Modeling Earth's Climate: Water Vapor, Cloud, Lapse Rate, & Surface Albedo Feedbacks as well as Effect of Aerosols on Clouds
ACC 433/633 & CHEM 433

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2017

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

21 February 2017

Upcoming Schedule

Thurs, 23 Feb, 2 pm: P Set #2 due

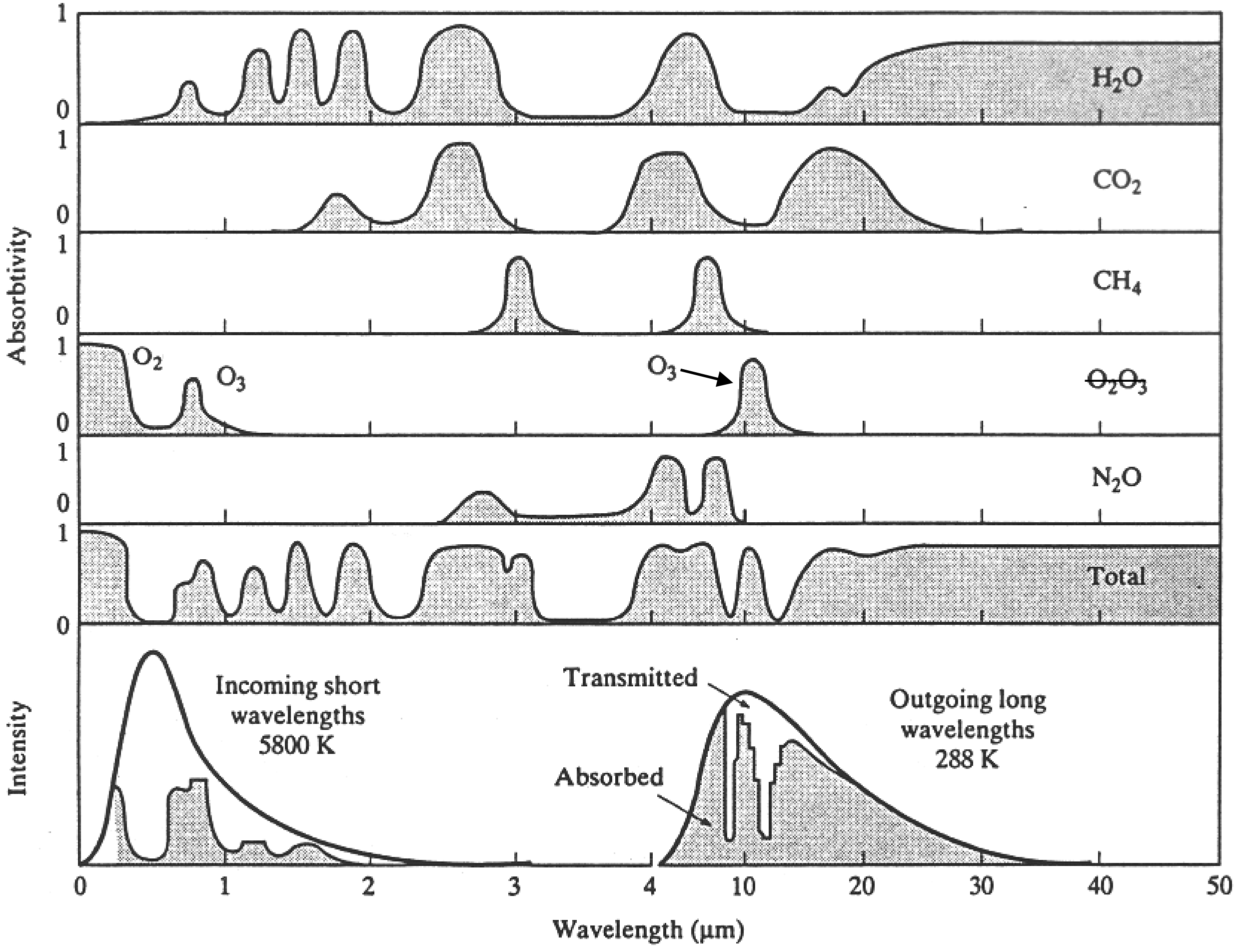
Mon, 27 Feb, 6:00 pm: Review of second problem set

We will return graded problem sets at the start of the review, but only guarantee return of graded problem sets turned in prior to start of the weekend

Tues, 28 Feb, 2 pm: First Exam (a lot more about this on Thurs)

Will be closed book, no notes

Absorption vs. Wavelength



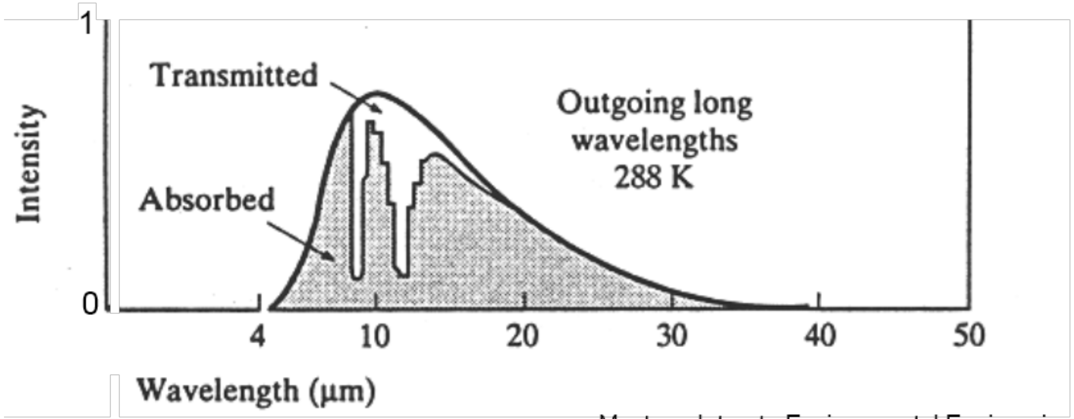
Gray shaded region denotes normalized absorptivity.

"0" – all radiation transmitted through atmosphere.

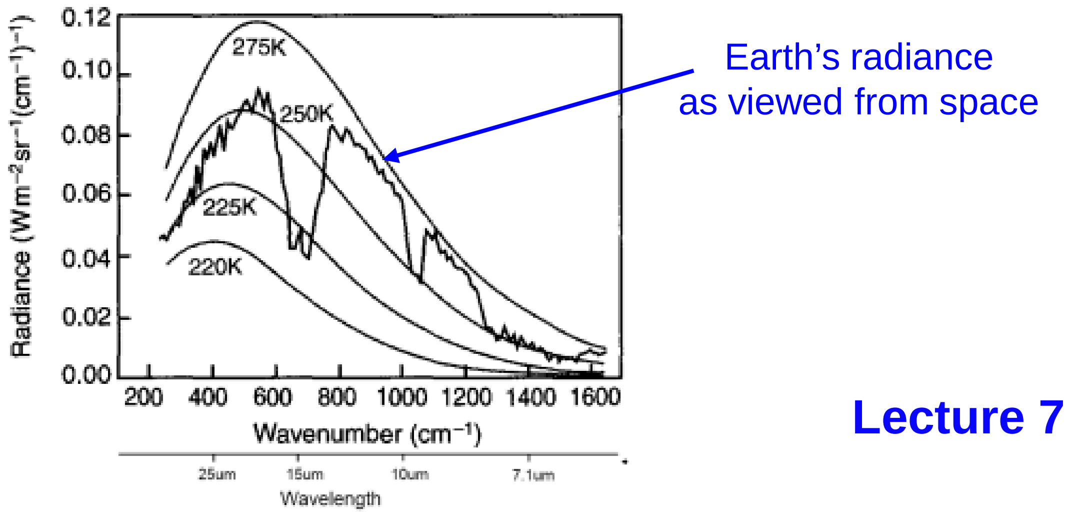
"1" – complete absorption.

Lecture 7, Slide 16

Masters, Intro. to Environmental Engineering and Science, 2nd ed.



Masters, Intro. to Environmental Engineering and Science, 2nd ed.



Lecture 7, Slide 17

Fig. 2.9

The spectrum of the infrared energy emitted by the Earth.[32] The various features are the absorption/emission bands of atmospheric gases, especially water vapour, ozone, and carbon dioxide (Fig. 2.5). The area under the Earth's spectrum, when averaged over latitude, longitude, and time, and integrated over wavelength, is about the same as the area obtained by integrating the Planck function (represented at four different temperatures by the smooth curves) for a temperature of 255K. At this temperature, the thermal infrared emission from the Earth just balances the incoming solar radiative energy at shorter UV, visible, and near-infrared wavelengths.

https://scienceofdoom.files.wordpress.com/2010/03/radiation-earth-from-space-taylor-499px.png

Radiative Forcing of Climate, 1750 to 2011

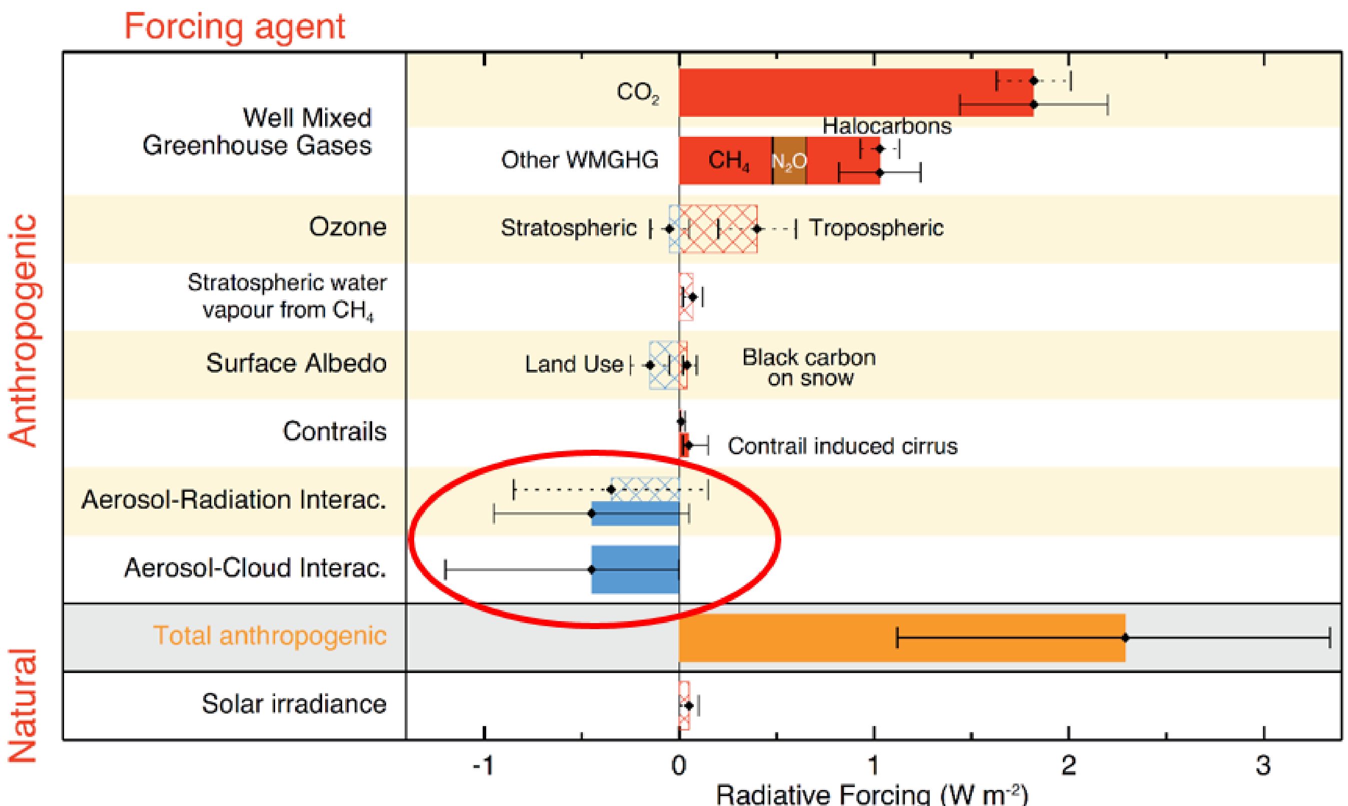


Fig 8.15, IPCC 2013

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)

Large uncertainty in aerosol RF

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

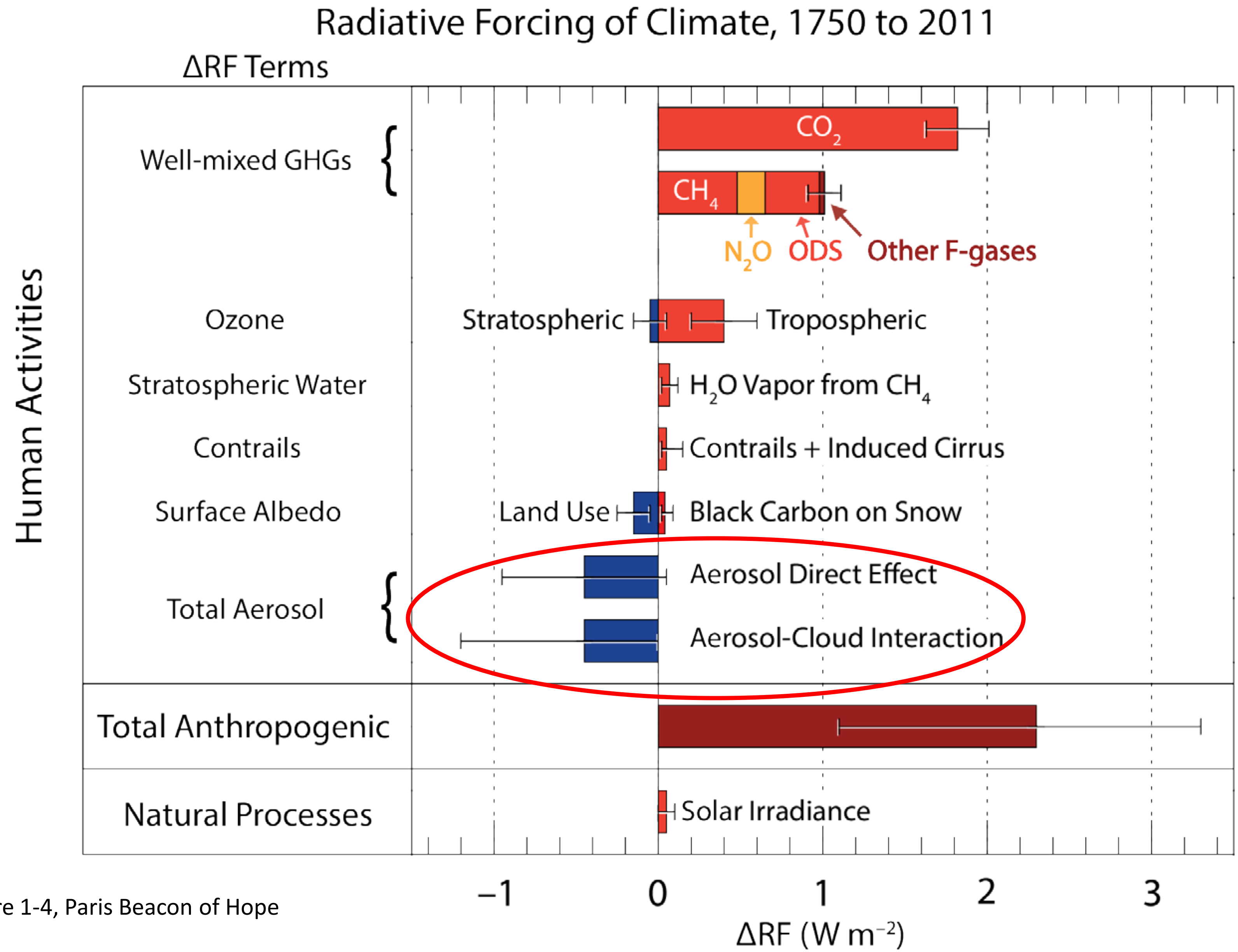


Figure 1-4, Paris Beacon of Hope

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

71 plausible scenarios for RF of climate due to Tropospheric aerosols (direct & indirect effect) from Smith and Bond (2012)

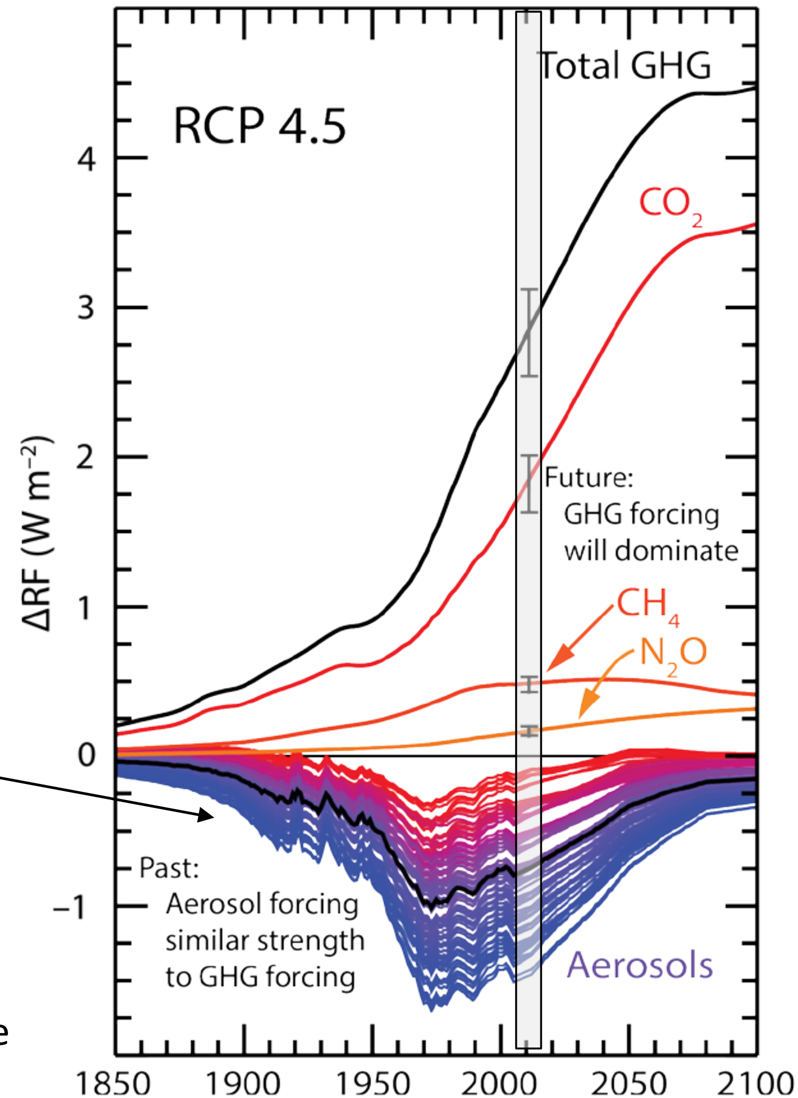


Figure 1-10, Paris Beacon of Hope

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 31

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

$\lambda_{BB} = 0.3\ K\ /\ W\ m^{-2}$; this term is also called λ_P, short for 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:

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

and $\lambda_{TOTAL} = \lambda_{WATER\ VAPOR} + \lambda_{CLOUDS} + \lambda_{LAPSE\ RATE} + \lambda_{ALBDEO} +$ etc

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

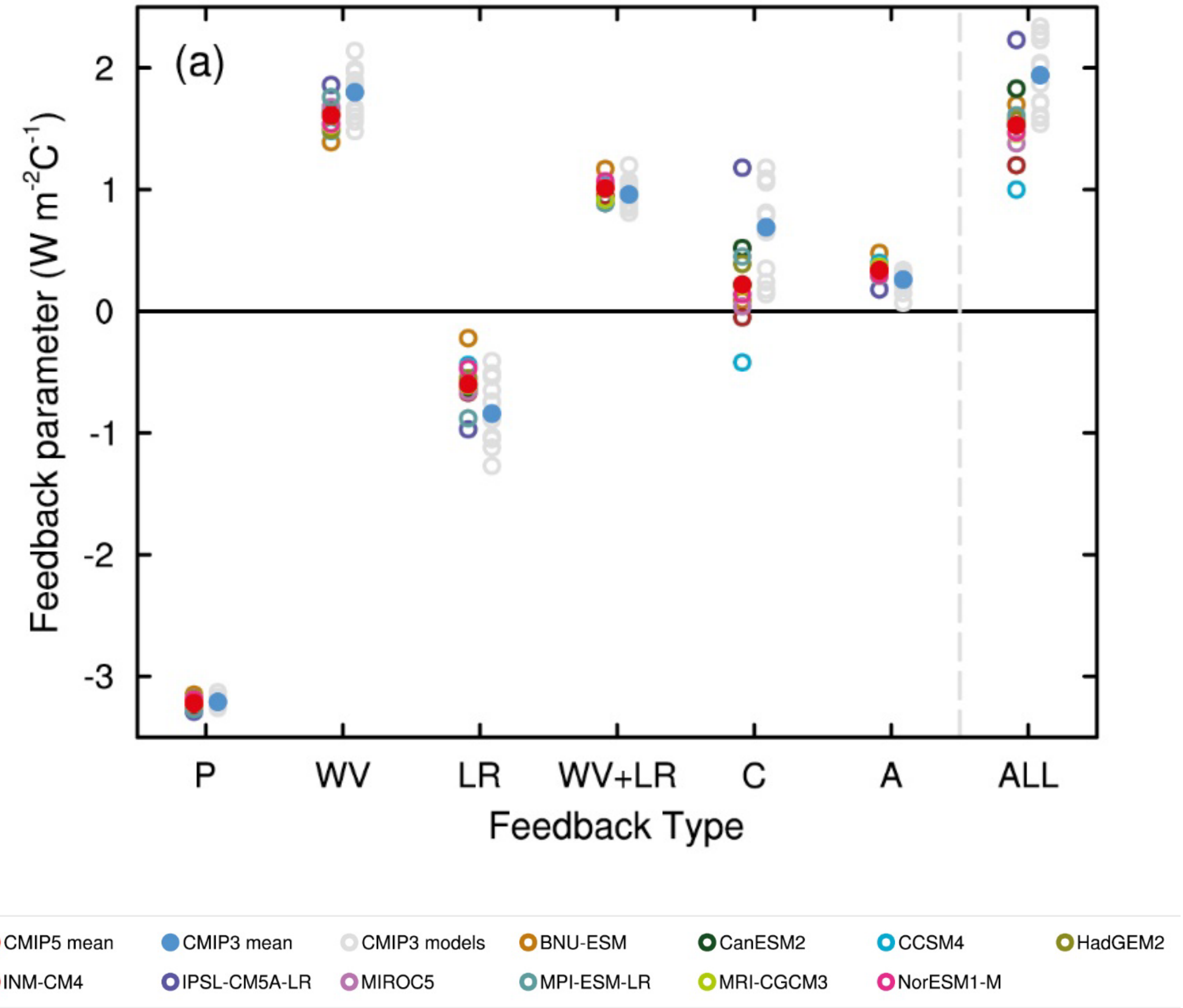
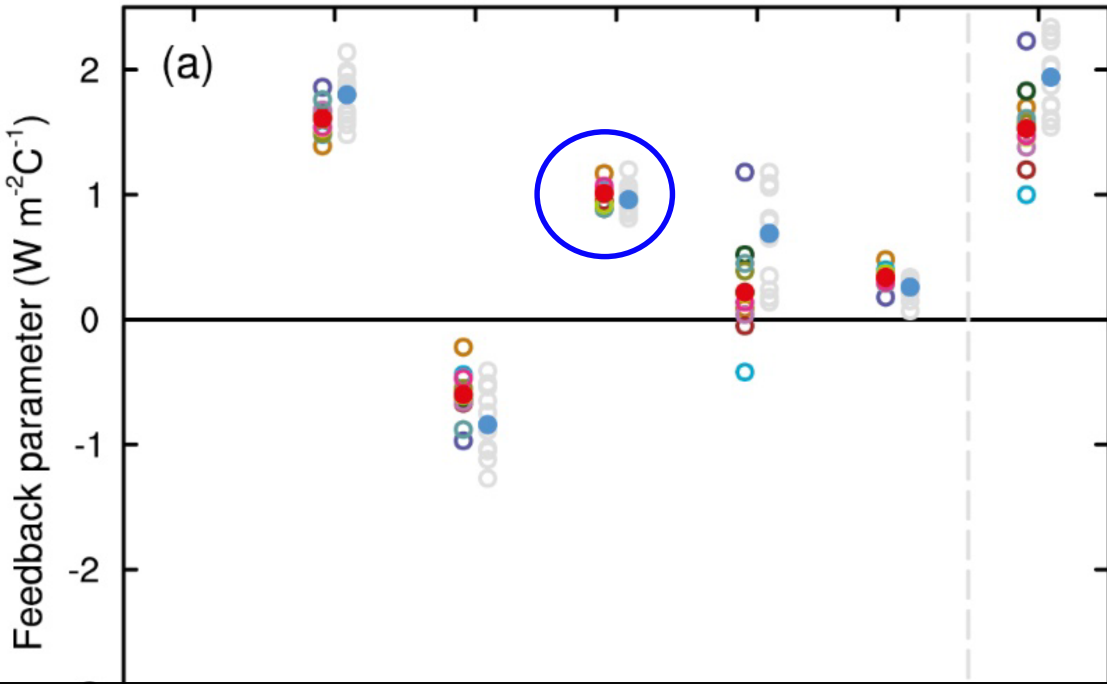


Fig 9.43, IPCC 2013

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

C: Clouds
A: Albedo
ALL: Our $\lambda_{TOTAL} =$

$$\lambda_{WATER\ VAPOR} + \lambda_{CLOUDS} + \lambda_{LAPSE\ RATE} + \lambda_{ALBDEO} + \text{etc}$$



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

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

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

$$f_{WV+LR} = 0.45$$

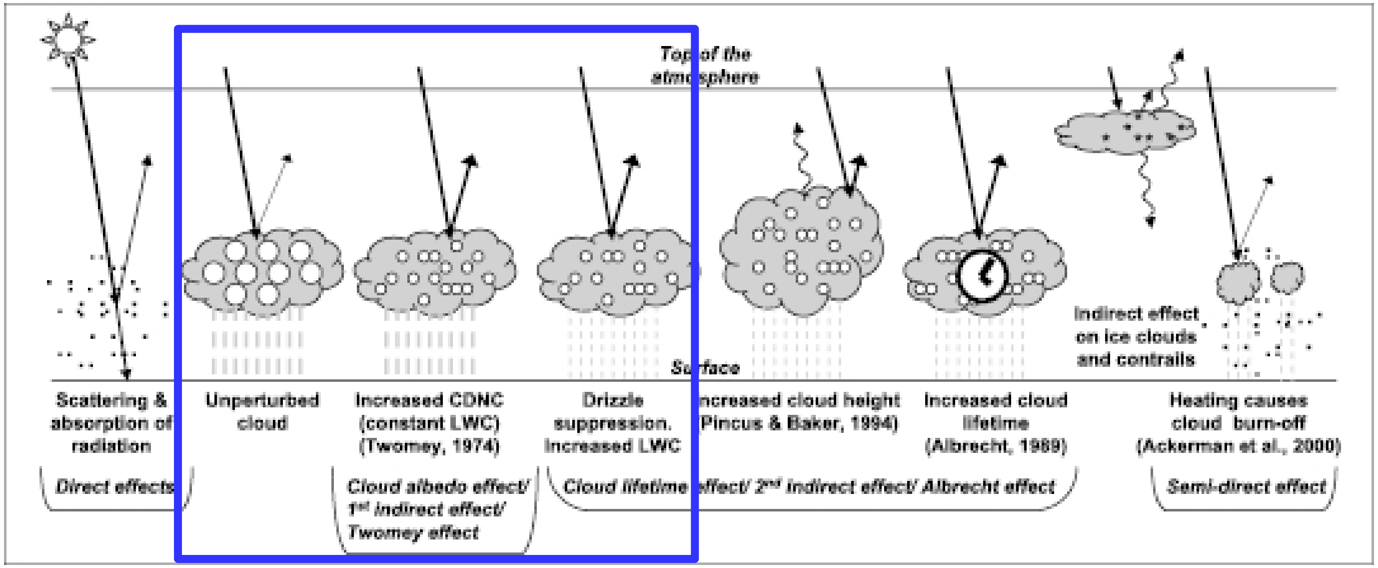
Indirect Effects of Aerosols on Clouds

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

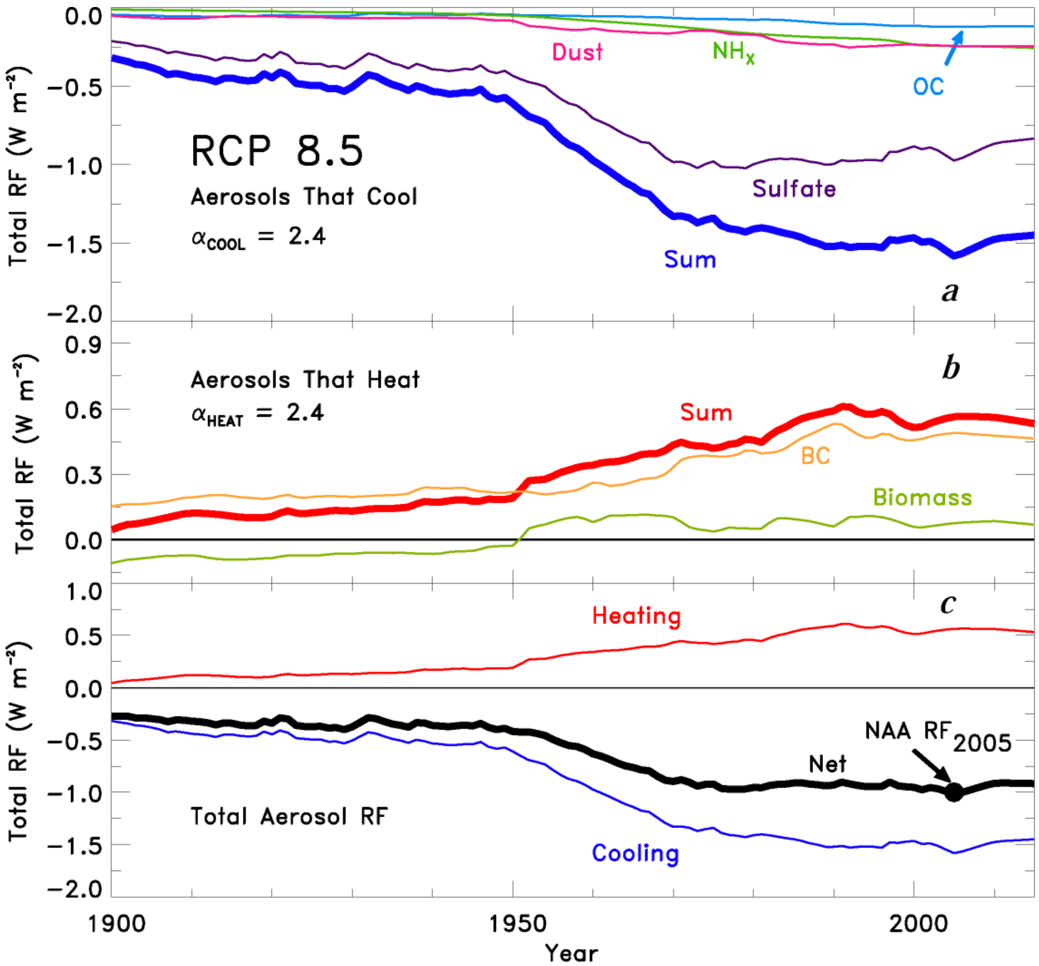


Large uncertainty in aerosol RF

Fig 2-10, IPCC 2007

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

RF of Climate due to Aerosols



RF due to Sulfate etc (aerosols that cool) is about –1.5 W m^{-2} in this projection (one of many possible)

RF due to Black Carbon (BC, or soot) is about +0.45 W m^{-2} in this projection (one of many possible)

Lecture 7, Slide 29

Fig 3, Canty et al., ACP, 2013: Direct & Indirect RF of aerosols considered

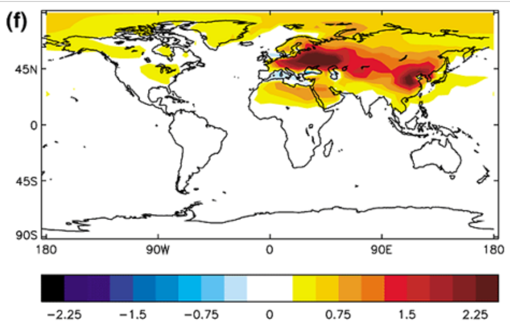
Radiative Properties of Aerosols

Black carbon (soot) aerosols:

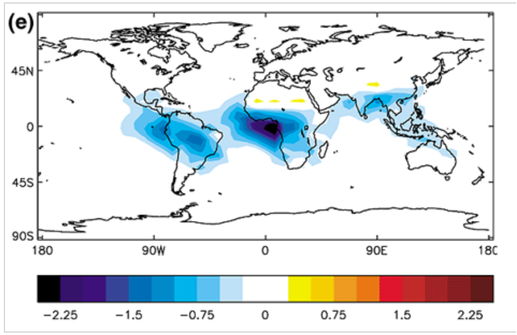
- **emitted from combustion of fossil fuels and biomass burning**
- **efficient absorbers of solar radiation: heat the local atmosphere !**
- **diesel engines notorious source of soot**

IPCC 2000

All forcings (1750–2000) are in W m^{-2}



Organic and black carbon from fossil fuel burning



Organic and black carbon from biomass burning

Lecture 7, Slide 33

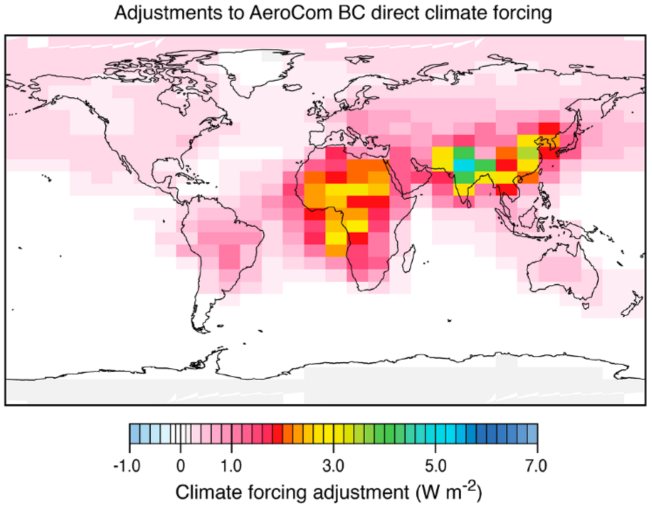


Figure 23. Adjustments to the annual mean, direct radiative forcing (W m^{-2}) by BC in the median AeroCom model required for consistency with the AERONET retrieved aerosol absorption optical depth (AAOD).

Bond et al., JGR, 2013

The best estimate of industrial-era climate forcing of black carbon through all forcing mechanisms, including clouds and cryosphere forcing, is +1.1 W m^{-2} with 90% uncertainty bounds of +0.17 to +2.1 W m^{-2}. Thus, there is a very high probability that black carbon emissions, independent of co-emitted species, have a positive forcing and warm the climate. We estimate that black carbon, with a total climate forcing of +1.1 W m^{-2}, is the second most important human emission in terms of its climate forcing in the present-day atmosphere; only carbon dioxide is estimated to have a greater forcing.

Ice-Albedo Feedback

Initial Action:
Humans Release CO_2

→ Initial Response:
$T_{SURFACE}$ Rises

↓ Then:
Ice Melts

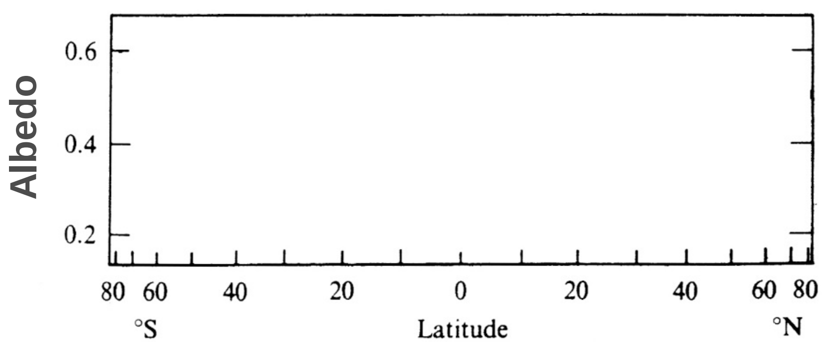
↓ Consequence:
Albedo Falls

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

2. Albedos of selected surfaces on Earth

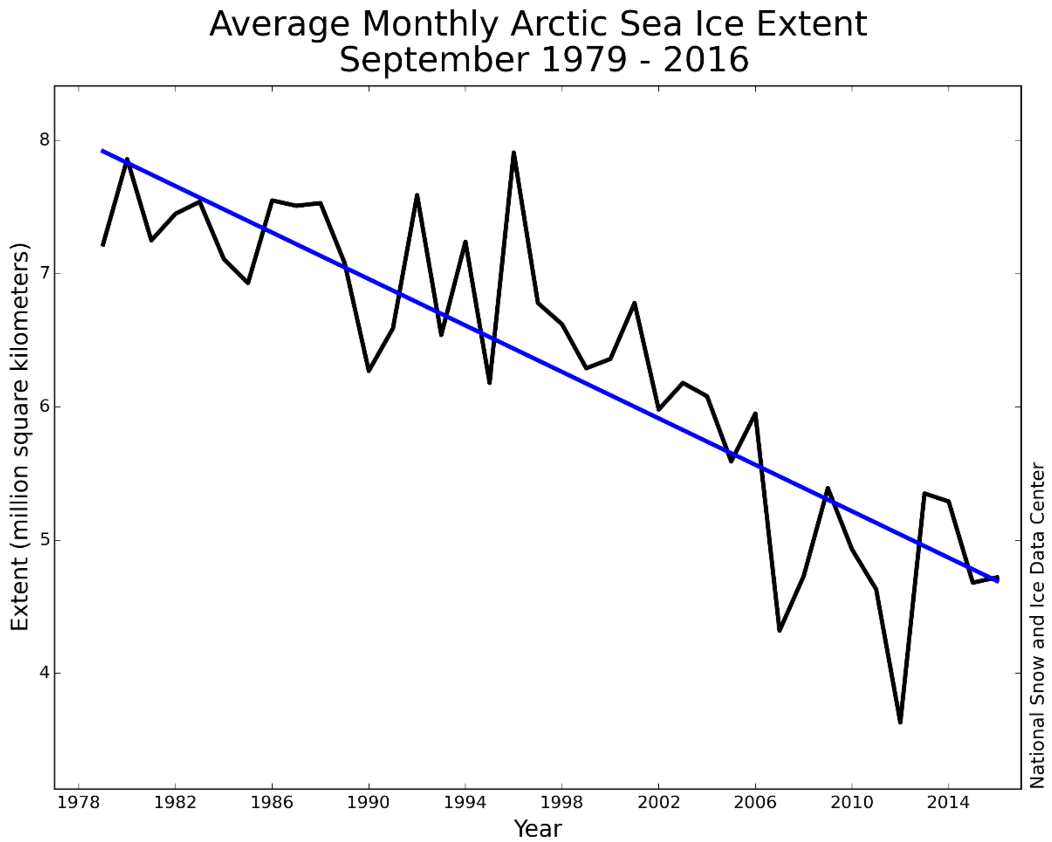
surface	albedo
snow	0.7 ± 0.2
sand	0.25 ± 0.05
grasslands	0.23 ± 0.03
bare soil	0.2 ± 0.05
forest	0.15 ± 0.1
water (highly dependent on surface roughness and incident angle of sunlight)	0.2 + 0.6 − 0.2

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



Houghton, *The Physics of Atmospheres*, 1991.

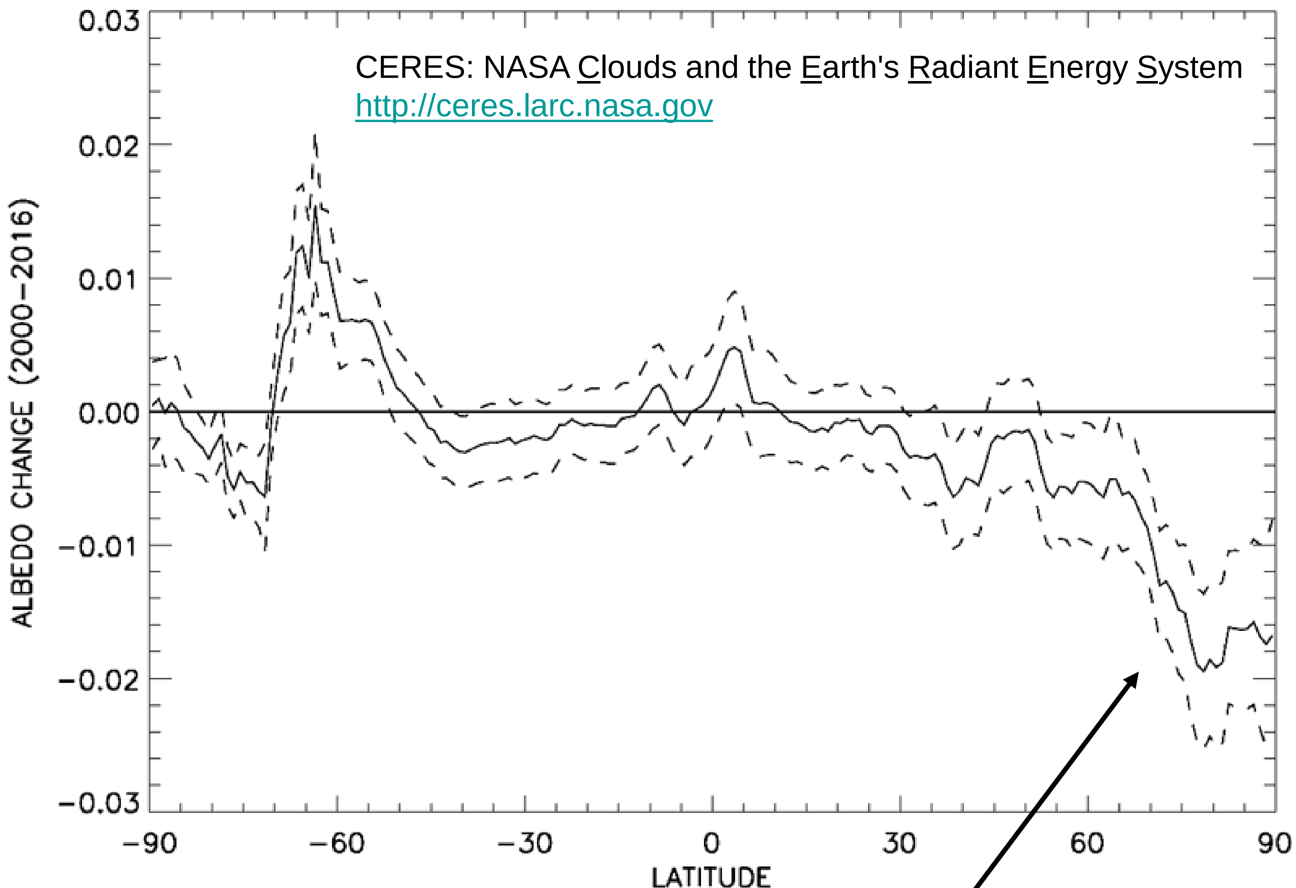
Arctic Sea-Ice: Canary of Climate Change



- 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

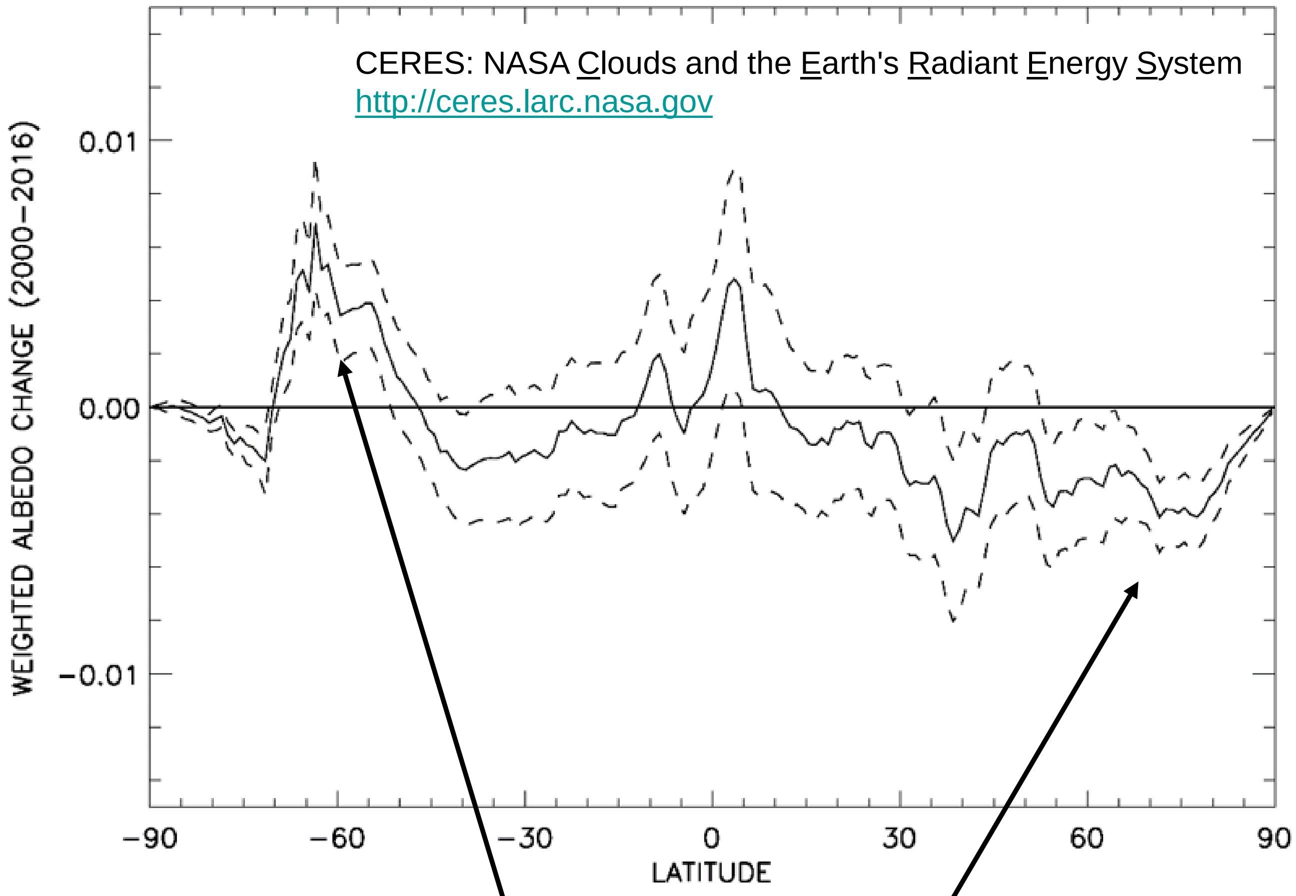
Albedo Anomaly (CERES) Change versus Latitude, No Weighting



Slide courtesy Austin Hope

NH high latitude darkening (melting sea ice) is apparent

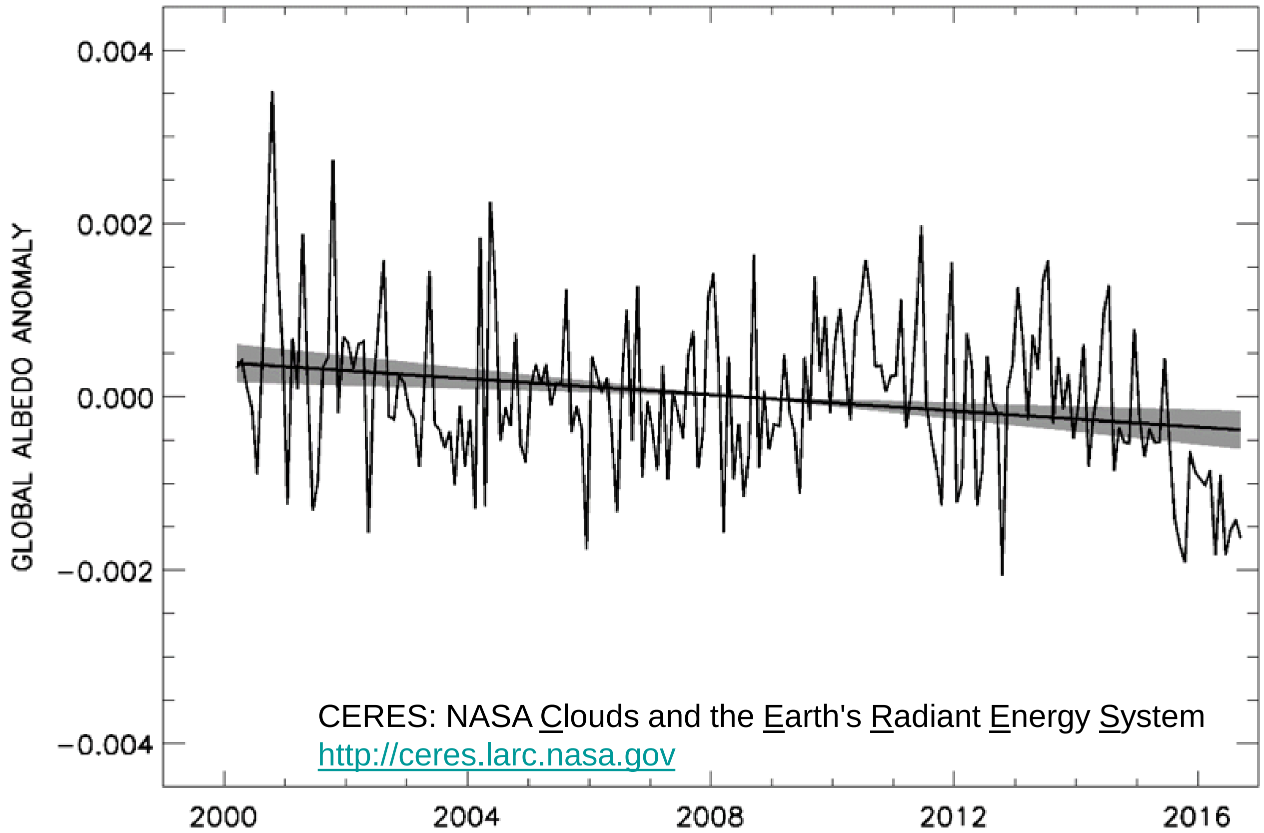
Albedo Anomaly (CERES) Change versus Latitude, *Weighted by Cosine Latitude*



Slide courtesy Austin Hope

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

Global Average Albedo Anomaly (CERES) versus time



Slide courtesy Austin Hope

Trend is -4.7×10^{-4} albedo units per decade,
with a two-sigma uncertainty of 2.6×10^{-4} albedo units per decade

Water Vapor Feedback

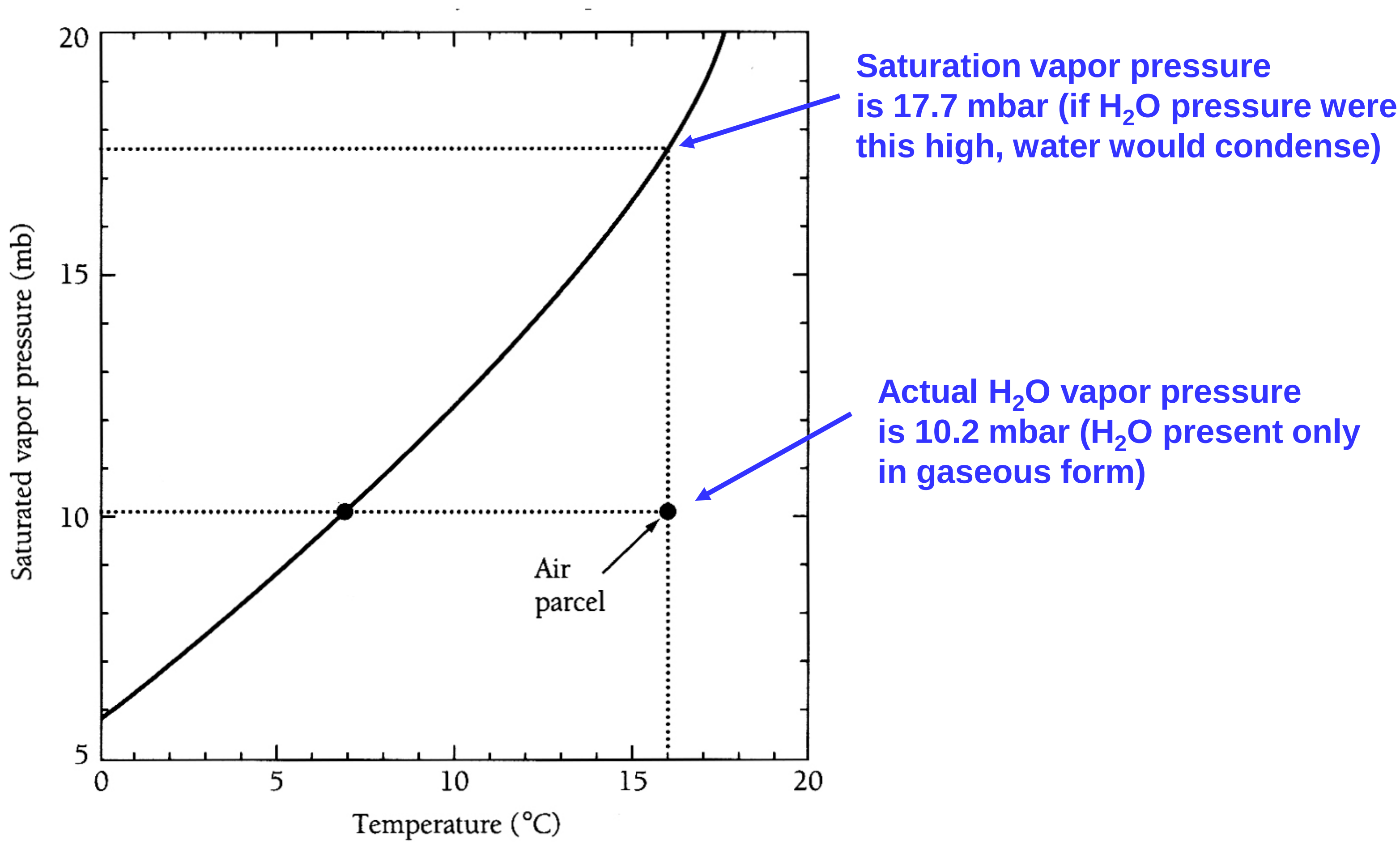


Figure 4.8a Relative humidity and the dew point.

McElroy, *Atmospheric Environment*, 2002

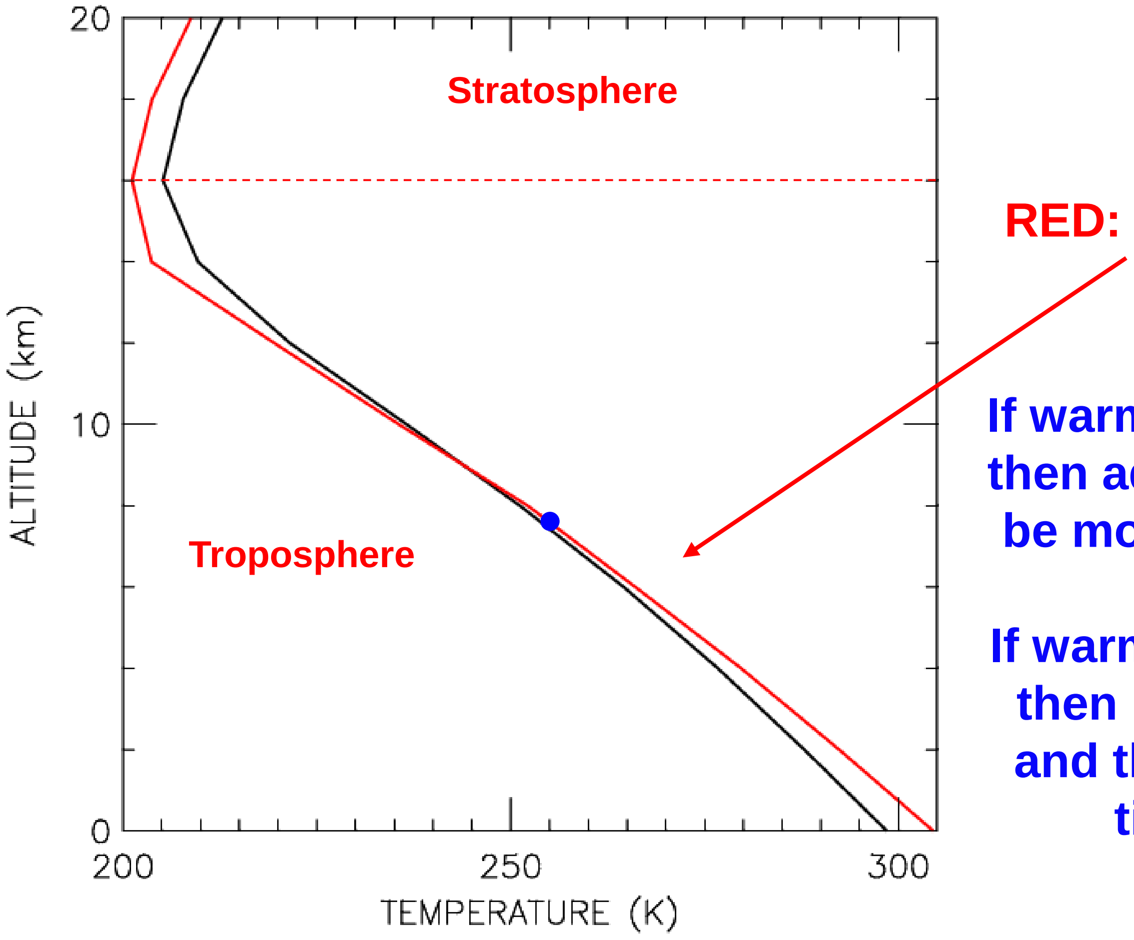
Clausius-Clapeyron relation describes the temperature dependence of the ***saturation vapor pressure of <u>water</u>.***

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

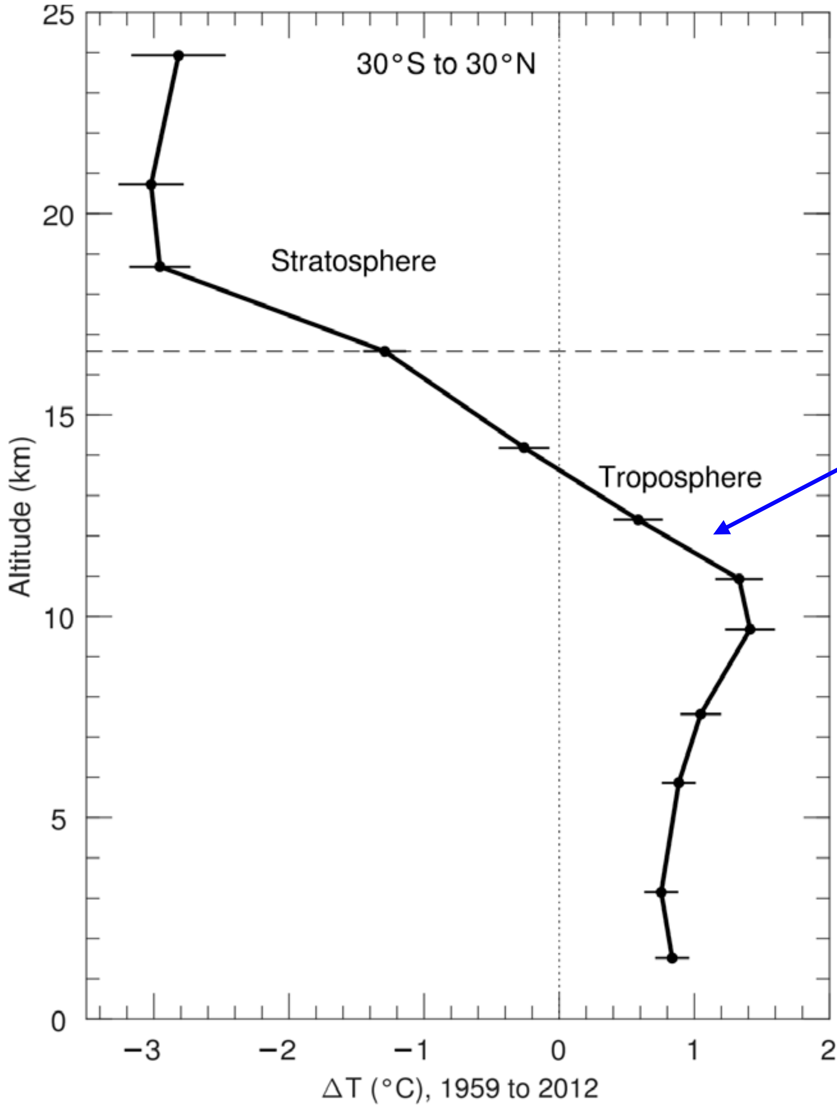


RED: Perturbed temperature profile

If warming is mainly in upper trop., then additional thermal energy can be more easily radiative to space.

If warming is mostly in lower trop., then lapse rate becomes weaker and thermal energy has a harder time escaping to space.

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

Situation if complicated by cooling above this level

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**

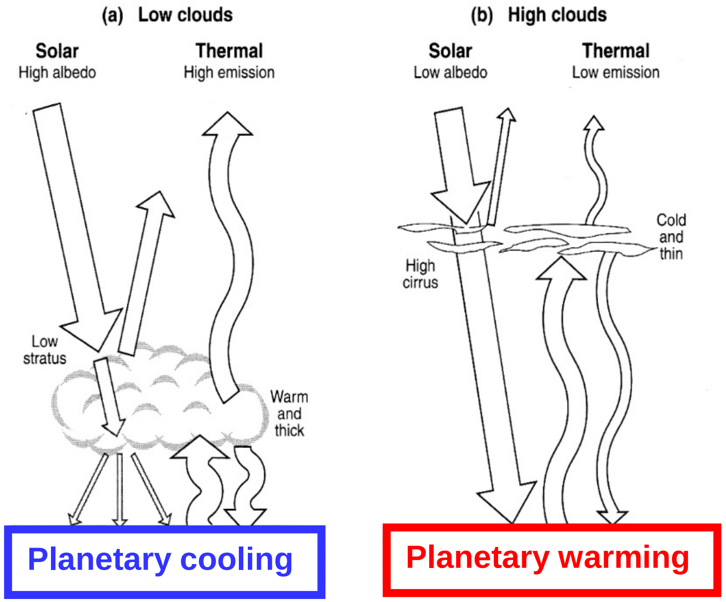


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The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

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

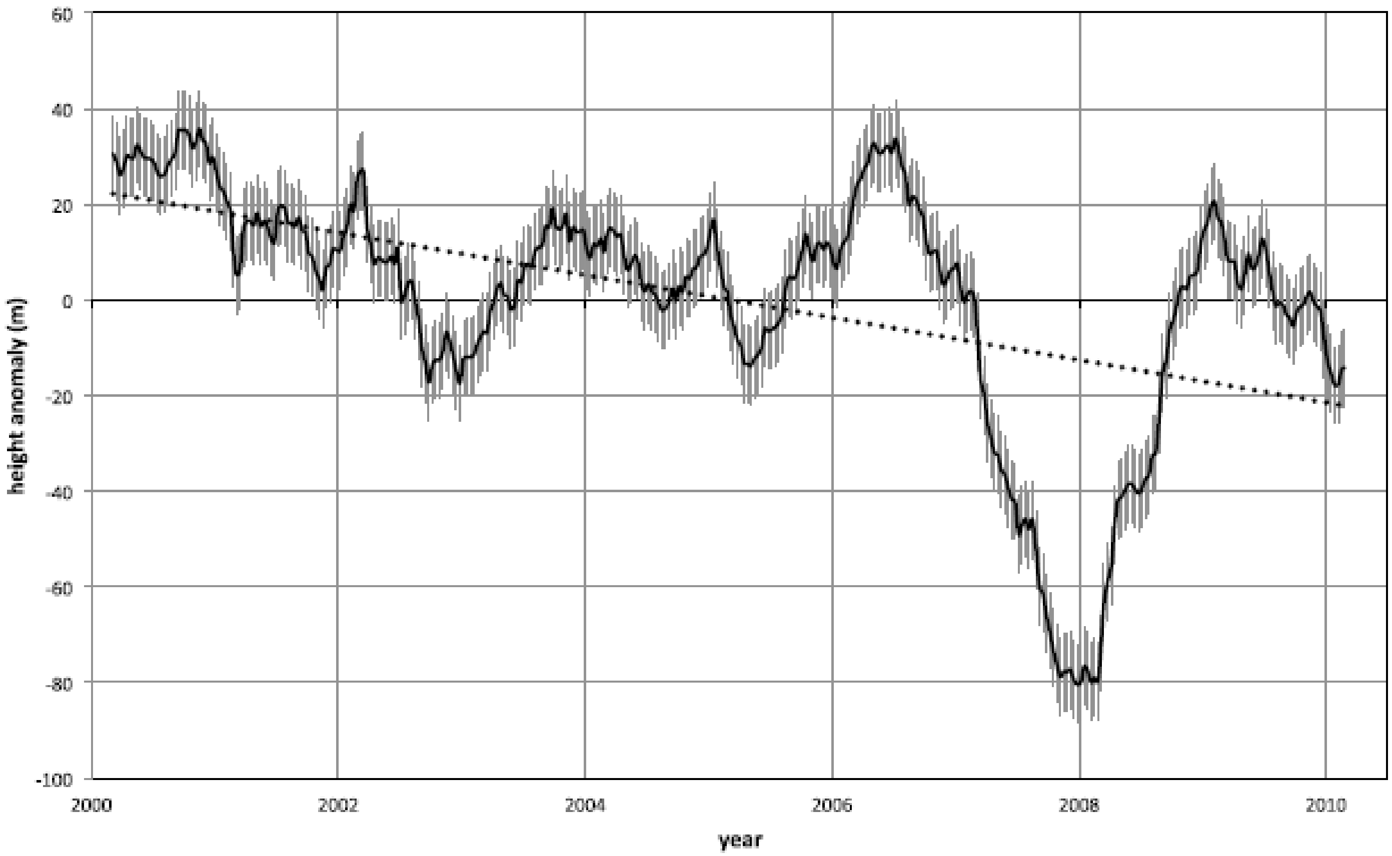
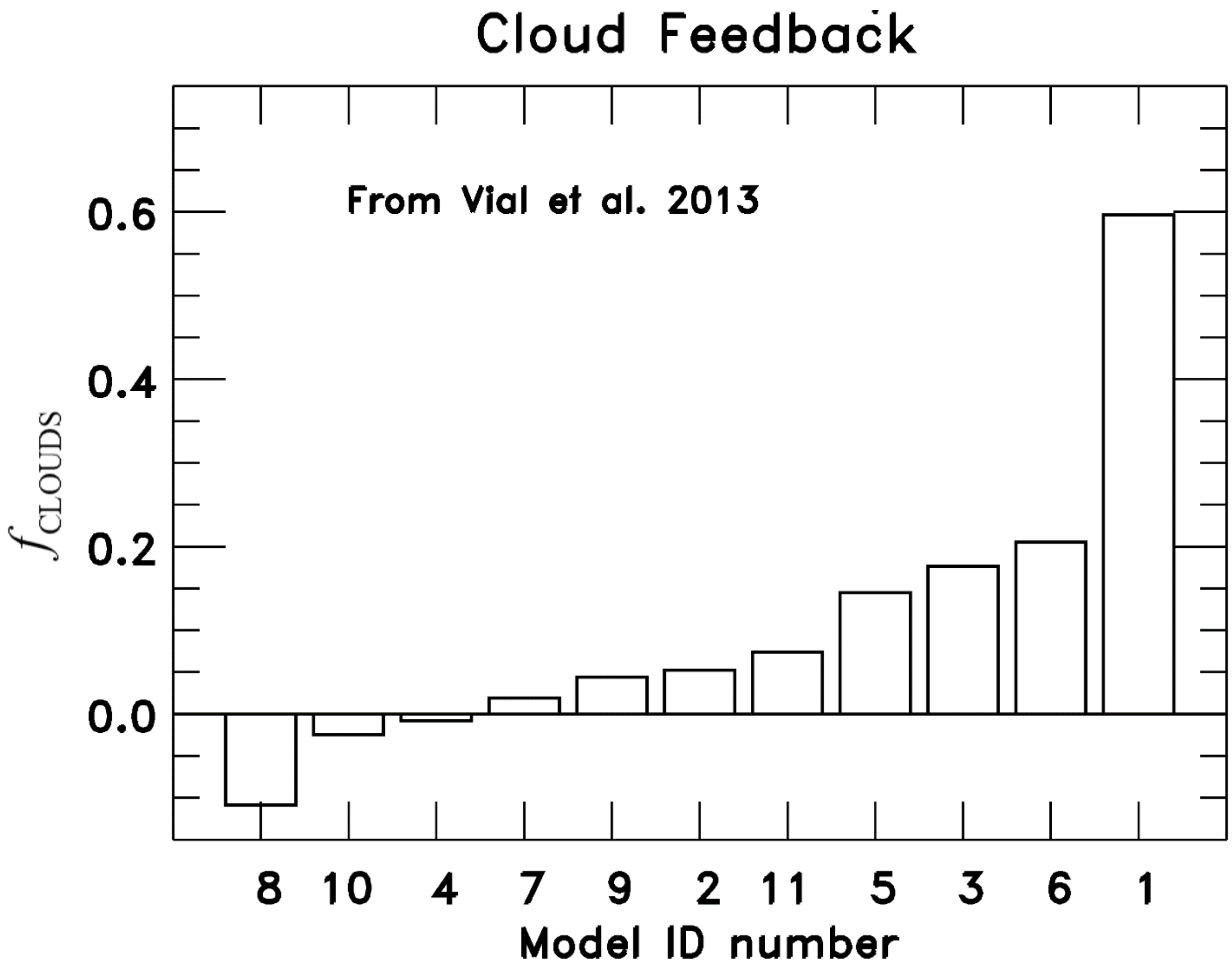


Figure 1. Deseasonalized anomalies of global effective cloud-top height from the 10-year mean. Solid line: 12-month running mean of 10-day anomalies. Dotted line: linear regression. Gray error bars indicate the sampling error (±8 m) in the annual average.

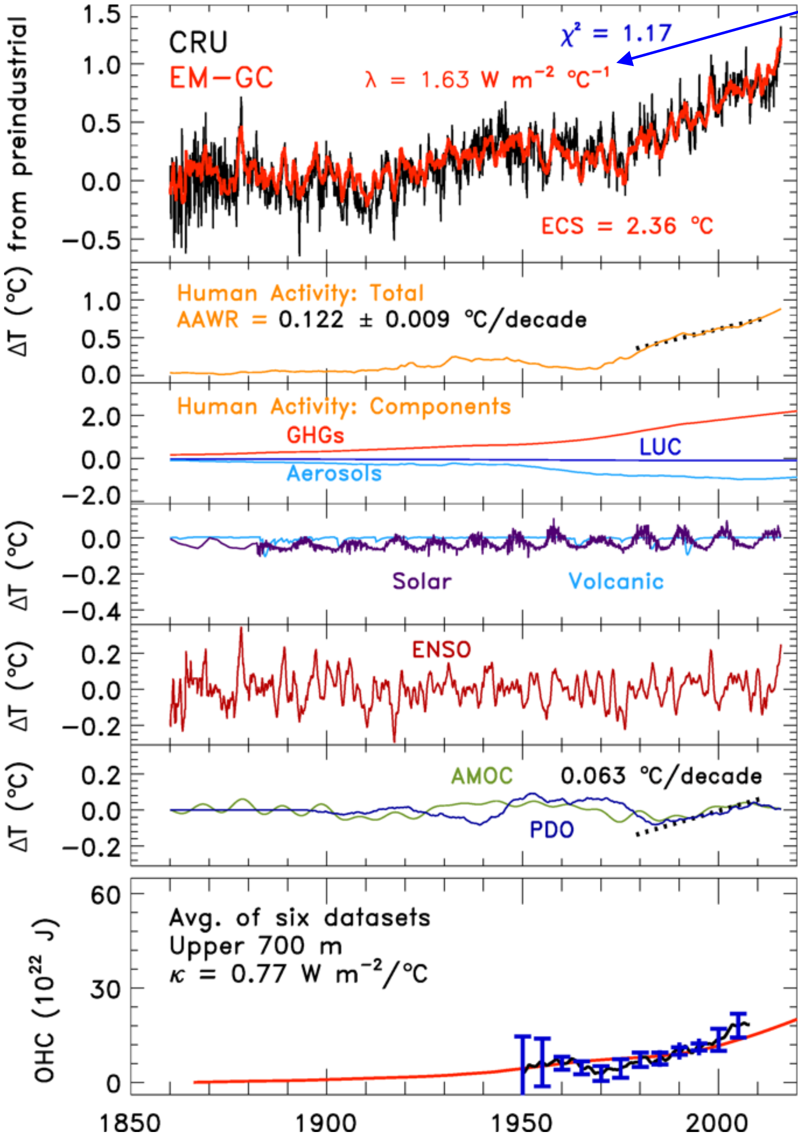
Davies and Molloy, GRL, 2012

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

Radiative Forcing of Clouds: IPCC 2013



Empirical Model of Global Climate (EM-GC)



Key model output parameter #1:
Climate Feedback Parameter, λ, units W m^{-2} °C^{-1}

$$\Delta T_{MDL\,i} = (1+\gamma)\,(\text{GHG RF}_i + \text{Aerosol RF}_i)/\lambda_P + C_0 + C_1\times\text{SOD}_{i-6} + C_2\times\text{TSI}_{i-1} + C_3\times\text{ENSO}_{i-2} + C_4\times\text{AMOC}_i - Q_{OCEAN\,i}/\lambda_P$$

where

λ_P = 3.2 W m^{-2} / °C

$1+\gamma = \{1 - \Sigma(\text{Feedback Parameters})/\lambda_P\}^{-1}$

Aerosol RF = total RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = El Niño Southern Oscillation

AMOC = Atlantic Meridional Overturning Circ.

Q_{OCEAN} = Ocean heat export = $\kappa\,(1+\gamma)\,\{(\text{GHG RF}_{i-72}) + (\text{Aerosol RF}_{i-72})\}$

$\lambda = \sum$ Feedback Parameters

ECS is Equilibrium Climate Sensitivity, i.e., ΔT for 2×CO_2

Model also considers RF due to human-induced Land Use Change (LUC), but this effect is small and is neglected in eqns shown here for convenience

EM-GC described in Canty *et al.*, ACP, 2013

Figure 2.4

Empirical Model of Global Climate (EM-GC)

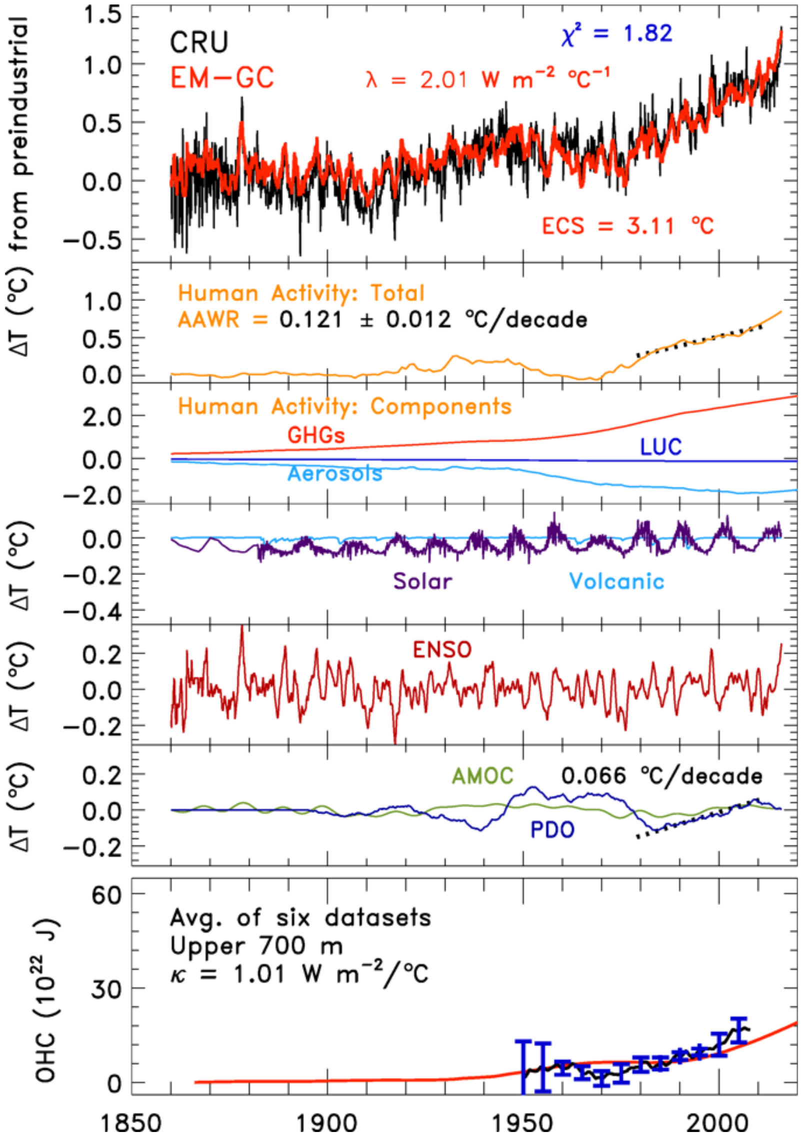


Figure 2.9, Paris Beacon of Hope

$$\Delta T_{MDL\ i} = (1+\gamma)\,(\text{GHG RF}_i + \text{Aerosol RF}_i)\,/\,\lambda_P + C_0 + C_1{\times}\text{SOD}_{i-6} + C_2{\times}\text{TSI}_{i-1} + C_3{\times}\text{ENSO}_{i-2} + C_4{\times}\text{AMOC}_i - Q_{OCEAN\ i}\,/\,\lambda_P$$

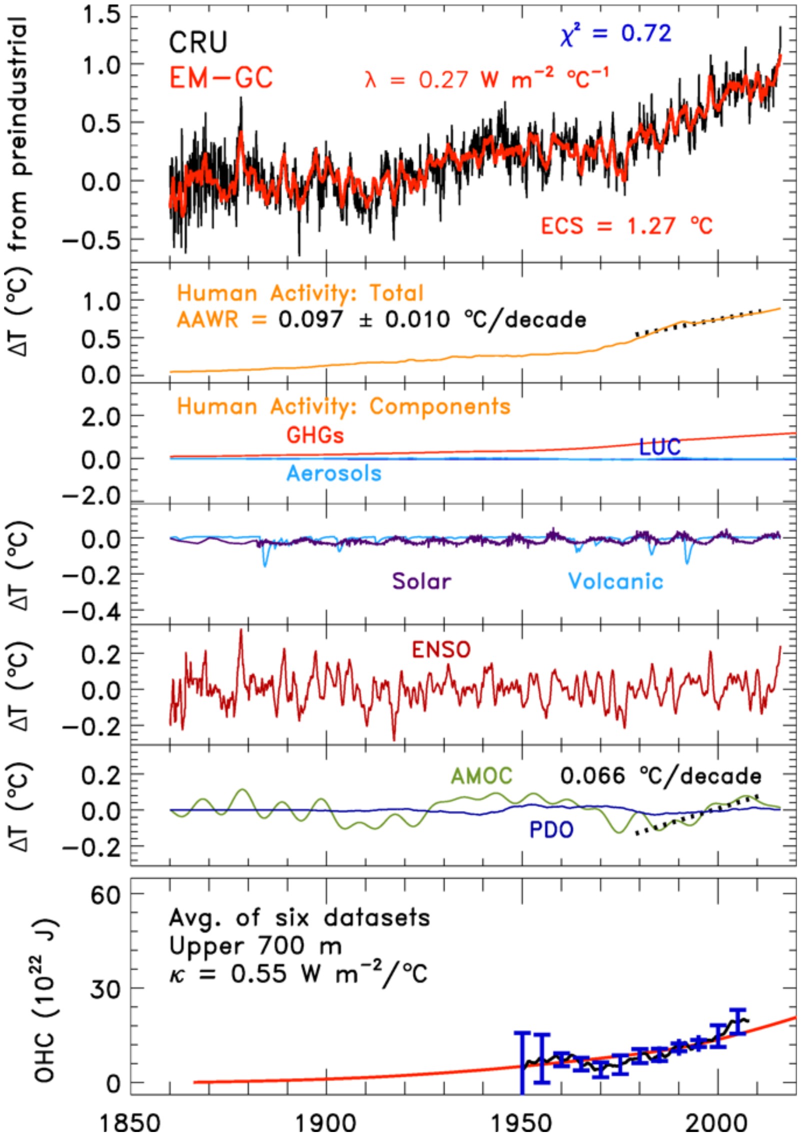
Model used Aerosol RF $_{2011}$ = −1.9 W m^{-2}

$$1 + f_{TOTAL} = \frac{1}{1 - \dfrac{2.01\ \text{W m}^{-2}\ {}^\circ\text{C}^{-1}}{3.2\ \text{W m}^{-2}\ {}^\circ\text{C}^{-1}}} = 2.69$$

Therefore, $f_{TOTAL} = 1.69$

If $f_{WV+LR} = 0.45$, then in this model framework, $f_{CLOUDS+ALBEDO}$ is strongly positive

Empirical Model of Global Climate (EM-GC)



$$\Delta T_{MDL\,i} = (1+\gamma)\,(\text{GHG RF}_i + \text{Aerosol RF}_i)\,/\,\lambda_P + C_0 + C_1\times\text{SOD}_{i-6} + C_2\times\text{TSI}_{i-1} + C_3\times\text{ENSO}_{i-2} + C_4\times\text{AMOC}_i - Q_{OCEAN\,i}\,/\,\lambda_P$$

Model used Aerosol RF $_{2011}$ = –0.1 W m^{-2}

$$1 + f_{\mathrm{TOTAL}} = \frac{1}{1 - \dfrac{0.27\ \mathrm{W\ m^{-2}\ ^\circ C^{-1}}}{3.2\ \mathrm{W\ m^{-2}\ ^\circ C^{-1}}}} = 1.09$$

Therefore, $f_{\mathrm{TOTAL}} = 0.09$

If $f_{\mathrm{WV+LR}} = 0.45$, then in this model framework, $f_{\mathrm{CLOUDS+ALBEDO}}$ is strongly negative

Figure 2.9, Paris Beacon of Hope

Empirical Model of Global Climate (EM-GC)

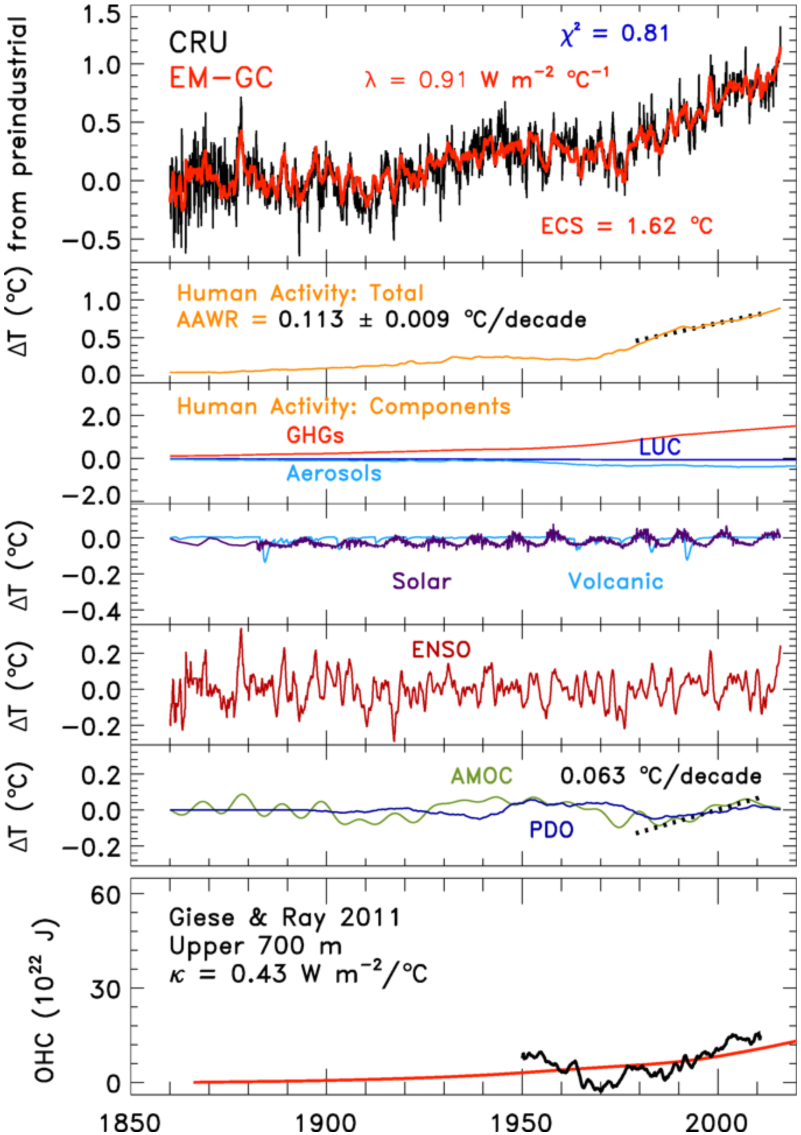


Figure 2.9, Paris Beacon of Hope

$$\Delta T_{MDL\, i} = (1+\gamma)\,(\text{GHG RF}_i + \text{Aerosol RF}_i)\,/\,\lambda_P + C_0 + C_1\times\text{SOD}_{i-6} + C_2\times\text{TSI}_{i-1} + C_3\times\text{ENSO}_{i-2} + C_4\times\text{AMOC}_i - Q_{OCEAN\, i}\,/\,\lambda_P$$

Model used Aerosol RF $_{2011}$ = –0.9 W m^{-2} & Ocean Heat Content record Giese & Ray

$$1 + f_{TOTAL} = \frac{1}{1 - \dfrac{0.91\ \text{W m}^{-2}\ {}^\circ\text{C}^{-1}}{3.2\ \text{W m}^{-2}\ {}^\circ\text{C}^{-1}}} = 1.40$$

Therefore, $f_{TOTAL} = 0.40$

If $f_{WV+LR} = 0.45$, then in this model framework, $f_{CLOUDS+ALBEDO}$ is neutral (i.e., near zero)

Empirical Model of Global Climate (EM-GC)

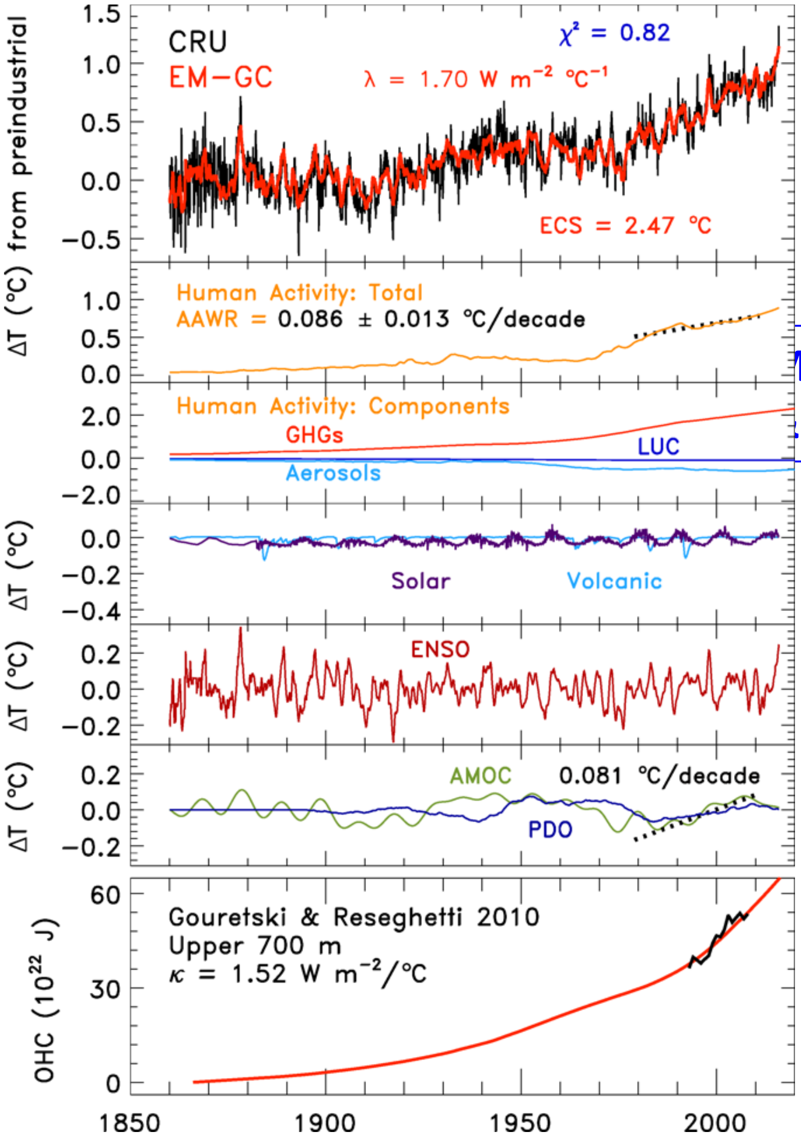


Figure 2.9, Paris Beacon of Hope

$$\Delta T_{MDL\,i} = (1+\gamma)\,(\text{GHG RF}_i + \text{Aerosol RF}_i)\,/\,\lambda_P + C_0 + C_1\times\text{SOD}_{i-6} + C_2\times\text{TSI}_{i-1} + C_3\times\text{ENSO}_{i-2} + C_4\times\text{AMOC}_i - Q_{OCEAN\,i}\,/\,\lambda_P$$

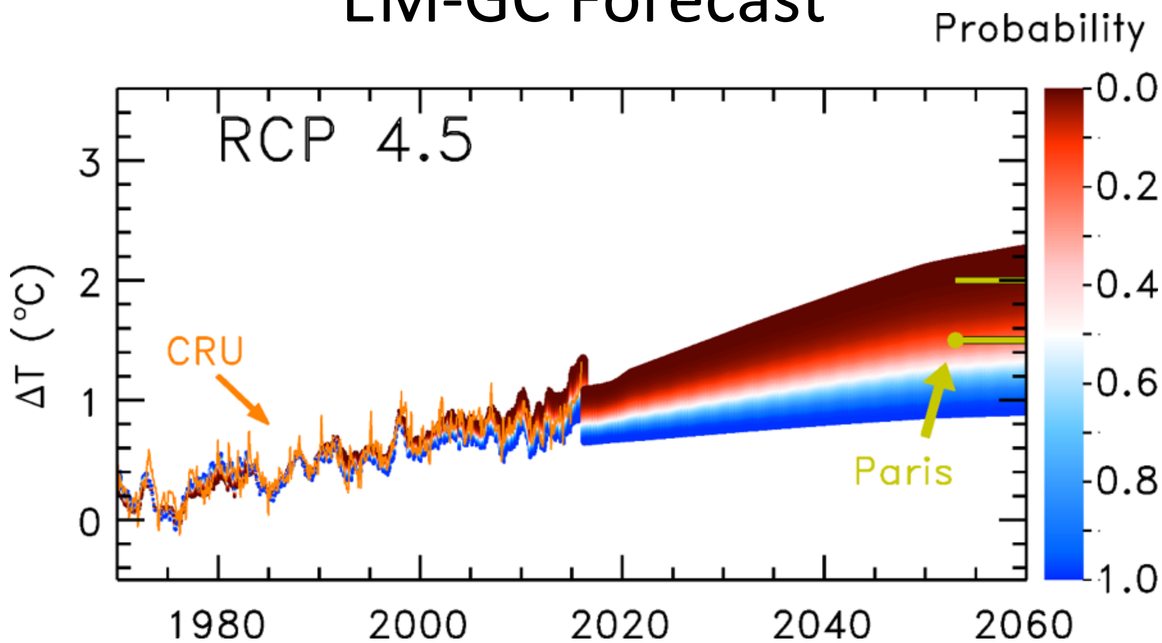
lodel used Aerosol RF $_{2011}$ = –0.9 W m^{-2}
: Ocean Heat Content record Gouretski & Reseghetti

$$1+f_{TOTAL} = \frac{1}{1-\dfrac{1.70\ \text{W m}^{-2}\ {}^\circ\text{C}^{-1}}{3.2\ \text{W m}^{-2}\ {}^\circ\text{C}^{-1}}} = 2.13$$

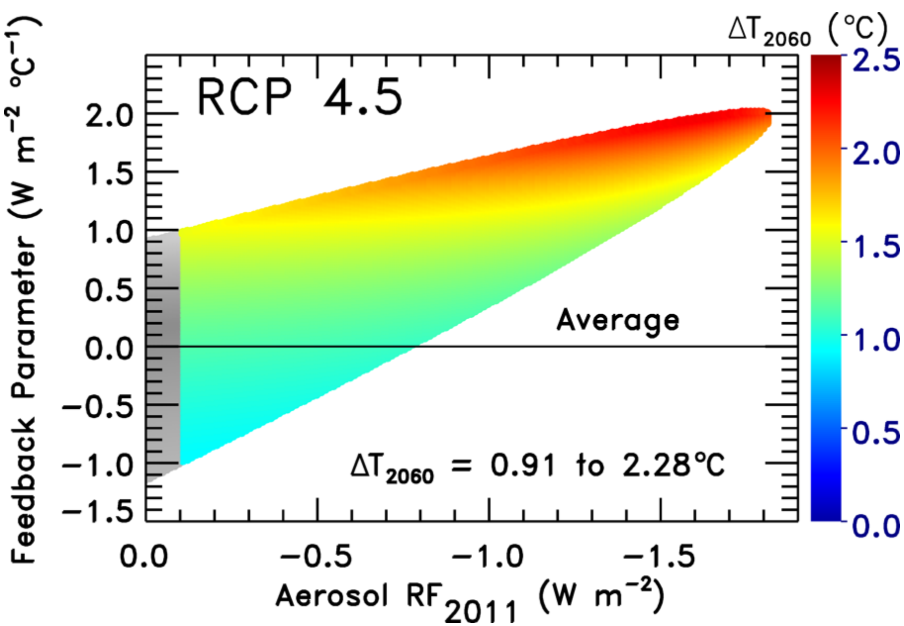
Therefore, $f_{TOTAL} = 1.13$

If $f_{WV+LR} = 0.45$, then in this model framework, $f_{CLOUDS+ALBEDO}$ is positive

EM-GC Forecast

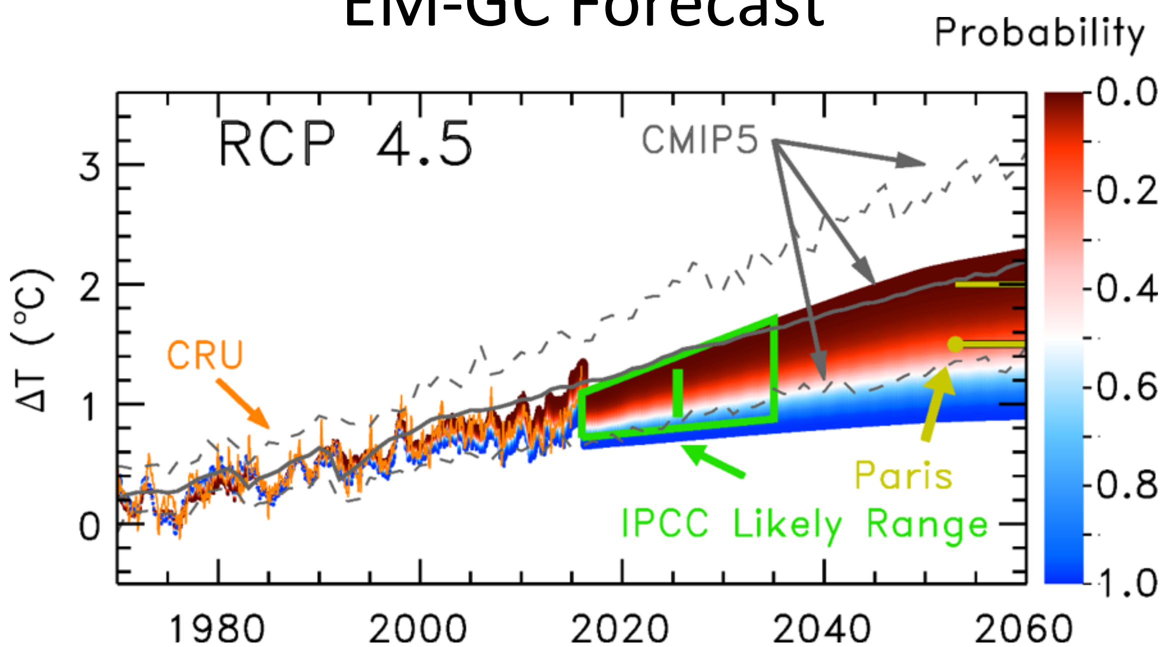


After Figure 2.19



After Figure 2.15

EM-GC Forecast



After Figure 2.19

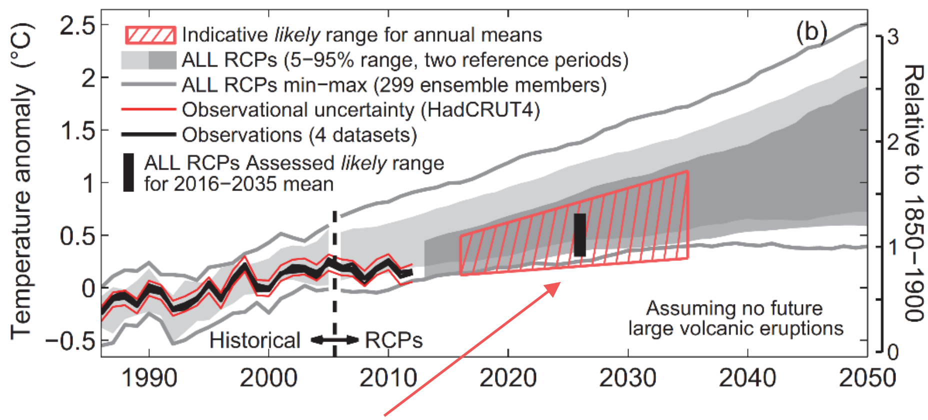
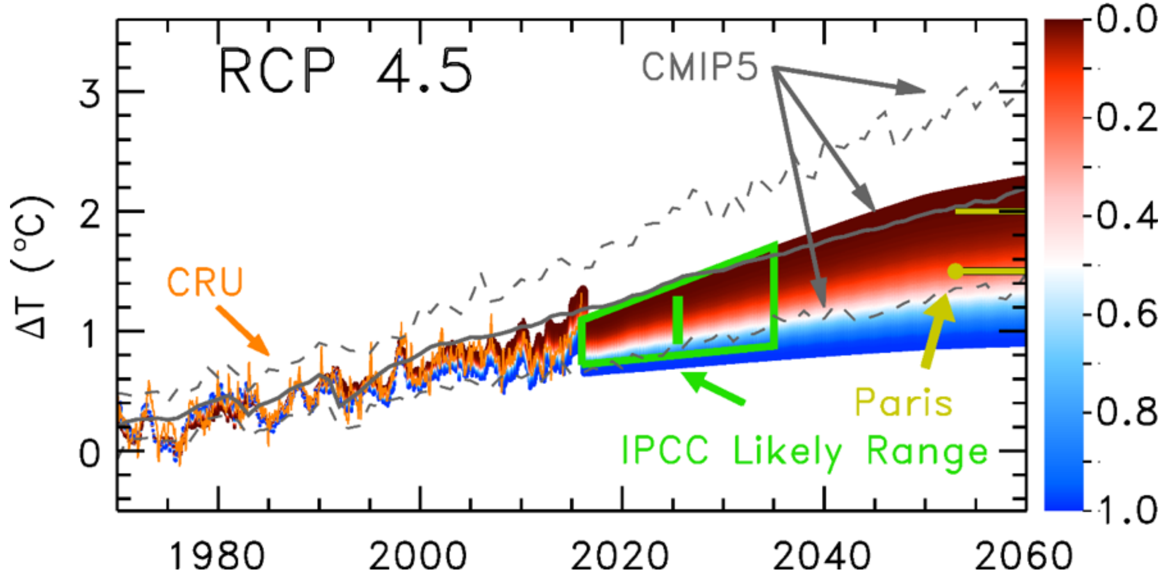


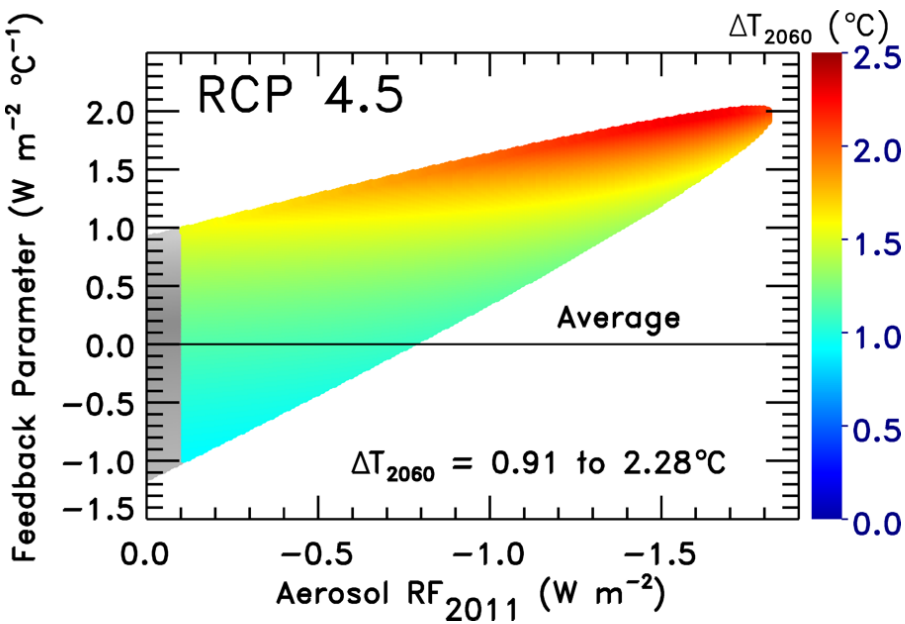
Fig 11.25b, IPCC 2013

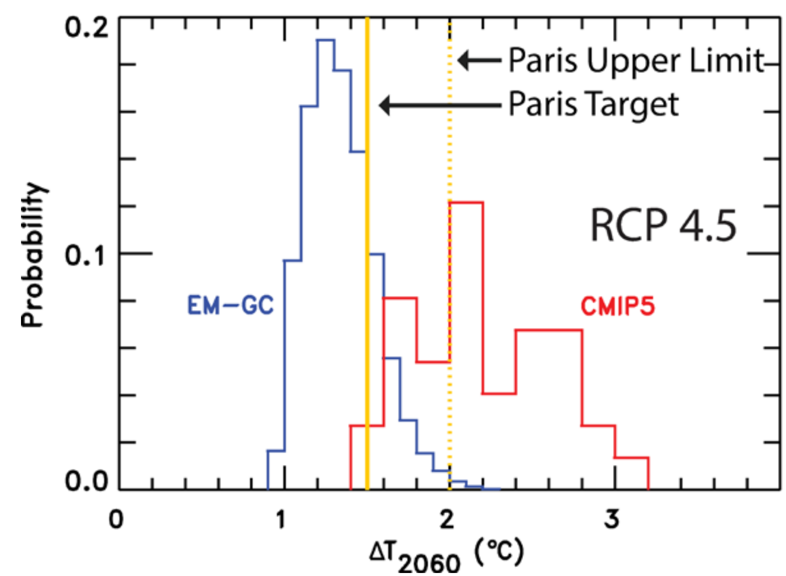
Red hatched region: likely range for annual, global mean surface temp (GMST) anomaly during 2016–2035
Black bar: likely range for the 20-year mean GMST anomaly for 2016–2035

EM-GC Forecast



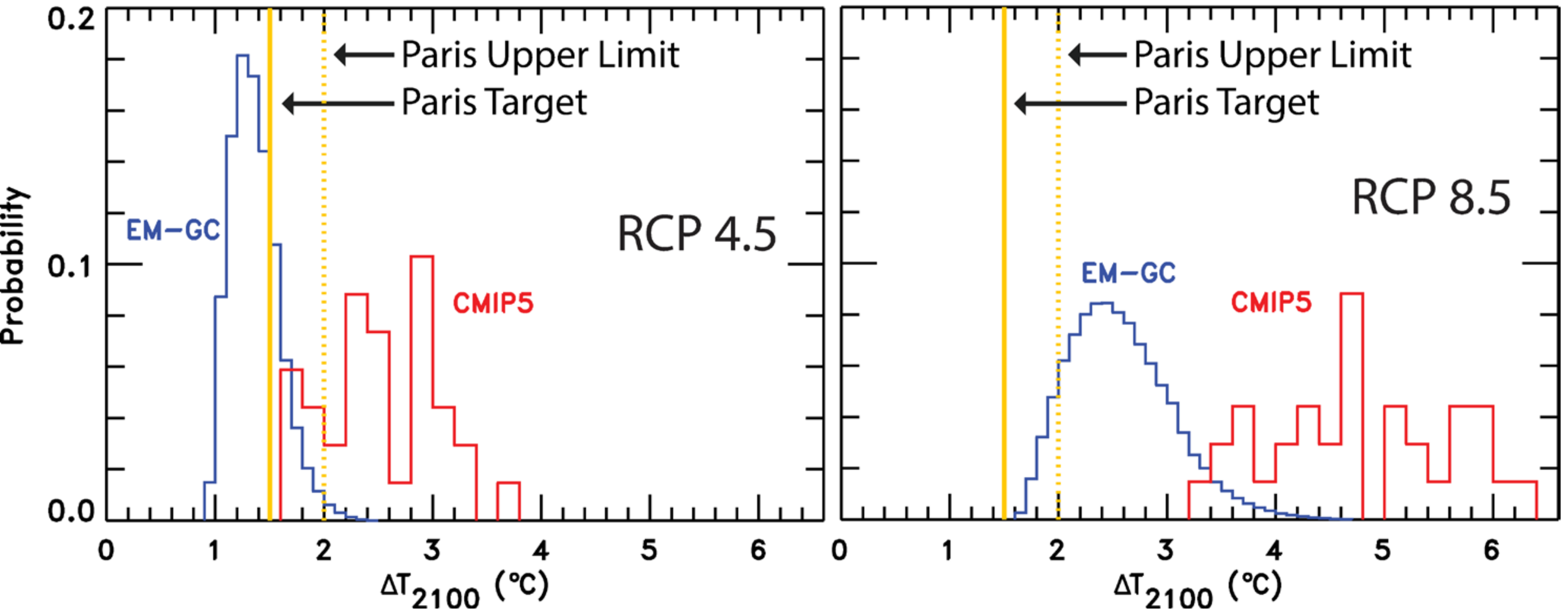
After Figure 2.19





After Figure 2.17

EM-GC Forecast



After Figure 2.18

Univ of Md Empirical Model of Global Climate indicates RCP 4.5 is the 2°C warming pathway