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

AOSC / CHEM 433 & AOSC 633

Ross Salawitch & Walter Tribett

Goals:

1. Aerosol RF of climate: 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: using the past to project future

Lecture 08

26 February 2019

Announcements

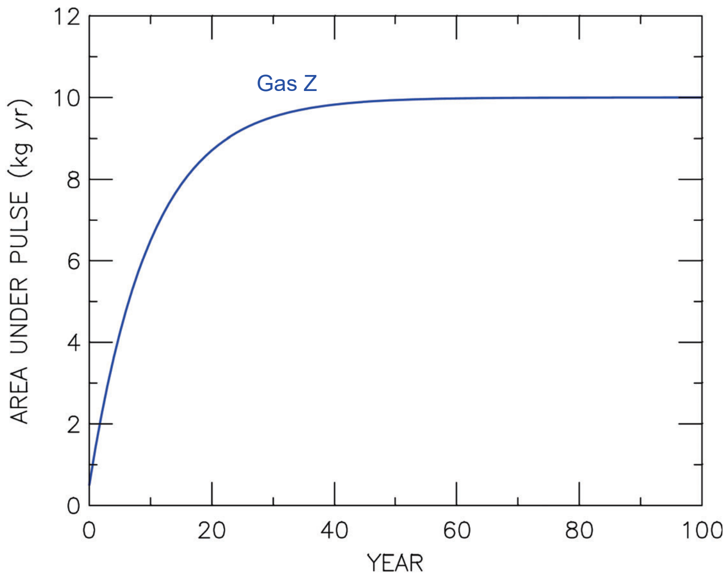
- Problem Set #2 due Thurs, 28 Feb
  – ***Late penalty***: No late penalty since some of the material helpful for completion will be covered in class today. We'll review on Monday, March 4, 5 pm, ATL 2428. To receive credit, your solutions must be turned in prior to the start of the review.

  – We'll return graded solutions on March 4 for anyone who turns in completed solutions this Friday by 9 pm. On Friday, can either hand solutions to Ross (ATL 2403), Walt (ATL 4100), or place under Ross's door.

  – Please work with version of P Set #2 updated on 25 Feb

- First exam is Tues, 5 Mar (a week from today) in class:
  – Closed book, no calculator or e-device
  – Will focus on concepts rather than calculations
  – New exams every year; we will review prior exam in class on Thursday

b) (10 points) Explain why the numerical values of GWP for Gas Z vary in the manner you have found in part a).



$$\int_0^T Z(t)\,dt = Z_o \int_0^T e^{\frac{-t}{\tau}}\,dt = Z_o\tau\,(1 - e^{\frac{-T}{\tau}}) \quad \text{Units: kg yr}$$

$$\int_0^\infty Z(t)\,dt = Z_o \int_0^\infty e^{\frac{-t}{\tau}}\,dt = Z_o\tau\,(1 - e^{\frac{-\infty}{\tau}}) = Z_o\tau \text{ or 10 kg yr for Gas Z}$$

Lecture 7, corrected

How does RF change with concentration?

Table 8.SM.1 | Supplementary for Table 8.3: RF formulae for CO_2, CH_4 and N_2O.

Gas	RF (in W m^{-2})	Constant α
CO_2	$\Delta F = \alpha \ln(C/C_0)$	5.35
CH_4	$\Delta F = \alpha\left(\sqrt{M} - \sqrt{M_0}\right) - \left(f(M,N_0) - f(M_0,N_0)\right)$	0.036
N_2O	$\Delta F = \alpha\left(\sqrt{N} - \sqrt{N_0}\right) - \left(f(M_0,N) - f(M_0,N_0)\right)$	0.12

Notes:

$f(M, N) = 0.47 \ln [1 + 2.01\times10^{-5}\,(MN)^{0.75} + 5.31\times10^{-15}\,M\,(MN)^{1.52}]$

C is CO_2 in ppm.

M is CH_4 in ppb.

N is N_2O in ppb.

The subscript 0 denotes the unperturbed molar fraction for the species being evaluated. However, note that for the CH_4 forcing N_0 should refer to present-day N_2O, and for the N_2O forcing M_0 should refer to present-day CH_4.

IPCC Fifth Assessment Report, 2013

Atmospheric CH_4

AT6, Q3:

What are the Global Warming Potentials for CH_4 :

a) given in Table 3.2 of Chemistry in Context: **21**

b) used for the 20-year time horizon in the first full paragraph on page 26 of *Paris, Beacon of Hope: **84***

c) used for the 100-year time horizon in the first full paragraph on page 26 of *Paris, Beacon of Hope: **28***

The ~10 year atmospheric lifetime for CH_4 has important policy implications. This is best illustrated by comparing the human release of CH_4 to that of CO_2. Throughout the world, humans presently release about 335 Tg of CH_4 and 39 Gt of CO_2 per year. Since 1000 Tg = 1 Gt, these sources are 0.335 Gt of CH_4 and 39 Gt of CO_2 per year: i.e., the mass of CO_2 released to the atmosphere each year by human society is about 116 times more than the mass of CH_4. The impact on climate is entirely dependent on the time scale of interest. Nearly all of the CH_4 released to the atmosphere in year 2015 will be gone by the end of this century. The ***CO_2-equivalent*** emission of CH_4, found by multiplying the current release by the GWP for CH_4 for a 100-year time horizon, is 28 × 0.335 Gt of CH_4 or 9.4 Gt per year. If our concern is global warming over the next century, then we would conclude the human release of CO_2 in year 2015 was about four times more harmful for climate (39 ÷ 9.4 = 4.1) than the release of CH_4. However, if our concern is the next two decades, we must consider the GWP of CH_4 over a 20-year time horizon. In this case, the CO_2-equivalent emission of CH_4 is 84 × 0.335 Gt or 28.1 Gt per year, and we would conclude the present human release of CH_4 is nearly as harmful for climate (28.1 versus 39) as the release of CO_2.

CO_2 – equiv. emiss.^{2015} , 20-yr horiz

$$= CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$$
$$= 9.7\,(44/12) + 1.62(44/12) + 84\times0.335 + 264\times0.0069 \quad \text{Gt } CO_2$$
$$= 35.6 + 5.9 + 28.1 + 1.8 = 71.4 \text{ Gt } CO_2$$

CH_4 & N_2O constitute (29.9 / 71.4) or 42% of emissions, for the big three

Atmospheric CH_4

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a) given in Table 3.2 of Chemistry in Context: **21**

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CO_2 – equiv. emiss.^{2015} , 100-yr horiz

$$= CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$$
$$= 9.7\,(44/12) + 1.62(44/12) + 28\times0.335 + 265\times0.0069 \quad \text{Gt } CO_2$$
$$= 35.6 + 5.9 + 9.4 + 1.8 = 52.7 \text{ Gt } CO_2$$

CH_4 & N_2O constitute (11.2 / 52.7) or 21% of emissions, for the big three

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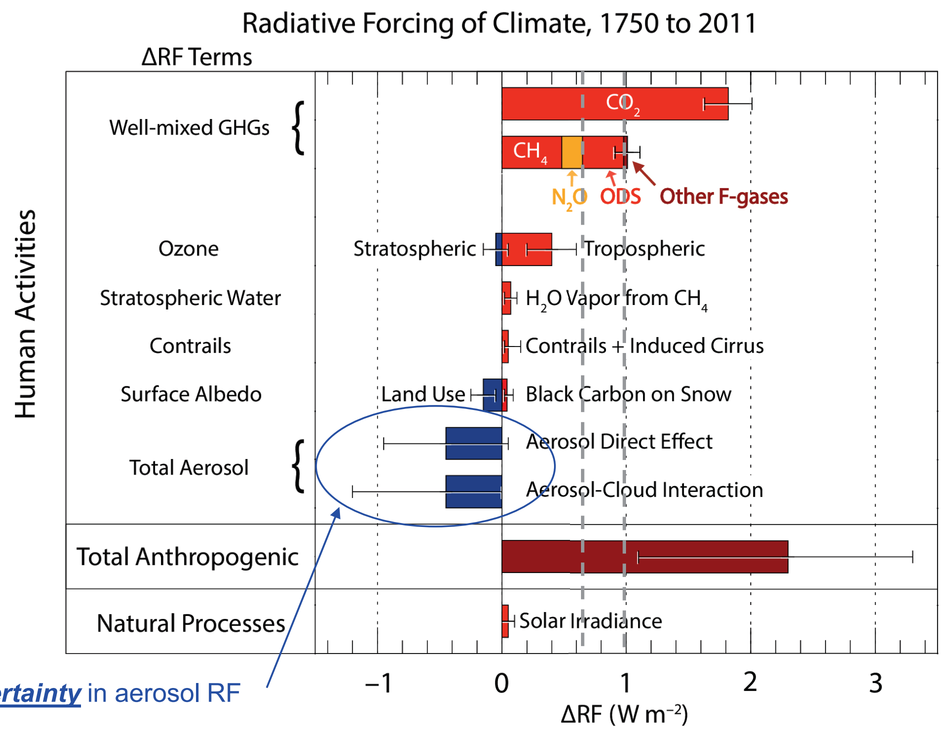
ΔRF of Climate



Large uncertainty in aerosol RF

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

Radiative Forcing of Climate, 1750 to 2011

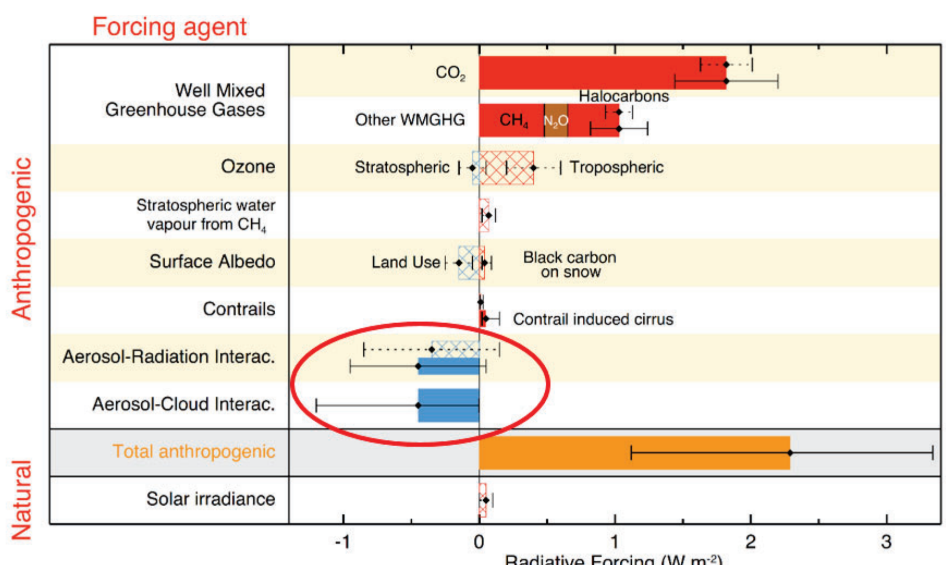


Fig 8.15, IPCC 2013

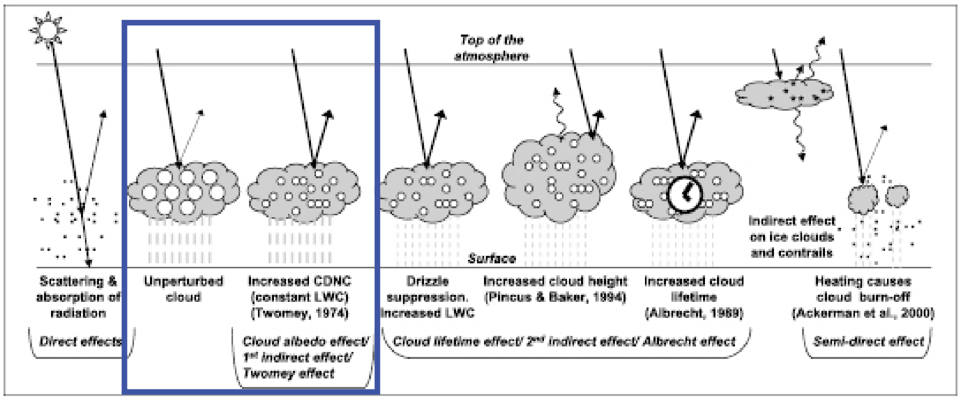
Hatched bars correspond to a newly introduced concept called Effective RF, which allows for some "tropospheric adjustment" to initial perturbation

Solid bars represent traditional RF (quantity typically shown)

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

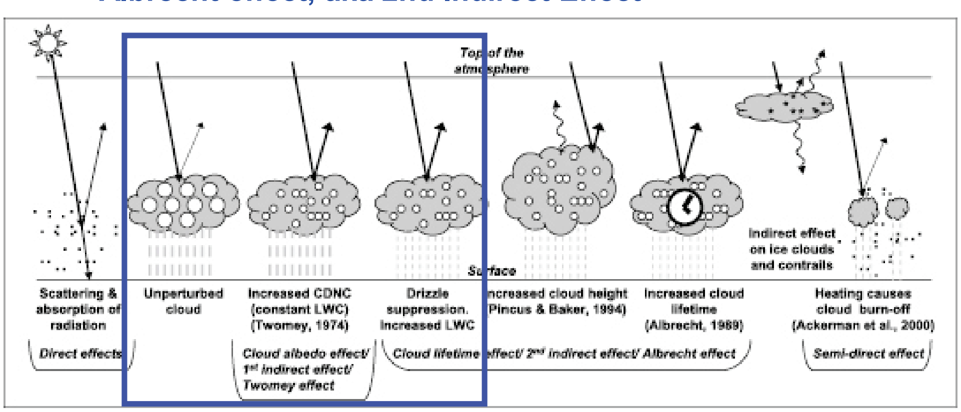
Fig 2-10, IPCC 2007

- 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

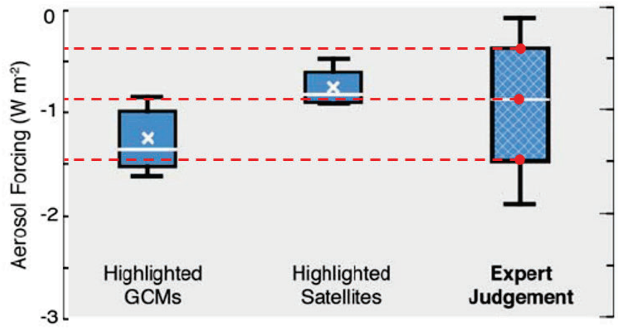


Large uncertainty in aerosol RF

Fig 2-10, IPCC 2007

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

Tropospheric Aerosol RF



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

Figure 7.19B, IPCC 2013

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

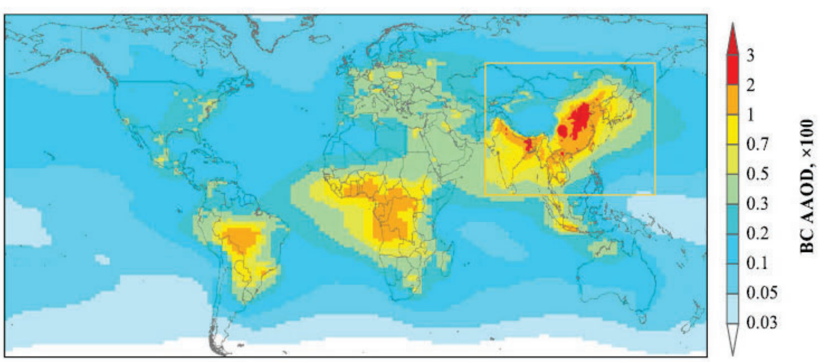
ΔRF_{2011} Aerosols: best estimate is –0.9 W m^{-2}, probably between –0.4 W m^{-2} and –1.5 W m^{-2};
could be between –0.1 W m^{-2} and –1.9 W m^{-2}

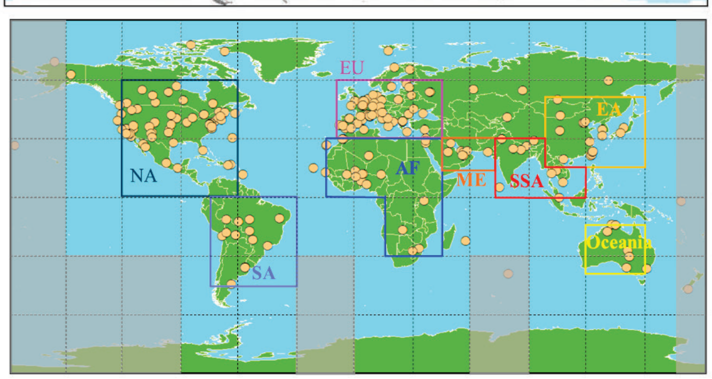
Large uncertainty in aerosol RF

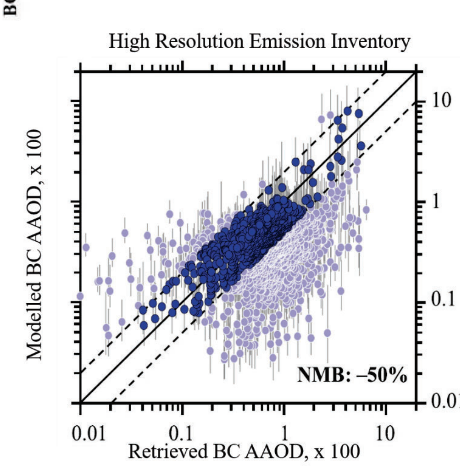
- scatter and absorb radiation (**direct radiative forcing**)
- affect cloud formation (**indirect radiative forcing**)

Black Carbon Aerosols

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





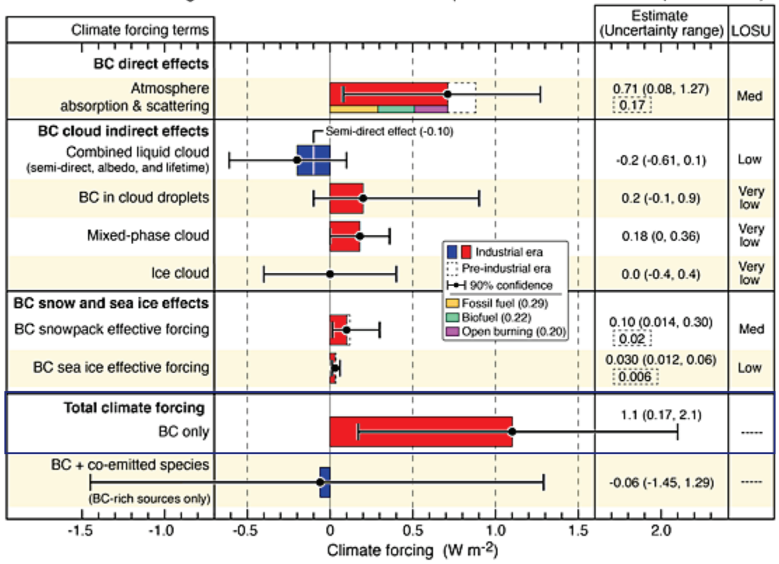


Wang et al., *JGR*, 2016
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JD024326

Black Carbon Aerosols

Bond *et al*., Bounding the role of black carbon in the climate system: A scientific assessment, *JGR*, 2013

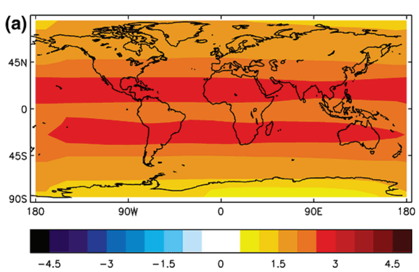
Global climate forcing of black carbon and co-emitted species in the industrial era (1750 - 2005)



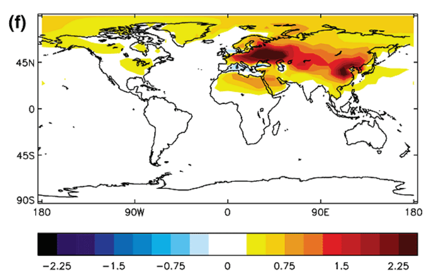
	Total Climate Forcing, Black Carbon Aerosols (W m^{-2})			
Report	IPCC (1995)	IPCC (2001)	IPCC (2007)	**IPCC (2013)**
ΔRF, BC	0.1 (0.03 to 0.3)	0.2 (0.1 to 0.4)	0.2 (0.05 to 0.35)	**0.4 (0.05 to 0.80)**

Global View

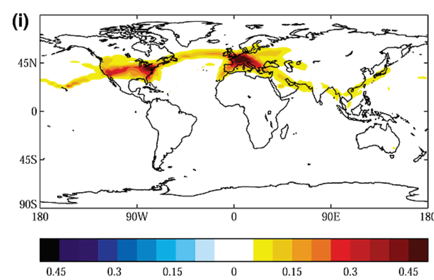
All forcings (1750-2000) are in Wm^{-2}

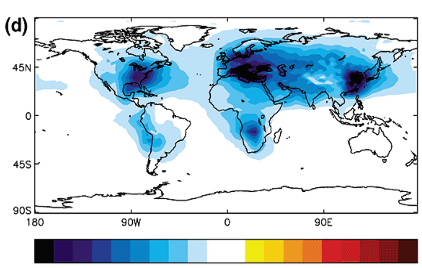


Greenhouse gases

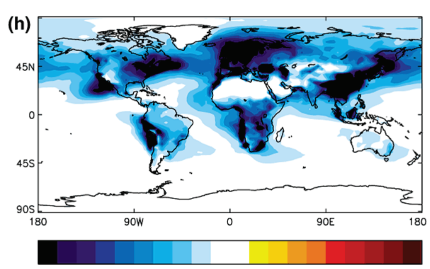


Organic and black carbon from fossil fuel burning

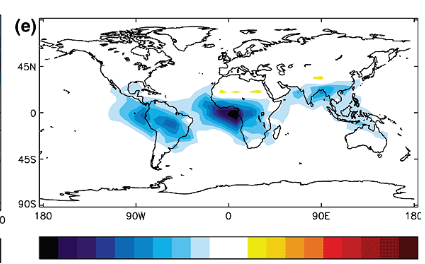




Direct effect from sulphate aerosols



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/

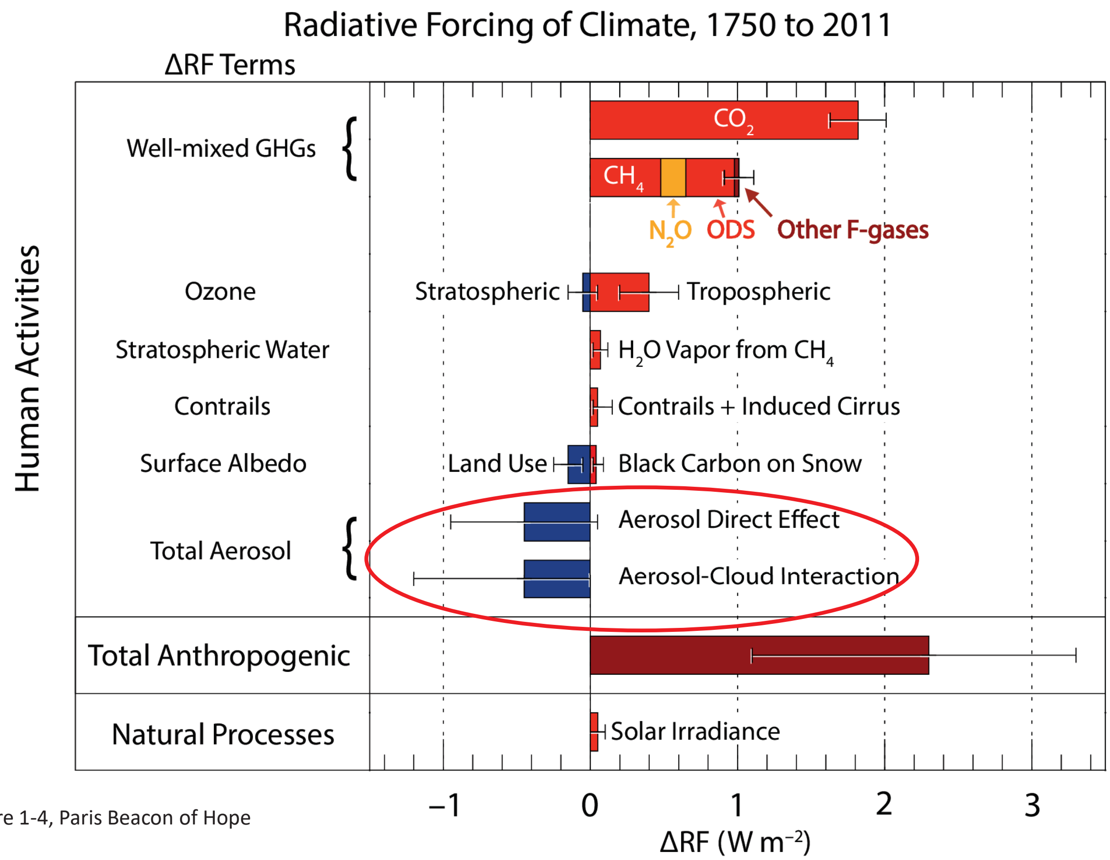


Figure 1-4, Paris Beacon of Hope

RF of Climate due to GHGs and Aerosols

- Past: tropospheric aerosols have offset some *unknown* fraction of GHG warming
- Future: this "mask" is going away due to air quality concerns

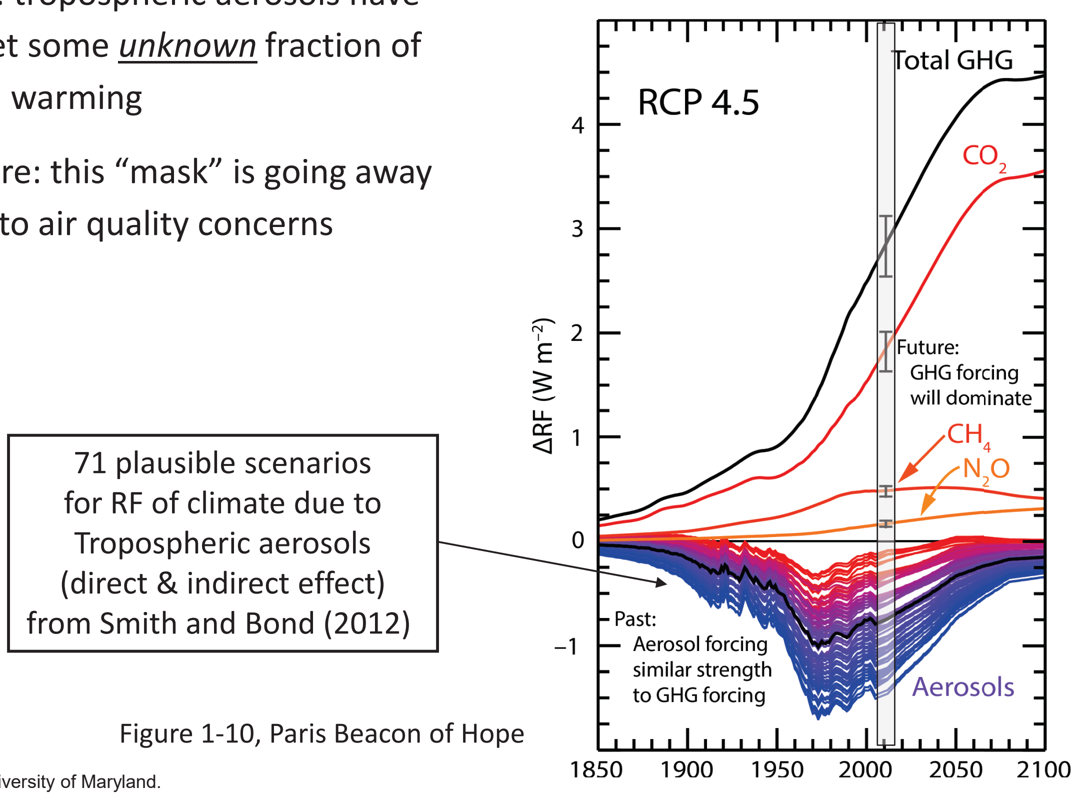


Figure 1-10, Paris Beacon of Hope

Combining RF GHGs & Aerosols

RF due to all GHGs

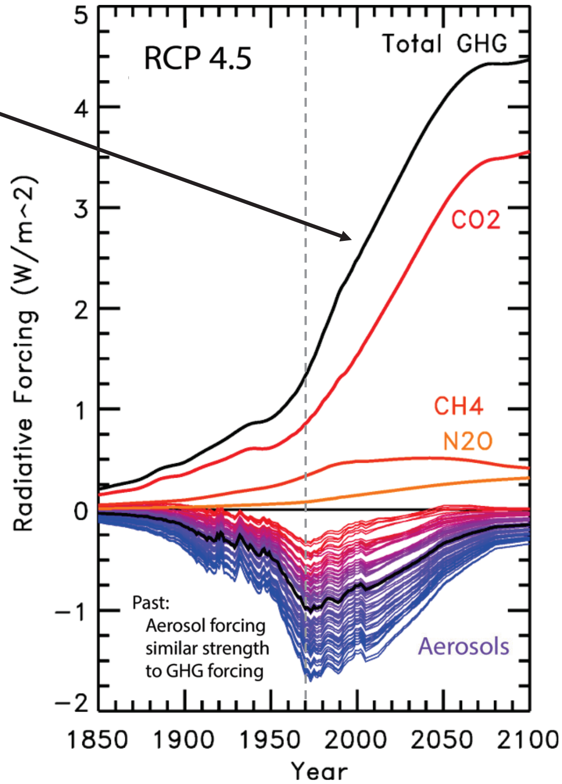


Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols

RF due to all GHGs
minus RF due to Aerosols,
for curve with –0.4 W m^{-2}
in year 2011

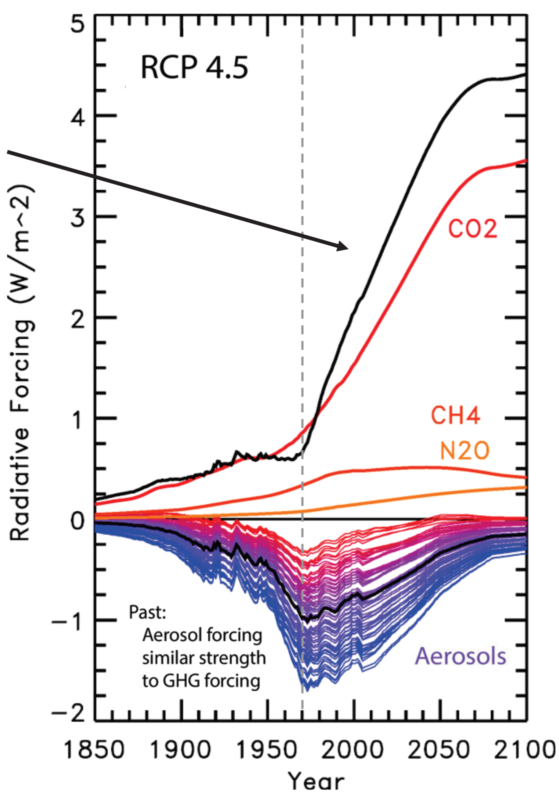


Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols

RF due to all GHGs minus RF due to Aerosols, for curve with –0.9 W m^{-2} in year 2011

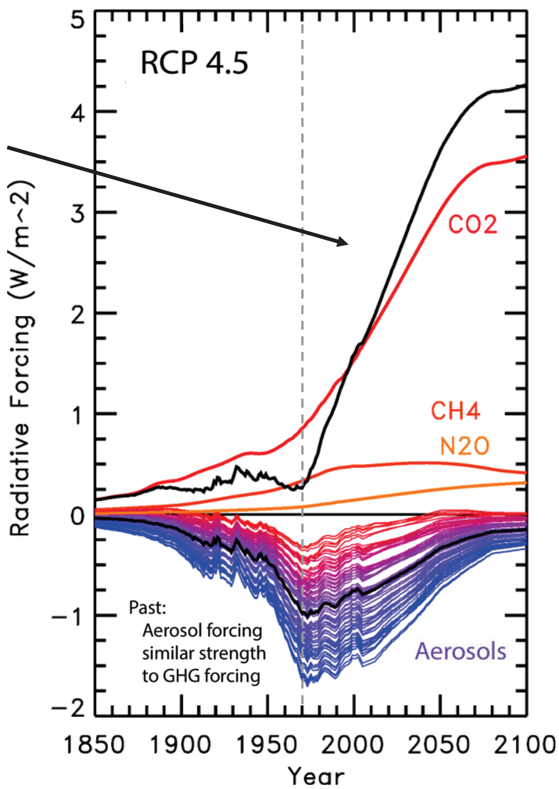


Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols

RF due to all GHGs minus RF due to Aerosols, for curve with –1.5 W m^{-2} in year 2011

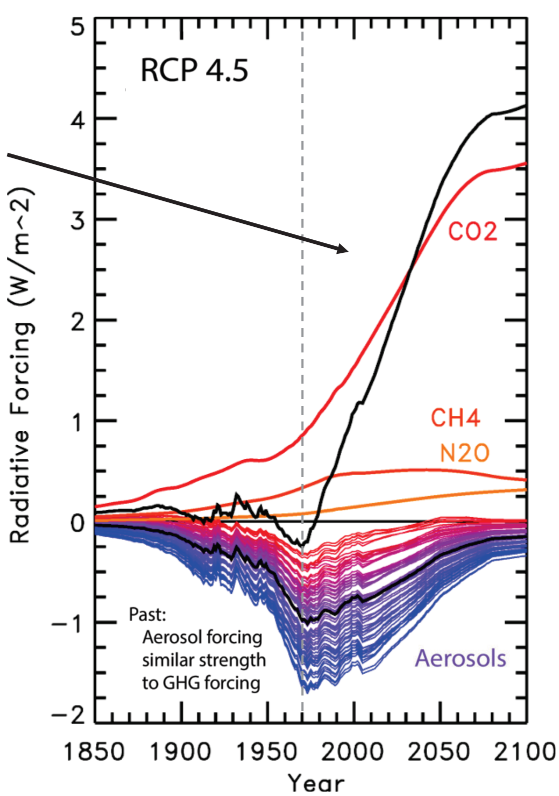


Fig 1.10, *Paris, Beacon of Hope*

Simple Climate Model

$$\Delta T = \lambda_{BB}\ (1 + f_{H2O})\ (\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{OTHER\ GHGs} + \Delta F_{AEROSOLS})$$

where

$$\lambda_{BB} = 0.3\ K\ /\ W\ m^{-2}$$

Climate models that consider water vapor feedback find:

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

Lecture 4, Slide 35

Slightly More Complicated Climate Model

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

where

$$\lambda_{BB} = 0.3\ K\ /\ W\ m^{-2};\ \text{this term is also called}\ \lambda_{PLANCK}$$

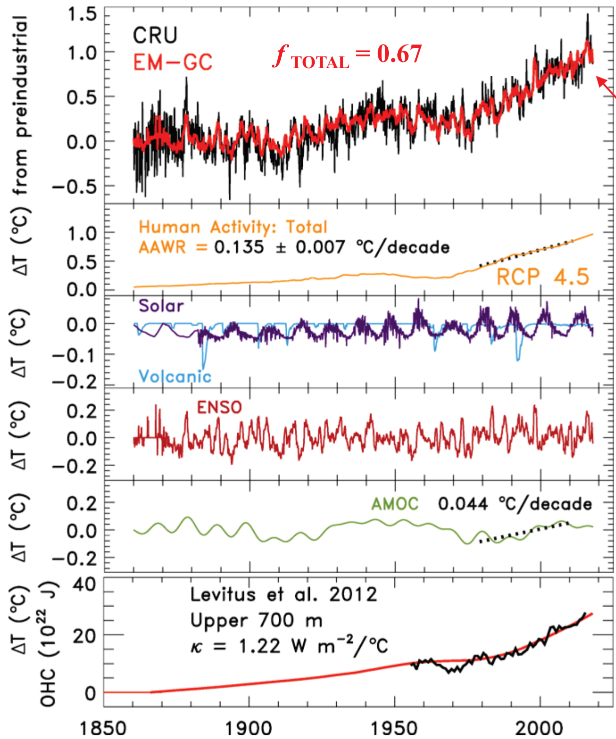
where f_{TOTAL} is dimensionless climate sensitivty parameter that represents feedbacks,
and is related to IPCC definition of feedbacks (see Bony et al., J. Climate, 2006) via:

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

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

Each FB term has units of $W\ m^{-2}\ {}^{\circ}C^{-1}$; the utility of this approach is that feedbacks can be summed to get FB_{TOTAL}

Empirical Model of Global Climate (EM-GC)



$\Delta T_{MDL\,i} = (1 + f_{TOTAL})\lambda_{BB}(GHG\ RF_i + LUC\ RF_i + Aerosol\ RF_i) +$
$C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} +$
$C_4 \times AMOC_i - \lambda_{BB}\, Q_{OCEAN_i}$

where:

i = month

$\lambda_{BB} = 0.3$ °C / W m^{-2}

$$1 + f_{TOTAL} = \frac{1}{1 - FB_{\Sigma}\,\lambda_{BB}}$$

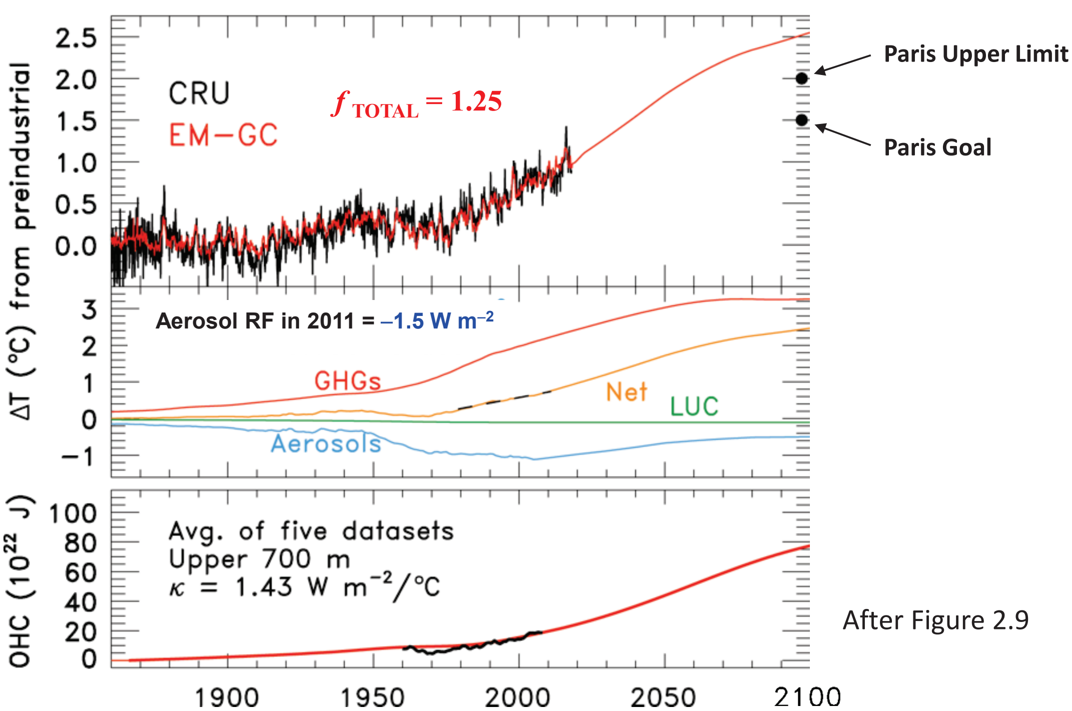
FB_{Σ} = Sum of All Feedbacks, i.e.,

$FB_{\Sigma} = FB_{WV} + FB_{LR} + FB_{SURFACE\ ALBEDO} + FB_{CLOUDS}$
in units of W m^{-2} °C^{-1}

Aerosol RF = total RF due to Tropospheric Aerosols
LUC RF = RF due to Land Use Change
SOD = Stratospheric Optical Depth
TSI = Total Solar Irradiance
ENSO = El Niño Southern Oscillation
AMOC = Atlantic Meridional Overturning Circ.
Q_{OCEAN} = Ocean heat export =
$\kappa(1 + f_{TOTAL})\{\Delta T_{MDL\,i} - \Delta T_{OCEAN\ SURFACE\ i}\}$

Canty *et al.*, *ACP*, 2013 https://www.atmos-chem-phys.net/13/3997/2013/acp-13-3997-2013.html
updated by Austin Hope & Laura McBride

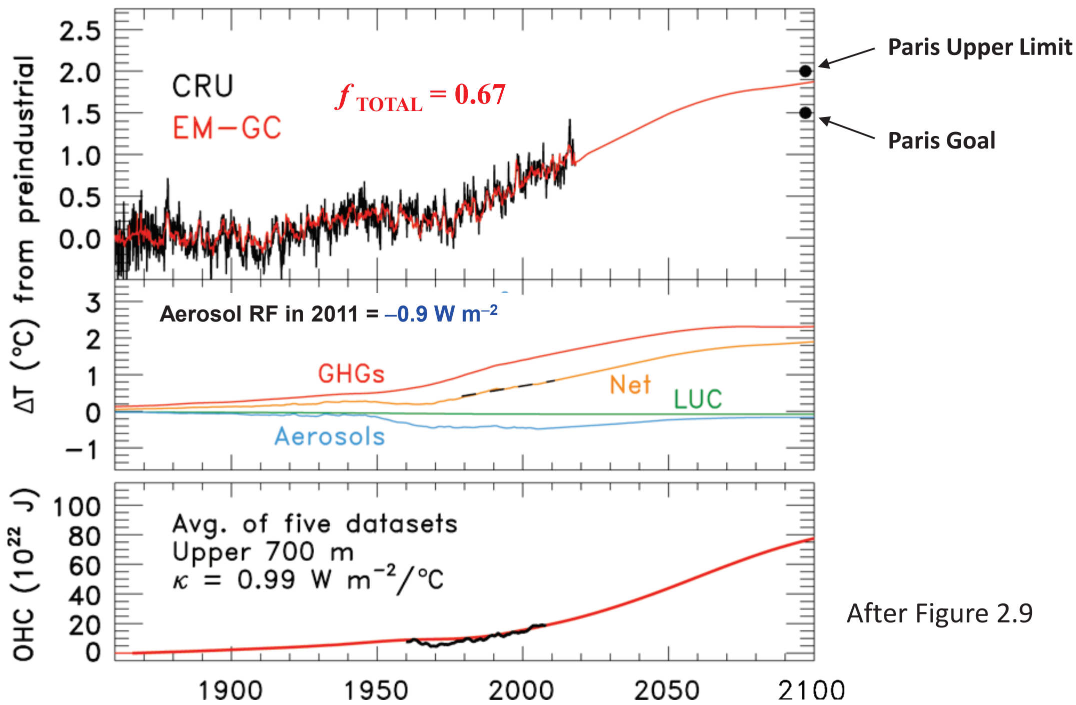
EM-GC Forecast for RCP 4.5 GHG scenario



After Figure 2.9

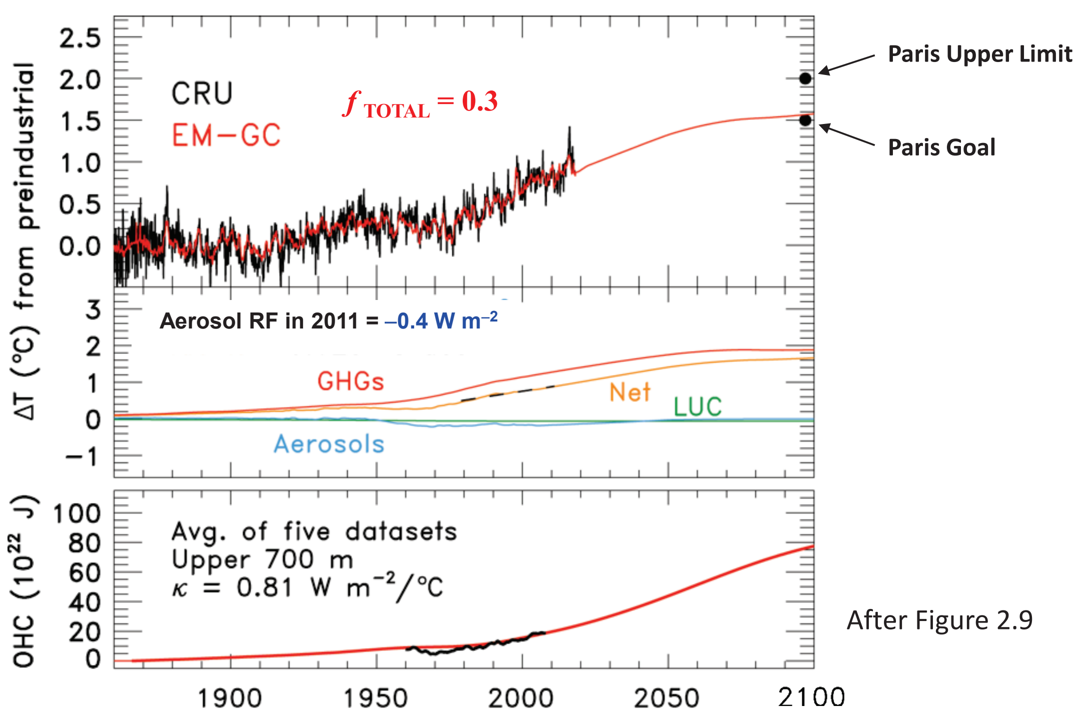
We assume that whatever value of climate feedback is inferred from the climate record will persist into the future.
For Aerosol RF in 2011 of **−1.5 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct,
this simulation implies sum of <u>other feedbacks</u> (clouds, surface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

EM-GC Forecast for RCP 4.5 GHG scenario



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 ***slightly positive***.

EM-GC Forecast for RCP 4.5 GHG scenario



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 ***negative***.

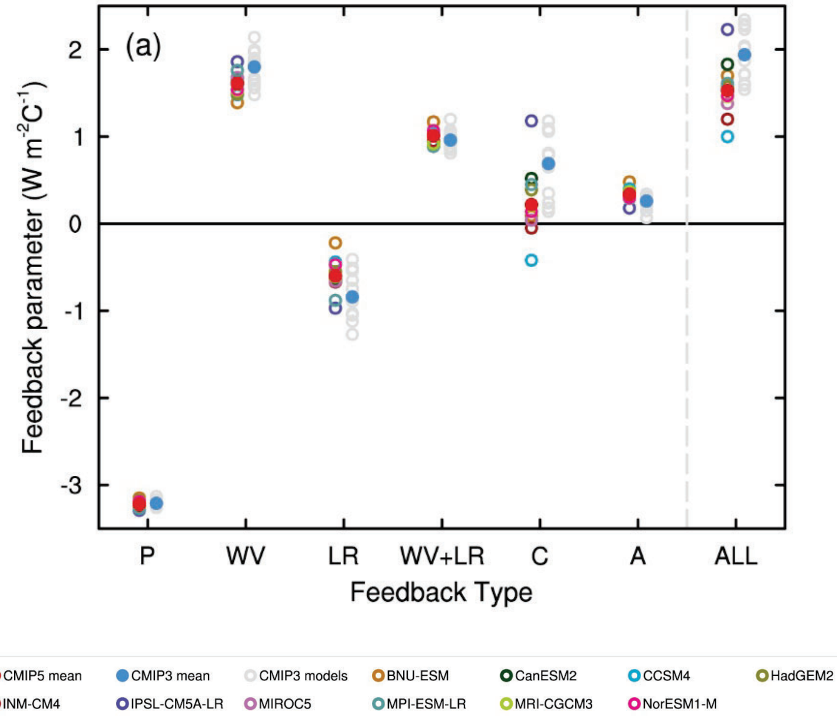
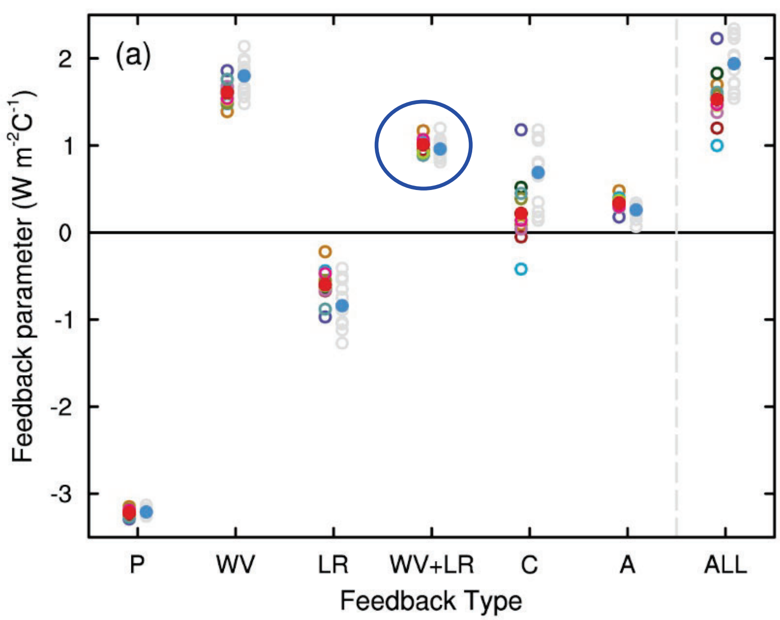


Fig 9.43, IPCC 2013

P : Planck
WV: Water Vapor
LR: Lapse Rate
WV + LR : Water Vapor + Lapse Rate
C: Clouds
A: Albedo
ALL: Our



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

$$1 + f_{TOTAL} = \frac{1}{1 - \dfrac{1.0\ W\ m^{-2}\ {}^{\circ}C^{-1}}{3.2\ W\ m^{-2}\ {}^{\circ}C^{-1}}} = 1.45$$

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

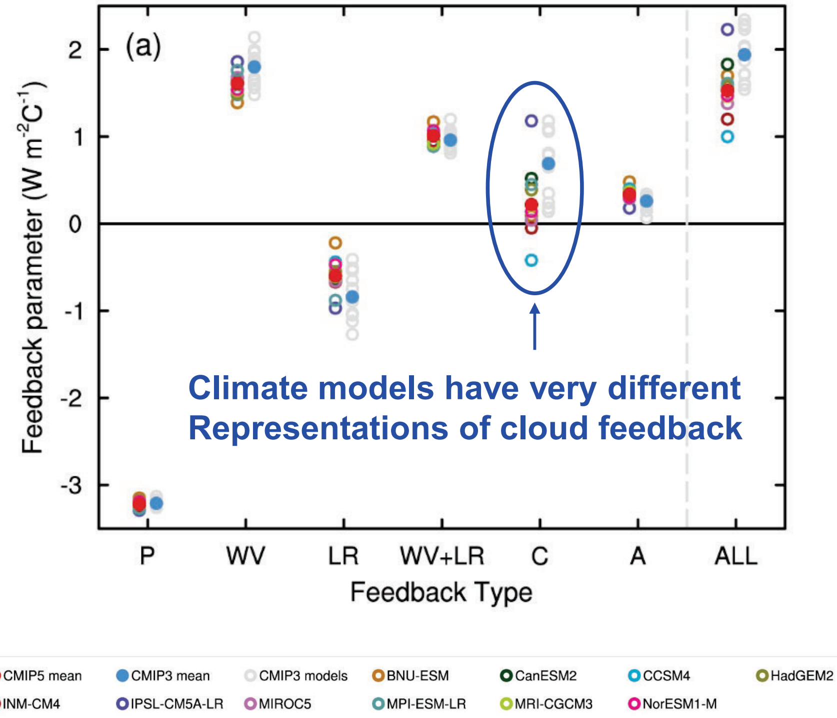


Fig 9.43, IPCC 2013

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

C: Clouds
A: Albedo
ALL: Our

Ice-Albedo Feedback

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

Then: Ice Melts

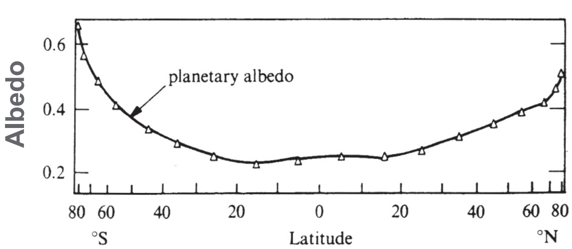
Consequence: Albedo Falls

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

2. Albedos of selected surfaces on Earth

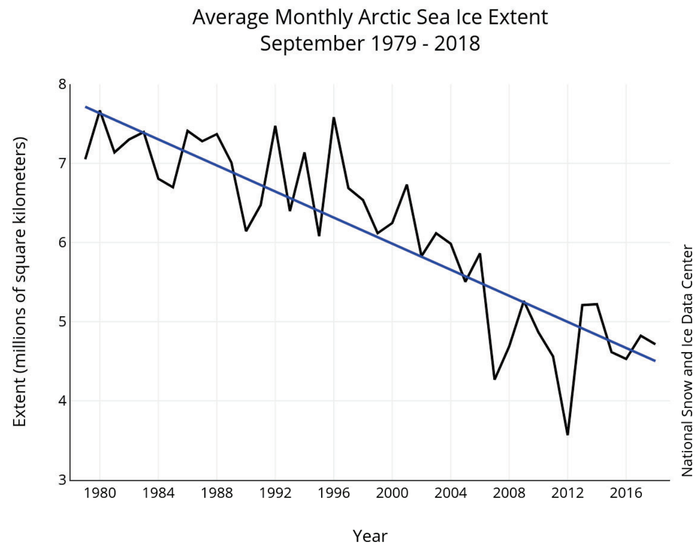
surface	albedo
snow	0.7 ± 0.2
sand	0.25 ± 0.05
grasslands	0.23 ± 0.03
bare soil	0.2 ± 0.05
forest	0.15 ± 0.1
water (highly dependent on surface roughness and incident angle of sunlight)	0.2 + 0.6 − 0.2

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



Houghton, *The Physics of Atmospheres*, 1991.

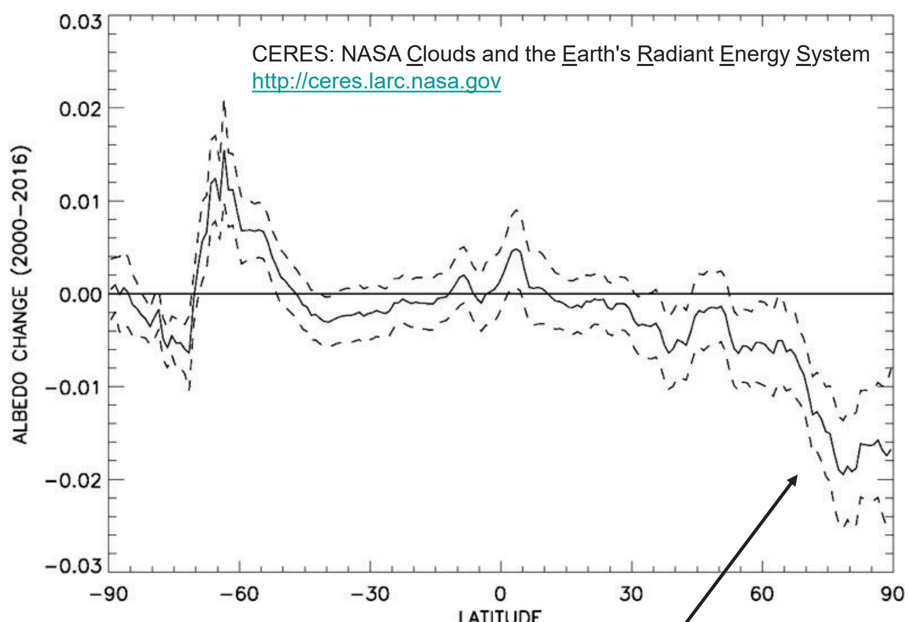
Arctic Sea-Ice: Canary of Climate Change



- Sea ice: ice overlying ocean
- Annual minimum occurs each September
- Decline of ~13.3% / decade over satellite era

http://nsidc.org/arcticseaicenews/files/2014/10/monthly_ice_NH_09.png

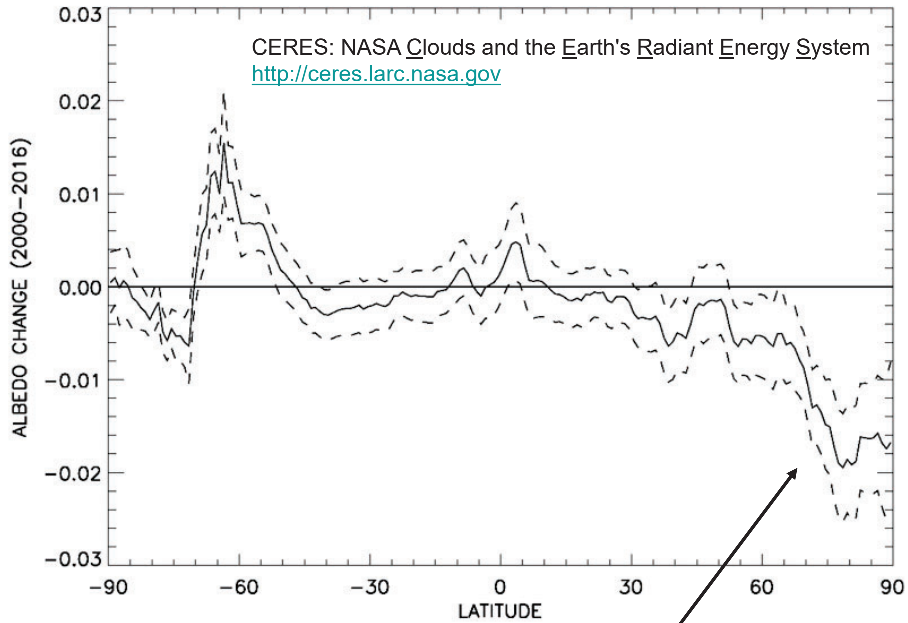
Albedo Anomaly (CERES) Change versus Latitude, No Weighting



Slide courtesy Austin Hope; analysis to the end of 2016

NH high latitude darkening (melting sea ice) is apparent

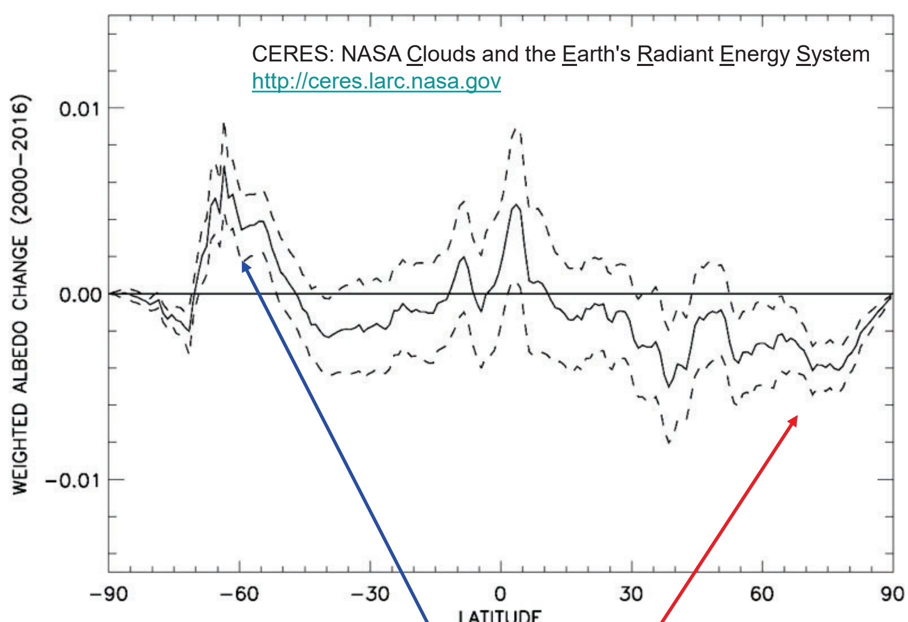
Albedo Anomaly (CERES) Change versus Latitude, No Weighting



Slide courtesy Austin Hope; analysis to the end of 2016

NH high latitude darkening (melting sea ice) is apparent

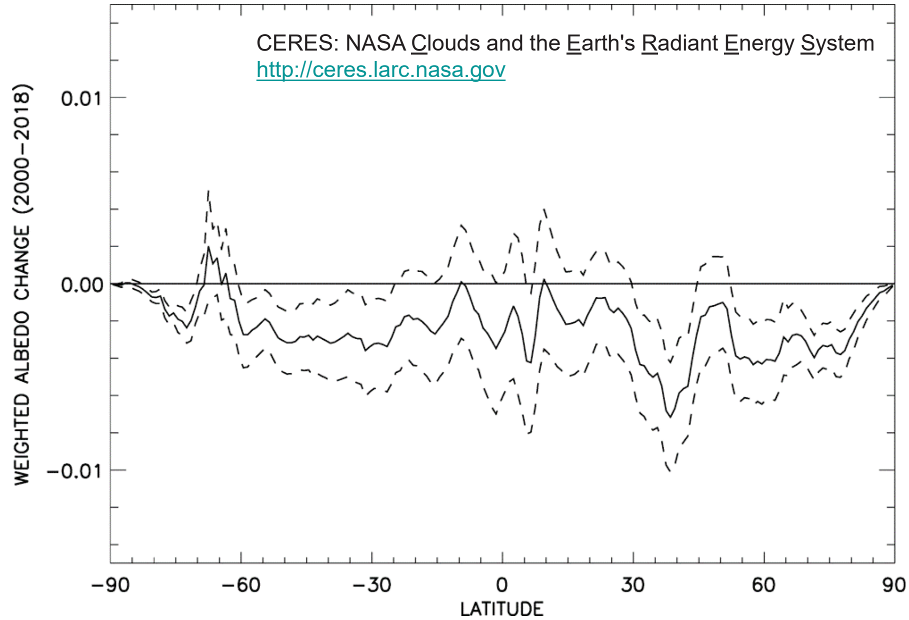
Albedo Anomaly (CERES) Change versus Latitude, *Weighted by Cosine Latitude*



Slide courtesy Austin Hope;
analysis to the end of 2016

NH high latitude darkening (melting sea ice) has been partially offset by SH brightening since year 2000

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



Slide courtesy Laura McBride;
analysis to the end of 2018

NH high latitude darkening hard to distinguish
due to apparent, near global darkening ?!?

Water Vapor Feedback

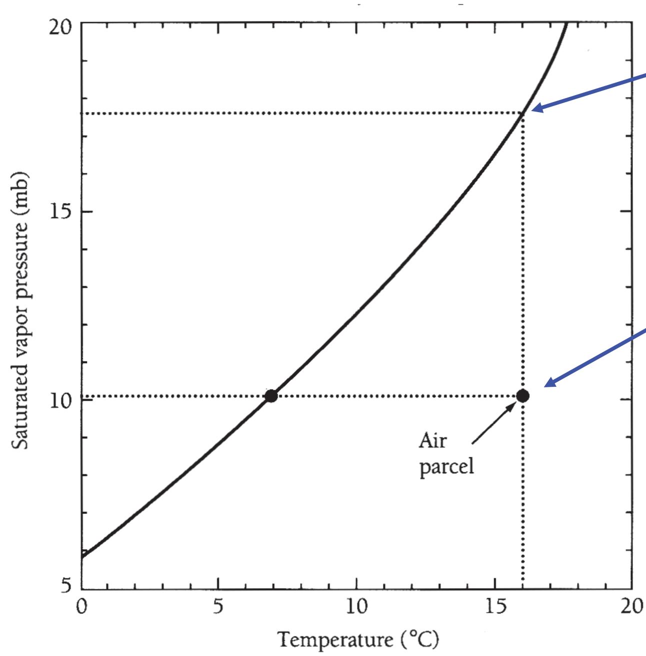


Figure 4.8a Relative humidity and the dew point.

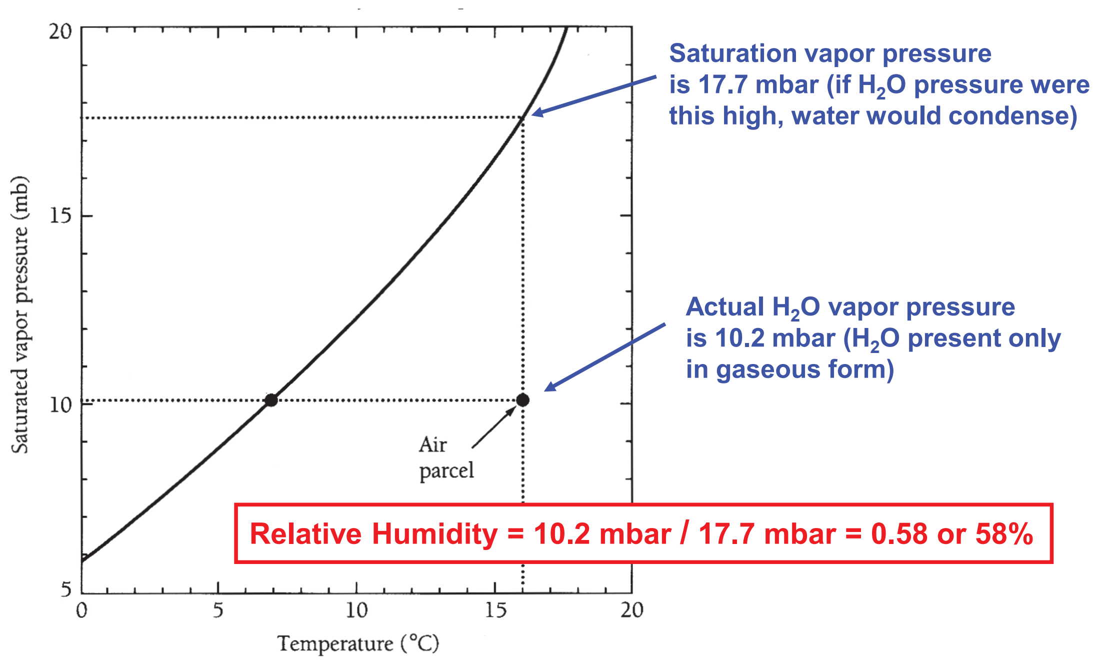
McElroy, *Atmospheric Environment*, 2002

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)

Clausius-Clapeyron relation describes the temperature dependence of the ***saturation vapor pressure of <u>water</u>*.**

Water Vapor Feedback



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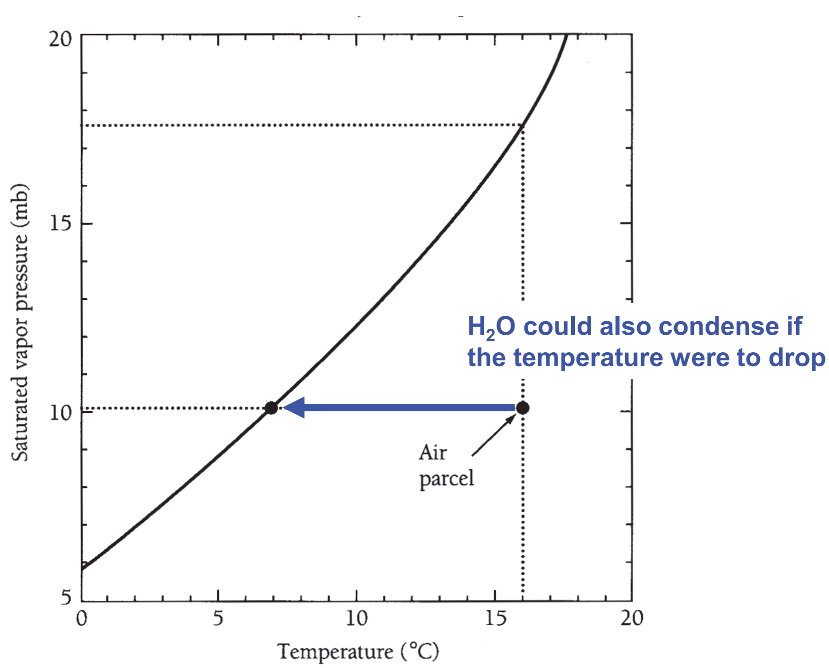

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McElroy, *Atmospheric Environment*, 2002

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

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Water Vapor Feedback

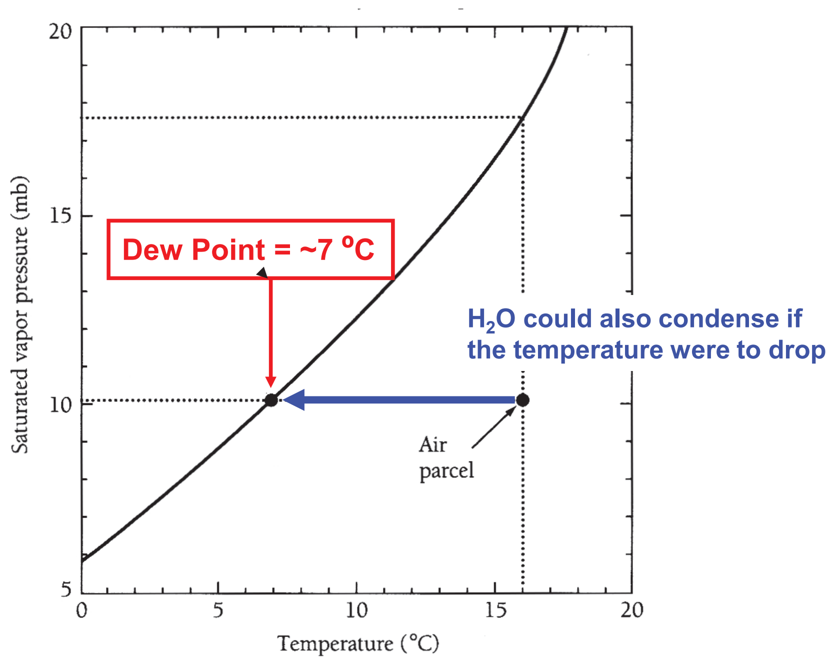


Figure 4.8a Relative humidity and the dew point.

McElroy, *Atmospheric Environment*, 2002

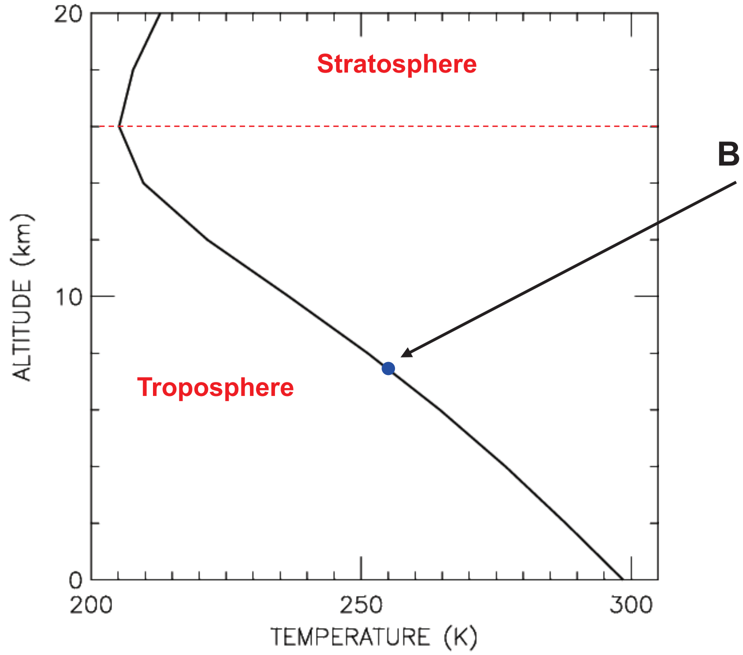
Clausius-Clapeyron relation describes the temperature dependence of the ***saturation vapor pressure of water.***

Water Vapor Feedback

Extensive literature on water vapor feedback:

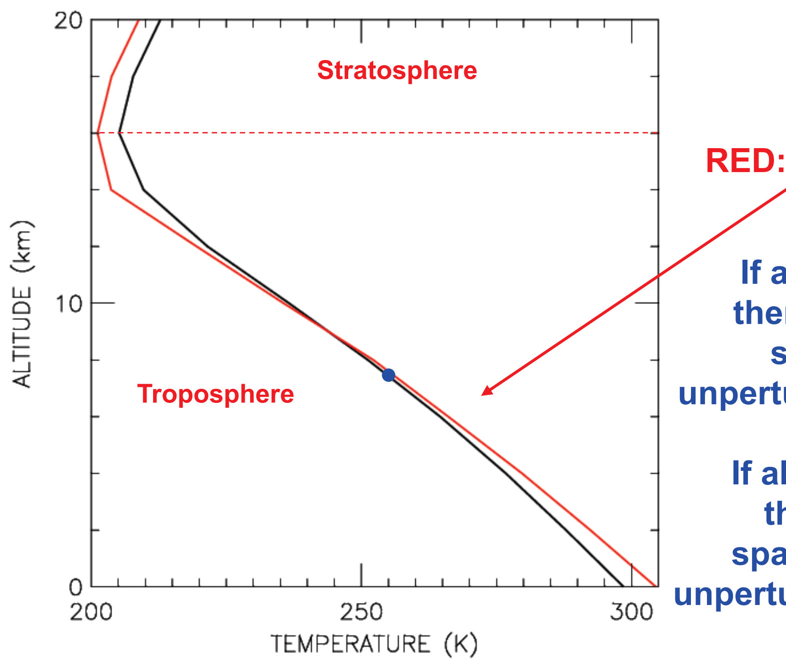
- Soden *et al.* (*Science*, 2002) analyzed global measurements of H_2O obtained with a broadband radiometer (TOVS) and concluded the atmosphere generally obeys fixed relative humidity: **strong positive** feedback
  - ⇨data have extensive temporal and spatial coverage but limited vertical resolution.
- 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



BLACK: Initial temperature profile

Lapse Rate Feedback

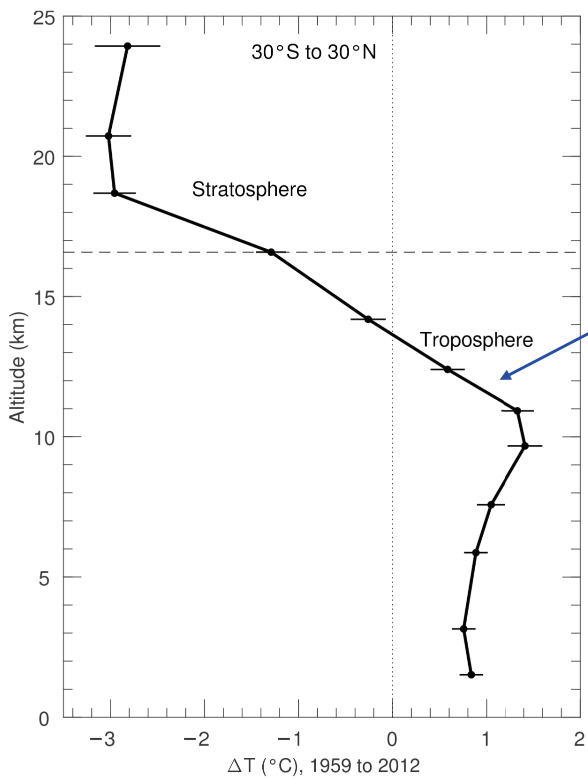


RED: Perturbed temperature profile

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**

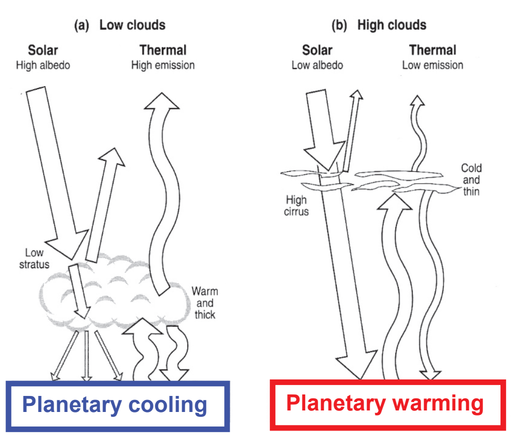


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The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

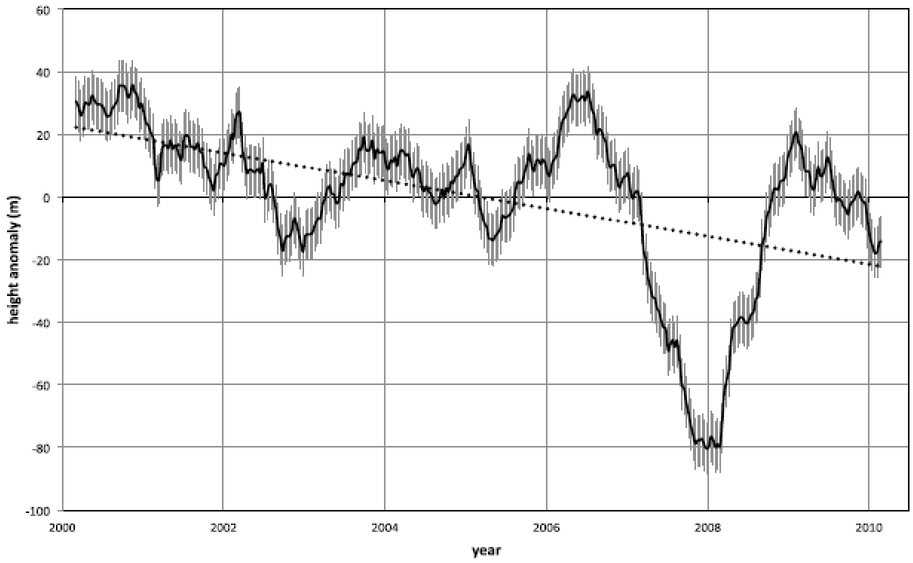


Figure 1. Deseasonalized anomalies of global effective cloud-top height from the 10-year mean. Solid line: 12-month running mean of 10-day anomalies. Dotted line: linear regression. Gray error bars indicate the sampling error (±8 m) in the annual average.

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

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

Radiative Forcing of Clouds: Observation C

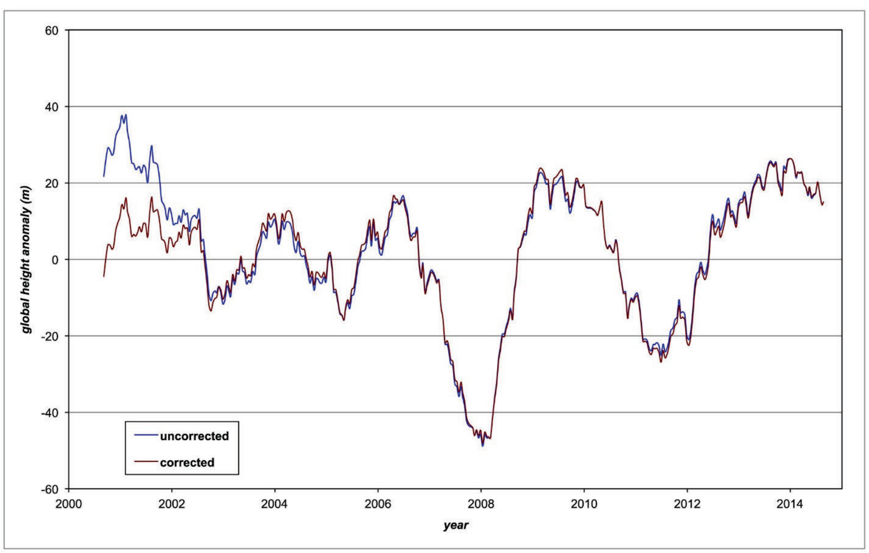
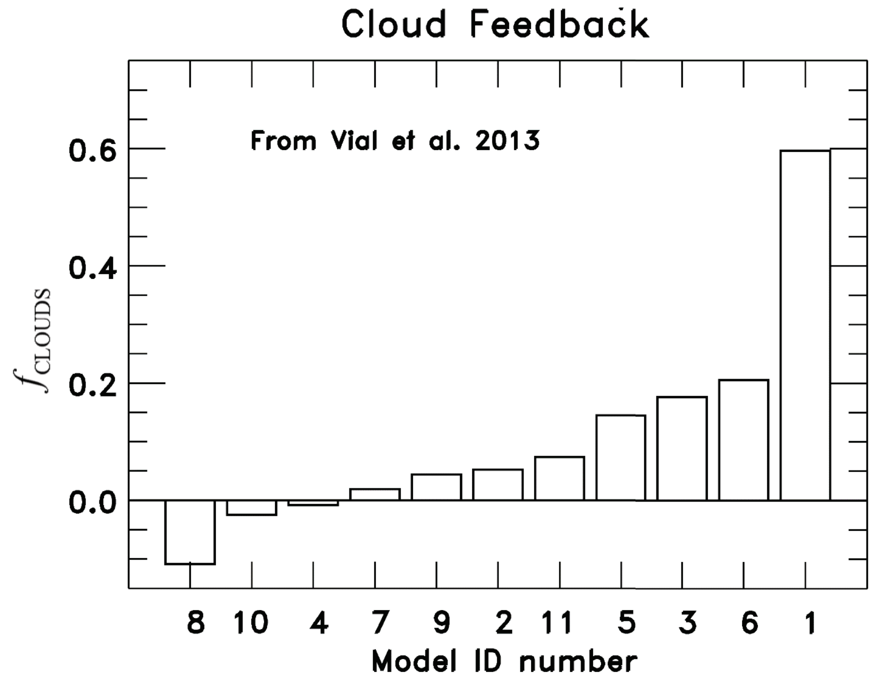


Figure 5. The 15-year time series of global height anomalies from March 2000 to February 2015. Corrected for shift in glitter pattern (brown), and uncorrected (blue). Data have been smoothed by a 12 month running mean.

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

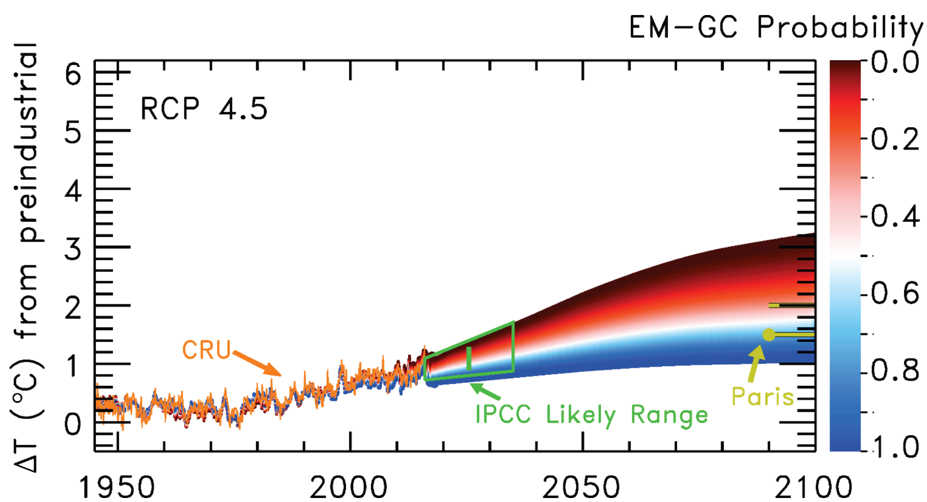
Correction for orbital drift early in the mission reveals no trend in cloud height, but strong ENSO signature

Radiative Forcing of Clouds: IPCC 2013



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

EM-GC Forecast

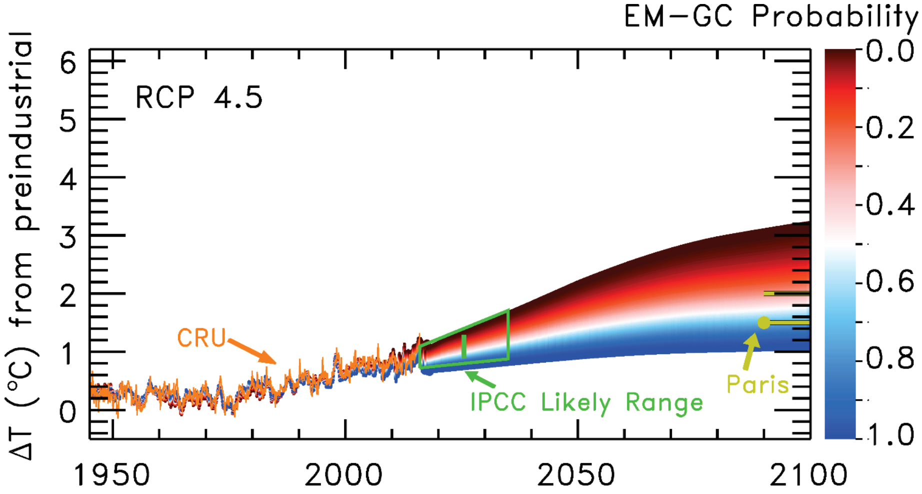


Future ΔT projected running EM-GC forward in time, for neutral TSI, ENSO, SOD, & AMOC for:
a) all combinations of Aerosol RF & Feedback for which the past ΔT can be fit at $\chi^2 \leq 2$
b) whatever value of Feedback is able to provide a fit past climate will persist into future

If GHGs follow RCP 4.5, **21%** chance rise GMST stays below **1.5°C** and **65%** chance stays below **2.0°C**

ΔT is difference in GMST (Global Mean Surface Temperature) relative to pre-industrial, or GMST anomaly
CRU: Climate Research Unit, Easy 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

EM-GC Forecast



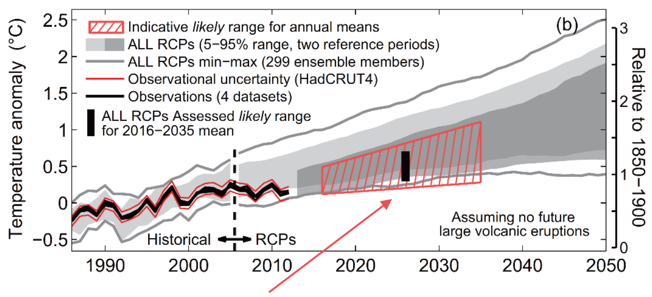
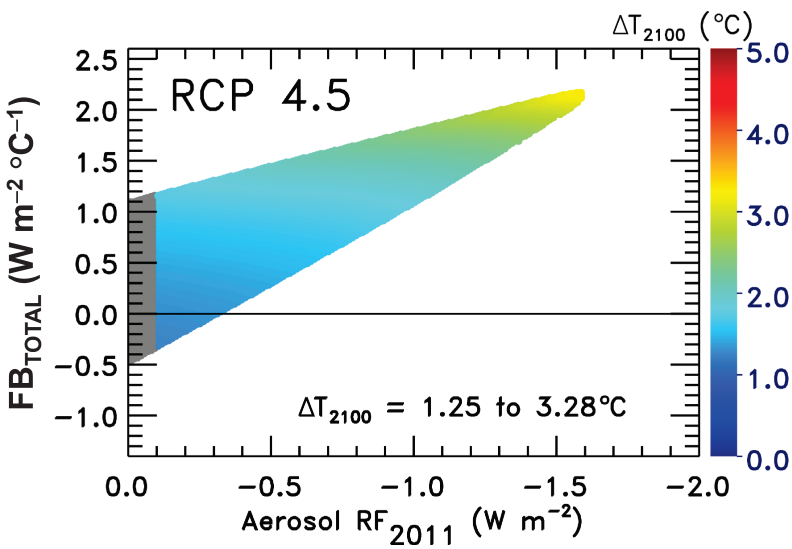


Fig 11.25b, IPCC 2013

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

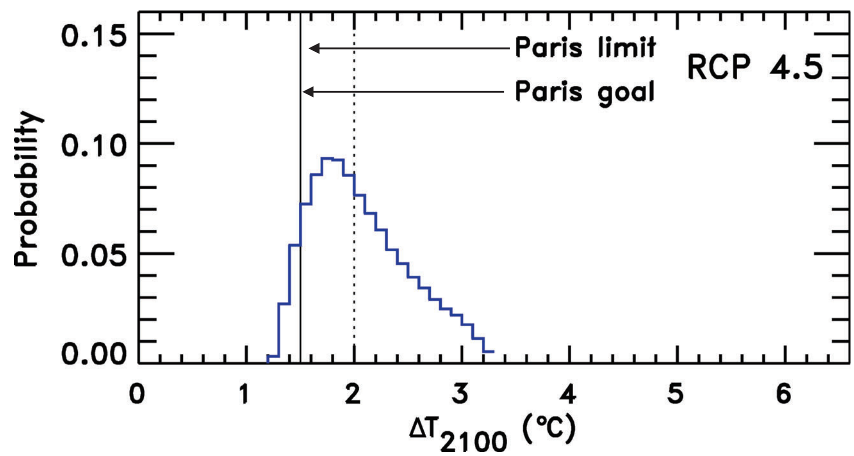
EM-GC Forecast



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

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

EM-GC Forecast



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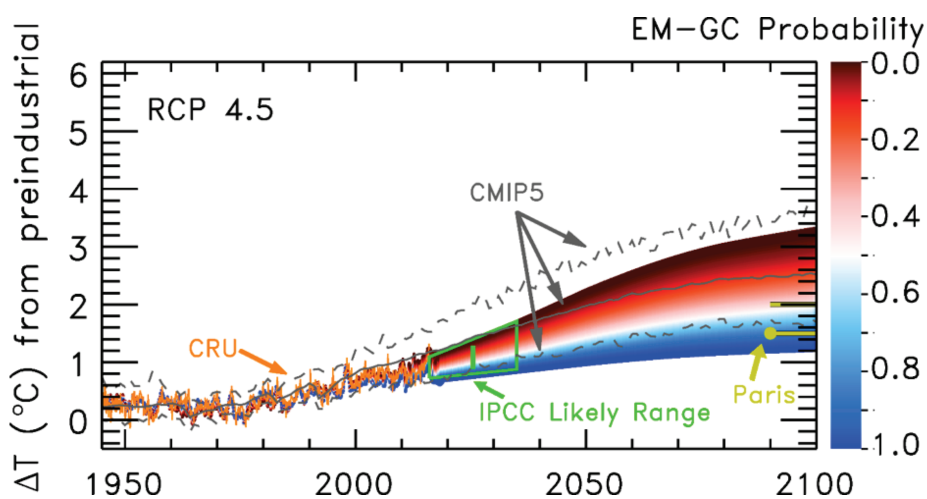
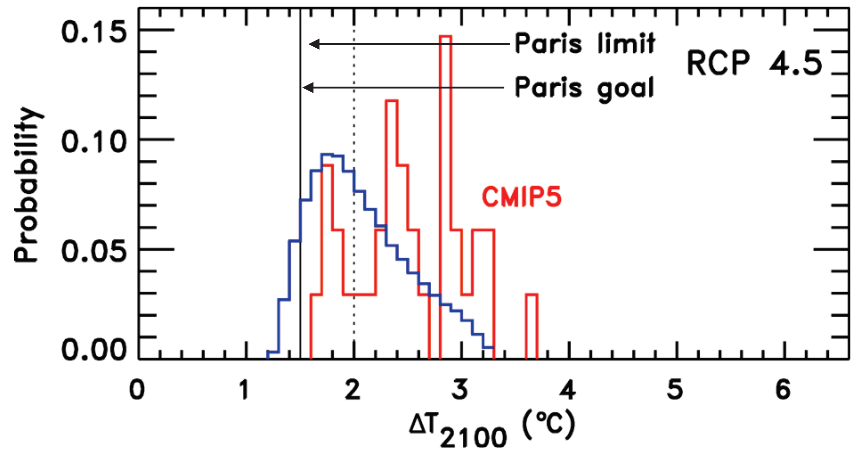
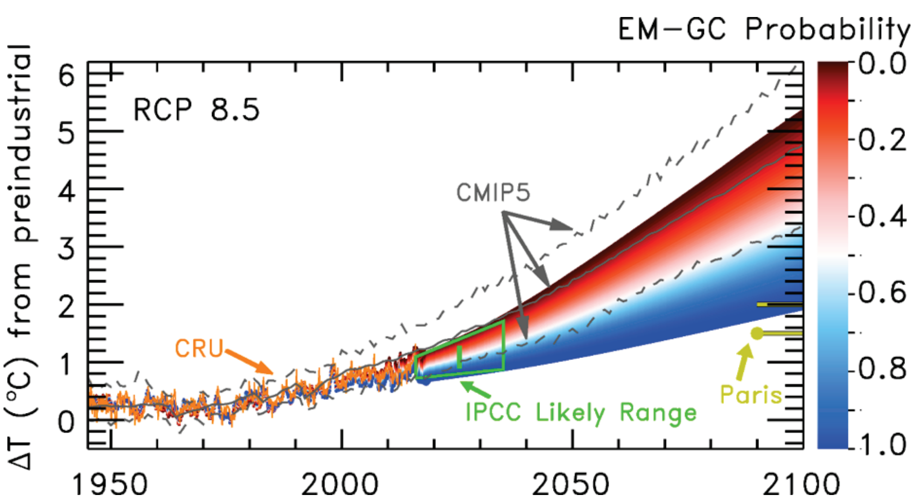


Projections of GMST from CMIP5 climate models used by IPCC lie on the "Warm Side" and in some cases well above our EM-GC projections

EM-GC Forecast



EM-GC Forecast



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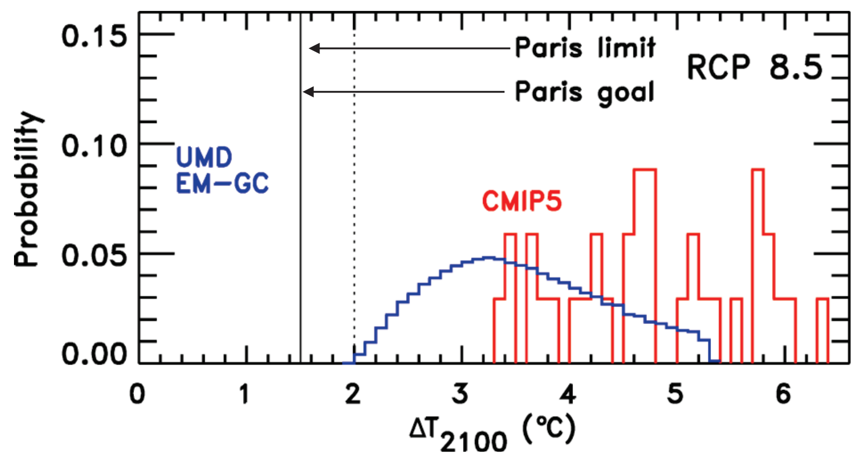
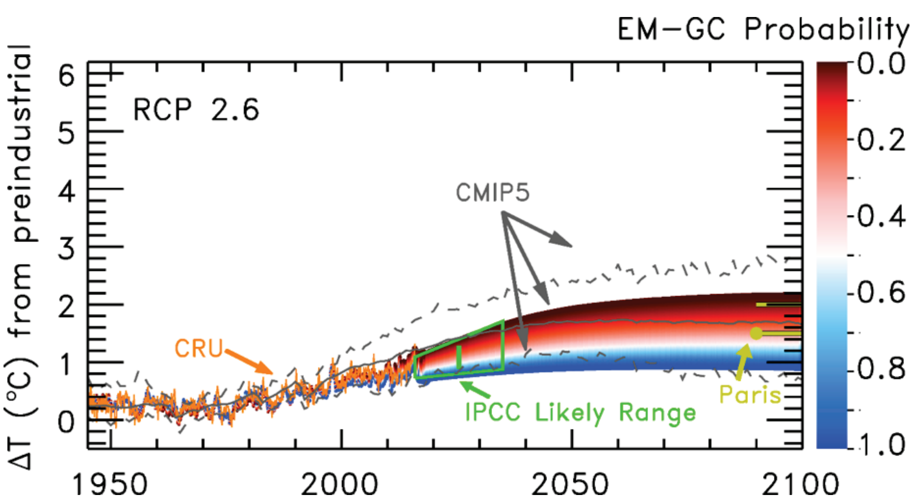


EM-GC Forecast



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