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

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.

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

Infrared radiation is emitted from the Earth's surface.
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

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

\[ \alpha = 31\% \]

\[ 69\% = 1 - \alpha \]

\[ 237 \approx 254 K = -2^\circ F \]

\[ 106 \quad \text{Rayleigh} \quad 27 \quad \text{Aerosol} \quad 4 \]

\[ 390 \approx 288 K = 59^\circ F \]

\[ 30 \quad 31 \quad 90 \quad 16 \quad 169 \]

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

\[ \text{Latent heat} \quad \text{Sensible heat} \]

\[ \text{Schwartz, 1996, modified from Ramanathan, 1987} \]
ATMOSPHERIC RADIATION

Energy per area per time

Power per area

Unit:
Watt per square meter
W m\(^{-2}\)
ATMOSPHERIC CARBON DIOXIDE IS INCREASING

Global carbon dioxide concentration and infrared radiative forcing over the last thousand years
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.
INCREASES IN CO₂ OVER THE INDUSTRIAL PERIOD
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 CO₂

Comparison of *cumulative* CO₂ emissions from fossil fuel combustion and land use changes with measured increases in atmospheric CO₂.

Prior to 1970 the increase in atmospheric CO₂ was dominated by emissions from land use changes, not fossil fuel combustion.
DEFORESTATION AS A SOURCE OF ATMOSPHERIC CO$_2$
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.
FRACTION OF EMMITTED 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$_2$?
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 $\Delta T_{2\times}$.

$$\Delta T_{2\times} = \lambda \Delta F_{2\times}$$

$$\Delta F_{2\times} \approx 3.7 \text{ W m}^{-2}$$
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* 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.*
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.**
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: $1 \text{ W m}^{-2}$ cooling.

In continental U. S. typical aerosol optical thickness is 0.1: $3 \text{ W m}^{-2}$ cooling.
AEROSOL OPTICAL DEPTH
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 $\tau$
$\lambda = 865$ nm

Ångström Exponent $\alpha$
$\alpha = -\frac{\ln \tau}{\ln \lambda}$
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?
SECONDARY AEROSOL PRODUCTION

Parcel age measured using $-\log(\text{NO}_x/\text{NO}_y)$ as clock

Concentration

Normalized concentration

Dilution is accounted for by normalizing aerosol concentration to CO above background.

$\sim 5 \times \text{increase}$ in total aerosol; $\sim 7 \times \text{increase}$ in organic aerosol.

Measured increase in organic aerosol exceeds modeled based on laboratory experiments and measured volatile organic carbon tenfold.
Indirect forcing is highly sensitive to perturbations in cloud drop concentration.

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

Losu denotes level of scientific understanding.
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.

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.
CORRELATION OF AEROSOL FORCING, TOTAL FORCING, AND SENSITIVITY IN CLIMATE MODELS

Eleven models used in 2007 IPCC analysis

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 EMISSIONS

Scenarios
- A1B
- A1T
- A1FI
- A2
- B1
- B2
- IS92a

CO2 emissions (Gt C/yr)

Year

2000 2020 2040 2060 2080 2100

25
20
15
10
5
0
PROJECTIONS OF FUTURE CO2 CONCENTRATIONS

[Graph showing projected CO2 concentrations for different scenarios over time]

- Scenarios: A1B, A1T, A1FI, A2, B1, B2, IS92a
PROJECTIONS OF FUTURE TEMPERATURE CHANGE
PROJECTIONS OF FUTURE SEA LEVEL RISE

Thermosteric (density change) only

Sea level rise (metres)

Year

2000  2020  2040  2060  2080  2100

Bars show the range in 2100 produced by several models

Model average all SRES envelope

Several models all SRES envelope

All SRES envelope including land-ice uncertainty

Scenarios
- A1B
- A1T
- A1F1
- A2
- B1
- B2
present
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.”
U.N. Report Describes Risks of Inaction on Climate Change

By ELISABETH ROSENTHAL

VALENCE, Spain, Nov. 17 — United Nations Secretary General Ban Ki-moon called climate change “the defining challenge of our age” today and called on the United States and China, the greatest emitters of greenhouse gases, to be play “a more constructive role” in coming negotiations for a new global climate treaty.

The panel, co-winner of this year’s Nobel Peace Prize, said the world would have to reverse the growth of greenhouse gas emissions by 2015 to avert major problems. “If there’s no action before 2012, that’s too late, there is not time,” said Rajendra Pachauri, a scientist and economist who heads the Intergovernmental Panel on Climate Change. “What we do in the next two, three years will determine our future. This is the defining moment.”
Responding to climate change involves an iterative risk management process that includes both adaptation and mitigation and takes into account climate change damages, co-benefits, sustainability, equity, and attitudes to risk.

Impacts of climate change are very likely to impose net annual costs which will increase over time as global temperatures increase.

Aggregate estimates of costs mask significant differences in impacts across sectors, regions and populations and very likely underestimate damage costs because they cannot include many non-quantifiable impacts.

Costs and benefits of mitigation are broadly comparable in magnitude.

An emissions pathway or stabilisation level where benefits exceed costs cannot be unambiguously determined.

Climate sensitivity is a key uncertainty for mitigation scenarios for specific temperature levels.

Choices about the scale and timing of GHG mitigation involve balancing the economic costs of more rapid emission reductions now against the corresponding medium-term and long-term climate risks of delay.
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.