Mitigating Climate Change

- Sources and sinks of atmospheric CO2
- Emissions trading
- Historical and projected CO2 emissions
- Climate wedges
- Alternative energy

"Scientists are necessary, but not sufficient to solve the climate problem"

Dr. Ralph Cicerone, President of the National Academy of Science, November 2007

The Global Carbon Cycle

- Atmosphere: 775 + 4 GtC/yr
- Ocean: 38,000 GtC
- Land: 2000 GtC
- Humans: 8 GtC/yr

About half the CO2 released by humans is absorbed by oceans and land.

“Missing” carbon is hard to find among large natural fluxes.

Variable Sinks

- Some years almost all the fossil carbon goes into the atmosphere, some years almost none
- Interannual variability in sink activity is much greater than in fossil fuel emissions
- Sink strength is related to El Niño. Why? How?
European "cap-and-trade" market set up as described in Kyoto Protocol (http://www.europeanclimateexchange.com)

- 7/10/2009 price €16.19/ton of CO₂ emitted 12/2012 = $83.25/ton of Carbon
- Supply and demand!

Where Has All the Carbon Gone?

- **Into the oceans**
  - Solubility pump (CO₂ very soluble in cold water, but rates are limited by slow physical mixing)
  - Biological pump (slow "rain" of organic debris)

- **Into the land**
  - CO₂ Fertilization (plants eat CO₂ ... is more better?)
  - Nutrient fertilization (N-deposition and fertilizers)
  - Land-use change (forest regrowth, fire suppression, woody encroachment ... but what about Wal-Marts?)
  - Response to changing climate (e.g., Boreal warming)

Present Value of Carbon Sinks

- Terrestrial and marine exchanges currently remove more than 4 GtC per year from the atmosphere
- This free service provided by the planet constitutes an effective 50% emissions reduction, worth about $325 Billion per year at today's price on the ECX!
- Carbon cycle science is currently unable to quantitatively account for
  - The locations at which these sinks operate
  - The mechanisms involved
  - How long the carbon will remain stored
  - How long the sinks will continue to operate
  - Whether there is anything we can do to make them work better or for a longer time

Coupled Carbon-Climate Modeling

- "Earth System" Climate Models
  - Atmospheric GCM
  - Ocean GCM with biology and chemistry
  - Land biophysics, biogeochemistry, biogeography
- Prescribe fossil fuel emissions, rather than CO₂ concentration as usually done
- Integrate model from 1850-2100, predicting both CO₂ and climate as they evolve
- Oceans, plants, and soils exchange CO₂ with model atmosphere
- Climate affects ocean circulation and terrestrial biology, thus feeds back to carbon cycle
Coupled simulations of climate and the carbon cycle.

Given nearly identical human emissions, different models project dramatically different futures.

Emission Scenarios vs Reality

- Actual emissions: CDIAC
- Actual emissions: EIA
- 450ppm stabilisation
- 650ppm stabilisation
- A1F1
- A1B
- A1T
- A2
- B1
- B2

Actual emissions are above even the highest IPCC scenarios

Carbon intensity of the world economy fell steadily for 30 years

- Raupach et al. 2007 PNAS
- Canadell et al. 2007
Until 2000!

Dramatic contrast - history versus future

Canadell et al. 2007

Raupach et al. PNAS 2007

Dramatic contrast - history versus future

Raupach et al. PNAS 2007
**Dramatic contrast - history versus future**

- **CO₂ emissions**
  - Cumul
  - Flux
  - Growth
  - Pop

- **Countries**
  - Least Developed
  - Developing
  - India
  - China
  - Former Soviet
  - Other developed
  - Japan
  - Europe
  - USA

Raupach et al. PNAS 2007

**CO₂ “Budget” of the Atmosphere**

- **8 billion tons go in**
- **4 billion tons added every year**
- **800 billion tons carbon**
- **2 + 2 = 4 billion tons go out**

**How Far Do We Choose to Go?**

- **“Doubled” CO₂**
- **Today**
- **Pre-Industrial**
- **Glacial**

Past, Present, and Potential Future Carbon Levels in the Atmosphere

**Historical Emissions**

- **Billions of Tons Carbon Emitted per Year**
- **Historical emissions**
- **1950 to 2000**
- **2050 and 2100**

Scott Denning CSU CMMAP
The “Stabilization Triangle”

- Billions of Tons Carbon Emitted per Year
- Current path = "ramp"
- Interim Goal
- Flat path
- Historical emissions
- Stabilization Triangle
- 1.6 Billions of Tons
- 0 8 16
- 1950 2000 2050 2100

The Stabilization Triangle

- Billions of Tons Carbon Emitted per Year
- Current path = "ramp"
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- Historical emissions
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- 1.6
- 0 8 16
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The Stabilization Triangle

- Easier CO₂ target
- ~850 ppm
- 1.6
- 0 8 16
- 1950 2000 2050 2100

The “Stabilization Wedges”

- Billions of Tons Carbon Emitted per Year
- Current path = "ramp"
- Interim Goal
- Flat path
- Historical emissions
- Stabilization Triangle
- 16 GtC/yr
- Eight "wedges"
- Goal: In 50 years, same global emissions as today
- 1.6
- 0 8 16
- 1950 2000 2050 2100

What is a "Wedge"?

- A “wedge” is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr. The strategy has already been commercialized at scale somewhere.

- 1 GtC/yr
- 50 years

Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years. This is 2.5 trillion dollars at $100/tC.

A “solution” to the CO₂ problem should provide at least one wedge.
### Fifteen Wedges in 4 Categories

#### Energy Efficiency & Conservation (4)
- Fuel Switching (1)
- CO₂ Capture & Storage (3)

#### Renewable Fuels & Electricity (4)
- Stabilization Triangle

#### Forest and Soil Storage (2)

#### Nuclear Fission (1)

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### Efficiency

**Double the fuel efficiency of the world’s cars or halve miles traveled**

- Average coal plant efficiency is 33% today

**Produce today’s electric capacity with double today’s efficiency**

- There are about 600 million cars today, with 2 billion projected for 2055

**Use best efficiency practices in all residential and commercial buildings**

- Replacing all the world’s incandescent bulbs with CFL’s would provide 1/4 of one wedge

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### Fuel Switching

**Substitute 1400 natural gas electric plants for an equal number of coal-fired facilities**

- E, H / $  

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### Carbon Capture & Storage

**Implement CCS at**

- 800 GW coal electric plants
- 1600 GW natural gas electric plants
- 180 coal synfuels plants
- 10 times today’s capacity of hydrogen plants

**A wedge requires an amount of natural gas equal to that used for all purposes today**

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**Efficiency**

**Carbon Capture & Storage**
### Nuclear Electricity

Triple the world's nuclear electricity capacity by 2055

The rate of installation required for a wedge from electricity is equal to the global rate of nuclear expansion from 1975-1990.

![Graphic courtesy of NRC](image)

**E/ $$**

### Wind Electricity

Install 1 million 2 MW windmills to replace coal-based electricity, OR Use 2 million windmills to produce hydrogen fuel

A wedge worth of wind electricity will require increasing current capacity by a factor of 20

![Photo courtesy of DOE](image)

**E, T, H / $$-$$**

### Solar Electricity

Install 20,000 square kilometers for dedicated use by 2054

A wedge of solar electricity would mean increasing current capacity 700 times

![Photo courtesy of DOE Photovoltaics Program](image)

**E / $$5**

### Imagine it's 1800, and you're in charge ...

Somebody presents you with a grand idea for transforming the world economy:

- Dig 8 billion tons of carbon out of the ground every year
- Build a system of pipelines, supertankers, railroads, highways, and trucks to deliver it to every street corner on the planet
- Build millions of cars every year, and millions of miles of roads to drive them on
- Generate and pipe enough electricity to every house to power lights & stereos & plasma TVs

... “and here’s the itemized bill ...”
Thinking about Costs

• Our global society built that very system
• We didn’t go broke building it ...
• We got rich beyond the avarice of kings!

• Now we have to do it again!

• How?

Putting a Price on Carbon Emissions

• A new industrial revolution won’t happen because people want to "do the right thing"

• The government can’t just pass a law and create a new global energy economy, any more than they could 200 years ago

• If low-carbon-footprint goods and services cost less than "dirtier" ones, people will buy them

• The role of policy is to provide incentives, to put a price on carbon!

A Policy Spectrum

<table>
<thead>
<tr>
<th>“command and control”</th>
<th>“market capitalism”</th>
</tr>
</thead>
<tbody>
<tr>
<td>direct subsidy</td>
<td>“cap and trade”</td>
</tr>
<tr>
<td>“tax and rebate”</td>
<td></td>
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</tbody>
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Conclusions

• Rising levels of CO₂ will cause significant climate change in the 21st century and far beyond

• The only way to mitigate these changes is to stop burning coal, oil, and gas

• This can feasibly be done using today’s technology, but requires tremendous will

• Solving the climate problem will lead to a new industrial revolution, and huge wealth creation

• Dealing with this problem will be a major theme of history for centuries to come
We choose to do these things not because they are easy, but because they’re hard!

President John F. Kennedy
Rice University
September 12, 1962