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

Question #3, Problem Set #1

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

\[ \Delta RF_{1900 \text{ to present}} = \]

\[ \Delta T_{\text{EXPECTED}} = \]
How much would Earth’s surface temperature have risen, from 1900 to present, in response to this radiative forcing?

\[ \Delta R_{F \text{ 1900 to present}} = 3.38 \text{ W m}^{-2} - 0.62 \text{ W m}^{-2} = 2.76 \text{ W m}^{-2} \]

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

\[ \Delta T_{\text{ACTUAL}} = \sim 0.8 \text{ K} \]

**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

\[
\lambda_{BB} = 0.3 \text{ K} / \text{ W m}^{-2}
\]

Climate models that consider water vapor feedback find:

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

Water Vapor Feedback

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$_2$O obtained with a broadband radiometer (TOVS) and concluded the atmosphere generally obeys fixed relative humidity: strong positive feedback
  $\Rightarrow$ data have extensive temporal and spatial coverage but limited vertical resolution.

• Minschwaner et al. (JGR, 2006) analyzed global measurements of H$_2$O 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
  $\Rightarrow$ 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

---

**Claim:** large scale H$_2$O 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 Feedback Parameter, WV : water vapor

\[ \lambda_{\text{IPCC}} = 1.8 \pm 0.18 \text{ W m}^{-2}/^\circ\text{C} \]

\[ \lambda_{\text{CLASS}} = 0.56 \pm 0.06 \text{ K/}(\text{W m}^{-2}) \]

Slide 30, Lecture 4

Slightly More Complicated Climate Model

\[ \Delta T = \lambda_{\text{BB}} \left( 1 + f_{\text{H}_2\text{O}} + f_{\text{CLOUDS}} + f_{\text{SURFACE ALBEDO}} \right) \times \]

\[ (\Delta F_{\text{CO}_2} + \Delta F_{\text{CH}_4+N_2O} + \Delta F_{\text{OTHER GHGs}} + \Delta F_{\text{AEROSOLS}}) \]

where

\[ \lambda_{\text{BB}} = 0.3 \text{ K/ W m}^{-2} \]

and \( f_{\text{CLOUDS}} \) & \( f_{\text{SURFACE ALBEDO}} \) 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 $\mu$m 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

(a) Low clouds
(b) High clouds

Solar High albedo
Thermal Low emission

Solar Low albedo
Thermal High emission

Low clouds
High clouds

Planetary cooling
Planetary warming

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.


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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 $0.54 \pm 0.74 (2\sigma)$ 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. Desesasonalized 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 ($\pm 8$ 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

2. Albedos of selected surfaces on Earth

- snow: 0.7 ± 0.2
- sand: 0.23 ± 0.05
- grasslands: 0.2 ± 0.05
- bare soil: 0.15 ± 0.1
- water (highly dependent on surface roughness and incident angle of sunlight): 0.2 ± 0.6


Initial Action: Humans Release CO₂

Initial Response: \( T_{\text{SURFACE}} \) Rises

Then: Ice Melts

Consequence: Albedo Falls

Feedback: \( \Rightarrow \) Effect of falling Albedo on \( T_{\text{SURFACE}} \)

Surface Albedo: Observation A

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?

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

\[ \Delta F_{GHG} = 2.4 \, \text{W/m}^2 \]

To compensate for this \( \Delta F \) by simply changing albedo:

\[ S = \frac{1370 \, \text{W/m}^2}{4} = 342.4 \, \text{W/m}^2 \]

\[ \frac{2.4 \, \text{W/m}^2}{342.4 \, \text{W/m}^2} = 0.007 \text{ or } 7 \times 10^{-3} \]

That is, an albedo decrease of \( 7 \times 10^{-3} \) would have the same surface \( \Delta F \) 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\(_2\)SO\(_4\))**
- formed from SO\(_2\) emitted by either coal (C\(_{135}H_{96}O_{9}NS\)) combustion or oceanic biology ((CH\(_3\))\(_2\)S)
- 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\(_{135}H_{96}O_{9}NS\) 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

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)

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
Aerosol Loading vs Time, Historical

Peak in 1989

Levels in 2000 comparable to those in 1960s

Stern et al., Chemosphere, 2005

Aerosol Loading vs Time, Future

Analysis of RCP 8.5 Aerosol Precursor Emissions

Mascioli et al., ACPD 2012
Global Average Temperature: Multiple Linear Regression

\[ \Delta T_{ML} = \frac{1 + \gamma}{\lambda_p} \left\{ (\text{GHG RF}_i) + NAA RF_i \right\} + C_0 + \]
\[ C_1 \times \text{SOD}_i + C_2 \times \text{TSI}_{i-1} + C_3 \times \text{ENSO}_{i-2} + \]
\[ \frac{Q_{\text{OCEAN}}}{\lambda_p} \]

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

Q_{\text{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

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

\[ \Delta T_{\text{MDL}} = \frac{1 + \gamma}{\lambda_p} \left( \text{GHG RF} + \text{NAA RF} \right) + C_o + \frac{C_1 \times \text{SOI}_i + C_2 \times \text{TSI}_{i-1} + C_3 \times \text{ENSO}_{i-2} + C_4 \times \text{AMO}_i + C_5 \times \text{PDO}_i + C_6 \times \text{IOD}_i}{\lambda_p} - Q_{\text{OCEAN},i} \]

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

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!

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

Mascioli et al., ACPD 2012

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