Modeling Earth's Climate: Water Vapor, Cloud, and Surface Albedo Feedbacks & RF Due to Aerosols
ACC 433/633 & CHEM 433

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2015

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)
   - Clouds (somewhat complicated; not well known)
3. An empirical model of climate: using the past to project future

Lecture 08

24 February 2015

Upcoming Schedule

Thurs, 26 Feb, 2 pm: P Set #2 due

Mon, 2 Mar, 6:30 pm, CSS 2403: Review of second problem set

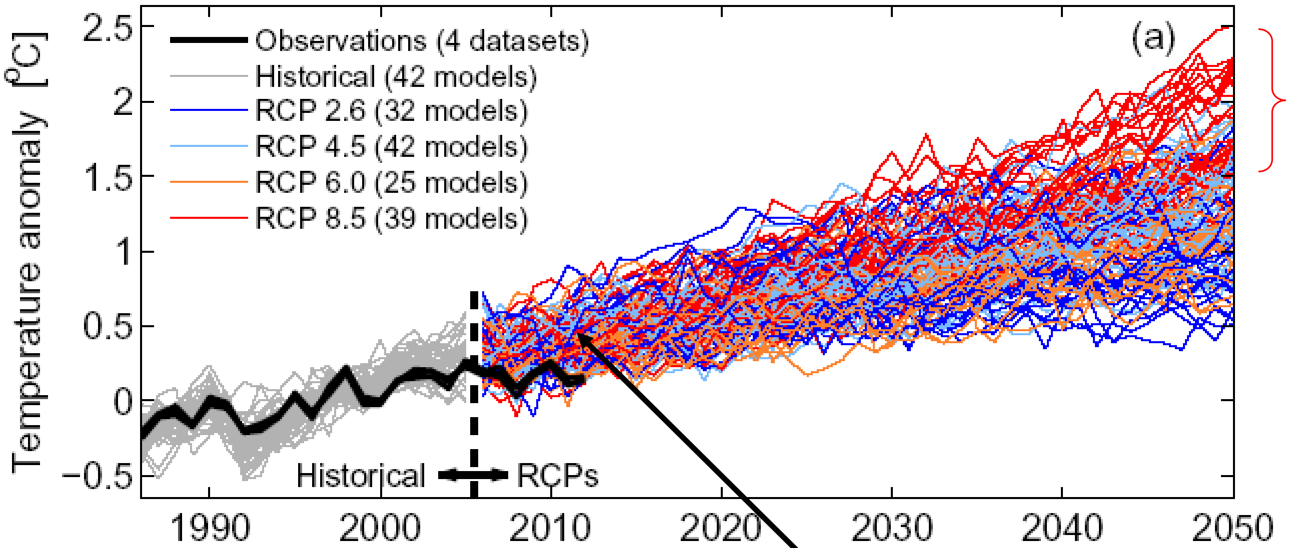
We will return graded problem sets at the start of the review but only guarantee return of graded problem sets turned in prior to start of the weekend

Tues, 3 Mar, 2 pm: First Exam (a lot more about this on Thurs)

Will be closed book, no notes, no calculator

IPCC (2013) projects 2°C rise in global mean temperature if CO_2 reaches 560 ppm, twice the pre-industrial level

RCP 8.5: CO_2 reaches 560 ppm in year 2053



Rise in global mean T, RCP 8.5, relative to 1961 to 1990 baseline:
- Mean = 2.24 ± 0.41 °C
- Median = 2.25 °C

Fig 11.25a, IPCC 2013

CMIP5 GCM estimates of global mean T anomaly diverge from data, past decade

What are consequences of this divergence for future projections of global warming?

CMIP5: Coupled Model Intercomparison Project Phase 5
http://cmip-pcmdi.llnl.gov/cmip5

Radiative Forcing of Climate, 1750 to 2011

IPCC (2013)

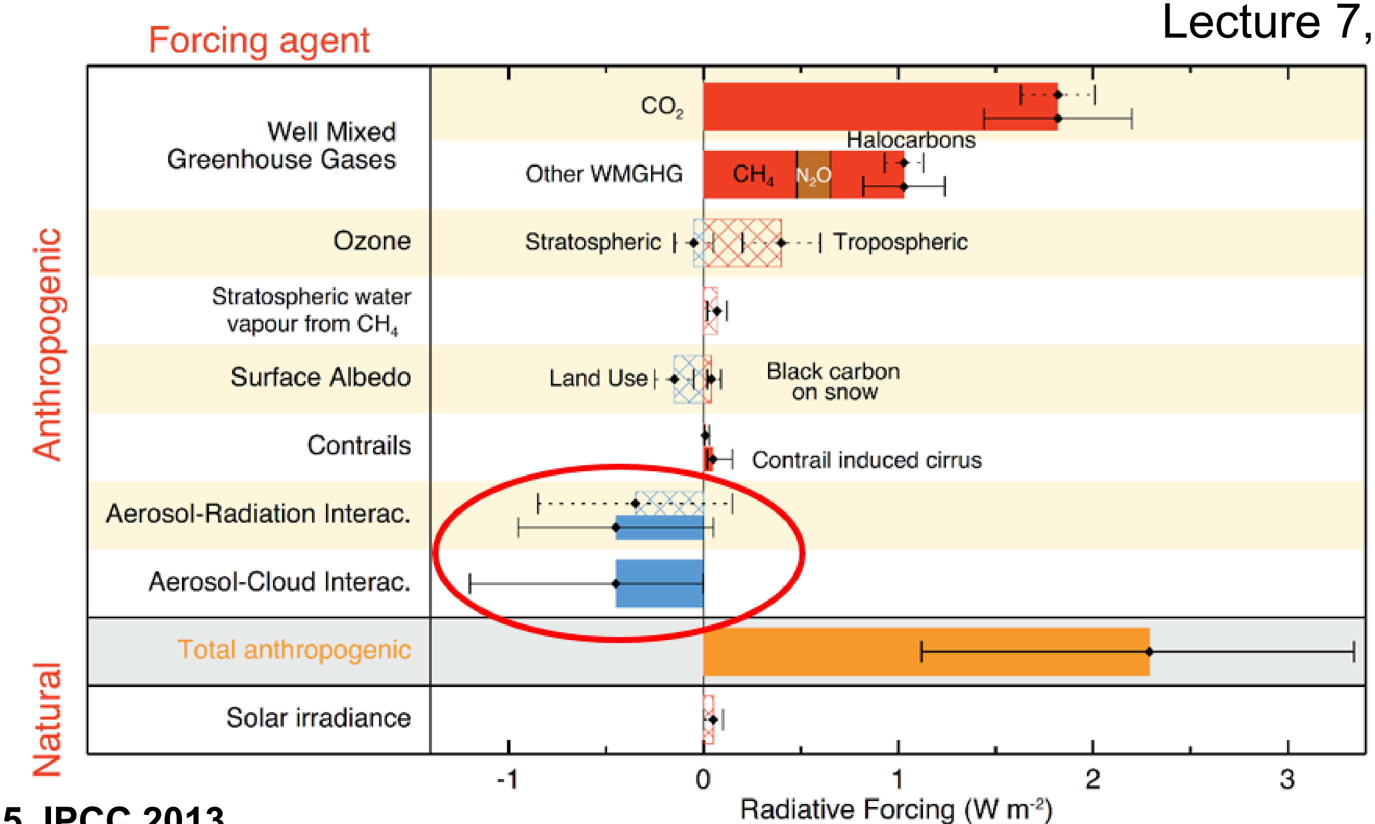


Fig 8.15, IPCC 2013

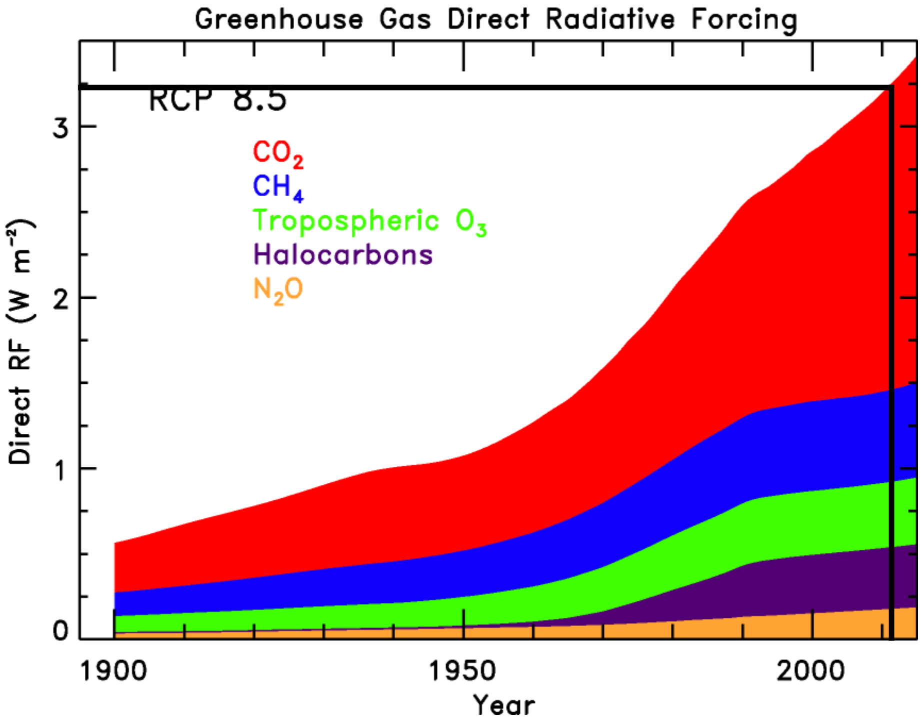
Hatched bars correspond to a newly introduced concept called Effective RF, which allows for some "tropospheric adjustment" to initial perturbation

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**)

RF of Climate due to Rising GHGs



RCP: Representative Concentration Pathways

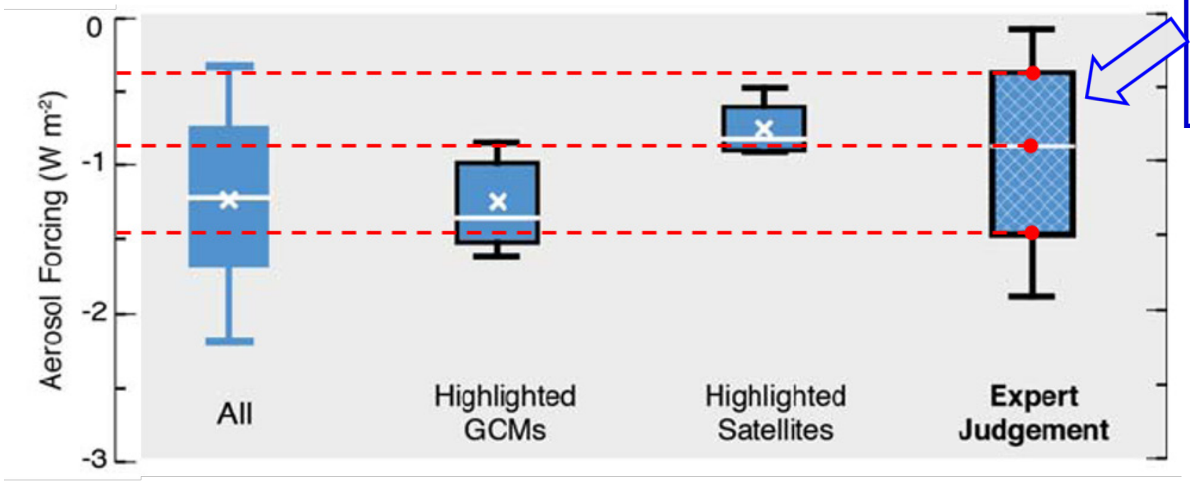
RF scenarios prepared for IPCC (2013)

Canty et al., ACP, 2013

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

RF of Climate due to Rising Aerosols

Figure 7.19B, IPCC 2013



IPCC (2013) best estimate of NAA RF_{2010} is
Slightly less than −1.0 W m^{-2}
Likely range: −0.4 to −1.5 W m^{-2}

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

NAA RF
Net Anthropogenic Aerosol Radiative Forcing

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

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**

Sulfate aerosols (H_2SO_4)

- **formed from SO_2 emitted by either coal ($C_{135}H_{96}O_9NS$)# combustion or oceanic biology ($(CH_3)_2S$)**
- **efficient scatters of solar radiation: cool the local atmosphere !**

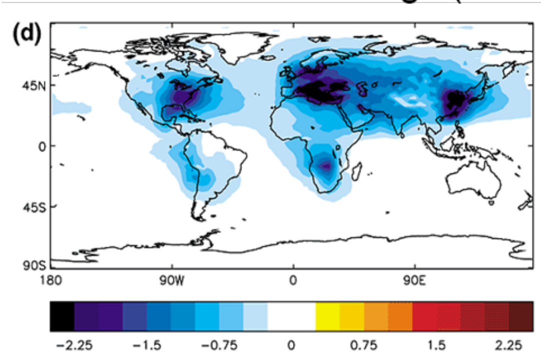
Whether a particular aerosol heats or cools the surface is a function of optical properties of particle as well as reflectivity of underlying surface:

- **Over dark surfaces like the ocean, nearly all aerosols tend to cool the local environment because reflection of solar radiation will dominate "trapping" of reflected solar by scattering**
- **Over bright surfaces like ice or snow, aerosols more likely to heat the local environment due to "trapping" of reflected solar by scattering**

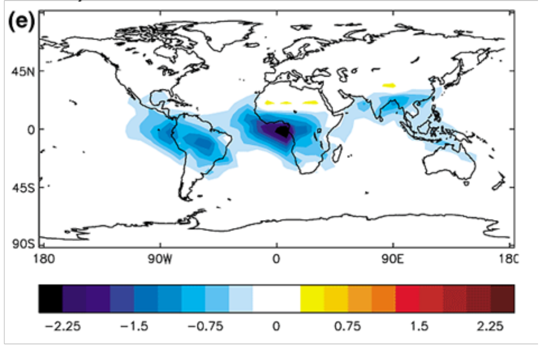
#Canonical formula for coal is $C_{135}H_{96}O_9NS$ (pg 257 of Chemistry in Context)

IPCC 2000

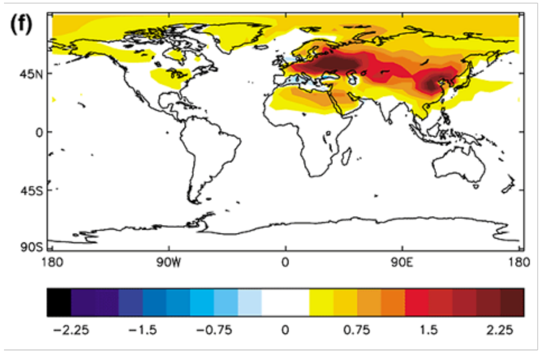
All forcings (1750–2000) are in W m^{-2}



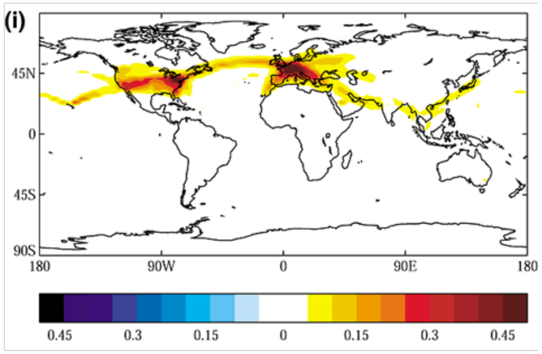
Direct effect from sulphate aerosols



Organic and black carbon from biomass burning



Organic and black carbon from fossil fuel burning



Aircraft contrails

Lecture 7, Slide 33

http://www.grida.no/climate/IPCC_tar/wg1/253.htm#fig67

Large uncertainty in aerosol RF

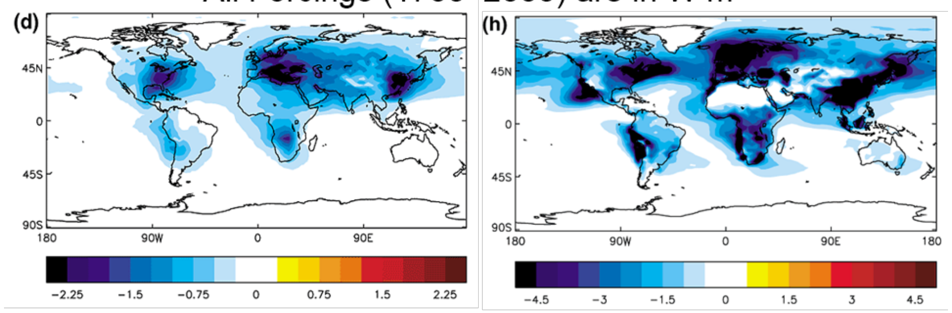
- scatter and absorb radiation (**direct radiative forcing**)
- affect cloud formation (**indirect radiative forcing**)

IPCC 2000

Lecture 7, Slide 33

http://www.grida.no/climate/IPCC_tar/wg1/253.htm#fig67

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



Direct effect from sulphate aerosols

Indirect effect from sulphate aerosols

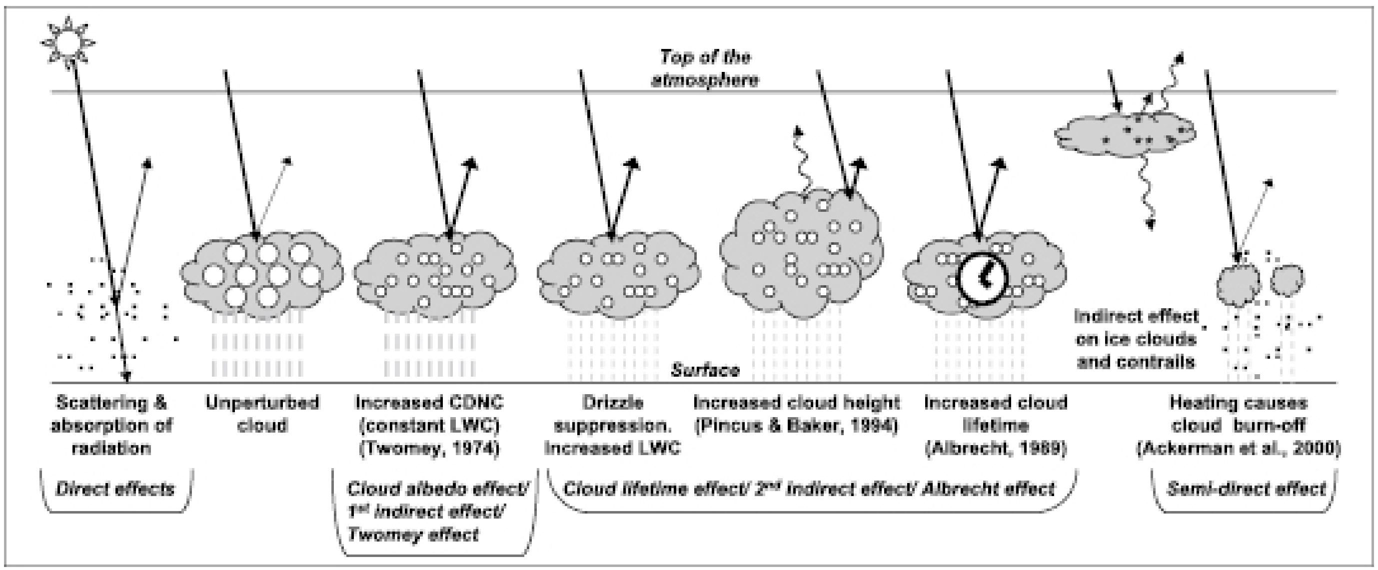


Fig 2-10, IPCC 2007

Large uncertainty in aerosol RF

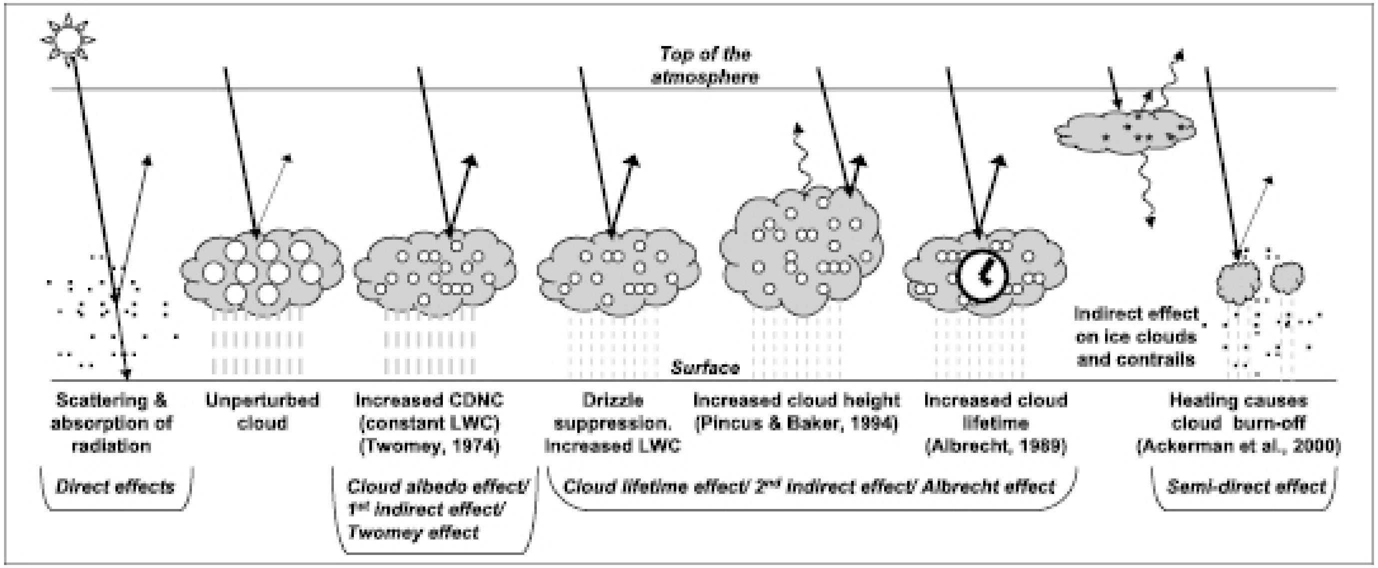
- scatter and absorb radiation (**direct radiative forcing**)
- affect cloud formation (**indirect radiative forcing**)

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) ⇨

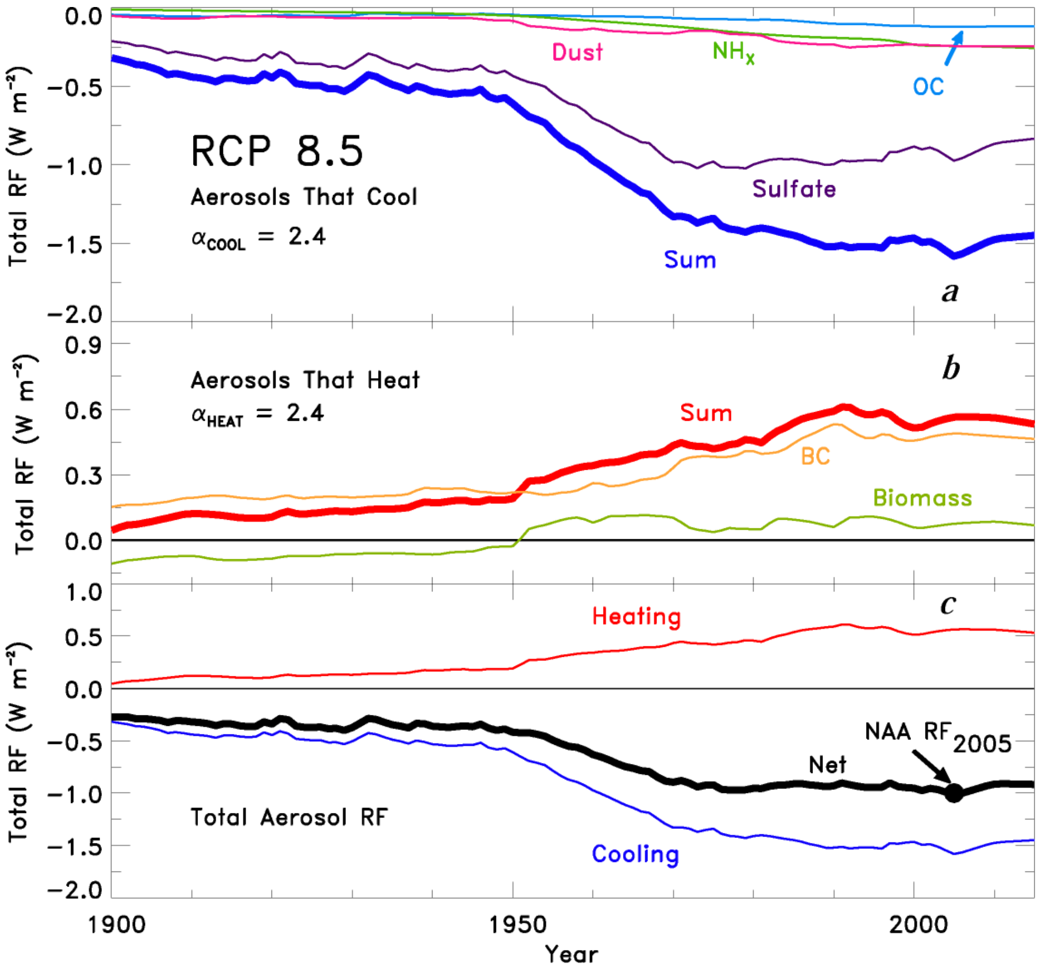


Large uncertainty in aerosol RF

Fig 2-10, IPCC 2007

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

RF of Climate due to Aerosols



Lecture 7, Slide 30

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

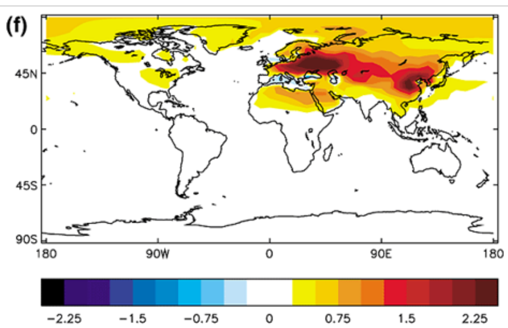
Radiative Properties of Aerosols

Black carbon (soot) aerosols:

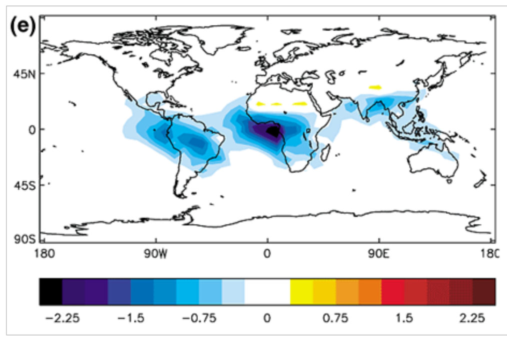
- **emitted from combustion of fossil fuels and biomass burning**
- **efficient absorbers of solar radiation: heat the local atmosphere !**
- **diesel engines notorious source of soot**

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

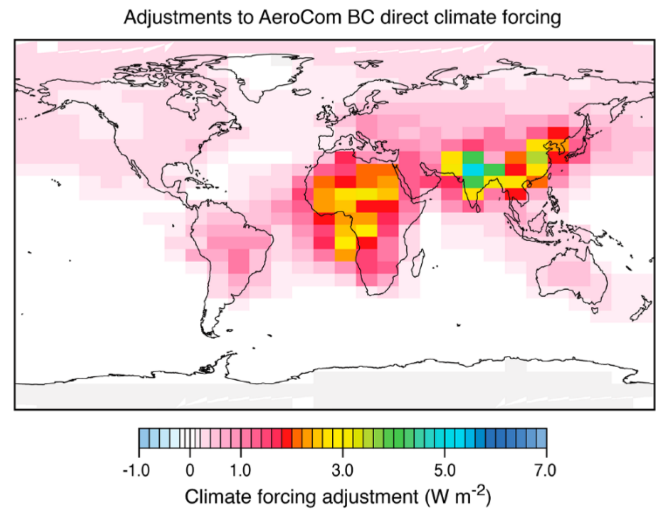
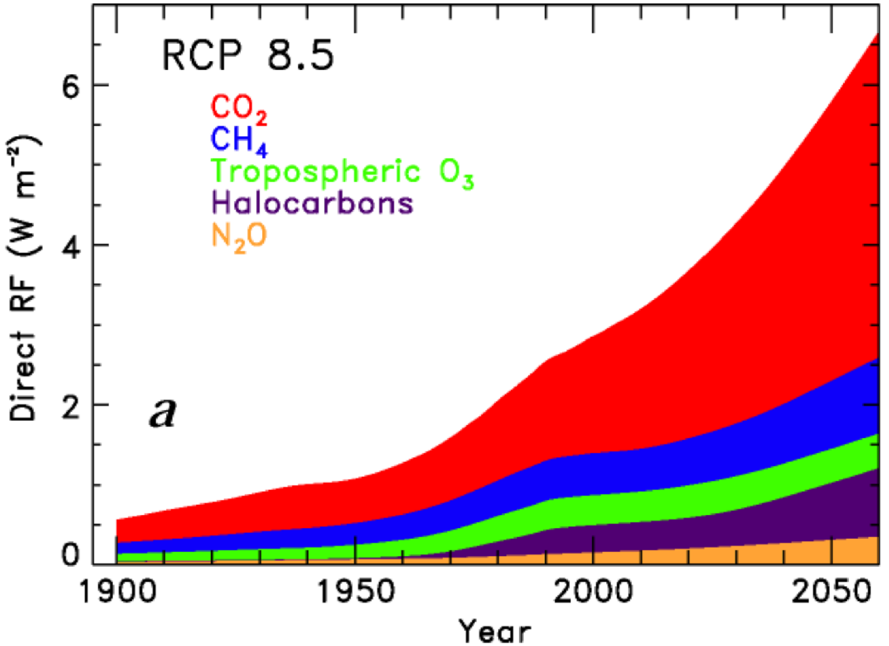


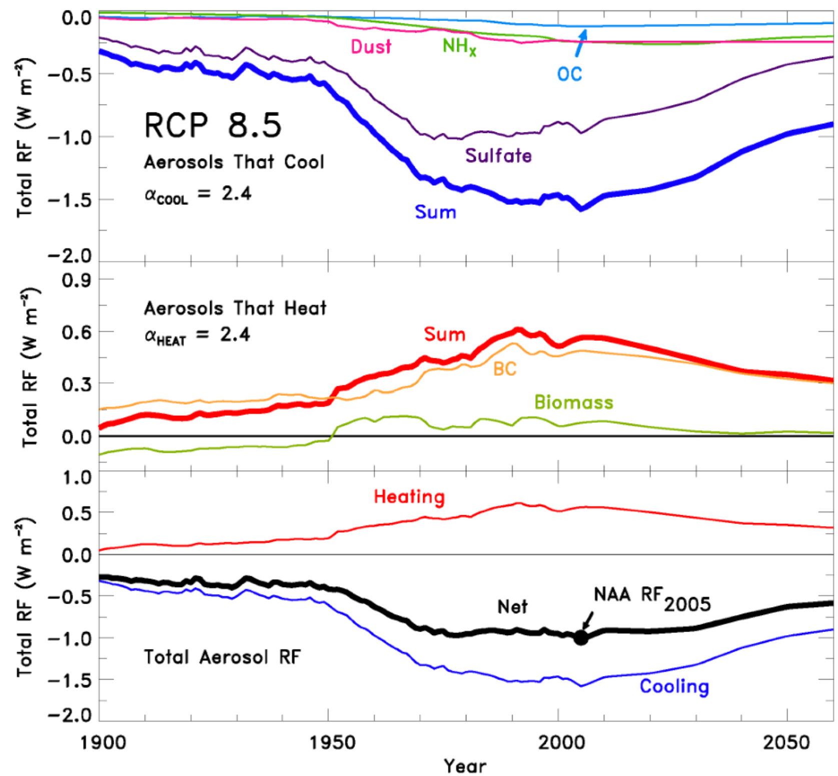
Figure 23. Adjustments to the annual mean, direct radiative forcing (W m^{-2}) by BC in the median AeroCom model required for consistency with the AERONET retrieved aerosol absorption optical depth (AAOD).

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.

RCPs project GHG RG to rise and Aerosol RF to decline





Mascioli et al., ACPD 2012

Ice-Albedo Feedback

Initial Action:
Humans Release CO_2

Initial Response:
$T_{SURFACE}$ Rises

Then:
Ice Melts

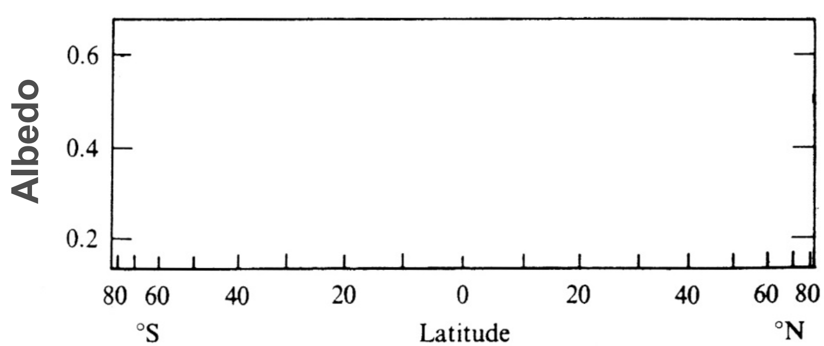
Consequence:
Albedo Falls

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

2. Albedos of selected surfaces on Earth

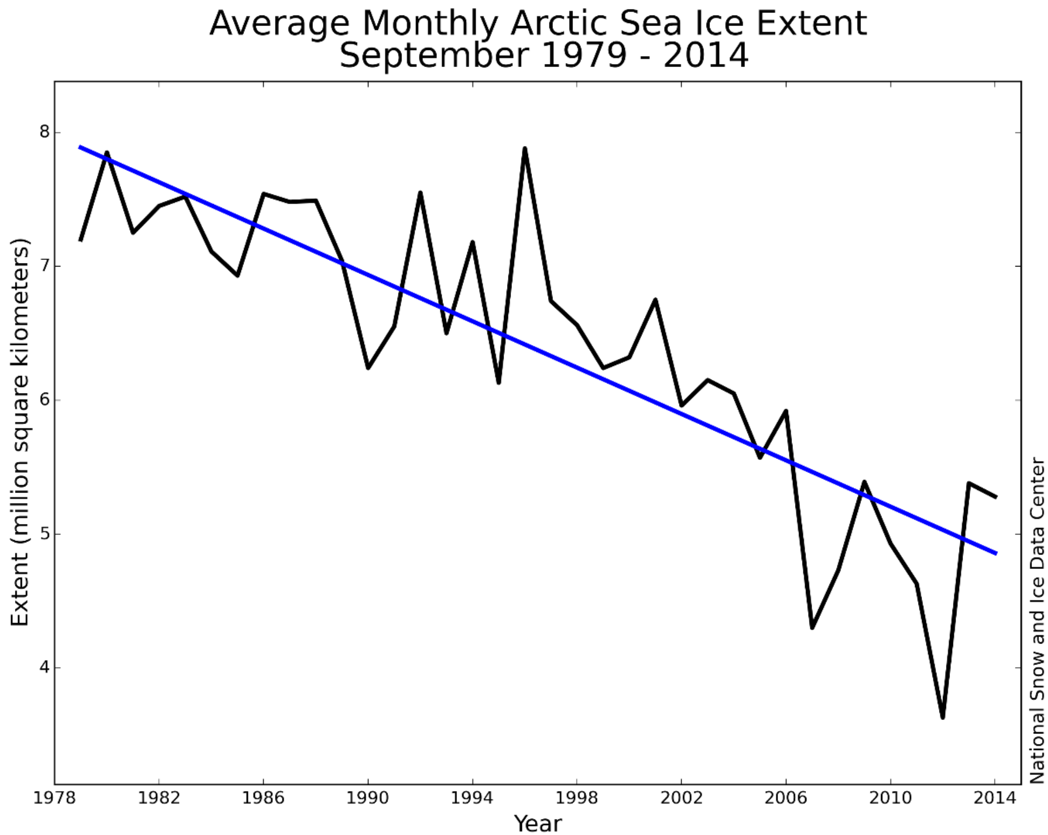
surface	albedo
snow	0.7 ± 0.2
sand	0.25 ± 0.05
grasslands	0.23 ± 0.03
bare soil	0.2 ± 0.05
forest	0.15 ± 0.1
water (highly dependent on surface roughness and incident angle of sunlight)	0.2 + 0.6 − 0.2

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



Houghton, *The Physics of Atmospheres*, 1991.

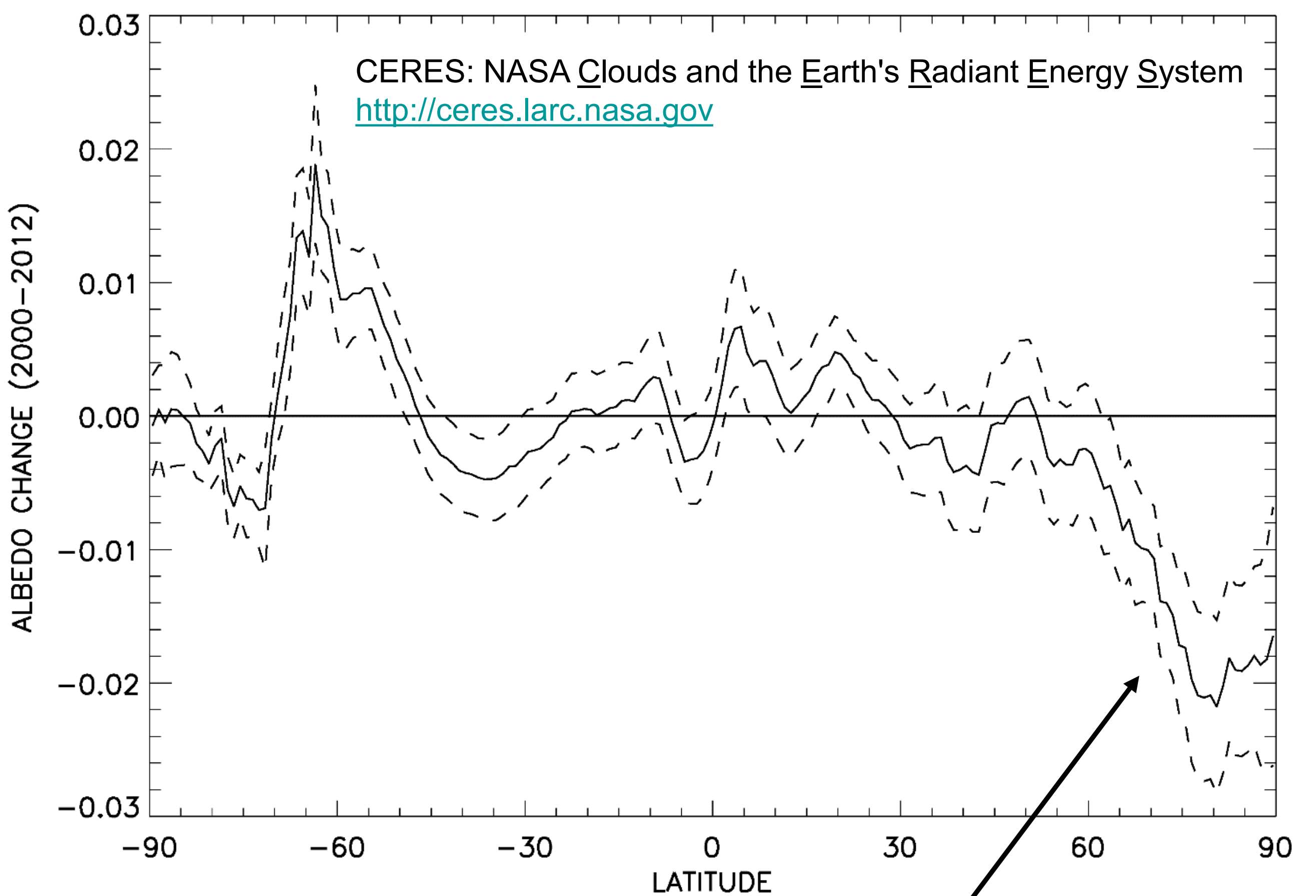
Arctic Sea-Ice: Canary of Climate Change



- 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

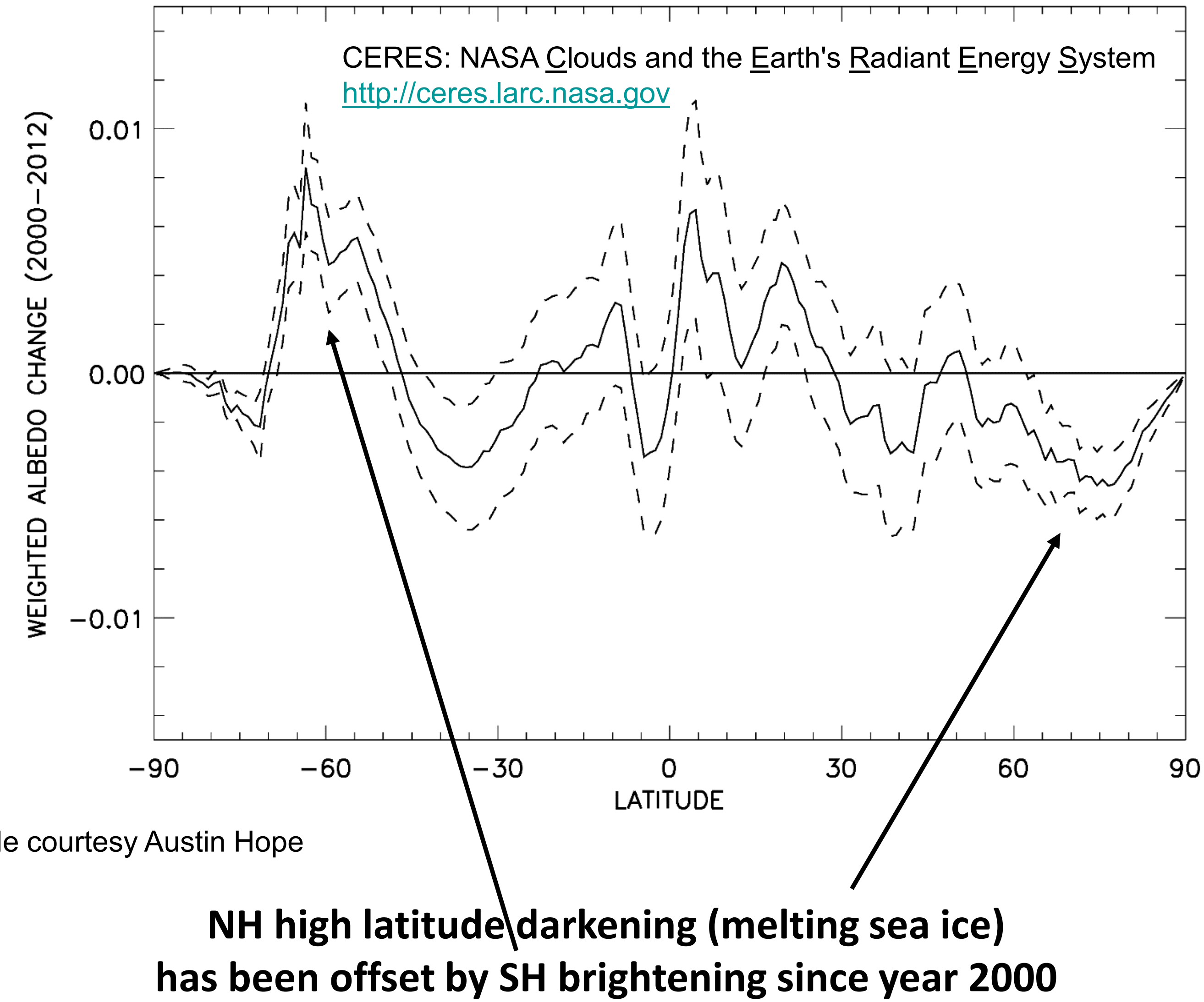
Albedo Anomaly (CERES) Change versus Latitude, No Weighting



Slide courtesy Austin Hope

NH high latitude darkening (melting sea ice) is apparent

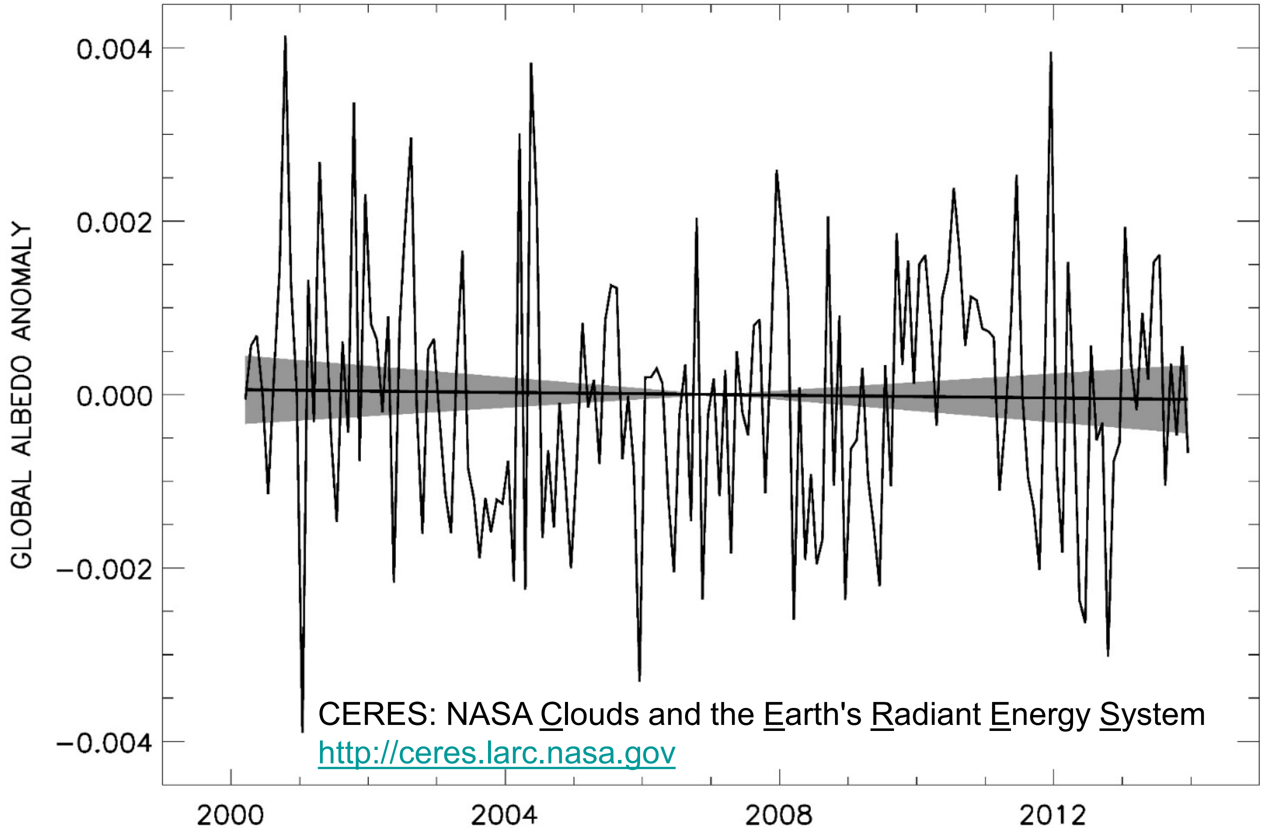
Albedo Anomaly (CERES) Change versus Latitude, Weighted by Cosine Latitude



Slide courtesy Austin Hope

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

Global Average Albedo Anomaly (CERES) versus time



Slide courtesy Austin Hope

No statistically significant trend in Earth's planetary albedo over the lifetime of CERES

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 30

Water Vapor Feedback

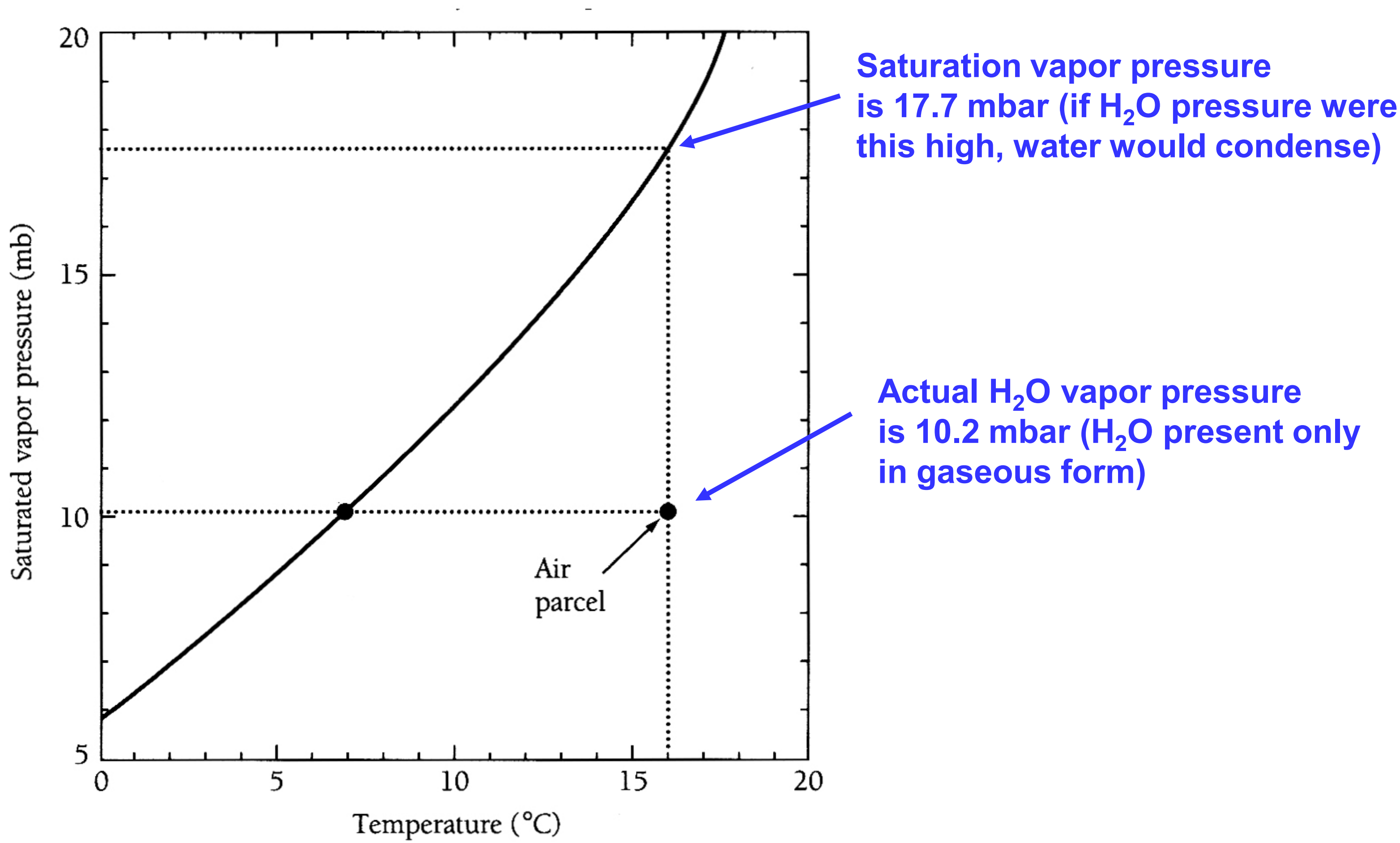


Figure 4.8a Relative humidity and the dew point.

McElroy, *Atmospheric Environment*, 2002

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

Water Vapor Feedback

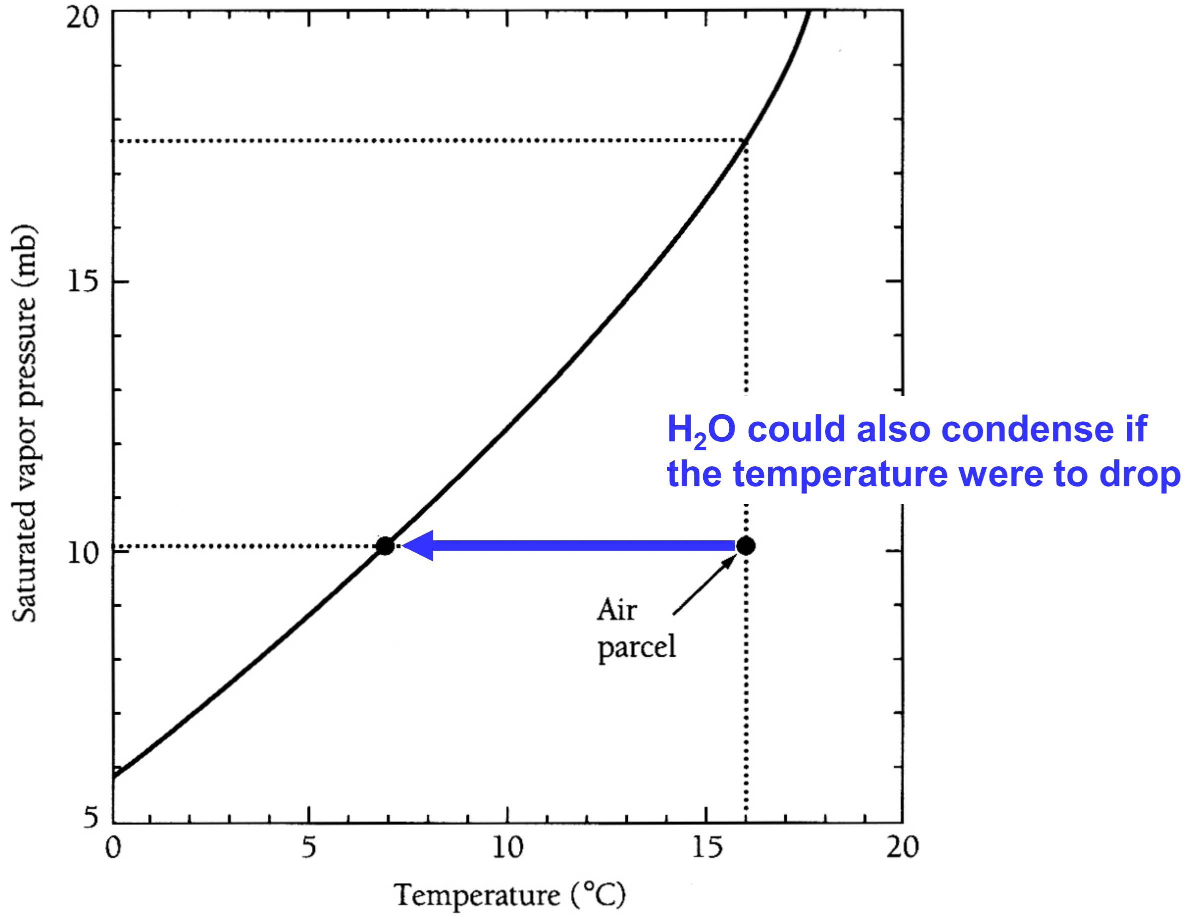


Figure 4.8a Relative humidity and the dew point.

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**

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**

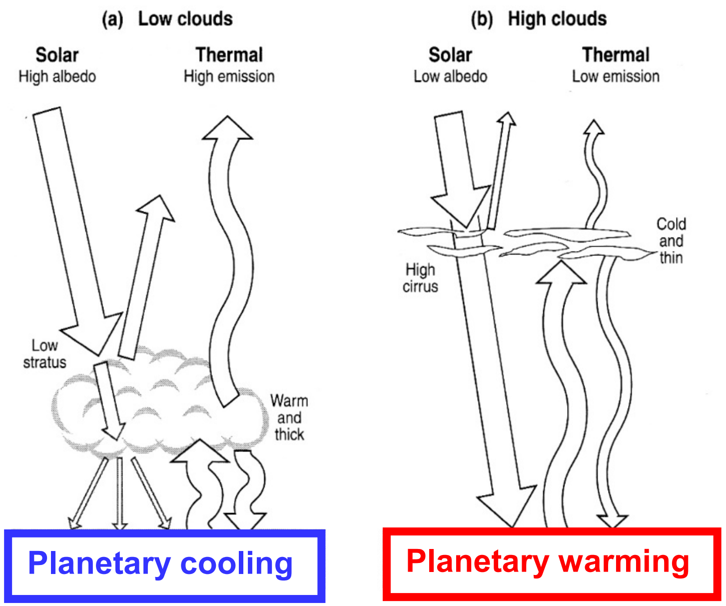


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The 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: IPCC 2007

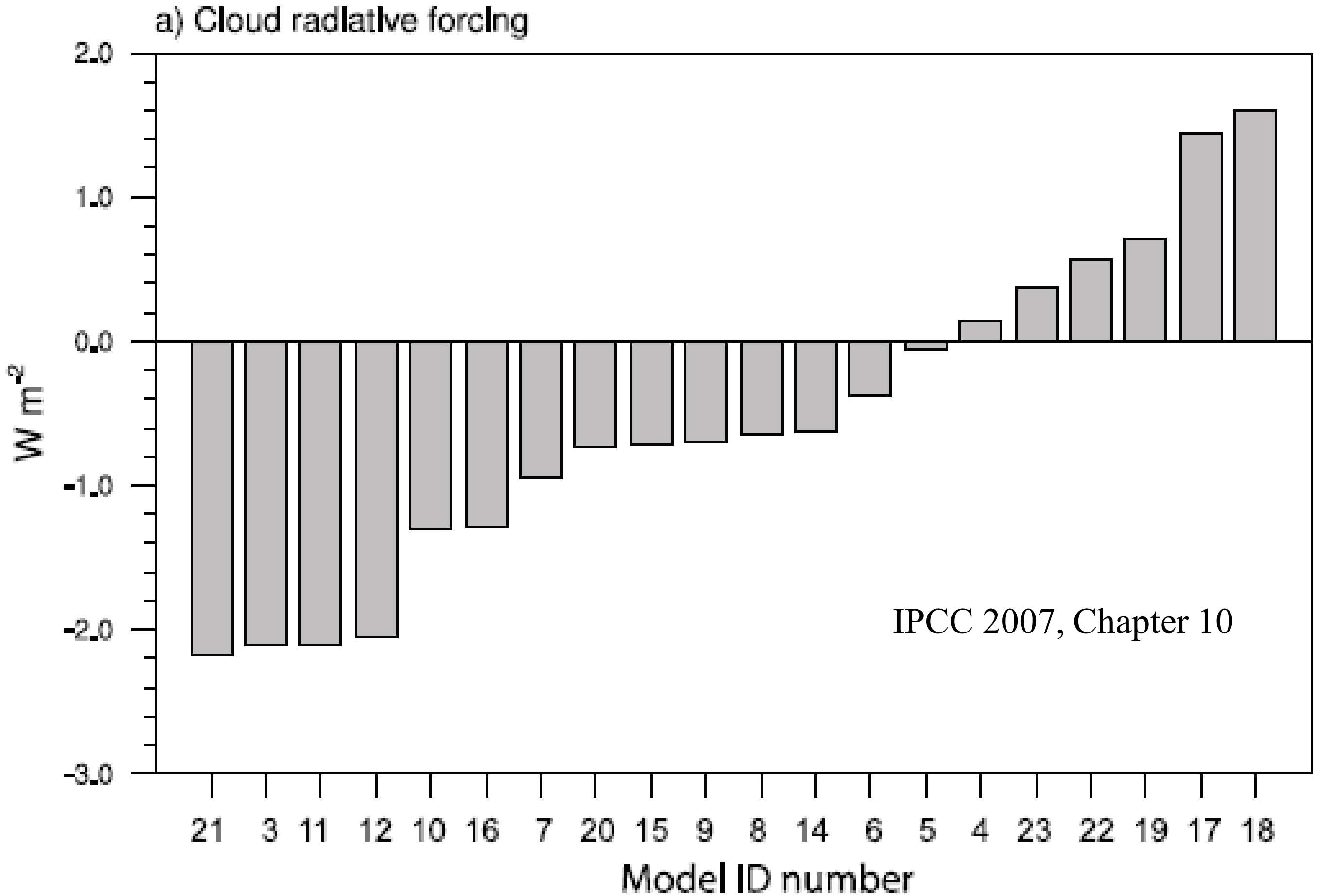


Figure 10.11. *Changes in (a) global mean cloud radiative forcing (W m^{-2}) from individual models (see Table 10.4 for the list of models)*

Changes are annual means for the SRES A1B scenario for the period 2080 to 2099 relative to 1980 to 1999.

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 B

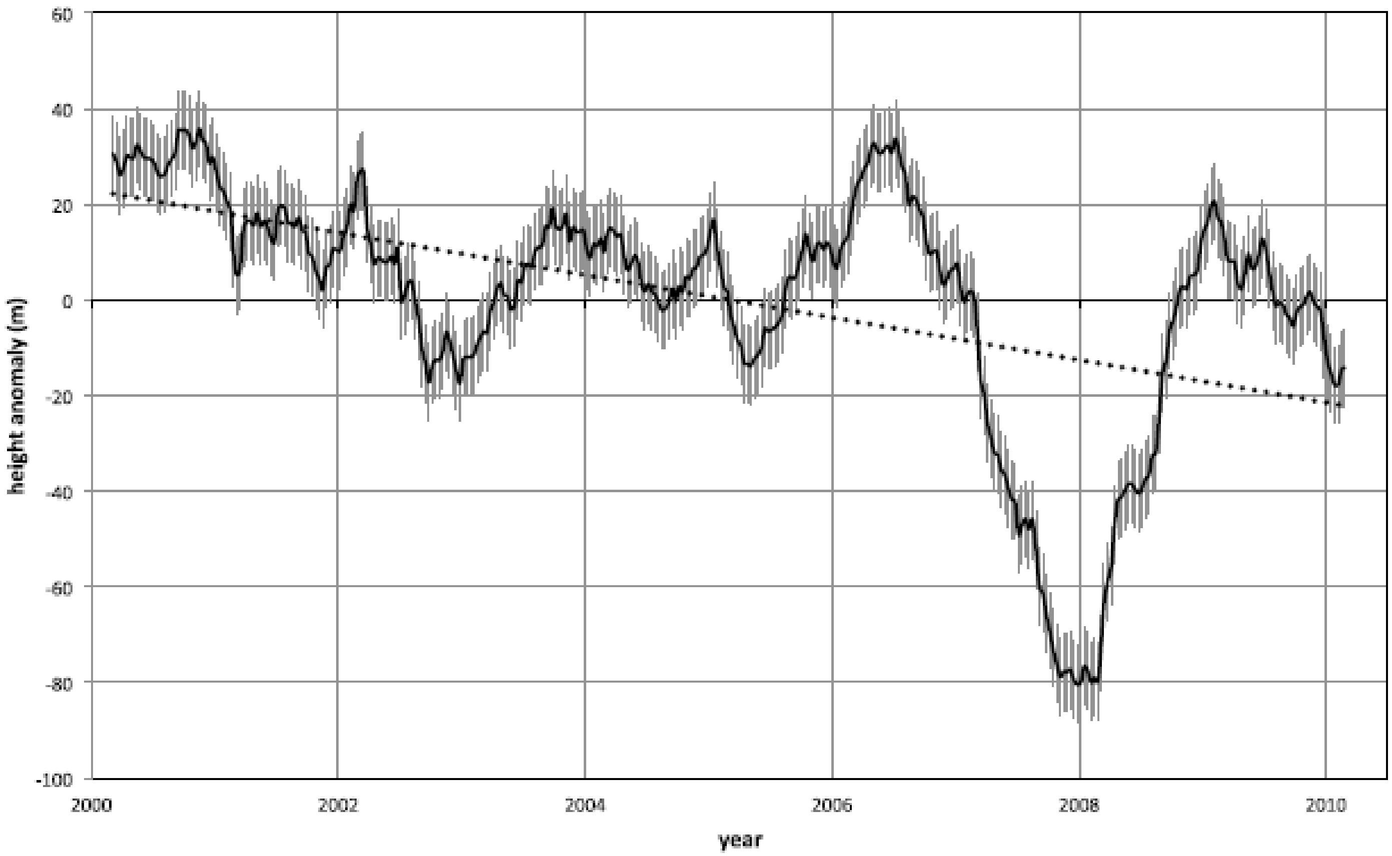


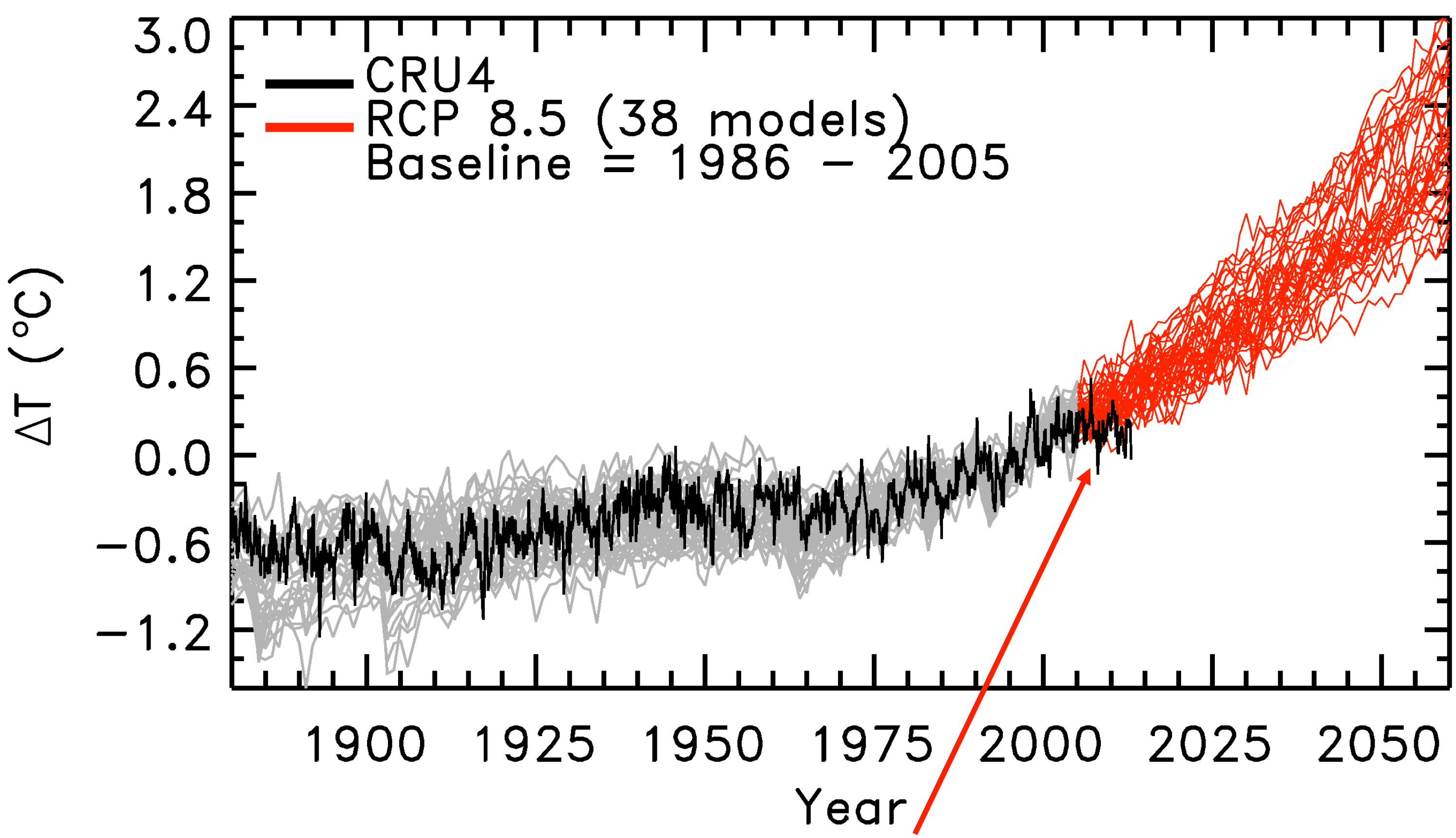
Figure 1. Deseasonalized anomalies of global effective cloud-top height from the 10-year mean. Solid line: 12-month running mean of 10-day anomalies. Dotted line: linear regression. Gray error bars indicate the sampling error (±8 m) in the annual average.

Davies and Molloy, GRL, 2012

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

Future Warming

GMST: Global Mean Surface Temperature



CMIP5 estimates of GMST anomaly diverge from data, past decade

What are consequences of this divergence for future projections of global warming?

More Complete Climate Model

$$\Delta T = \lambda_{BB}\ (1 + f_{H2O} + f_{CLOUDS} + f_{SURFACE\ ALBEDO} + f_{LAPSE\ RATE}) \times$$
$$(\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{OTHER\ GHGs} + \Delta F_{AEROSOLS})$$

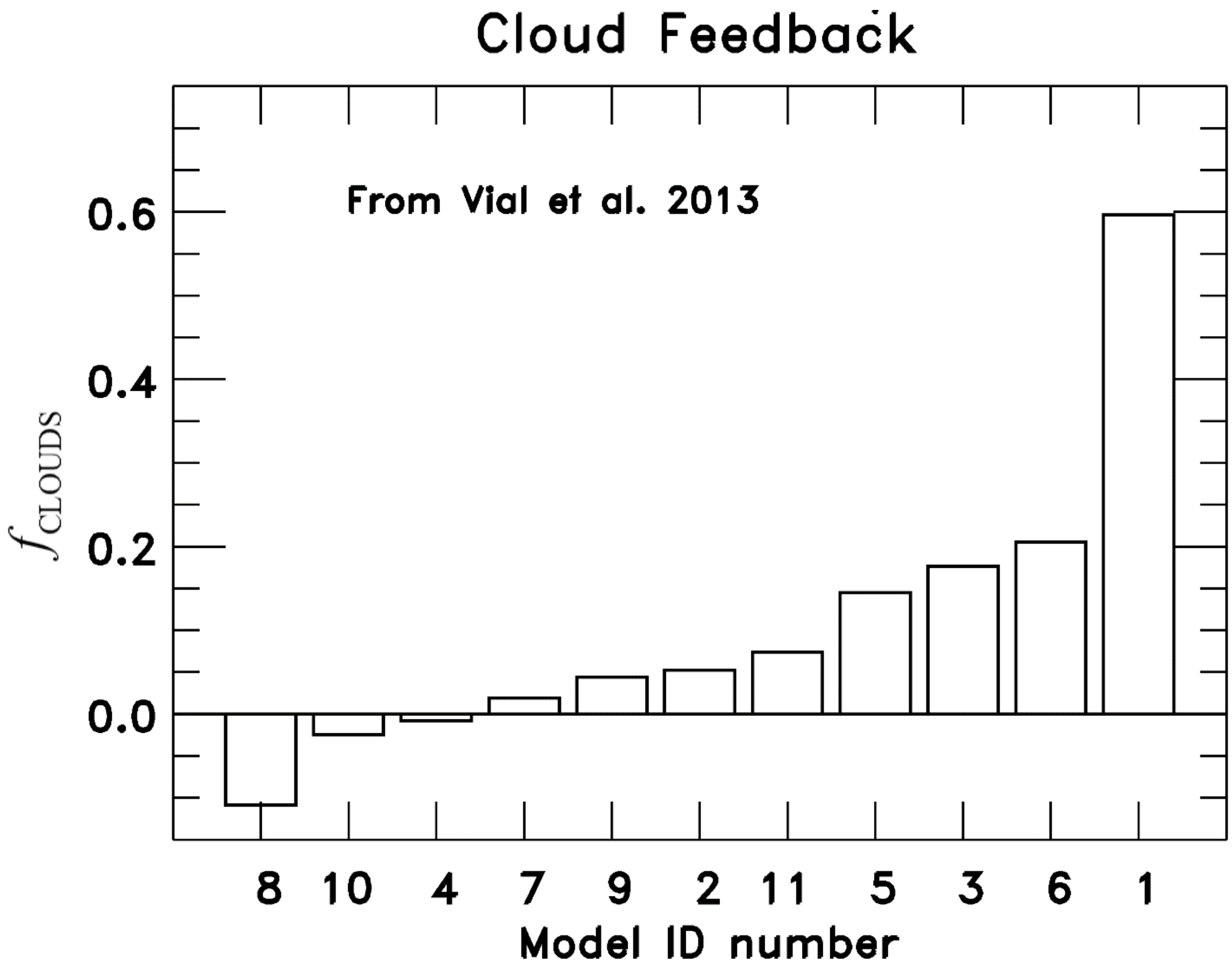
where

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

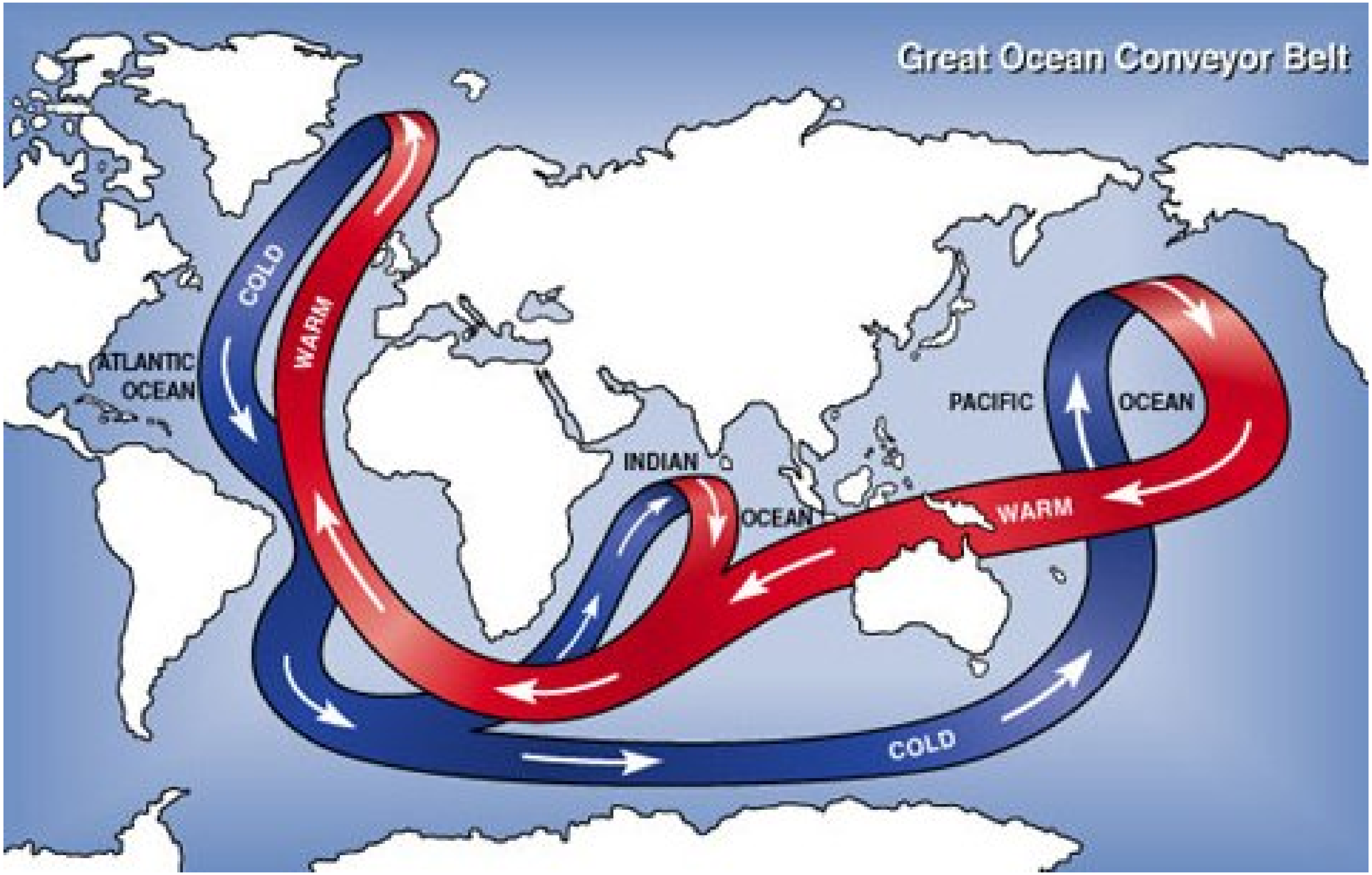
and f_{CLOUDS} & $f_{SURFACE\ ALBEDO}$ represent the response of Clouds & Surface Albedo (internal response) to an external perturbation of the climate system due to GHGs & Aerosols

Analysis of climate model output suggests $f_{H2O} = 1.08$ (Lecture 4, Slide 30)

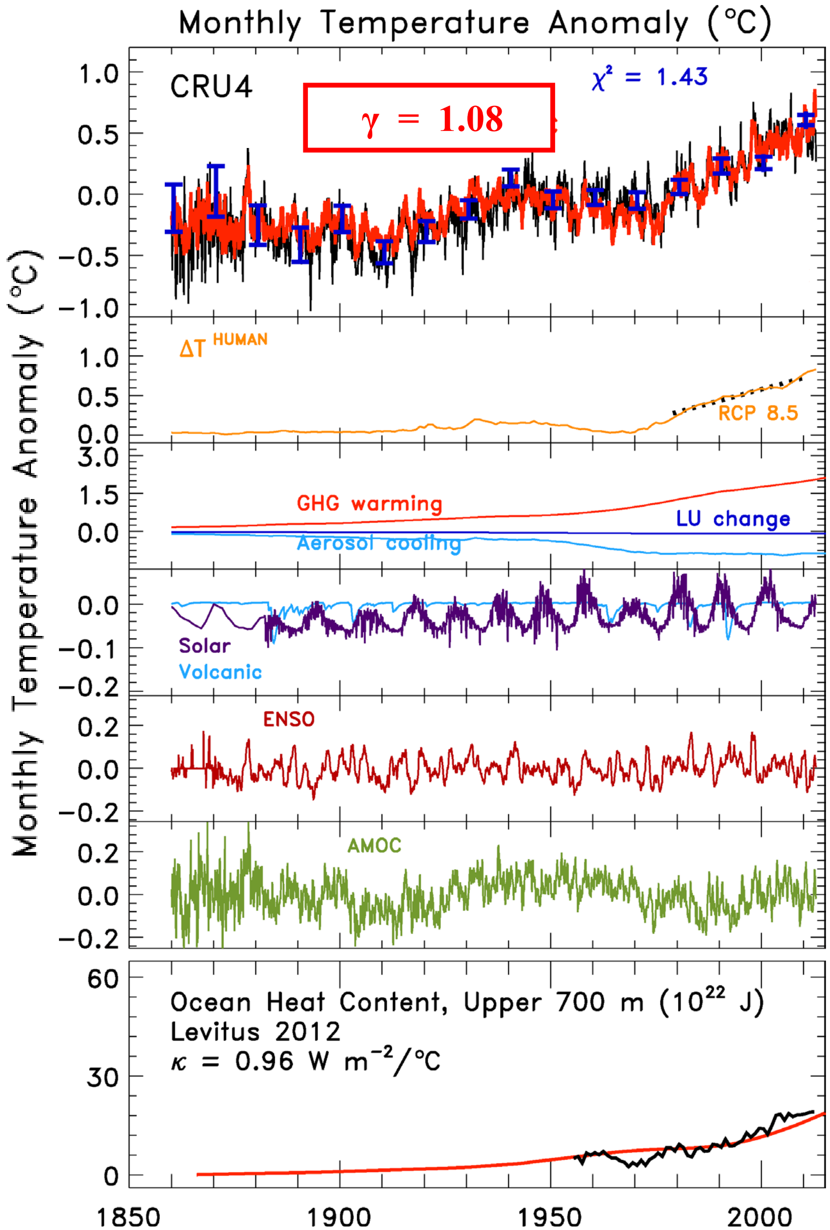
Radiative Forcing of Clouds: IPCC 2013



AMOC: Atlantic Meridional Overturning Circulation



http://science.nasa.gov/science-news/science-at-nasa/2004/05mar_arctic



$$\Delta T_{MDL\,i} = (1+\gamma)\,\lambda_{BB}\,(GHG\ RF_{i} + NAA\ RF_{i}) + C_0 + C_1\times SOD_{i-6} + C_2\times TSI_{i-1} + C_3\times ENSO_{i-2} + C_4\times AMOC_{i} - Q_{OCEAN\,i}\ /\ \lambda_P$$

where

λ_{BB} = °C / W m^{-2}

$1+\gamma = \{1 + f_{H2O} + f_{CLOUDS} + f_{SURFACE\ ALB} + f_{LAPSE\ RATE}\}$

NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

AMOC = Atlantic Meridional Overturning Circul.

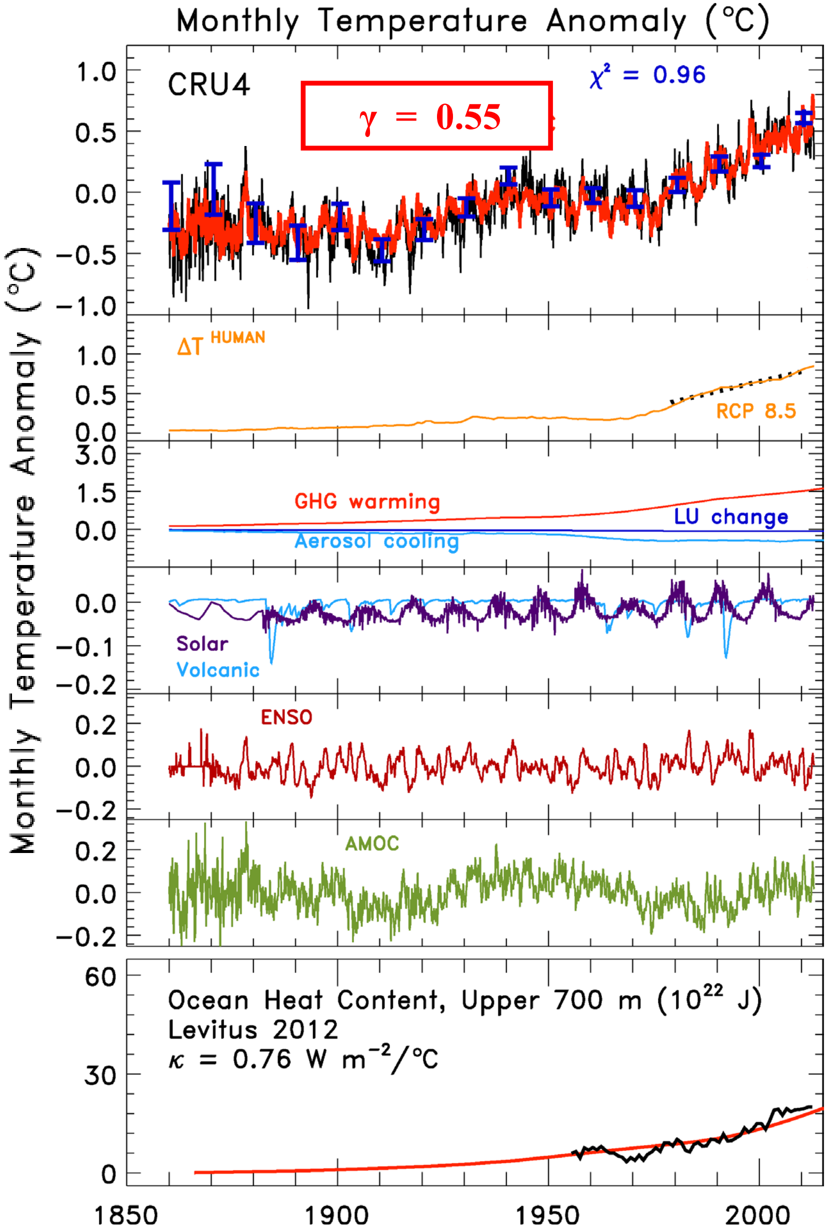
Q_{OCEAN} = Ocean heat export

$= \kappa\,(1+\gamma)\,\{(GHG\ RF_{i-72}) + (NAA\ RF_{i-72})\}$

$NAA\ RF_{2005} = -1.5\ W\ m^{-2}$

If f_{H2O} truly = 1.08, then sum other feedbacks = 0

Mascioli et al., ACPD, 2012; Canty et al., ACP, 2013; Hope et al., in prep, 2015



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

where

$\lambda_{BB} = 0.3\ °\text{C} / \text{W m}^{-2}$

$1+\gamma = \{1 + f_{H2O} + f_{CLOUDS} + f_{SURFACE\ ALB} + f_{LAPSE\ RATE}\}$

NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

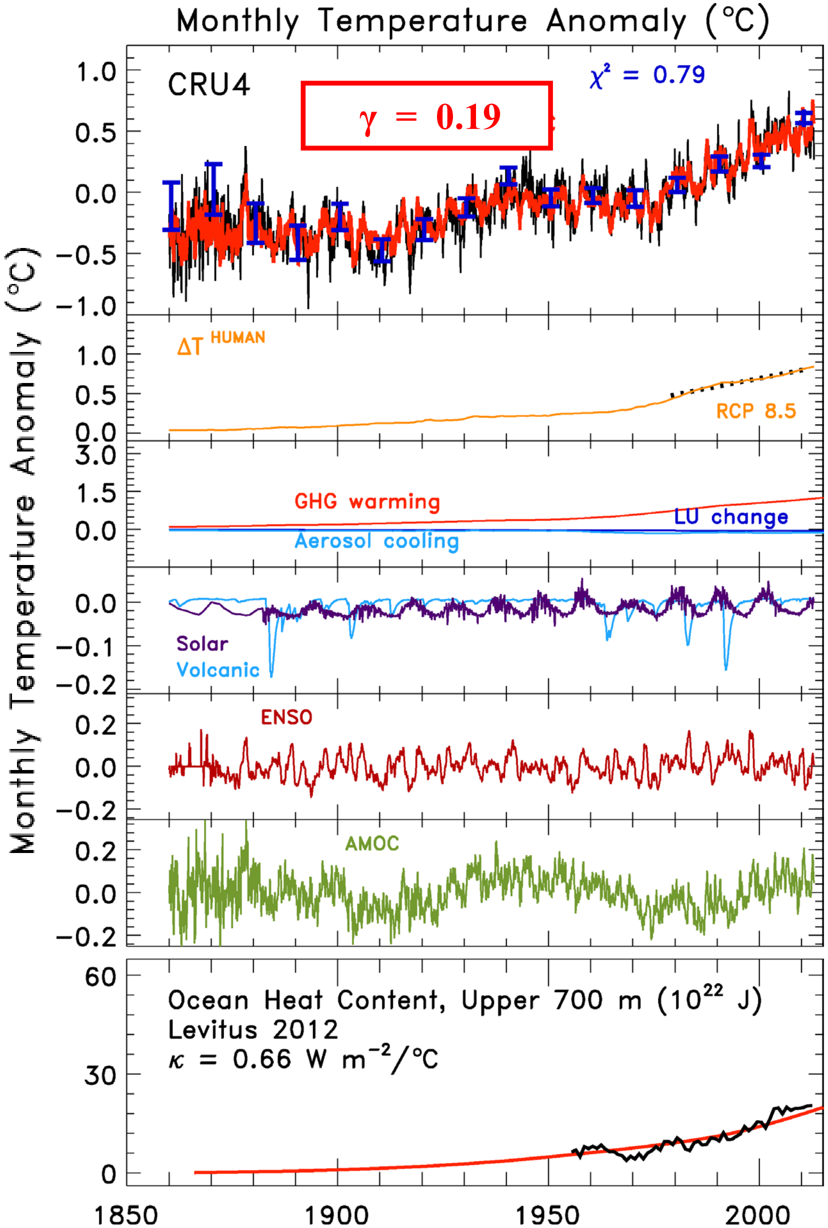
AMOC = Atlantic Meridional Overturning Circul.

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

$\text{NAA RF}_{2005} = -1.0\ \text{W m}^{-2}$

If f_{H2O} truly = 1.08, then sum other feedbacks = –0.53

Mascioli et al., ACPD, 2012; Canty et al., ACP, 2013; Hope et al., in prep, 2015



$$\Delta T_{MDL\,i} = (1+\gamma)\,\lambda_{BB}\,(GHG\ RF_i + NAA\ RF_i) + C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} + C_4 \times AMOC_i - Q_{OCEAN\,i}\ /\ \lambda_P$$

where

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

$1+\gamma = \{\,1 + f_{H2O} + f_{CLOUDS} + f_{SURFACE\ ALB} + f_{LAPSE\ RATE}\}$

NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

AMOC = Atlantic Meridional Overturning Circul.

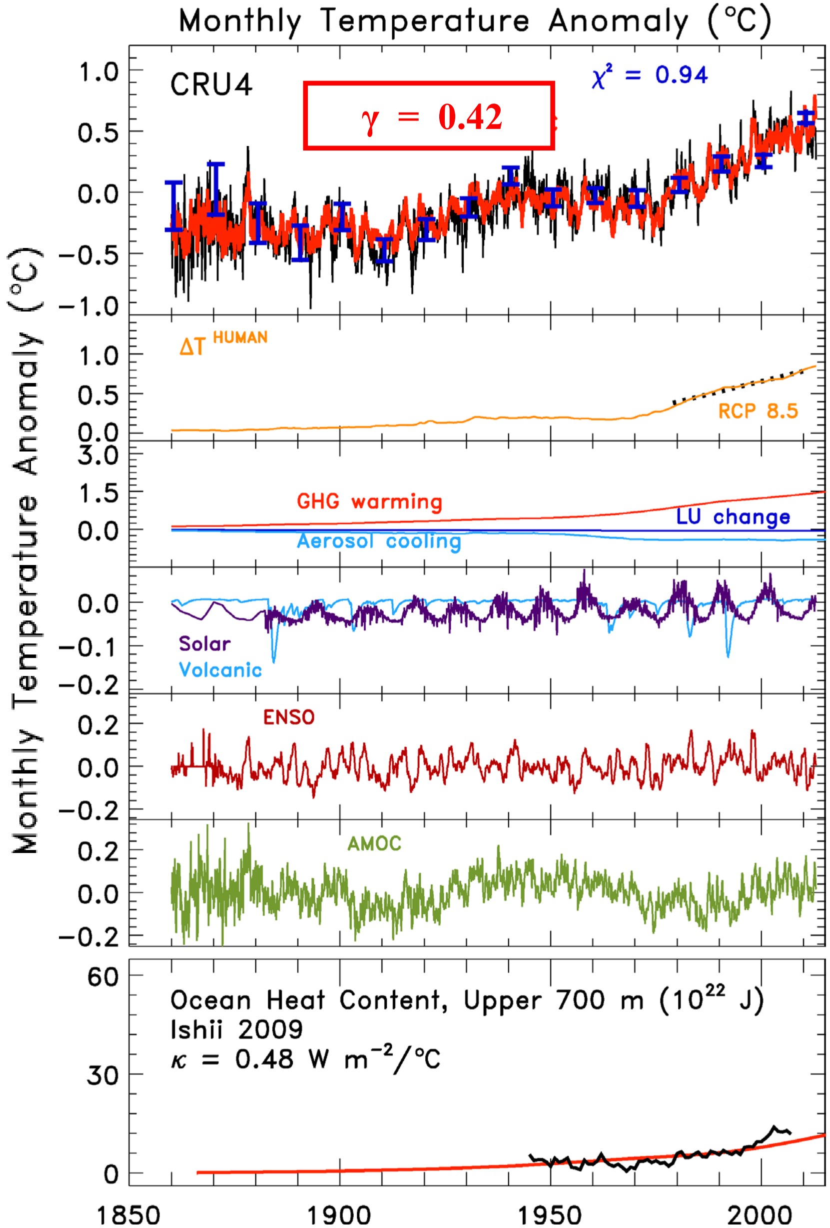
Q_{OCEAN} = **Ocean heat export**

$= \kappa\,(1+\gamma)\,\{(GHG\ RF_{i-72}) + (NAA\ RF_{i-72})\}$

$NAA\ RF_{2005} = -0.4\ W\ m^{-2}$

If f_{H2O} truly = 1.08, then sum other feedbacks = –0.89

Mascioli et al., ACPD, 2012; Canty et al., ACP, 2013; Hope et al., in prep, 2015



$$\Delta T_{MDL\,i} = (1+\gamma)\,\lambda_{BB}\,(GHG\,RF_i + NAA\,RF_i) + $$
$$+ C_o + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2}$$
$$+ C_4 \times AMOC_i - Q_{OCEAN\,i} \;/\; \lambda_P$$

where

$\lambda_{BB} = 0.3\ °C / W\ m^{-2}$

$1+\gamma = \{1 + f_{H2O} + f_{CLOUDS} + f_{SURFACE\ ALB} + f_{LAPSE\ RATE}\}$

NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

AMOC = Atlantic Meridional Overturning Circul.

Q_{OCEAN} = Ocean heat export

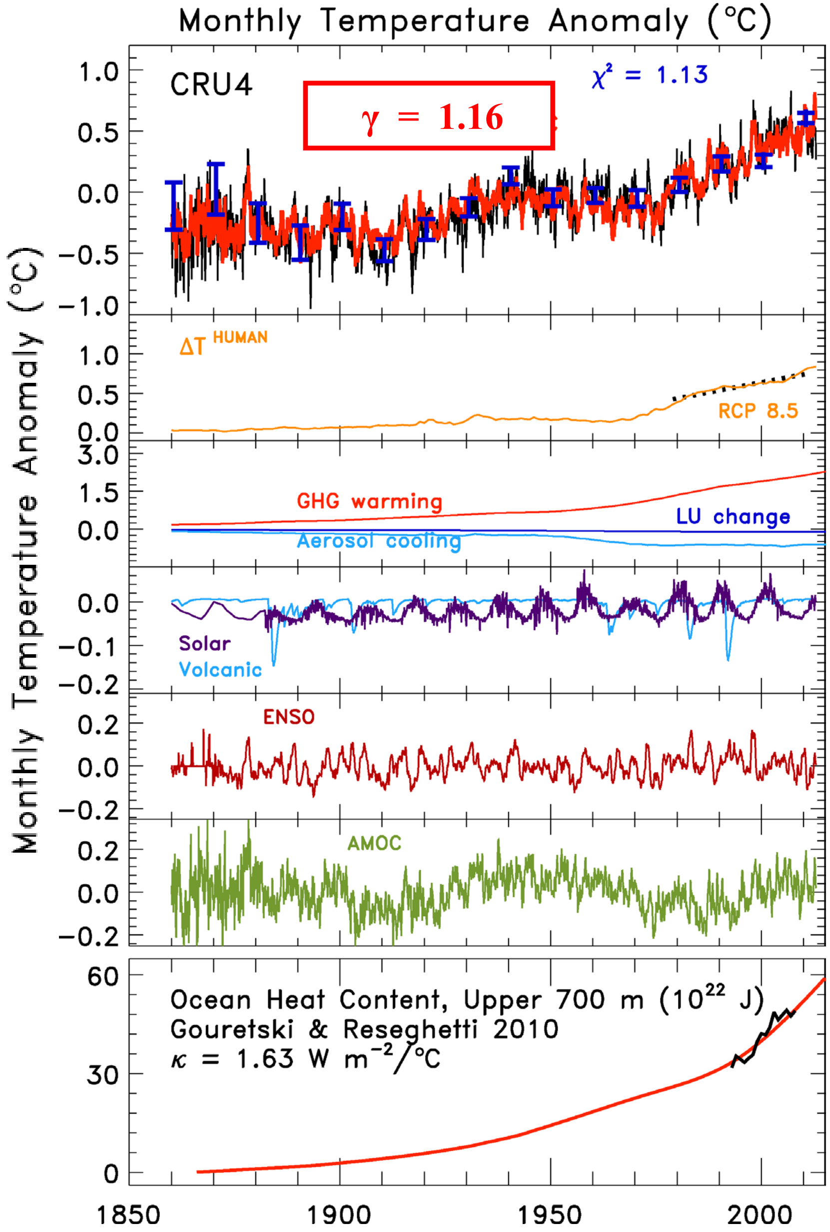
$= \kappa\,(1+\gamma)\,\{(GHG\,RF_{i-72}) + (NAA\,RF_{i-72})\}$

$NAA\ RF_{2005} = -1.0\ W\ m^{-2}$

If f_{H2O} truly = 1.08, then sum other feedbacks = –0.66

OHC Record: Ishii

Mascioli et al., ACPD, 2012; Canty et al., ACP, 2013; Hope et al., in prep, 2015



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

where

$$\lambda_{BB} = 0.3\ ^\circ\text{C} / \text{W m}^{-2}$$

$$1+\gamma = \{1 + f_{H2O} + f_{CLOUDS} + f_{SURFACE\ ALB} + f_{LAPSE\ RATE}\}$$

NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

AMOC = Atlantic Meridional Overturning Circul.

Q_{OCEAN} = Ocean heat export

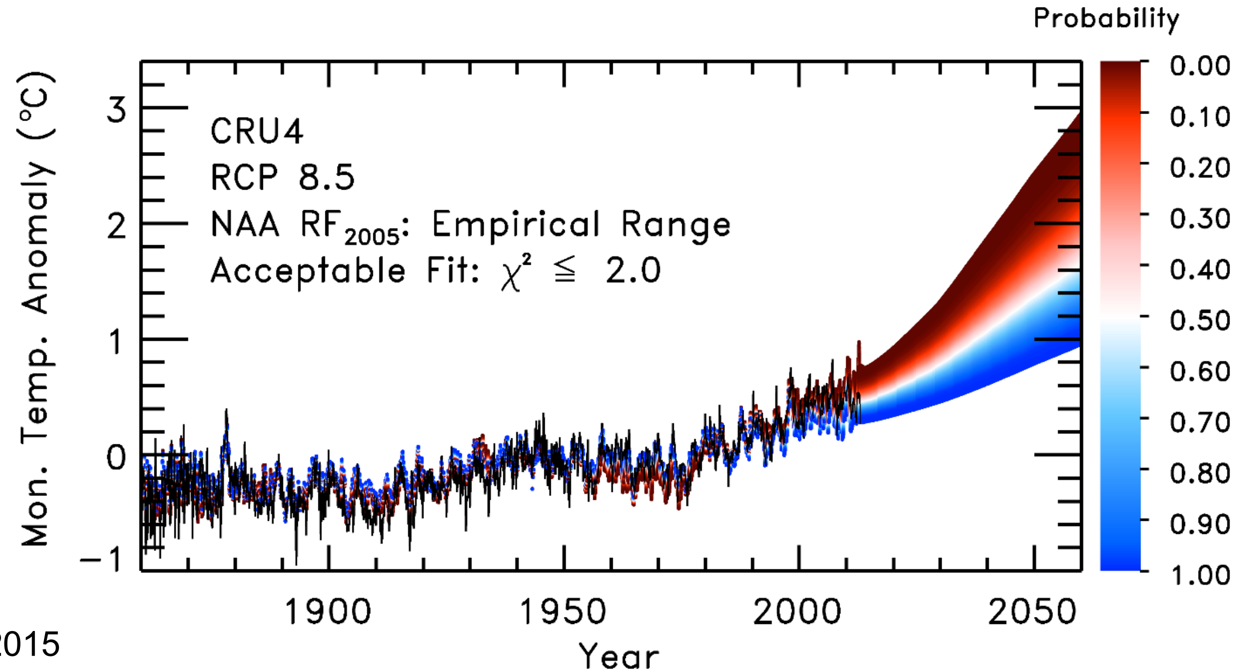
$$= \kappa\,(1+\gamma)\,\{(\text{GHG RF}_{i-72}) + (\text{NAA RF}_{i-72})\}$$

$\text{NAA RF}_{2005} = -1.0\ \text{W m}^{-2}$

If f_{H2O} truly = 1.08, then sum other feedbacks = +0.08

OHC Record: Gouretski and Reseghetti

Mascioli et al., ACPD, 2012; Canty et al., ACP, 2013; Hope et al., in prep, 2015



Hope et al., in prep, 2015

Future warming projected running our model forward in time, for mean TSI as well as neutral ENSO, SOD, and AMOC,
assuming:

a) **whatever value of climate feedback needed to fit past climate (1860 to present) will persist into the future**
b) **we do not now NAA RF_{2005} (or NAA RF_{2010}), so model is run for 100s of thousands of possible values, projections are selected if and only if the past climate record can be simulated reasonably well ($\chi^2 \leq 2$), and projections are weighted by $1/\chi^2$**

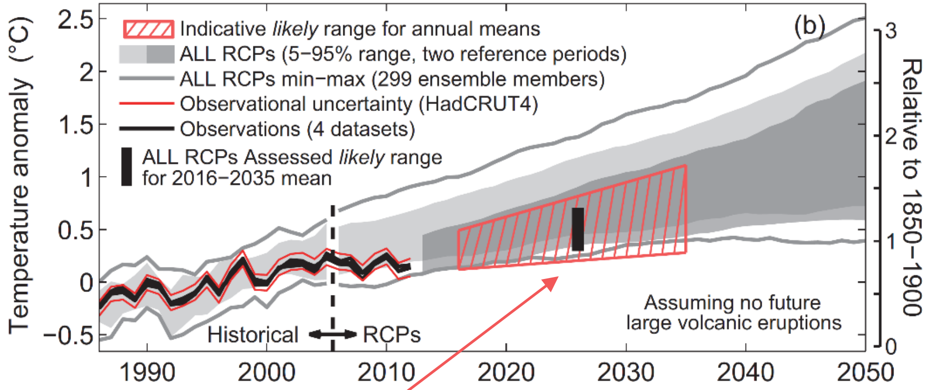
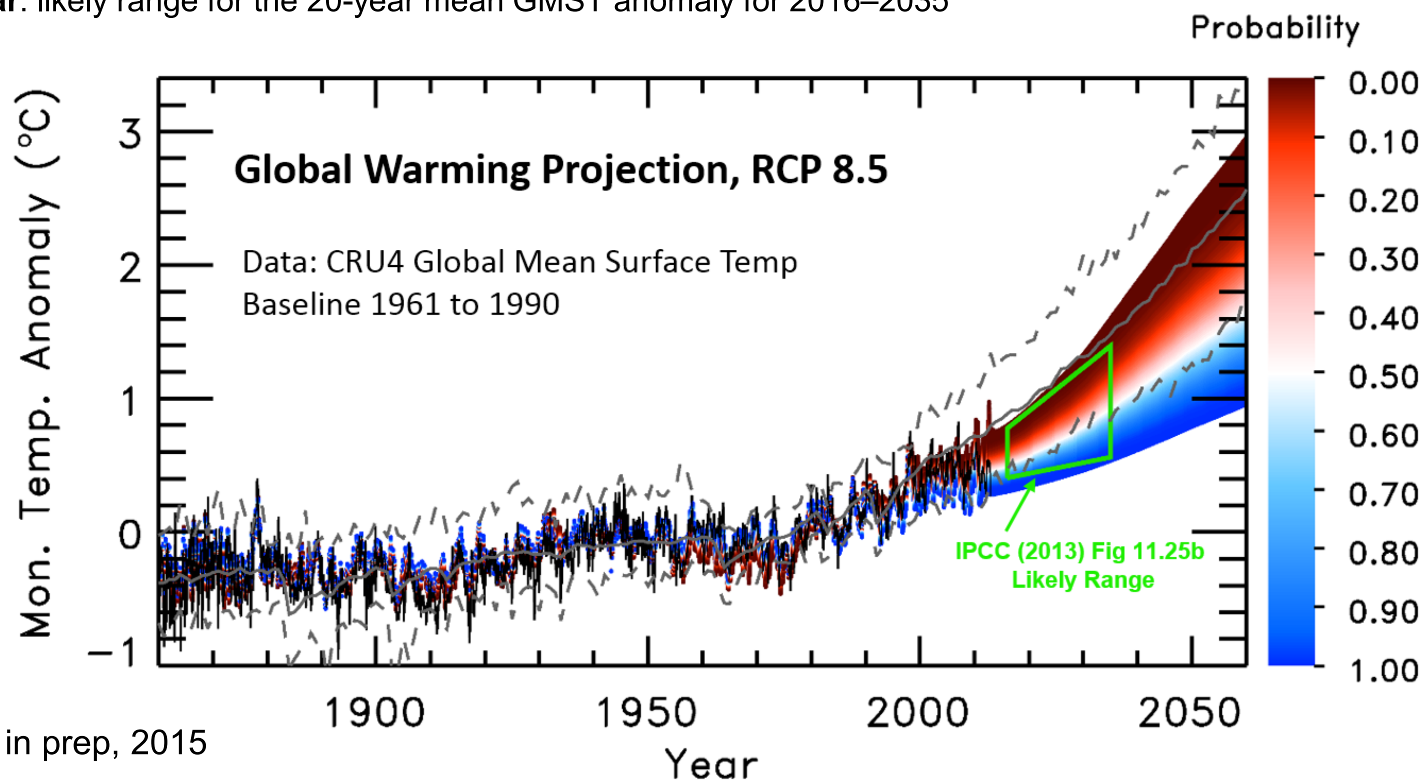


Fig 11.25b, IPCC 2013

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



Hope et al., in prep, 2015

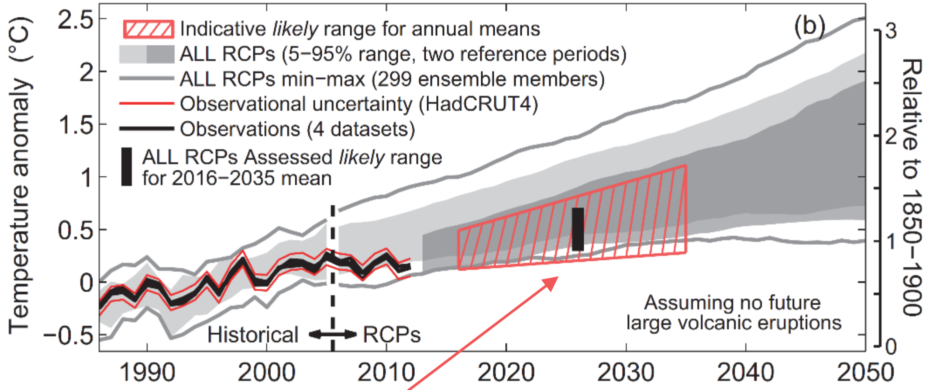
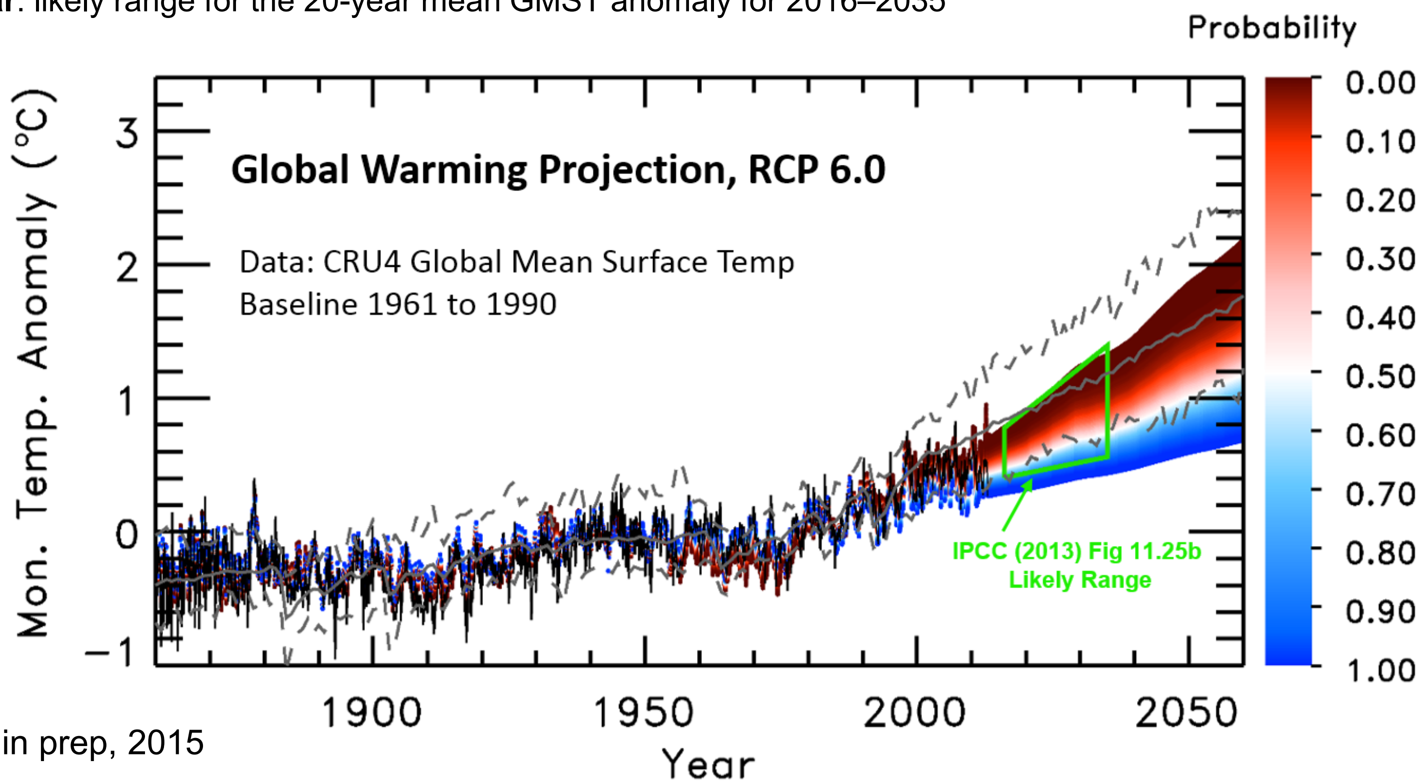


Fig 11.25b, IPCC 2013

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



Hope et al., in prep, 2015

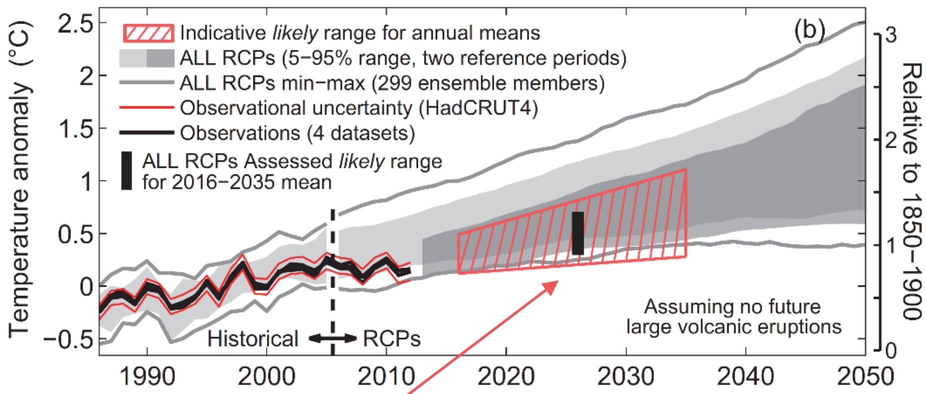
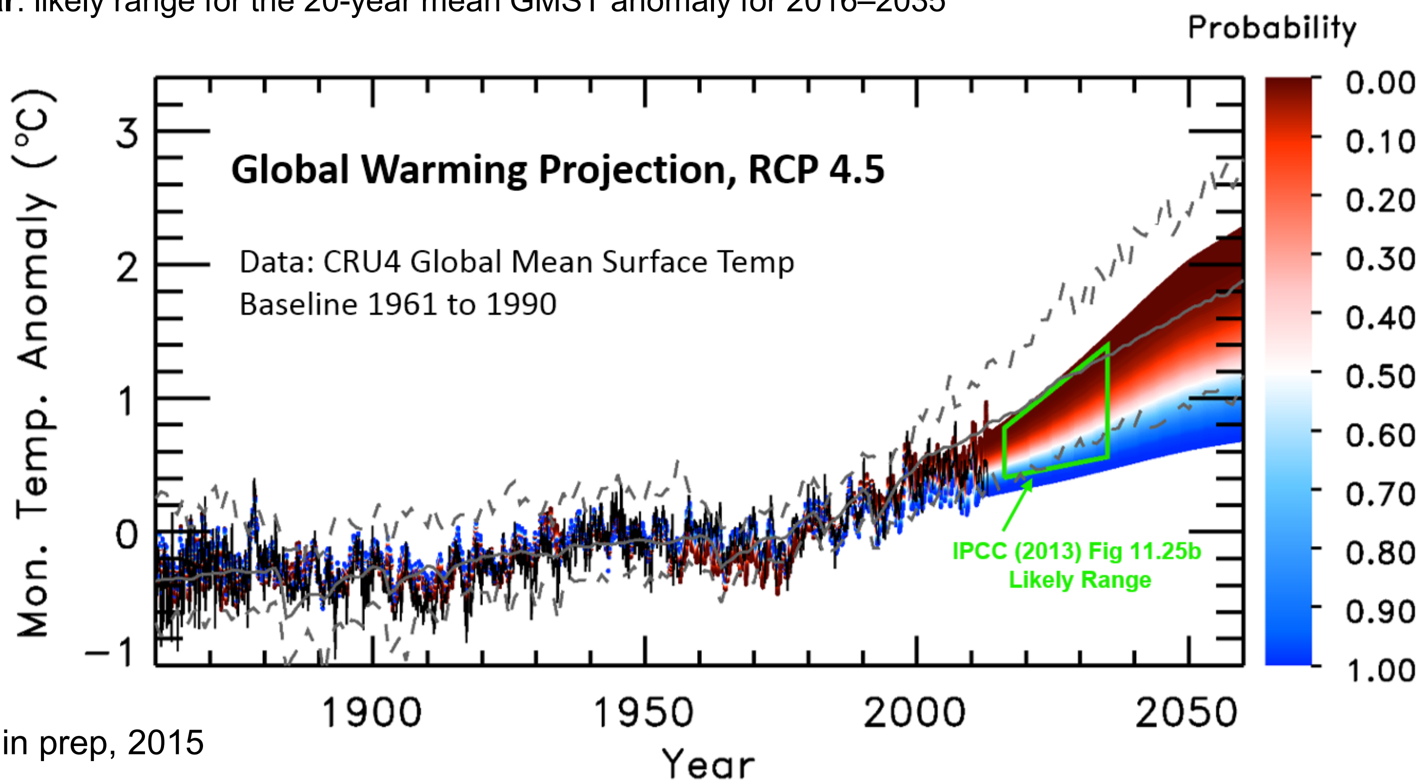


Fig 11.25b, IPCC 2013

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



Hope et al., in prep, 2015

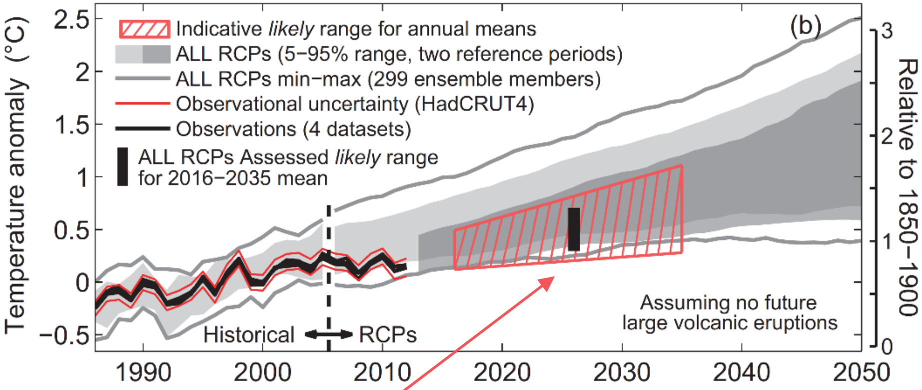
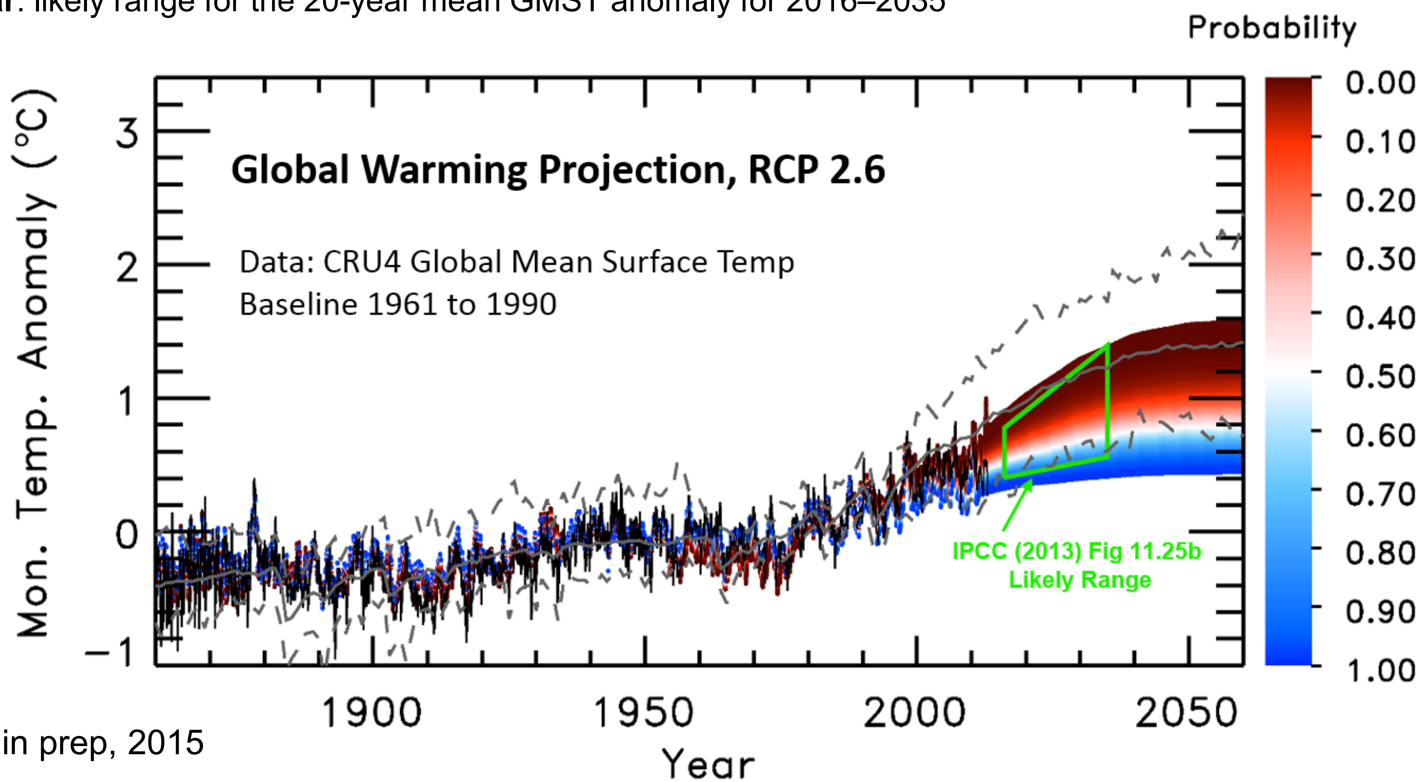


Fig 11.25b, IPCC 2013

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



Hope et al., in prep, 2015