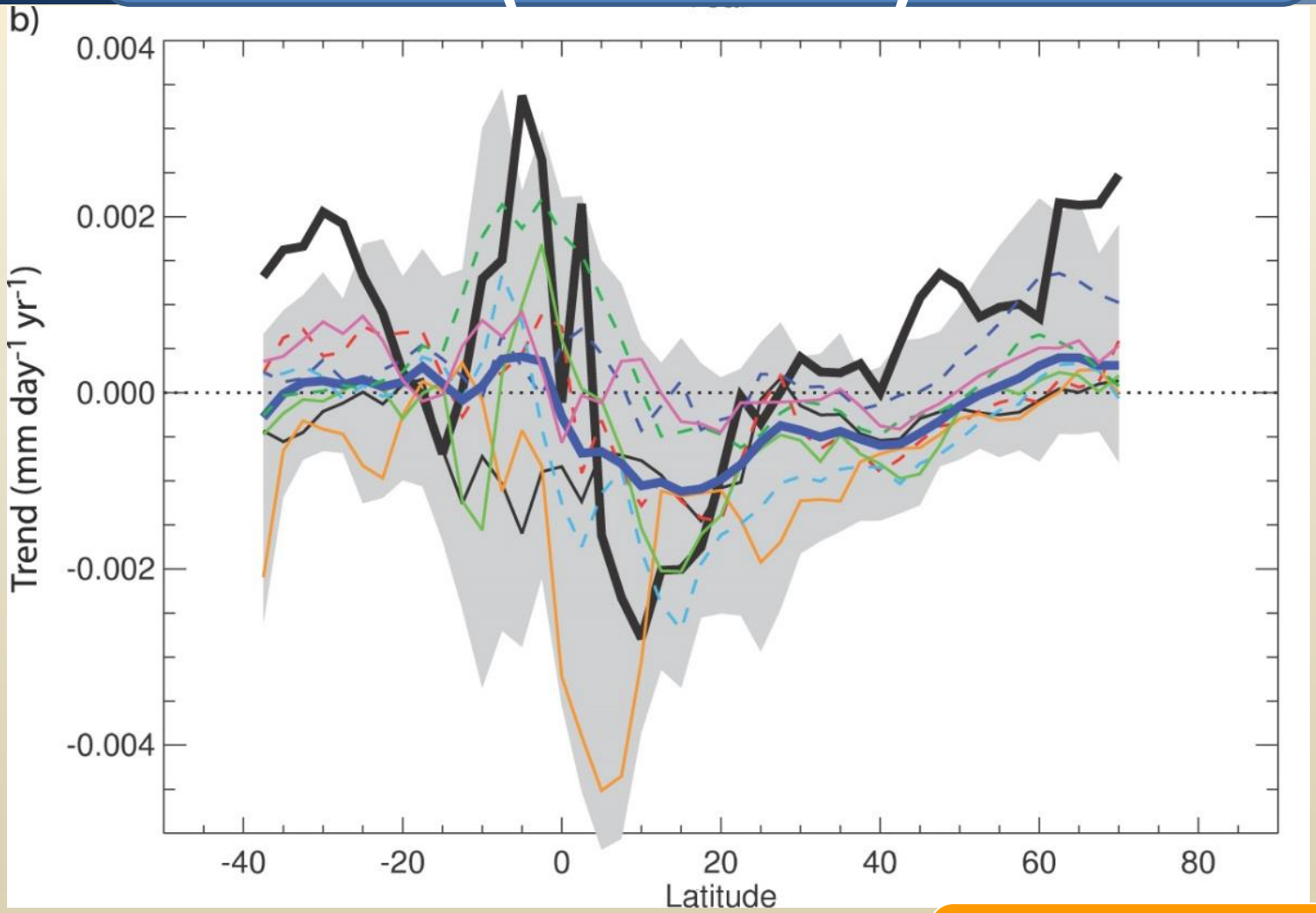
SURFACE BALANCE

Net SW = 160 W/m2
Net LW = - 56W/m2
SH + LH = - 103 W/m2
LH/ SH ~ 4


Global Mean Near Surface Air Temperature Change,T
Observations: Berkeley Earth
CM4: Well Mixed Greenhouse Gases
CM4: Aerosol
CM4: Volcano,Solar,O3,Land Use
CM4: All Forcing
CM4
Offset of GHG effects by Aerosols
K
Year
2
1.5
1
0.5
0
-0.5
-1
1875
1900
1925
1950
1975
2000
Change
GHG → 1.5K
Aero → -0.5K

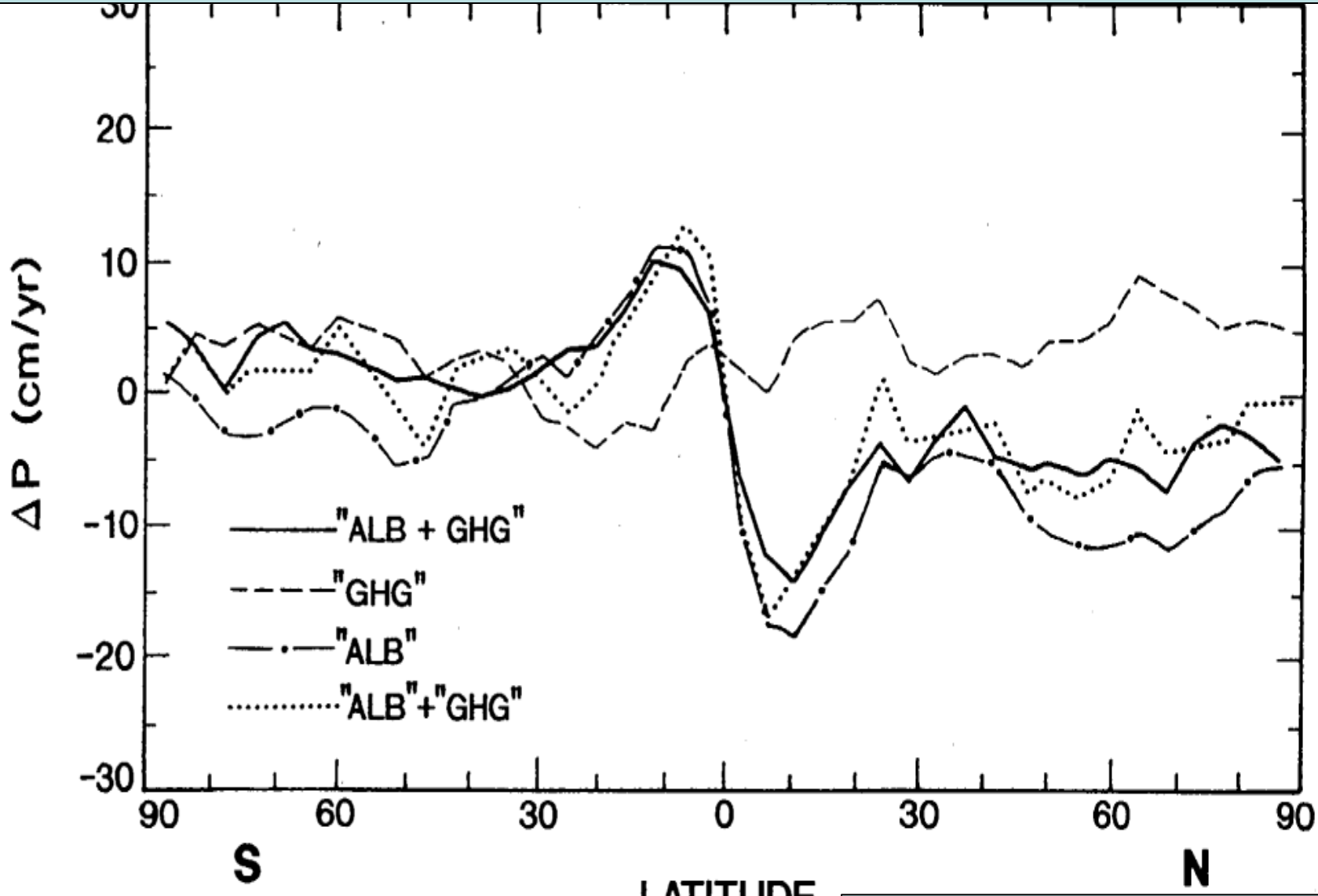

Global Mean Precipitation Change,P
Observations: NOAA PRECipitation REConstruction
CM4: Well Mixed Greenhouse Gases
CM4: Aerosol
CM4: Volcano,Solar,O3,Land Use
CM4: All Forcing
CM4
Offset of GHG effects by Aerosols on precipitation – more than on temperature
Change
GHG → 2 W/m2
Aero → -1.8 W/m2
Wm-2
Year
4
3
2
1
0
-1
-2
-3
-4
1875
1900
1925
1950
1975
2000

Zonal-mean precipitation trend (1901-1998)



IPCC AR4 (2007); see also AR6

Atmos + Mixed-Layer R15 "MCM"
GHG = CO2 forcing; ALB = "NH sulfate". GHG+ALB = "0" global-mean forcing

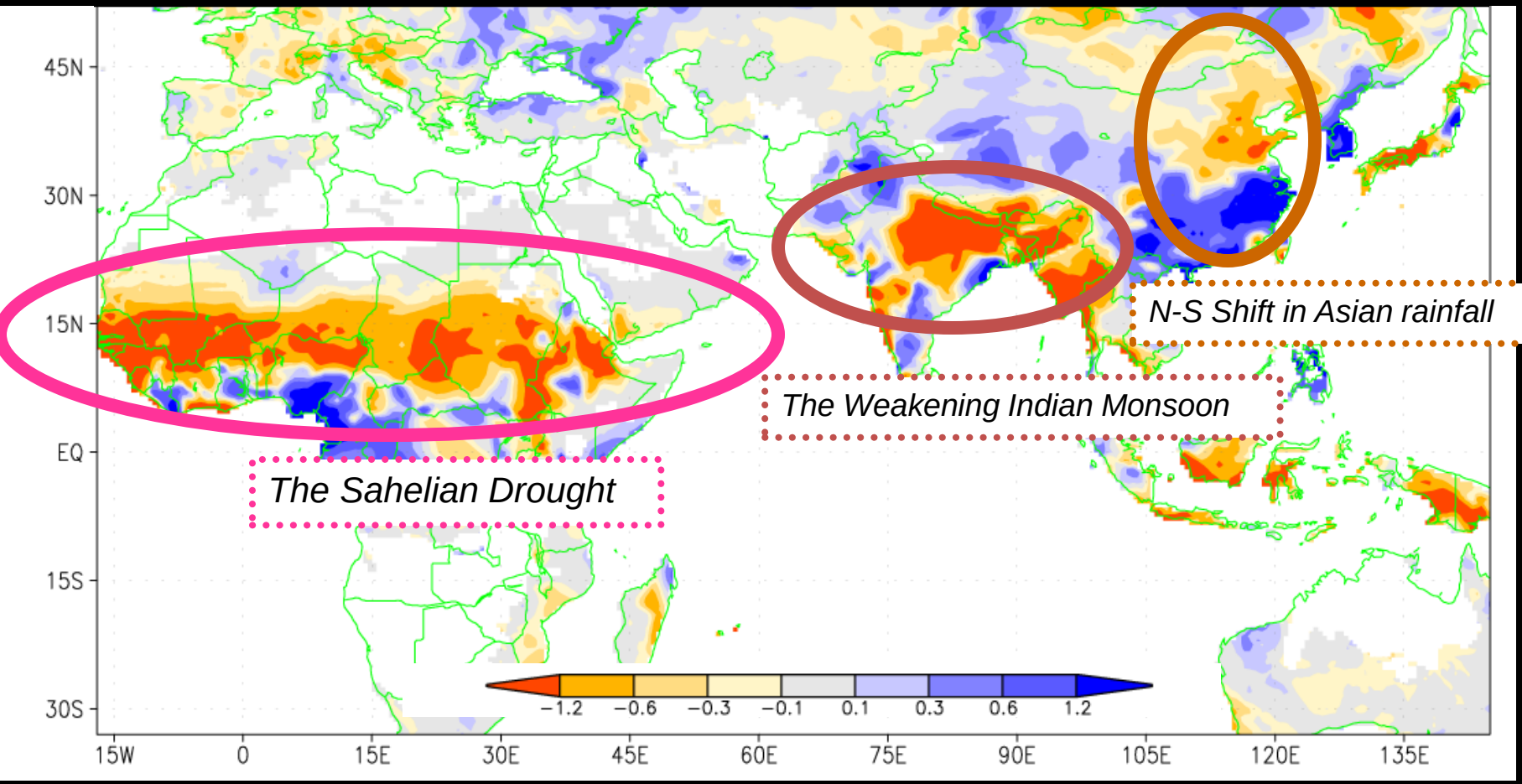


Ramaswamy-Chen (GRL, 1997)

Major Rainfall Shifts during the last 50 Years

Chung and Ramanathan 2006

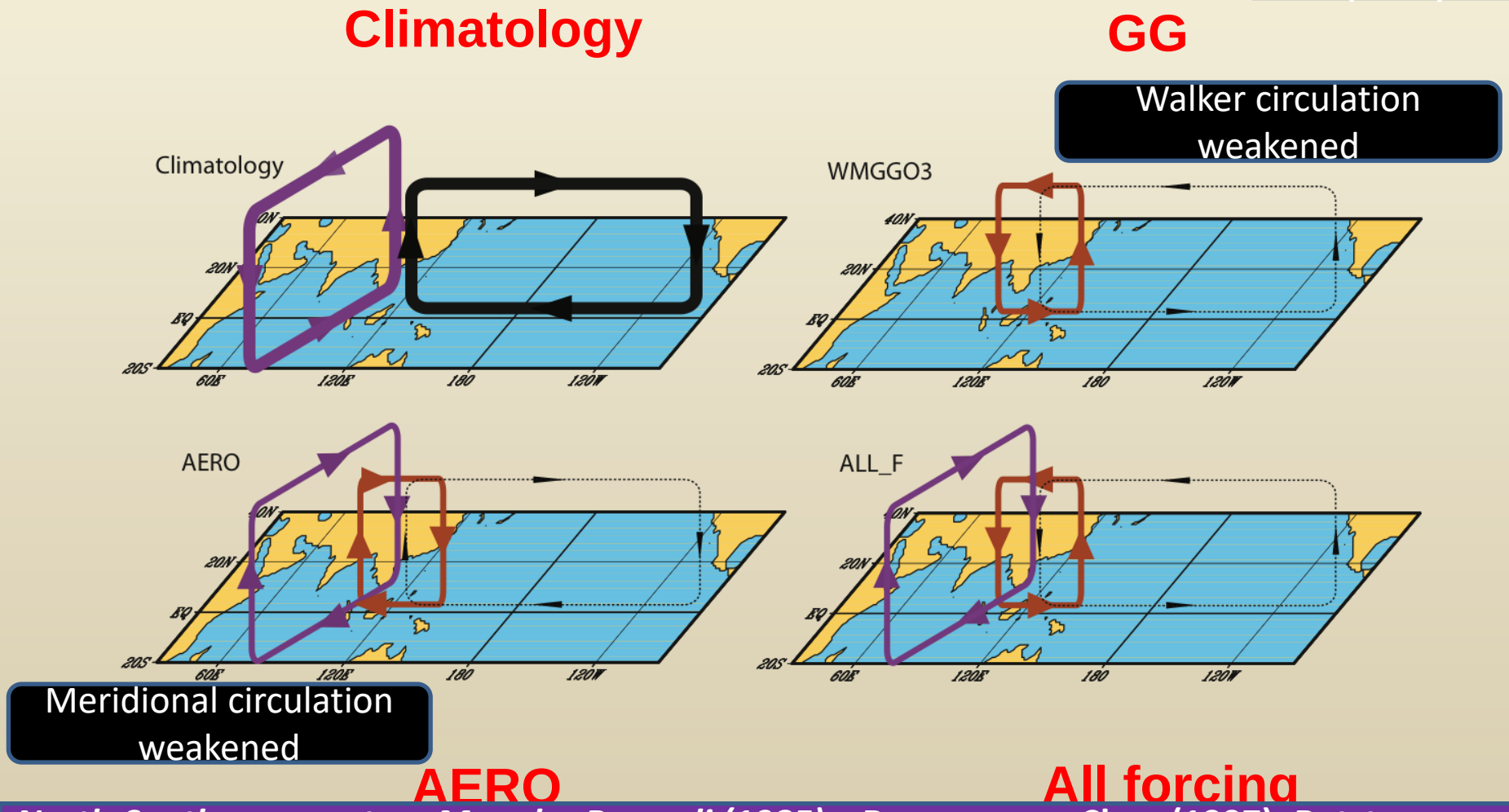
Observed Trends in Summer Rainfall: 1950 to 2002



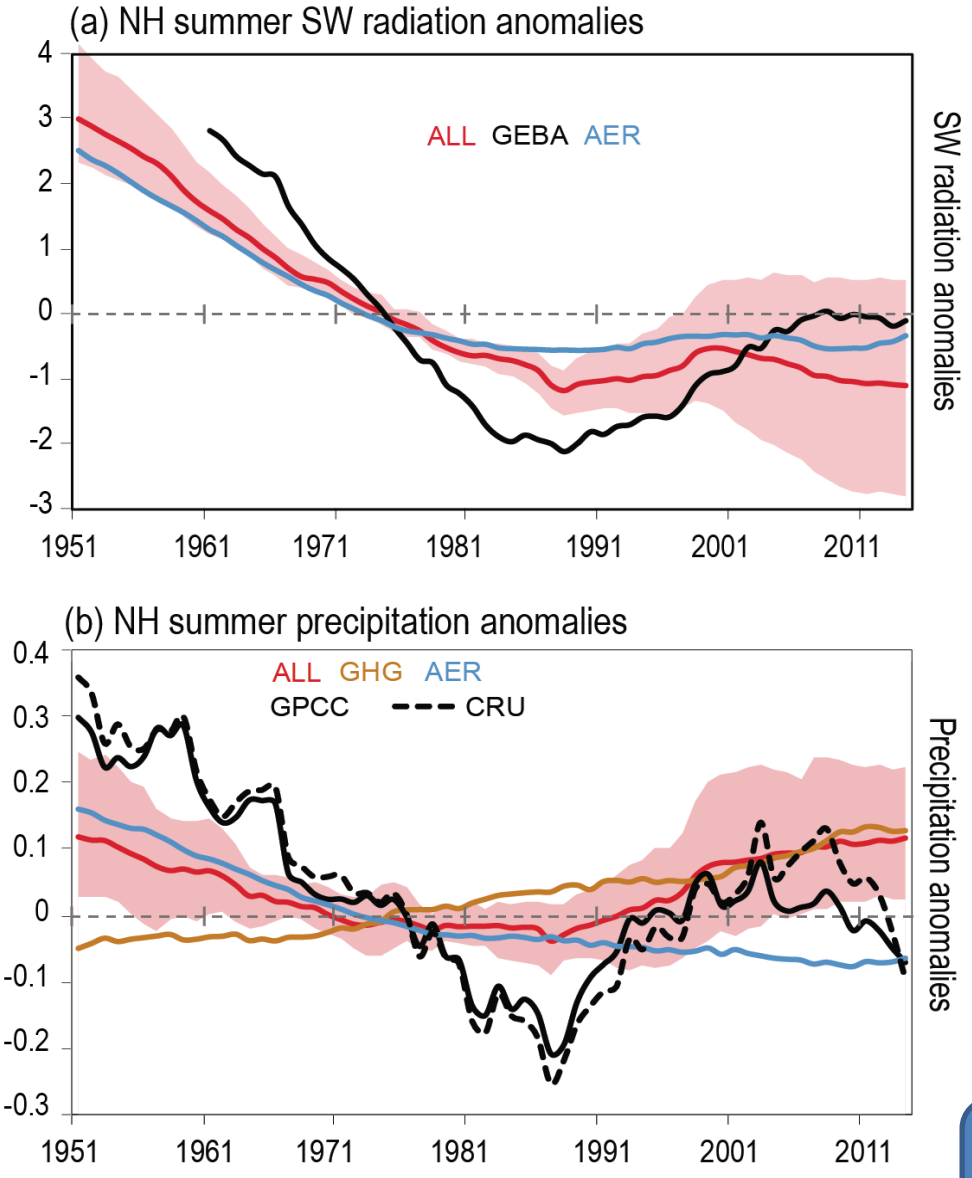
How Hadley and Walker circulations respond to green-house gases and aerosols? {*Climatology, and the changes*}

Anthropogenic aerosols induce NH-SH asymmetry

Bollasina et al. (2011)



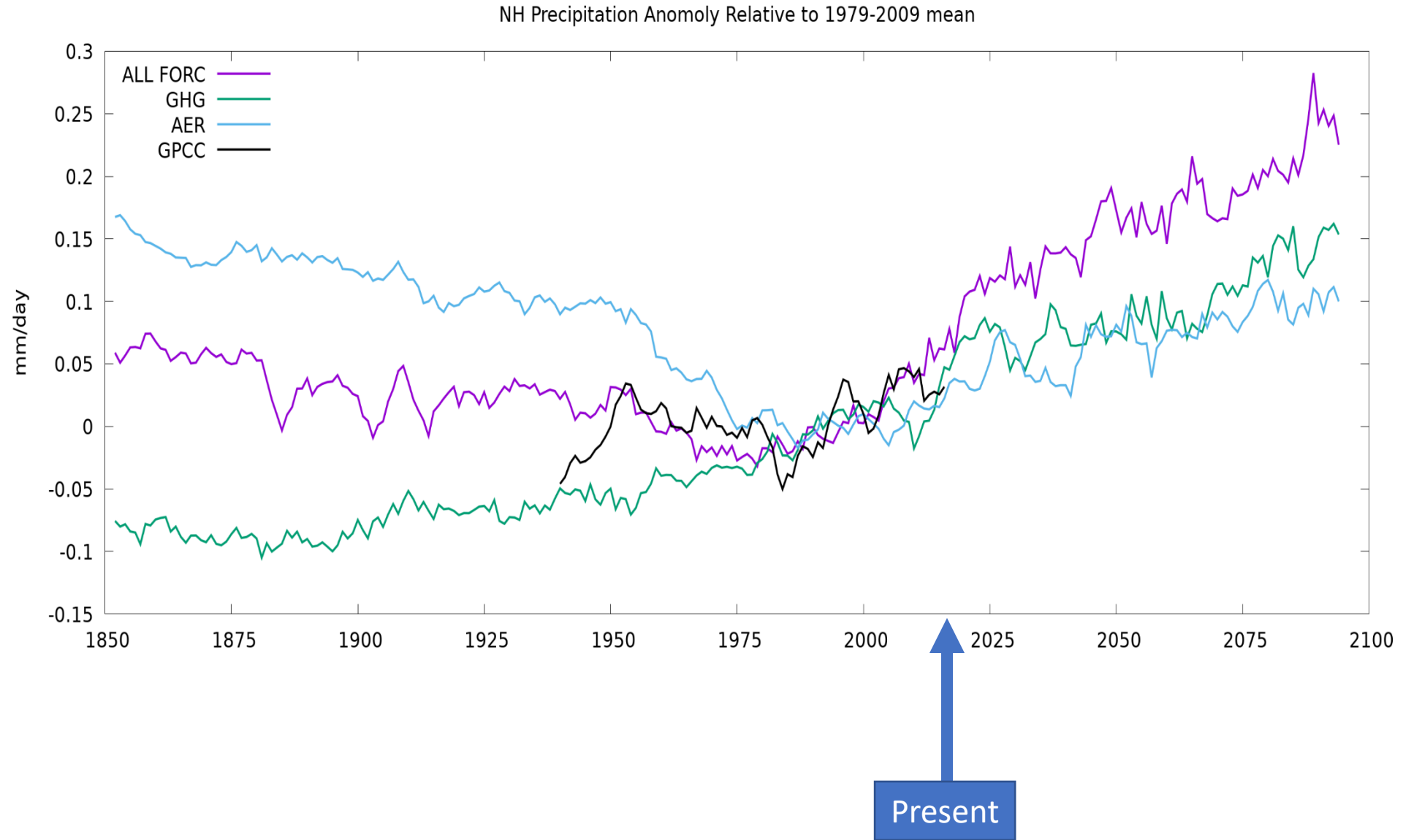
North-South asymmetry : Manabe-Broccoli (1985); **Ramaswamy-Chen (1997); Rotstayn-Lohmann (2002); Ramanathan et al. (2003); Chung-Seinfeld (2005); Yoshimori-Broccoli (2008); Hwang et al. (2013); Hill et al. (2014)**


(a) NH summer SW radiation anomalies
ALL GEBA AER
SW radiation anomalies
4
3
2
1
0
-1
-2
-3
1951
1961
1971
1981
1991
2001
2011
(b) NH summer precipitation anomalies
ALL GHG AER
GPCC CRU
Precipitation anomalies
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
1951
1961
1971
1981
1991
2001
2011

The 21st C Scenarios

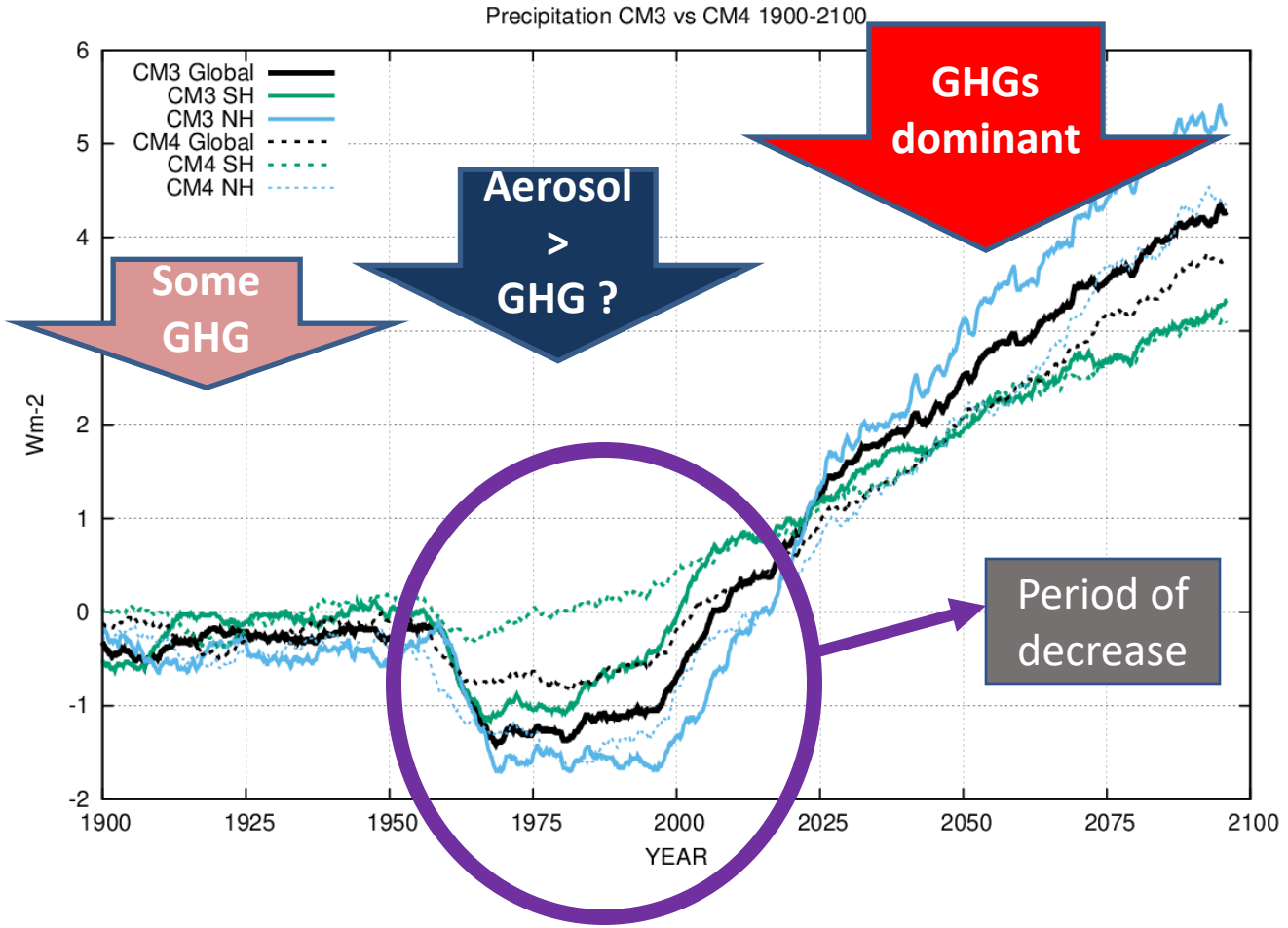
- ***WMGG increases***
- ***Aerosol decreases***

➔ ***Reversal of late 20th C effects ?***

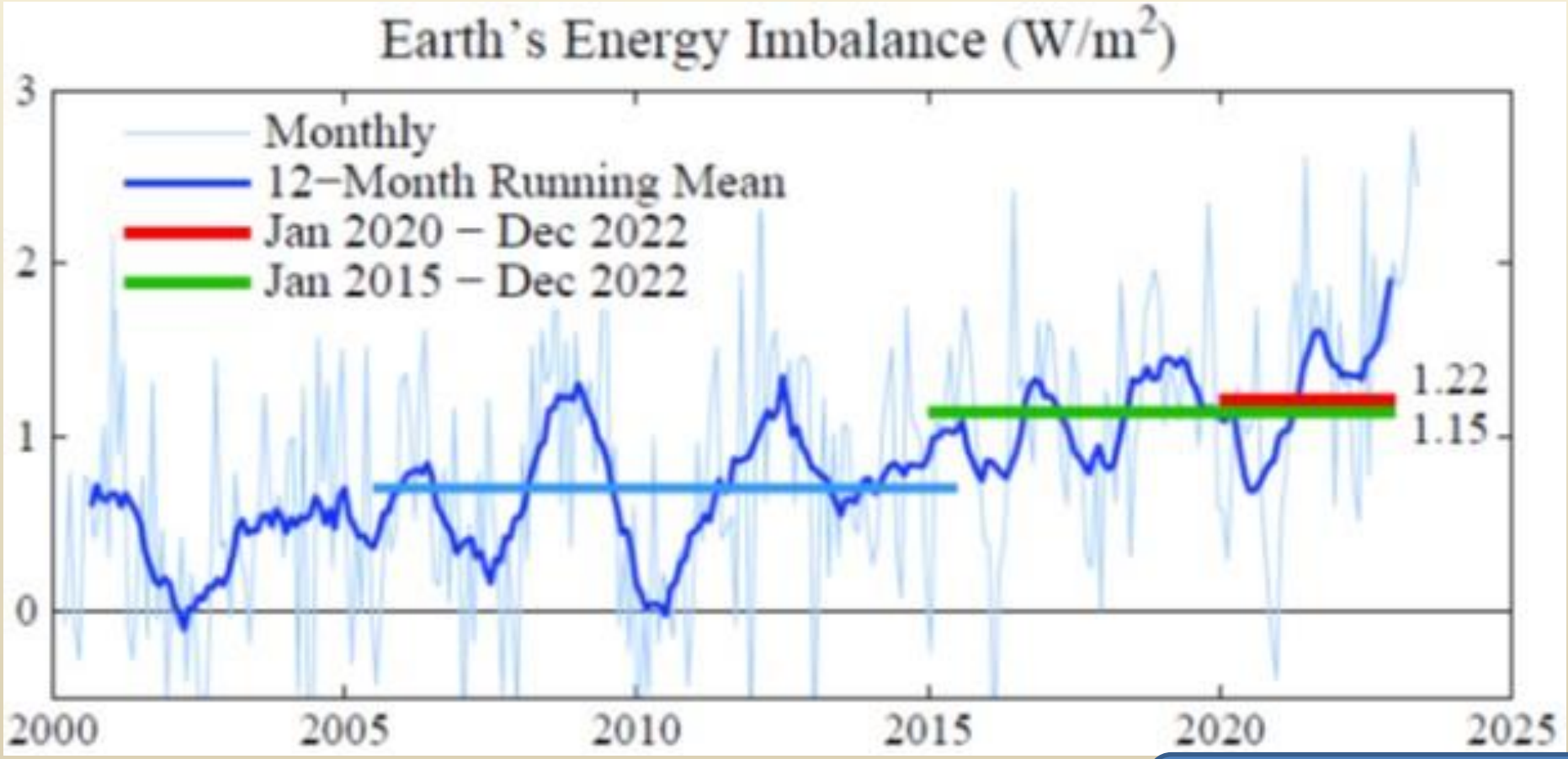

NH Precipitation Anomoly Relative to 1979-2009 mean
ALL FORC
GHG
AER
GPCC
mm/day
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
1850
1875
1900
1925
1950
1975
2000
2025
2050
2075
2100
Present

A plausible precipitation evolution picture

Precipitation (relative) (in flux units)



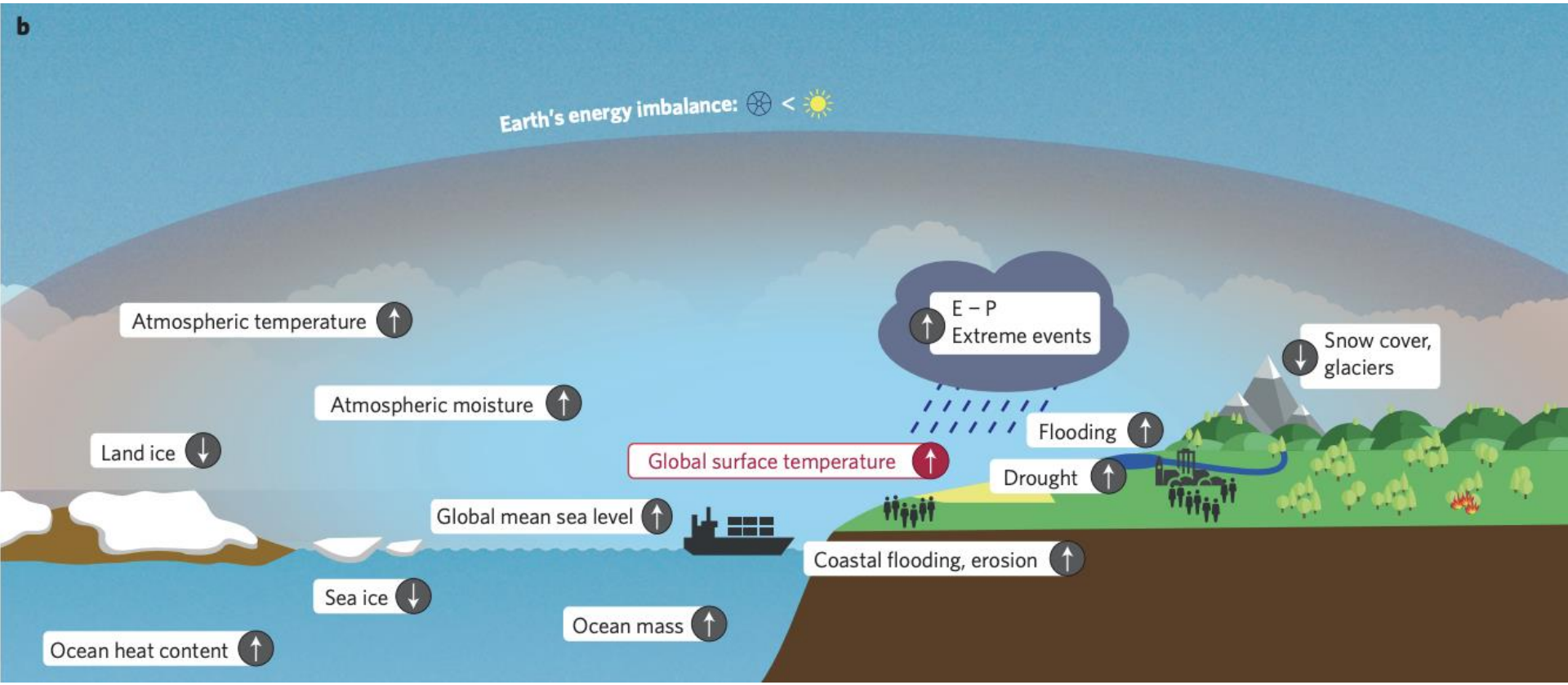
CM3, CM4 model results



Courtesy:
J. Hansen (2023)

Radiative Forcings →

'Symptoms' of an imbalanced Earth



von Schuckmann et al., 2016

IPCC AR6

With every increment of global warming, changes get larger in regional mean temperature, precipitation and soil moisture

Figure SPM.5