ENERGY FLOWS
FORCINGS
CLIMATE CHANGE
A REALLY TOUGH PROBLEM

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The Greenhouse Effect

Solar radiation passes through the clear atmosphere.

Some solar radiation is reflected by the Earth and the atmosphere.

Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.

CO₂, Carbon Dioxide

Most radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted from the Earth's surface.
THE GREENHOUSE EFFECT

Earth’s Energy Budget: A Delicate Balance

- Sunlight heats the Earth.
- The warm Earth radiates energy (in the form of infrared radiation, or heat) back out to space.
- Some of this infrared radiation is trapped in the atmosphere, giving Earth its temperate climate.

This is the greenhouse effect.

Global average temperature 15°C or 59°F

Without it, the Earth’s climate would be like the moon’s, harsh and severe.

Global average temperature -19°C or -2 °F
ATMOSPHERIC RADIATION

Power per area

Energy per time per area

Unit:
Watt per square meter
W m$^{-2}$
**STEFAN - BOLTZMANN RADIATION LAW**

Emitted thermal radiative flux from a black body

\[ F = \sigma T^4 \]

- \( F \) = Emitted flux, W m\(^{-2}\)
- \( T \) = Absolute temperature, K
- \( \sigma \) = Stefan-Boltzmann constant, W m\(^{-2}\) K\(^{-4}\)

Stefan-Boltzmann law “converts” temperature to radiative flux.
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

Schwartz, 1996, modified from Ramanathan, 1987
RADIATIVE FORCING

A *change* in a radiative flux term in Earth’s radiation budget, $\Delta F$, W m$^{-2}$.

**Working hypothesis:**

*On a global basis radiative forcings are additive and fungible.*

- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.
Global carbon dioxide concentration and infrared radiative forcing over the last thousand years.
CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)

Greenhouse gas forcing is considered accurately known.
Gases are uniformly distributed; radiation transfer is well understood.
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GLOBAL ANNUAL TEMPERATURE ANOMALY, 1880-2010

Data: Goddard Institute for Space Studies
HOW MUCH WARMING IS EXPECTED?

Equilibrium change in global mean surface temperature

\[ \Delta T = S \times F \]

\( S \) is *equilibrium* sensitivity. Units: K/(W m\(^{-2}\))

Sensitivity is commonly expressed as “CO\(_2\) doubling temperature”

\[ \Delta T_{2\times} \equiv S \times F_{2\times} \]

where \( F_{2\times} \) is the “CO\(_2\) doubling forcing” ca. 3.7 W m\(^{-2}\).
Current estimates of Earth’s climate sensitivity are centered about a CO₂ doubling temperature $\Delta T_{2\times} = 3 \text{ K}$, but with substantial uncertainty. Range of sensitivities of current models roughly coincides with IPCC “likely” range.
HOW MUCH WARMING IS EXPECTED?

For increases in CO₂, CH₄, N₂O, and CFCs over the industrial period

\[ F = 2.6 \text{ W m}^{-2} \]

*Expected* temperature increase:

\[ \Delta T_{\text{exp}} = \frac{F}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.6}{3.7} \times 3 \text{ K} = 2.1 \text{ K} \]

*Observed* temperature increase:

\[ \Delta T_{\text{obs}} = 0.8 \text{ K} \]

IPCC, 2007
Best Estimate

Warming Discrepancy
AEROSOL IN MEXICO CITY BASIN
Light scattering by aerosols decreases absorption of solar radiation.
Fire plumes from southern Mexico transported north into Gulf of Mexico.
CLOUD BRIGHTENING BY SHIP TRACKS

Satellite photo off California coast

Aerosols from ship emissions enhance reflectivity of marine stratus.
Global average sulfate optical thickness is 0.03: $1 \text{ W m}^{-2}$ cooling.

In continental U. S. typical aerosol optical thickness is 0.1: $3 \text{ W m}^{-2}$ cooling.
AEROSOL OPTICAL DEPTH AT ARM SGP
Fifteen years of daily average 500 nm AOD in North Central Oklahoma

Green curve is LOWESS (locally weighted scatterplot smoothing) fit.
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Total forcing includes other anthropogenic and natural (solar) forcings. Forcing by tropospheric ozone, ~0.35 W m$^{-2}$, is the greatest of these. Uncertainty in aerosol forcing dominates uncertainty in total forcing.
THE PATH FORWARD

*Determine aerosol forcing with high accuracy.*

Multiple approaches are required:

* **Laboratory studies** of aerosol processes.

* **Field measurements** of aerosol processes and properties: emissions, new particle formation, evolution, size distributed composition, optical properties, CCN properties, removal processes . . .

Represent aerosol processes in *chemical transport models*.

Evaluate models by *comparison with observations*.

* **Satellite measurements** for spatial coverage.

Calculate forcings in *chemical transport models and GCMs*.

*Measurement based determination of aerosol forcings.*
AEROSOL PROCESSES THAT MUST BE UNDERSTOOD AND REPRESENTED IN MODELS

- condensation
- evaporation
- surface chemistry
- coagulation
- light scattering and absorption
- water uptake
- oxidation
- precursor emissions
- autoconversion
- dry deposition
- primary emissions
- radiation transfer in clouds
- new particle formation
- aqueous chemistry
- subcloud scavenging
- scavenging
- diffusion
- evaporation
- oxidation
- scavenging

APPROACH TO DETERMINE AEROSOL FORCING

Numerical simulation of physical processes

Isomorphism of processes to computer code

Modeling aerosol processes requires understanding these processes, developing and testing their numerical representations, and incorporating these representations in global scale models.