Climate Change:
Forcings, Feedbacks, and Forecasts

Some of these slides are taken from the IPCC’s recently released Fourth Assessment.
Beautiful but complicated

Scott Denning already told you about this...
Climate is what you expect. Weather is what you get.

So let’s start by asking:
Why can’t those turkeys predict the weather?

Small errors in the initial conditions lead to large errors in forecasts. This “sensitive dependence on initial conditions” limits the range of useful forecasts to about two weeks.

Limited predictability is a property of the atmosphere, and so cannot be eliminated even if we had a perfect forecast model.

“Dr. Chaos,” Ed Lorenz
Climate change can be *forced*.

- Changes in the average weather are often “forced” by changing external influences, e.g.:
  - The day-night cycle
  - The seasonal cycle
  - Ice ages
  - Anthropogenic changes in the composition of the atmosphere

A long-range forecast: *July 2008 will be warmer, in Fort Collins, than January 2008.*

This will be a forced change.
The change in the forcing is itself predictable.
How can we predict climate change, if we can’t predict the weather?

• Day-to-day changes are due to weather systems growing, moving, dying, etc. -- This is simply the atmosphere going about its business.

• The predictability of such weather changes is limited, to about 2 weeks, by sensitive dependence on initial conditions.

• Changes in climate can arise from changes in forcing by “external” influences.

• If the external forcings can be predicted, and if they are strong enough, then the resulting climate change can also be predicted.
So, we need to talk about forcings.
Kinds of Forcings

- Anthropogenic changes in the gaseous composition of the atmosphere
- Anthropogenic changes in atmospheric aerosols
- Changes in land use
- Volcanic eruptions
- Changes in solar output
- Changes in the Earth’s orbital parameters (on very long time scales)
Solar radiation powers the climate system.

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

About half the solar radiation is absorbed by the Earth’s surface and warms it.

Infrared radiation is emitted from the Earth’s surface.

The Greenhouse Effect

Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth’s surface and the lower atmosphere.
Here “radiative forcing” refers to the effects of a perturbation on the radiation at the top of the atmosphere.
Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750

Global mean radiative forcing (Wm⁻²)

- **Greenhouse gases**
  - Halocarbons
  - N₂O
  - CH₄
  - CO₂
  - Tropospheric ozone

- **Aerosols + clouds**
  - Black carbon from fossil fuel burning
  - Mineral Dust
  - Aviation
  - Contrails
  - Cirrus
  - Land use (albedo only)
  - Organic carbon from fossil fuel burning
  - Biomass burning

The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.
Feedbacks
What Is Feedback?

- Forcing
- Climate System
- Response

Feedbacks
Kinds of Feedbacks

- Albedo Feedback
- Water vapor feedback
- Lapse-rate feedback
- Cloud feedback(s)
Albedo Feedback

- Increasing greenhouse gases → Warming
  - Melting snow and ice
  - Reduced albedo, more absorbed sunshine
Warming in the Arctic is roughly double that for the whole Earth.

*Note different scales*
As water vapor increases, precipitation and evaporation also increase.
Changes in Water Vapor

To produce the red curve, a global atmospheric model was forced with the observed sea-surface temperatures for the years shown.
What is the “lapse rate?”

The “lapse rate” is the rate at which temperature decreases upward.

In the future climate, the temperature is predicted to increase throughout the troposphere, but it increases more aloft than near the surface. The lapse rate is, therefore, said to decrease.
How the lapse rate can feed back:

Warmer air up high can radiate heat away to space more easily than warmer air near the ground.
Lapse-Rate Feedback

- Increasing greenhouse gases
- Warming
  - Decreased lapse rate
  - More cooling to space
Cloud Feedback(s)

- Cloud amount
- Cloud top height
- Cloud optical properties
Low-Cloud Feedback

Note: This feedback can be either positive or negative.
High-Cloud Feedback

Increasing greenhouse gases → Warming → More high cloud and Increased cloud greenhouse effect

Note: This feedback can be either positive or negative.
So, let’s see what we’ve got...
Feedbacks in Real Climate Change Simulations

![Graph showing feedbacks in real climate change simulations. The graph compares different feedback types (WV, C, A, LR, WV+LR, ALL) across various models: Colman 2003 (PRP), Colman 2003 (RCMs), Soden and Held 2006, Soden and Held 2006 (Fixed RH), Winton 2006.]
The positive feedbacks are stronger than the negative feedbacks.

The combined effect of all feedbacks is to increase the warming by about a factor of two.
Forecasts
First, a reality check:
Can we “predict” past changes?
The observed changes are shown by the black curves.

Results from about 20 models are shown in red (upper panel) and blue (lower panel).

However, these results are not completely convincing, because:

- Many of the prescribed forcing components are uncertain,
- The forcings have not been “standardized,” and
- Inspection of the model results shows that model-sensitivity is inversely correlated with the strength of the forcing used.
IPCC

- Warming of \( \sim 3 \) K for doubling \( \text{CO}_2 \)
- Rising sea level \( \sim 1 \) m in 21st century
- Stronger storms
- More droughts

All based on simulations with complicated computer models.

But before we get to that...
Climate Modeling
On the Back of an Envelope
Warning: The next two slides have equations.
Increasing CO$_2$ Perturbs the Earth’s Radiation Budget

\[(1 - \alpha)S \pi a^2 = \varepsilon (\sigma T_S^4) 4 \pi a^2\]

\[(1 - \alpha)S = 4 \varepsilon (\sigma T_S^4)\]

\[0 = 4(\Delta \varepsilon)(\sigma T_S^4) + 4 \varepsilon (4 \sigma T_S^3 \Delta T_S)\]

Assumptions: 1) Only CO$_2$ is perturbed; 2) No feedbacks.

\[\Delta T_S = -\frac{T_S \Delta \varepsilon}{4 \varepsilon}\]
Let’s put in some numbers:

\[ \Delta T_S = -\frac{T_S \Delta \varepsilon}{4 \varepsilon} \]

\[ \varepsilon(\sigma T_s^4) = 240 \quad W m^{-2} \]

\[ (\Delta \varepsilon)(\sigma T_s^4) = -4 \quad W m^{-2} \]

\[ T_S = 288 \quad K \]

\[ \Delta T_S = -\frac{288}{4} \cdot \frac{K}{(-\frac{4}{240})} = 1.2 \quad K \]

\[ \sim 0.5\% \]
Lessons Learned

• We don’t need no stinking computer models!

• Feedbacks are important.
Past and future CO₂ atmospheric concentrations

Scenarios:
- A1B
- A1T
- A1Fi
- A2
- B1
- B2
- IS92a
Predicted Precipitation Changes
CO₂ concentration, temperature, and sea level continue to rise long after emissions are reduced

Magnitude of response

- CO₂ emissions peak 0 to 100 years

Time taken to reach equilibrium

- Sea-level rise due to ice melting: several millennia
- Sea-level rise due to thermal expansion: centuries to millennia
- Temperature stabilization: a few centuries
- CO₂ stabilization: 100 to 300 years
Conclusions

- Long-term climate change can be predicted when it is due to predictable changes in external forcing.
- Feedbacks are expected to amplify the response to the forcing.
- A simple estimate of surface temperature change due to increasing CO$_2$ (without feedbacks) can be made on the back of an envelope.
- Predictions for the 21st century show warming of the troposphere especially in the Arctic, an increase in precipitation extremes, a decrease in snow and ice cover, and an increase in sea level.
Recommended Reading

- “Chaos: The Making of a New Science,” by James Gleick
- “The Two-Mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future,” by Richard Alley