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

AOSC / CHEM 433 & AOSC / CHEM 633

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2020
https://myelms.umd.edu/courses/1291919

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

29 September 2020

Announcements: Class

- No admission ticket for Thursday's lecture (hip hip, horray!)

- Problem Set #2 due Fri, 2 Oct, 5 pm (boo dat!)
  - Has been posted
  - Slightly different assignment for students enrolled in 433 & students enrolled in 633

09/24	Radiative Forcing	Chemistry in Context, Sec 2.4, 2.5, 2.6, 3.3 & 3.4 (14 pages) Paris Beacon of Hope Sec 1.2 (intro), 1.2.1 (please review), & 1.2.3.6 (8 pages)	AT 7	Lecture 7 2020 Zoom Video		Green Chemistry, Chapter 3.4 (Sections 3.4.4.1 to 3.4.4.4 provide a nice mathematical complement to the lecture material) Myhre *et al.*, *GRL*, 1998 Bera *et al.*, *JPC*, 2009	Quiz 7
09/29	Modeling Earth's Climate: Water Vapor, Aerosol, Cloud, & Albedo Feedbacks	Chemistry in Context, Sec 3.9 (6 pages) Houghton, pg 105-116	AT 8	Lecture 8 2020 Zoom Video		Bony et al., 2006	Quiz 8
10/01	Consequences of Climate Change	Chemistry in Context, Sec 3.10 (5 pages) Forbes Article	No AT	Lecture 9 2020 Zoom Video		Union of Concerned Scientists Climate Reality Project Climate Change and Disease NY Times, Bangladesh NY Times, Kiribati	No Quiz
10/02					**Problem Set 2 due today at 5 pm:** **433 Students** **633 Students**		

http://www2.atmos.umd.edu/~rjs/class/fall2020

Announcements: Outside of Class

1) Thurs, 1 Oct : AOSC Weekly Seminar (3:30 pm)

Dr. Erik van Sebille, Utrecht University

Chasing Water: How ocean currents transport plastic & plankton around the globe

The ocean is in constant motion, with water circulating within and flowing between basins. As the water moves around, it carries heat and nutrients, as well as planktonic organisms and plastic litter around the globe.

The most natural way to study the pathways of water and the connections between ocean basins is using particle trajectories. The trajectories can come from either computing of virtual floats in high-resolution ocean models.

In this seminar, I'll give an overview of some recent work with Lagrangian particles. I will introduce our new open-source oceanparcels.org framework. I will show applications to marine microbiology and ecology, palaeoclimatology and plastic pollution. Central to each of these studies is the question on how connected the different ocean basins are, and on what time scales water flows between the different regions of the ocean.

https://aosc.umd.edu/seminars/department-seminar

Email Joseph Knisely at jknisely@umd.edu for Zoom connection info

Radiative Forcing of Climate, 1750 to 2011

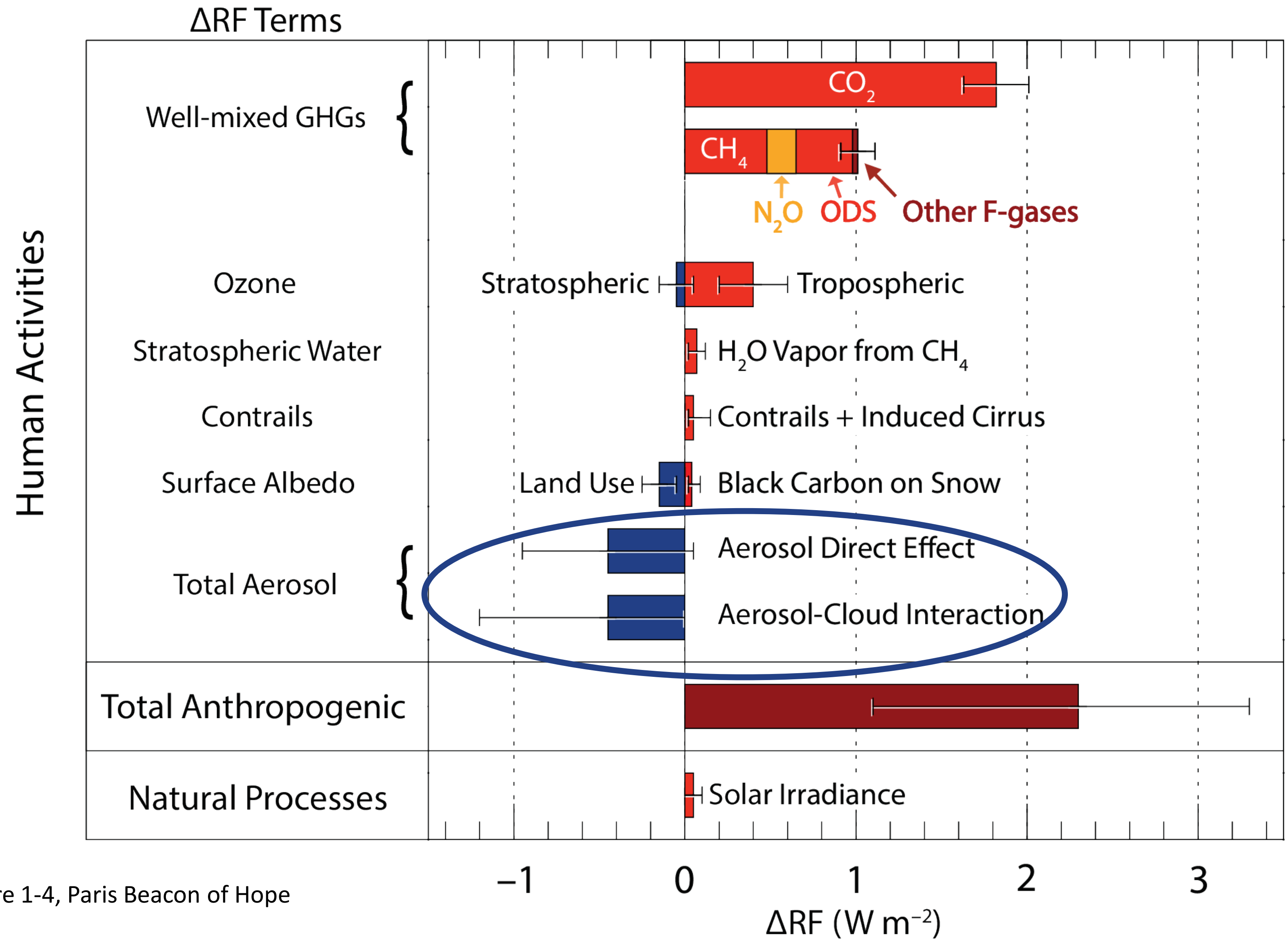

Figure 1-4, Paris Beacon of Hope

Radiative Forcing (RF) Due to Tropospheric Aerosols

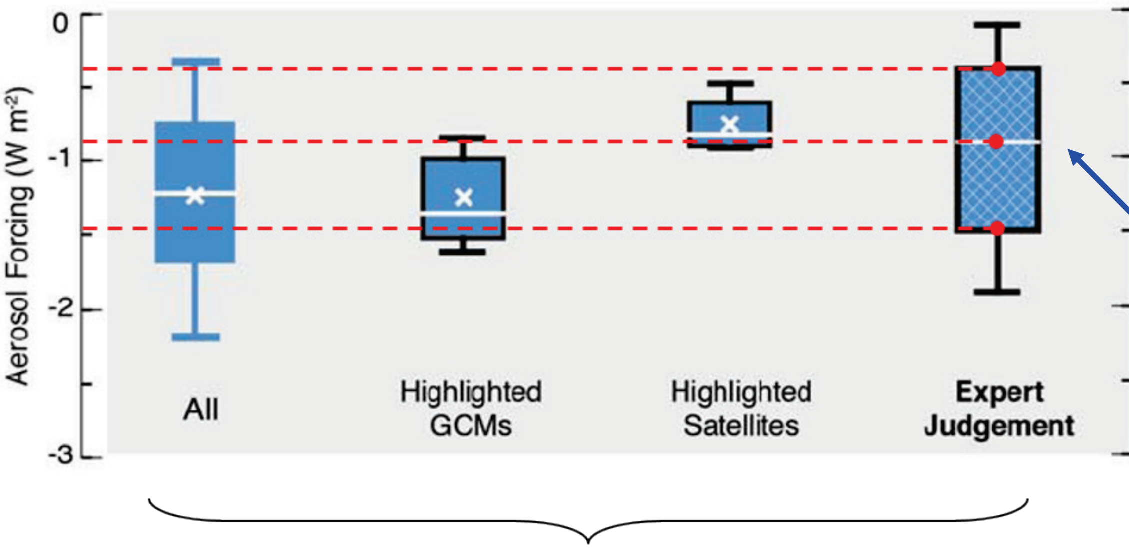

Figure 7.19B, IPCC 2013

Box & Whisker Plots:
mean (X), median (middle line)
17th and 83th percentiles
(likely range; boundaries)
5th and 95th percentiles (whiskers)

IPCC (2013) estimates of Aerosol$_{RF}$ 2011:
best estimate: –0.9 W m^{-2}
likely range: –0.4 W m^{-2} to –1.5 W m^{-2}
5th and 95th percentiles: –0.1 W m^{-2} to –1.9 W m^{-2}

ΔRF$_{1750 \text{ to } 2011}$ All Anthropogenic GHGs ≈ 3.2 W m^{-2}
⇨ climate change is complex but this quantity is ***well known***

Dang problem is we do not know whether climate system has responded to a low (–0.1 to –0.4 W m^{-2}), moderate (–0.9 W m^{-2}), or large (–1.5 to –1.9 W m^{-2}) offset to GHG induced rise in RF of climate

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

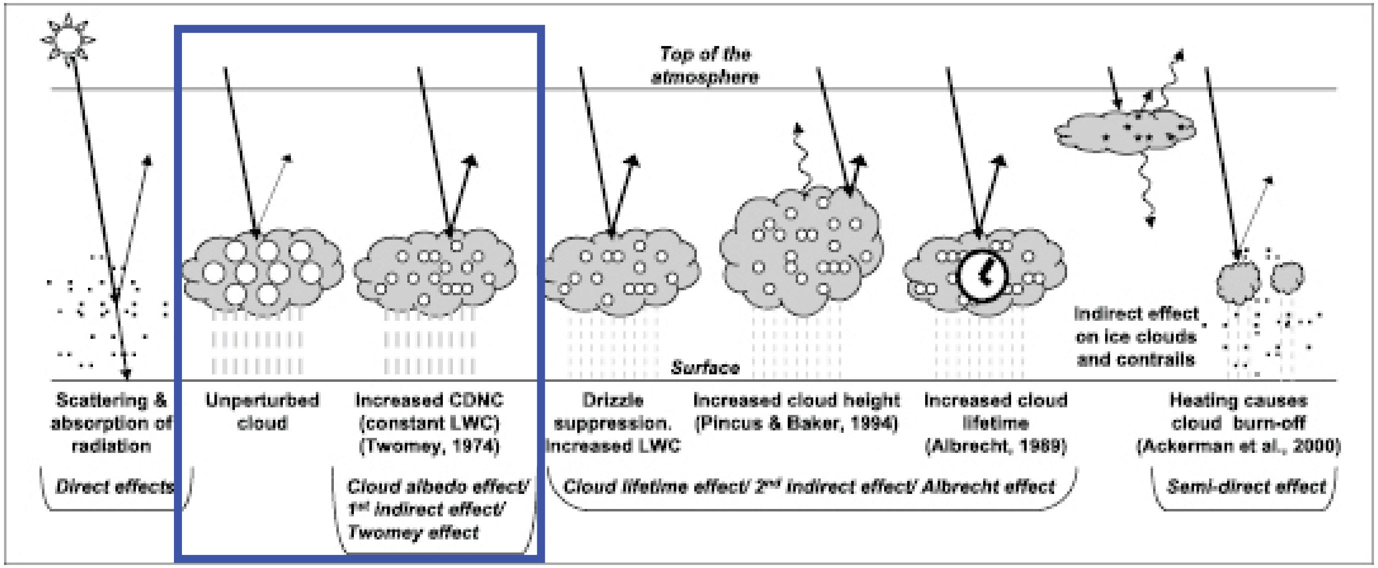

Fig 2-10, IPCC 2007

Large uncertainty in aerosol RF

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

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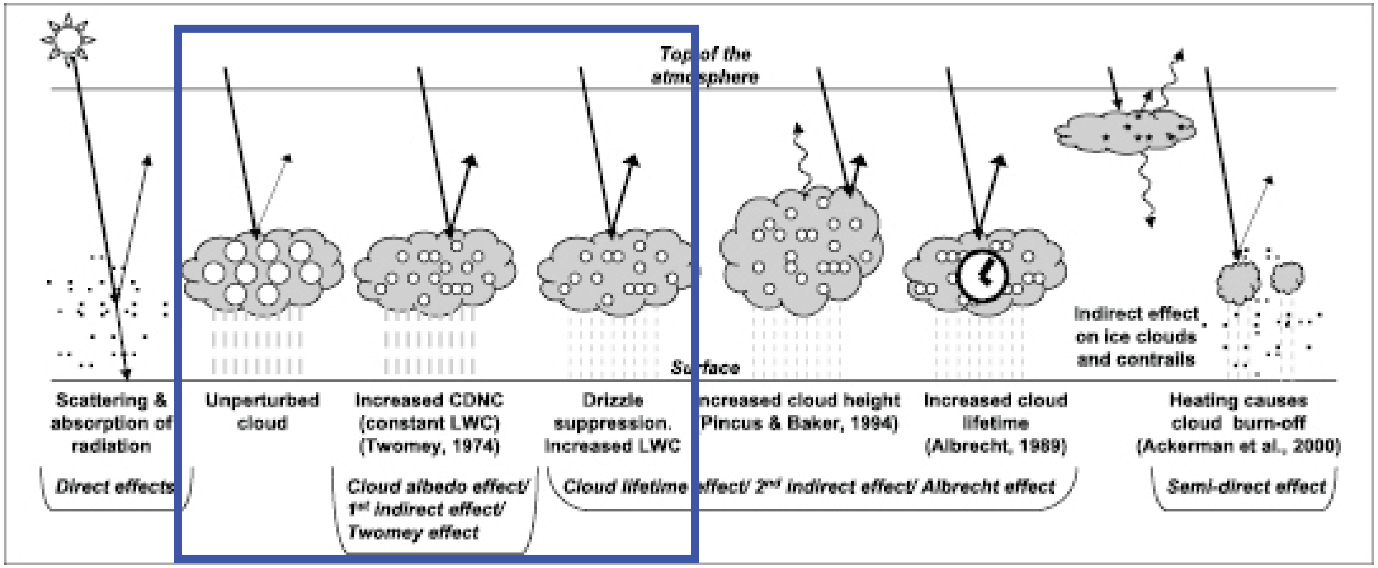
Resulting cloud particles consist of smaller droplets, promoted by more sites (CCN) for cloud nucleation
The cloud that is formed is therefore brighter (reflects more sunlight) ***and*** has less efficient precipitation, i.e. is longer lived) ⇨
Albrecht effect, aka 2nd Indirect Effect



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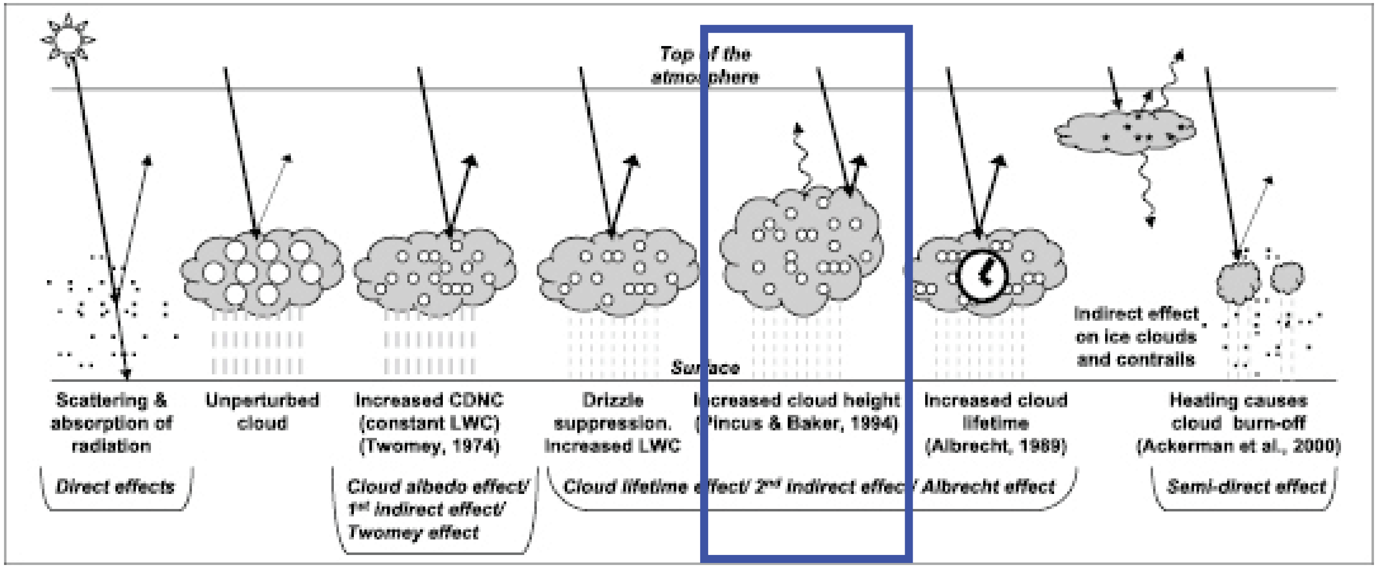


Fig 2-10, IPCC 2007

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 61*

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

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

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

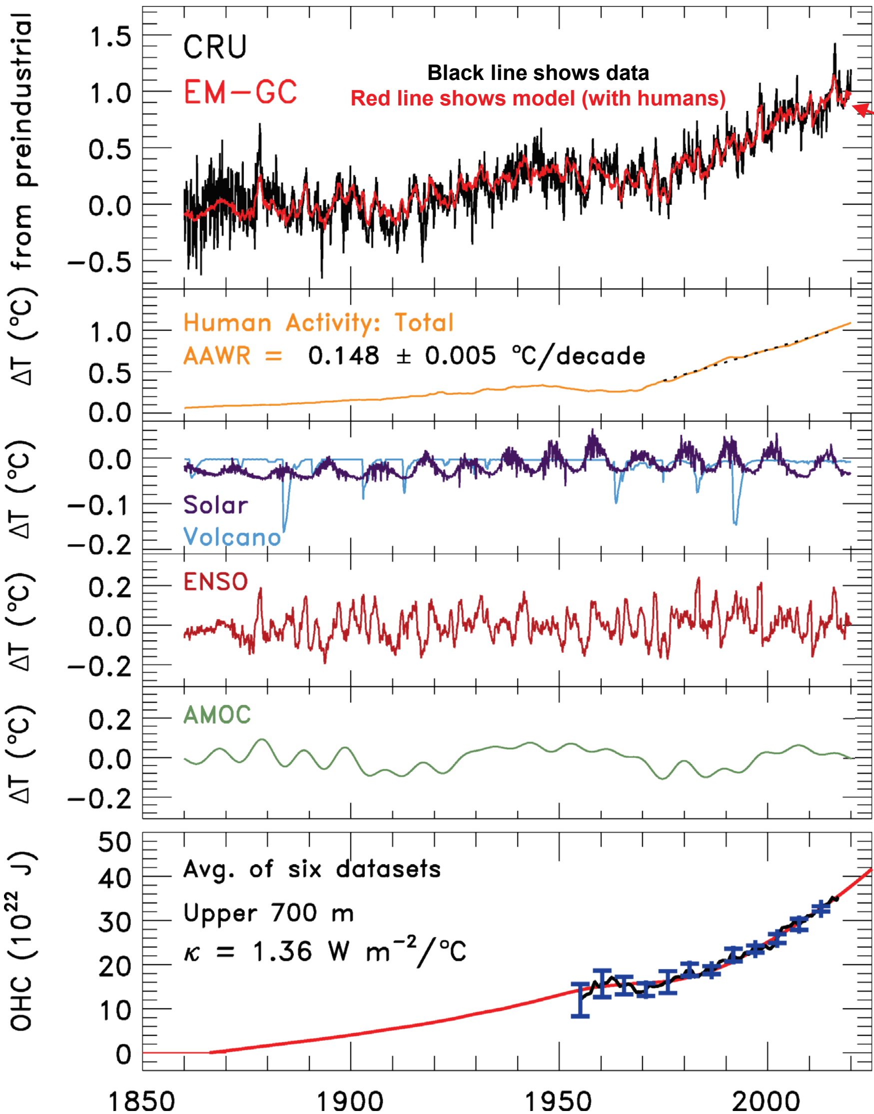
and $FB_{TOTAL} = FB_{WATER\ VAPOR} + FB_{LAPSE\ RATE} + FB_{CLOUDS} + FB_{SURFACE\ ALBEDO} + \text{etc}$

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}.

See Lecture 4, Slides 66 to 69

Are humans responsible?



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

$$\Delta T = \lambda_P\,(1 + f_{TOTAL})\,(\Delta F_{CO_2} + \Delta F_{CH4+N2O} + \Delta F_{OTHER\ GHGs} + \Delta F_{AEROSOLS}) - OHE$$

Here, $f_{TOTAL} = 0.99$

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:

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

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

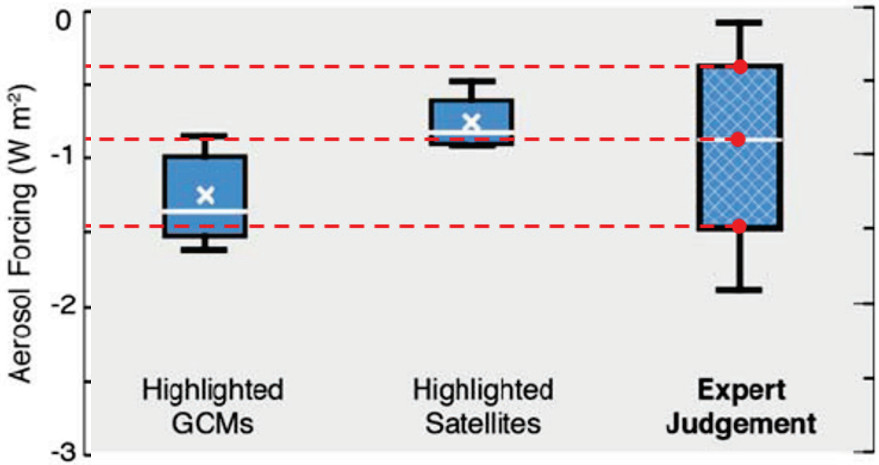
Each FB term has units of W m^{-2} K^{-1}, the recipricol of the units of λ_P

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

Similar to *Lecture 2, Slide 37*

Canty *et al.*, 2013 https://www.atmos-chem-phys.net/13/3997/2013/acp-13-3997-2013.html
Hope *et al.*, 2017 https://link.springer.com/chapter/10.1007/978-3-319-46939-3_2
as well as Hope *et al.* (2020, submitted) & McBride *et al.* (2020, submitted).
Figure provided by Laura McBride.

Tropospheric Aerosol RF:
1750 to 2011



Box & Whisker Plots:
mean (X), median (middle line)
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Figure 7.19B, IPCC 2013

ΔRF_{2011} GHGs ≈ 3.2 W m^{-2} ⇨ climate change is complex but this quantity is ***well known***

ΔRF_{2011} Aerosols: best estimate is –0.9 W m^{-2}, probably between –0.4 W m^{-2} and –1.5 W m^{-2}; could be between –0.1 W m^{-2} and –1.9 W m^{-2}

Large uncertainty in aerosol RF

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

Slide 57, Lecture 7

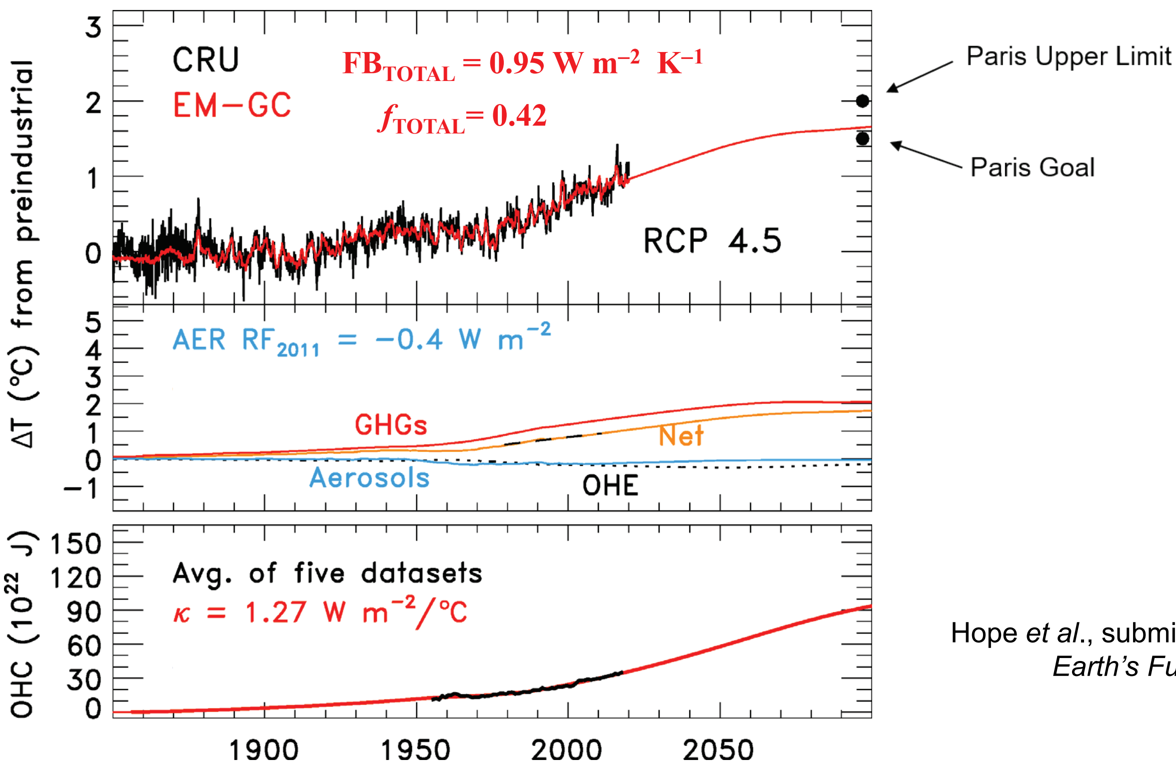
Uncertainty in RF due to aerosols is a huge complication that places a fundamental uncertainty on how well future global warming can be forecast

$$\Delta T \approx \lambda_P \, (1 + f_{TOTAL}) \, \Delta RF - OHE \quad ; \qquad 1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL} \, \lambda_P}$$

f_{TOTAL} : total feedback term (dimensionless) due to water vapor, lapse rate, clouds, etc. that directly amplifies RF

FB_{TOTAL} : sum of individual feedback terms (units W m^{-2} K^{-1}) computed using IPCC formalism

OHE : export of heat from atmosphere to world's ocean



Hope *et al*., submitted to AGU journal *Earth's Future*, 2020.

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **−0.4 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of other feedbacks (clouds, surface albedo) must be ***close to zero***.

Uncertainty in RF due to aerosols is a huge complication that places a fundamental uncertainty on how well future global warming can be forecast

$$\Delta T \approx \lambda_P \, (1 + f_{TOTAL}) \, \Delta RF - OHE \quad ; \qquad 1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL} \, \lambda_P}$$

f_{TOTAL} : total feedback term (dimensionless) due to water vapor, lapse rate, clouds, etc. that directly amplifies RF

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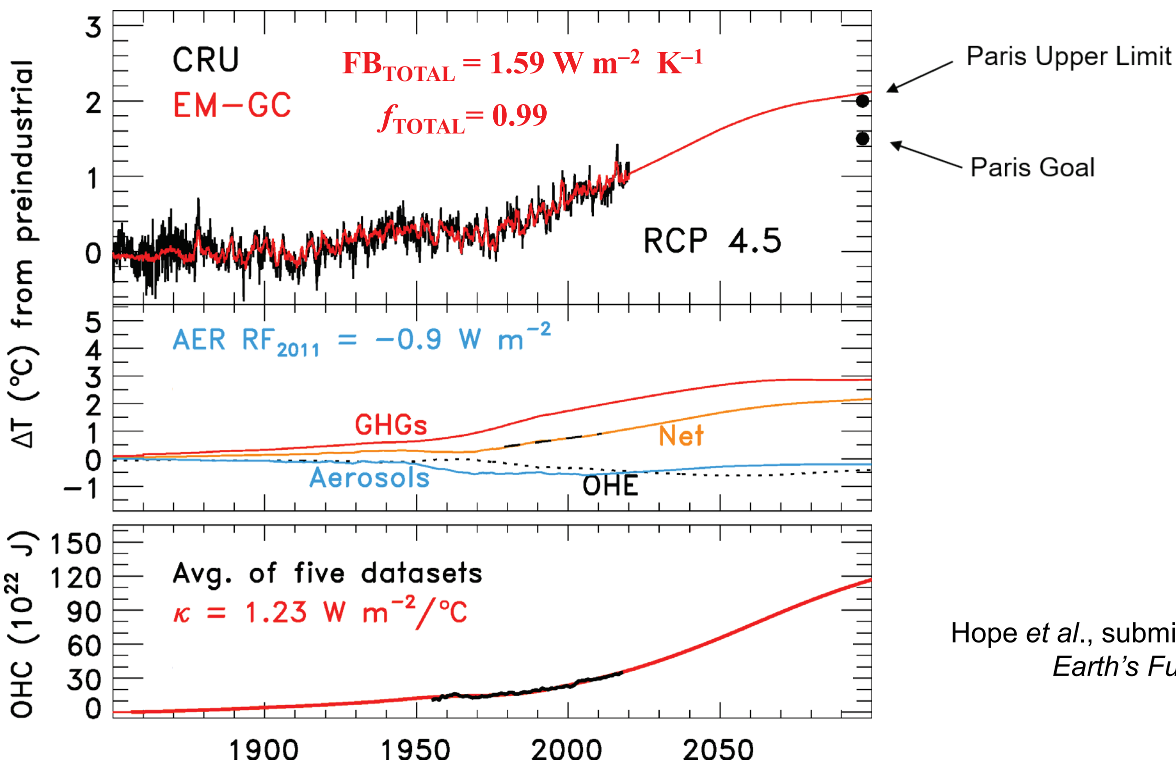

Hope *et al*., submitted to AGU journal *Earth's Future*, 2020.

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **−0.9 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of other feedbacks (clouds, surface albedo) must be ***moderately positive***.

Uncertainty in RF due to aerosols is a huge complication that places a fundamental uncertainty on how well future global warming can be forecast

$$\Delta T \approx \lambda_P \, (1 + f_{TOTAL}) \, \Delta RF - OHE \quad ; \qquad 1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL} \, \lambda_P}$$

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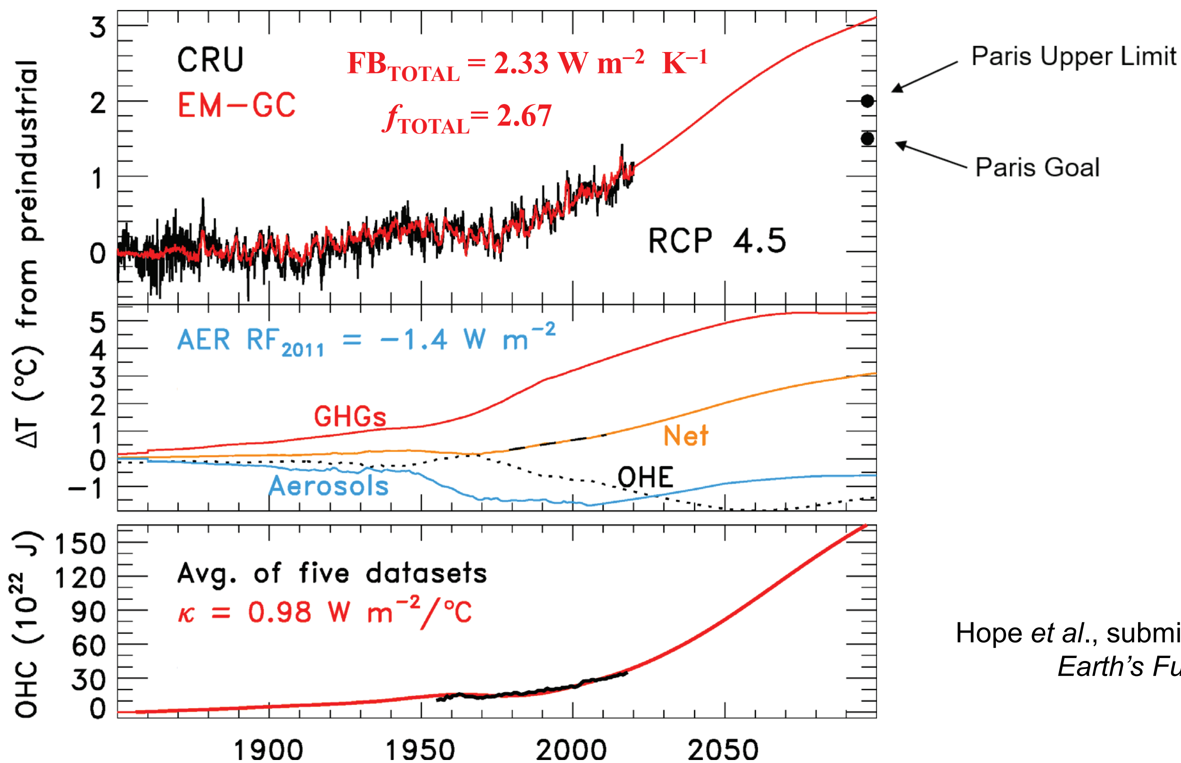


Hope *et al.*, submitted to AGU journal *Earth's Future*, 2020.

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **−1.5 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of <u>other feedbacks</u> (clouds, surface albedo) must be ***strongly positive***.

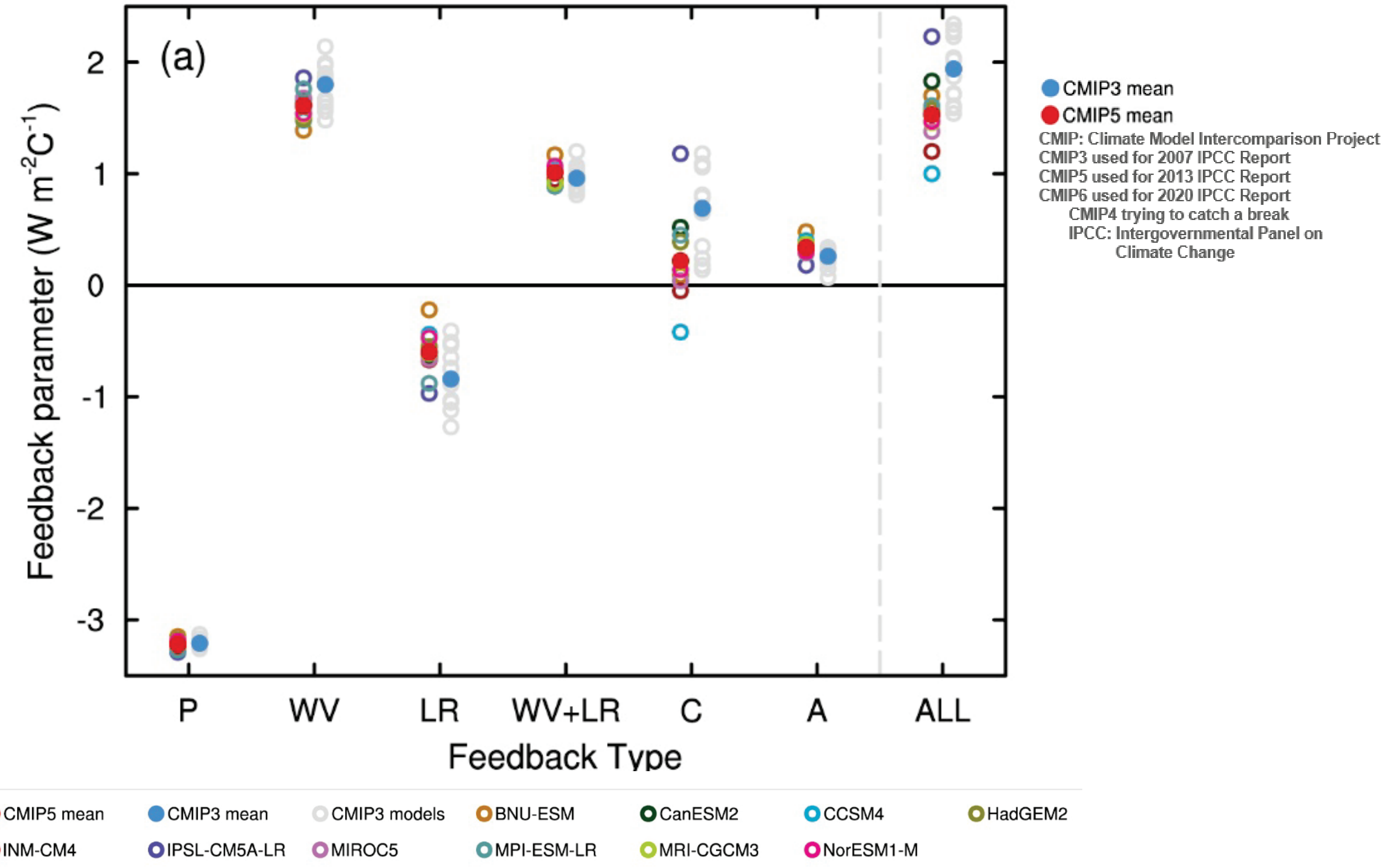
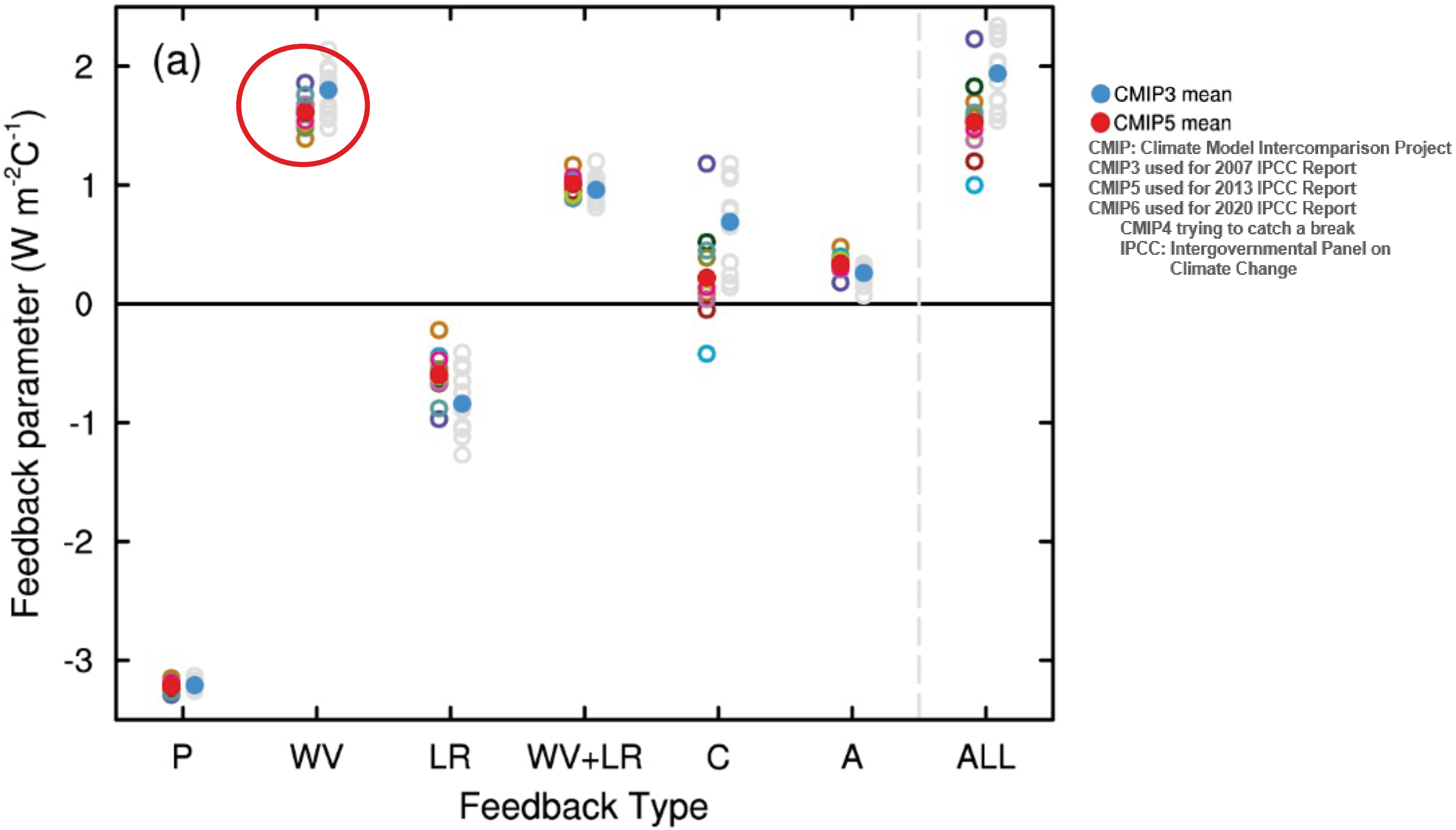


Fig 9.43, IPCC 2013

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

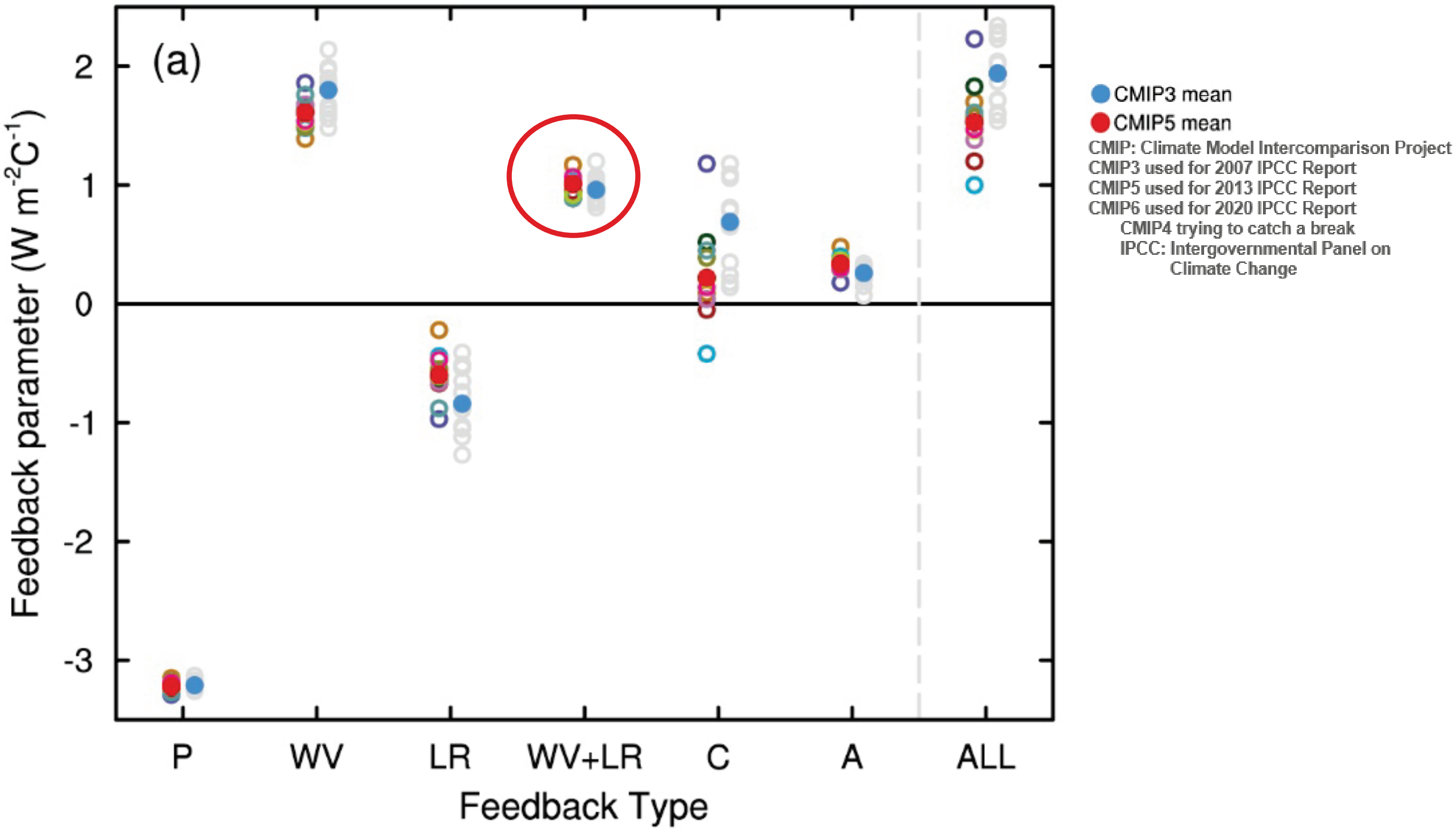
C: Clouds
A: Albedo
ALL: Sum of other feedback terms



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

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

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



If $FB_{WV+LR} = 1.0\ \mathrm{W\ m^{-2}\ K^{-1}}$ and we assume other feedbacks are zero, then:

$$1 + f_{TOTAL} = \frac{1}{1 - 1.0\ \mathrm{W\ m^{-2}\ K^{-1}} \times 0.31\ \mathrm{K\ W\ m^{-2}}} = 1.45$$

Therefore, $f_{TOTAL} = 0.45$; i.e., climate models suggest $f_{WV+LR} = 0.45$

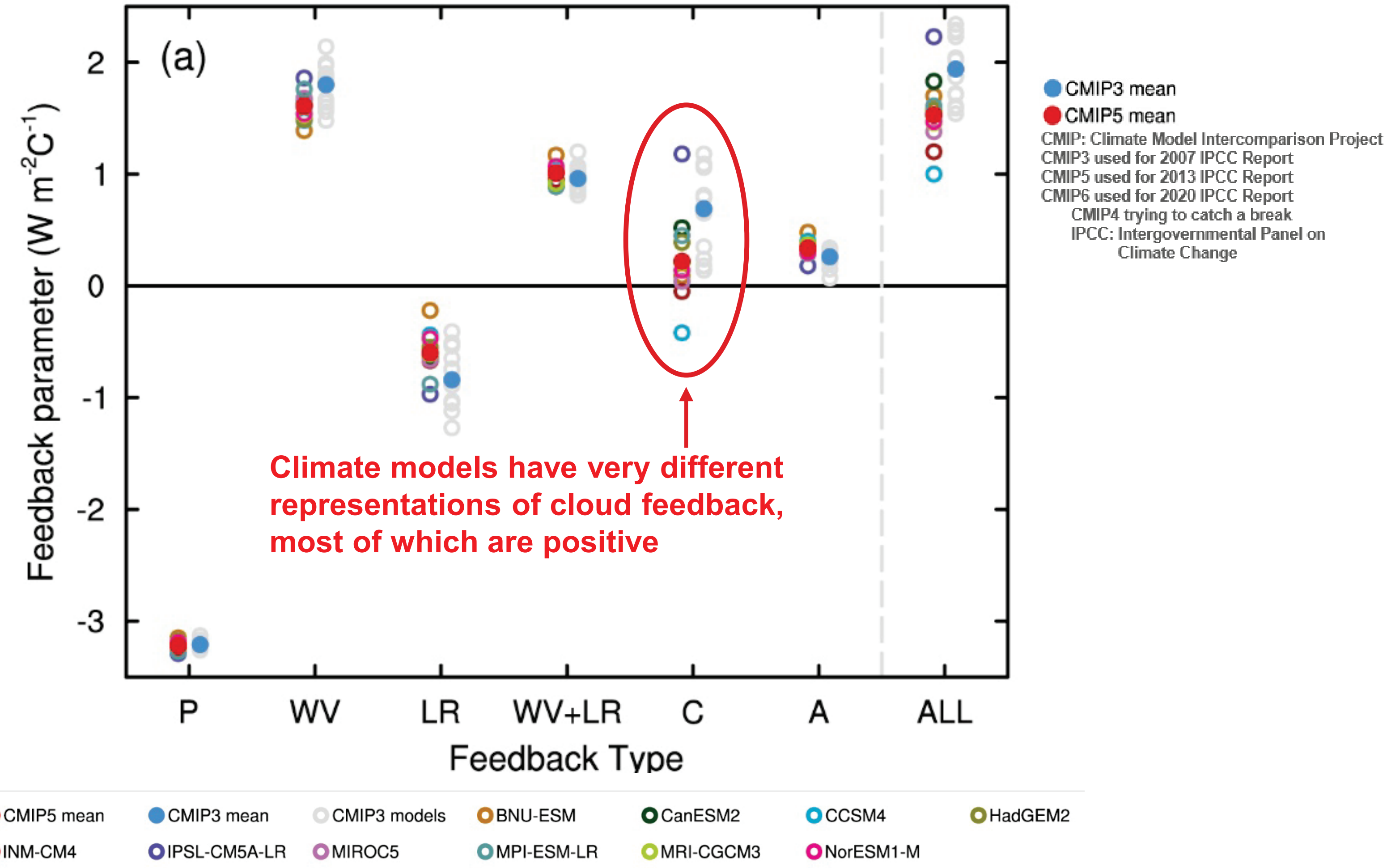


Fig 9.43, IPCC 2013

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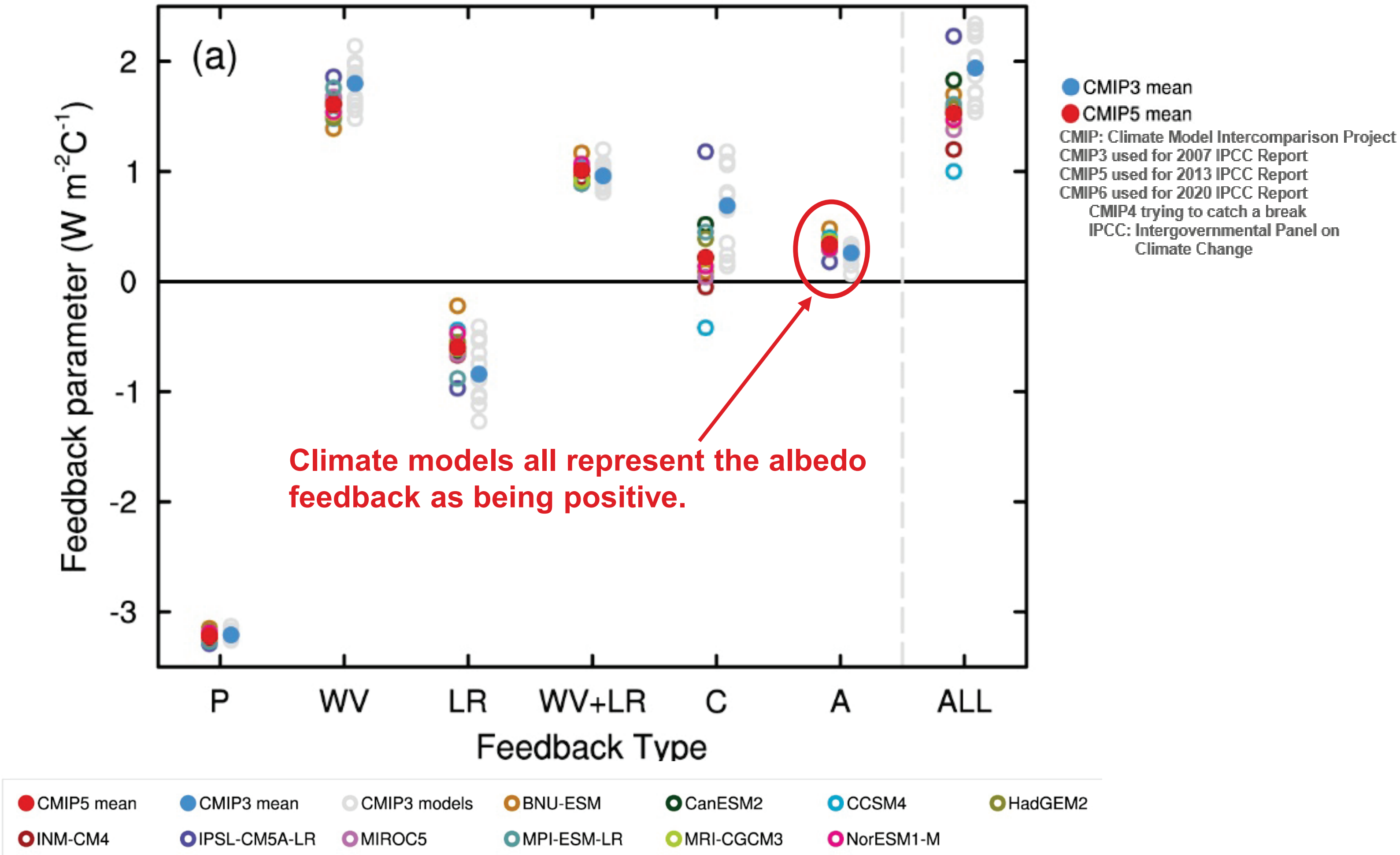
ALL: Sum of other feedback terms



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C: Clouds
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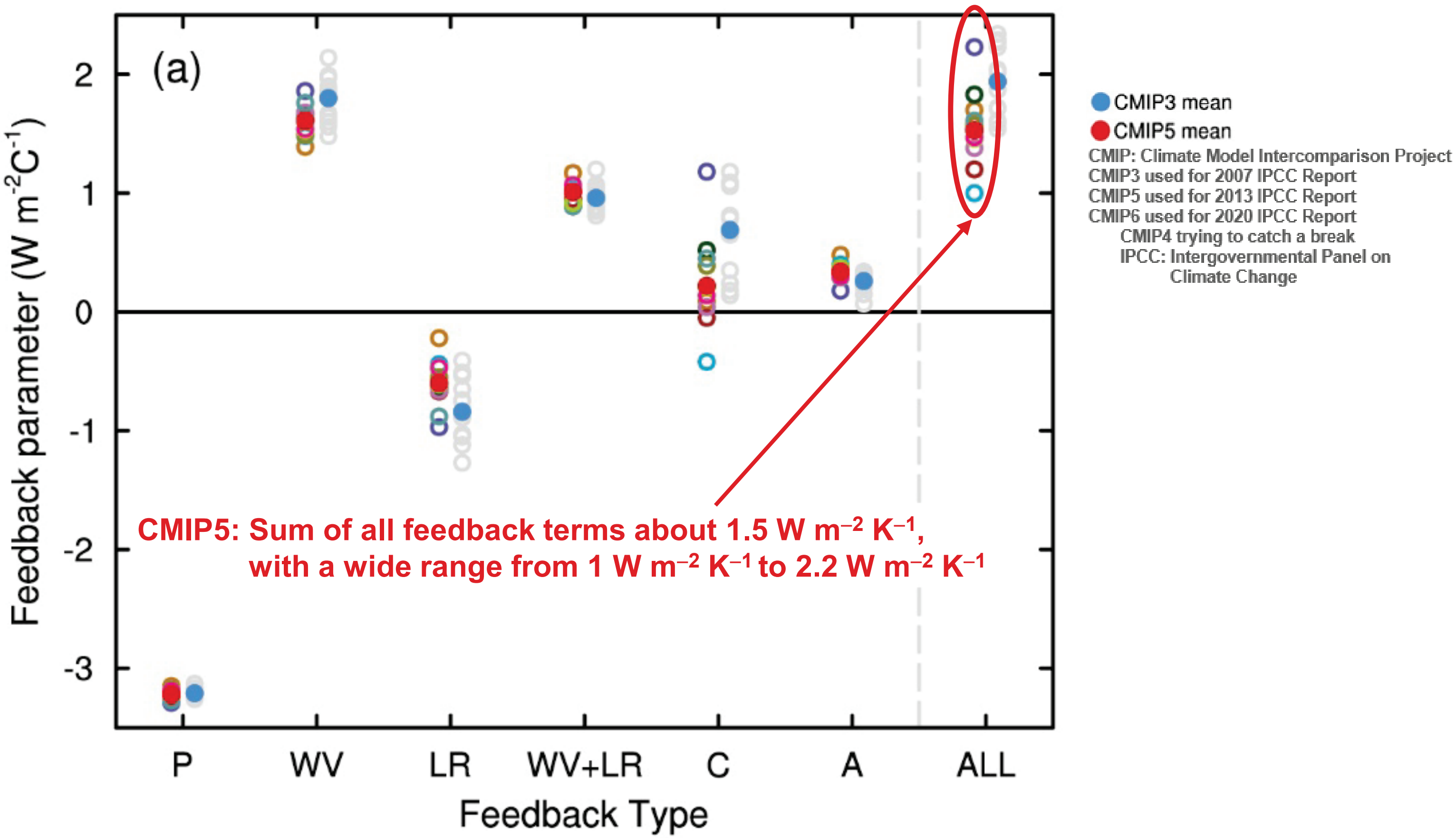
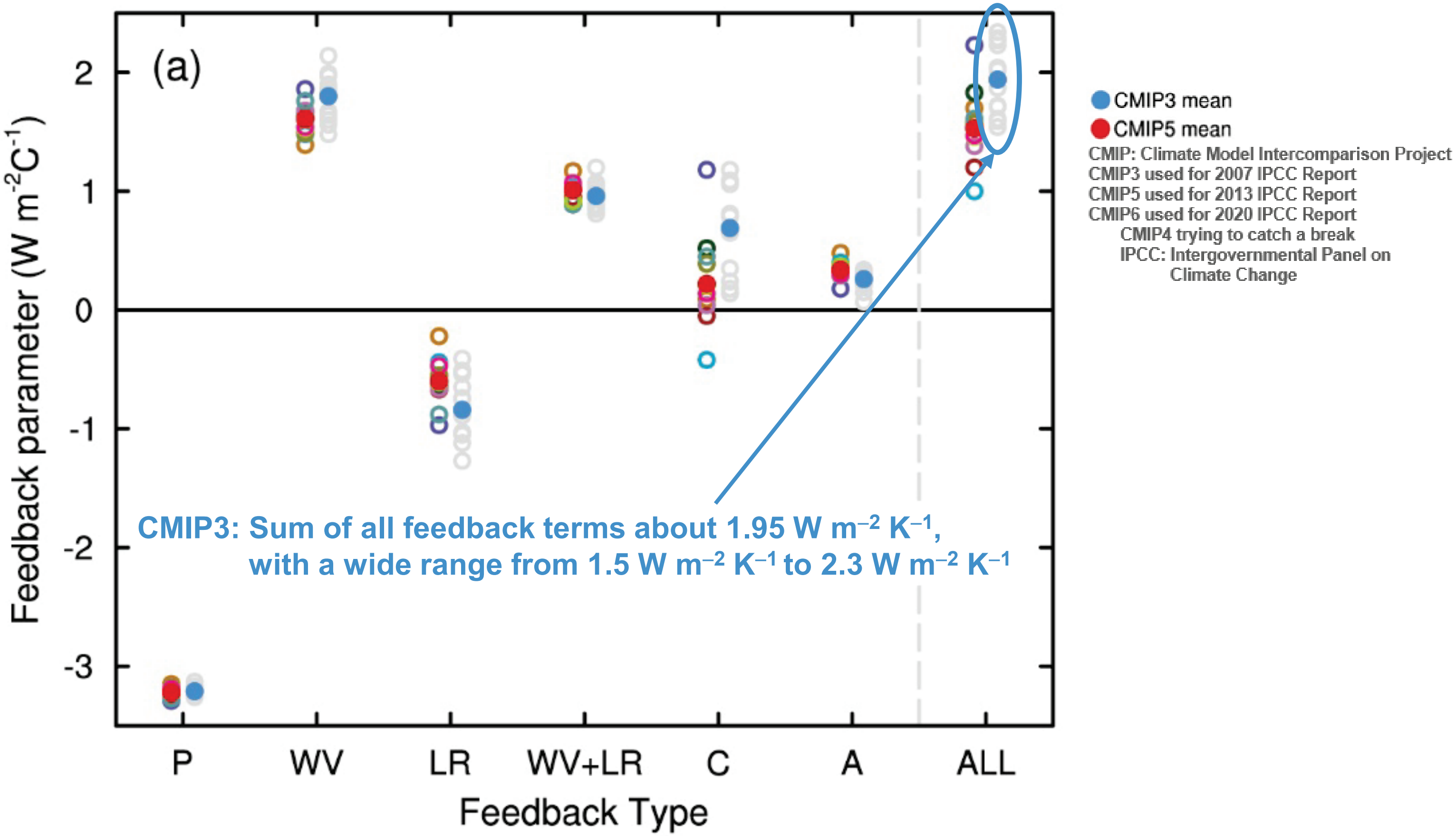
ALL: Sum of other feedback terms



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 $f_{ALL} = 0.87$



If $FB_{ALL} = 1.95\ \mathrm{W\ m^{-2}\ K^{-1}}$ and we assume other feedbacks are zero, then:

$$1 + f_{TOTAL} = \frac{1}{1 - 1.95\ \mathrm{W\ m^{-2}\ K^{-1}} \times 0.31\ \mathrm{K\ W\ m^{-2}}} = 2.53$$

Therefore, $f_{TOTAL} = 1.53$; i.e., CMIP3 climate models suggest $f_{ALL} = 1.53$

AT Question

Question 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?

Correct Answer

- The warming will be amplified by about 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 approximately double the increase in global average temperature that would arise in the absence of any feedbacks.

  Text on page 107 reads "The warming will be approximately double the increase in global average temperature that would arise with fixed water vapour". The question, however, states "with all feedbacks operative" and we had hoped students would realize the correct answers is amplification by a factor of 2.9 (i.e., about 3) based on the text at the bottom of page 113.

Full credit will be given to anyone who gave this answer.

- The warming will be amplified by about a factor of 1.5.

  Sorry, this is not correct based on what is stated in the Houghton reading. Ironically, a faction of 1.5 amplification might be the true actual real-world amplification factor. Here, however, we had hoped students would realize the correct answers is amplification by a factor of 2.9 (i.e., about 3) based on the text at the bottom of page 113.

- The warming will be amplified by about a factor of 4..

  Yikes, we'd all be in trouble if this amplification factor were to happen. Literally, we'd have to head for the hills. Here, however, we had hoped students would realize the correct answers is amplification by a factor of 2.9 (i.e., about 3) based on the text at the bottom of page 113.

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, which could be considered to be approximately 2

AT Question

Climate feedback comparisons

Climate feedbacks affect the *sensitivity* of the climate in terms of the temperature change ΔT_s at the surface that occurs for a given change ΔQ in the amount of net radiation entering the top of the troposphere (known as the radiative forcing[15]). ΔQ and ΔT_s are related by a *feedback parameter f* (units $\mathrm{Wm^{-2}\,K^{-1}}$) according to

$$\Delta Q = f \Delta T_s$$

If nothing changes other than the temperature (see Figure 2.8), f is just the basic temperature feedback parameter $f_0 = 3.2\ \mathrm{W\,m^{-2}\,K^{-1}}$ (i.e. the change in radiation at the top of the troposphere that leads to a 1°C change at the surface).

However, as we have seen other changes occur that result in feedbacks. The total feedback parameter f allows all the feedbacks to be added together:

$$f = f_0 + f_1 + f_2 + f_3 + \ldots$$

where f_1, f_2, f_3 etc. are the feedback parameters describing water vapour, cloud, ice-albedo feedbacks, etc.

The amplification a of the temperature change ΔT_s that occurs with a total feedback parameter f compared with the basic temperature feedback f_0 is

$$a = f_0/f$$

Estimates of the feedback parameters for the main feedbacks from different climate models are:[16]

Water vapour (including lapse rate feedback – see Note 13)	-1.2 ± 0.5
Cloud	-0.6 ± 0.7
Ice albedo	-0.3 ± 0.3
Total feedback parameter (sum of f_0 and the three above[17])	1.1 ± 0.5

Note that with this total feedback parameter the amplification factor is about 2.9 and the resulting climate sensitivity to doubled carbon dioxide a little over 3°C.

Amplification factor $a = f_o / f = 3.2\ \mathrm{W\,m^{-2}\,K^{-1}} / 1.1\ \mathrm{W\,m^{-2}\,K^{-1}} = 2.9$

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Note that with this total feedback parameter the amplification factor is about 2.9 and the resulting climate sensitivity to doubled carbon dioxide a little over 3°C.

Amplification factor $a = f_o / f$ = 3.2 W m^{-2} K^{-1} / 1.1 W m^{-2} K^{-1} = 2.9

In our framework, $1+f_{\mathrm{TOTAL}} = 1 / (1 - 2.1 \times 0.31) = 2.9$, so f_{TOTAL} actually equals 1.9

Um sorry Sir John, but the amplification factor is about 2, not about 3 !

Ice-Albedo Feedback

Initial Action: Humans Release CO_2 → Initial Response: $T_{SURFACE}$ Rises

Then: Ice Melts

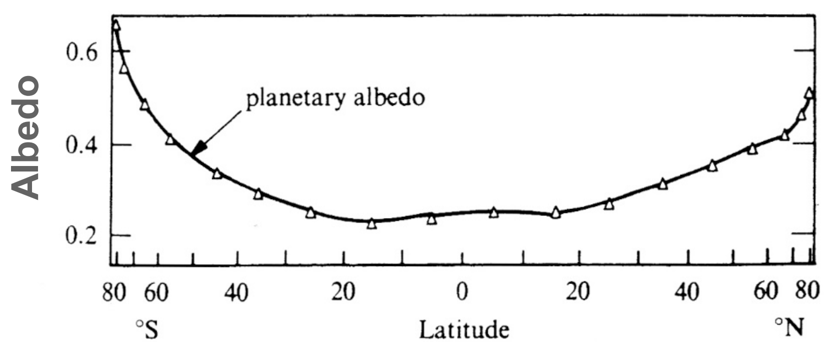
Consequence: Albedo Falls

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

2. Albedos of selected surfaces on Earth

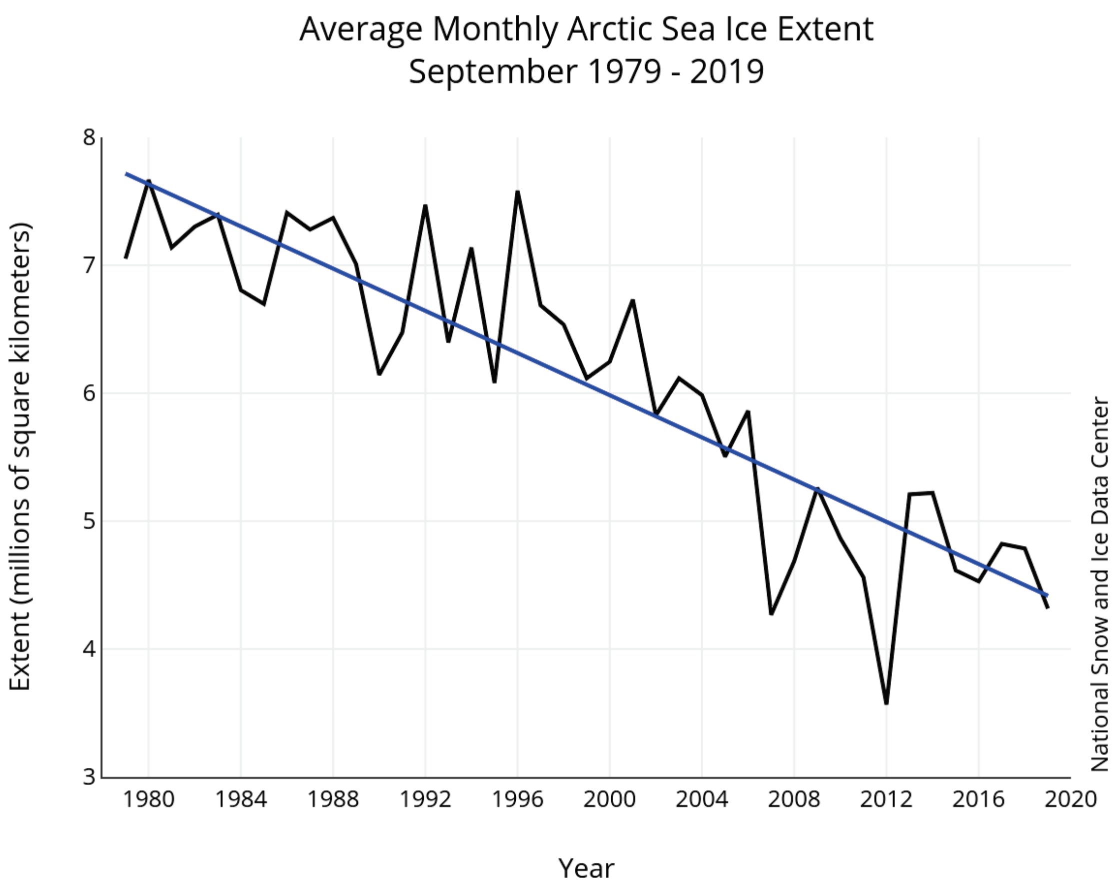
surface	albedo
snow	0.7 ± 0.2
sand	0.25 ± 0.05
grasslands	0.23 ± 0.03
bare soil	0.2 ± 0.05
forest	0.15 ± 0.1
water (highly dependent on surface roughness and incident angle of sunlight)	0.2 + 0.6 − 0.2

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 ~13% / decade over satellite era

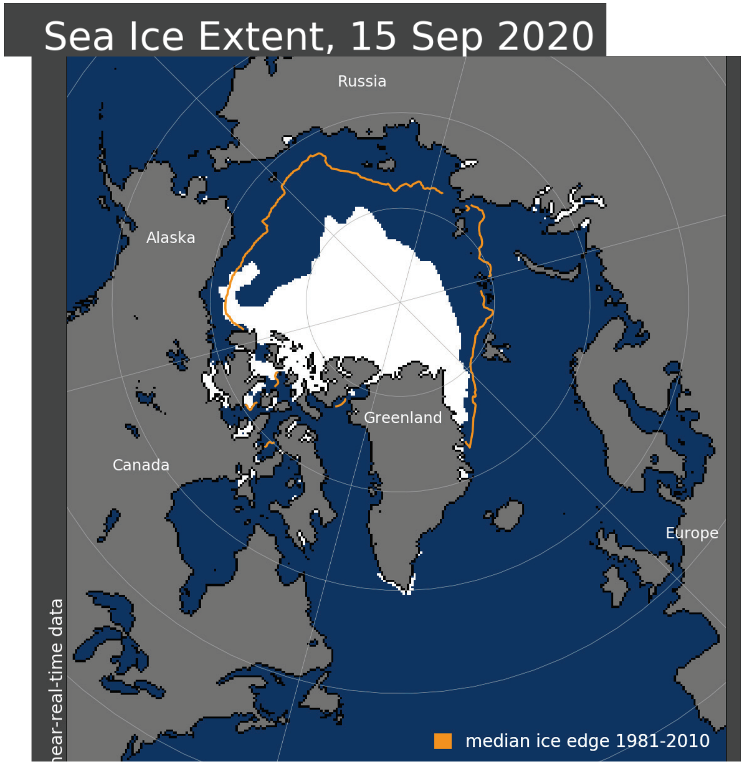
http://nsidc.org/arcticseaicenews/2019/10/

Arctic Sea Ice News & Analysis

September 21, 2020

Arctic sea ice decline stalls out at second lowest minimum

On September 15, Arctic sea ice likely reached its annual minimum extent of 3.74 million square kilometers (1.44 million square miles). The minimum ice extent is the second lowest in the 42-year-old satellite record, reinforcing the long-term downward trend in Arctic ice extent. Sea ice extent will now begin its seasonal increase through autumn and winter. In the Antarctic, sea ice extent is now well above average and within the range of the ten largest ice extents on record, underscoring its high year-to-year variability. The annual maximum for Antarctic sea ice typically occurs in late September or early October.



https://nsidc.org/arcticseaicenews/2020/09/arctic-sea-ice-decline-stalls-out-at-second-lowest-minimum/

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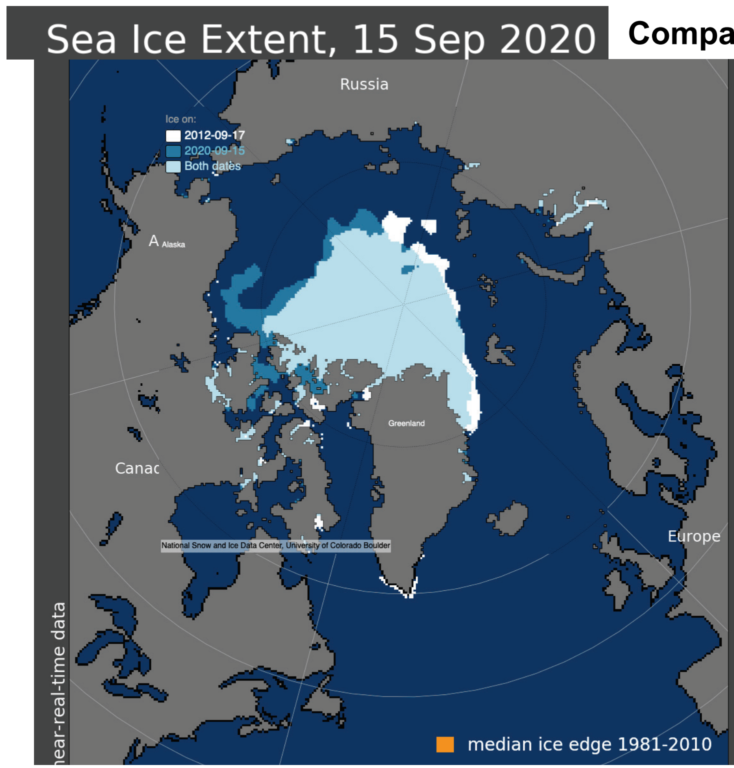
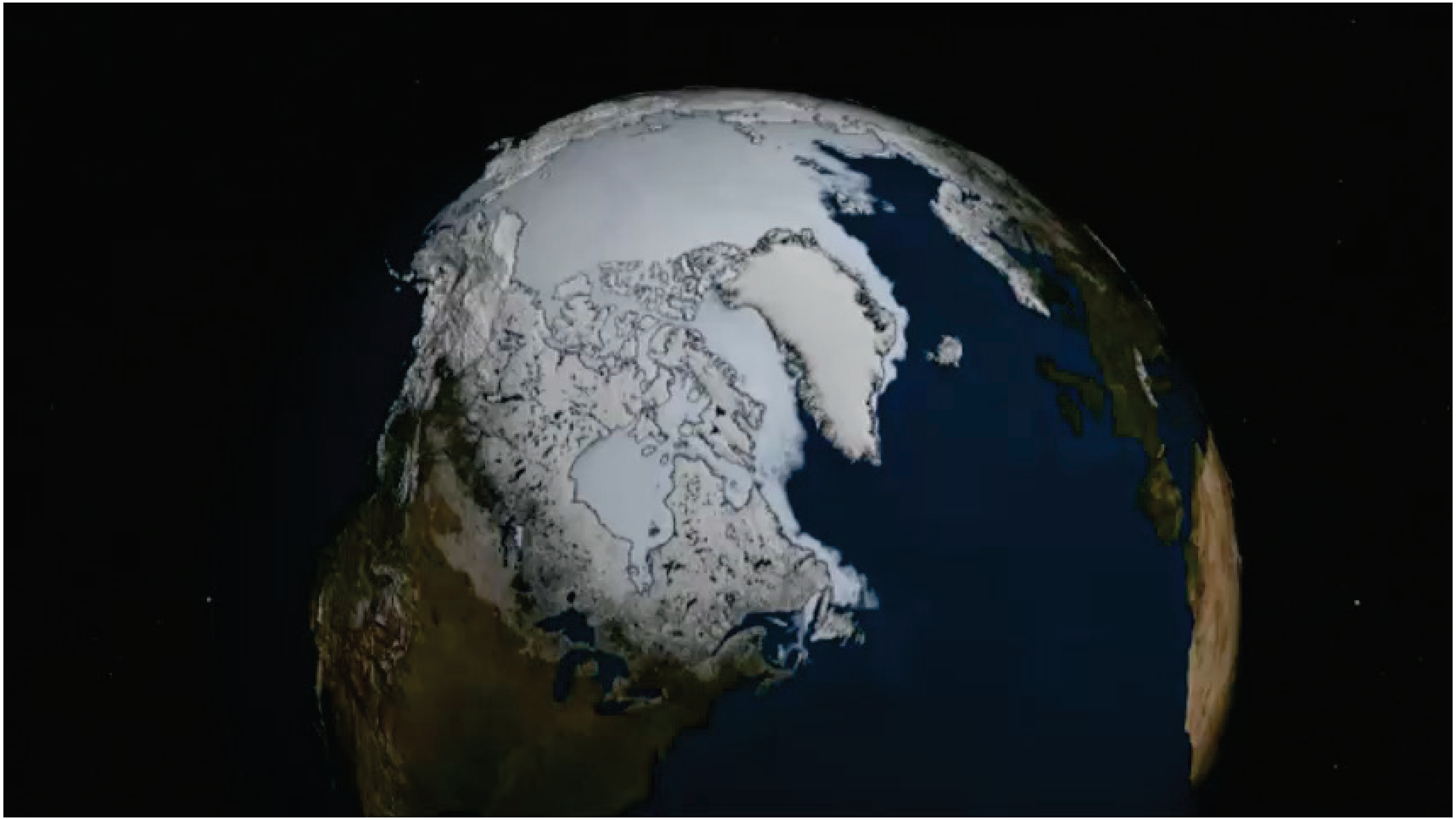


Compared to 2012

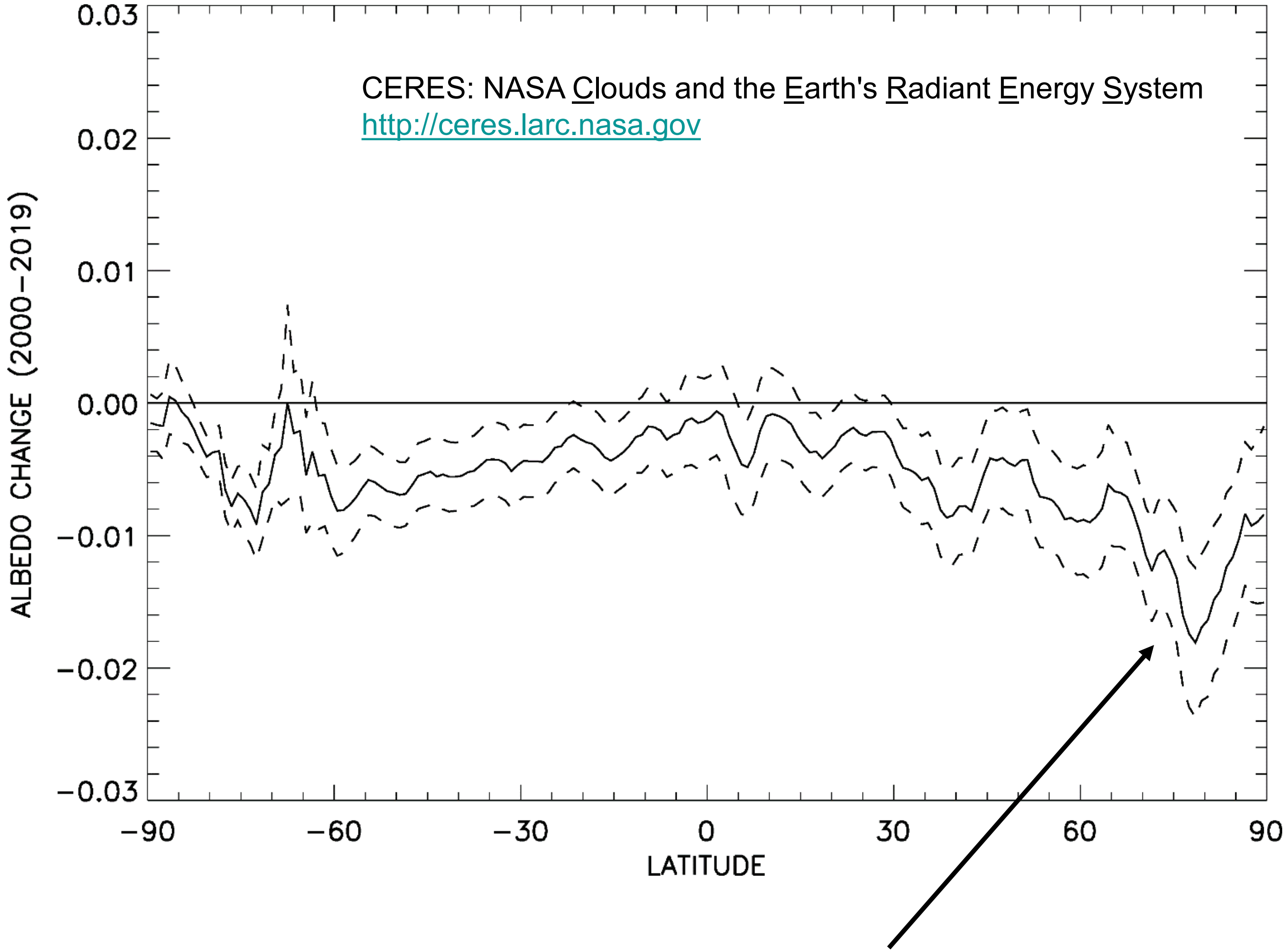
https://nsidc.org/arcticseaicenews/2020/09/arctic-sea-ice-decline-stalls-out-at-second-lowest-minimum/

Arctic Sea Ice Animation



https://www.youtube.com/watch?v=jjwpOWeRZus
See also https://svs.gsfc.nasa.gov/11654

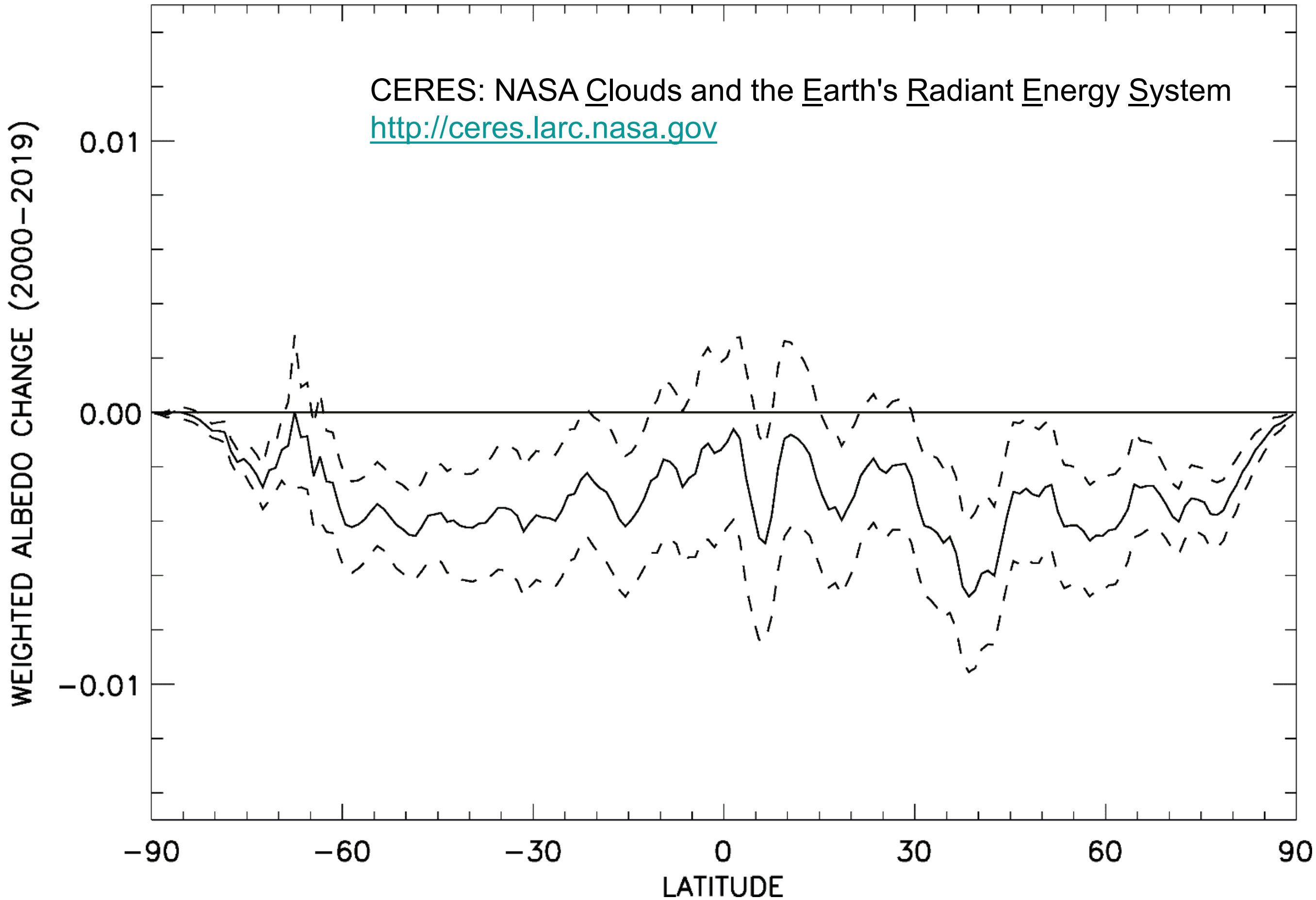
Albedo Anomaly (CERES) Change versus Latitude, No Weighting



NH high latitude darkening (melting sea ice) is apparent

Slide courtesy Laura McBride; analysis to the end of 2019

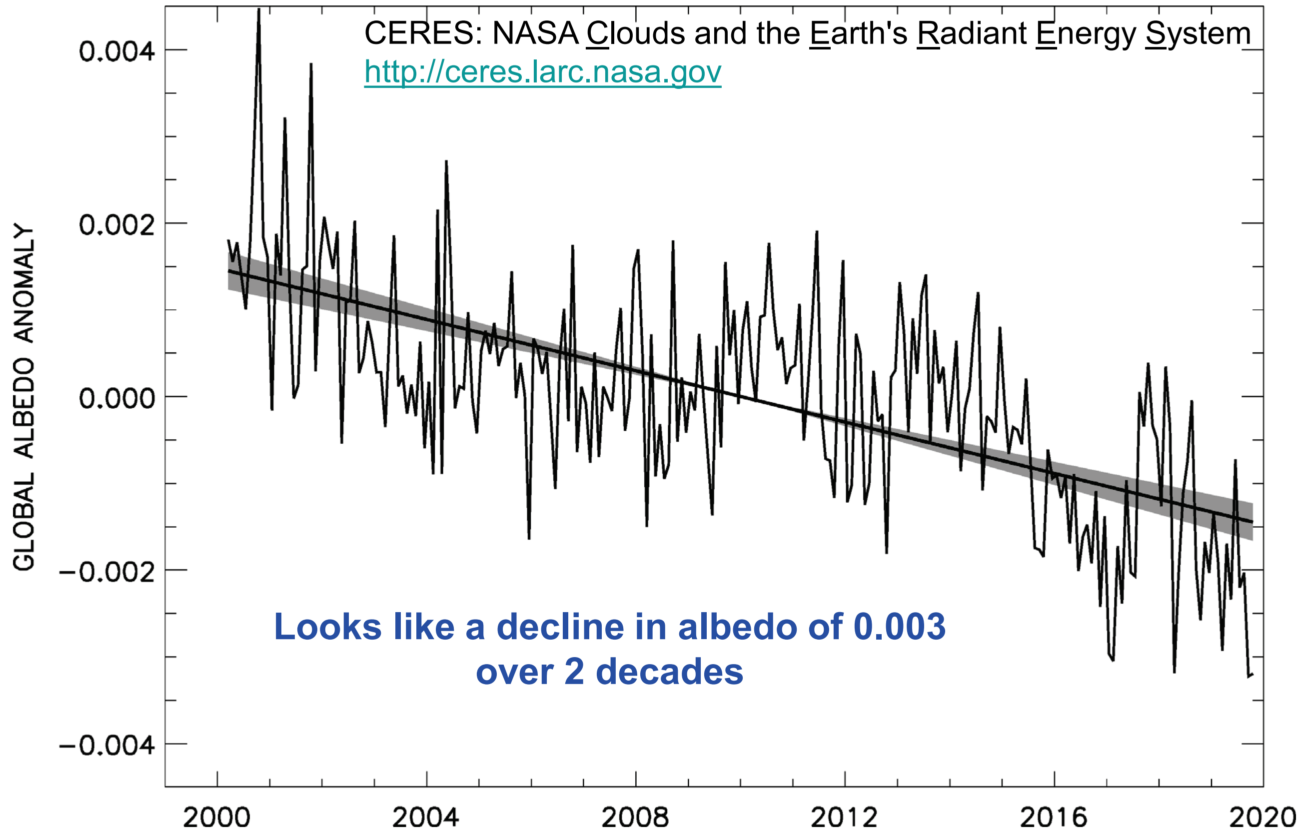
Albedo Anomaly (CERES) Change versus Latitude, *Weighted by Cosine Latitude*



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

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

$$T_{EFF} = \left\{ (1-0.3) \times \frac{1370\ \mathrm{W\ m^{-2}}}{4} \times \frac{1}{5.67\times10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}} \right\}^{1/4} = 255.002\ \mathrm{K}$$

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

$$T_{EFF} = \left\{ (1-0.297) \times \frac{1370\ \mathrm{W\ m^{-2}}}{4} \times \frac{1}{5.67\times10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}} \right\}^{1/4} = 255.275\ \mathrm{K}$$

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 0.136 K per decade, which is ***an enormous effect*.**

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

$$T_{EFF} = \left\{ (1-0.3) \times \frac{1370 \text{ W m}^{-2}}{4} \times \frac{1}{5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}} \right\}^{1/4} = 255.002 \text{ K}$$

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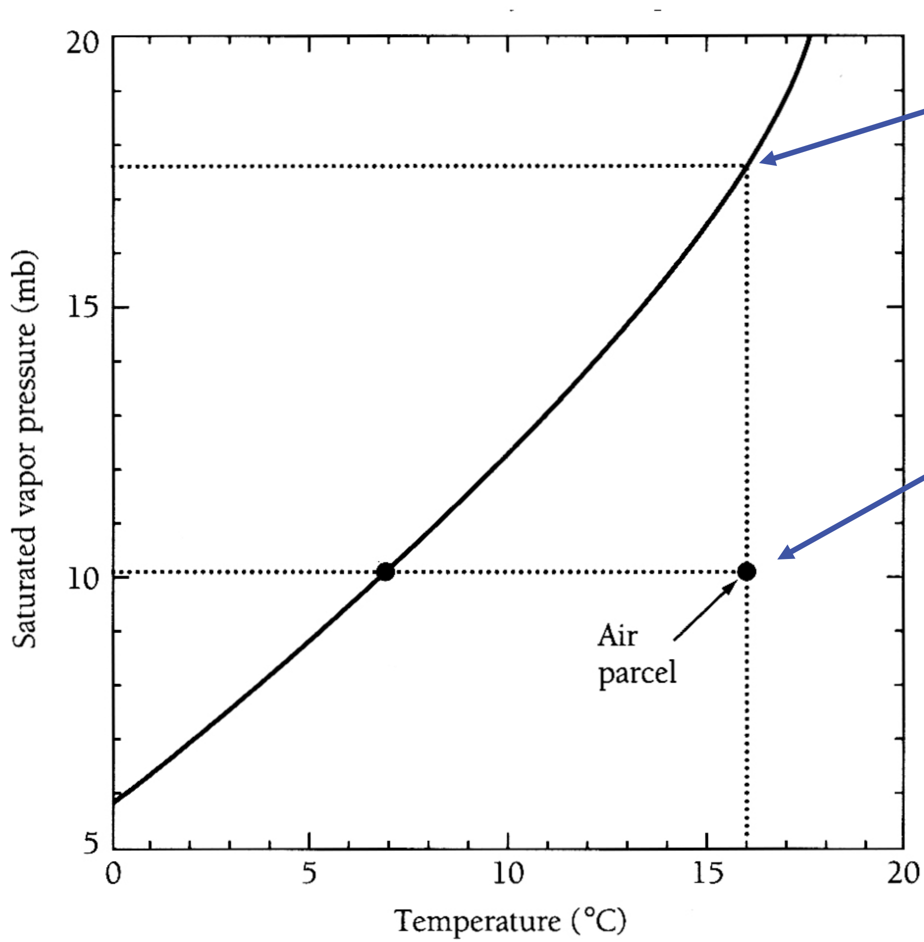
If Earth's albedo truly decline by about 0.003 over 2 decades this would have driven a rise in Earth's effective temperature of 0.136 K per decade, which is ***an enormous effect*.**

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.

Water Vapor Feedback



Saturation vapor pressure is 17.7 mbar (if H_2O pressure were this high, water would condense)

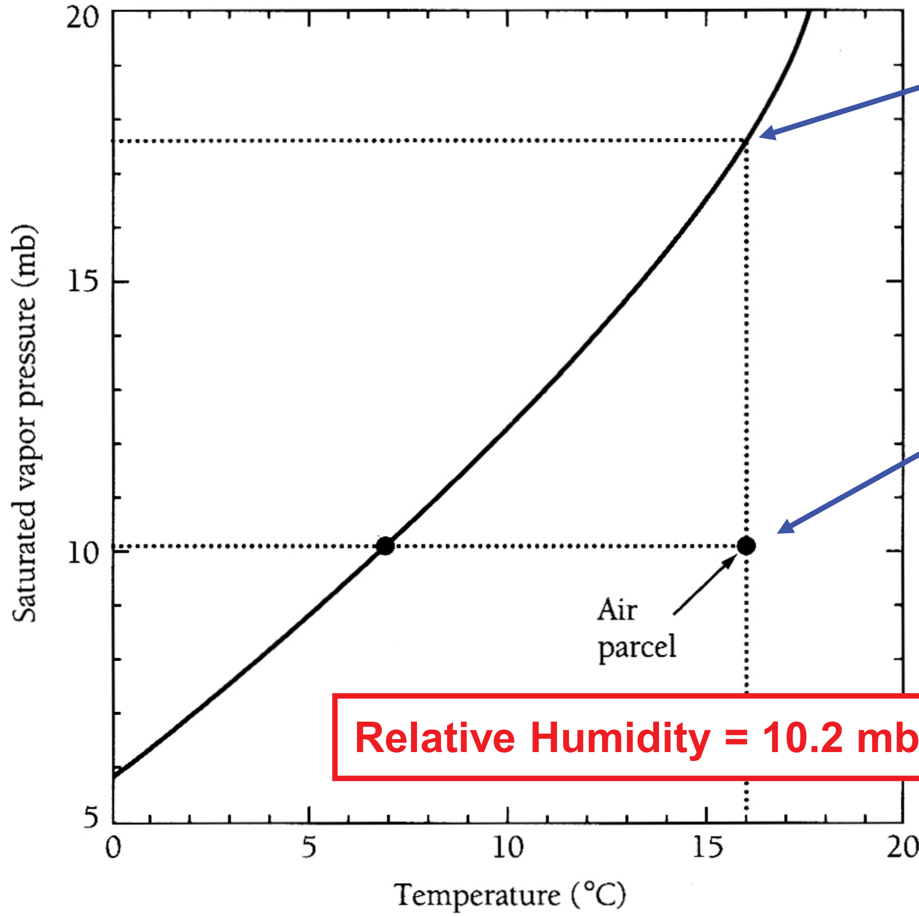
Actual H_2O vapor pressure is 10.2 mbar (H_2O present only in gaseous form)

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



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Actual H_2O vapor pressure is 10.2 mbar (H_2O present only in gaseous form)

Relative Humidity = 10.2 mbar / 17.7 mbar = 0.58 or 58%

Figure 4.8a Relative humidity and the dew point.

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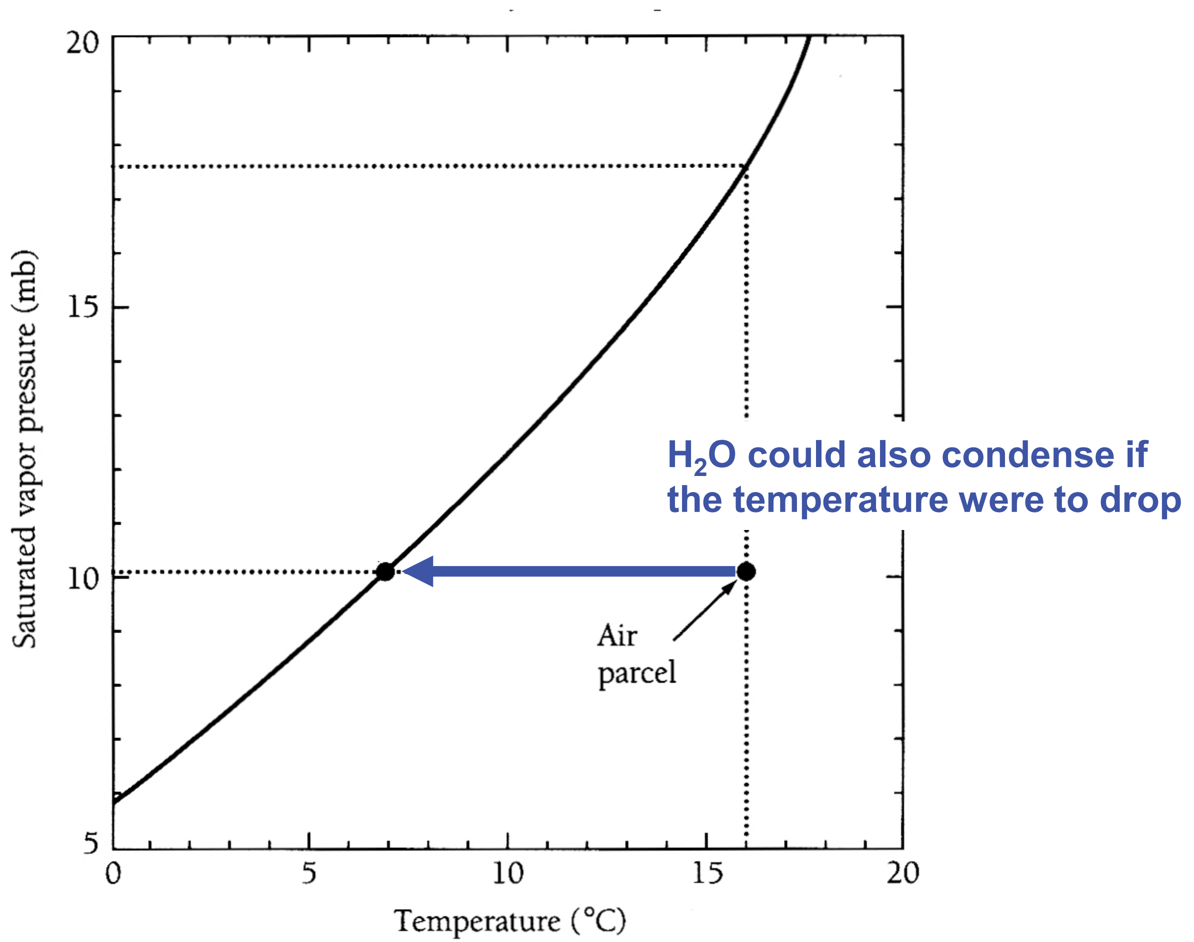
Water Vapor Feedback



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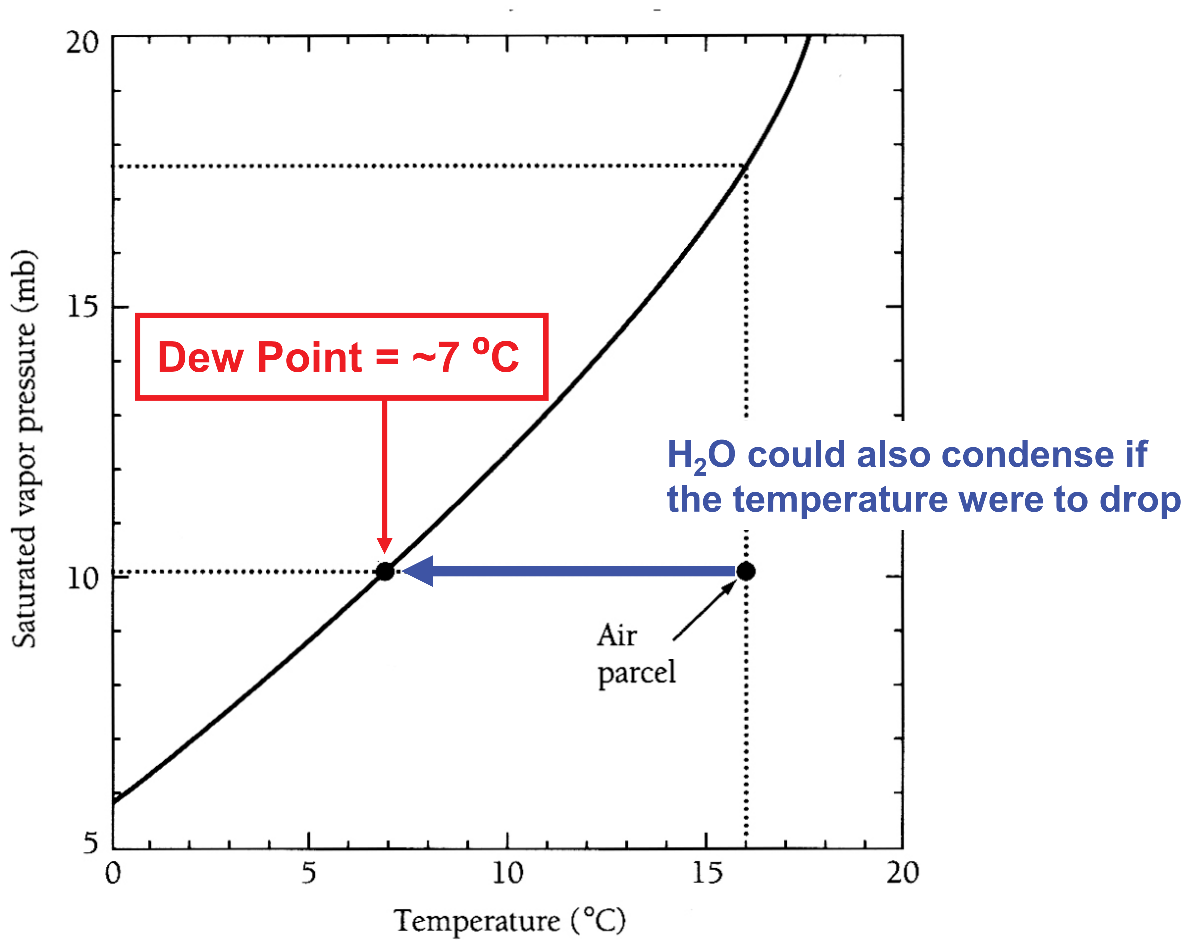
Water Vapor Feedback



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McElroy, *Atmospheric Environment*, 2002

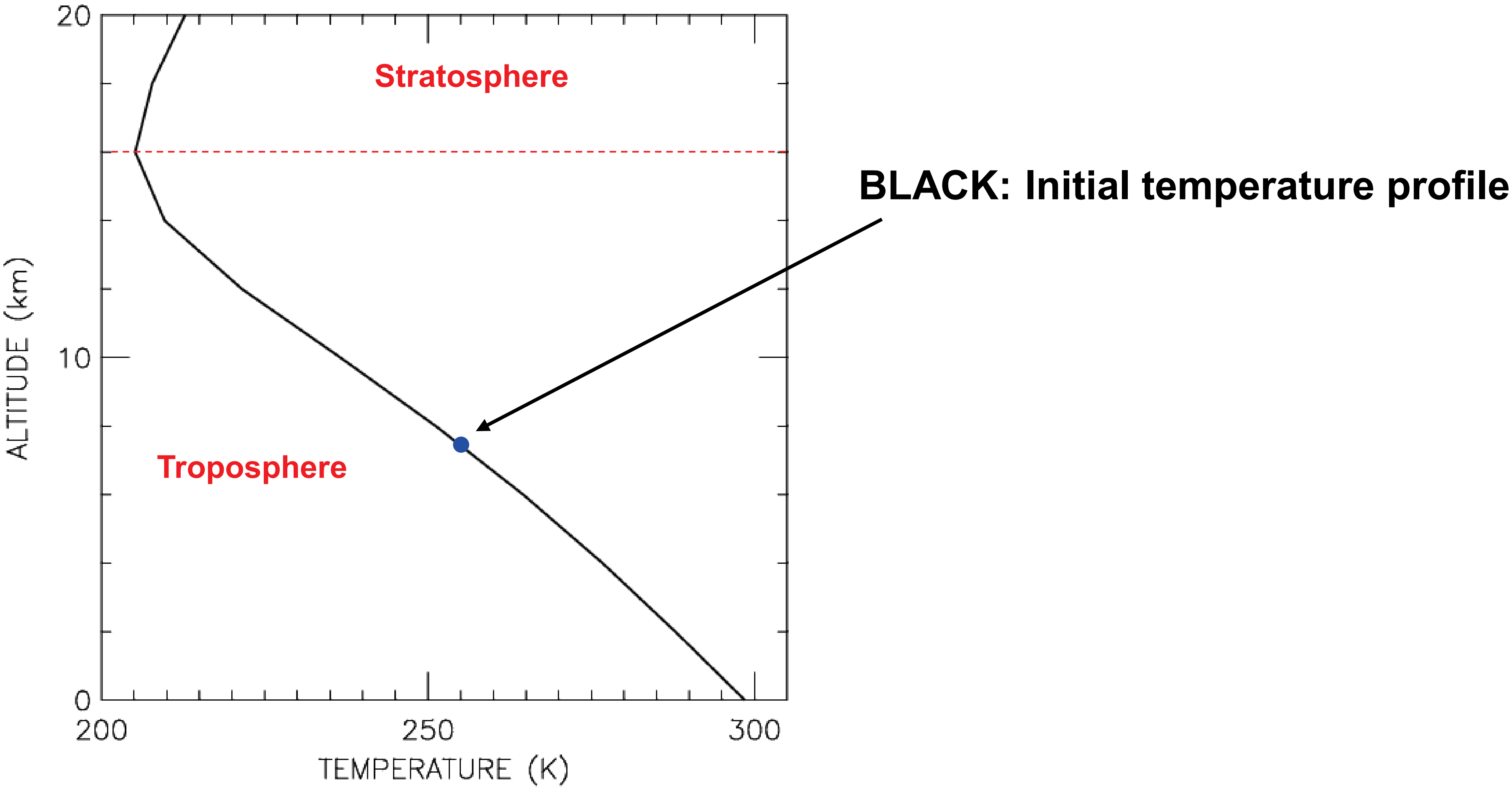
Clausius-Clapeyron relation describes the temperature dependence of the ***saturation vapor pressure of water.***

Water Vapor Feedback

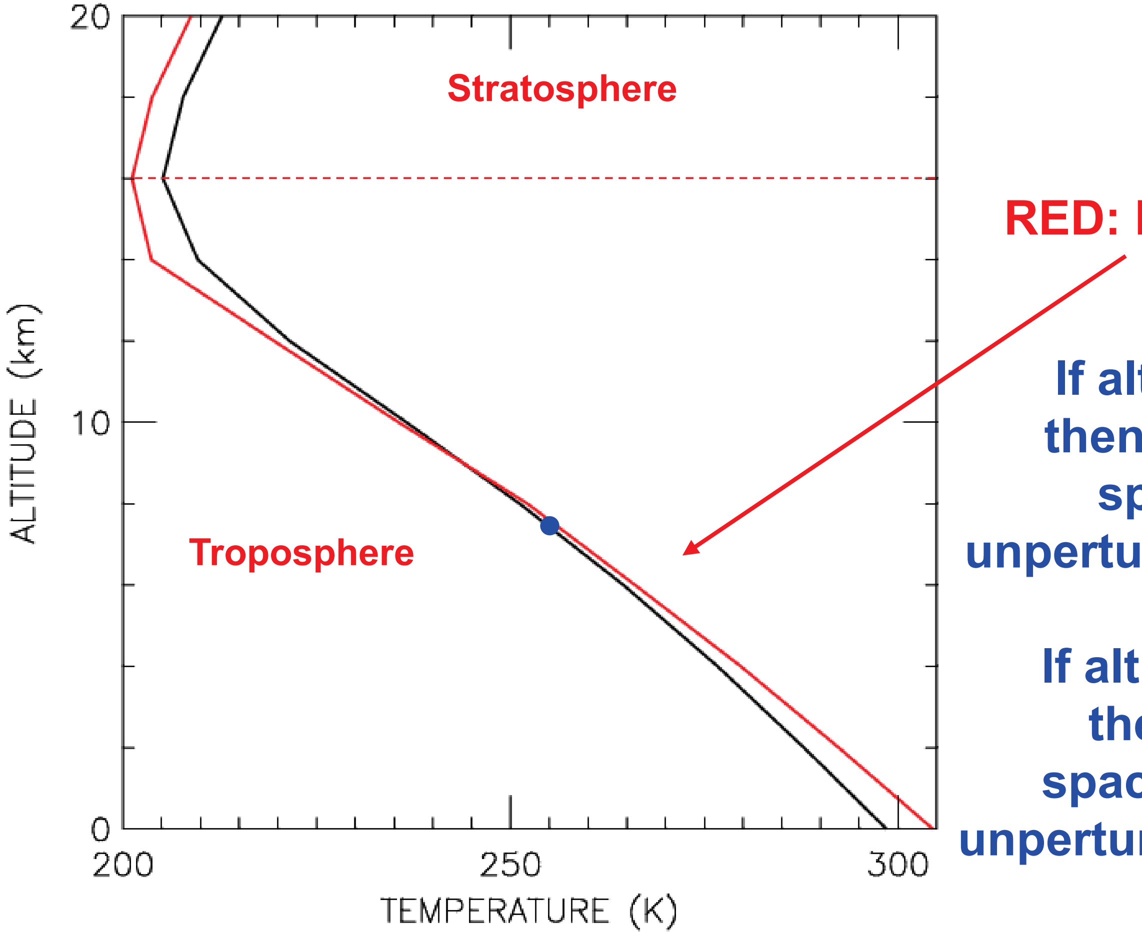
Extensive literature on water vapor feedback:

- 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



Lapse Rate Feedback

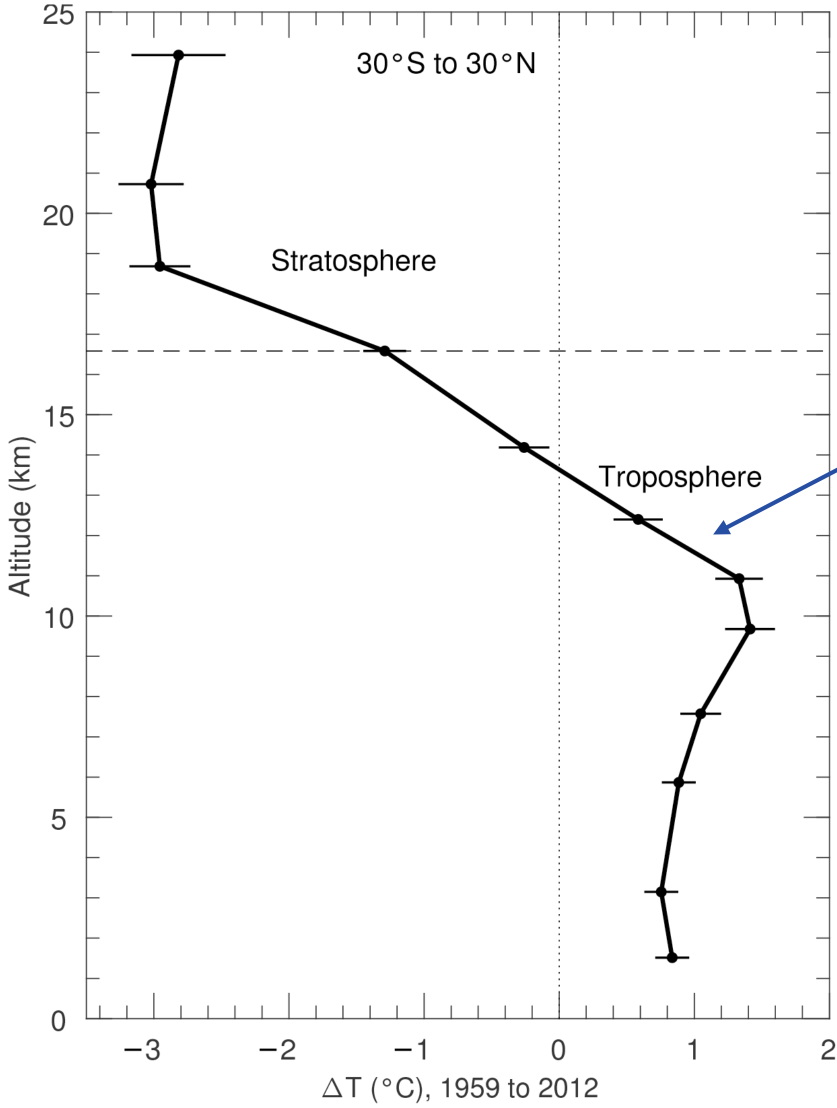


RED: Perturbed temperature profile

If altitude above 255 K cools, then energy will not radiate to space as effectively as in unperturbed state: positive feedback

If altitude above 255 K warms, then energy will radiate to space more effectively than in unperturbed state: negative feedback

Lapse Rate Feedback



This figure shows warming at 10 km is larger than warming at the surface supporting notion that the lapse rate feedback is negative

Fig. 1.5, Paris Beacon of Hope

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**

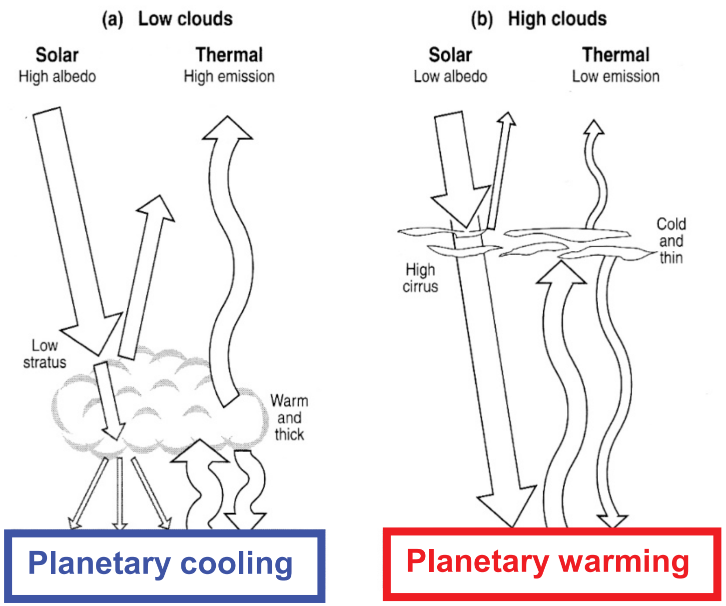


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The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

Radiative Forcing of Clouds: Observation A

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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.

Radiative Forcing of Clouds: Observation B

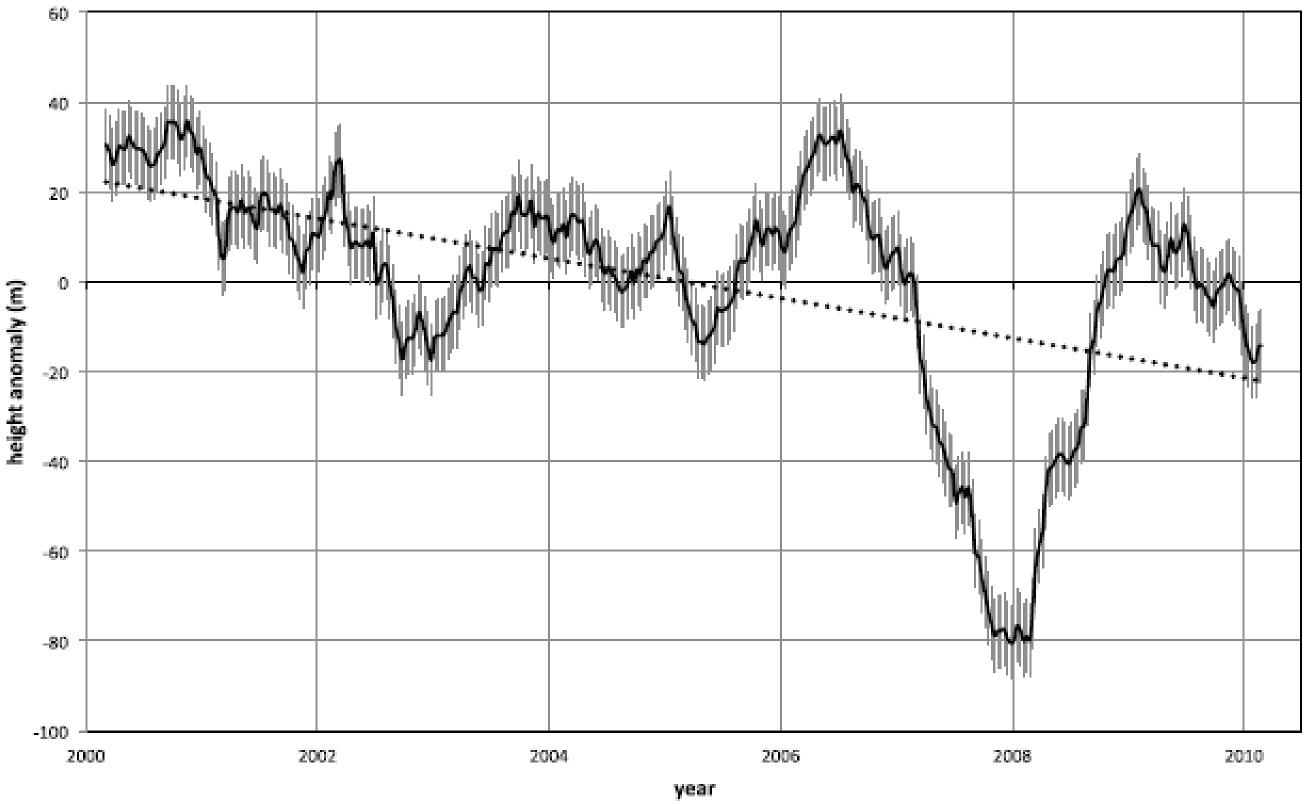


Figure 1. Deseasonalized anomalies of global effective cloud-top height from the 10-year mean. Solid line: 12-month running mean of 10-day anomalies. Dotted line: linear regression. Gray error bars indicate the sampling error (±8 m) in the annual average.

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

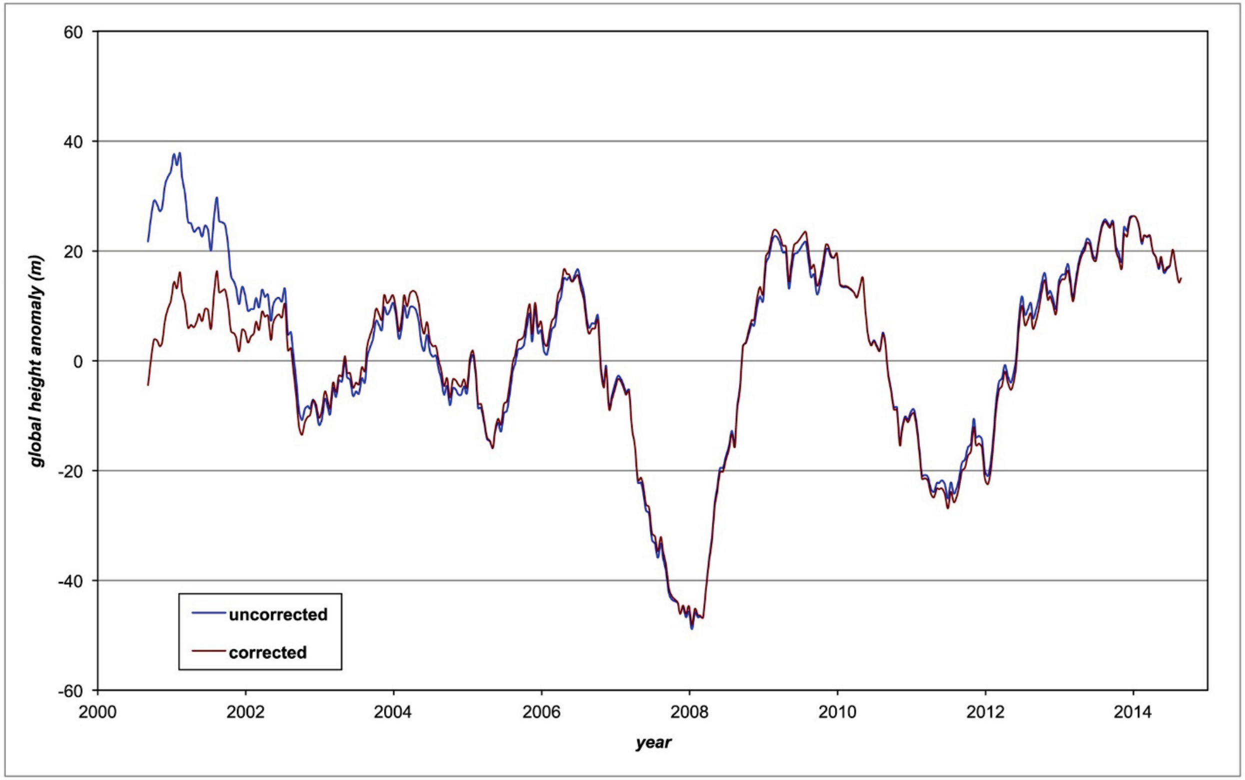
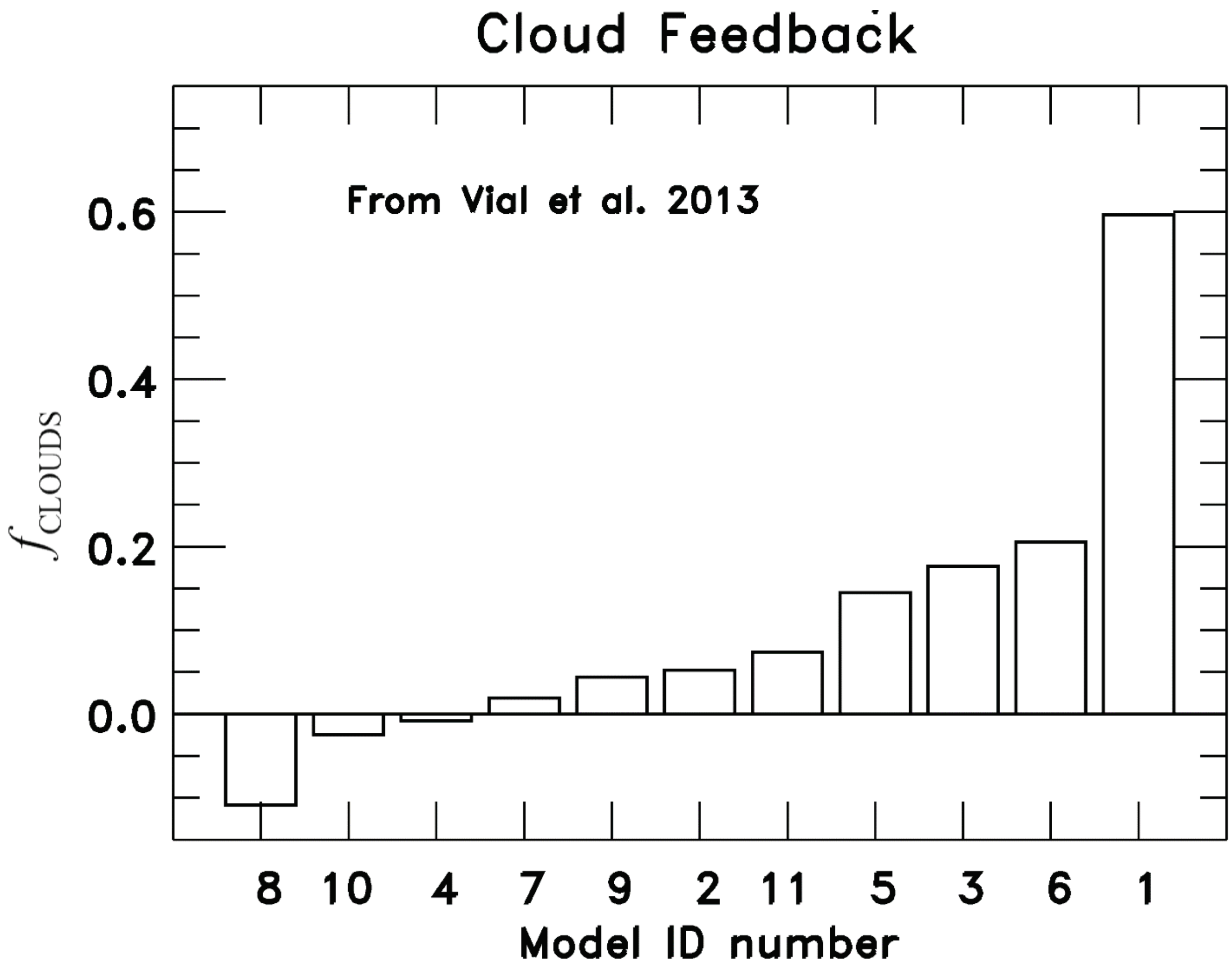


Figure 5. The 15-year time series of global height anomalies from March 2000 to February 2015. Corrected for shift in glitter pattern (brown), and uncorrected (blue). Data have been smoothed by a 12 month running mean.

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

Radiative Forcing of Clouds: IPCC 2013



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

Radiative Forcing of Clouds: 2017 Review Paper

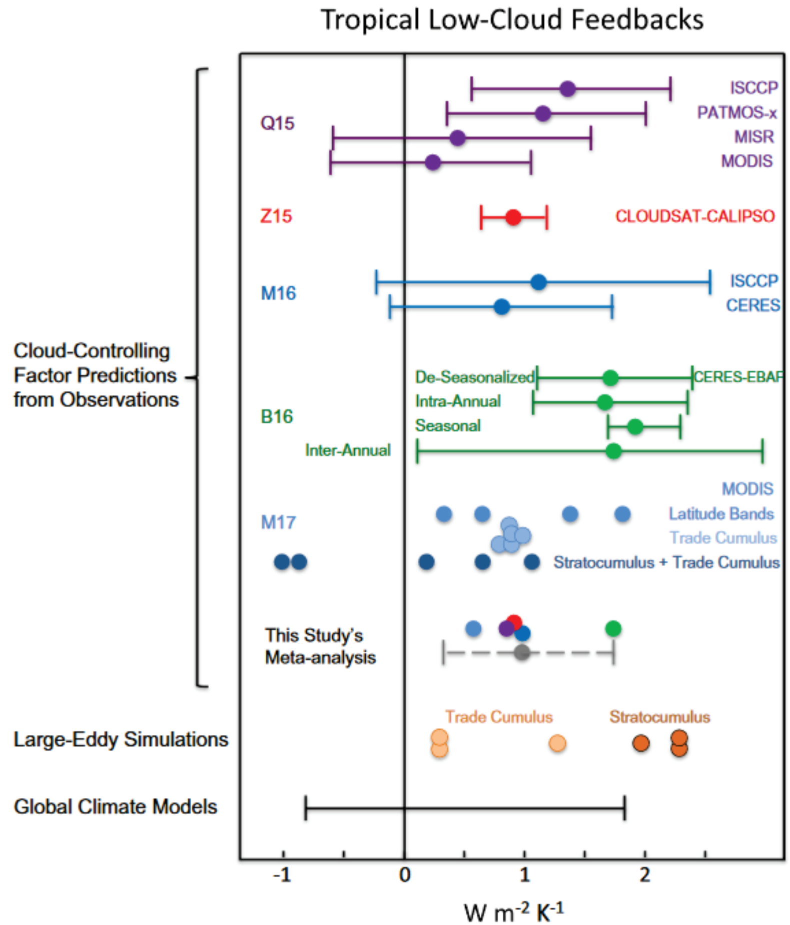


Fig. 3 Values of local tropical low-cloud feedbacks predicted from recent observational studies, large-eddy simulations and global climate models. Local feedbacks are defined as the local change in top-of-atmosphere radiation from tropical low clouds per degree increase in global mean surface air temperature. Bar widths for observational studies (unavailable for M17) and this study's meta-analysis represent 90% confidence intervals. Values from individual large-eddy simulation studies are shown. The bar width for global climate models indicates the range of model results. See the "Appendix" for details

Klein et al., *Surveys in Geophysics*, 2017 https://link.springer.com/article/10.1007/s10712-017-9433-3

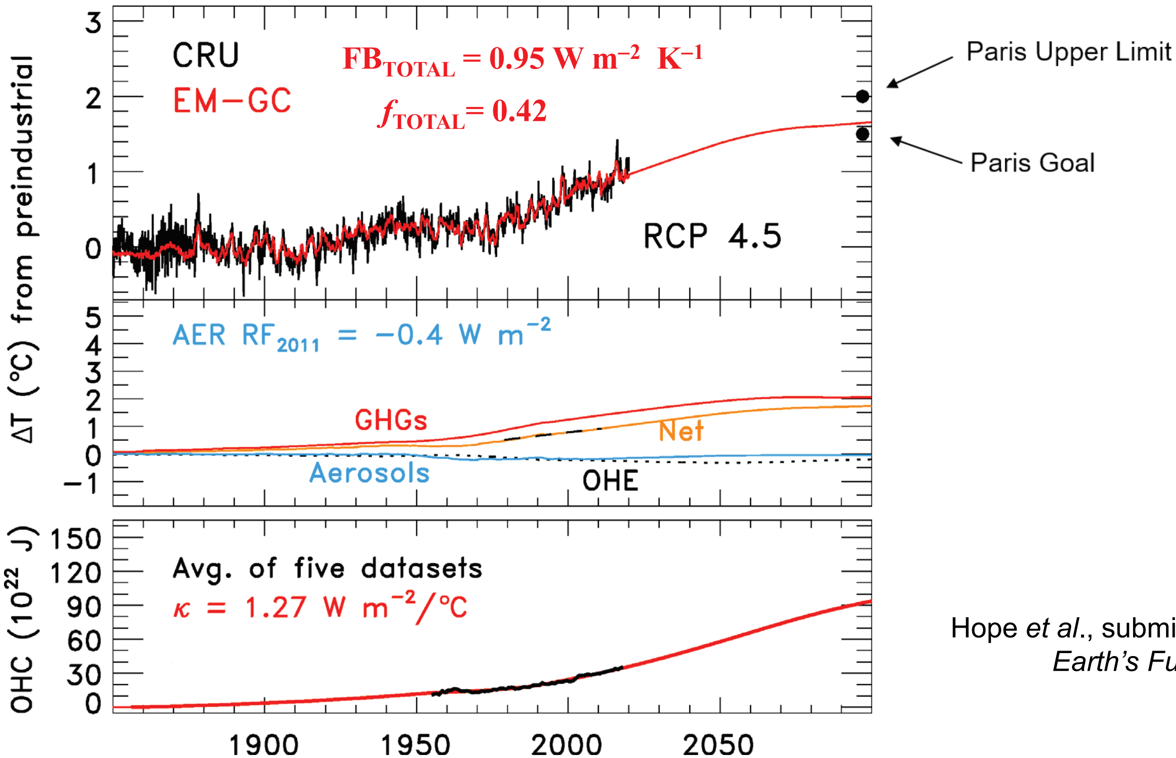
Uncertainty in RF due to aerosols is a huge complication that places a fundamental uncertainty on how well future global warming can be forecast

$$\Delta T \approx \lambda_P \,(1 + f_{TOTAL})\,\Delta RF - OHE \quad ; \qquad 1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL}\;\lambda_P}$$

f_{TOTAL} : total feedback term (dimensionless) due to water vapor, lapse rate, clouds, etc. that directly amplifies RF

FB_{TOTAL} : sum of individual feedback terms (units W m^{-2} K^{-1}) computed using IPCC formalism

OHE : export of heat from atmosphere to world's ocean



Hope *et al.*, submitted to AGU journal *Earth's Future*, 2020.

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **−0.4 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of other feedbacks (clouds, surface albedo) must be ***close to zero***.

Uncertainty in RF due to aerosols is a huge complication that places a fundamental uncertainty on how well future global warming can be forecast

$$\Delta T \approx \lambda_P \,(1 + f_{TOTAL})\,\Delta RF - OHE \quad ; \qquad 1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL}\,\lambda_P}$$

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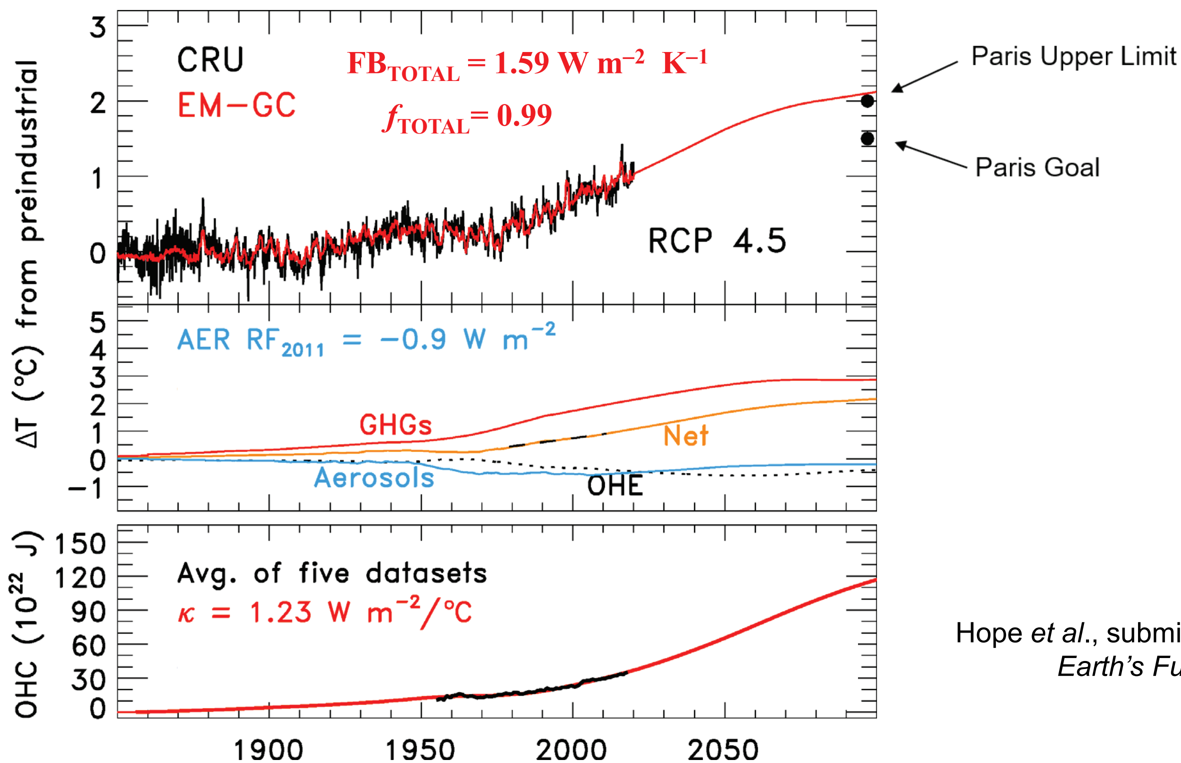

Hope *et al.*, submitted to AGU journal *Earth's Future*, 2020.

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future.
For Aerosol RF in 2011 of **−0.9 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of other feedbacks (clouds, surface albedo) must be ***moderately positive***.

Uncertainty in RF due to aerosols is a huge complication that places a fundamental uncertainty on how well future global warming can be forecast

$$\Delta T \approx \lambda_P \, (1 + f_{TOTAL}) \, \Delta RF - OHE \quad ; \qquad 1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL} \, \lambda_P}$$

f_{TOTAL} : total feedback term (dimensionless) due to water vapor, lapse rate, clouds, etc. that directly amplifies RF

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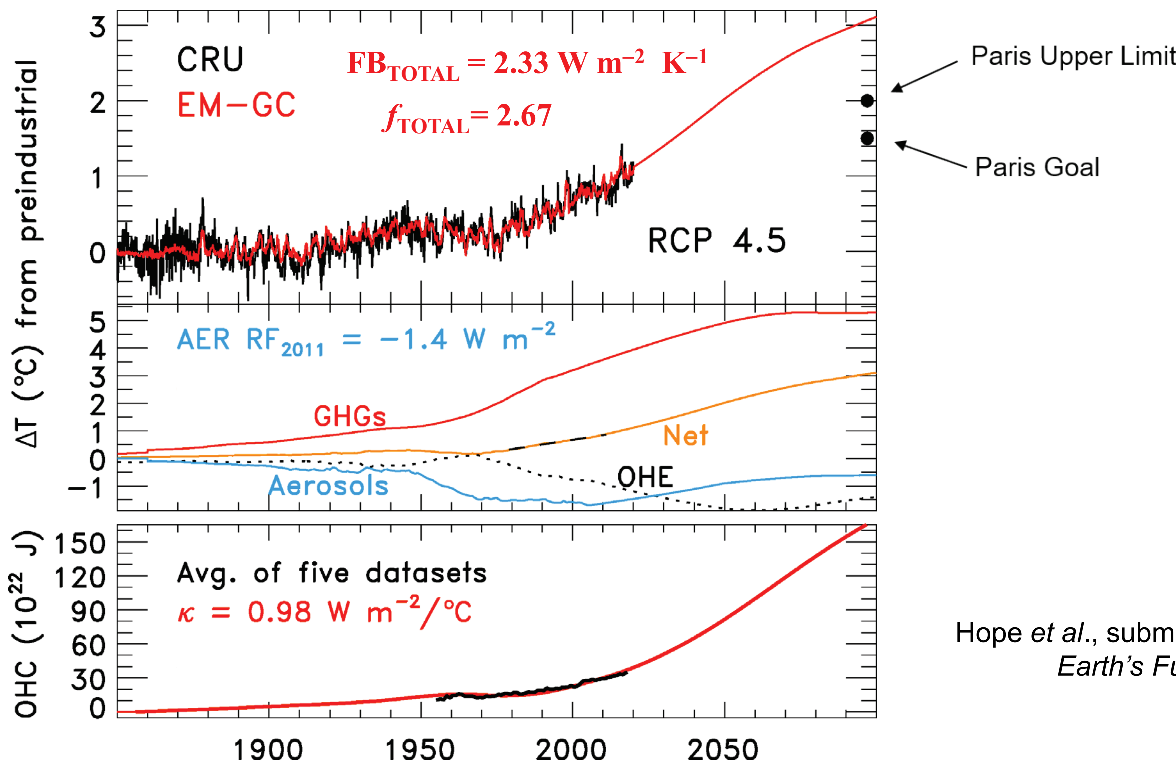
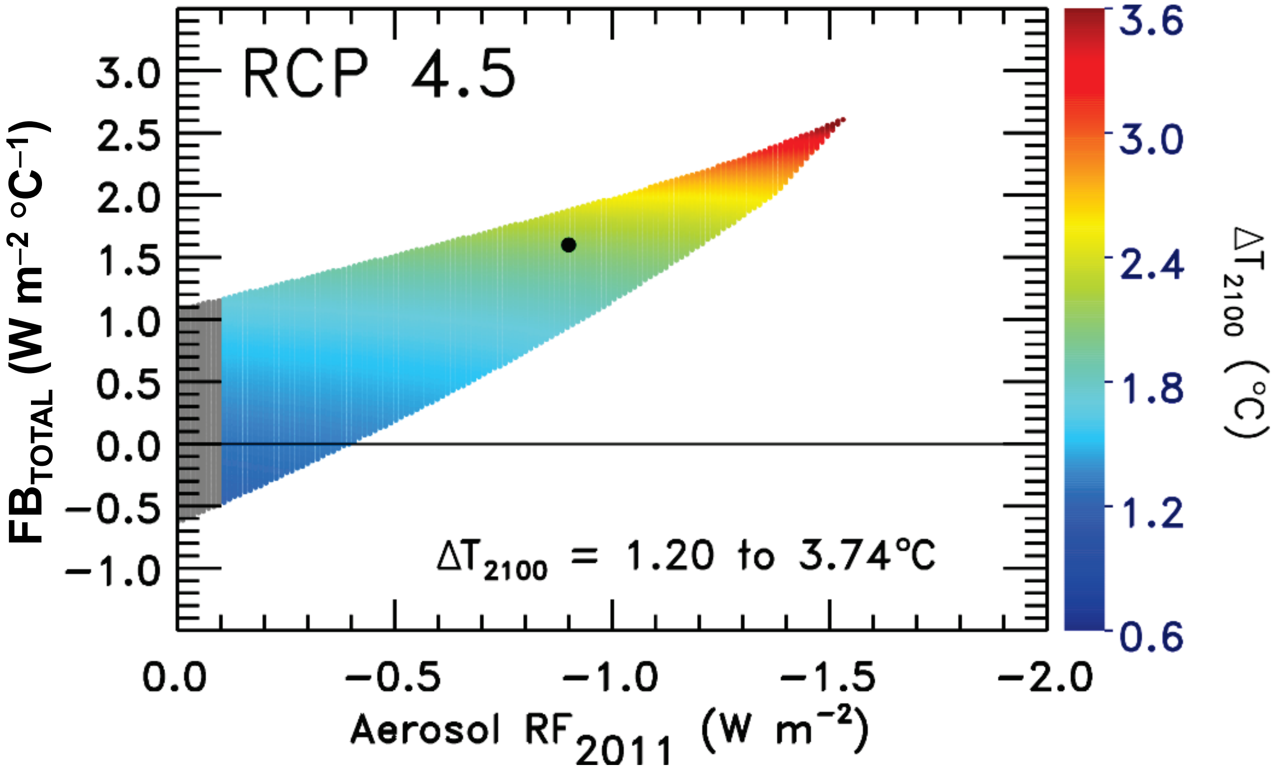


Hope *et al.*, submitted to AGU journal *Earth's Future*, 2020.

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **–1.5 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of other feedbacks (clouds, surface albedo) must be ***strongly positive***.

Feedback versus Aerosol RF

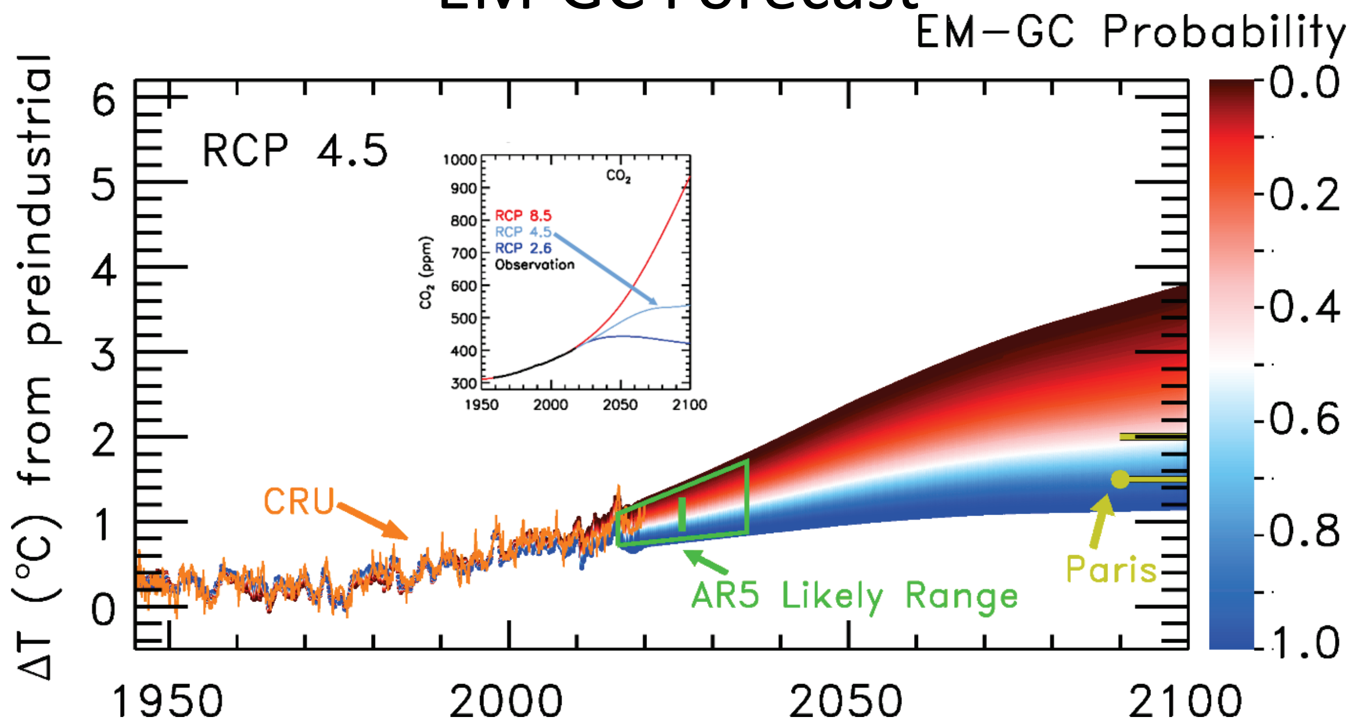


Model space for which at $\chi^2 \leq 2$, where:

$$\chi^2 = \frac{1}{(N_{YEARS} - N_{FITTING\ PARAMETERS} - 1)} \times \sum_{j=1}^{N_{YEARS}} \frac{1}{(\sigma_{OBS\,j}{}^2)} \left(\langle \Delta T_{OBS\,j} \rangle - \langle \Delta T_{EM-GC\,j} \rangle \right)^2$$

Hope *et al*., *Earth's Future*, submitted, 2020.

EM-GC Forecast



Future ΔT projected running EM-GC forward in time, for neutral TSI, ENSO, SOD, & AMOC for:

a) all combinations of Aerosol RF & Feedback for which the past ΔT can be fit at $\chi^2 \leq 2$

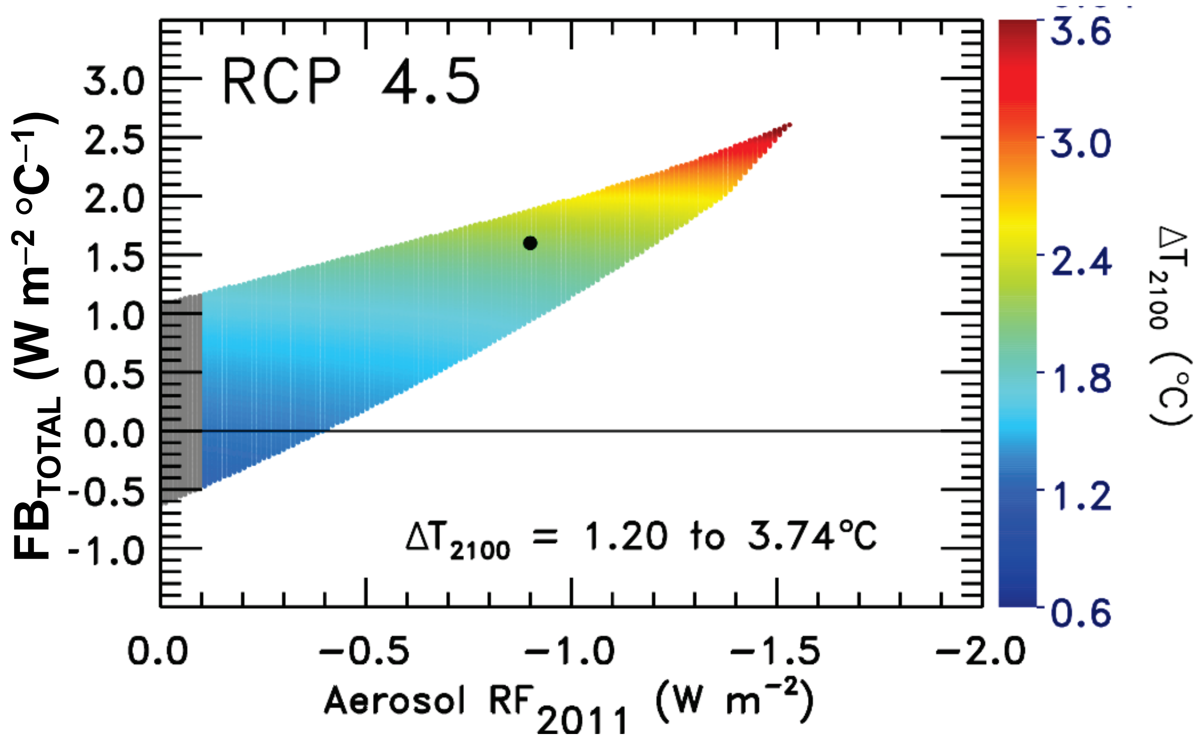
b) whatever value of Feedback is able to provide a fit past climate will persist into future

If GHGs follow RCP 4.5, **9%** chance rise GMST stays below **1.5°C** and **51%** chance stays below **2.0°C**

Hope *et al.*, *Earth's Future*, submitted, 2020.

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, East Anglia, UK: Premier source of data for ΔT
IPCC Likely Range of ΔT : From Fig 11.25b of the 2013 Intergovernmental Panel on Climate Change Report

Feedback versus Aerosol RF



Model space for which at $\chi^2 \leq 2$, where:

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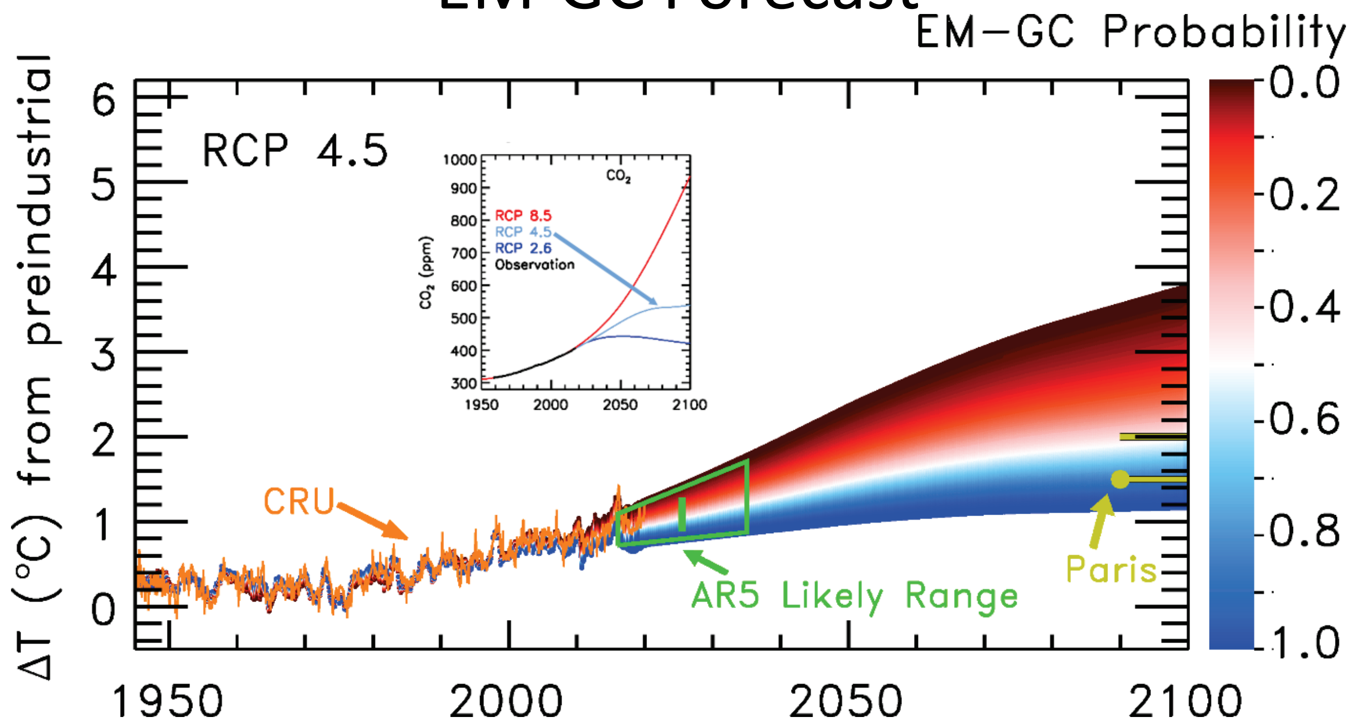

Future ΔT projected running EM-GC forward in time, for neutral TSI, ENSO, SOD, & AMOC for:

a) all combinations of Aerosol RF & Feedback for which the past ΔT can be fit at $\chi^2 \leq 2$

b) whatever value of Feedback is able to provide a fit past climate will persist into future

If GHGs follow RCP 4.5, **10%** chance rise GMST stays below **1.5°C** and **50%** chance stays below **2.0°C**

Hope *et al.*, *Earth's Future*, submitted, 2020.

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
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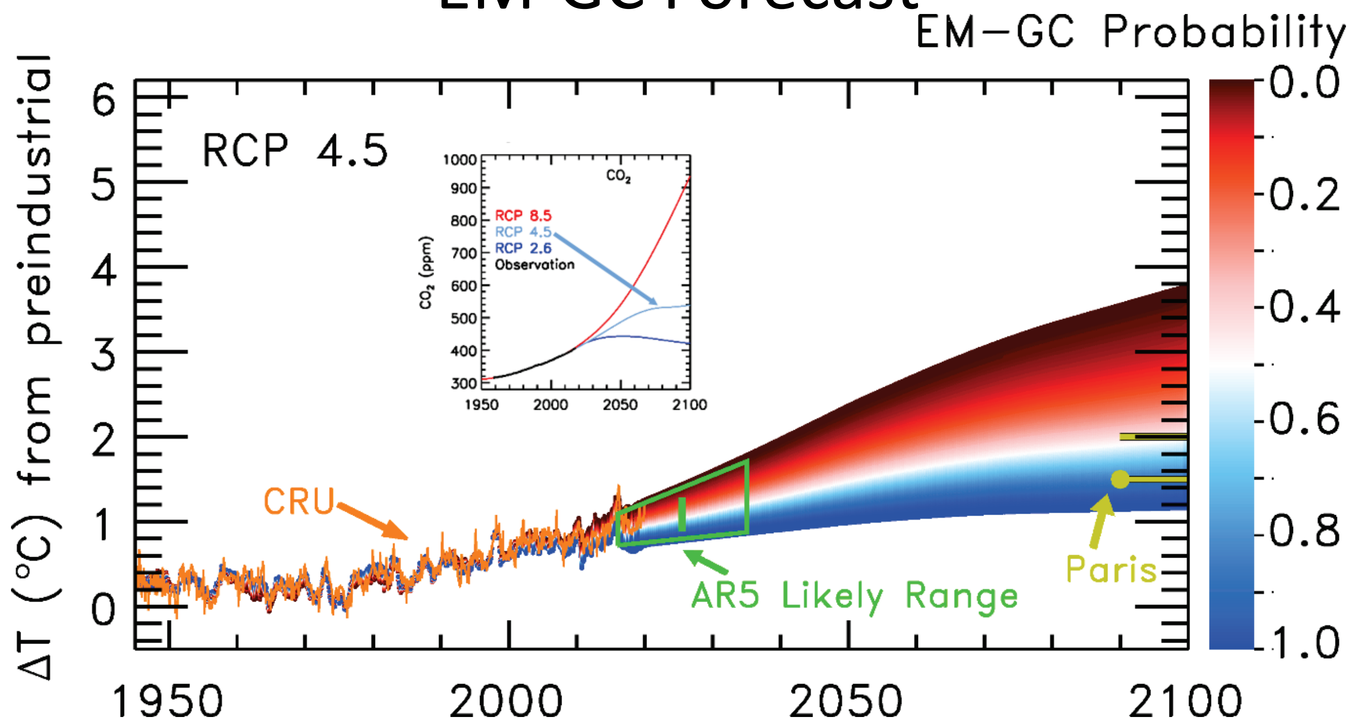


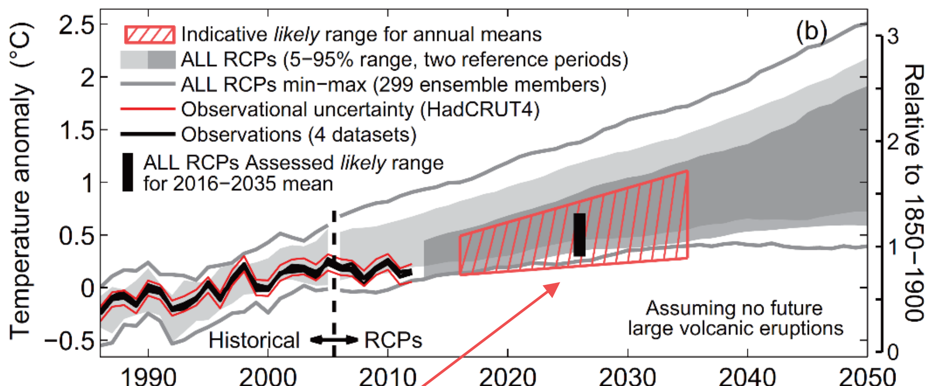
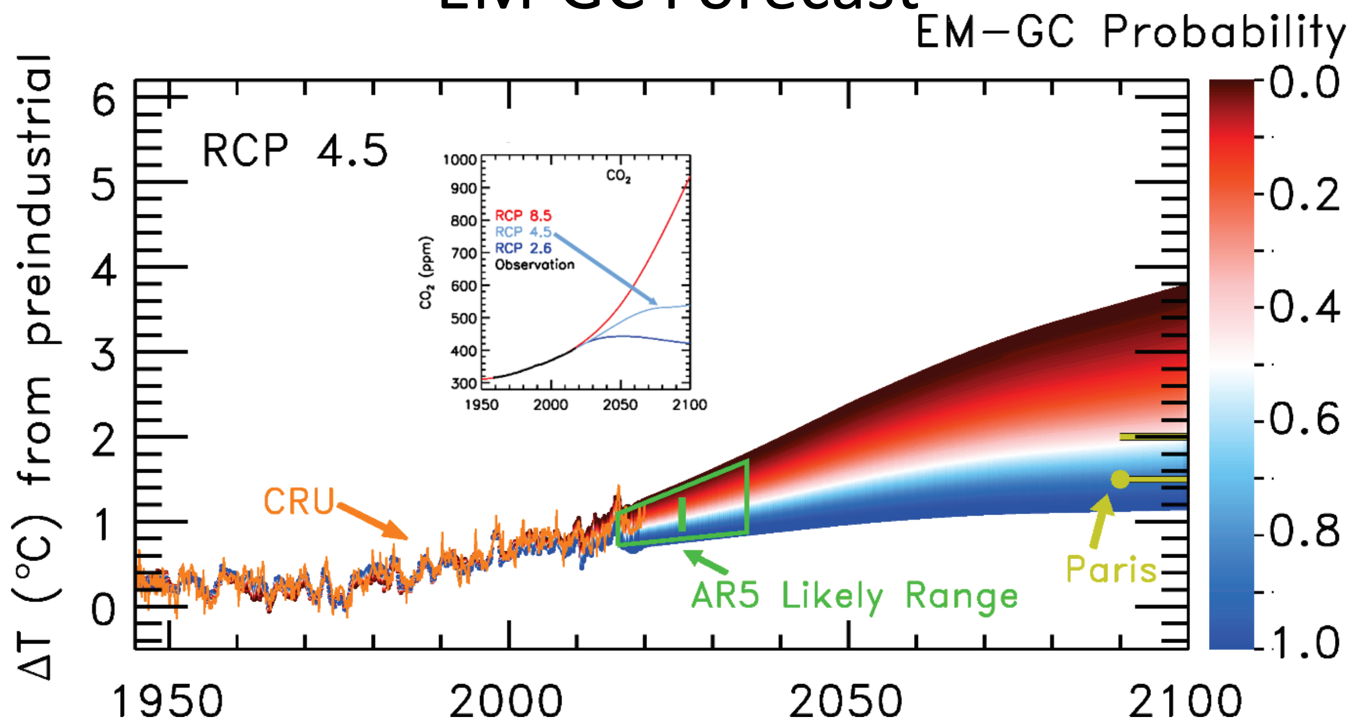
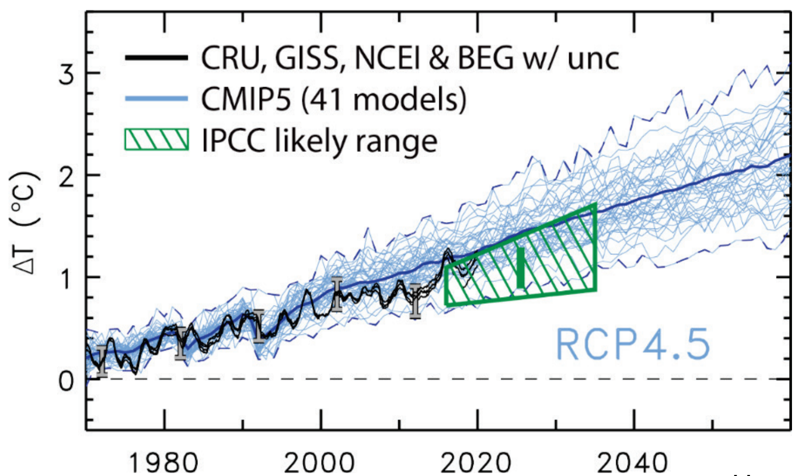


Fig 11.25b, IPCC 2013

Red hatched region: likely range for annual, global mean surface temp (GMST) anomaly during 2016–2035
Black bar: likely range for the 20-year mean GMST anomaly for 2016–2035

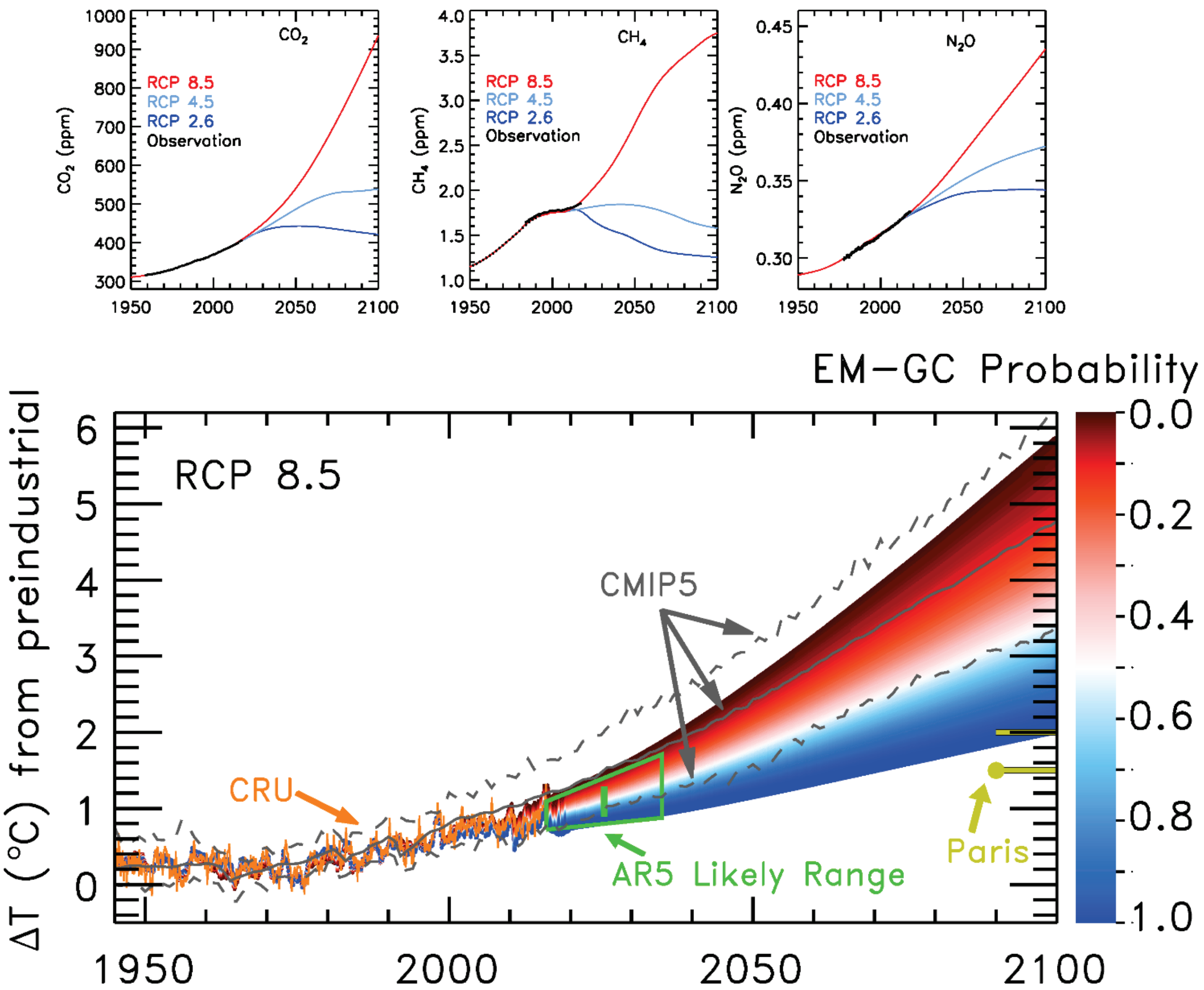
EM-GC Forecast





Hope *et al.*, *Earth's Future*, submitted, 2020.

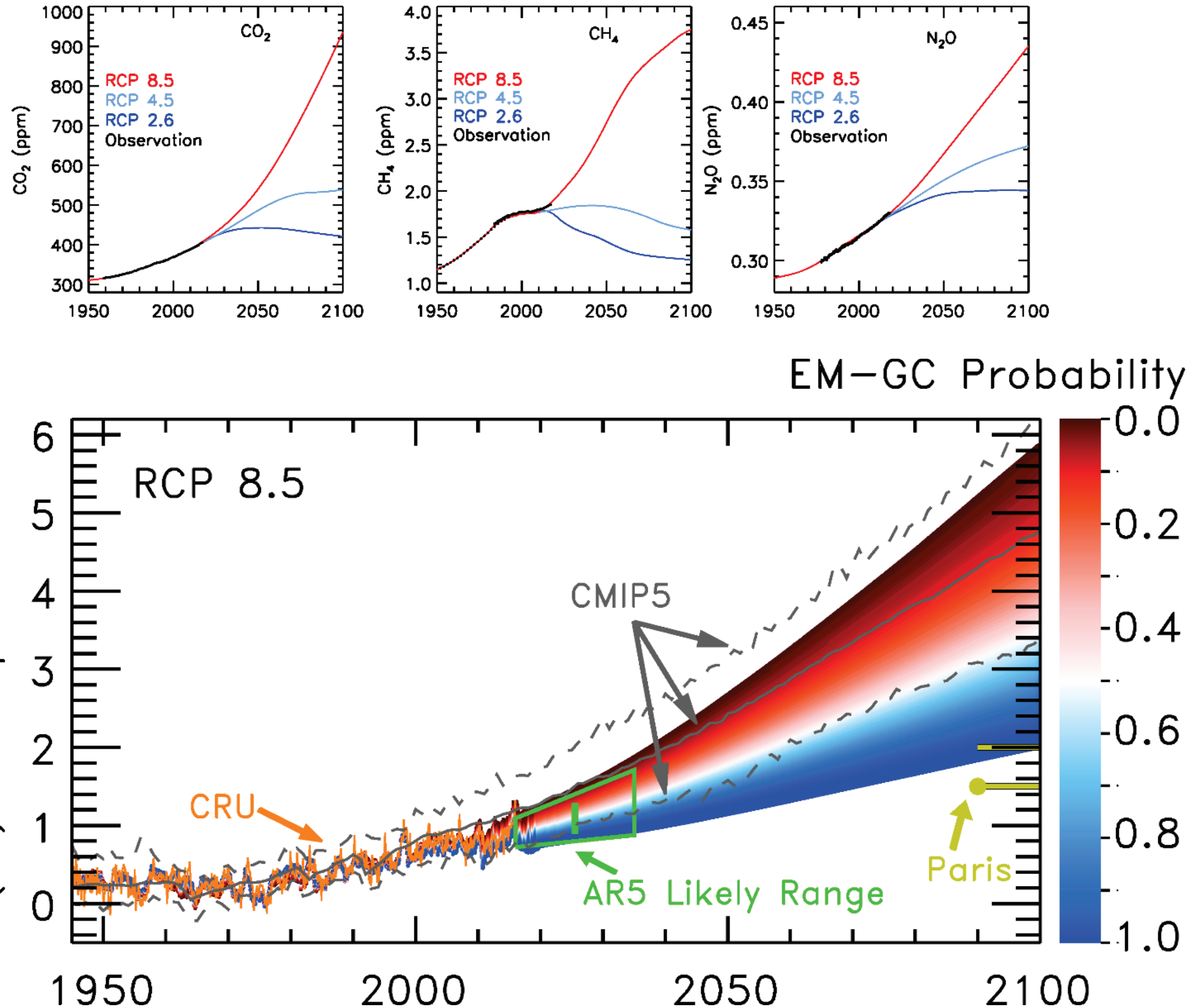
EM-GC Forecast vs CMIP5



Projections of GMST from CMIP5 climate models used by IPCC lie on the "Warm Side" and in some cases well above our EM-GC projections

Hope *et al.*, *Earth's Future*, submitted, 2020.

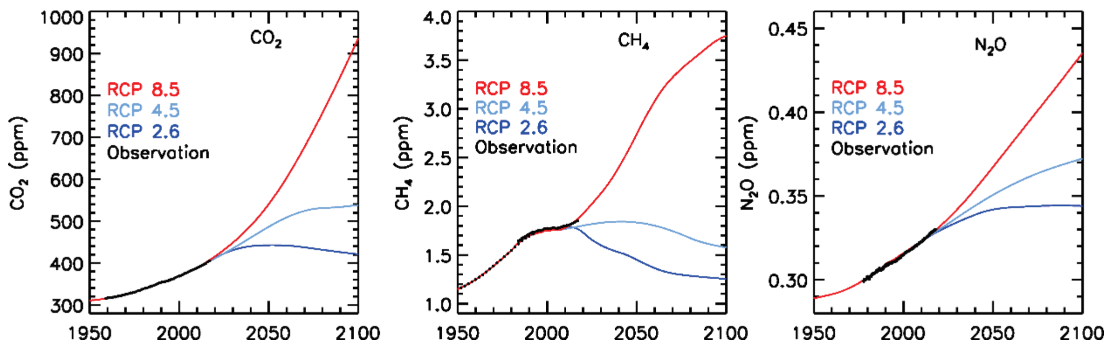
EM-GC Forecast vs CMIP5

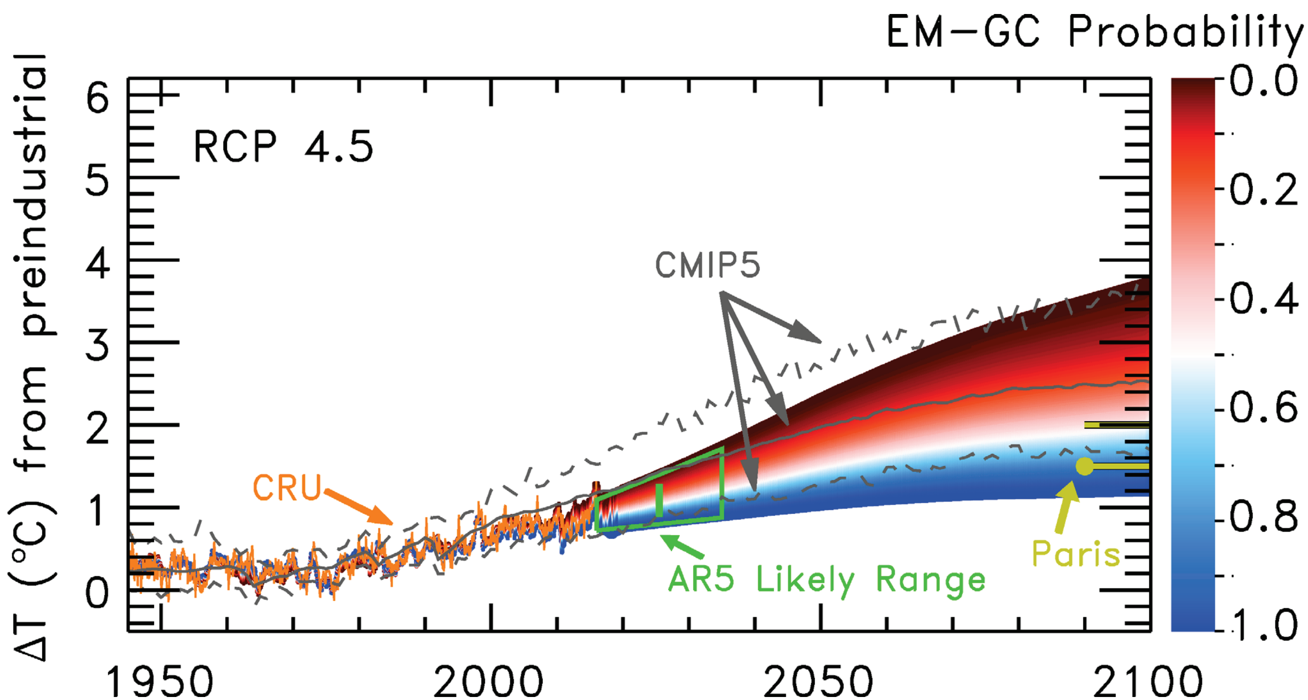


If GHGs follow RCP 8.5, **0%** chance rise GMST stays below **1.5°C** and **0%** chance stays below **2.0°C**

Hope *et al.*, *Earth's Future*, submitted, 2020.

EM-GC Forecast vs CMIP5

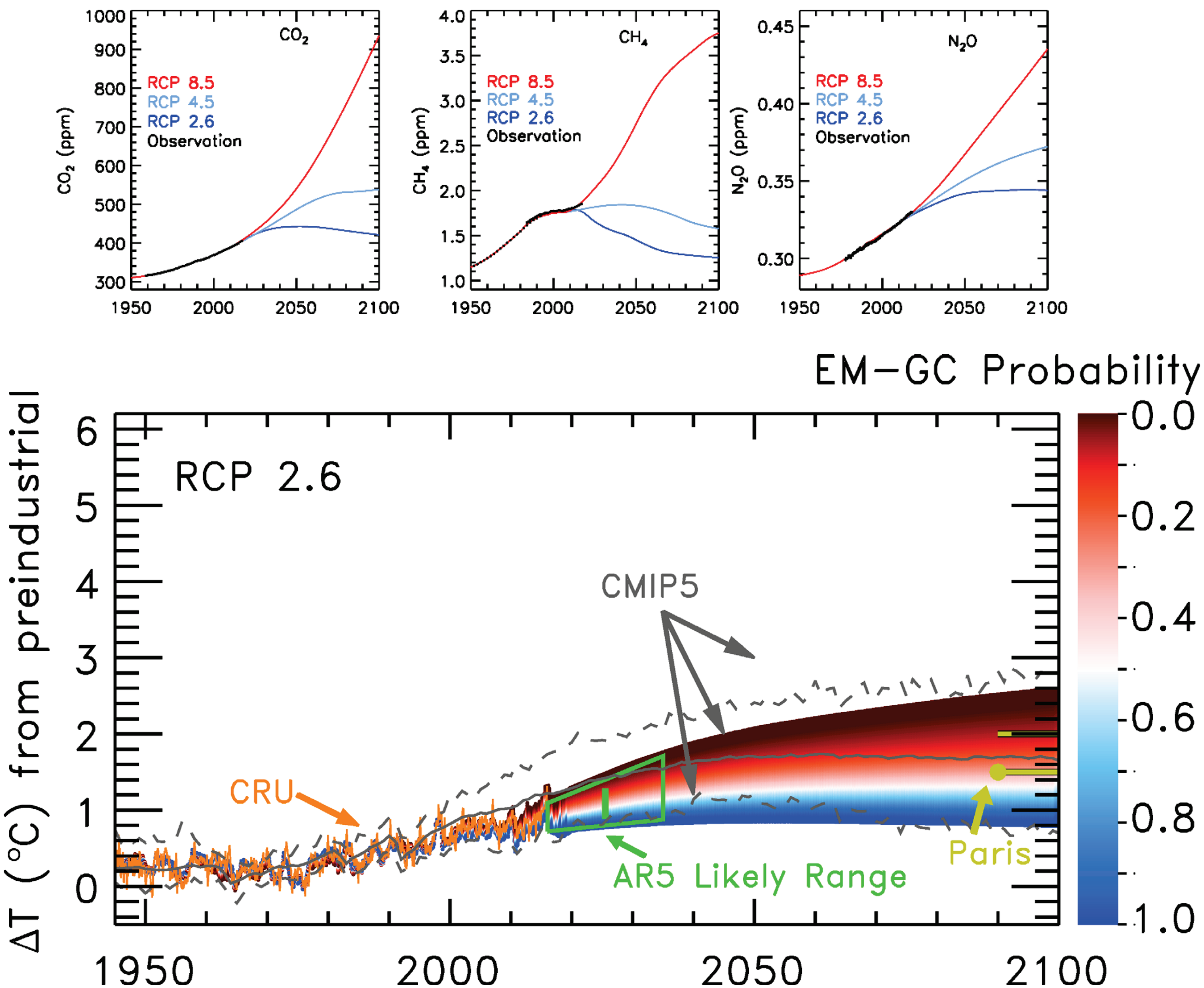




If GHGs follow RCP 4.5, **10%** chance rise GMST stays below **1.5°C** and **50%** chance stays below **2.0°C**

Hope *et al*., *Earth's Future*, submitted, 2020.

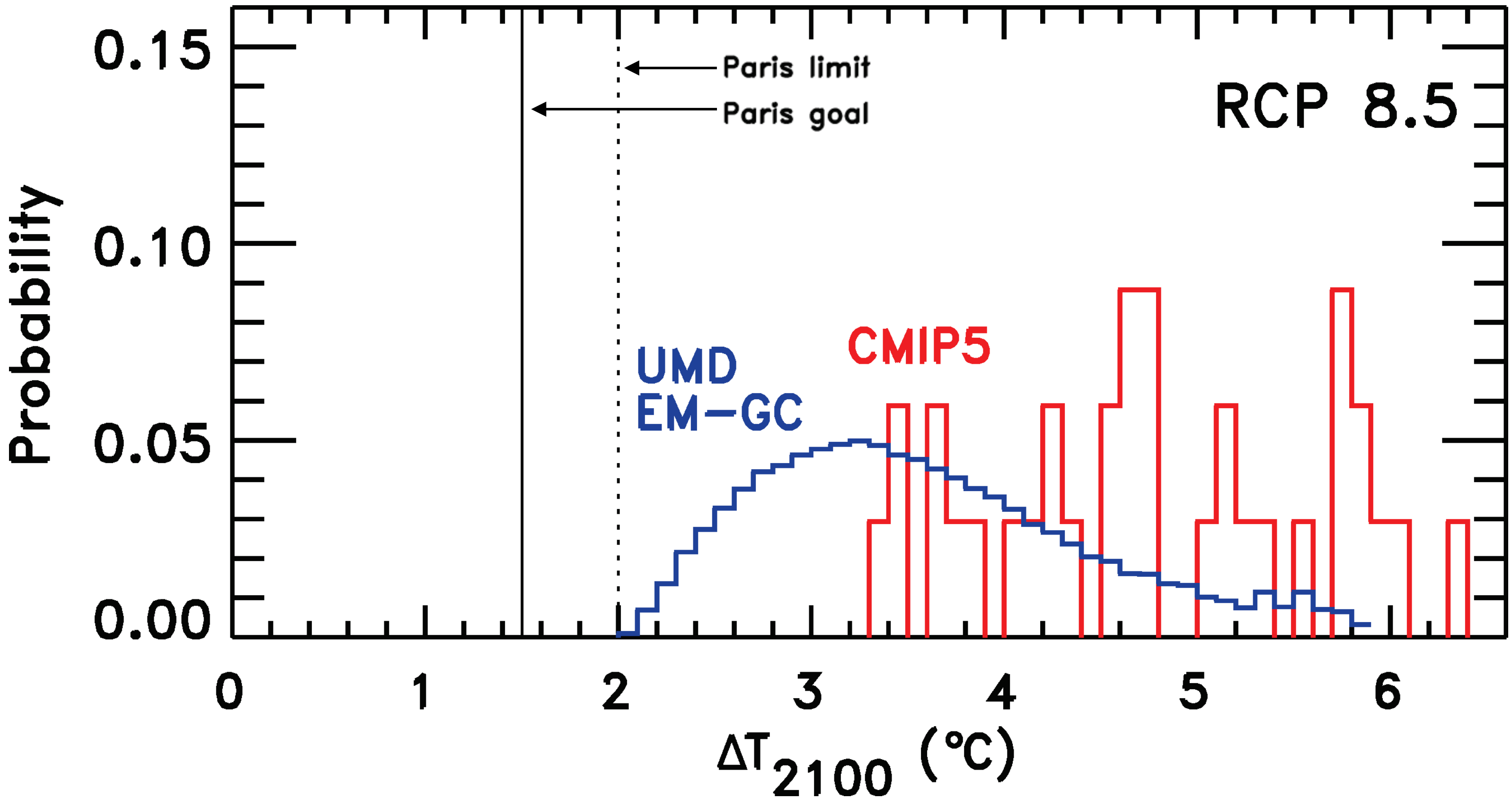
EM-GC Forecast vs CMIP5



If GHGs follow RCP 2.6, **67%** chance rise GMST stays below **1.5°C** and **92%** chance stays below **2.0°C**

Hope *et al*., *Earth's Future*, submitted, 2020.

EM-GC Forecast vs CMIP5



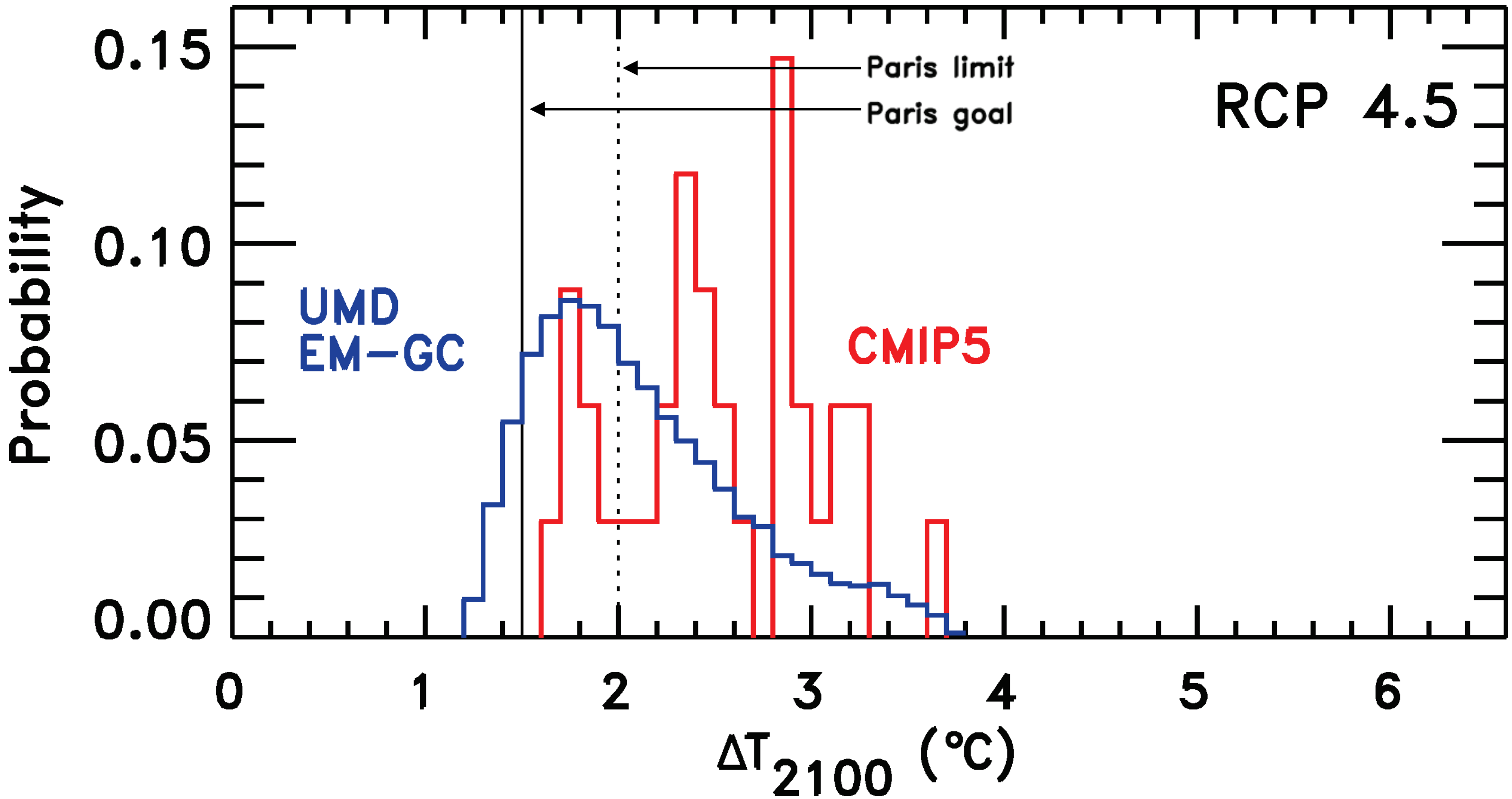
If GHGs follow RCP 8.5:

EM-GC: **0%** chance rise GMST stays below **1.5°C** and **0%** chance stays below **2.0°C**

CMIP5: **0%** chance rise GMST stays below **1.5°C** and **0%** chance stays below **2.0°C**

Hope *et al.*, *Earth's Future*, submitted, 2020.

EM-GC Forecast vs CMIP5



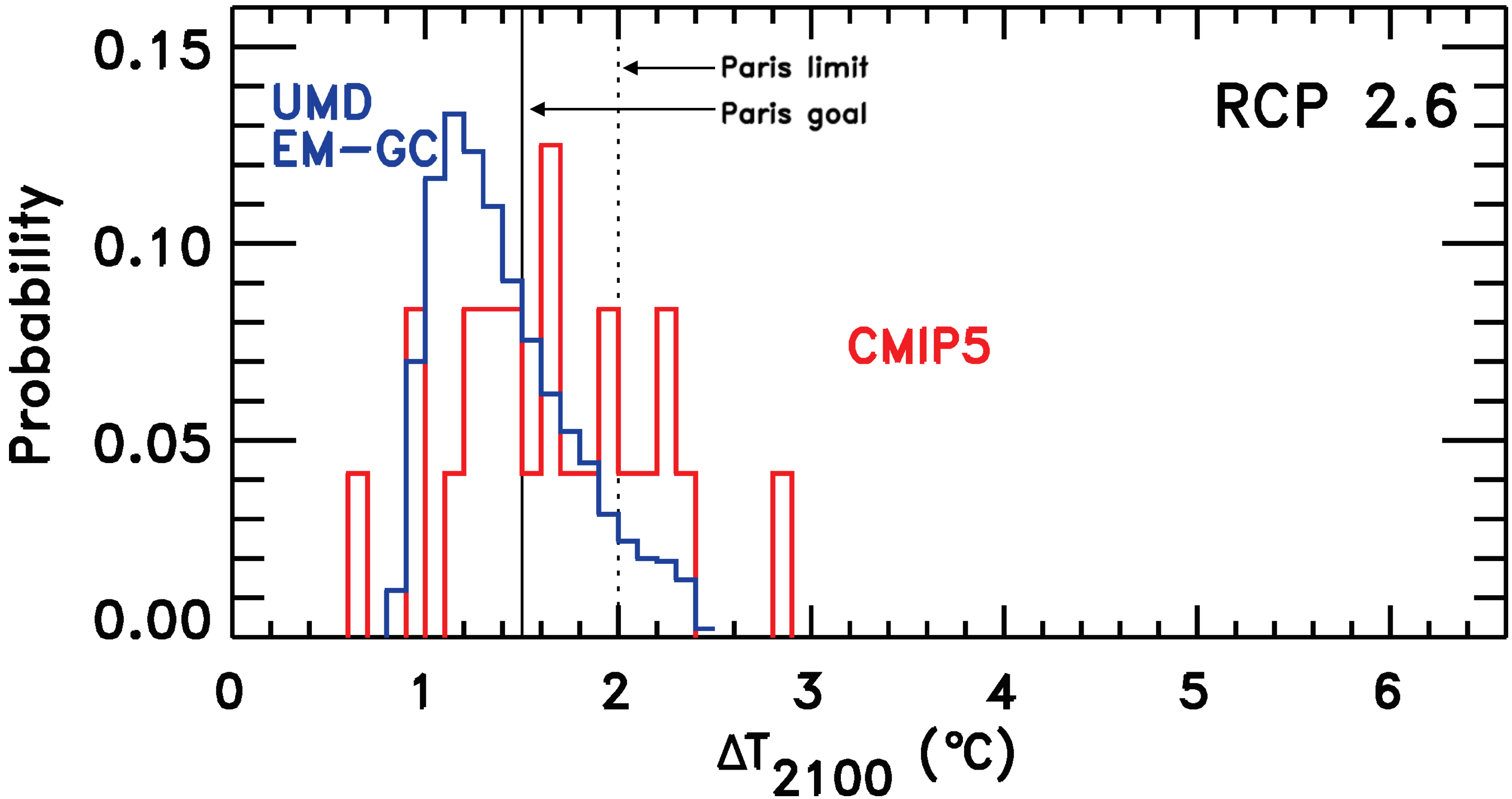
If GHGs follow RCP 4.5:

EM-GC: **10%** chance rise GMST stays below **1.5°C** and **50%** chance stays below **2.0°C**

CMIP5: **0%** chance rise GMST stays below **1.5°C** and **21%** chance stays below **2.0°C**

Hope *et al*., *Earth's Future*, submitted, 2020.

EM-GC Forecast vs CMIP5



If GHGs follow RCP 2.6:

EM-GC: **67%** chance rise GMST stays below **1.5°C** and **92%** chance stays below **2.0°C**

CMIP5: **40%** chance rise GMST stays below **1.5°C** and **76%** chance stays below **2.0°C**

Hope *et al*., *Earth's Future*, submitted, 2020.