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

Ross Salawitch and Tim Canty

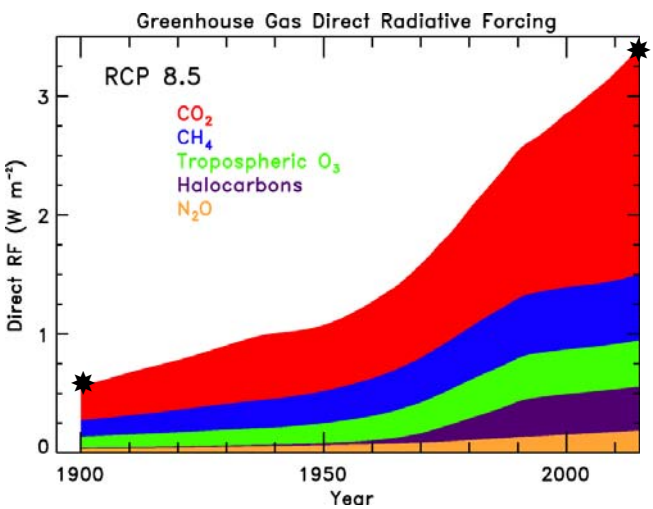
Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2013

1. Feedbacks (internal response) to RF of climate (external forcings) due to anthropogenic GHGs & Aerosols:
   - Water vapor (straight forward & fairly well known)
   - Surface albedo (straight forward but not well known)
   - Clouds (somewhat complicated; not well known)
2. Aerosols RF (very complicated; not well known)
3. An empirical model of climate: using the past to project future

Lecture 08

19 February 2013

Question #3, Problem Set #1



RCP: Representative Concentration Pathways

RF of climate scenarios prepared for next IPCC report

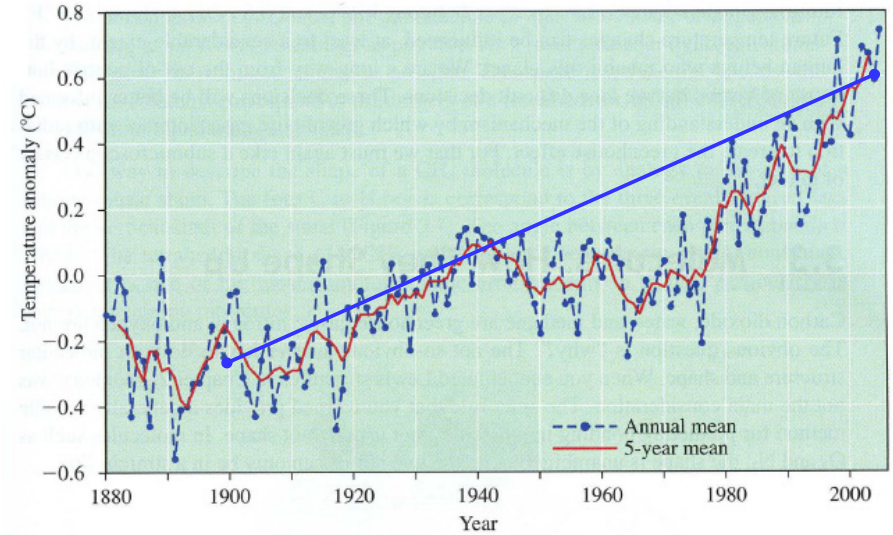
Canty et al., ACPD, 2012

How much would Earth's surface temperature have risen, from 1900 to present, in response to this radiative forcing?

$\Delta RF_{1900 \text{ to present}} =$

$\Delta T_{EXPECTED} =$

Question #3, Problem Set #1



How much would Earth's surface temperature have risen, from 1900 to present, in response to this radiative forcing?

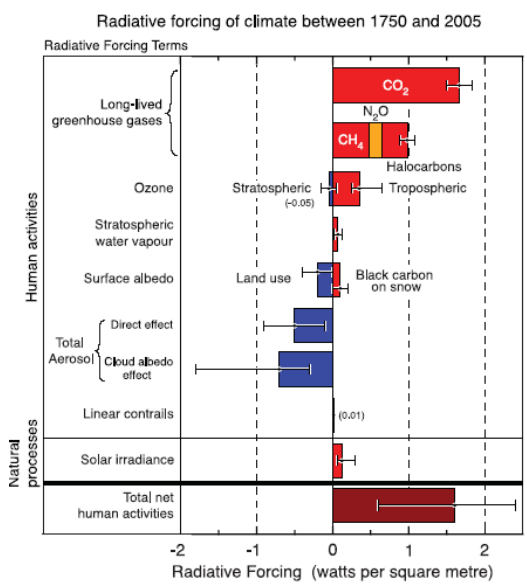
$\Delta RF_{1900\ \text{to present}}$ =

$\Delta T_{\text{EXPECTED}}$ =

ΔT_{ACTUAL} =

Figure 3.6, Chemistry in Context (Reading for Lecture 4)

Similar info in Fig 4.1, Houghton, also assigned for Lecture 4



Question 2.1, IPCC, 2007

Slide 5, Lecture 2 and many other slides in numerous lectures ☺

How much would Earth's surface temperature have risen, from 1900 to present, in response to this radiative forcing?

$\Delta RF_{1900\ \text{to present}} = 3.38\ \text{W m}^{-2} - 0.62\ \text{W m}^{-2} = 2.76\ \text{W m}^{-2}$

$\Delta T_{\text{EXPECTED}} = 0.56\ \text{K} / (\text{W m}^{-2}) \times 2.76\ \text{W m}^{-2} = 1.55\ \text{K}$

$\Delta T_{\text{ACTUAL}} = \sim 0.8\ \text{K}$

Difference is nearly a factor of two: this is significant!

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:

$$\lambda \approx 0.56\ K\ /\ W\ m^{-2},\ \text{from which we deduce}\ f_{H2O} = 0.87$$

Water Vapor Feedback

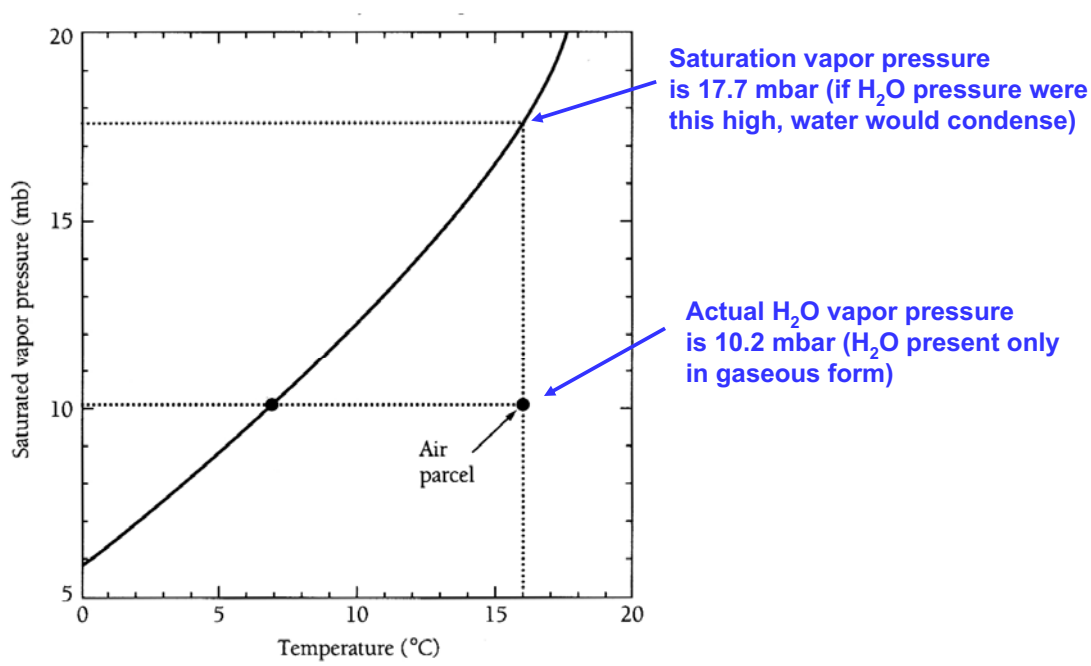


Figure 4.8a Relative humidity and the dew point.

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
- No *observational evidence* for **negative** water vapor feedback, despite the very provocative (and, in our opinion, very important!) work of Linzden (BAMS, 1990) that suggested the feedback could be **negative**

Water Vapor Feedback

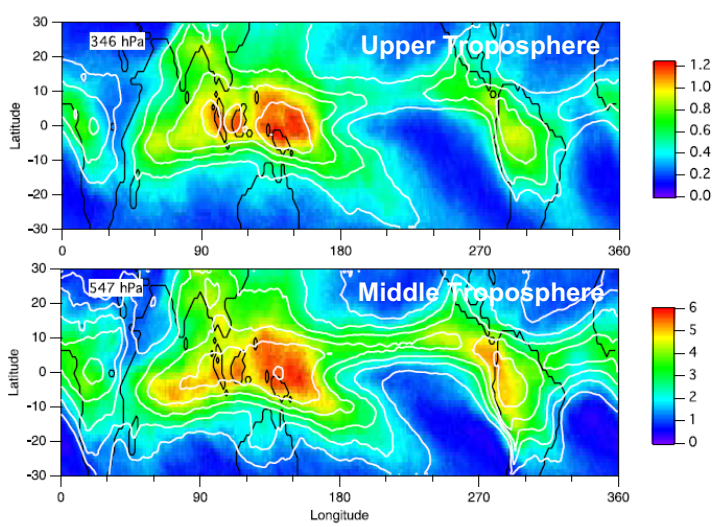
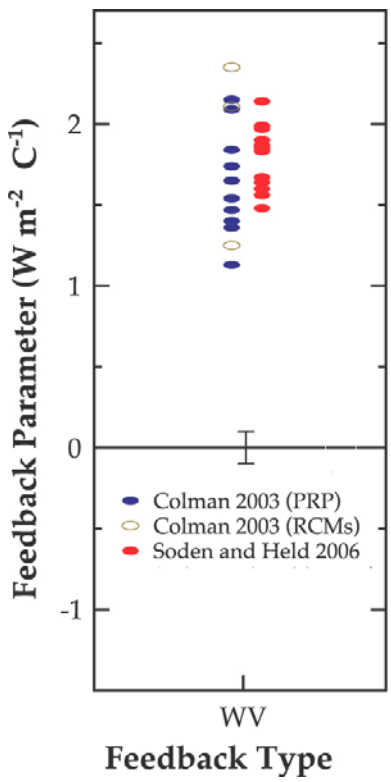


Figure 1. Model-simulated H_2O mixing ratio (g/kg) at 346 hPa (top) and 547 hPa (bottom), averaged from 1 March 2003 to 28 Feb. 2004. White contours are contours of AIRS-measured H_2O in the 400- to 300-hPa layer (top) and the 600- to 500-hPa layer (bottom). In the top plot, the outer contour is 0.4 g/kg and the interval is 0.15 g/kg; in the bottom plot, the outer contour is 1.5 g/kg and the interval is 0.625 g/kg.

Claim: large scale H_2O field can be simulated well by a model that contains no microphysics other than the requirement that water vapor is immediately removed to prevent RH from ever exceeding 100%

Dessler and Minschwaner, *JGR*, 2007

Water Vapor Feedback



IPCC Fig 8.14

IPCC Feedback Parameter, WV : water vapor

λ_{IPCC} = 1.8 ± 0.18 W m^{-2}/ °C

λ_{CLASS} = **0.56 ± 0.06 K / (W m^{-2})**

Slide 30, Lecture 4

ATMOSPHERIC SCIENCE

A Matter of Humidity

Andrew E. Dessler[1] and Steven C. Sherwood[2]

Thus, although there continues to be some uncertainty about its exact magnitude, the water vapor feedback is virtually certain to be strongly positive, with most evidence supporting a magnitude of 1.5 to 2.0 W/m^2/K, sufficient to roughly double the warming that would otherwise occur. To date, observational but evidence for the water vapor feedback—and the large future climate warming it implies—is now strong.

20 FEBRUARY 2009 VOL 323 SCIENCE

Slightly More Complicated Climate Model

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

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

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**

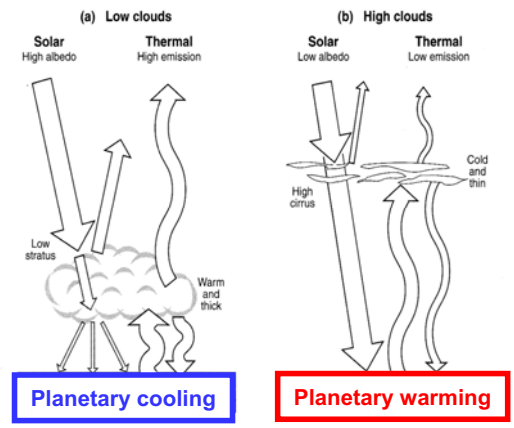


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The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

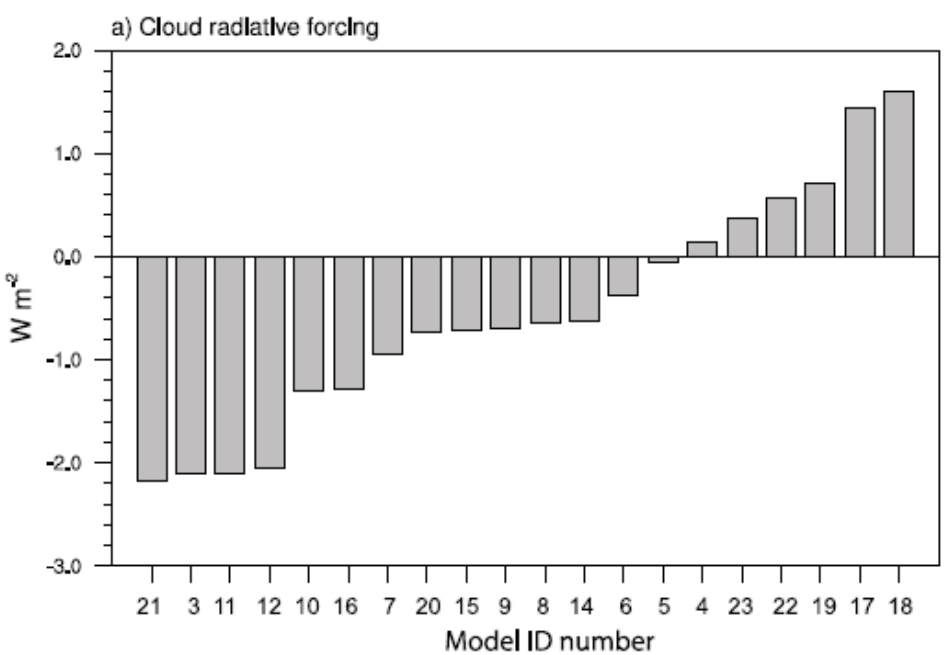


Figure 10.11. *Changes in (a) global mean cloud radiative forcing (W m^{-2}) from individual models (see Table 10.4 for the list of models)*

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

IPCC 2007, Chapter 10

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

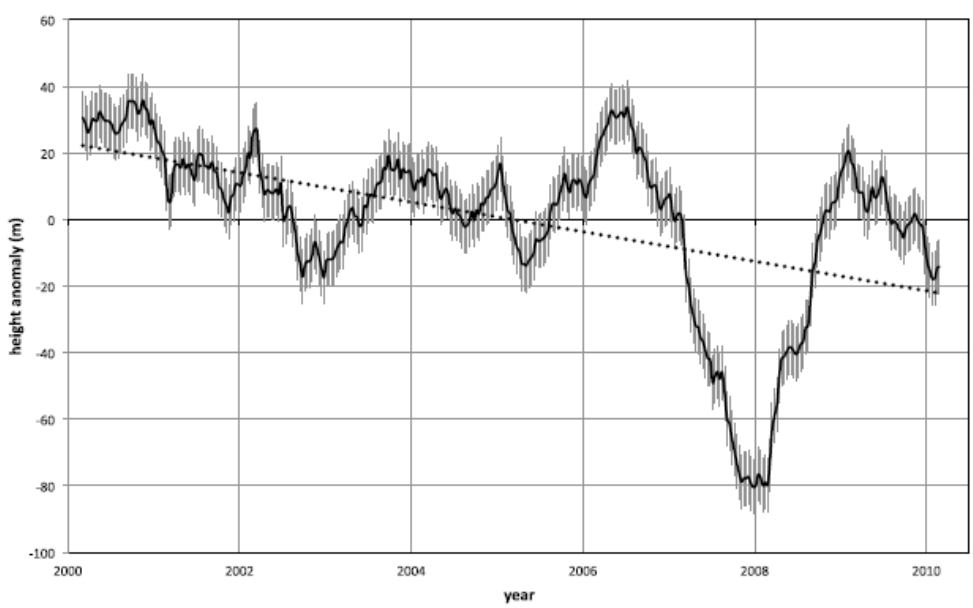


Figure 1. Deseasonalized anomalies of global effective cloud-top height from the 10-year mean. Solid line: 12-month running mean of 10-day anomalies. Dotted line: linear regression. Gray error bars indicate the sampling error (±8 m) in the annual average.

Davies and Molloy, GRL, 2012

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

Ice-Albedo Feedback

Initial Action:
Humans Release CO_2

→ Initial Response:
$T_{SURFACE}$ Rises

↓ Then:
Ice Melts

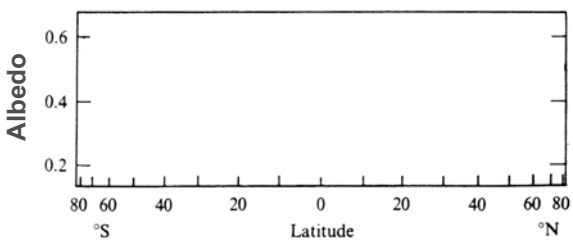
↓ Consequence:
Albedo Falls

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

2. Albedos of selected surfaces on Earth

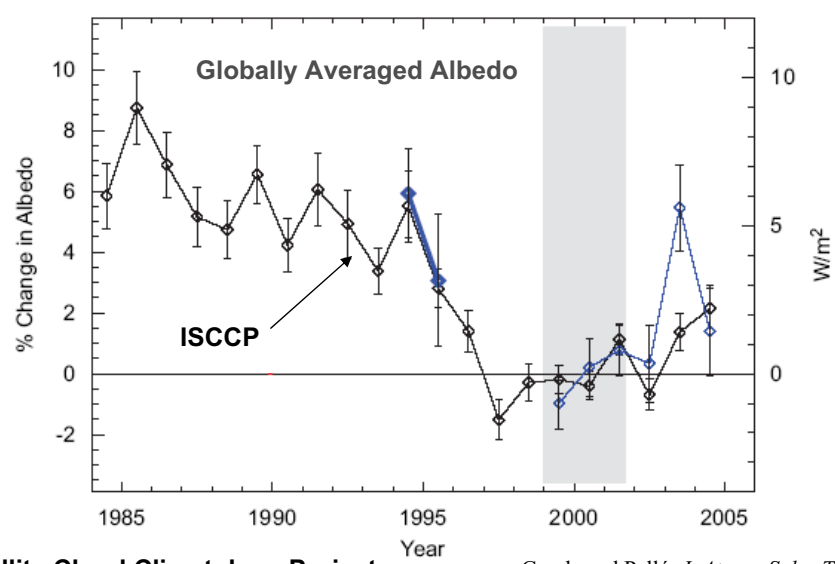
surface	albedo
snow	0.7 ± 0.2
sand	0.25 ± 0.05
grasslands	0.23 ± 0.03
bare soil	0.2 ± 0.05
forest	0.15 ± 0.1
water (highly dependent on surface roughness and incident angle of sunlight)	0.2 + 0.6 − 0.2

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



Houghton, *The Physics of Atmospheres*, 1991.

Surface Albedo: Observation A



ISCCP: Int'l Satellite Cloud Climatology Project
Earthshine: Observations of the moon

Goode and Pallé, *J. Atmos. Solar Terrestrial Physics*, 2007

Data suggest: a) major decrease in global albedo, 1985 to ~1999
b) slight increase in global albedo, 1999 to 2005

$$\Delta F_{1985 \text{ to } 1999} = 0.06 \times 0.3 \times 1370 \text{ W m}^{-2} / 4 \approx 6 \text{ W m}^{-2}$$

What is sign of change?

Does this forcing heat or cool the surface?

Surface Albedo: Synthesis

Charlson, Valero, Seinfeld, *Science*, 2005.

LARGE INCONSISTENCIES

Climatic observations and forcings	Equivalent change in albedo × 10^3
Enhanced greenhouse effect during industrial era (2.4 ± 0.2 W/m^2) (*6*)	−7 ± 0.6
Anthropogenic aerosol forcing during industrial era (*6*)	+4 ± 4
Albedo change estimated from earthshine data (2000 to 2004) (2, *8*, *9*)	+16
Albedo change estimated from low-orbit satellite data (2000 to 2004) (*2*)	−6
Change in irradiance at Earth's surface measured with satellites (1983 to 2001) (*3*)	−8
Change in irradiance at Earth's surface measured at the surface (1985 to 2000) [Fig. 1 in (*4*)]	−13
Change in irradiance at Earth's surface measured at the surface (1950 to 1990) [Fig. 1 in (*4*)]	+20

ΔF_{GHG} = 2.4 W/m^2

To compensate for this ΔF by simply changing albedo:

S = 1370 W/m^2 / 4 = 342.4 W/m^2

2.4 W/m^2/ 342.4 W/m^2 = 0.007 or 7 × 10^{-3}

That is, an albedo *decrease* of 7 × 10^{-3} would have the same surface ΔF as the perturbation caused by rising GHGs

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, among other things, 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**

$C_{135}H_{96}O_9NS$ is canonical formula for coal given on pg 252 of Chemistry in Context

Aerosol Indirect Effect: Effect of Aerosols on Clouds

Clouds are difficult to simulate properly in climate models

- **microphysics occurs on small spatial and short temporal scales**
- **effects of aerosols on clouds subject of concerted research effort**

Aerosols determine which scenario is followed

Scenario I

- **all aerosols become CCN**
  many small water droplets
- **drops not large enough to rain**
  persistent cloud cover
- **greater cooling than Sc II**
  (provided low altitude clouds)
  (see slide 26)

Scenario II

- **few aerosols become CCN**
  some large drops
- **drops rain out**
  brief cloud cover
- **less cooling than Sc I**
  (provided low altitude clouds)
  (see slide 26)

CCN: cloud condensation nuclei; aerosols that nucleate water vapor

Radiative Properties of Aerosols

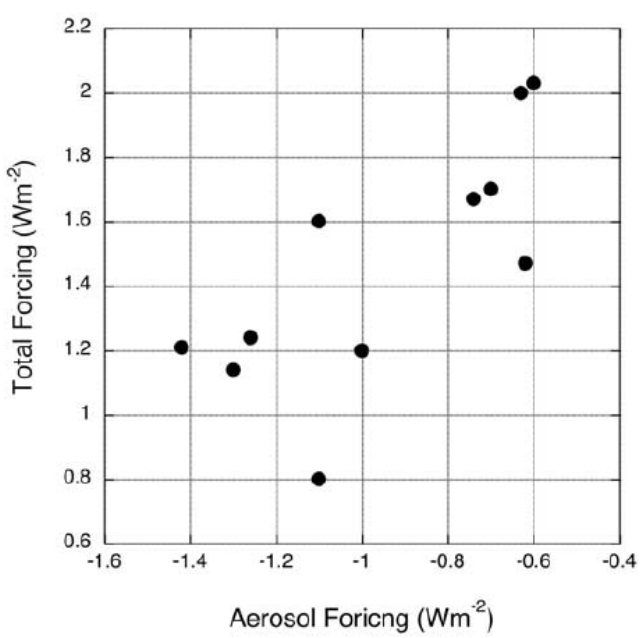


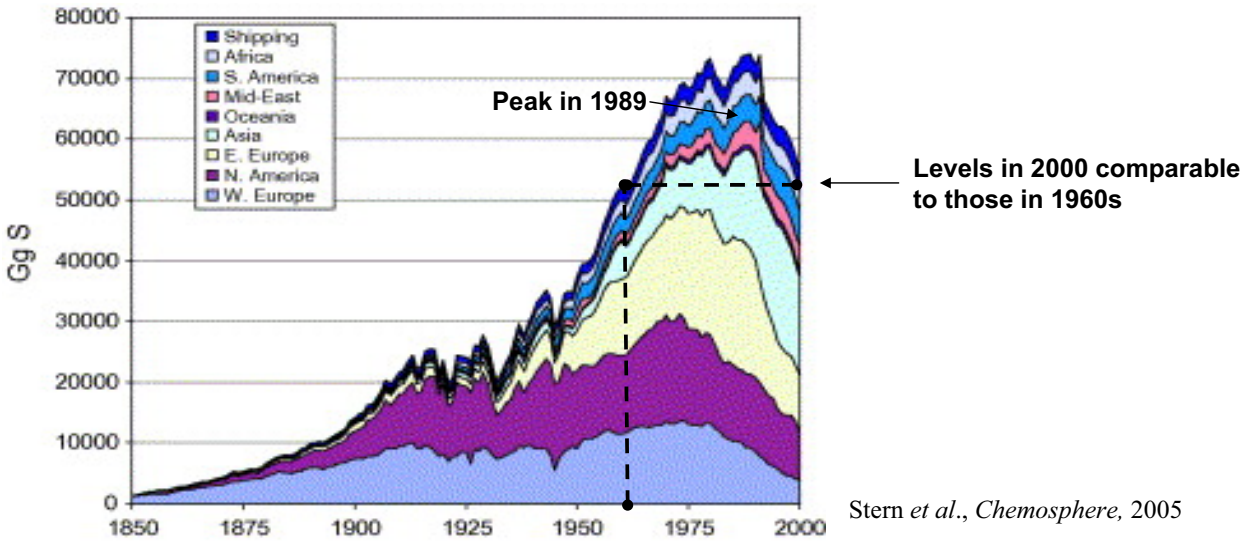
Figure 2. Total anthropogenic forcing (Wm^{-2}) versus aerosol forcing (Wm^{-2}) from nine fully coupled climate models and two energy balance models used to simulate the 20th century.

Kiehl, *Geophysical Research Letters, 2007*

Global effect of aerosols over 20th Century believed to be cooling

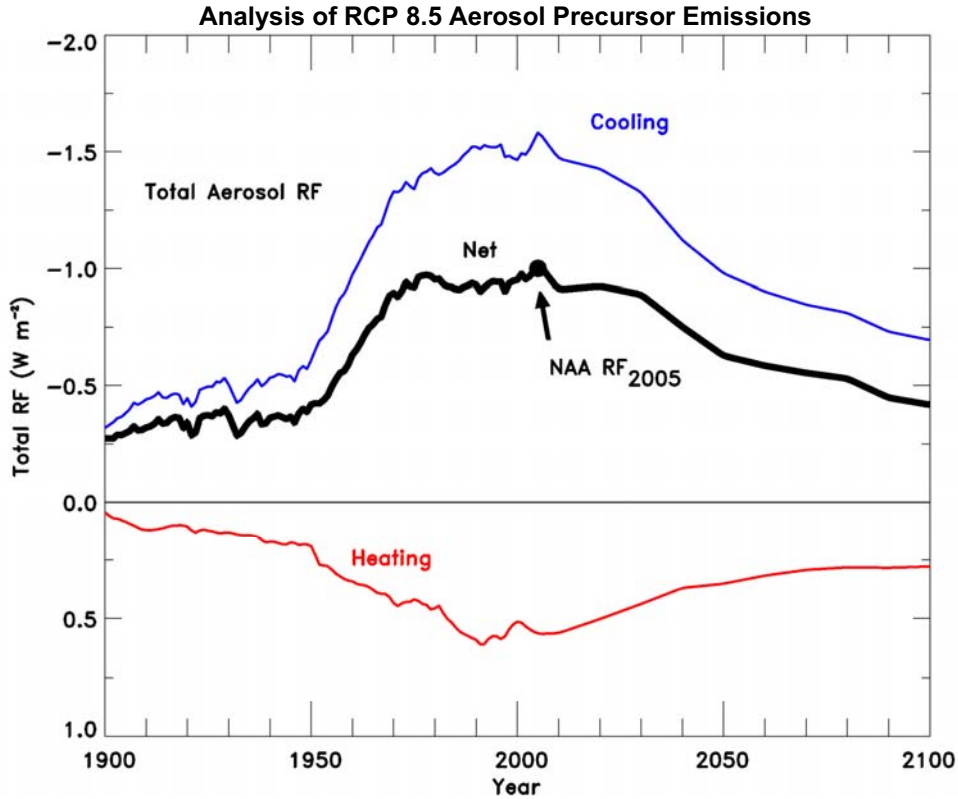
- **magnitude very uncertain**
- **representation in climate models varies by a factor of 3 (Slide 29, Lecture 7)**

Aerosol Loading vs Time, Historical



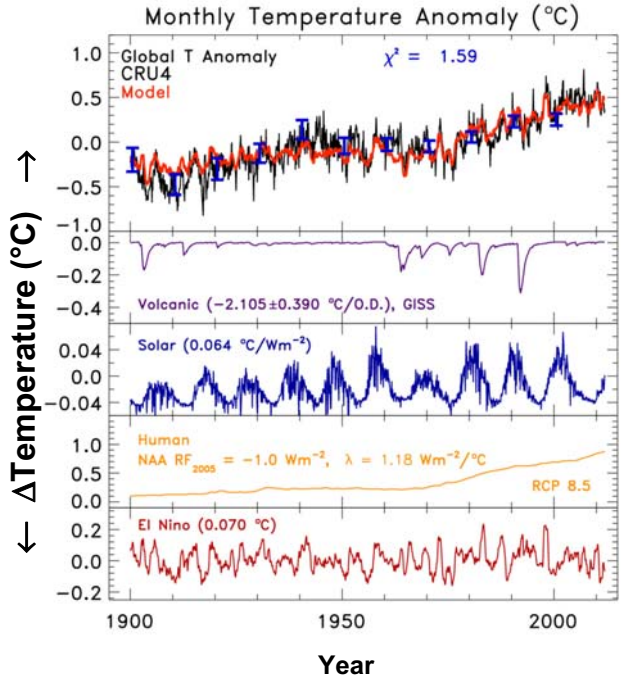
Stern *et al*., *Chemosphere,* 2005

Aerosol Loading vs Time, Future



Mascioli et al., ACPD 2012

Global Average Temperature: Multiple Linear Regression



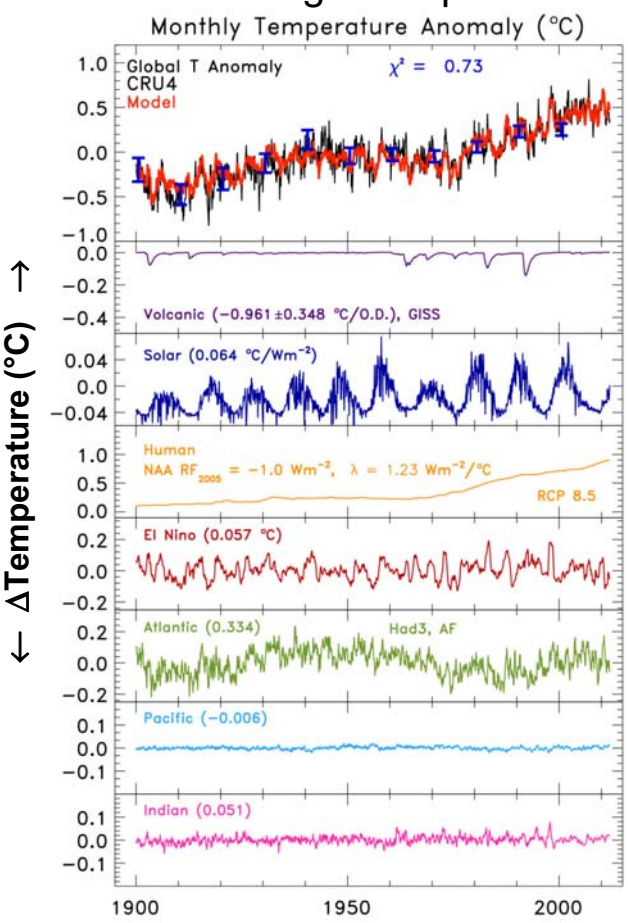
$$\Delta T_{\mathrm{MDL}\ i} = \frac{1+\gamma}{\lambda_p}\{(\mathrm{GHG\ RF}_i) + \mathrm{NAA\ RF}_i)\} + C_o + C_1 \times \mathrm{SOD}_{i-6} + C_2 \times \mathrm{TSI}_{i-1} + C_3 \times \mathrm{ENSO}_{i-2} + \frac{Q_{\mathrm{OCEAN}\ i}}{\lambda_p}$$

SOD: Stratospheric Optical Depth (major volcanoes)
TSI: Total solar irradiance (11 year solar cycle)
ENSO: El Niño Southern Oscillation

Q_{OCEAN}: Flow of heat to ocean

Canty, Mascioli, Smarte, and Salawitch
ACPD 2012
http://www.atmos-chem-phys-discuss.net/12/23829/2012/acpd-12-23829-2012.html

Global Average Temperature: Multiple Linear Regression



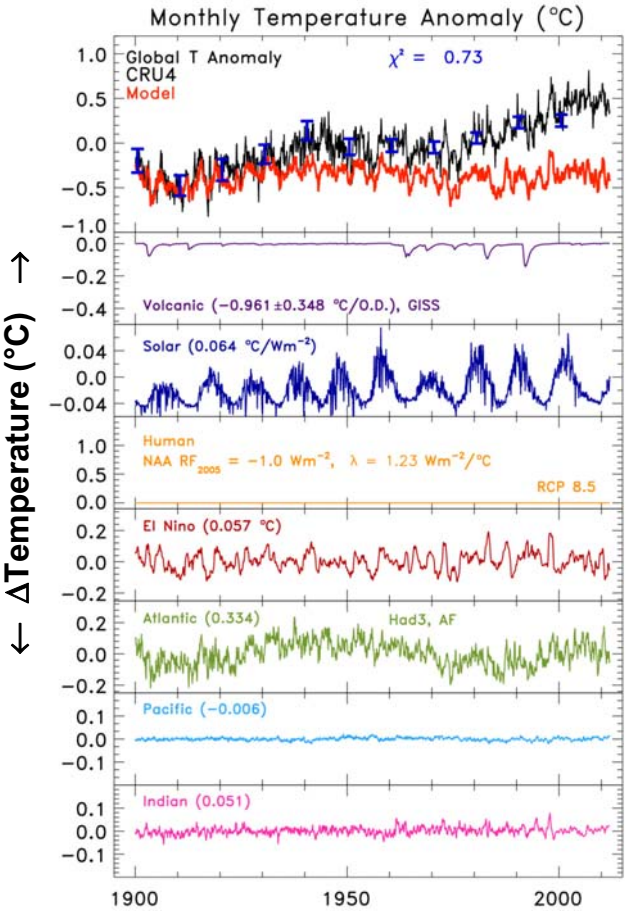
$$\Delta T_{\mathrm{MDL}\ i} = \frac{1+\gamma}{\lambda_p}\{(\mathrm{GHG\ RF}_i) + \mathrm{NAA\ RF}_i)\} + C_o + C_1 \times \mathrm{SOD}_{i-6} + C_2 \times \mathrm{TSI}_{i-1} + C_3 \times \mathrm{ENSO}_{i-2} + \boxed{C_4 \times \mathrm{AMO}_i} + C_5 \times \mathrm{PDO}_i + C_6 \times \mathrm{IOD}_i - \frac{Q_{\mathrm{OCEAN}\ i}}{\lambda_p}$$

AMO: Index of Sea Surface Temperature in the North Atlantic, termed the Atlantic Multidecadal Oscillation & aka Atlantic Multidecadal Variability, that may serve as a valid proxy for variations in the strength of the ocean thermohaline circulation

See for instance Srokosz et al., BAMS, 2012:
http://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-11-00151.1

Canty et al.,ACPD 2012

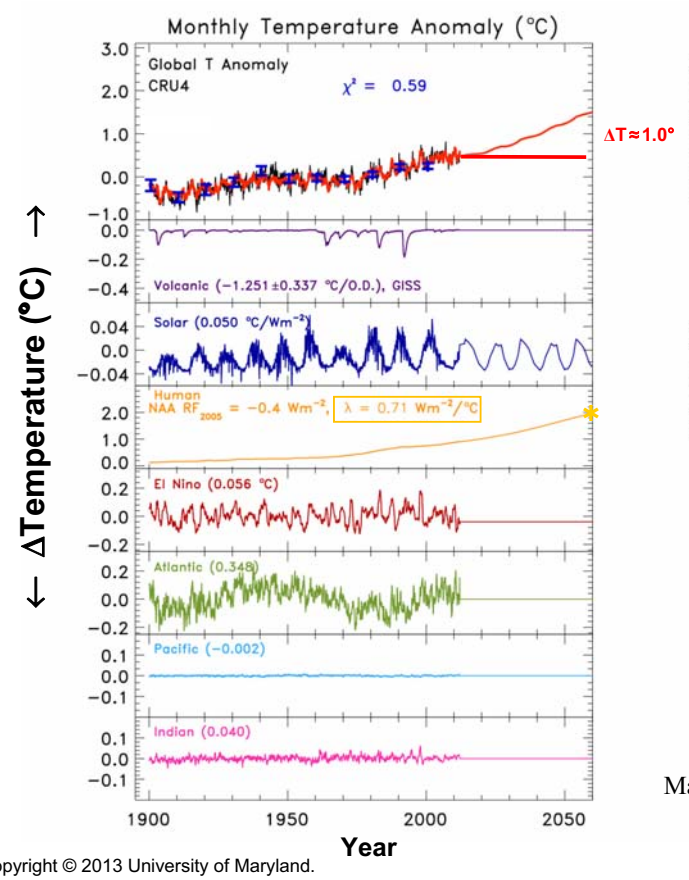
Global Average Temperature: Multiple Linear Regression



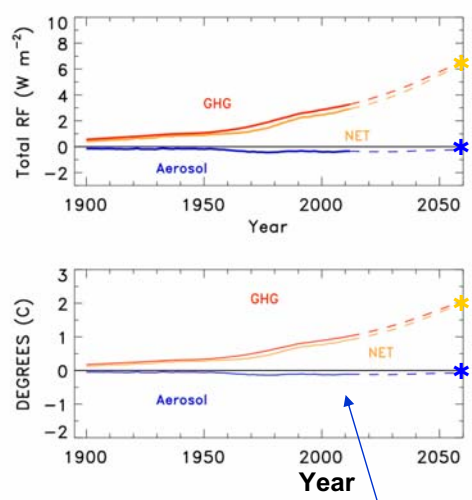
$$\Delta T_{\mathrm{MDL}\ i} = \frac{1+\gamma}{\lambda_p}\{(\mathrm{GHG\ RF}_i) + \mathrm{NAA\ RF}_i)\} + C_o + C_1 \times \mathrm{SOD}_{i-6} + C_2 \times \mathrm{TSI}_{i-1} + C_3 \times \mathrm{ENSO}_{i-2} + C_4 \times \mathrm{AMO}_i + C_5 \times \mathrm{PDO}_i + C_6 \times \mathrm{IOD}_i - \frac{Q_{\mathrm{OCEAN}\ i}}{\lambda_p}$$

Canty et al.,ACPD 2012

Much harder to predict future than understand the past !



Human Forcing = GHG + Aerosol Forcing

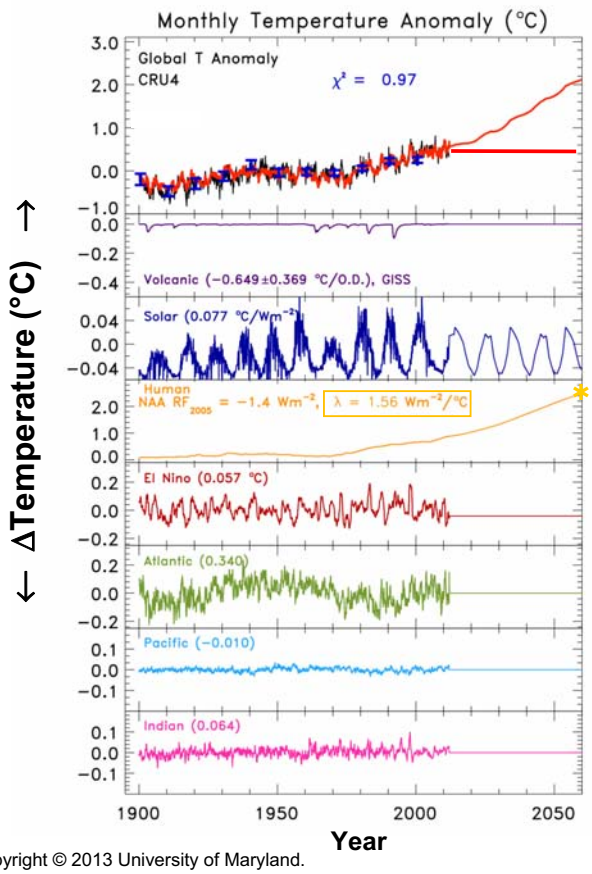


Scenario 1 :
Aerosols have weak net cooling. If so, future clean up doesn't matter much for climate, but matters a lot for air quality!

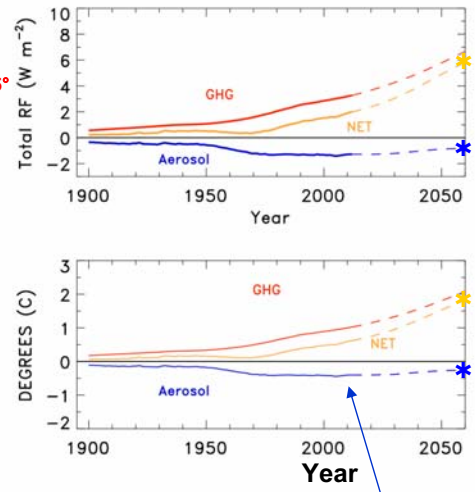
Mascioli et al., ACPD 2012

Much harder to predict future than understand the past !

Human Forcing = GHG + Aerosol Forcing



ΔT≈1.65°

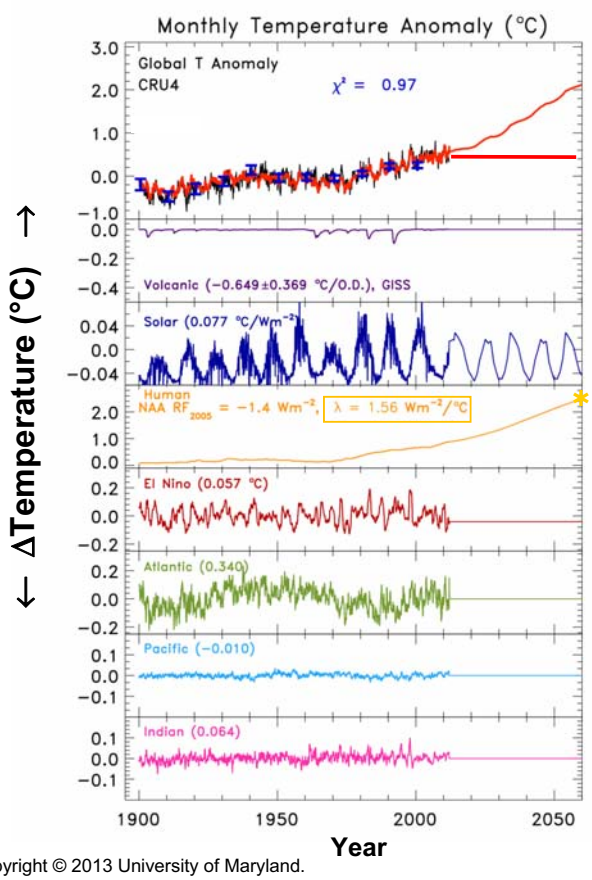


Scenario 2 :
Aerosols have strong net cooling & there will be a concerted effort for future clean up !

Mascioli et al., ACPD 2012

Much harder to predict future than understand the past !

Human Forcing = GHG + Aerosol Forcing



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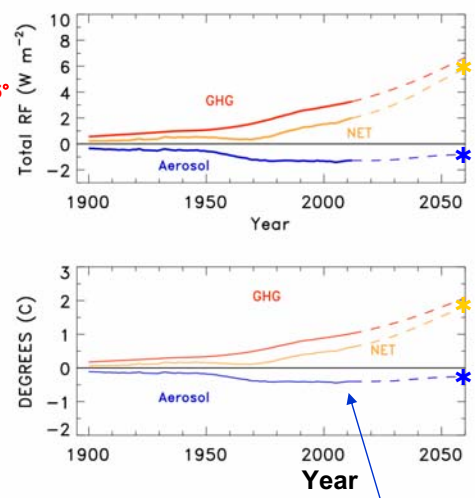
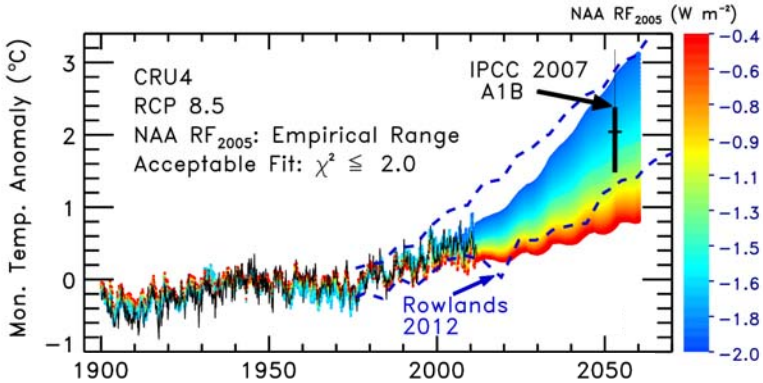


Scenario 2 :
Aerosols have strong net cooling & there will be a concerted effort for future clean up !

This will "unleash" GHG warming

Mascioli et al., ACPD 2012

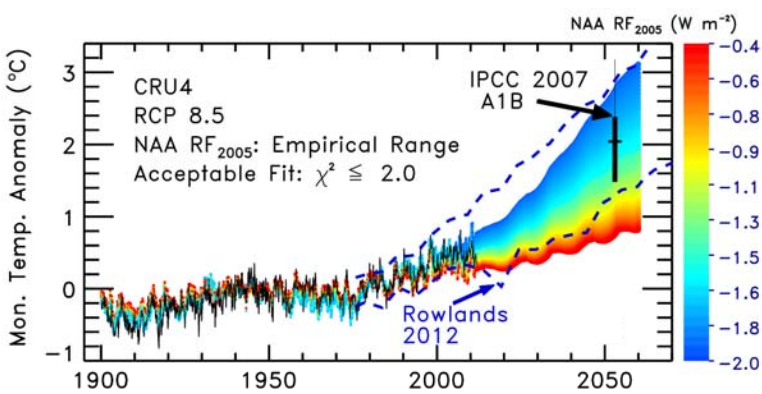
Much harder to predict future than understand the past !



Mascioli et al., ACPD 2012

If we could better quantify NAA RF (net anthropogenic aerosol RF) for contemporary atmosphere, we would gain a handle on magnitude of future warming !

Much harder to predict future than understand the past !



Mascioli et al., ACPD 2012