Modeling Earth's Climate: Effect of Aerosols on Clouds & Water Vapor, Cloud, Lapse Rate, & Surface Albedo Feedbacks

AOSC 680

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2024
https://umd.instructure.com/courses/1367293

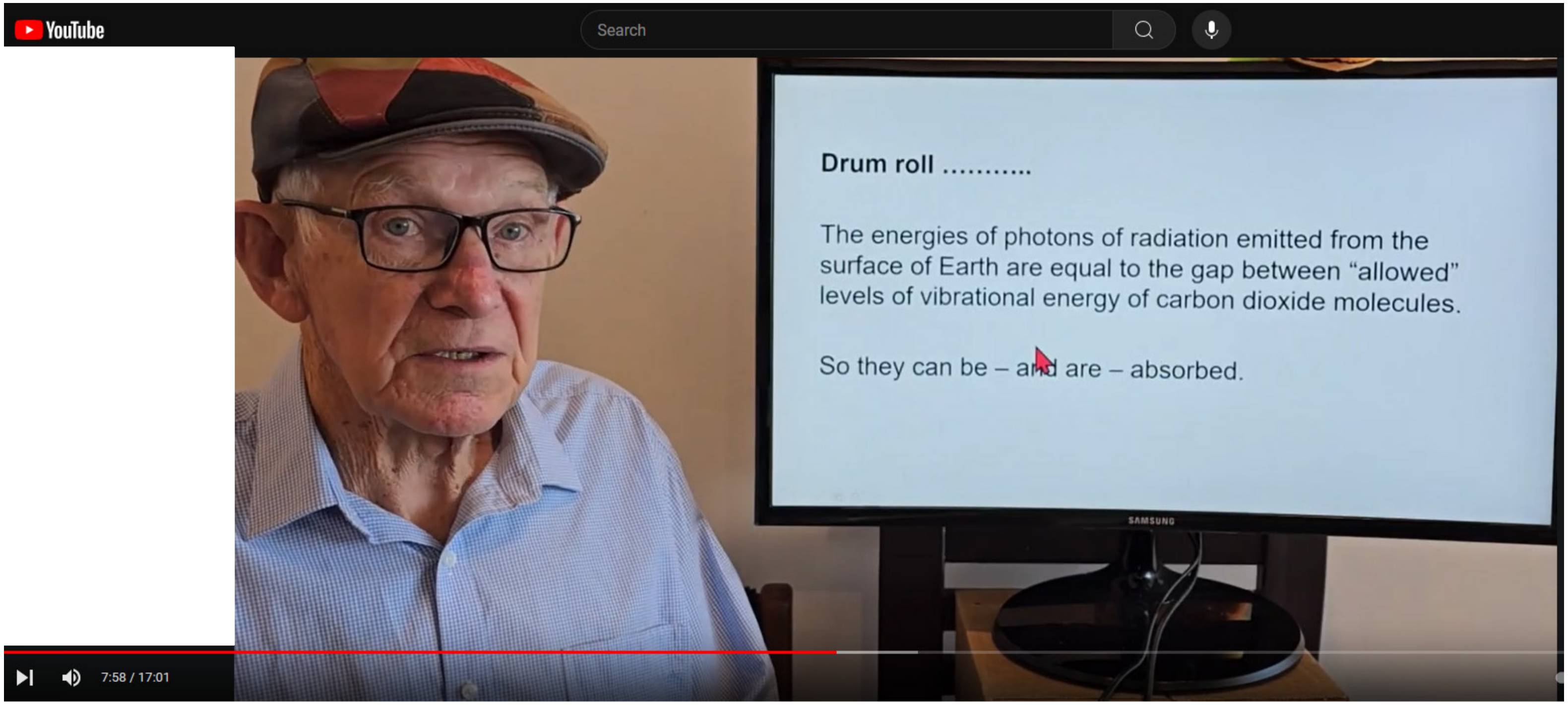
Goals:

1. Aerosol RF of climate
    - black carbon
    - direct & indirect effect
2. Feedbacks (internal response) to RF of climate (external forcings) due to anthropogenic GHGs & Aerosols:
    - Surface albedo (straight forward but surprisingly *not well known*)
    - Water vapor (straight forward & fairly well known)
    - Lapse rate (straight forward, well known, but *generally overlooked*)
    - Clouds (quite complicated; not well known)
3. An empirical model of climate: trying to use the past to project future

Lecture 8

24 September 2024

Announcement 1: Interaction of photons w/ GHGs

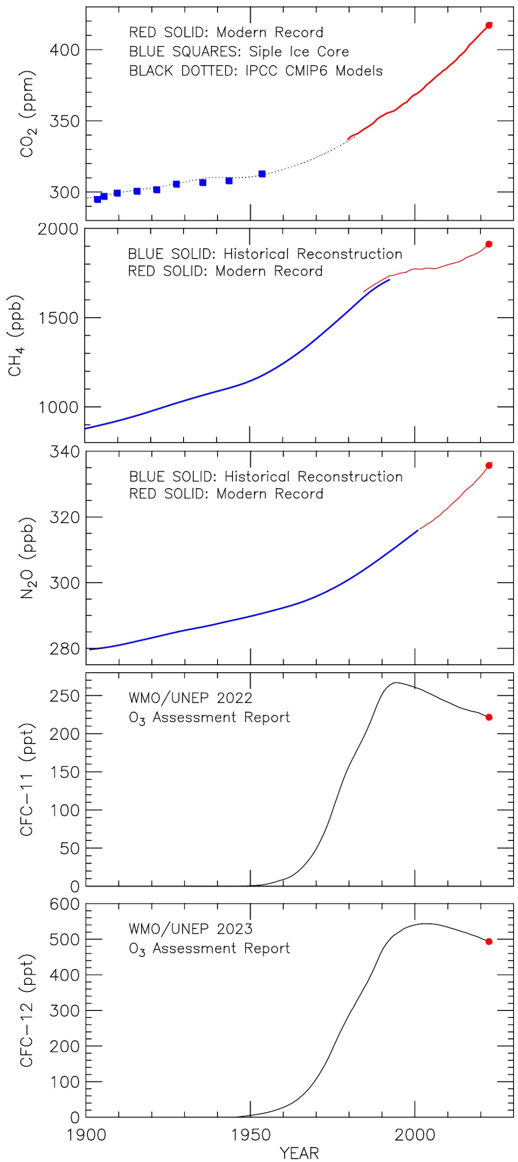


2706 Why does CO2 ‘trap’ heat from Earth?

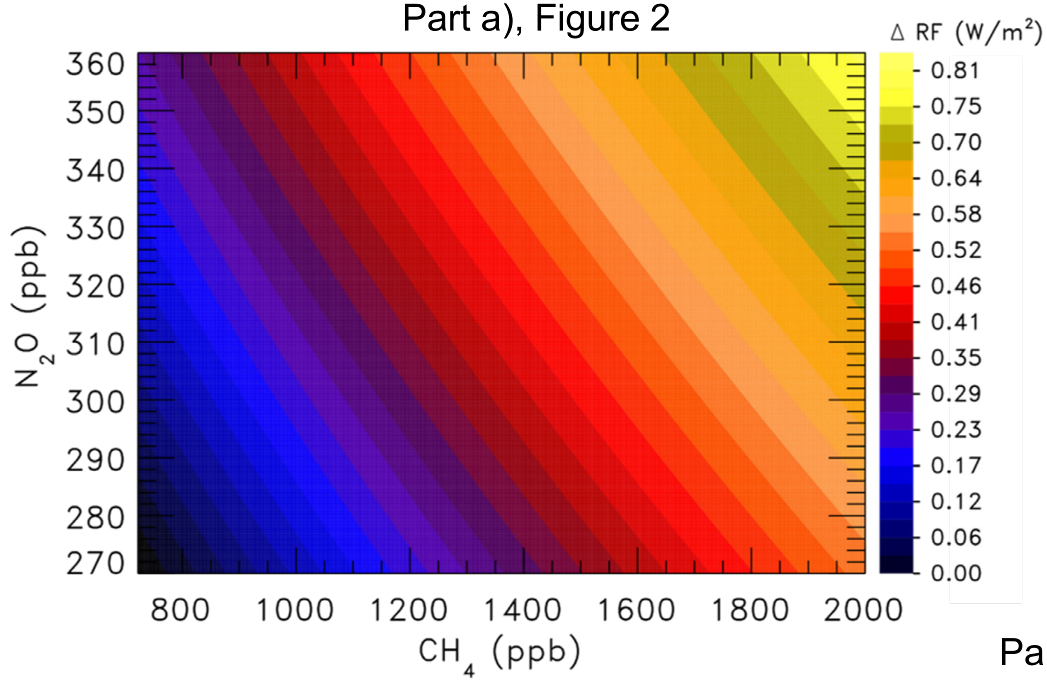
See also https://wiki.anton-paar.com/ph-en/infrared-spectrum-of-carbon-dioxide/
and https://youtu.be/EaRxu3i_vZw?si=7TsWvJpcdyJ2eQPw&t=428

Problem Set 2 Figures

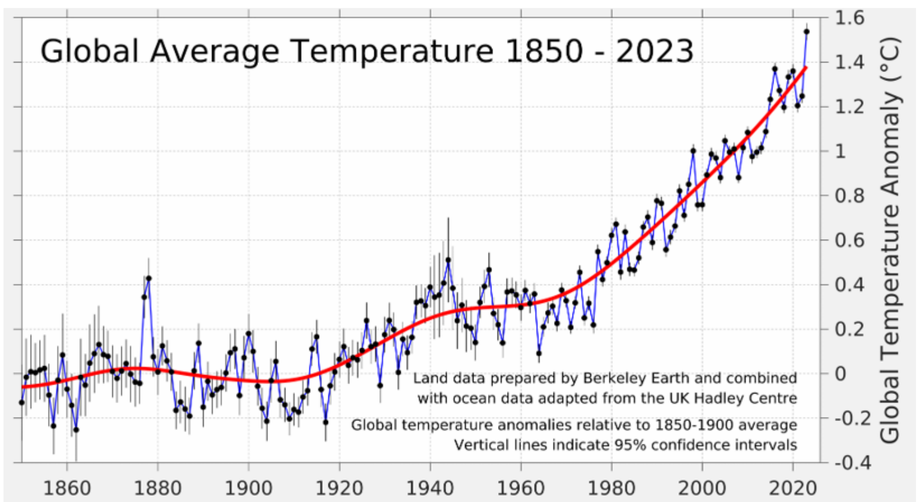
Part a), Figure 1



Part a), Figure 2



Part d)



Combining RF GHGs & Aerosols

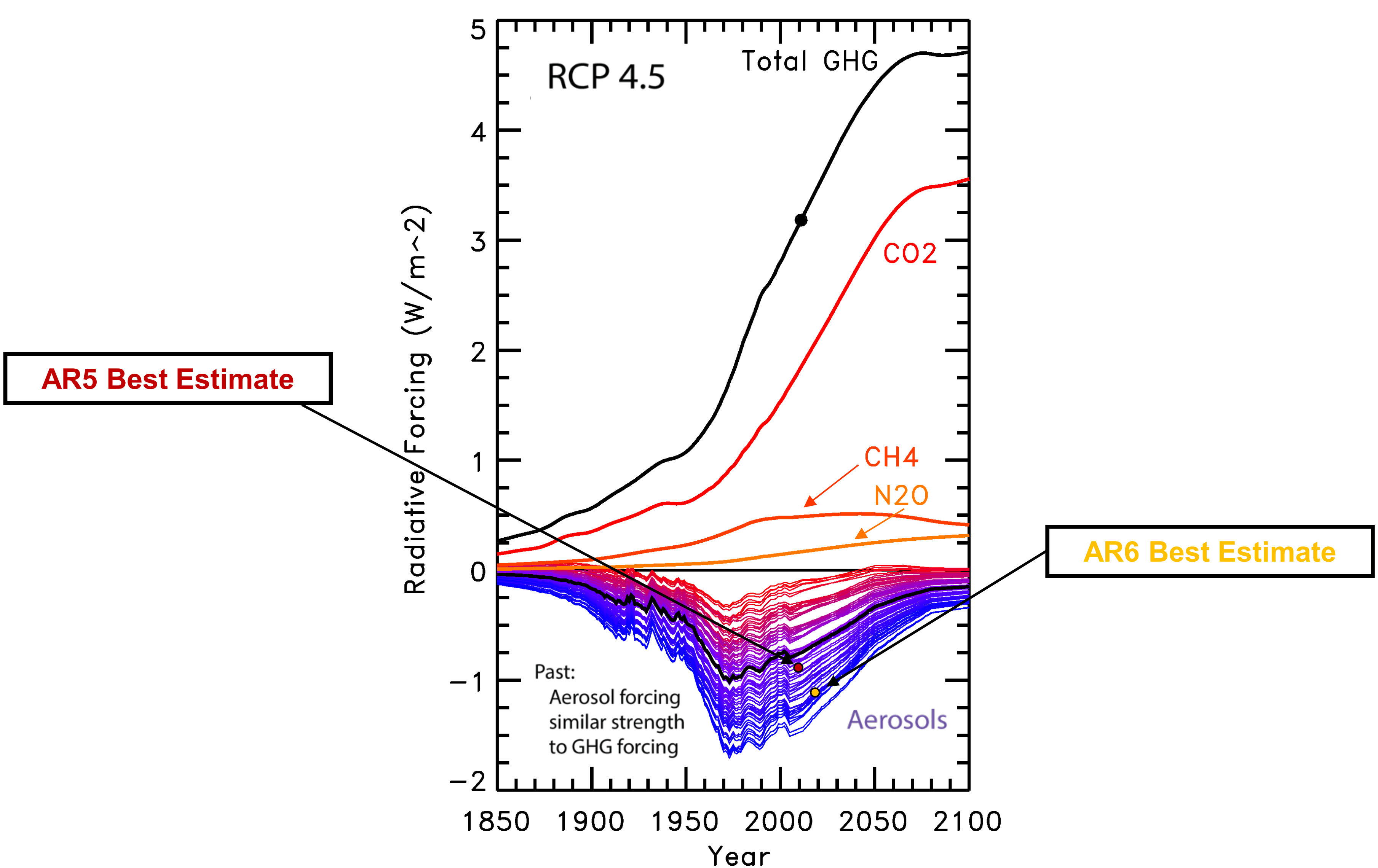
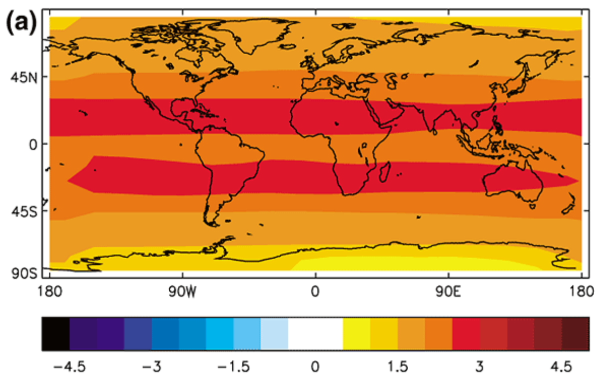


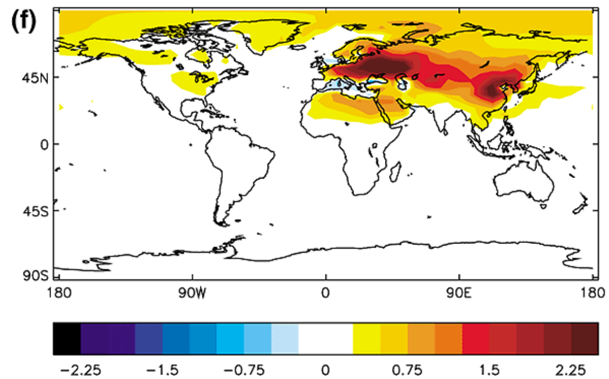
Fig 1.10, *Paris, Beacon of Hope*

Global View

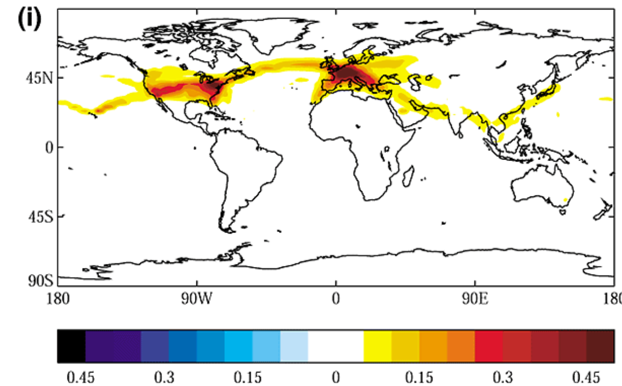
All forcings (1750-2000) are in Wm^{-2}

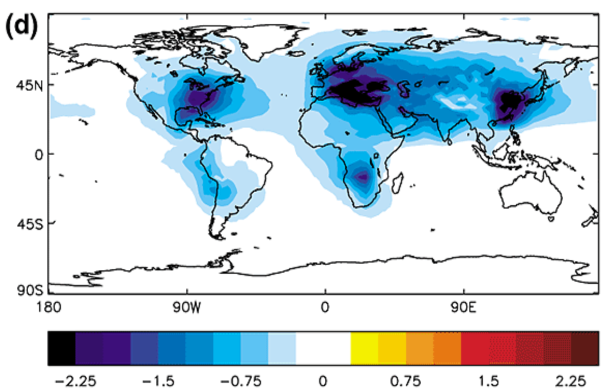


Greenhouse gases

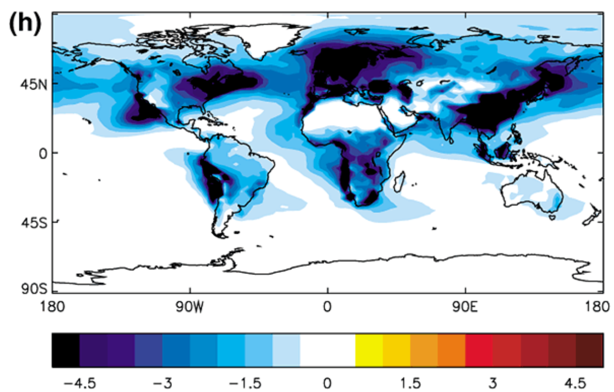


Organic and black carbon from fossil fuel burning

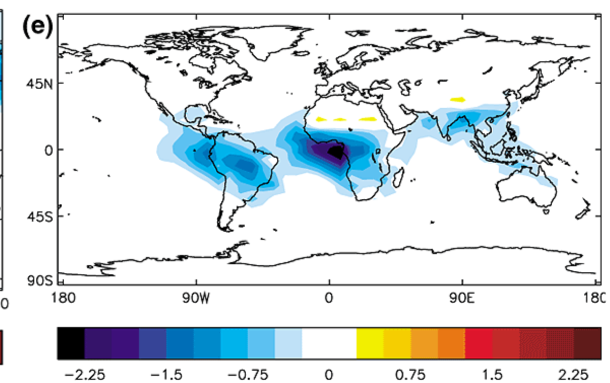




Direct effect from sulphate aerosols



Indirect effect from sulphate aerosols



Organic and black carbon from biomass burning

https://www.ipcc.ch/report/ar3/wg1/chapter-6-radiative-forcing-of-climate-change/

Black Carbon Aerosols, AR6

Chapter 6:

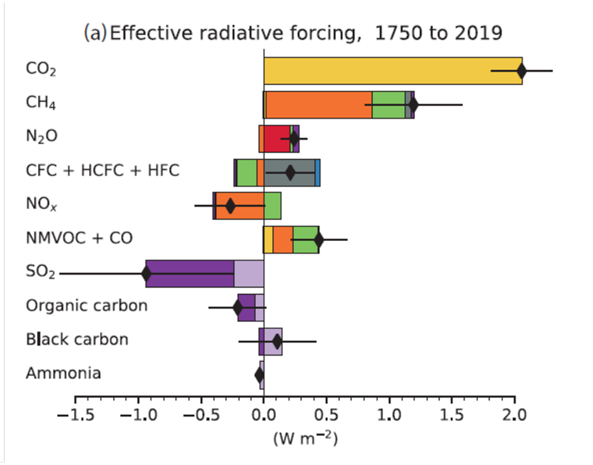


Figure 6.12 | Contribution to effective radiative forcing (ERF) (a) and global mean surface air temperature (GSA

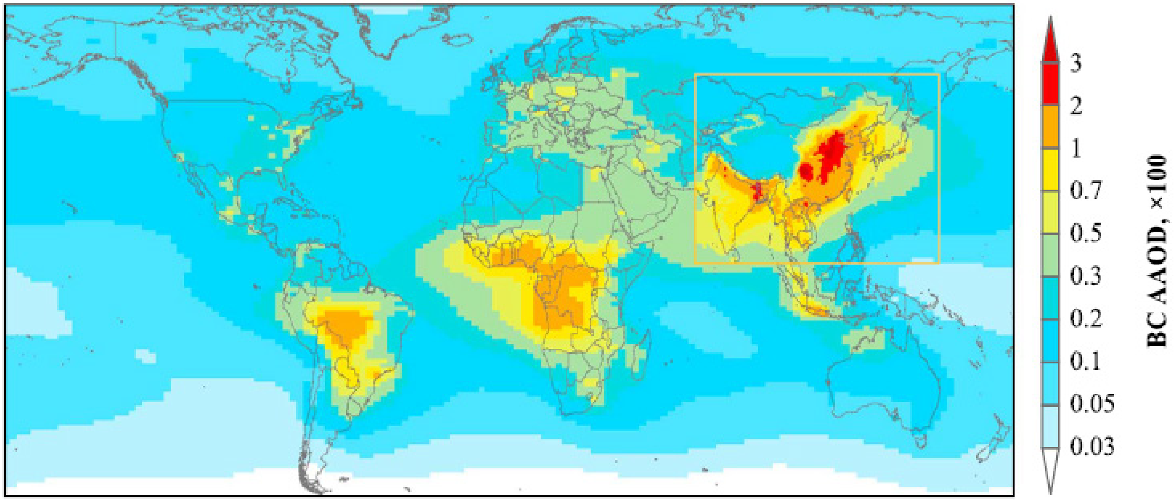
The best estimate for the ERF due to emissions of BC is reduced from the AR5, and is now estimated to be 0.11 [–0.20 to 0.42] W m^{-2} with an uncertainty also including negative values. As discussed in Section 7.3.3.1.2, a significant portion of the positive BC forcing from aerosol–radiation interactions is offset by negative atmospheric adjustments due to cloud changes, as well as lapse rate and atmospheric water vapour changes, resulting in a smaller positive net ERF for BC compared with AR5. The large range in the forcing estimate stems from variation in the magnitude and sign of atmospheric adjustments across models and is related to the differences in the model treatment of different processes affecting BC (e.g., ageing, mixing) and its interactions with clouds and cryosphere (Section 7.3.3; Thornhill et al., 2021b).

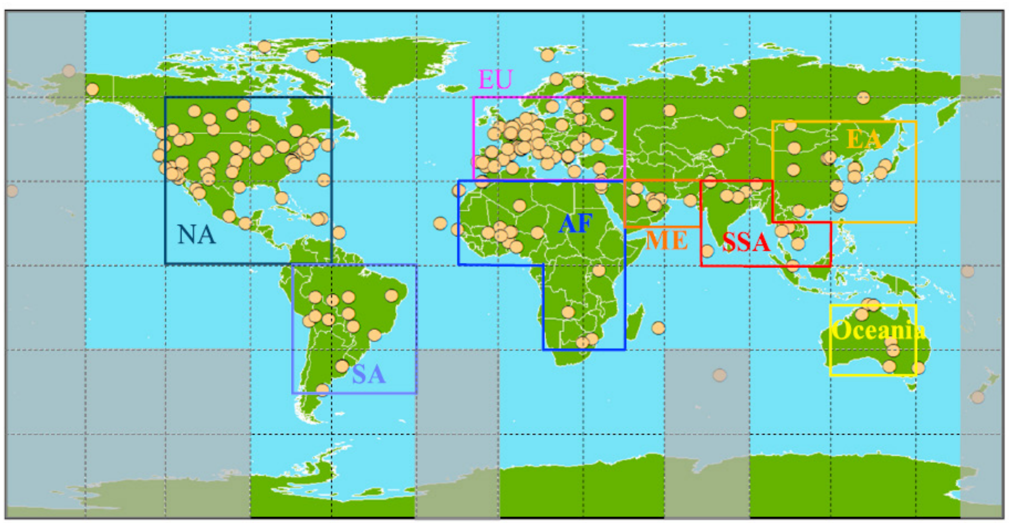
Chapter 7:

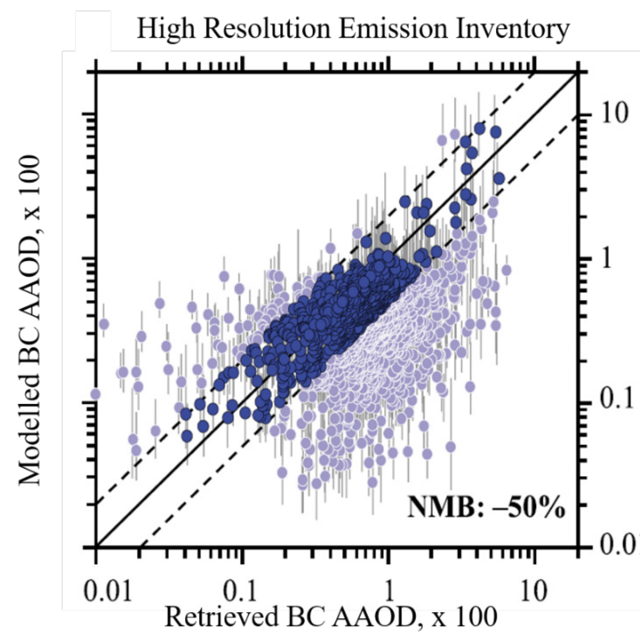
In AR5, the assessment of the black carbon (BC) contribution to IRFari was markedly strengthened in confidence by the review by Bond et al. (2013), where a key finding was a perceived model underestimate of atmospheric absorption when compared to Aeronet observations (Boucher et al., 2013). This assessment has since been revised considering: new knowledge on the effect of the temporal resolution of emissions inventories (Wang et al., 2016); the representativeness of Aeronet sites (Wang et al., 2018); issues with comparing absorption retrieval to models (E. Andrews et al., 2017); and the ageing (Peng et al., 2016), lifetime (Lund et al., 2018b) and average optical parameters (Zanatta et al., 2016) of BC.

Black Carbon Aerosols

Simulated Black Carbon Aerosol Absorption Optical Depth (AAOD) at 900 nm for year 2007







Wang et al., *JGR,* 2016

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JD024326

RF Due to Tropospheric Aerosols: Indirect Effect

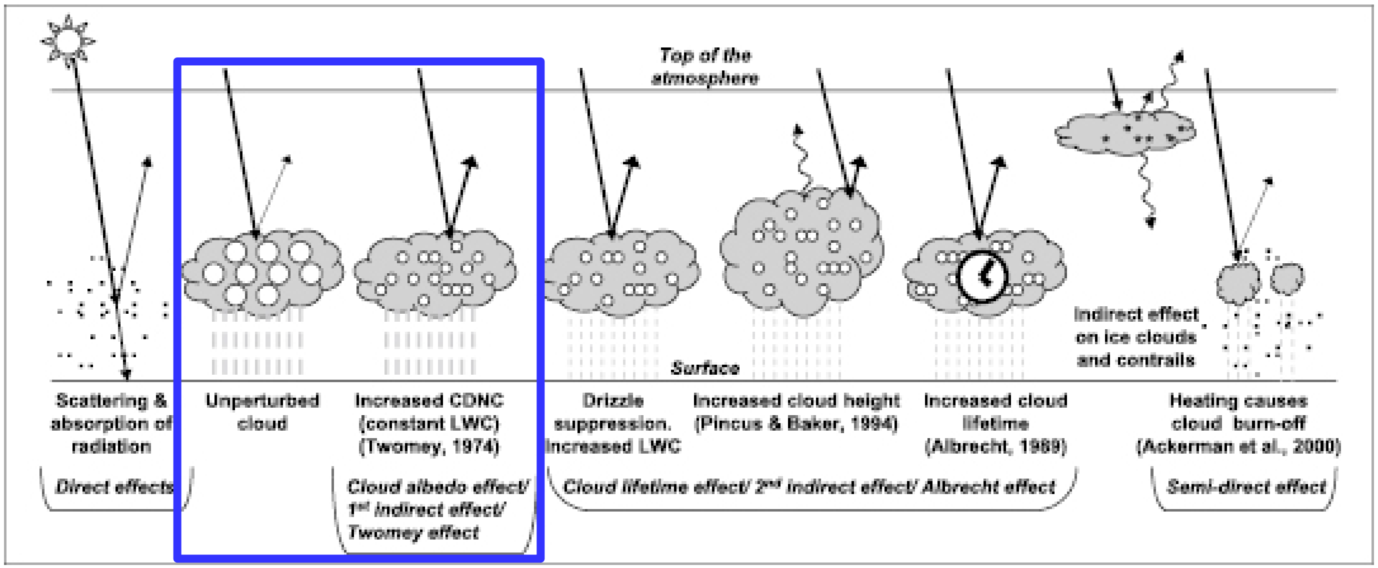
Indirect Effects of Aerosols on Clouds

Anthropogenic aerosols lead to more cloud condensation nuclei (CCN)

Resulting cloud particles consist of smaller droplets, promoted by more sites (CCN) for cloud nucleation

The cloud that is formed is therefore brighter (reflects more sunlight) ⇨

Twomey effect, aka 1st Indirect Effect



Large uncertainty in aerosol RF

Fig 2-10, IPCC 2007

- scatter and absorb radiation (**direct radiative forcing**)
- affect cloud formation (**indirect radiative forcing**)

RF Due to Tropospheric Aerosols: Indirect Effect

Indirect Effects of Aerosols on Clouds

Anthropogenic aerosols lead to more cloud condensation nuclei (CCN)

Resulting cloud particles consist of smaller droplets, promoted by more sites (CCN) for cloud nucleation

The cloud that is formed is therefore brighter (reflects more sunlight) ***and*** has less efficient precipitation, i.e. is longer lived) ⇨

Albrecht effect, aka 2nd Indirect Effect; Increased cloud height part of 2nd indirect effect

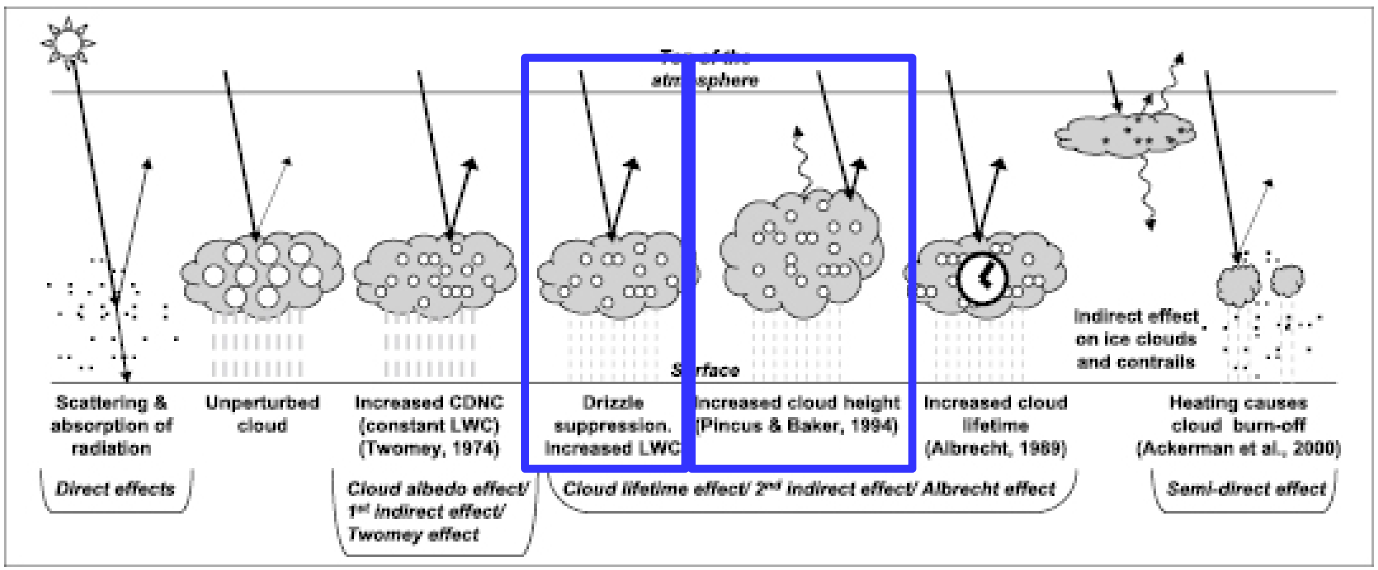


Fig 2-10, IPCC 2007

Large uncertainty in aerosol RF

- scatter and absorb radiation (**direct radiative forcing**)
- affect cloud formation (**indirect radiative forcing**)

Simple Climate Model

$$\Delta T = \underbrace{\lambda_P \ (1 + f_{H2O})}_{\lambda} \ (\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{OTHER\ GHGs} + \Delta F_{AEROSOLS})$$

where

$$\lambda_P = 0.31 \text{ K} \ / \ \text{W m}^{-2}$$

Climate models that consider water vapor feedback find:

$$\lambda \approx 0.63 \text{ K} \ / \ \text{W m}^{-2}, \text{ from which we deduce } f_{H2O} = 1.08$$

See *Lecture 4, Slide 35* (handout)

Slightly More Complicated Climate Model

$$\Delta T = \lambda_P \ (1 + f_{TOTAL}) \ (\Delta F_{CO2} + \ \Delta F_{CH4+N2O} + \Delta F_{OTHER\ GHGs} + \ \Delta F_{AEROSOLS})$$

where

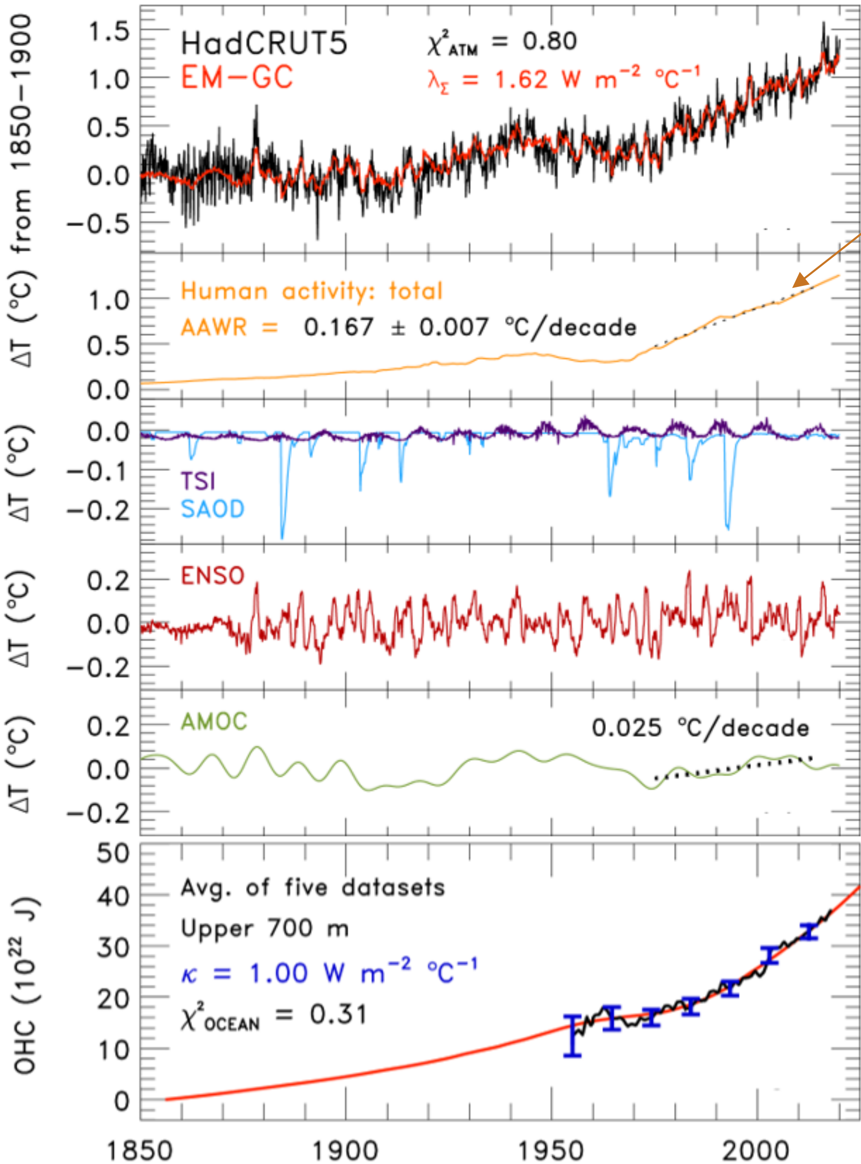
$\lambda_P = \ 0.31\ K \ / \ W\ m^{-2};$ this term is also called λ_{PLANCK}

where f_{TOTAL} is dimensionless climate sensitivty parameter that represents feedbacks,
and is related to IPCC definition of feedbacks (see Bony et al., J. Climate, 2006) via:

$$1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL}\ \lambda_P}$$

$$\text{and} \ \ FB_{TOTAL} = FB_{WATER\ VAPOR} + \ FB_{LAPSE\ RATE} + FB_{CLOUDS} + FB_{SURFACE\ ALBEDO} + \ \text{etc}$$

Each FB term has units of $W\ m^{-2}\ K^{-1}$, the recipricol of the units of λ_P.
The utility of this approach is that feedbacks can be summed to get FB_{TOTAL}.



CRU: Climate Research Unit of East Anglia, United Kingdom
EM-GC: Empirical Model of Global Climate, Univ of Maryland

$$\Delta T^{HUMAN} = \lambda_P (1 + f_{TOTAL})(\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{OTHER\ GHGs} + \Delta F_{AEROSOLS}) - OHE$$

Here, $f_{TOTAL} \approx$ **1.0**

where f_{TOTAL} is dimensionless climate sensitivty parameter that represents feedbacks,
and is related to IPCC definition of feedbacks (Bony et al., *J. Climate*, 2006) via:

$$1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL}\ \lambda_P}$$

$$\text{and}\ FB_{TOTAL} = FB_{WATER\ VAPOR} + FB_{LAPSE\ RATE} + FB_{CLOUDS} + FB_{SURFACE\ ALBEDO} + \text{etc}$$

Each FB term has units of W m^{-2} K^{-1}, the recipricol of the units of λ_P
The utility of this approach is that feedbacks can be summed to get FB_{TOTAL}

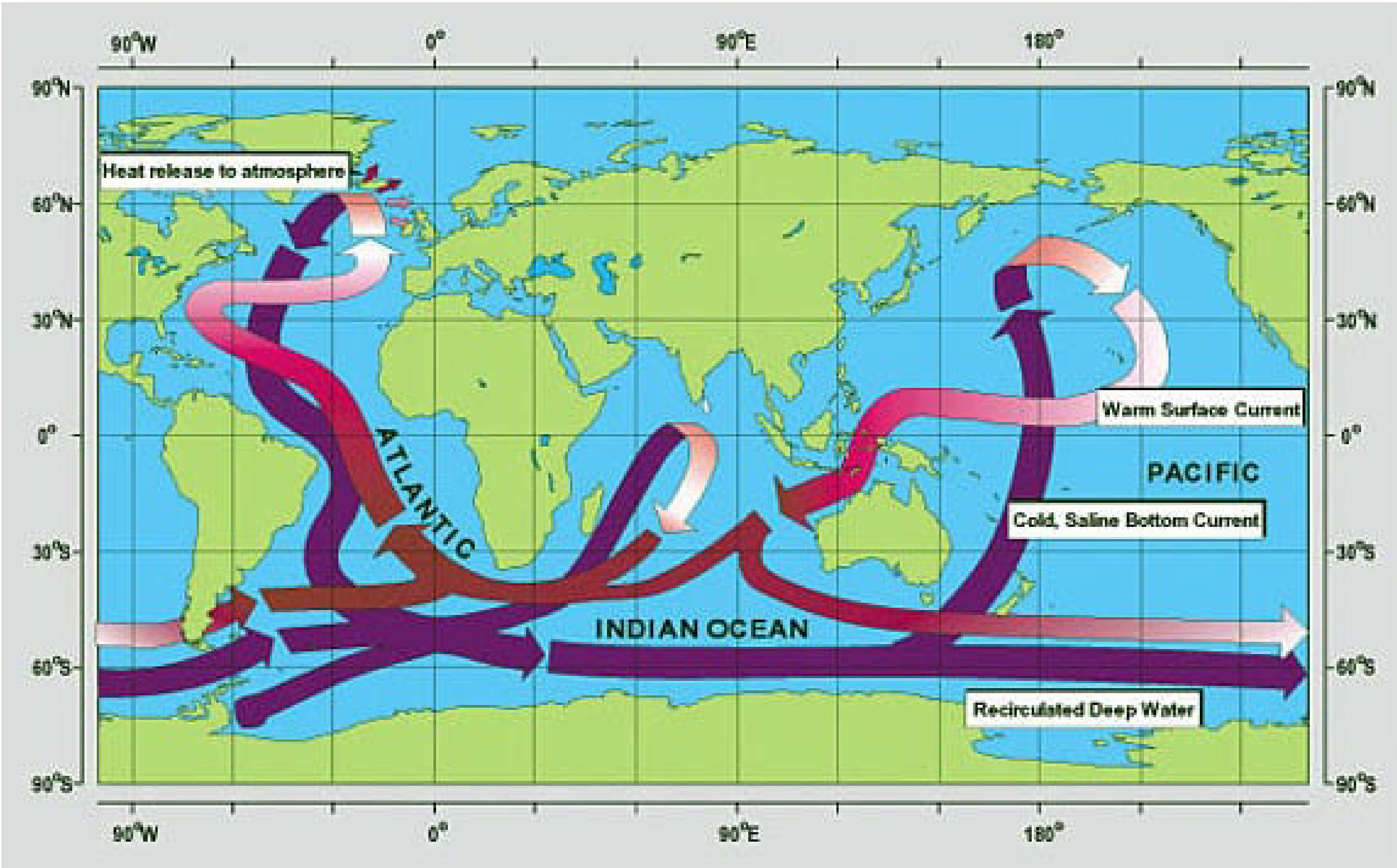
$$1 + f_{TOTAL} = \frac{1}{1 - 1.62\ \text{W m}^{-2} / \text{K} \times 0.31\ \text{K} / \text{Wm}^{-2}}$$

$$= \frac{1}{1 - 0.506} = 2.02 \approx 2$$

Similar to *Lecture 2, Slide 19* (Handout)

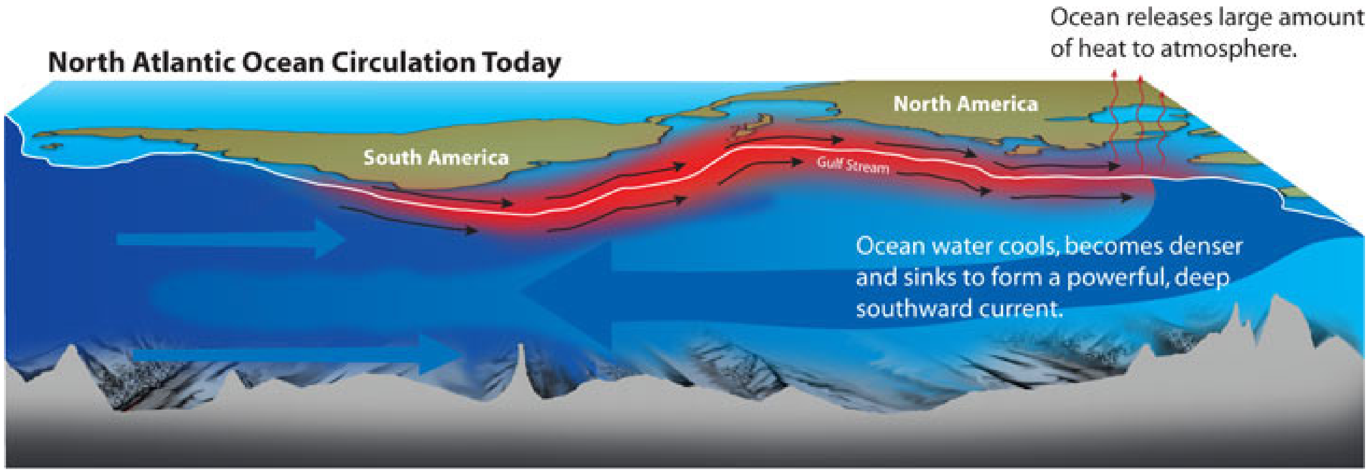
McBride *et al*., 2021: https://esd.copernicus.org/articles/12/545/2021

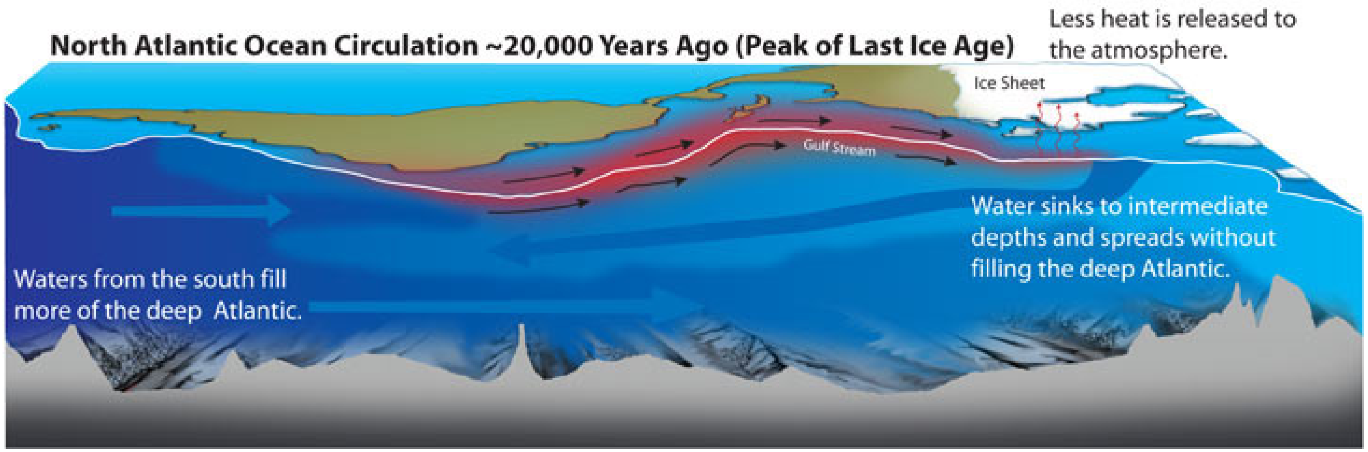
Ocean Heat Transport



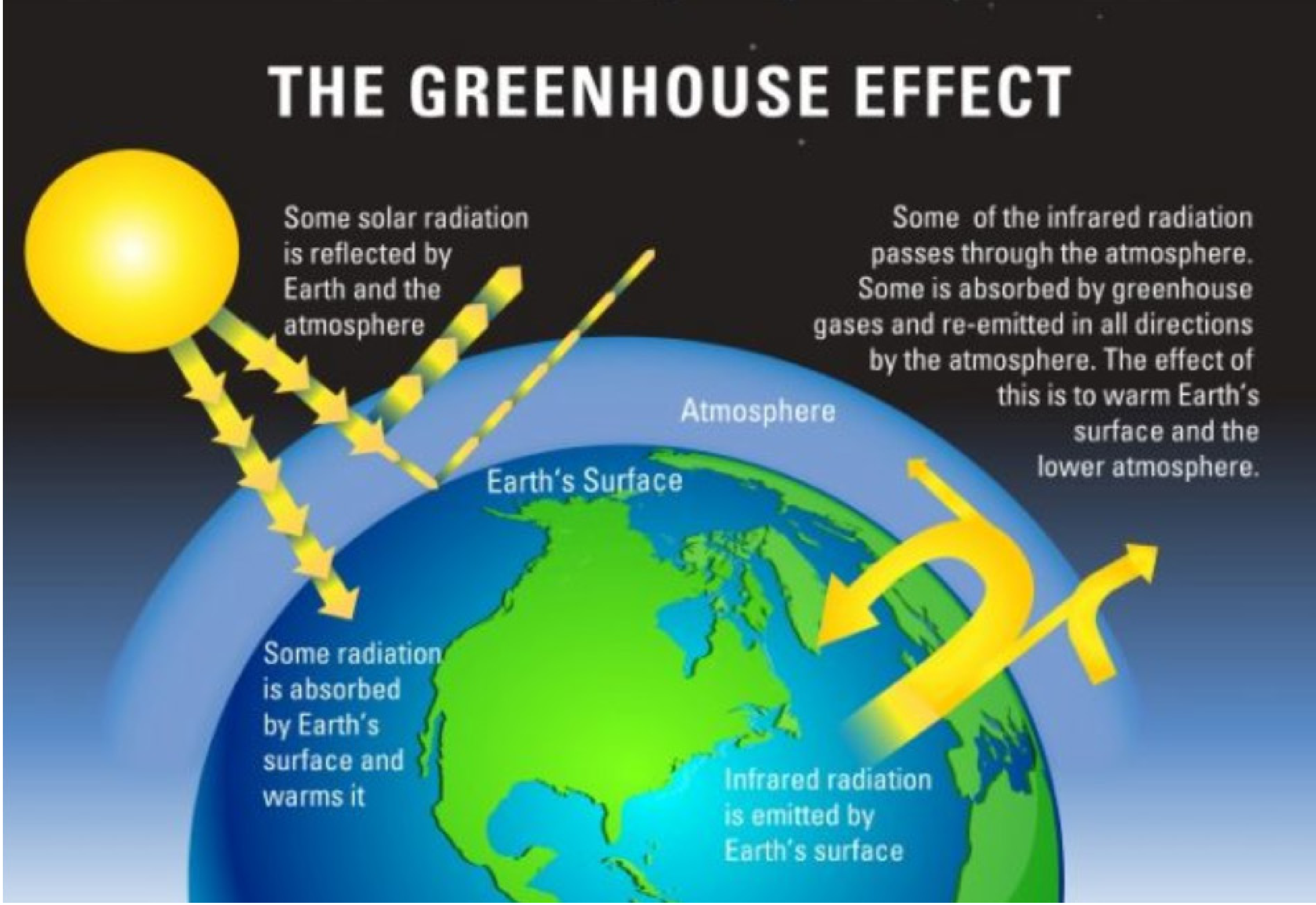
http://www.whoi.edu/oceanus/feature/the-once-and-future-circulation-of-the-ocean

Ocean Heat Transport

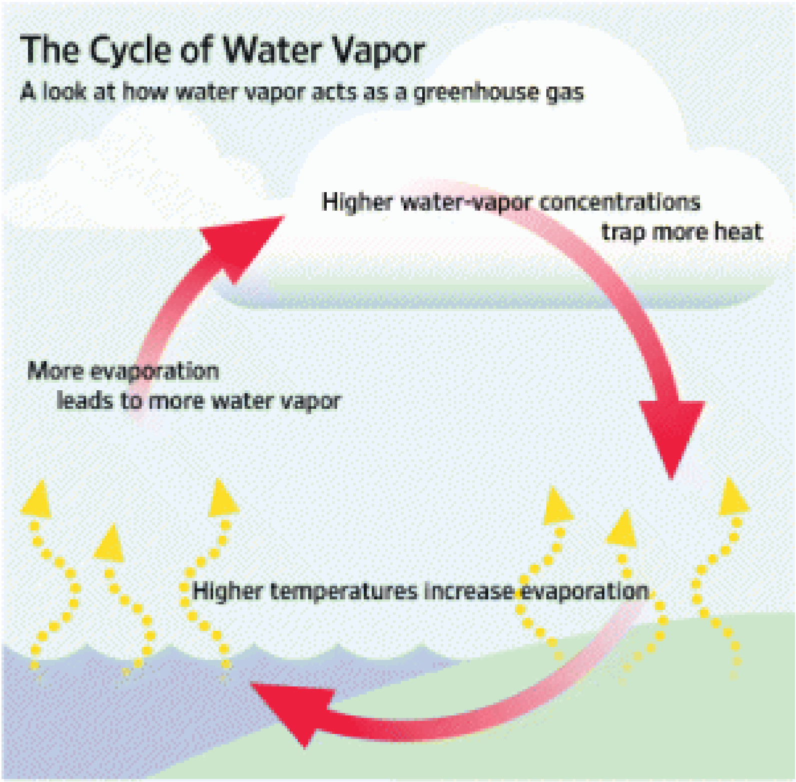


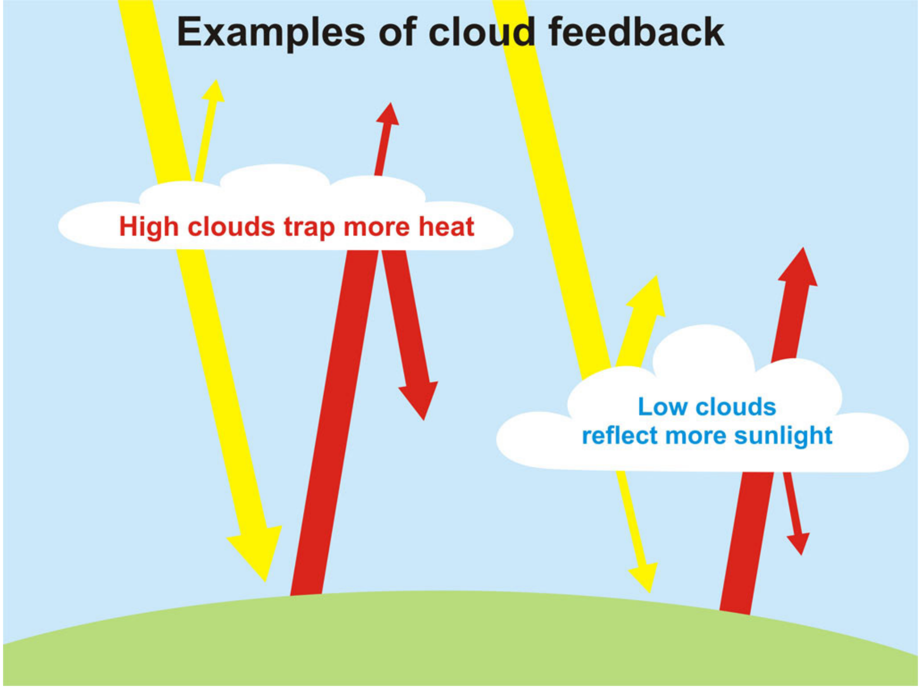


http://www.whoi.edu/oceanus/feature/the-once-and-future-circulation-of-the-ocean



https://www.environmentblog.net/what-is-the-greenhouse-effect/





https://www.environmentblog.net/what-is-the-greenhouse-effect/

AT Question

Table 5.1 Estimates of global average temperature changes under different assumptions about changes in greenhouse gases and clouds

Greenhouse gases	Clouds	Change (in °C) from current average global surface temperature of 15°C
As now	As now	0
None	As now	−32
None	None	−21
As now	None	4
As now	As now but +3% high cloud	0.3
As now	As now but +3% low cloud	−1.0
Doubled CO_2 concentration otherwise as now	As now (no additional cloud feedback)	1.2
Doubled CO_2 concentration + best estimate of feedbacks	Cloud feedback included	3

3 / 1.2 = 2.5

Ice-Albedo Feedback

Initial Action:
Humans Release CO_2

Initial Response:
$T_{SURFACE}$ Rises

Then:
Ice Melts

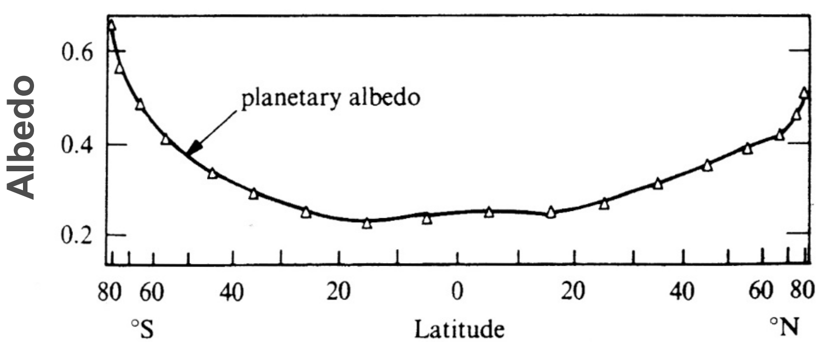
Consequence:
Albedo Falls

Feedback:
⇨ Effect of falling Albedo on $T_{SURFACE}$

2. Albedos of selected surfaces on Earth

surface	albedo
snow	0.7 ± 0.2
sand	0.25 ± 0.05
grasslands	0.23 ± 0.03
bare soil	0.2 ± 0.05
forest	0.15 ± 0.1
water (highly dependent on surface roughness and incident angle of sunlight)	0.2 + 0.6 − 0.2

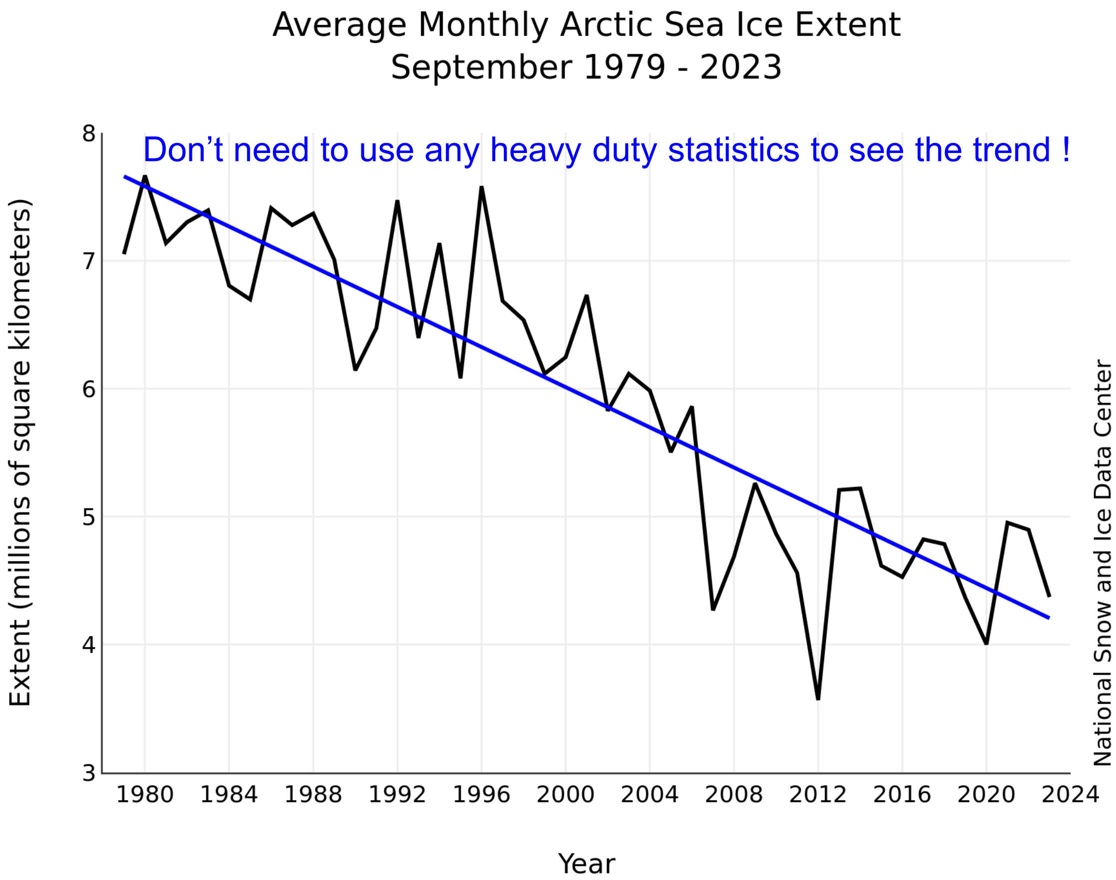
Harte, *Consider a Spherical Cow: A Course in Environmental Problem Solving*, 1988.



Houghton, *The Physics of Atmospheres*, 1991.

Arctic Sea-Ice: Canary of Climate Change

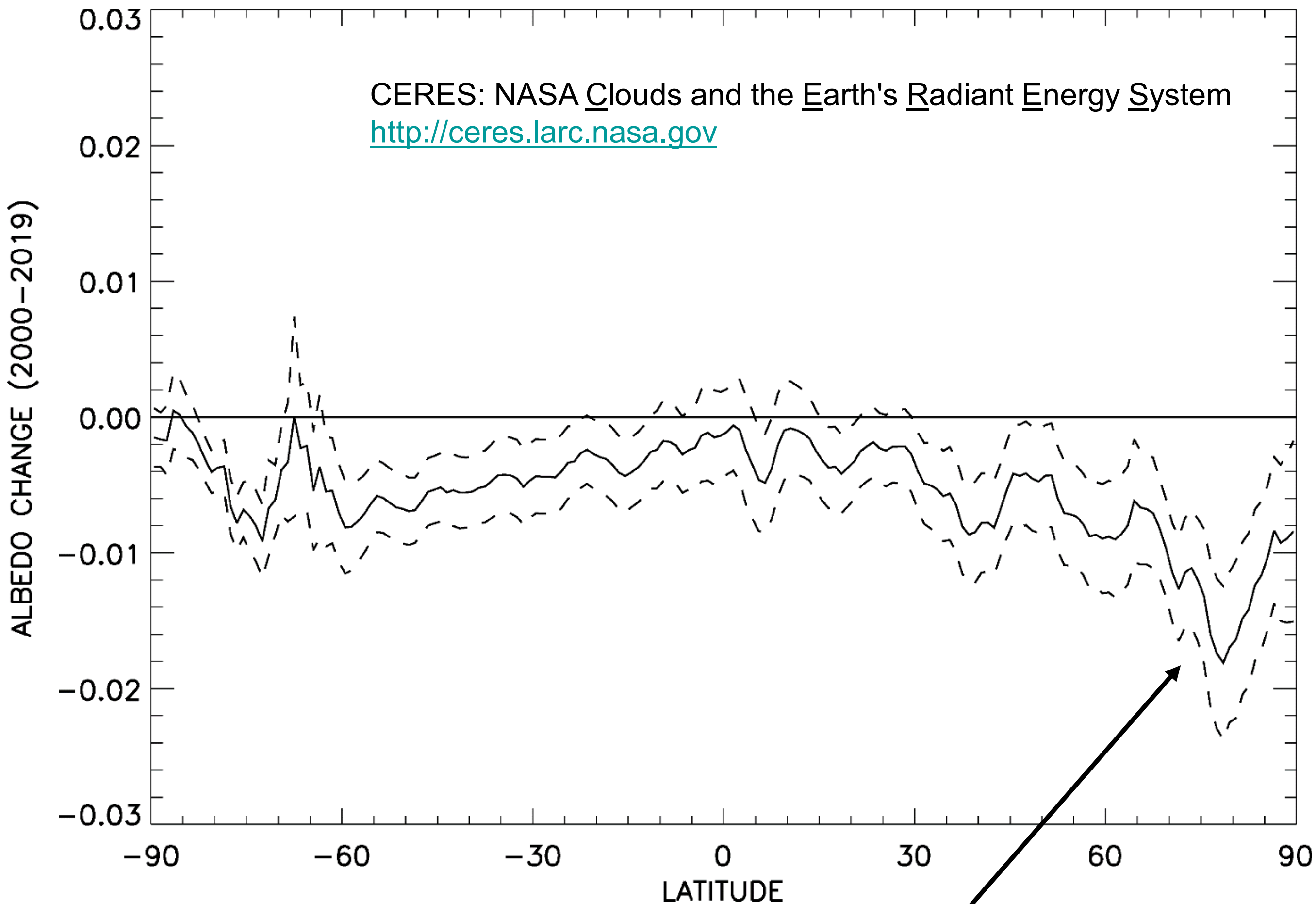
Lecture 2, Slide 29 **(handout)**



- Sea ice: ice overlying ocean
- Annual minimum occurs each September
- Decline of ~12.2% / decade over satellite era

http://nsidc.org/arcticseaicenews/2023/10
as archived at http://web.archive.org/web/20240702095340/https://nsidc.org/arcticseaicenews/2023/10/

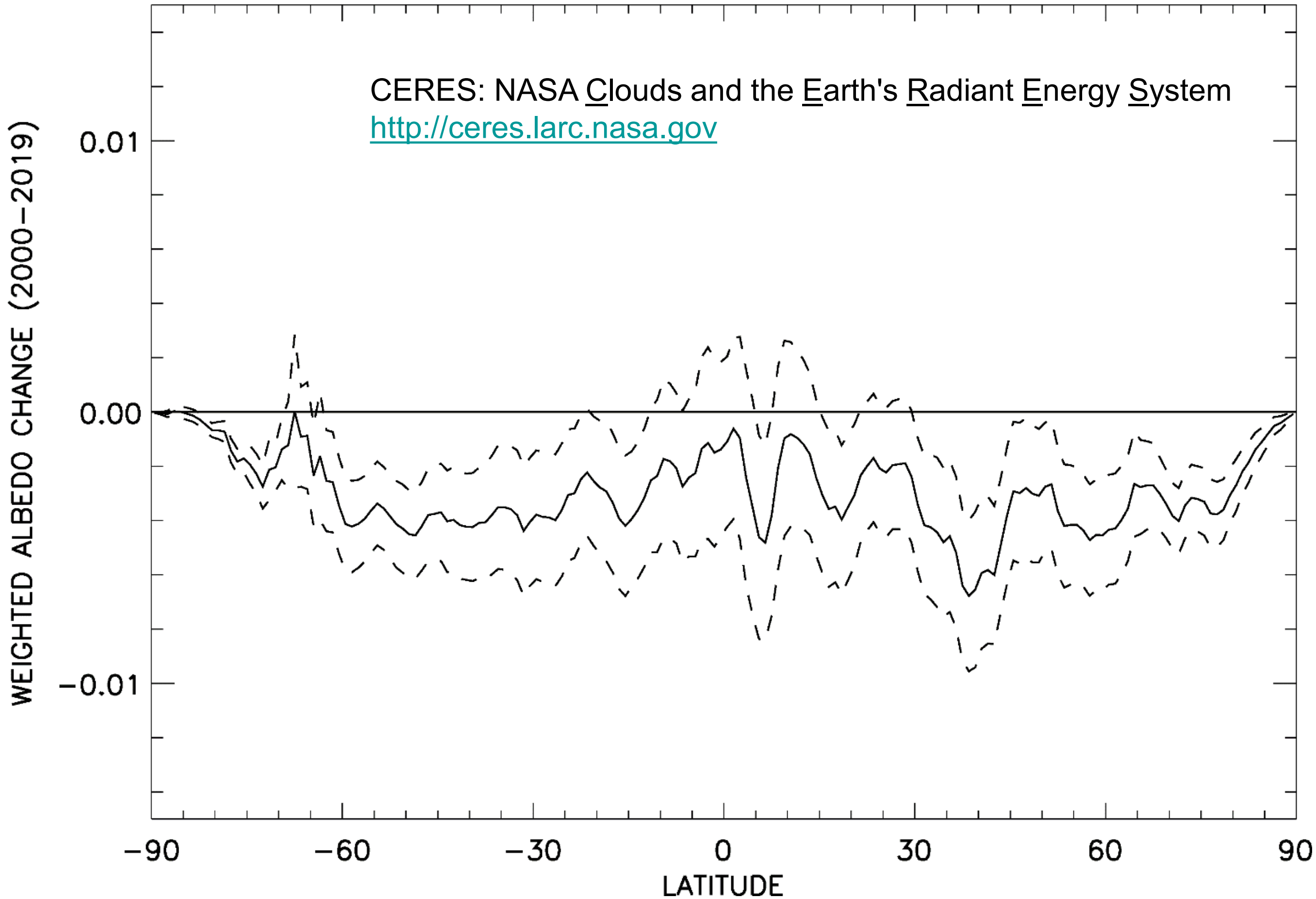
Albedo Anomaly (CERES) Change versus Latitude, No Weighting



NH high latitude darkening (melting sea ice) is apparent

Slide courtesy Laura McBride; analysis to the end of 2019

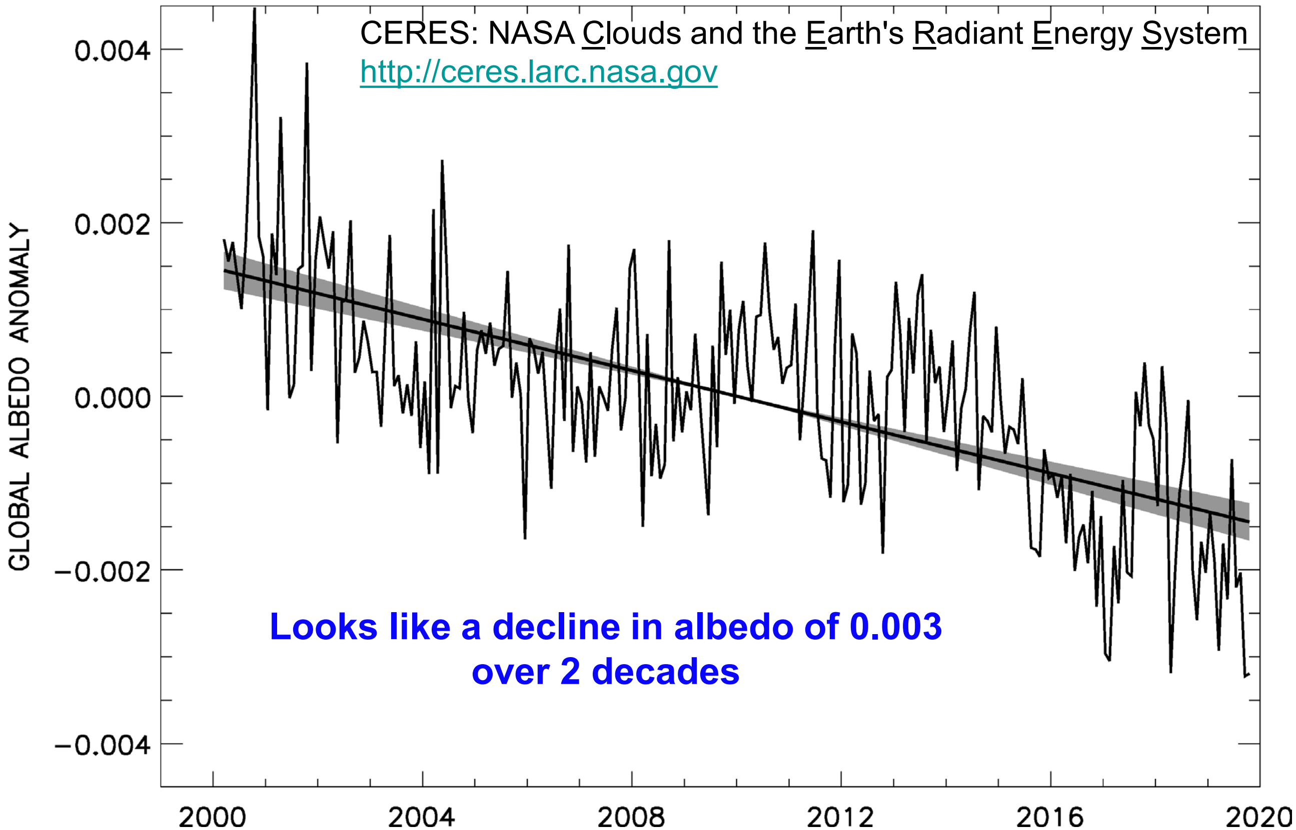
Albedo Anomaly (CERES) Change versus Latitude, *Weighted by Cosine Latitude*



NH high latitude darkening hard to distinguish
due to apparent, near global, slight darkening.

Slide courtesy Laura McBride; analysis to the end of 2019

Trend in CERES Albedo Anomaly, *Weighted by Cosine Latitude*



Slide courtesy Laura McBride; analysis to the end of 2019

Implications of CERES Albedo Anomaly

Albedo Anomaly (CERES) Change versus Latitude, *Weighted by Cosine Latitude*

$$T_{EFF} = \left\{ (1-0.29) \times \frac{1370\ \mathrm{W\ m^{-2}}}{4} \times \frac{1}{5.67\times10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}} \right\}^{1/4} = 255.91\ \mathrm{K}$$

where 5.67×10^{-8} W m^{-2} K^{-4} is the Stefan-Boltzmann constant,
1370 W m^{-2} is the "solar constant" at 1 AU
and the 4 appears due to fact Earth absorbs sunlight like a disk
and radiates thermal energy like a sphere

$$T_{EFF} = \left\{ (1-0.287) \times \frac{1370\ \mathrm{W\ m^{-2}}}{4} \times \frac{1}{5.67\times10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}} \right\}^{1/4} = 256.18\ \mathrm{K}$$

If Earth's albedo truly decline by about 0.003 over 2 decades
this would have driven a rise in Earth's effective temperature
of 0.135 K per decade, which is ***an enormous effect***.

The uniformity of the CERES decline in albedo versus latitude
leads to an ***obvious skepticism over the validity of the measured trend***
because it is unclear why Earth would become uniformly darker at all latitudes.

Skepticism about CERES Calibration

Geophysical Research Letters

Research Letter | Open Access

NASA CERES Spurious Calibration Drifts Corrected by Lunar Scans to Show the Sun Is not Increasing Global Warming and Allow Immediate CRF Detection

Grant Matthews

First published: 21 July 2021 | https://doi.org/10.1029/2021GL092994

Plain Language Summary

In contrast to NASA Clouds and the Earth's Radiant Energy System results, this paper shows that the Earth reflectivity has not changed since the year 2000, by comparing the sunlight bouncing off it to that from the Moon. Disagreeing with NASA, this provides physical evidence that global warming is not being increased by the Sun. It also immediately brings data to the standard requested by the climate community for cloud forcing/feedback signal detection. The Moon and Earth Radiation Budget Experiment data is being staged for free on the FAIR compliant website Pangaea for climate scientists.

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021GL092994

Skepticism about CERES Calibration

Understanding the trends in reflected solar radiation: a latitude- and month-based perspective

Ruixue Li, Bida Jian, Jiming Li, Deyu Wen, Lijie Zhang, Yang Wang, and Yuan Wang

Student answer, Problem Set 1

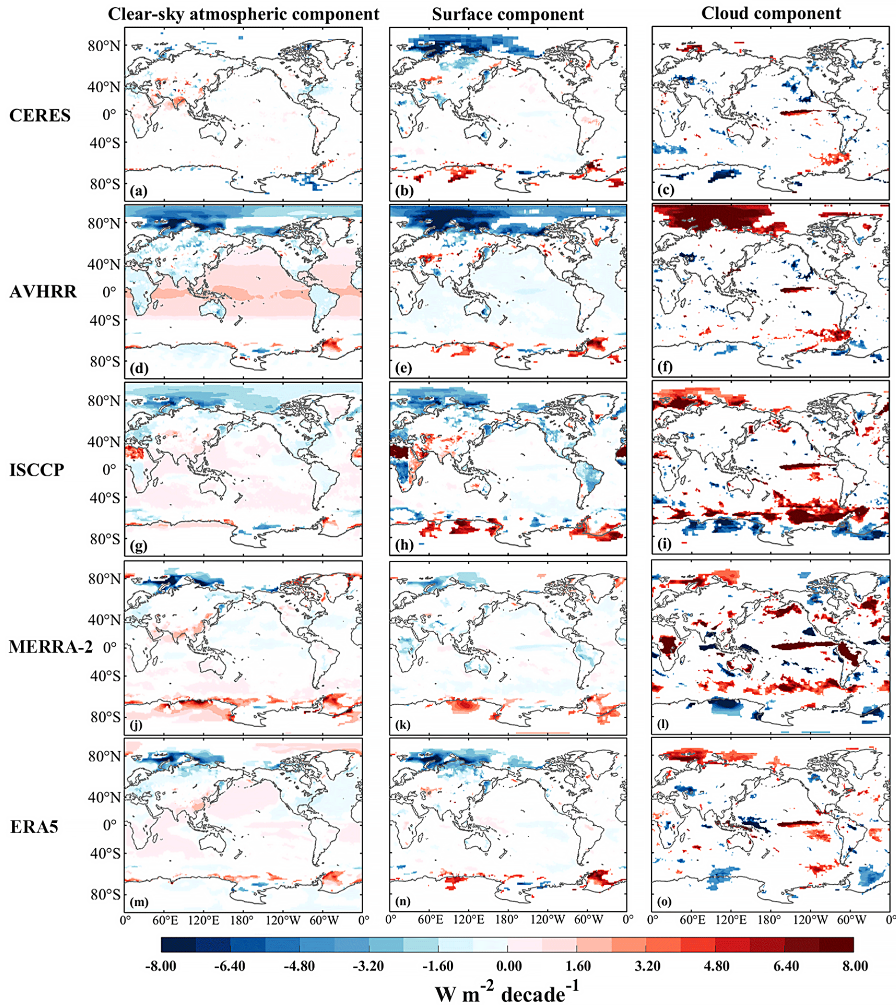


Figure 8 Trends in the TOA RSR flux of the clear-sky atmospheric component (left column), surface component (center column), and cloud component (right column) for March 2001–February 2016. **(a–c)** CERES, **(d–f)** AVHRR, **(g–i)** ISCCP, **(j–l)** MERRA-2, and **(m–o)** ERA5.

https://acp.copernicus.org/articles/24/9777/2024/

Water Vapor Feedback

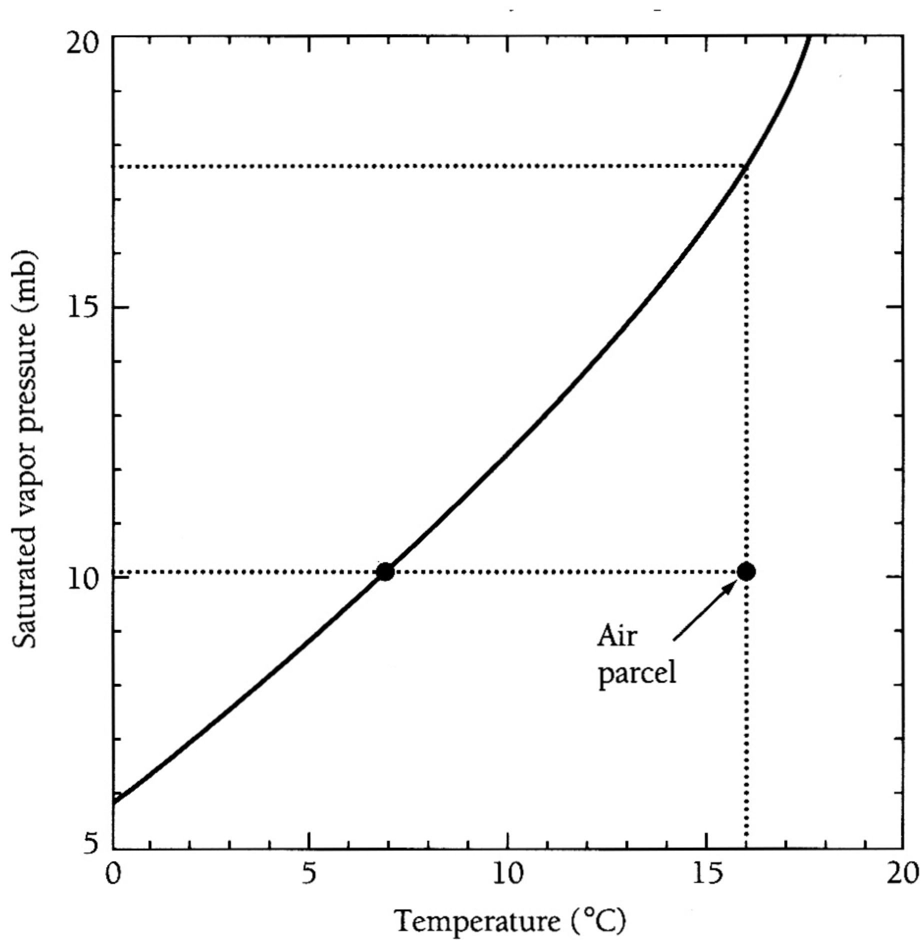


Figure 4.8a Relative humidity and the dew point.

McElroy, *Atmospheric Environment*, 2002

Clausius-Clapeyron relation describes the temperature dependence of the ***saturation vapor pressure of water.***

Water Vapor Feedback

Extensive literature on water vapor feedback:

- Soden *et al.* (*Science*, 2002) analyzed global measurements of H_2O obtained with a broadband radiometer (TOVS) and concluded the atmosphere generally obeys fixed relative humidity: **strong positive** feedback
  - ⇨data have extensive temporal and spatial coverage but limited vertical resolution.
- Minschwaner *et al*. (*JGR*, 2006) analyzed global measurements of H_2O obtained with a solar occultation filter radiometer (HALOE) and concluded water rises as temperature increases, but at a rate somewhat less than given by fixed relative humidity: **moderate positive** feedback
  - ⇨data have high vertical resol., good temporal coverage, but limited spatial coverage
- Su *et al*. (*GRL,* 2006) analyzed global measurements of H2O obtained by a microwave limb sounder (MLS) and conclude enhanced convection over warm ocean waters deposits more cloud ice, that evaporates and enhances the thermodynamic effect: **strong positive** feedback
  - ⇨data have extensive temporal/spatial coverage & high vertical resol in upper trop
- No *observational evidence* for **negative** water vapor feedback, despite the very provocative (and very important at the time!) work of Linzden (BAMS, 1990) that suggested the water vapor feedback could be **negative**

Lapse Rate Feedback

The vertical variations of the temperature change also have a climatic effect through the lapse-rate feedback λ_L. For instance, the models predict enhanced warming in the upper troposphere of tropical regions in response to an increase in the concentration of greenhouse gases. Because of this change in the lapse rate, the outgoing longwave radiation will be more than in an homogenous temperature change over the vertical. The system will then lose more energy, so inducing a negative feedback (Fig. 4.10). Moreover, at mid to high latitudes, a larger low level warming is projected as a response to the positive radiative warming, providing a positive feedback (Fig. 4.10). The global mean value of λ_L thus depends on the relative magnitude of those two opposite effects. On average, the influence of the tropics dominates, leading to a value of λ_L of around -0.8 $Wm^{-2}K^{-1}$ (Soden and Held, 2006) in recent models driven by a doubling of the CO_2 concentration in the atmosphere.

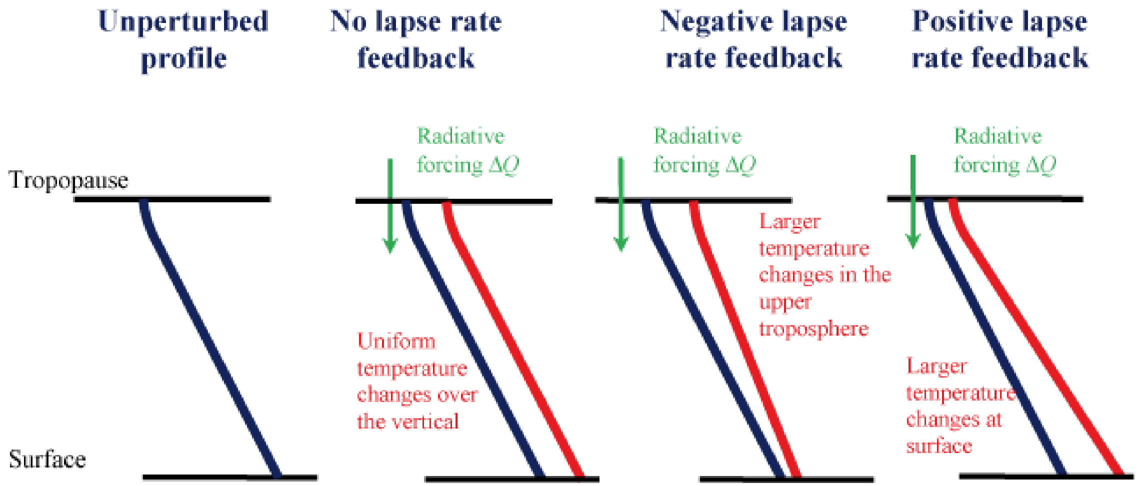


Figure 4.10: Schematic representation of positive and negative lapse-rate feedbacks.

However, as the effects of the two feedbacks discussed in this sub-section tend to compensate each other, the uncertainty in the sum $\lambda_L + \lambda_W$ is smaller than in the feedbacks individually. This uncertainty is estimated at about 0.1 $Wm^{-2}K^{-1}$, the standard deviation of the values provided by the different models presented in the 4th IPCC assessment report (Randall et al., 2007).

http://www.climate.be/textbook/chapter4_node7.html

Radiative Forcing of Clouds

Cloud : water (liquid or solid) particles at least 10 μm effective diameter

Radiative forcing involves absorption, scattering, and emission

- **Calculations are complicated and beyond the scope of this class**
- **However, general pictorial view is very straightforward to describe**

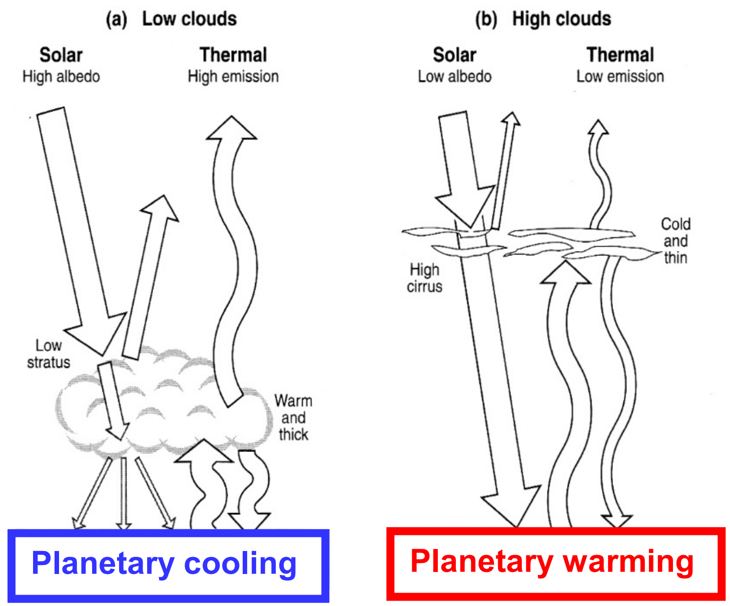


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The solar components are shown as straight arrows, and the infrared components, as curved arrows. The relative thicknesses of the arrows indicate the relative radiation intensities. The expected impact on surface temperature in each situation is noted along the bottom strip.

Turco, *Earth Under Siege: From Air Pollution to Global Change,* 1997.

Radiative Forcing of Clouds: Observation A

A Determination of the Cloud Feedback from Climate Variations over the Past Decade

A. E. Dessler

Estimates of Earth's climate sensitivity are uncertain, largely because of uncertainty in the long-term cloud feedback. I estimated the magnitude of the cloud feedback in response to short-term climate variations by analyzing the top-of-atmosphere radiation budget from March 2000 to February 2010. Over this period, the short-term cloud feedback had a magnitude of 0.54 ± 0.74 (2σ) watts per square meter per kelvin, meaning that it is likely positive. A small negative feedback is possible, but one large enough to cancel the climate's positive feedbacks is not supported by these observations. Both long- and short-wave components of short-term cloud feedback are also likely positive. Calculations of short-term cloud feedback in climate models yield a similar feedback. I find no correlation in the models between the short- and long-term cloud feedbacks.

Dessler, *Science, 2010*

The Dessler Cloud Feedback Paper in Science: A Step Backward for Climate Research

December 9th, 2010 by Roy W. Spencer, Ph. D.

https://www.drroyspencer.com/2010/12/the-dessler-cloud-feedback-paper-in-science-a-step-backward-for-climate-research
https://www.drroyspencer.com/wp-content/uploads/Spencer-Braswell-JGR-2010.pdf
https://www.realclimate.org/index.php/archives/2010/12/feedback-on-cloud-feedback

Radiative Forcing of Clouds: Observation B

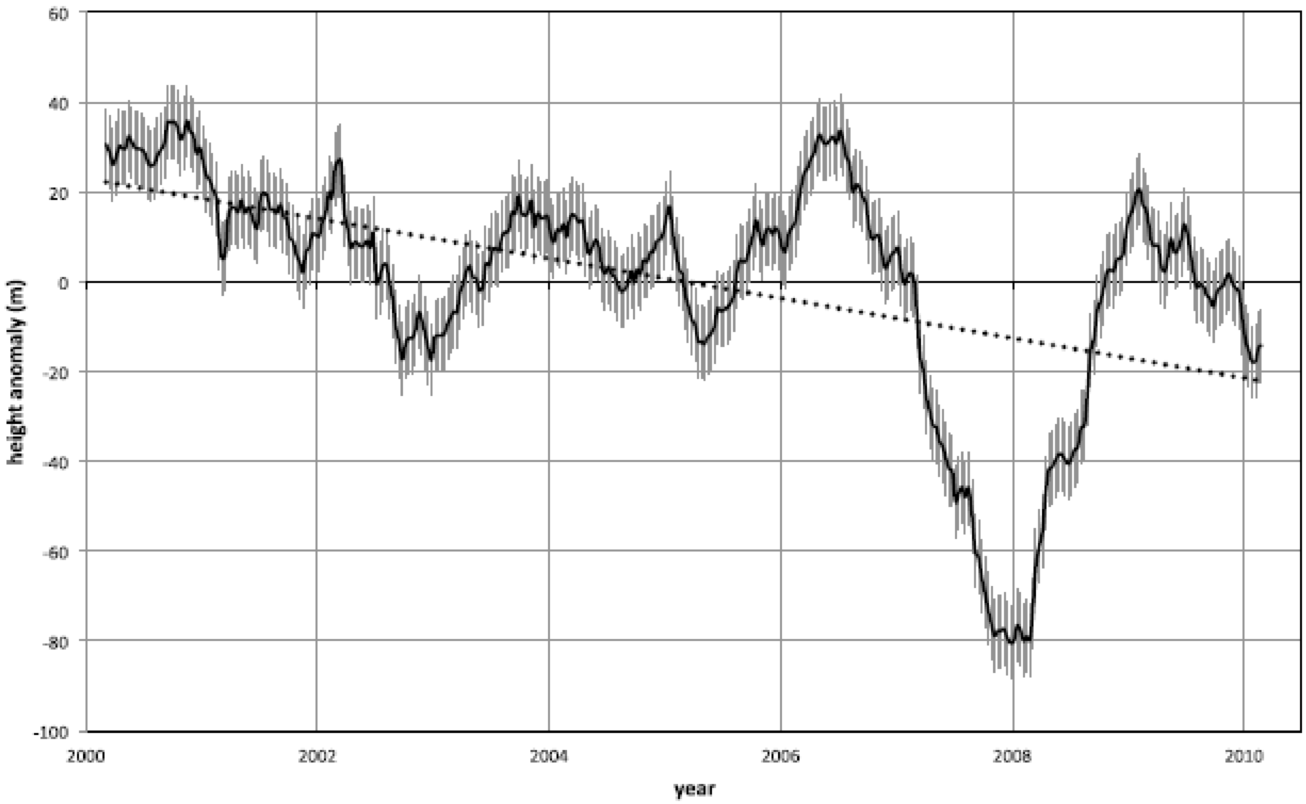


Figure 1. Deseasonalized anomalies of global effective cloud-top height from the 10-year mean. Solid line: 12-month running mean of 10-day anomalies. Dotted line: linear regression. Gray error bars indicate the sampling error (±8 m) in the annual average.

Davies and Molloy, GRL, 2012
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2011GL050506

If cloud height drops in response to rising T, this constitutes a negative feedback to global warming

Radiative Forcing of Clouds: Observation C

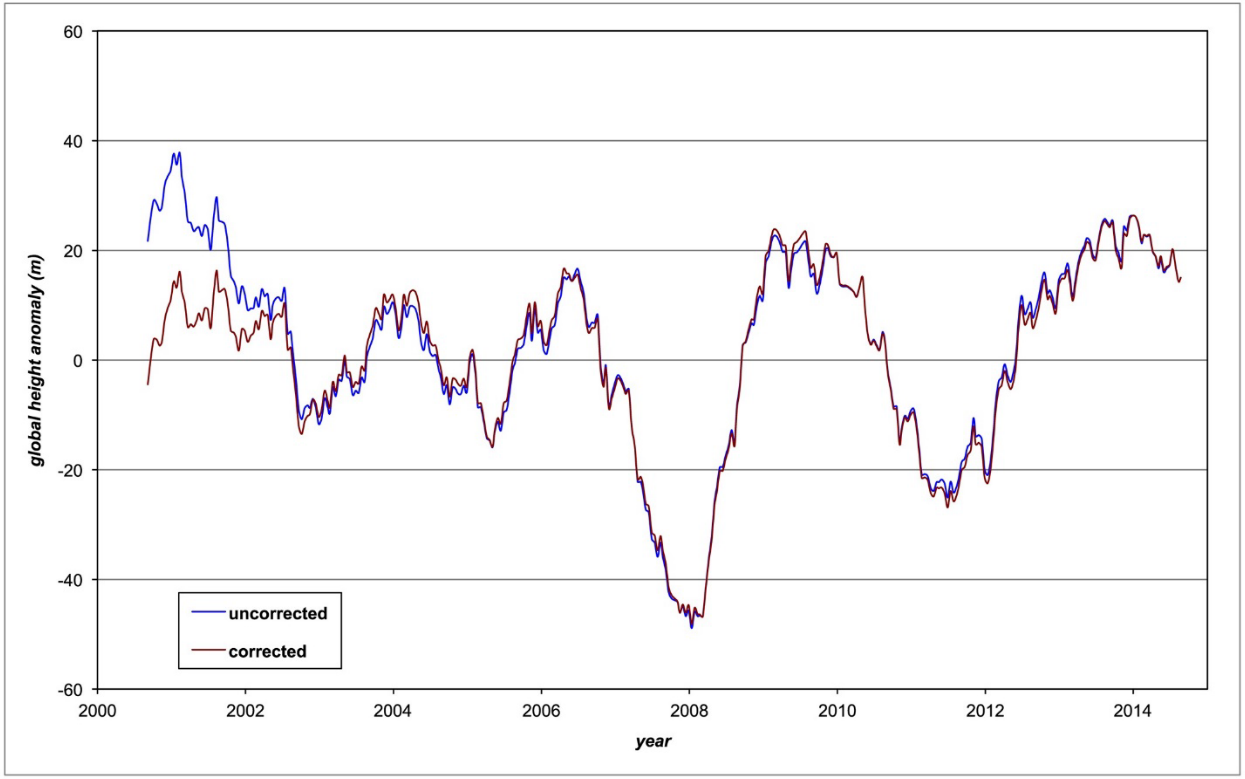
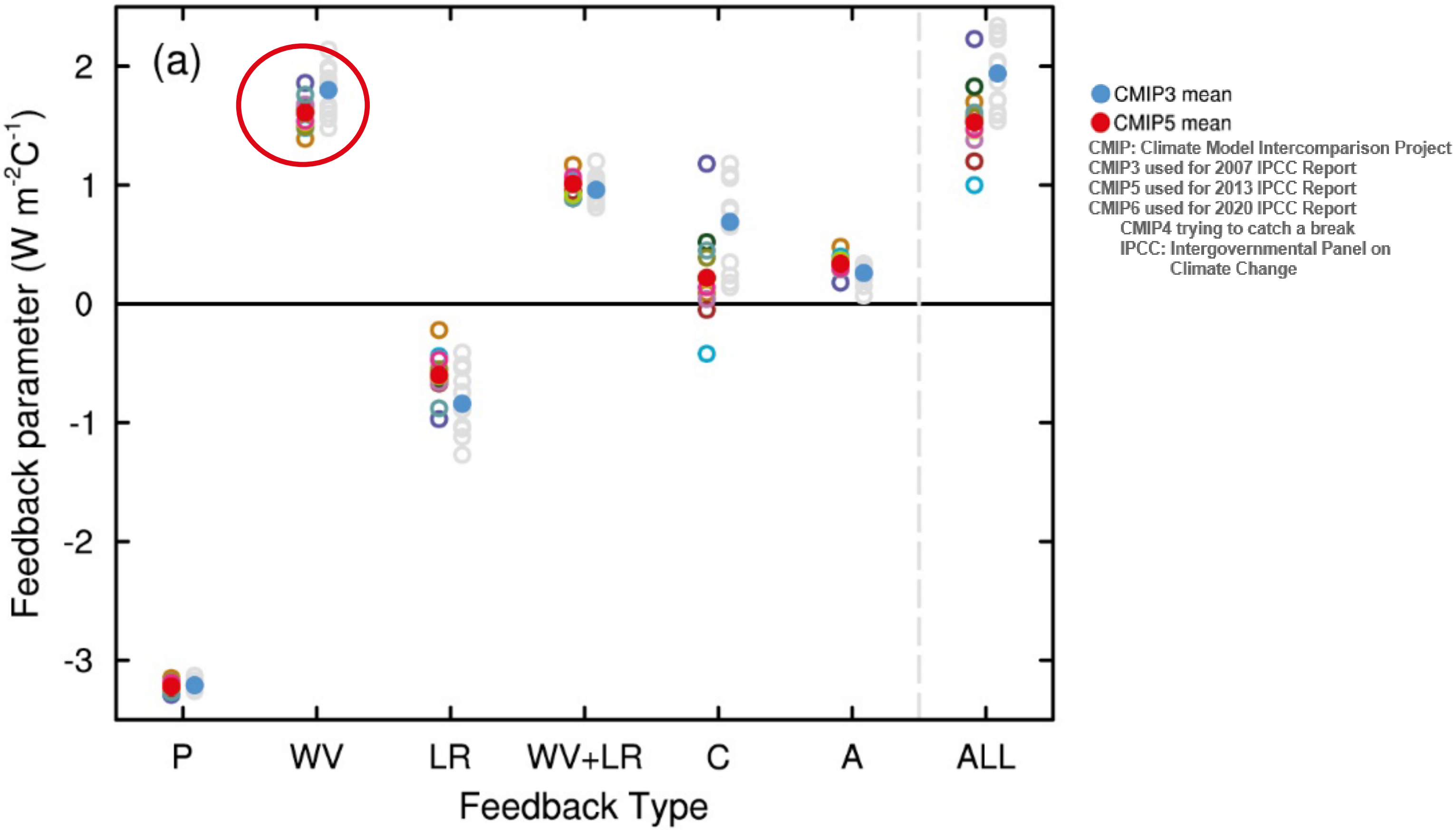


Figure 5. The 15-year time series of global height anomalies from March 2000 to February 2015. Corrected for shift in glitter pattern (brown), and uncorrected (blue). Data have been smoothed by a 12 month running mean.

Davies *et al.*, *JGR*, 2017
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017JD026456

Correction for orbital drift early in the mission reveals no trend in cloud height, but strong ENSO signature

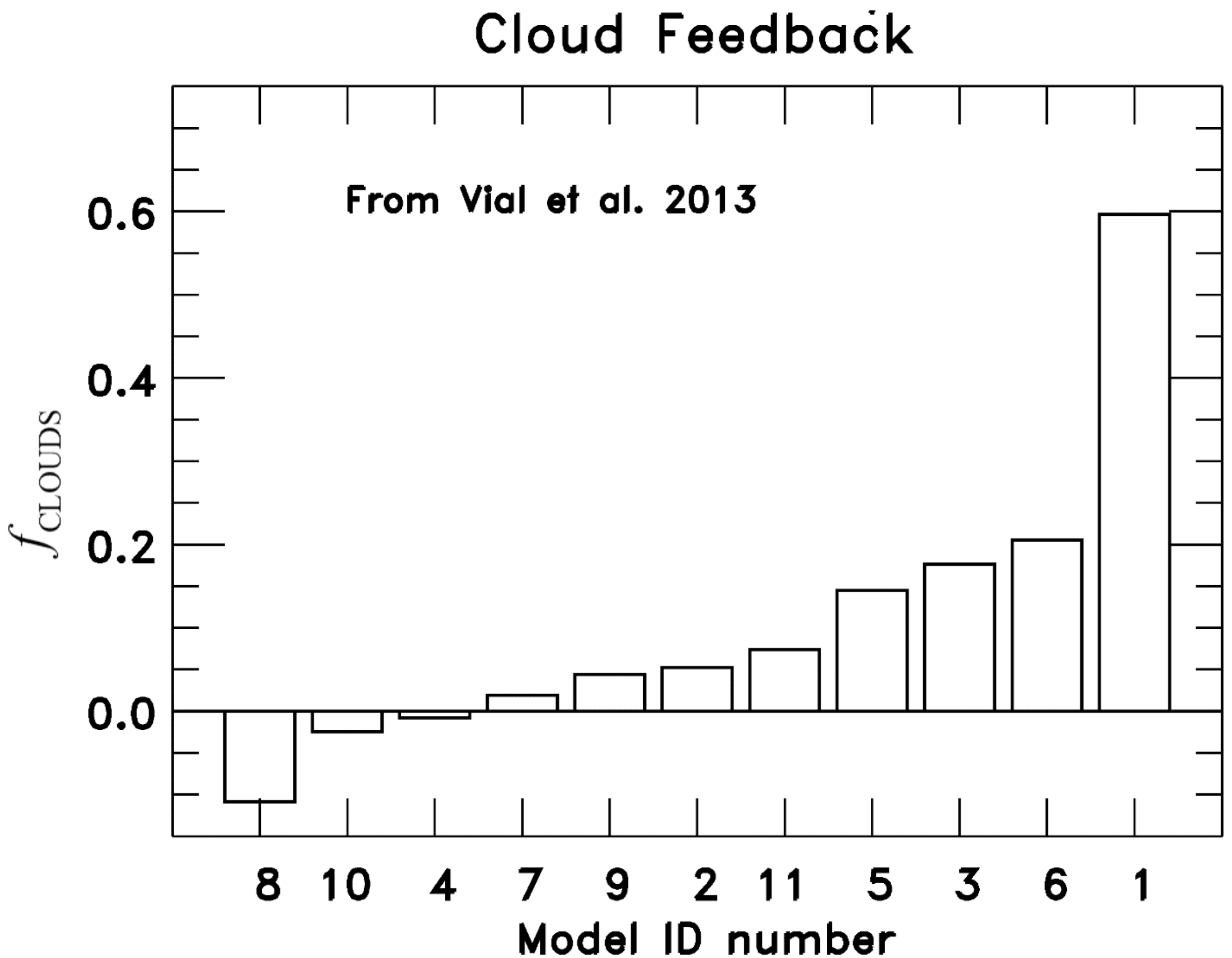


If $\mathrm{FB}_{\mathrm{WV}} = 1.6\ \mathrm{W\ m^{-2}\ K^{-1}}$ and we assume other feedbacks are zero, then:

$$1 + f_{\mathrm{TOTAL}} = \frac{1}{1 - 1.6\ \mathrm{W\ m^{-2}\ K^{-1}} \times 0.31\ \mathrm{K\ W\ m^{-2}}} = 1.98$$

Therefore, $f_{\mathrm{TOTAL}} = 0.98$; i.e., climate models suggest $f_{\mathrm{WV}} = 0.98$

Radiative Forcing of Clouds: IPCC 2013



https://link.springer.com/article/10.1007/s00382-013-1725-9

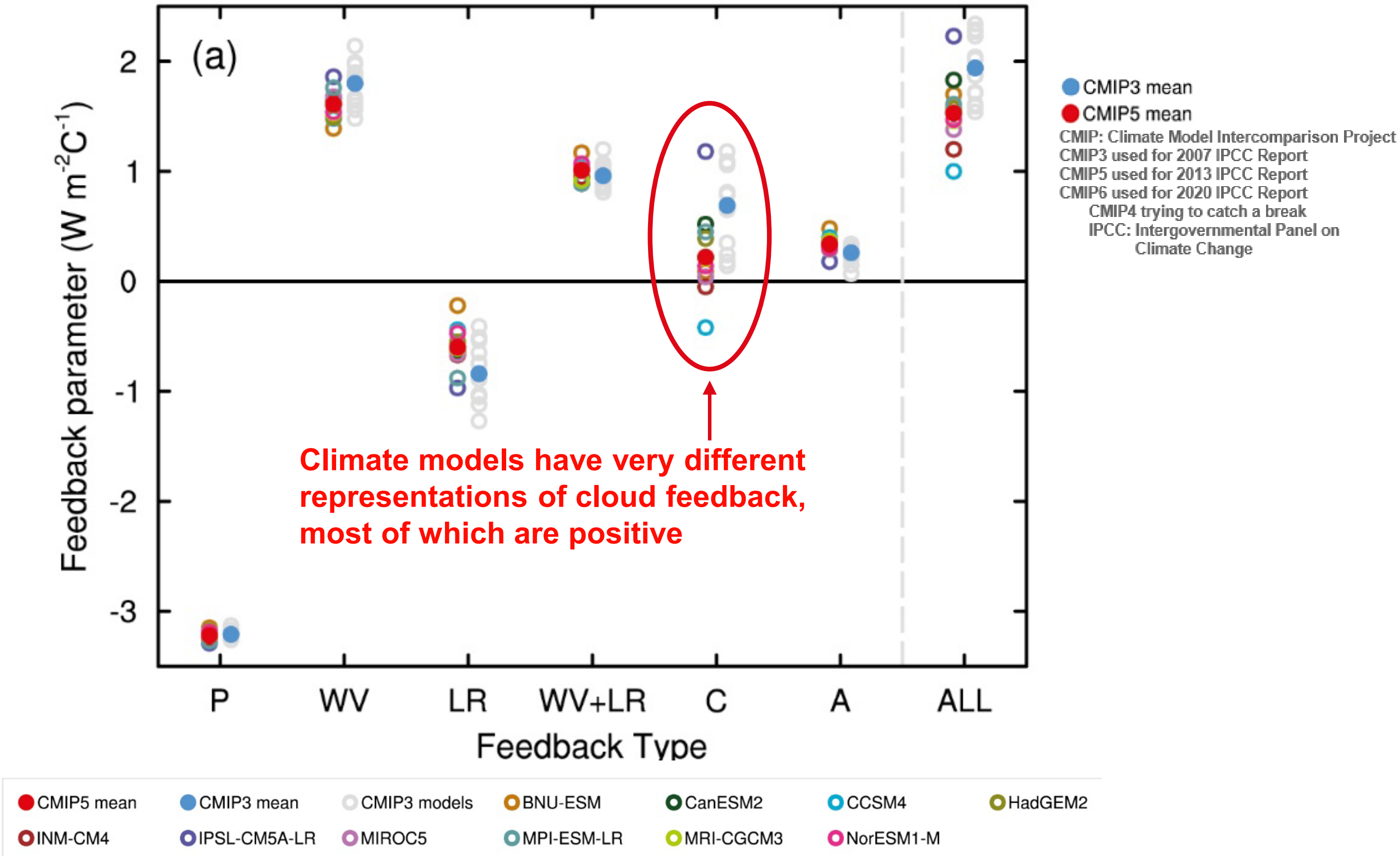
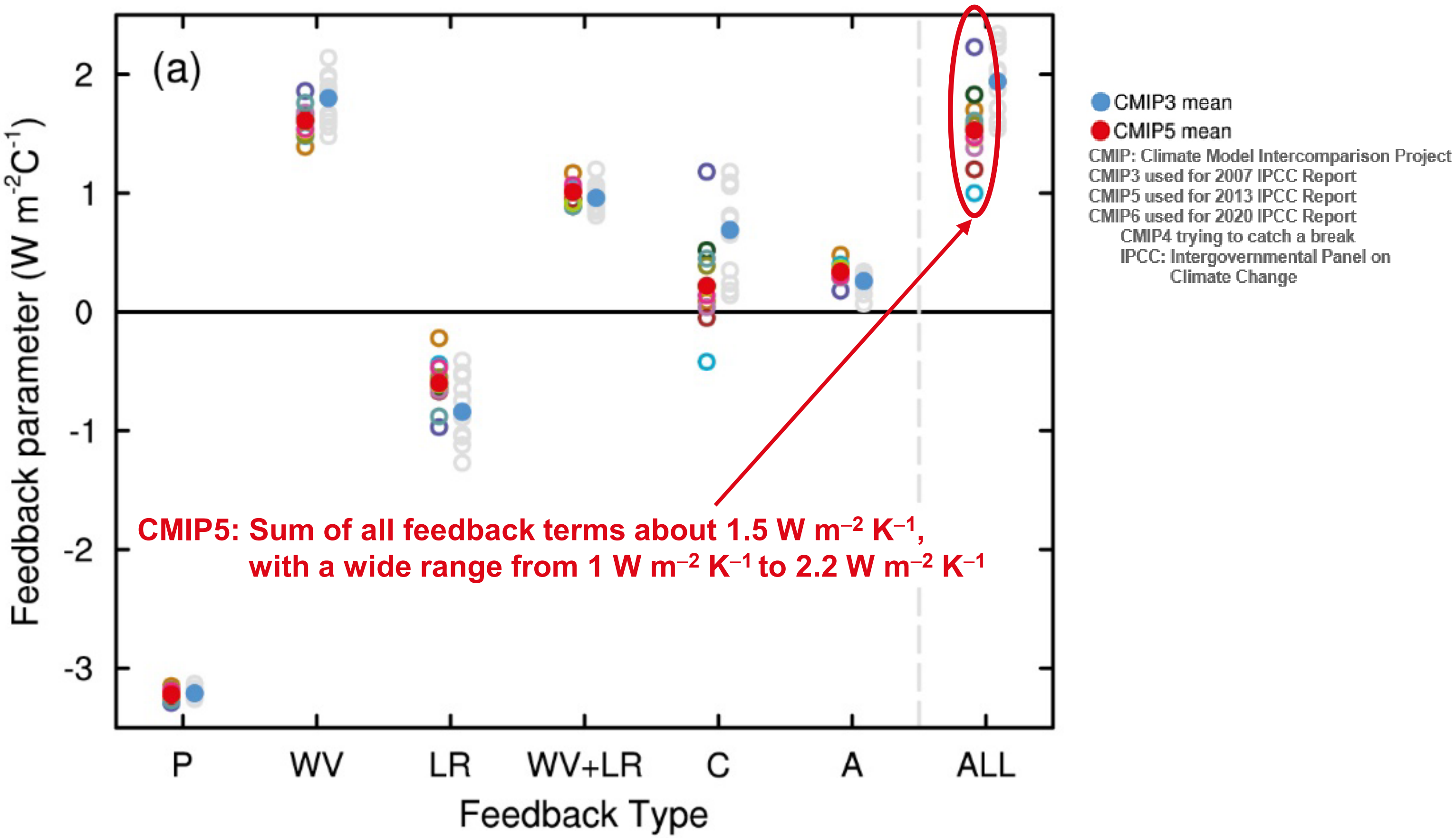


Fig 9.43, IPCC 2013

P : Planck
WV: Water Vapor
LR: Lapse Rate
WV + LR : Water Vapor + Lapse Rate

C: Clouds
A: Albedo
ALL: Sum of all feedback terms other than Planck



If $FB_{ALL} = 1.5\ \mathrm{W\ m^{-2}\ K^{-1}}$ and we assume other feedbacks are zero, then:

$$1 + f_{TOTAL} = \frac{1}{1 - 1.5\ \mathrm{W\ m^{-2}\ K^{-1}} \times 0.31\ \mathrm{K\ W\ m^{-2}}} = 1.87$$

Therefore, $f_{TOTAL} = 0.87$; i.e., CMIP5 climate models suggest sum of all feedbacks amplify by 0.87

If $FB_{ALL} = 2.25\ \mathrm{W\ m^{-2}\ K^{-1}}$ (upper limit) amplification rises to 2.3

If $FB_{ALL} = 1.0\ \mathrm{W\ m^{-2}\ K^{-1}}$ (lower limit) amplification drops to 0.45

IPCC AR5 “downgraded” warming forecast by CMIP5 models

Chapter 11 of IPCC (2013) suggested CMIP5 GCMs warm too quickly compared to observations, resulting in “likely range” (red trapezoid) for rise in GMST relative to pre-industrial baseline (ΔT) being considerably less than actual archived ΔT from the CMIP5 GCM runs

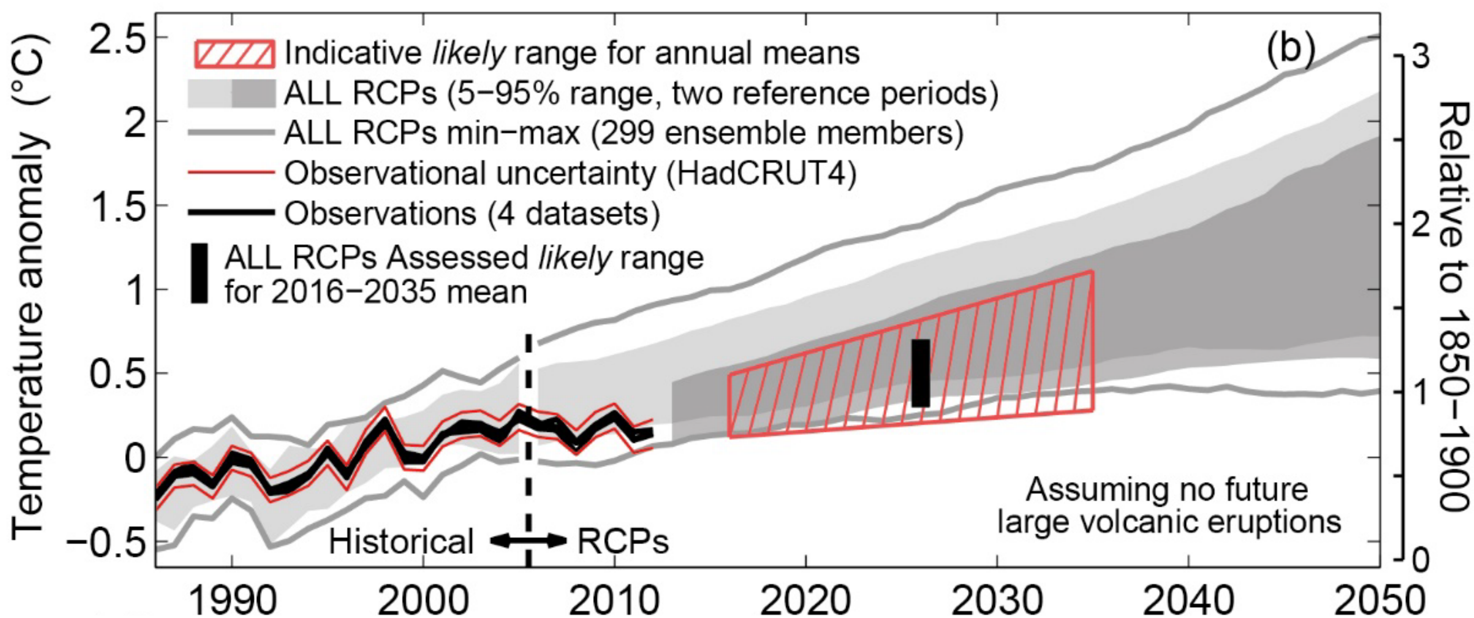


Fig 11.25b, IPCC (2013)

CMIP6 models used by AR6 warm faster than CMIP5 models due to, you guessed it, clouds!

Geophysical Research Letters

Causes of Higher Climate Sensitivity in CMIP6 Models

Mark D. Zelinka, Timothy A. Myers, Daniel T. McCoy, Stephen Po-Chedley, Peter M. Caldwell, Paulo Ceppi, Stephen A. Klein, Karl E. Taylor

First published: 03 January 2020 | https://doi.org/10.1029/2019GL085782 | Citations: 333

Plain Language Summary

The severity of climate change is closely related to how much the Earth warms in response to greenhouse gas increases. Here we find that the temperature response to an abrupt quadrupling of atmospheric carbon dioxide has increased substantially in the latest generation of global climate models. This is primarily because low cloud water content and coverage decrease more strongly with global warming, causing enhanced planetary absorption of sunlight—an amplifying feedback that ultimately results in more warming. Differences in the physical representation of clouds in models drive this enhanced sensitivity relative to the previous generation of models. It is crucial to establish whether the latest models, which presumably represent the climate system better than their predecessors, are also providing a more realistic picture of future climate warming.

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL085782

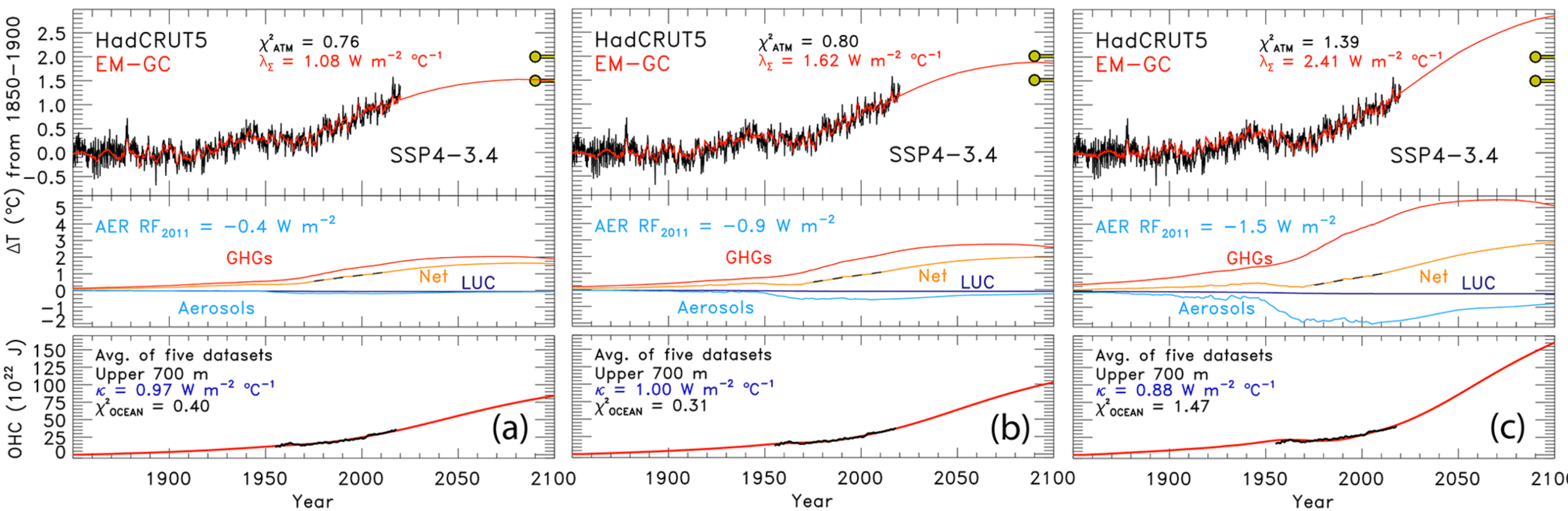
Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

$$\Delta T = \lambda_{Planck} \times (1 + f_{TOTAL}) \times \Delta RF - OHE$$

where:

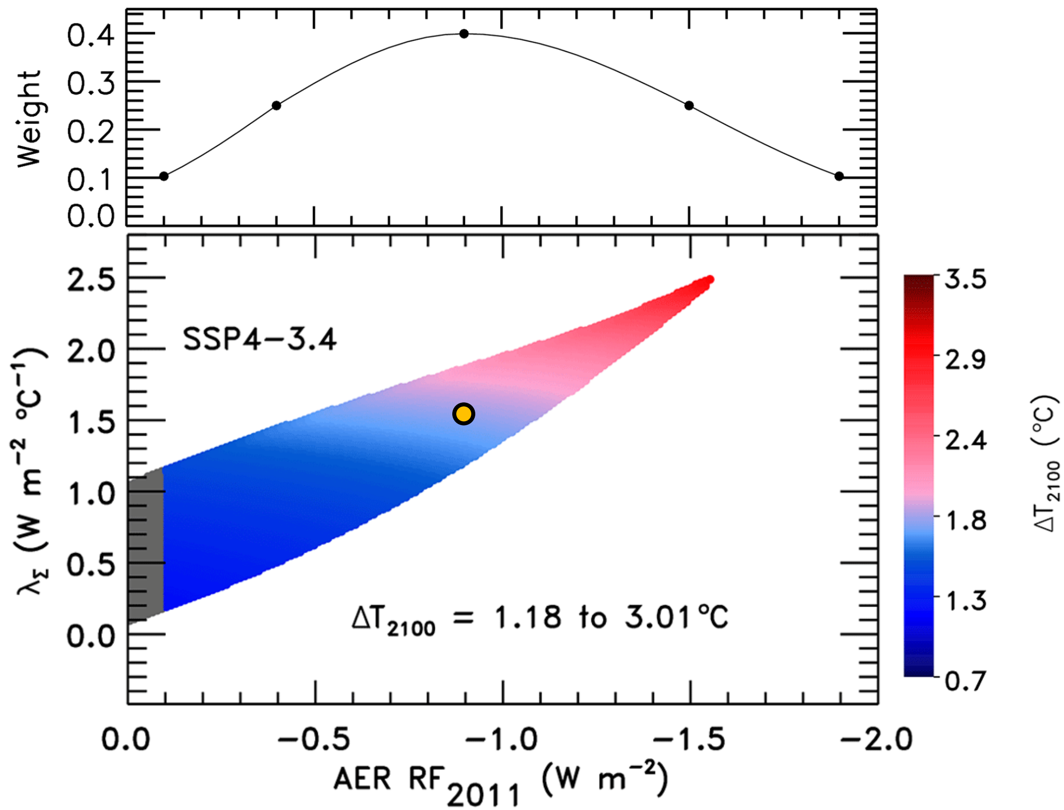
f_{TOTAL} = feedbacks due to water vapor, clouds, lapse rate, etc

OHE = ocean heat export



McBride *et al.*, 2021
https://esd.copernicus.org/articles/12/545/2021

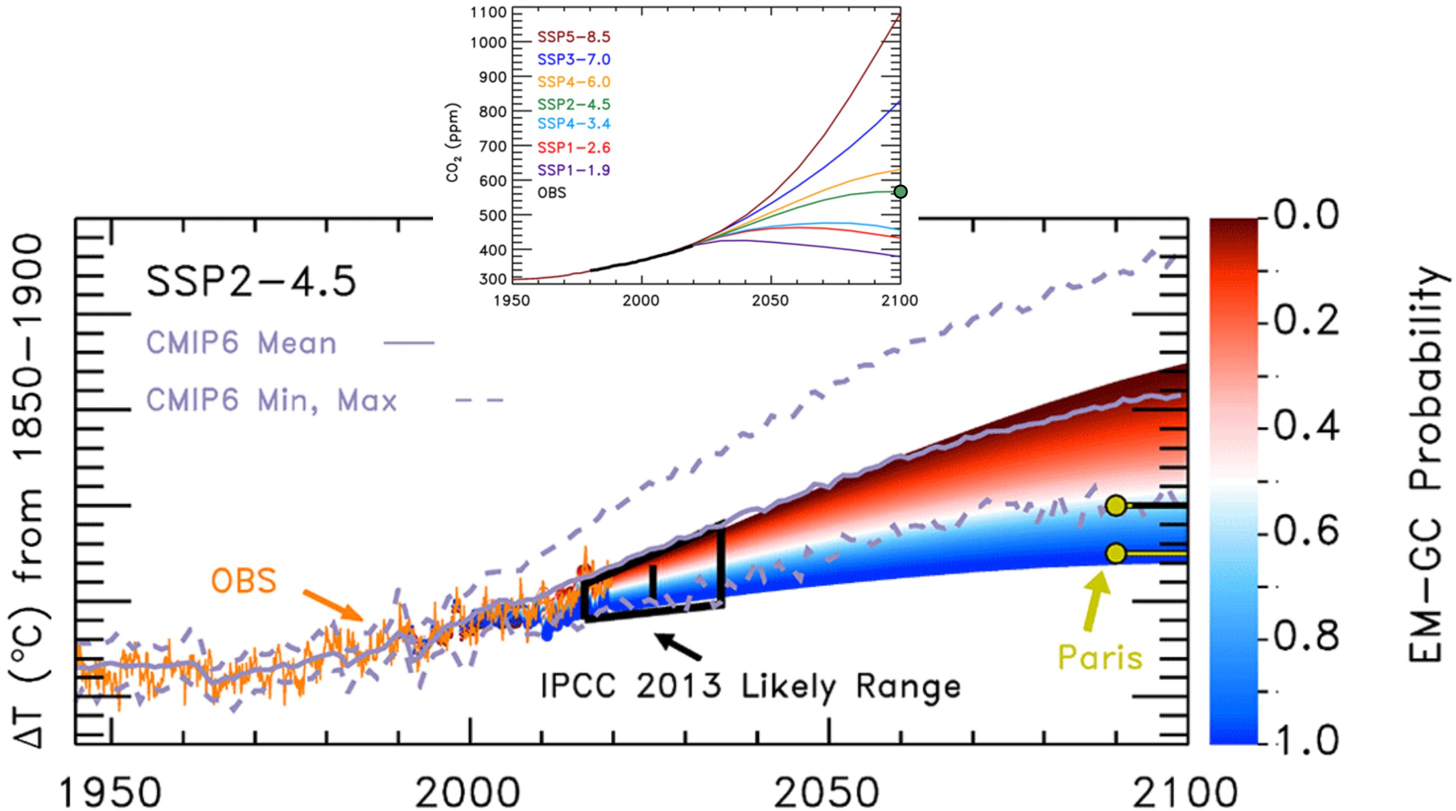
End of Century Warming, SSP4-3.4, as a fn of Feedback & Aerosol RF



Model space for which at $\chi^2 \leq 2$, where: $\chi^2 = \frac{1}{(N_{YEARS} - N_{FITTING\ PARAMETERS} - 1)} \times \sum_{j=1}^{N_{YEARS}} \frac{1}{(\sigma_{OBS\,j}{}^2)} \left(\langle \Delta T_{OBS\,j} \rangle - \langle \Delta T_{EM-GC\,j} \rangle \right)^2$

McBride *et al.*, 2021
https://esd.copernicus.org/articles/12/545/2021

Probabilistic Forecast of ***Human-Induced Rise in GMST*** for model trained on data acquired until end of 2019 and future GHG levels from SSP2-4.5

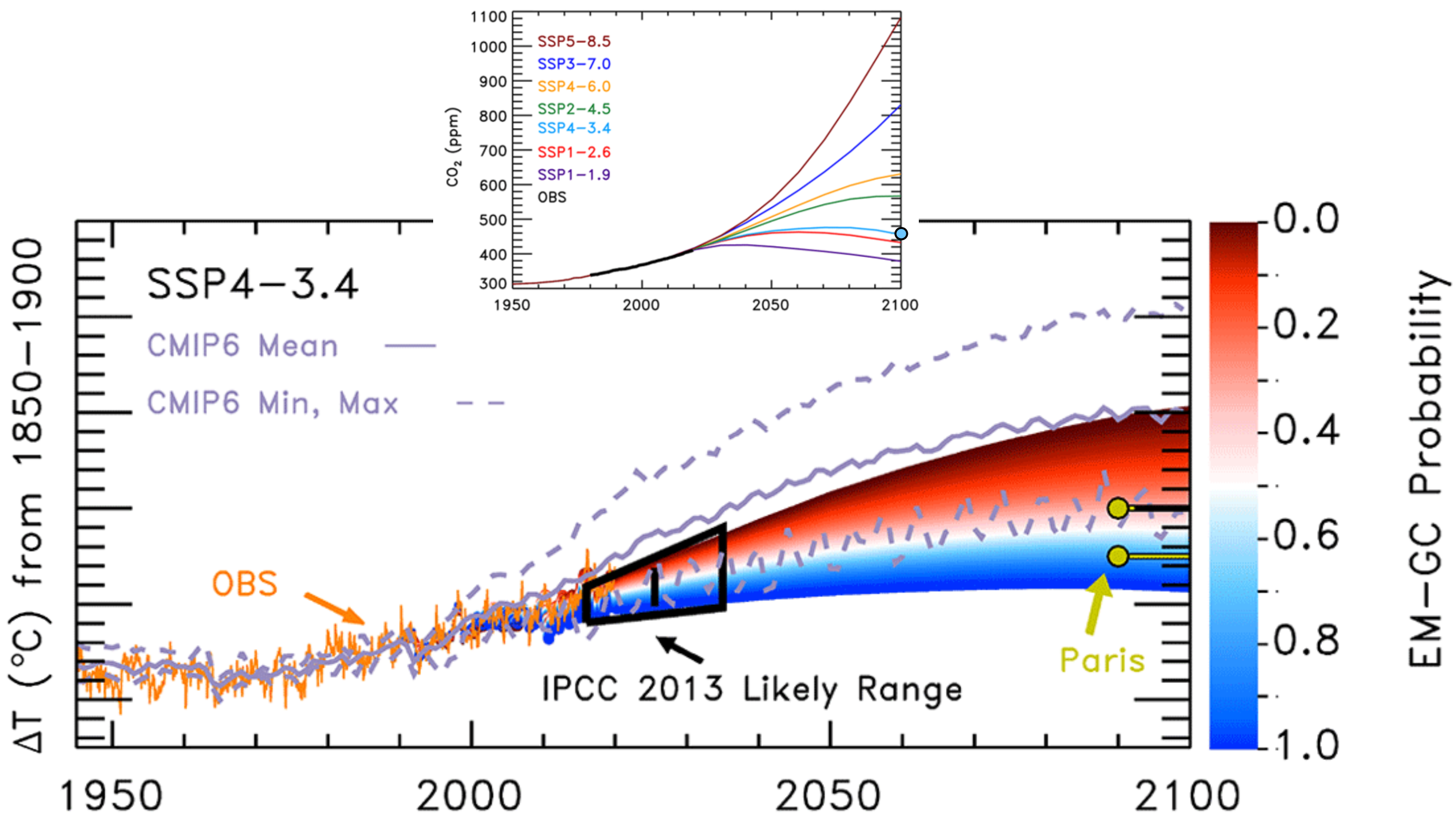


If GHGs follow SSP2-4.5, **2%** chance rise GMST stays below **1.5°C** and **33%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

McBride *et al*., 2021: https://esd.copernicus.org/articles/12/545/2021

Probabilistic Forecast of ***Human-Induced Rise in GMST*** for model trained on data acquired until end of 2019 and future GHG levels from SSP4-3.4

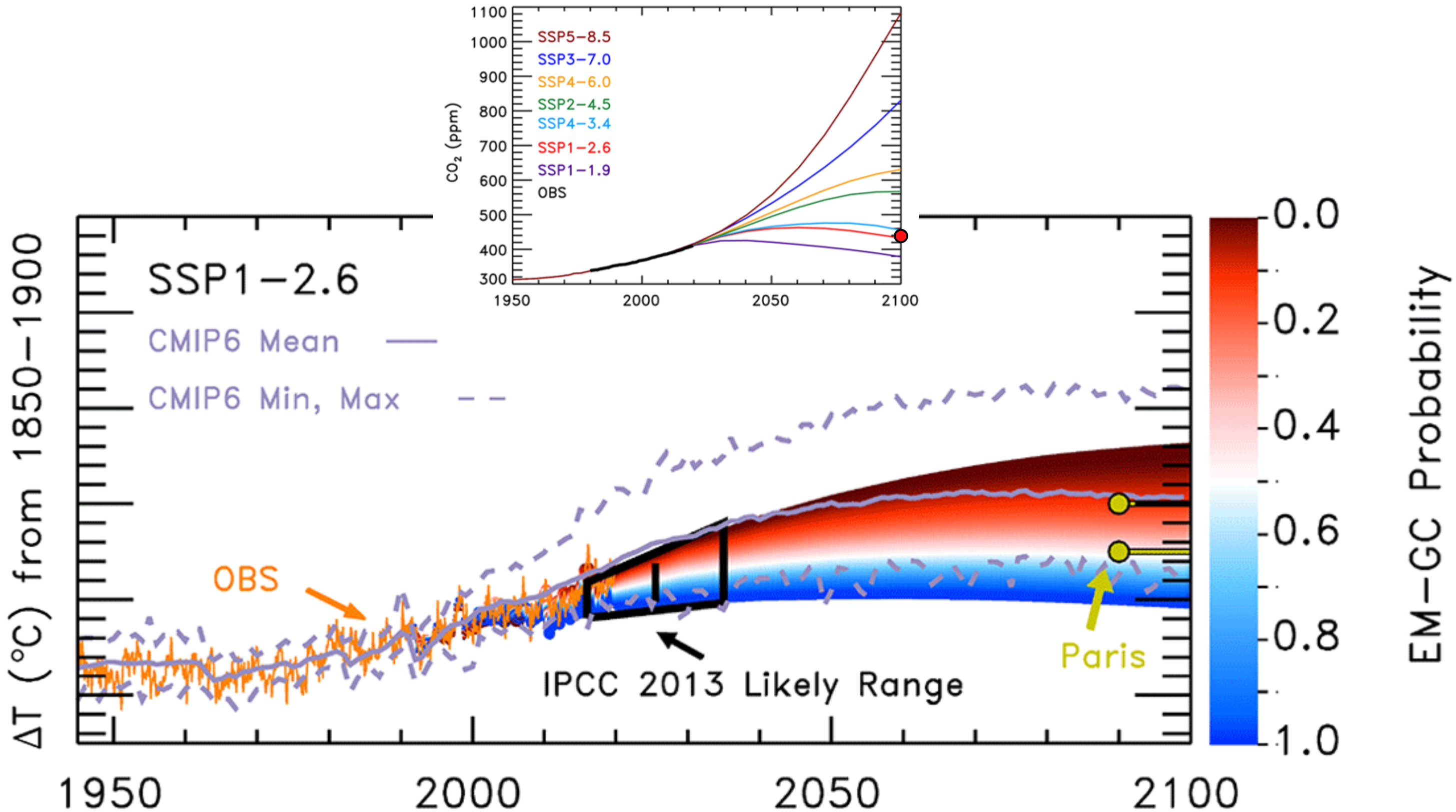


If GHGs follow SSP4-3.4, **19%** chance rise GMST stays below **1.5°C** and **64%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

McBride *et al*., 2021: https://esd.copernicus.org/articles/12/545/2021

Probabilistic Forecast of ***<u>Human-Induced Rise in GMST</u>*** for model trained on data acquired until end of 2019 and future GHG levels from SSP1-2.6

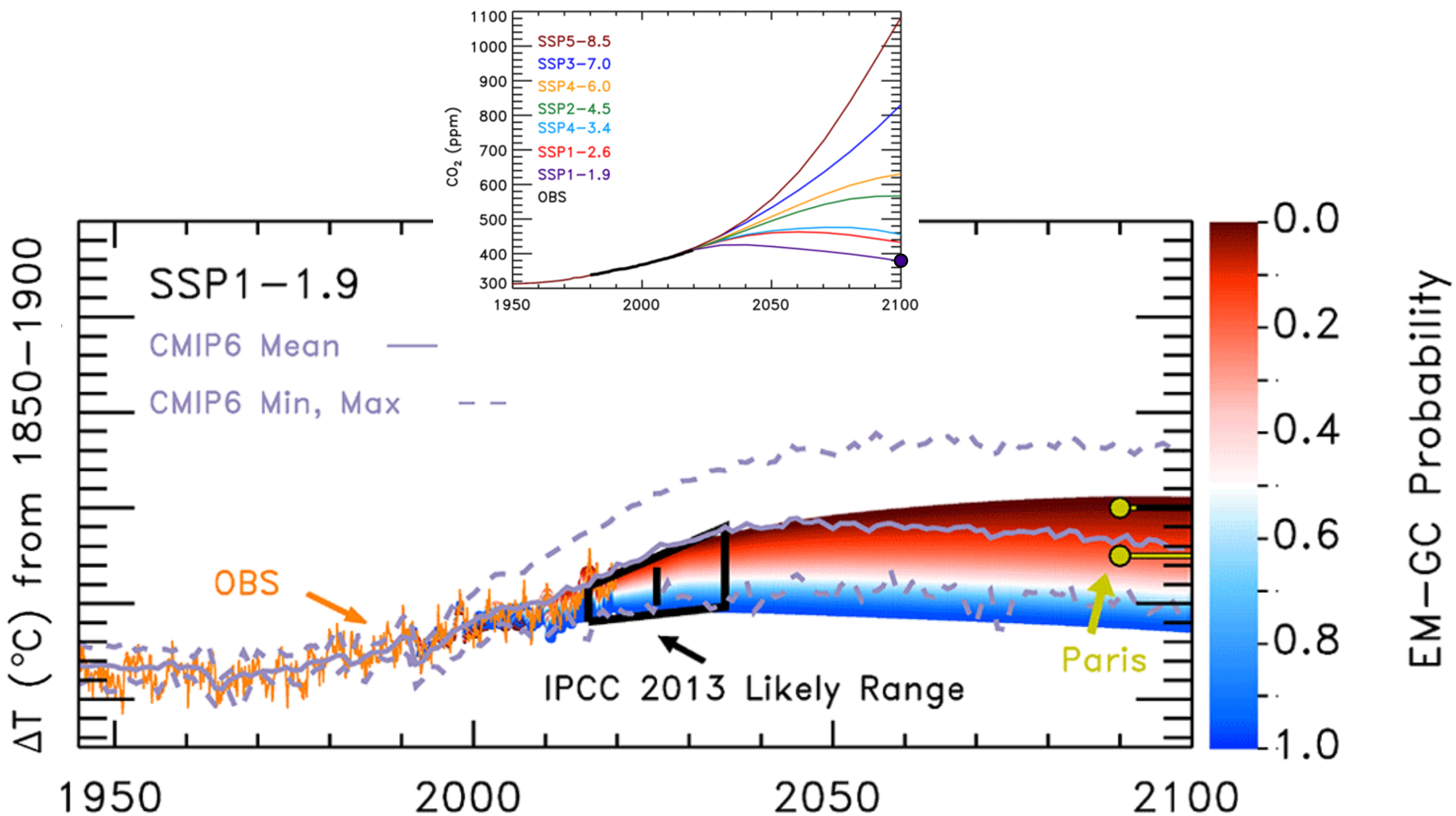


If GHGs follow SSP1-2.6, **53%** chance rise GMST stays below **1.5°C** and **86%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

McBride *et al.*, 2021: https://esd.copernicus.org/articles/12/545/2021

Probabilistic Forecast of ***<u>Human-Induced Rise in GMST</u>*** for model trained on data acquired until end of 2019 and future GHG levels from SSP1-1.9



If GHGs follow SSP1-1.9, **81%** chance rise GMST stays below **1.5°C** and **98%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

McBride *et al*., 2021: https://esd.copernicus.org/articles/12/545/2021