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/fall2022
https://umd.instructure.com/courses/1327017

Goals:

1. Aerosol RF of climate: direct & indirect effect (quick review)

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: using the past to project future

Lecture 8

27 September 2022

Announcements

1) Seminars on Thursday:

DR. ROBERT ATLAS

Abstract: This talk will complement Dr. Atlas's recent memoir "Weather Forecaster to Research Scientist" published by the American Meteorological Society. It will begin with an overview of the essential nature of weather forecasting and the main approaches that have been used. Dr. Atlas will then describe briefly his personal experience as an apprentice forecaster with the U.S. Weather Bureau in the early 1960's and as an operational forecaster in the U.S. Air Force in the 1970's. This will be followed by highlights from some of the research that Dr. Atlas has been involved in over the last 50 years, such as the initial impact of quantitative satellite data on numerical weather prediction, extreme weather events, and Observing System Simulation Experiments.

3:30 PM EDT
THURSDAY, SEPTEMBER 29, 2022
PRESENTED IN HYBRID VIRTUAL/IN-PERSON FORMAT
SEMINAR LOCATION: ATLANTIC BUILDING, ROOM 2400

2022 Russell Marker Lecture

with

David MacMillan

2021 Nobel Laureate in Chemistry
Professor of Chemistry, Princeton University

on

"Asymmetric Organocatalysis: Democratizing Catalysis for a Sustainable World"

Thursday, September 29, 2022
3:30 p.m. Reception
4 p.m. Lecture
Chemistry Building, Room 1407

2) Problem Set is due a week from today

- Please turn in hard copy, stapled, which will be graded the old-fashioned way

3) 10 points per day late, unless there is a legitimate medical or extra-curricular circumstance brought to my attention prior to the due date!

4) Will hold problem set review Tues, 4 Oct followed by review of Lectures 1 to 8

5) Exam is Thurs, 6 Oct:

- If held in class, will be closed book / no notes
- Will focus on concepts much more than calculations, although a very simple calculation-type question could appear

Combining RF GHGs & Aerosols

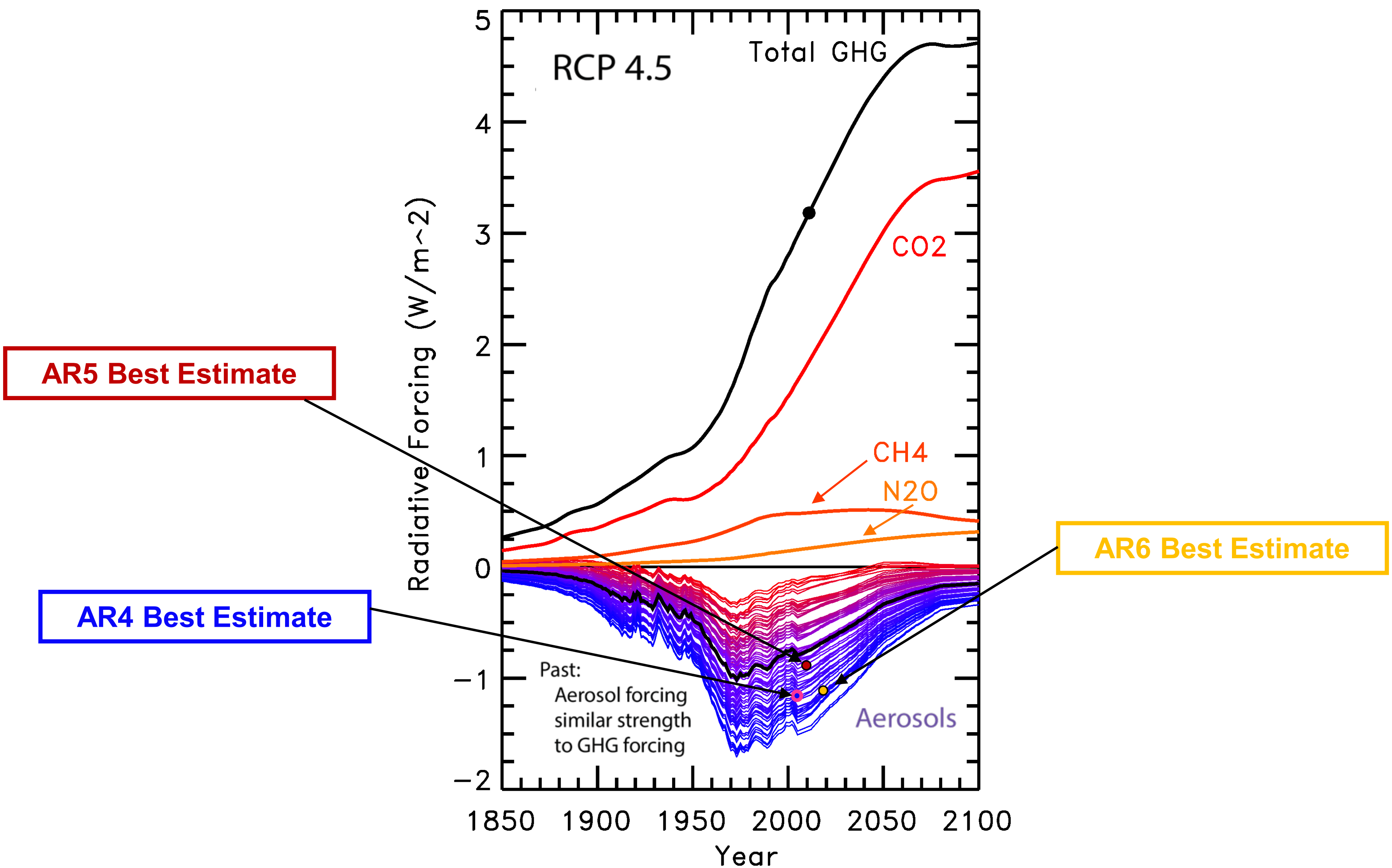
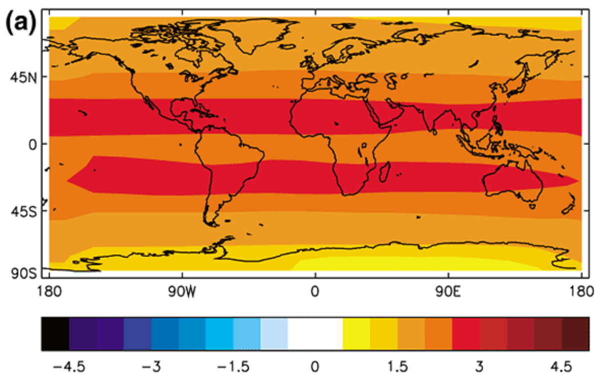


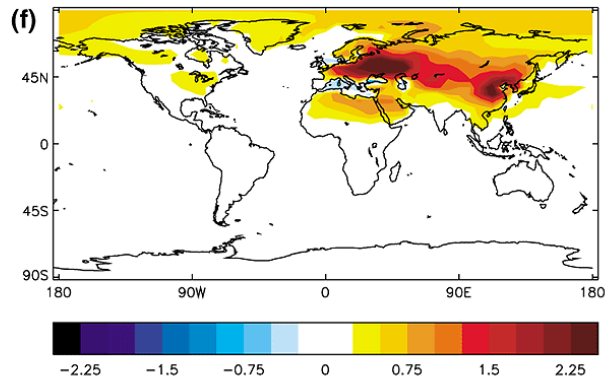
Fig 1.10, *Paris, Beacon of Hope*

Global View

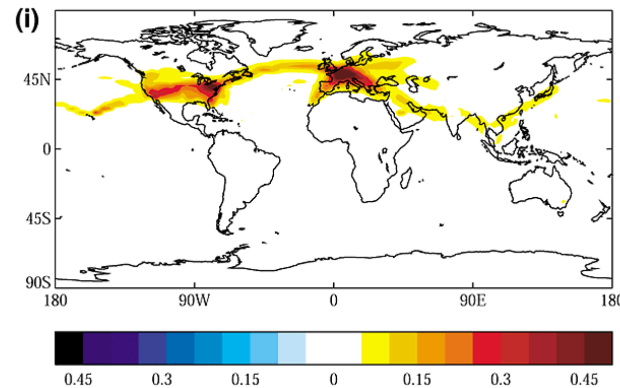
All forcings (1750-2000) are in Wm^{-2}

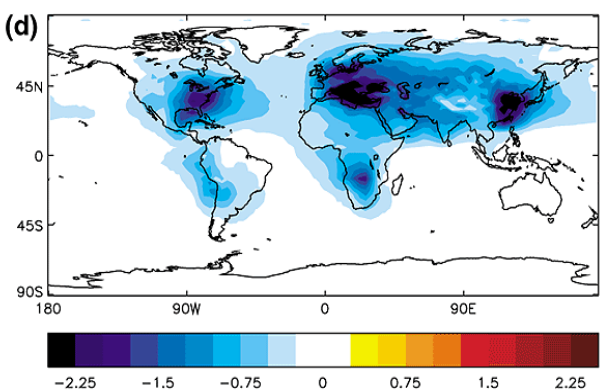


Greenhouse gases

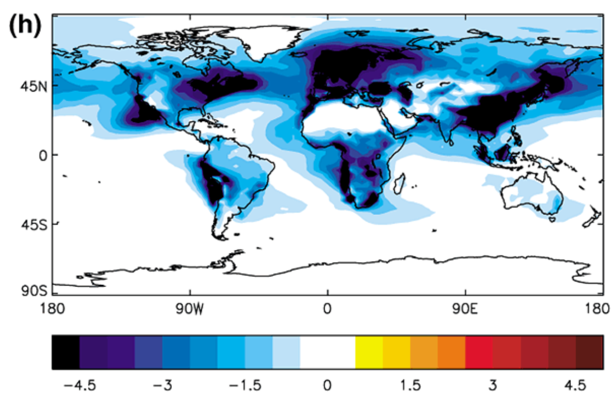


Organic and black carbon from fossil fuel burning

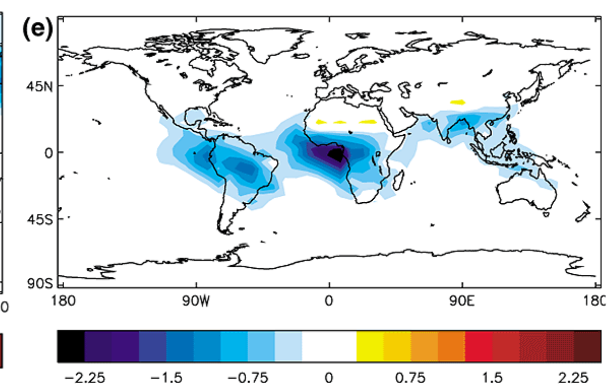




Direct effect from sulphate aerosols



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/

RF Due to Tropospheric Aerosols: Indirect Effect

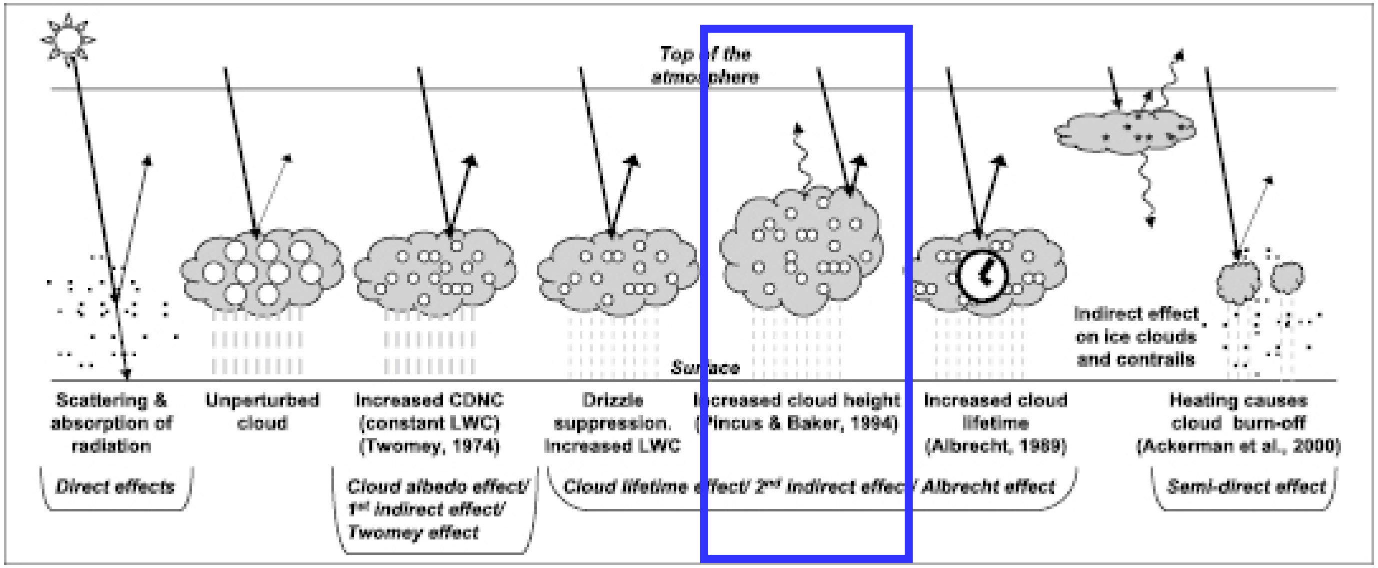
Indirect Effects of Aerosols on Clouds

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



Large uncertainty in aerosol RF

Fig 2-10, IPCC 2007

- 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 26* (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

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

where f_{TOTAL} is dimensionless climate sensitivty parameter that represents feedbacks,

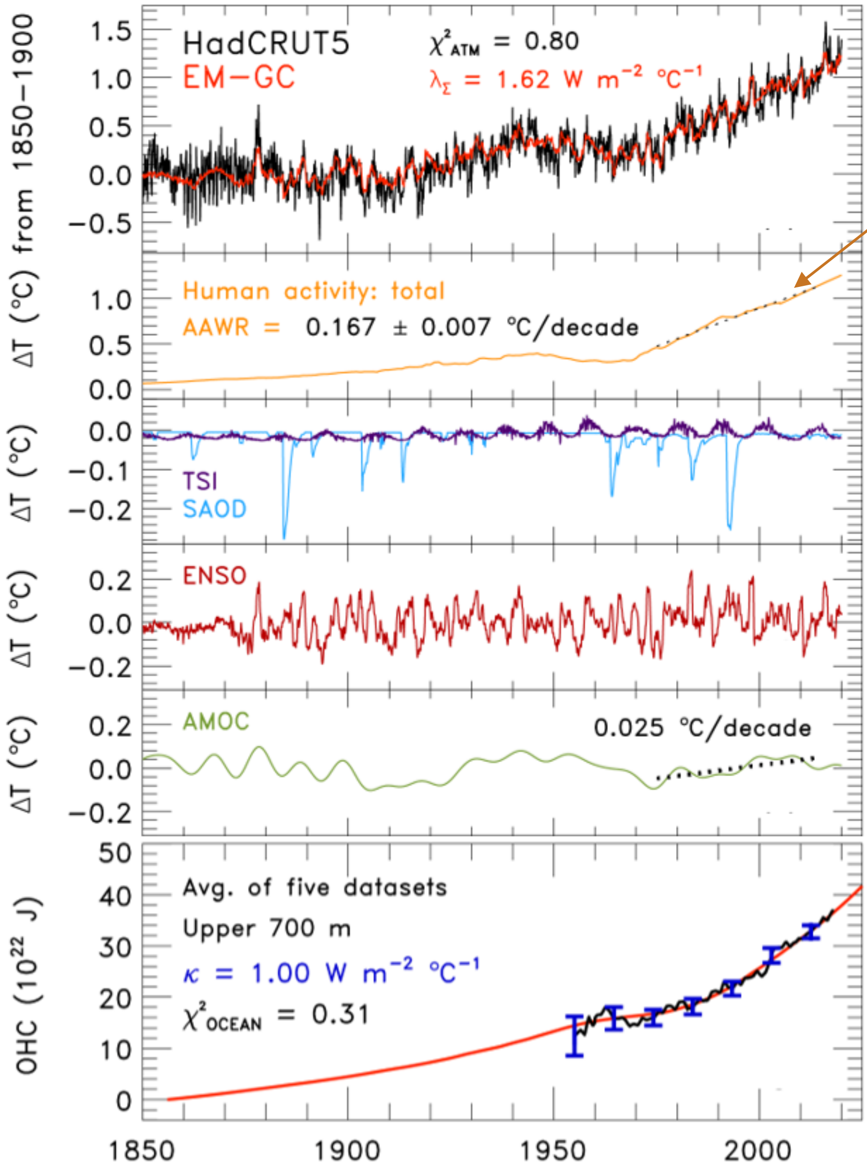
and is related to IPCC definition of feedbacks (see Bony et al., J. Climate, 2006) via:

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

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

Each FB term has units of $\text{W m}^{-2} \text{ K}^{-1}$, 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:

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

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

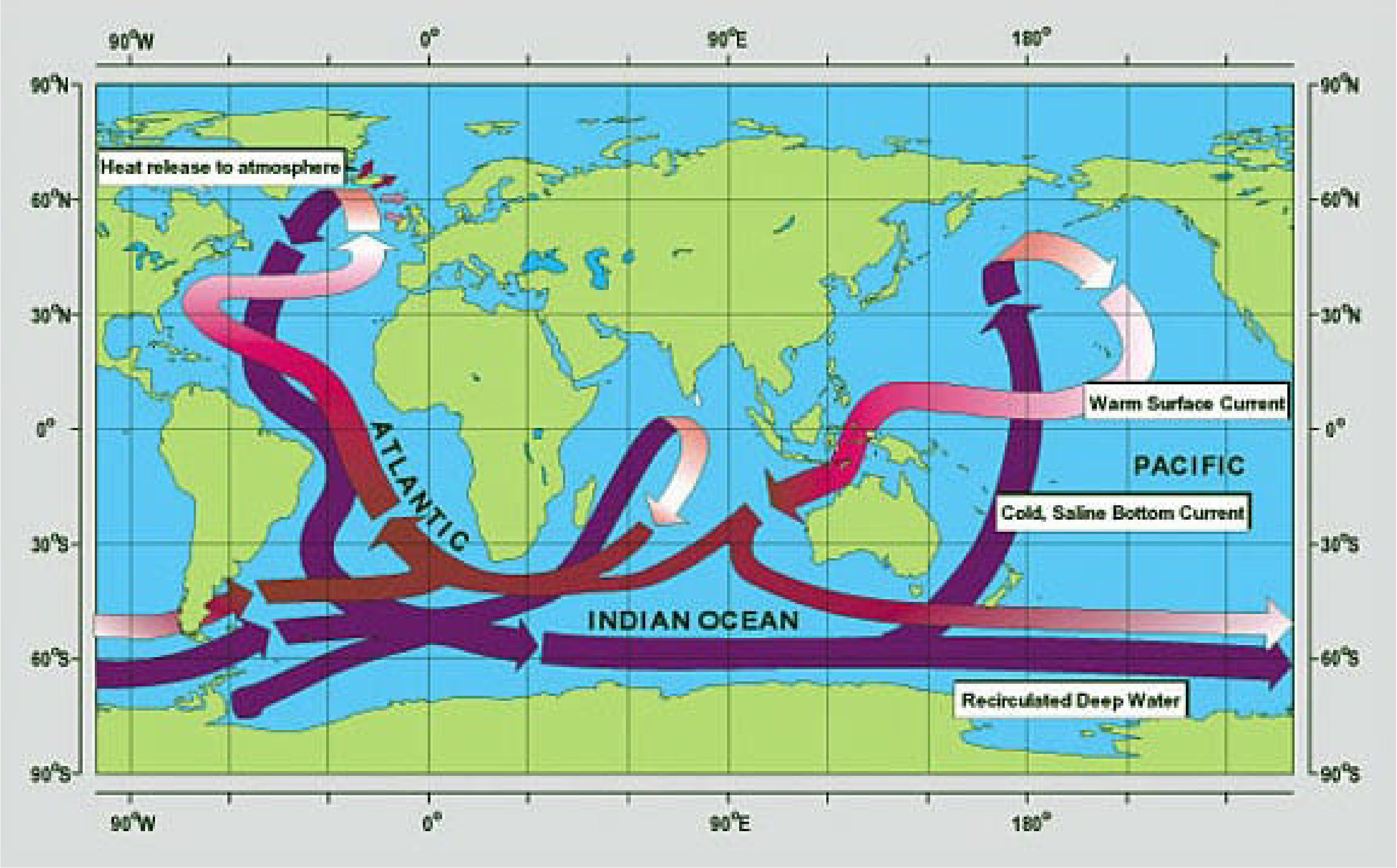
The utility of this approach is that feedbacks can be summed to get FB_{TOTAL}

$$1 + f_{TOTAL} = \frac{1}{1 - 1.62\ W\ m^{-2}/K \times 0.31\ K\ /\ Wm^{-2}} = \frac{1}{1-0.506} = 2.02 \approx 2$$

Similar to *Lecture 2, Slide 16* (Handout)

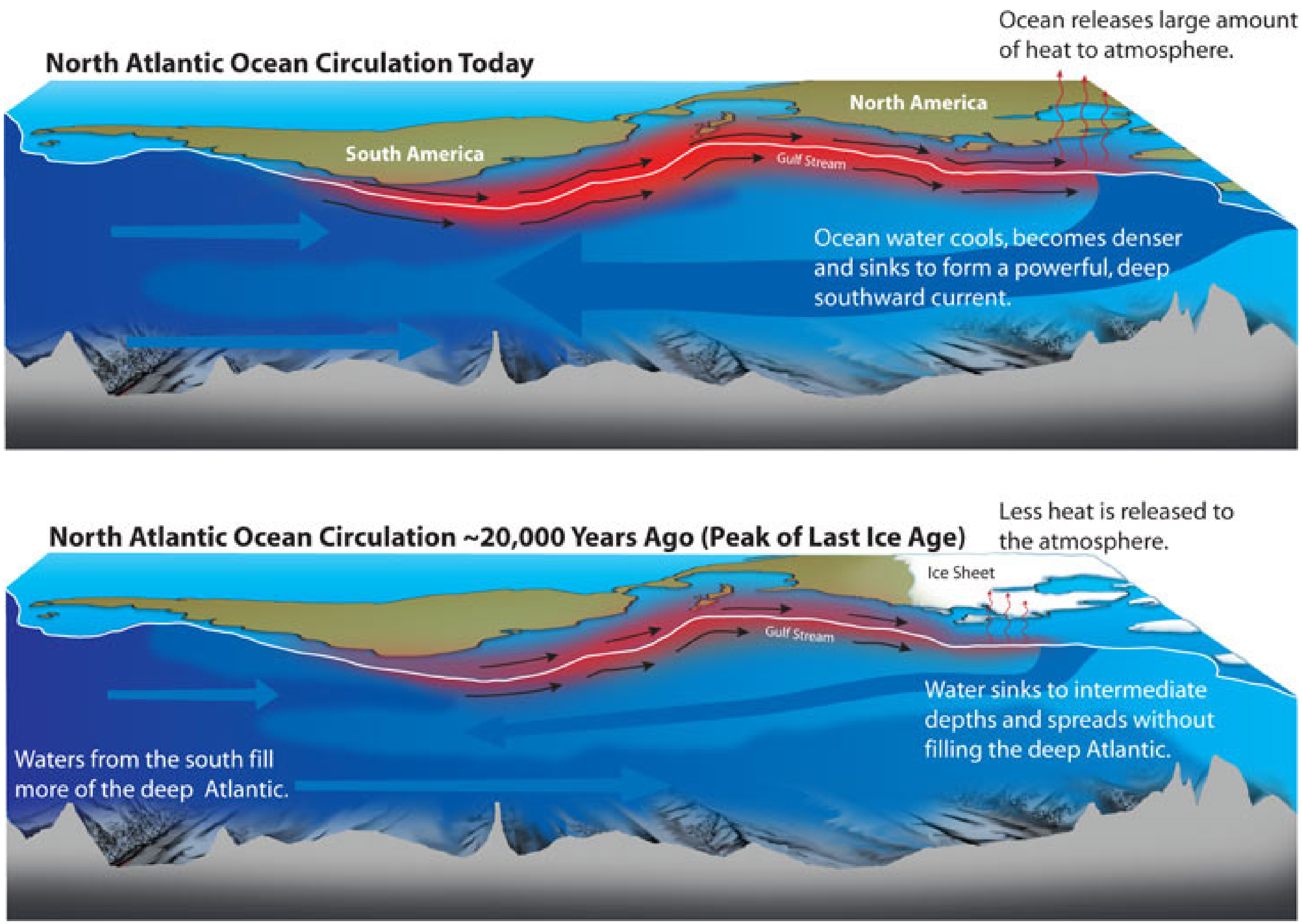
McBride *et al*., 2021: https://esd.copernicus.org/articles/12/545/2021

Ocean Heat Transport

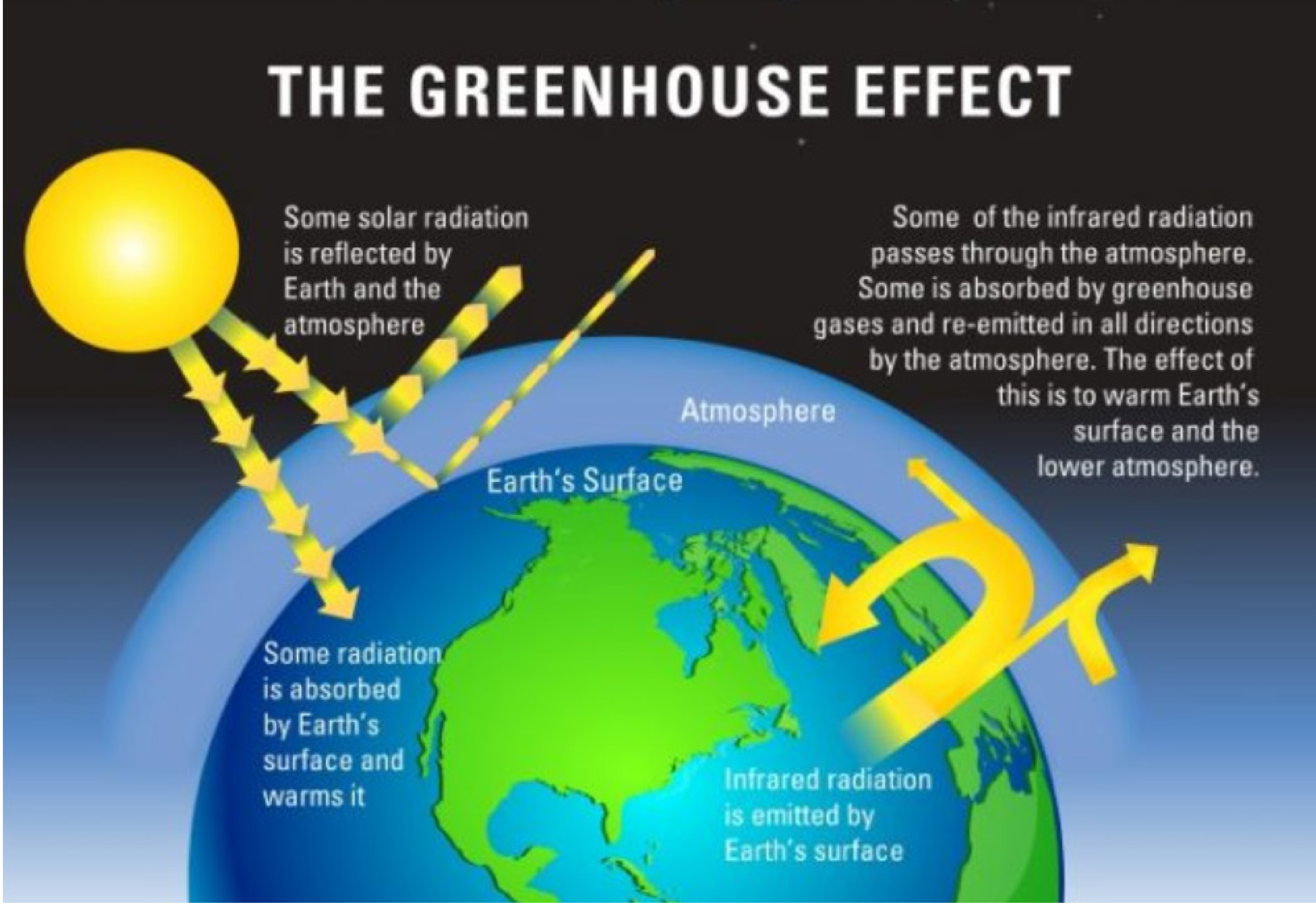


http://www.whoi.edu/oceanus/feature/the-once-and-future-circulation-of-the-ocean

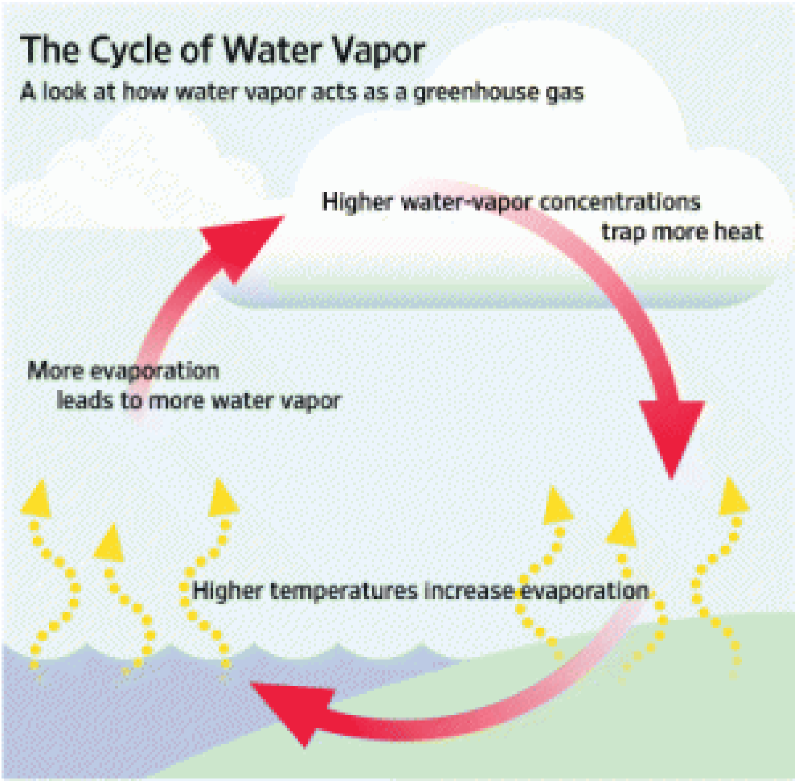
Ocean Heat Transport

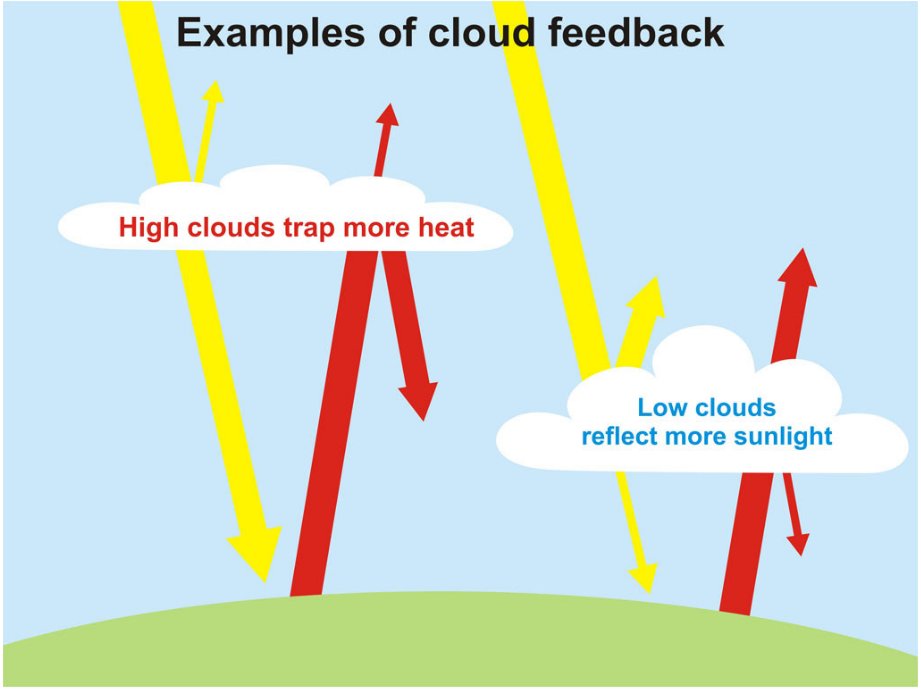


http://www.whoi.edu/oceanus/feature/the-once-and-future-circulation-of-the-ocean



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





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

AT Question

Question 3

2.5 / 2.5 pts

According to Houghton, how much more will the Earth warm in response to a doubling of carbon dioxide ***with all feedbacks operative***, relative to a situation where there are no operative feedbacks in the climate system?

- ○ The warming will be amplified by about a factor of 1.5 to 2.
- Correct! ◉ The warming will be amplified by about a factor of 2.5 to a factor of 3.

  Nice job; as we'll review in class, there is ***large uncertainty*** in the correct numerical value of this amplification factor.
- ○ The warming will be small, close to the increase in global average temperature that would arise in the absence of any feedbacks.
- ○ The warming will be amplified by about a factor of 4 to 5.

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

Amplification factor = 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

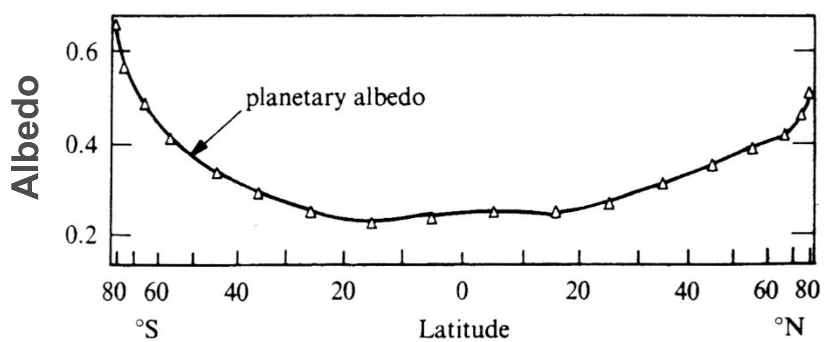
↓

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

2. Albedos of selected surfaces on Earth

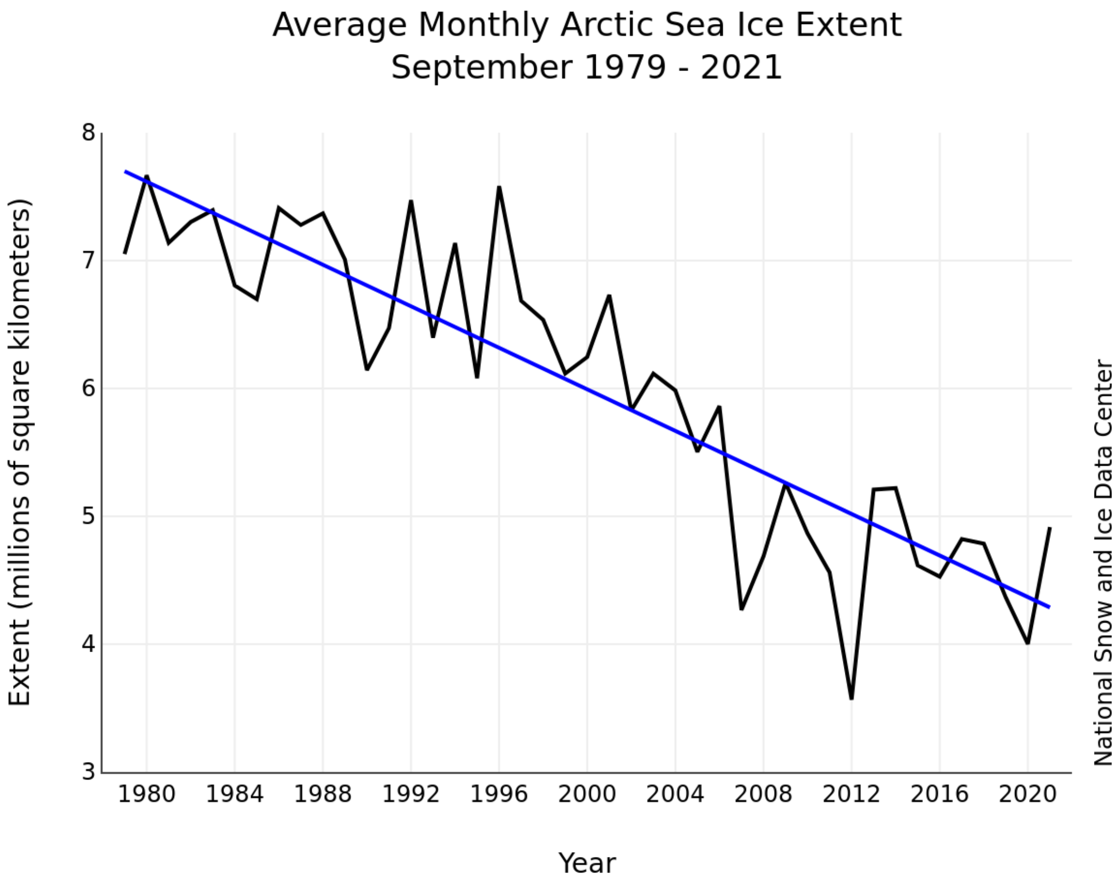
surface	albedo
snow	0.7 ± 0.2
sand	0.25 ± 0.05
grasslands	0.23 ± 0.03
bare soil	0.2 ± 0.05
forest	0.15 ± 0.1
water (highly dependent on surface roughness and incident angle of sunlight)	0.2 + 0.6 − 0.2

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



- Sea ice: ice overlying ocean
- Annual minimum occurs each September
- Decline of ~12.7% / decade over satellite era

http://nsidc.org/arcticseaicenews/2021/10/

NSIDC National Snow & Ice Data Center | DATA | RESEARCH | NEWS | ABOUT | SEARCH | Web pages

Arctic Sea Ice News & Analysis

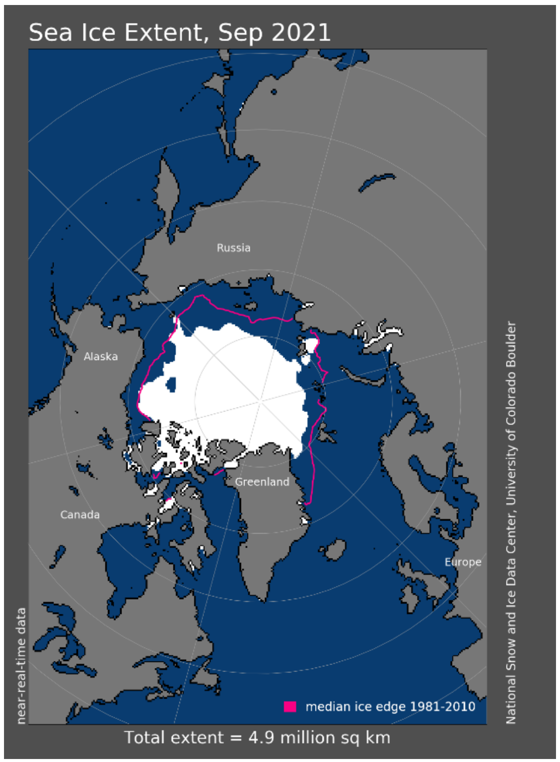
October 5, 2021

September turning

← Previous Next →

Search

The summer melt season has come to a modest end. The summer of 2021 was relatively cool compared to the most recent years and September extent was the highest since 2014. It was nevertheless an eventful summer, with many twists and turns.



Arctic sea ice extent for September averaged 4.92 million square kilometers (1.90 million square miles), the twelfth lowest in the 43-year satellite record. This is 1.35 million square kilometers (521,000 square miles) above the record low set in September 2012, and 1.49 million square kilometers (575,000 square miles) below the 1981 to 2010 average. The last 15 years (2007 to 2021) have had the 15 lowest September extents in the record.

Figure 1a. Arctic sea ice extent for September 2021 was 4.92 million square kilometers (1.90 million square miles). The magenta line shows the 1981 to 2010 average extent for that month. Sea Ice Index data. About the data

http://nsidc.org/arcticseaicenews/2021/10/september-turning/

Water Vapor Feedback

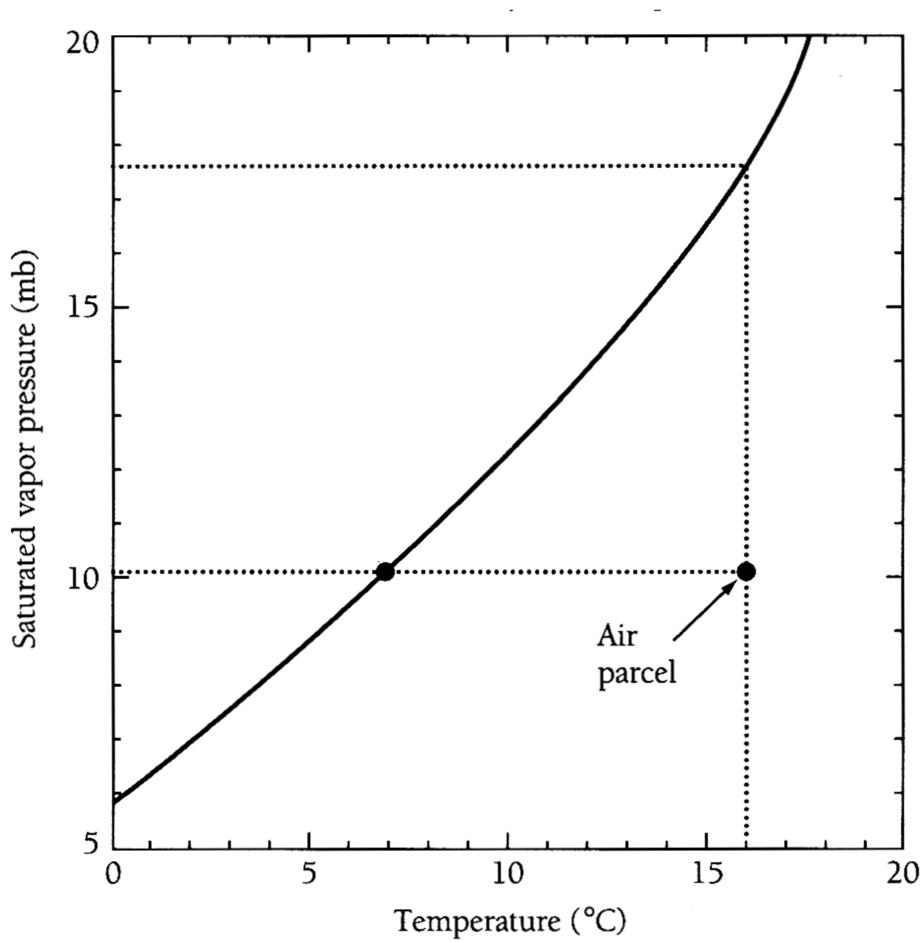


Figure 4.8a Relative humidity and the dew point.

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.

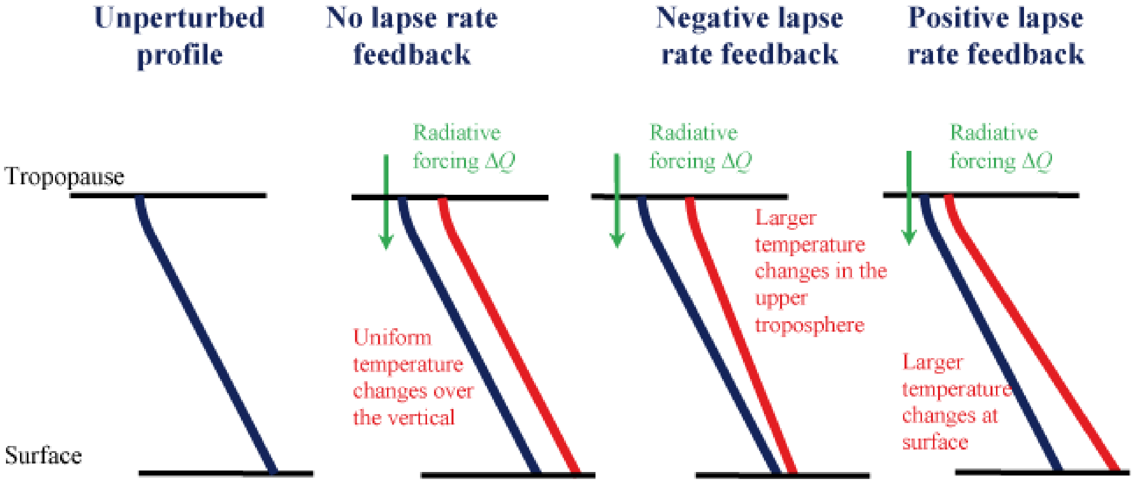


Figure 4.10: Schematic representation of positive and negative lapse-rate feedbacks.

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**

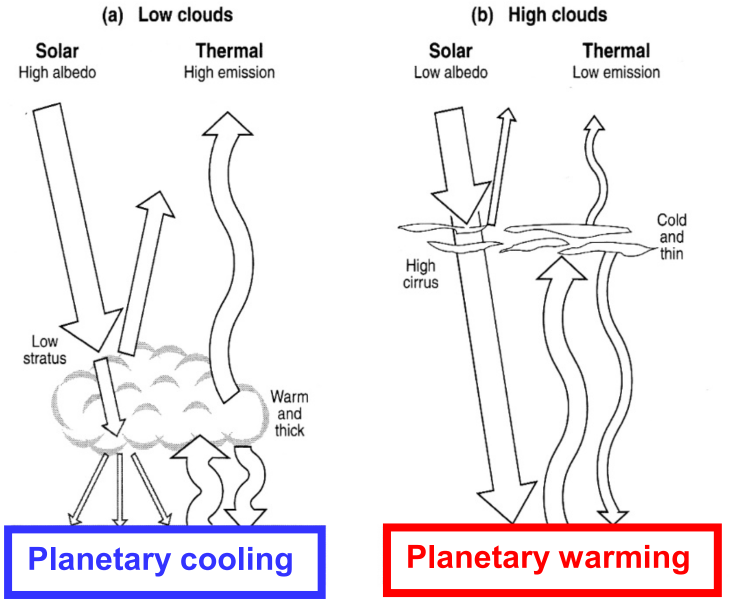


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The 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

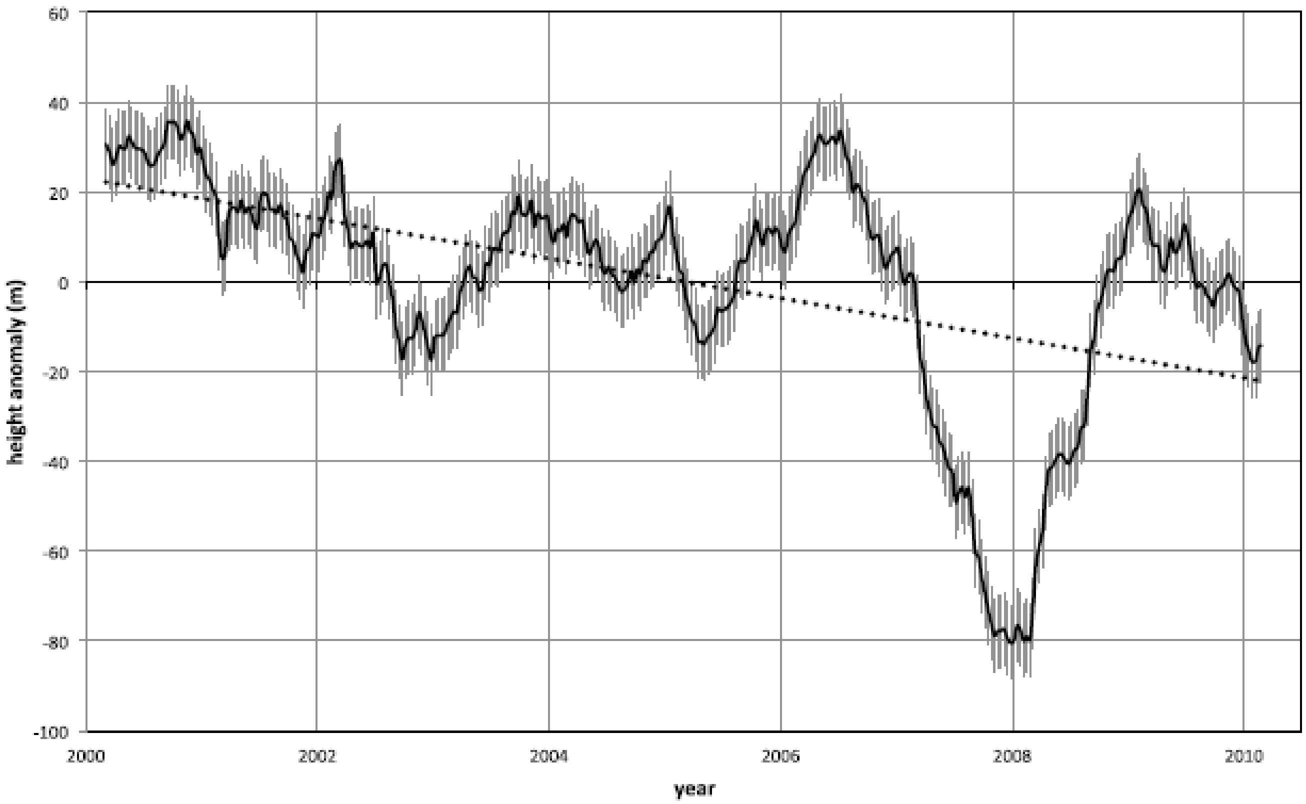


Figure 1. Deseasonalized anomalies of global effective cloud-top height from the 10-year mean. Solid line: 12-month running mean of 10-day anomalies. Dotted line: linear regression. Gray error bars indicate the sampling error (±8 m) in the annual average.

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

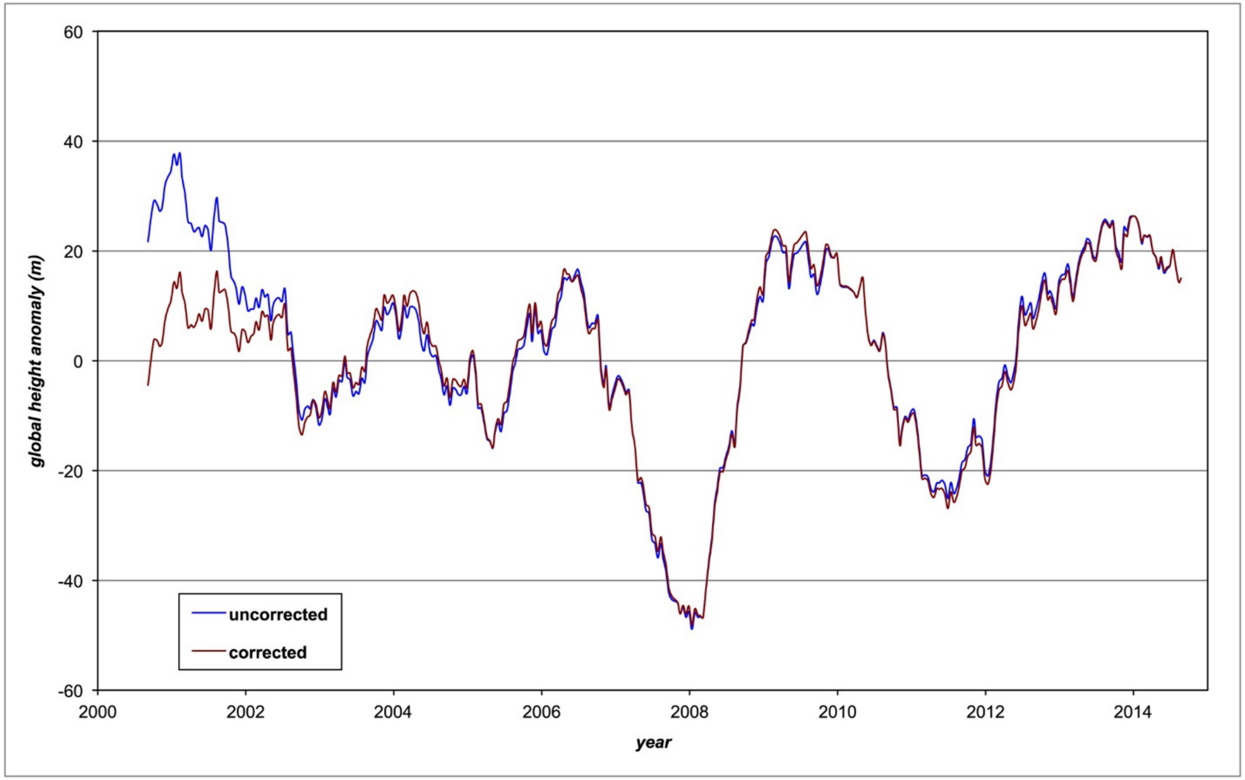
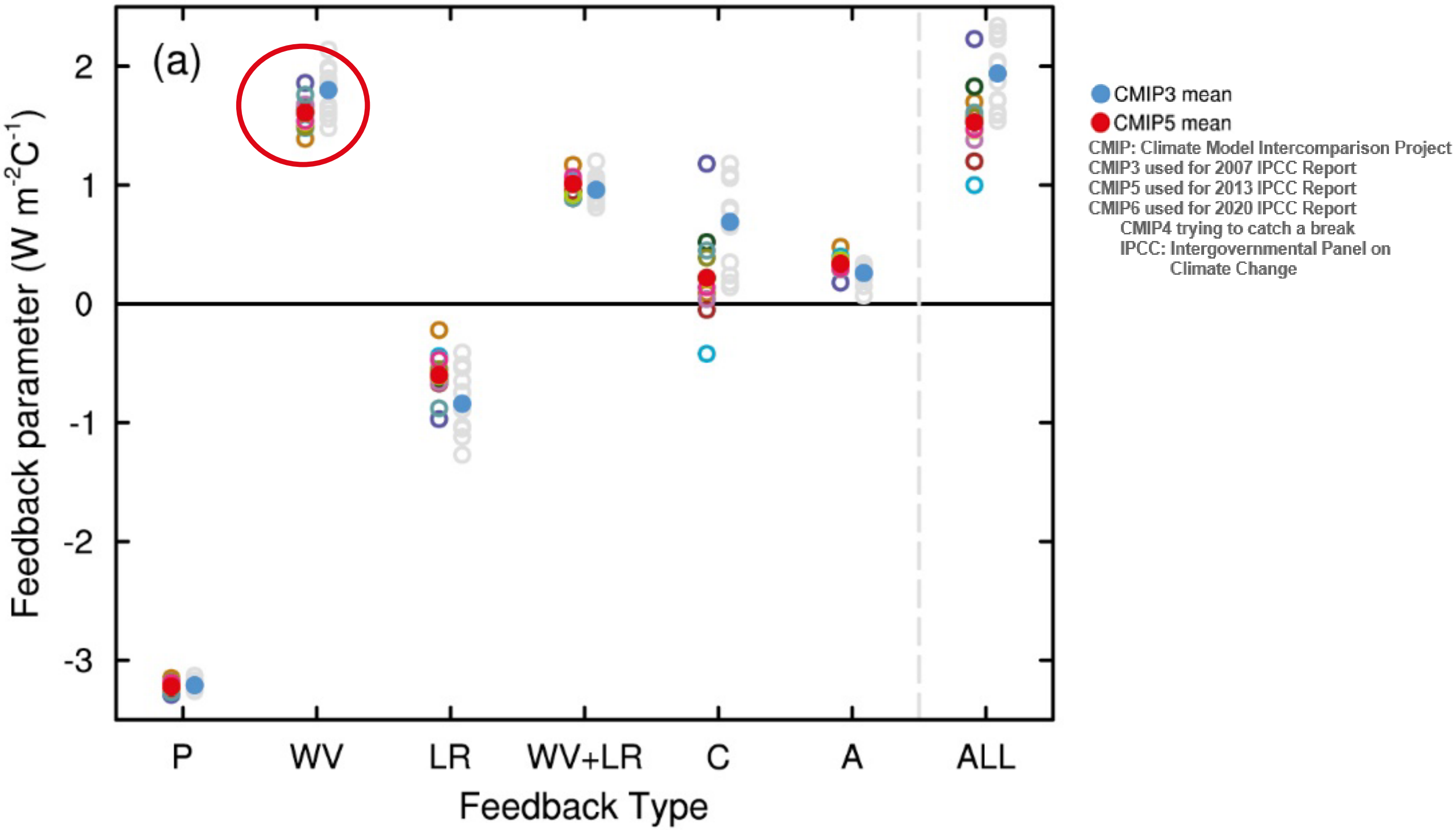


Figure 5. The 15-year time series of global height anomalies from March 2000 to February 2015. Corrected for shift in glitter pattern (brown), and uncorrected (blue). Data have been smoothed by a 12 month running mean.

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

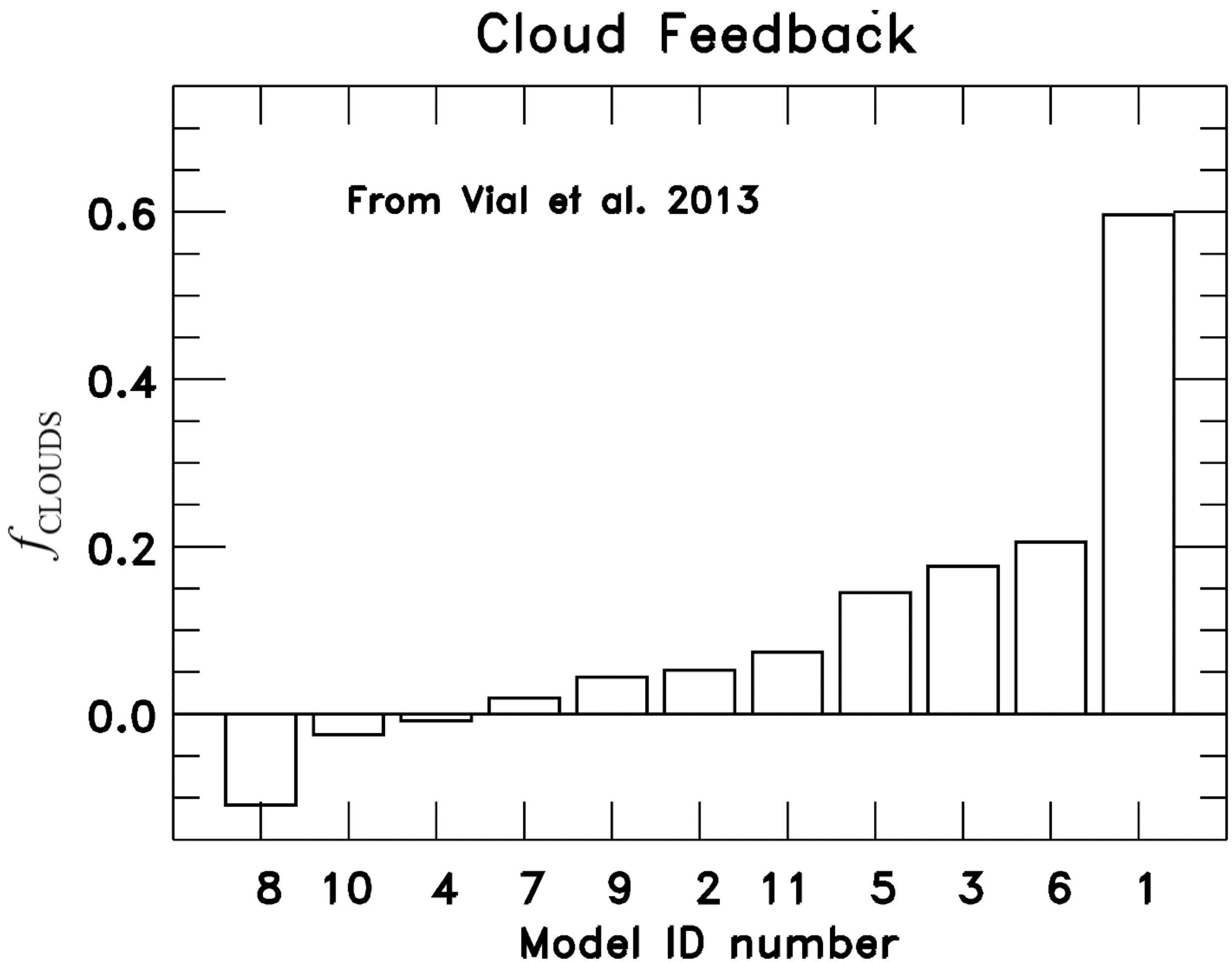


If $FB_{WV} = 1.6\ \mathrm{W\ m^{-2}\ K^{-1}}$ and we assume other feedbacks are zero, then:

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

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

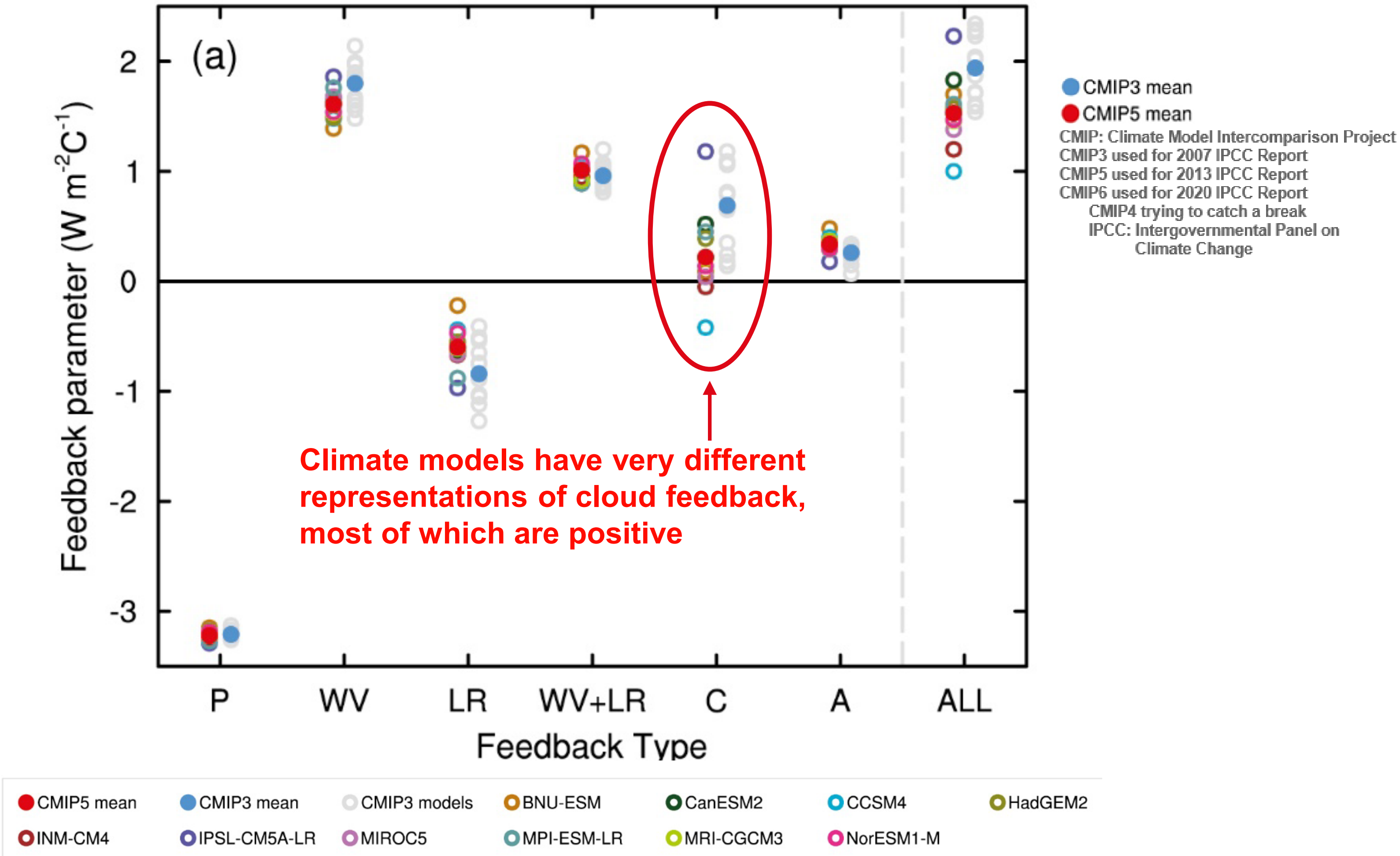
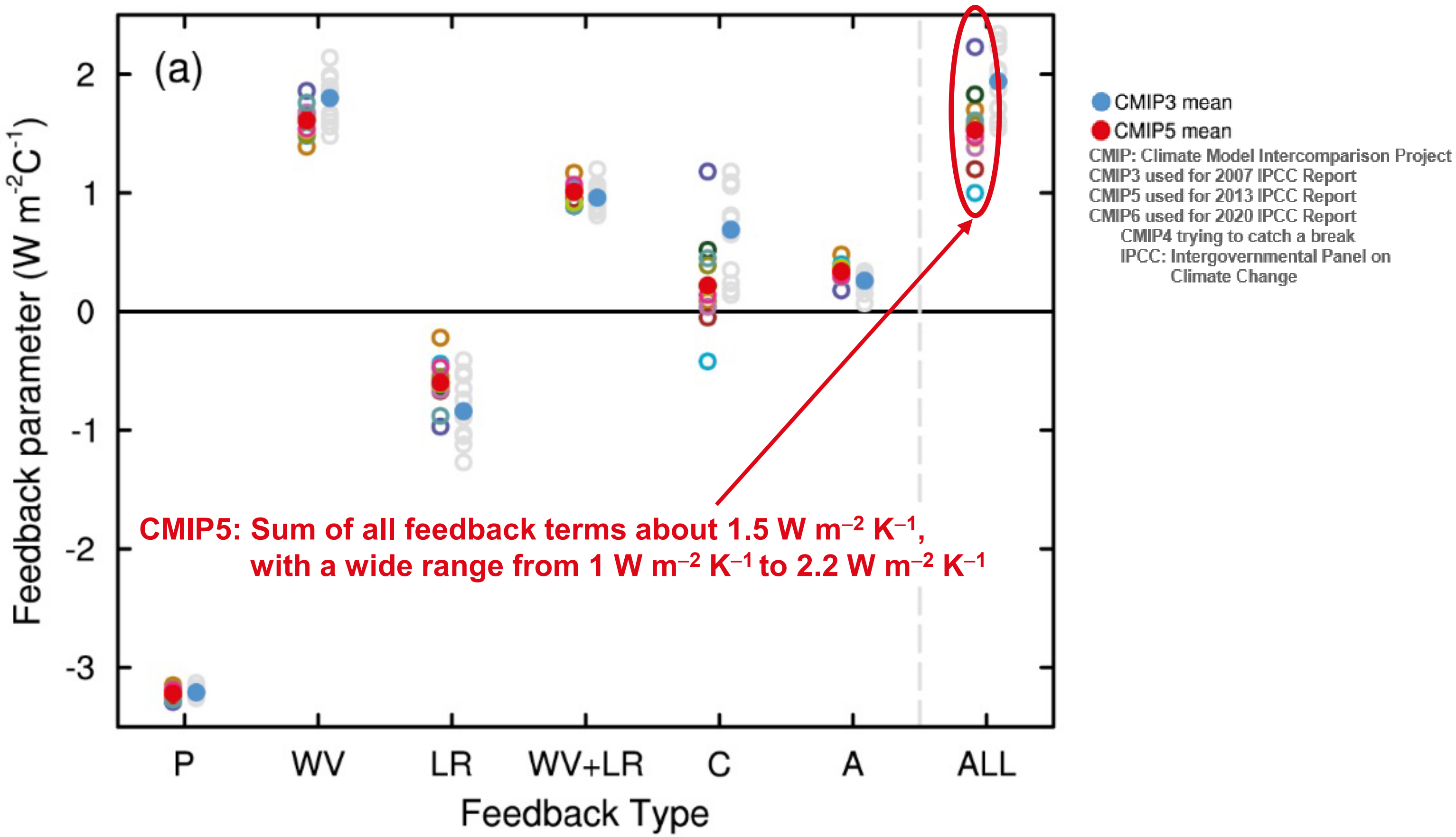


Fig 9.43, IPCC 2013

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 $FB_{ALL} = 1.0\ \mathrm{W\ m^{-2}\ K^{-1}}$ (upper 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

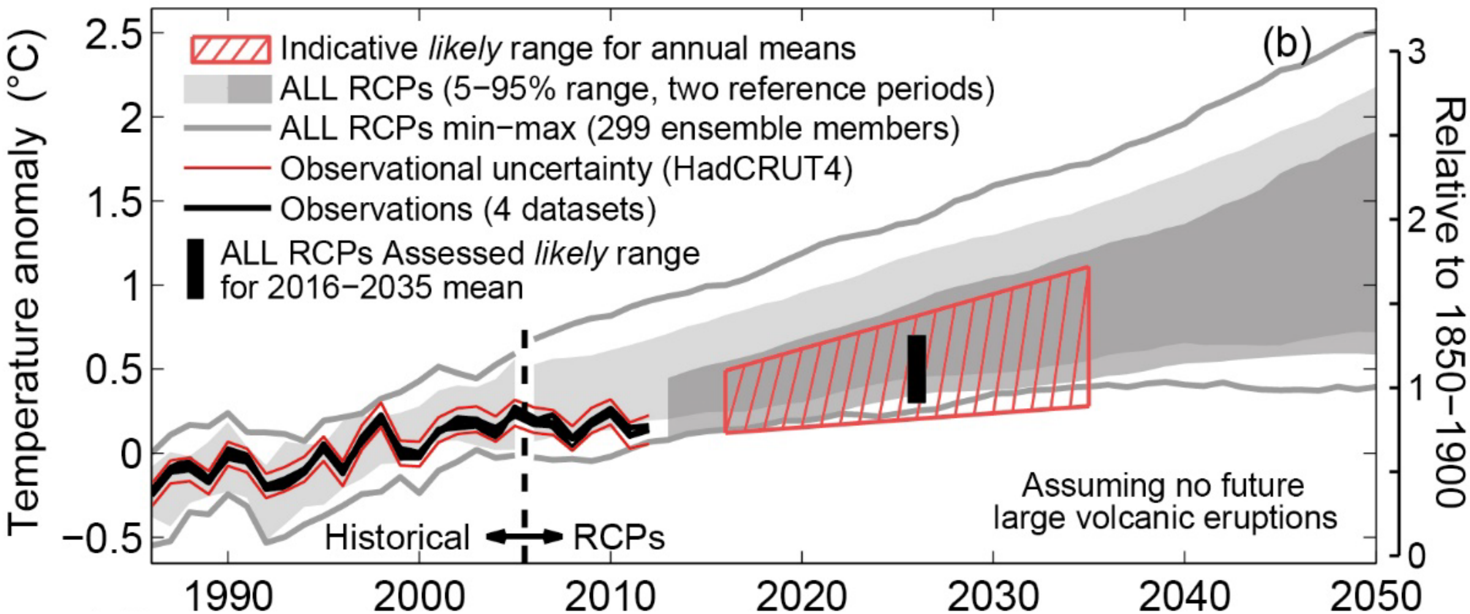


Fig 11.25b, IPCC (2013)

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

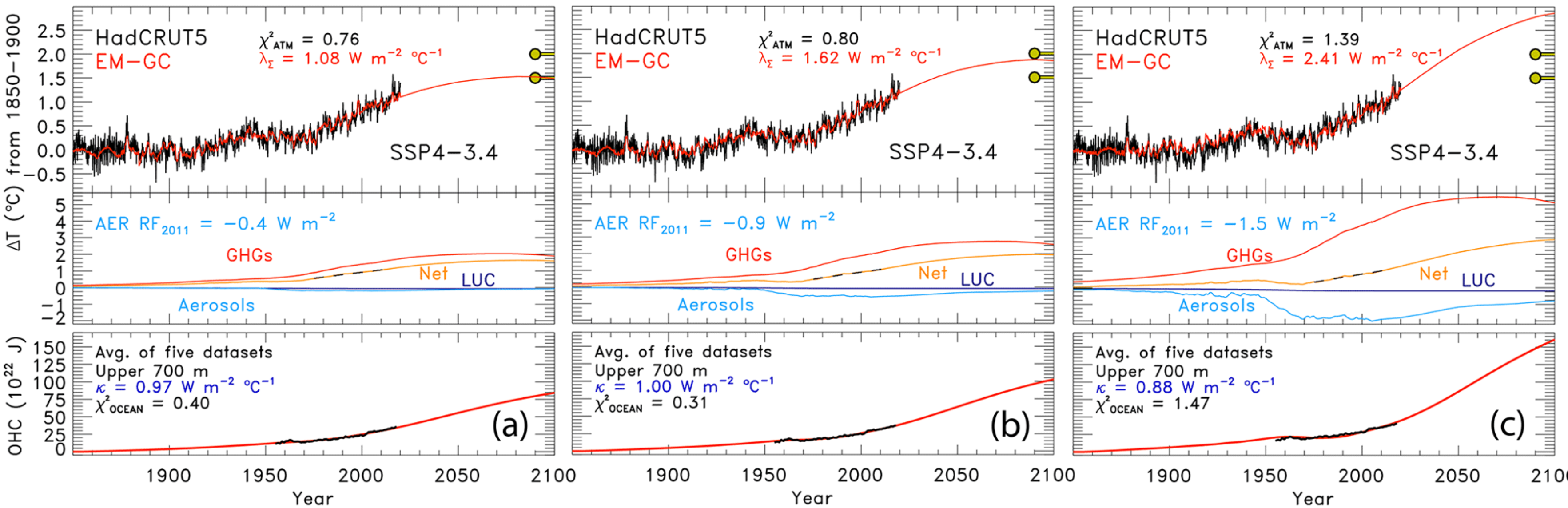
Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

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

where:

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

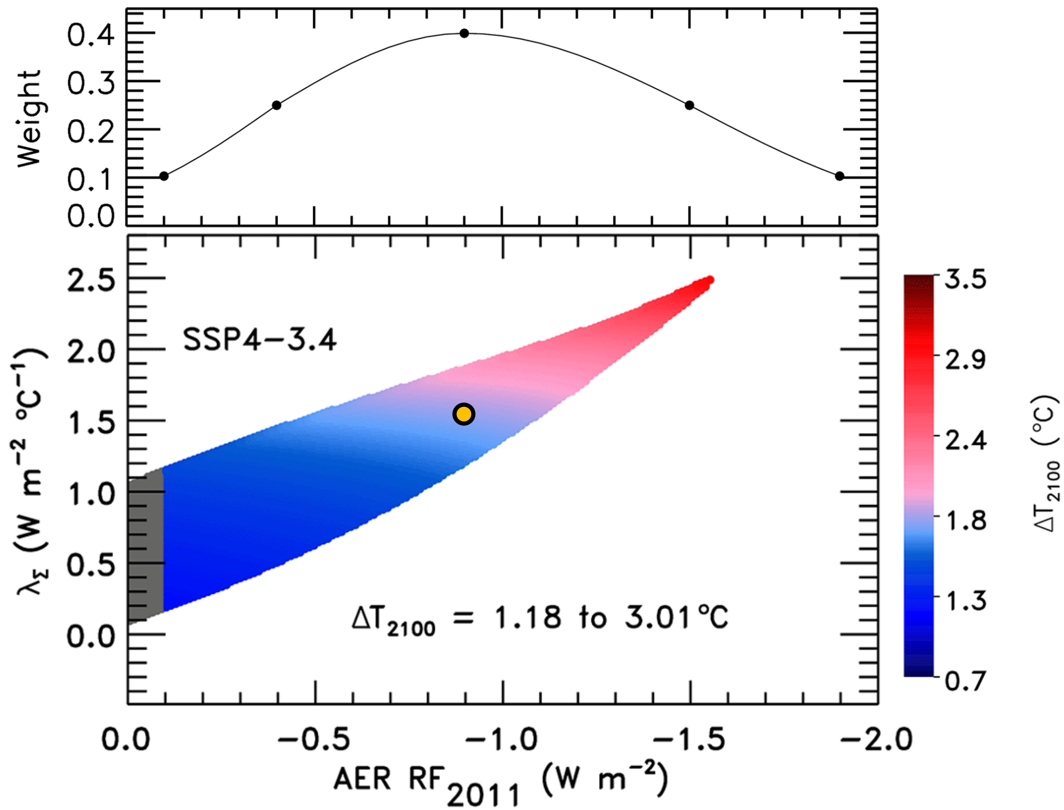
OHE = ocean heat export



McBride *et al.*, 2021

https://esd.copernicus.org/articles/12/545/2021

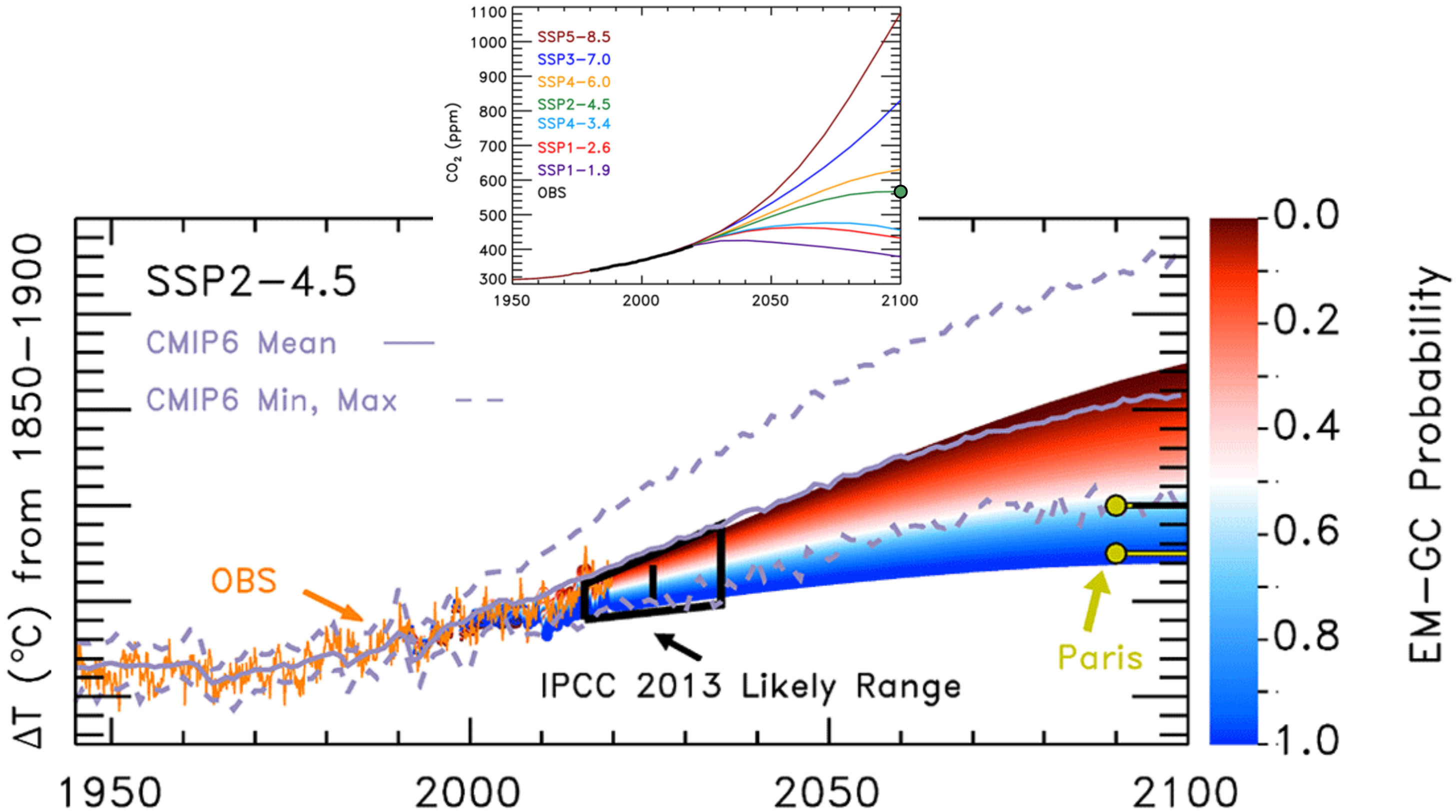
End of Century Warming, SSP4-3.4, as a fn of Feedback & Aerosol RF



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

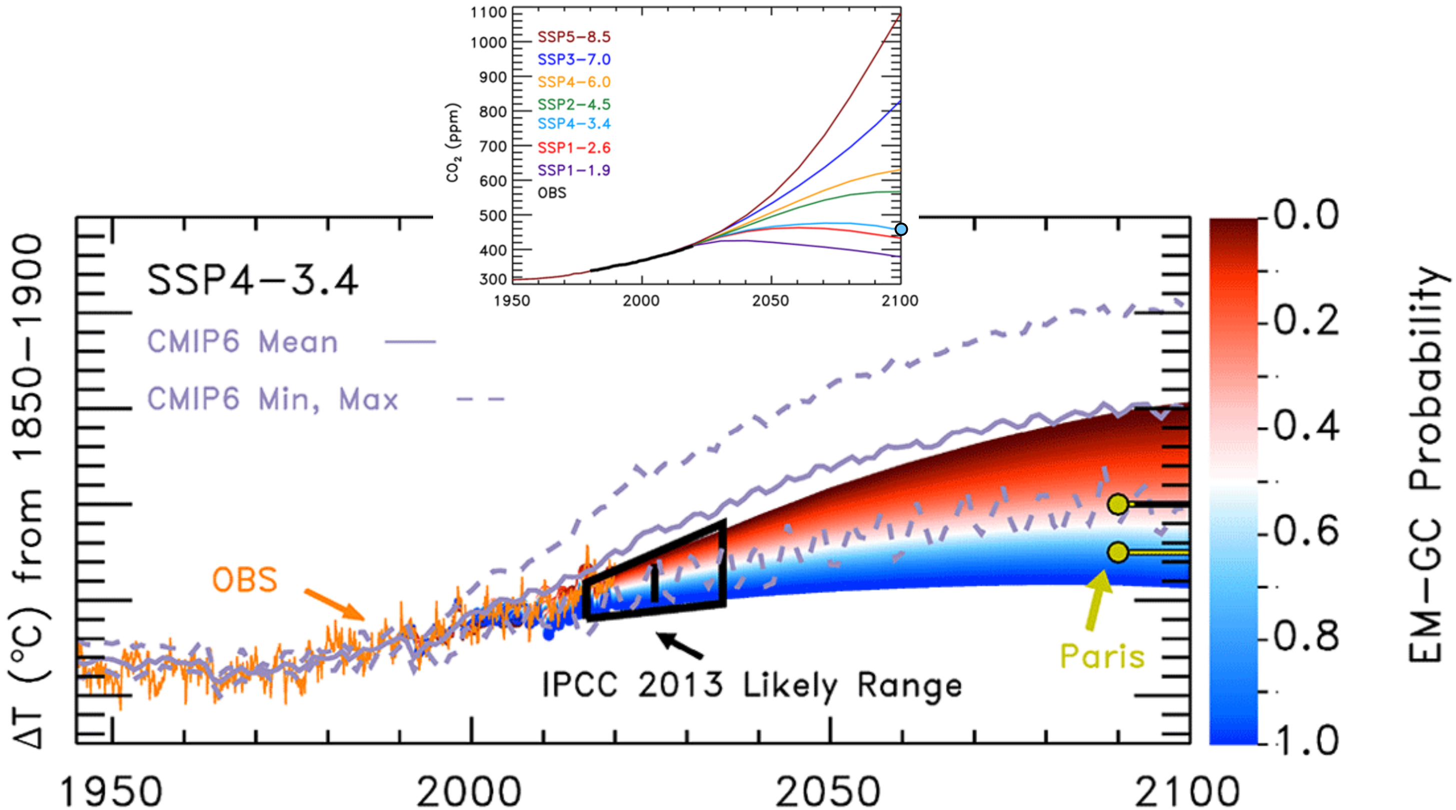


If GHGs follow SSP2-4.5, **2%** chance rise GMST stays below **1.5°C** and **33%** chance stays below **2.0°C**

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

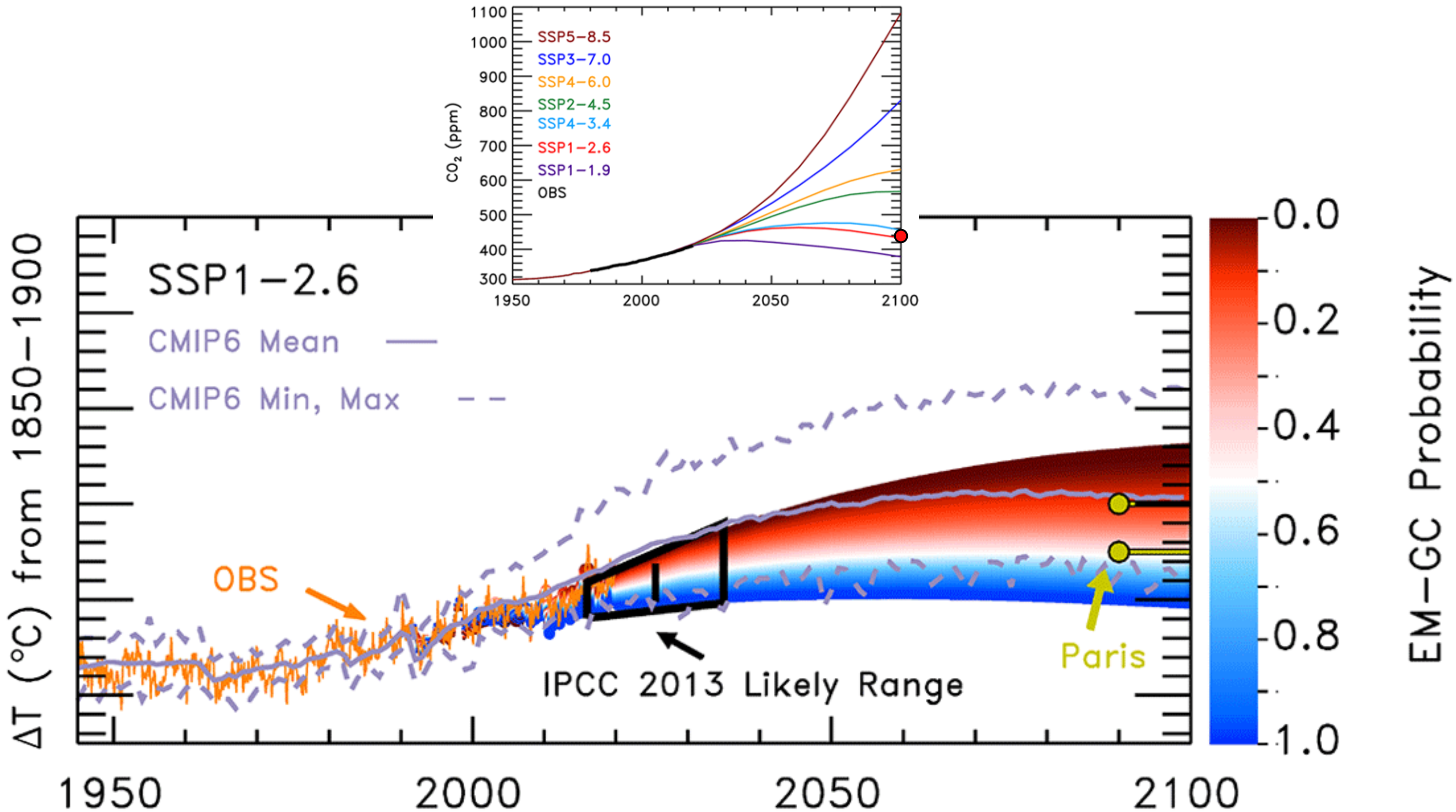


If GHGs follow SSP4-3.4, **19%** chance rise GMST stays below **1.5°C** and **64%** chance stays below **2.0°C**

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

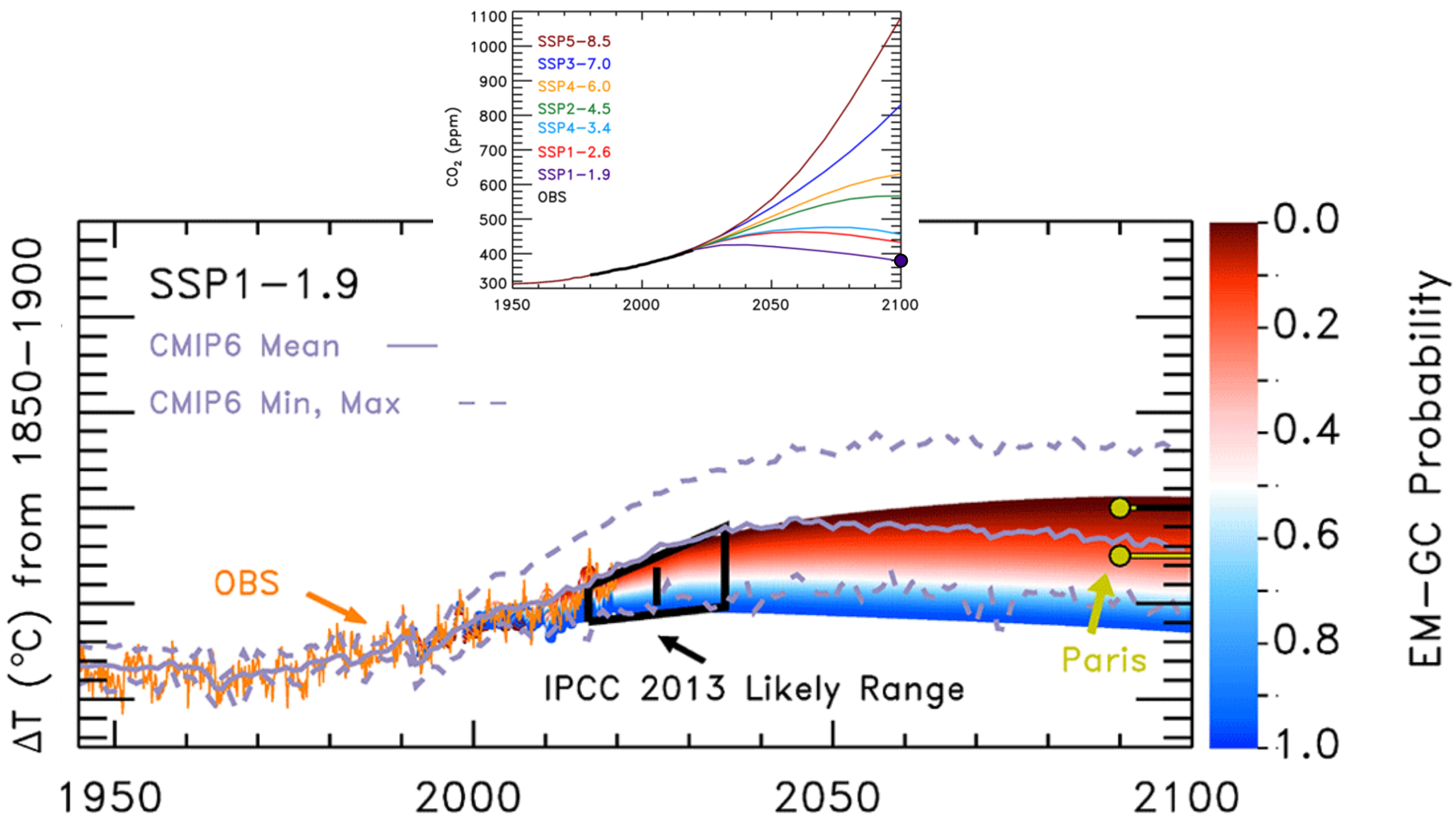


If GHGs follow SSP1-2.6, **53%** chance rise GMST stays below **1.5°C** and **86%** chance stays below **2.0°C**

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 ***Human-Induced Rise in GMST*** 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