OUTLINE

Earth’s energy balance
  Perturbations
  Carbon dioxide
Climate forcing and response
  Earth’s climate sensitivity
Influence of aerosols
Uncertainty in climate forcing and its implications
Looking to the future
Concluding remarks
The Greenhouse Effect

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

Solar radiation passes through the clear atmosphere

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

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.

Infrared radiation is emitted from the Earth's surface.
GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter

$\frac{1}{4} S_0$ 343

$\alpha = 31\%$

$\frac{1}{4} S_0 (1-\alpha) = \sigma T^4$

237

$\approx 254 K = -2^\circ F$

69% = 1 - $\alpha$

$106$ Rayleigh 27

Aerosol 4

45

$45 \pm 31 K = 59^\circ F$

390

$H_2O, CO_2, CH_4 \ldots$

$F = +2.6 \text{ W m}^{-2}$

31

$\approx 31 K$

$68$

$H_2O, CO_2, CH_4 \ldots$

296

$169$

Latent heat

Sensible heat

30

16

90

$S_0$ 343

$\approx 288 K = 59^\circ F$

$1/4 S_0 (1-\alpha) = \sigma T^4$

$F = +2.6 \text{ W m}^{-2}$

Schwartz, 1996, modified from Ramanathan, 1987
ATMOSPHERIC RADIATION

Energy per area per time

Power per area

Unit: Watt per square meter $W \text{ m}^{-2}$
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.
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.
ATMOSPHERIC CARBON DIOXIDE IS INCREASING

Global carbon dioxide concentration and infrared radiative forcing over the last thousand years
INCREASES IN CO$_2$ OVER THE INDUSTRIAL PERIOD
ATMOSPHERIC CARBON DIOXIDE
Time series 1700 - 2003

Law Dome (Antarctica)
Siple (Antarctica)
Mauna Loa (Hawaii)

Law - Etheridge et al.
Siple - Friedli et al.
Mauna Loa - Keeling
ATMOSPHERIC CO$_2$ EMISSIONS

Time series 1700 - 2003

Fossil Fuel Emissions - Marland
ATMOSPHERIC CARBON DIOXIDE
Time series 1700 - 2003
ATMOSPHERIC CARBON DIOXIDE
Time series 1700 - 2003

What’s missing?

Law - Etheridge et al.
Siple - Friedli et al.
Mauna Loa - Keeling
Fossil Fuel - Marland
DEFORESTATION AS A SOURCE OF ATMOSPHERIC CO₂
Carbon flux estimated as land area times carbon emissions associated with deforestation (or uptake associated with afforestation).
United States dominates emissions before 1900 and uptake after 1940.
Prior to 1910 CO₂ emissions from land use changes were dominant.
Subsequently fossil fuel CO₂ has been dominant and rapidly increasing!
ATtribution of Increase in Atmospheric CO$_2$

Comparison of *cumulative* CO$_2$ emissions from fossil fuel combustion and land use changes with measured increases in atmospheric CO$_2$.

Prior to 1970 the increase in atmospheric CO$_2$ was dominated by emissions from land use changes, not fossil fuel combustion.
FRACTION OF EMITTED CO$_2$ REMAINING IN THE ATMOSPHERE
Excess atmospheric CO$_2$ (relative to 1850) as fraction of cumulative emissions from 1850.

Is the atmospheric CO$_2$ fraction increasing?
What are the implications for future CO$_2$?
Net change in atmosphere is difference of large fluxes.
CLIMATE FORCING AND RESPONSE
GREENHOUSE GAS FORCING 1855-2004

Well mixed greenhouse gases: carbon dioxide, methane, nitrous oxide, CFC's

IPCC, 2001
GREENHOUSE GAS FORCING AND CHANGE IN GLOBAL MEAN SURFACE TEMPERATURE 1855-2004

IPCC, 2001; Climate Research Unit, University of East Anglia, UK
GREENHOUSE GASES AND TEMPERATURE OVER 450,000 YEARS

Vostok core, Antarctica

Modified from Petit et al., Nature, 1999
CLIMATE RESPONSE

The *change* in global and annual mean temperature, $\Delta T$, K, resulting from a given radiative forcing.

**Working hypothesis:**

The change in global mean temperature is proportional to the forcing, but independent of its nature and spatial distribution.

$$\Delta T = \lambda \Delta F$$
CLIMATE SENSITIVITY

The change in global and annual mean temperature per unit forcing, $\lambda$, K/(W m$^{-2}$),

$$\lambda = \Delta T/\Delta F.$$ 

Climate sensitivity is not known and is the objective of much current research on climate change.

Climate sensitivity is often expressed as the temperature for doubled CO$_2$ concentration $\Delta T_{2\times}$.

$$\Delta T_{2\times} = \lambda \Delta F_{2\times}$$
CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

Estimates of central value and uncertainty range from major national and international assessments.

Despite extensive research, climate sensitivity remains highly uncertain.
THE ‘BIBLE’ OF CLIMATE CHANGE

It's big and thick.
Every household should have one.
No one reads it from cover to cover.
You can open it up on any page and find something interesting.
It was written by a committee.
It is full of internal contradictions.
It deals with cataclysmic events such as floods and droughts.
It has its true believers and its rabid skeptics.

http://ipcc-wg1.ucar.edu/wg1/wg1-report.html
IMPLICATIONS OF UNCERTAINTY IN CLIMATE SENSITIVITY

Uncertainty in climate sensitivity translates directly into . . .

• Uncertainty in the amount of *incremental atmospheric* \( \text{CO}_2 \) that would result in a given increase in global mean surface temperature.

• Uncertainty in the amount of *fossil fuel carbon* that can be combusted consonant with a given climate effect.

*At present this uncertainty is about a factor of 3.*
KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

• Paleoclimate studies.
• Empirical, from climate change over the instrumental record.
• Climate modeling.

Climate models evaluated by comparison with observations are essential to informed decision making.
IMPORTANCE OF KNOWLEDGE OF CLIMATE TO INFORMED DECISION MAKING

• The lifetime of incremental atmospheric CO$_2$ is about 100 years.

• The expected life of a new coal-fired power plant is 50 to 75 years.

Actions taken today will have long-lasting effects.

Early knowledge of climate sensitivity can result in huge averted costs.
INFLUENCE OF AEROSOLS
Radiative Forcing by Tropospheric Aerosol

Partial Reflection and Absorption of Incoming Solar Radiation

Aerosol Haze

Clouds

Organics

Dust

SO₂

Soot

Sea salt

Dimethylsulfide

Land Use Changes

Industrial Emissions

Biomass Burning

Ocean
AEROSOL IN MEXICO CITY BASIN
Mexico City is a wonderful place to study aerosol properties and evolution.
Fire plumes from southern Mexico transported north into Gulf of Mexico.
AEROSOL: A suspension of particles in air

Atmospheric aerosols may result from primary emissions (dust, smoke) or from gas to particle conversion in the atmosphere (haze, smog).
Aerosols from ship emissions enhance reflectivity of marine stratus.
Global average sulfate optical thickness is 0.03: 1 W m\(^{-2}\) cooling.

In continental U. S. typical aerosol optical thickness is 0.1: 3 W m\(^{-2}\) cooling.
AEROSOL OPTICAL DEPTH
Determination by sun photometry

Beer’s law in the atmosphere:

\[ E_{d-n} = E_0 e^{-\tau/\cos(\theta_0)} \]

\[ \tau = -\cos(\theta_0) \ln\left( \frac{E_{d-n}}{E_0} \right) \]

\[ \tau = \tau_{\text{gas}} + \tau_{\text{aerosol}} \]

\[ \tau_{\text{aerosol}} = \tau - \tau_{\text{gas}} \]

\( \tau_{\text{gas}} \) calculated from known properties of air
AEROSOL OPTICAL DEPTH
Determined by sunphotometry
North central Oklahoma - Daily average at 500 nm

J. Michalsky et al., JGR, 2001
MONTHLY AVERAGE AEROSOL JUNE 1997
Polder radiometer on Adeos satellite

Optical Thickness $\tau$
$\lambda = 865 \text{ nm}$

Ångström Exponent $\alpha$
$\alpha = -\frac{d \ln \tau}{d \ln \lambda}$
AEROSOL OPTICAL DEPTH IN 18 MODELS (AEROCOM)

Comparison also with surface and satellite observations

Surface measurements: AERONET network.
Satellite measurements: composite from multiple instruments/platforms.
Are the models getting the “right” answer for the wrong reason?
Are the models getting the “right” answer because the answer is known?
Are the satellites getting the “right” answer because the answer is known?
Indirect forcing is highly sensitive to perturbations in cloud drop concentration.

A 30% increase in cloud drop concentration results in a forcing of $\sim 1 \text{ W m}^{-2}$.
UNCERTAINTY IN CLIMATE FORCING
GLOBAL-MEAN RADIATIVE FORCINGS (RF)
Pre-industrial to present (Intergovernmental Panel on Climate Change, 2007)

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF values (W m⁻²)</th>
<th>Spatial scale</th>
<th>LOSU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-lived greenhouse gases</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>1.66 [1.49 to 1.83]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.48 [0.43 to 0.53]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.16 [0.14 to 0.18]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>0.34 [0.31 to 0.37]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Stratospheric water vapour from CH₄</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stratospheric</td>
<td>-0.05 [-0.15 to 0.05]</td>
<td>Continental</td>
<td>Med</td>
</tr>
<tr>
<td>Tropospheric</td>
<td>0.35 [0.25 to 0.65]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Surface albedo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land use</td>
<td>-0.2 [-0.4 to 0.0]</td>
<td>Local to</td>
<td>Med</td>
</tr>
<tr>
<td>Black carbon on snow</td>
<td>0.1 [0.0 to 0.2]</td>
<td>continental</td>
<td>Low</td>
</tr>
<tr>
<td>Total Aerosol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct effect</td>
<td>-0.5 [-0.9 to -0.1]</td>
<td>Continental</td>
<td>Med</td>
</tr>
<tr>
<td>Cloud albedo effect</td>
<td>-0.7 [-1.8 to -0.3]</td>
<td>Continental</td>
<td>Low</td>
</tr>
<tr>
<td>Linear contrails</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Solar irradiance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>0.12 [0.06 to 0.30]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Total net anthropogenic</td>
<td>1.6 [0.6 to 2.4]</td>
<td>Global</td>
<td>Low</td>
</tr>
</tbody>
</table>

LOSU denotes level of scientific understanding.

Factor of 4 limits empirical inferences and model evaluation.
Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a *consistent explanation of the observed temperature record*.

These simulations used models with *different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings*. 
TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models

Uncertainty in modeled temperature increase – less than a factor of 2, red – is well less than uncertainty in forcing – a factor of 4, green.

Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007
TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models

The models *did not span the full range of the uncertainty* and/or . . .
The forcings used in the model runs were *anticorrelated with the sensitivities of the models.*

Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007
Total forcing increases with decreasing (negative) aerosol forcing. Climate models with higher sensitivity have lower total forcing. These models cannot all be correct.

This situation limits confidence that can be placed in the models.
Looking to the Future . . .
Prediction is difficult, especially about the future.

– Niels Bohr
PROJECTIONS OF FUTURE CO2 CONCENTRATIONS
PROJECTIONS OF FUTURE TEMPERATURE CHANGE
PROJECTIONS OF FUTURE SEA LEVEL RISE
Thermosteric (density change) only

![Graph showing sea level rise projections for different scenarios and models with bars indicating uncertainty range. The graph includes lines for scenarios A1B, A1T, A1FI, A2, B1, and B2, with shaded envelopes representing model average and all SRES envelopes. The bars show the range in 2100 produced by several models.]
1 meter

Weiss and Overpeck, University of Arizona
Complete melt of the Greenland ice sheet would raise the level of the global ocean 7 meters.
6 meters

Weiss and Overpeck, University of Arizona
“Gentlemen, it’s time we gave some serious thought to the effects of global warming.”
CONCLUDING REMARKS

Atmospheric carbon dioxide will continue to increase absent major changes in the world’s energy economy.

The consequences of this increase are not well known but they range from serious to severe to catastrophic.

Uncertainty in forcing by aerosols greatly limits present understanding of climate change.

Present scientific understanding is sufficient to permit “no regrets” decision making.

Research is urgently needed to refine “what if” projections.

Actions taken (or not taken) today will inevitably affect future generations.