Climate Change Mitigation and Some Links to Adaptation

*Susan Solomon*

1. Introduction
2. Forcing agents and the stock-flow concept of Sterman
3. Why do we emit so much carbon dioxide and why is mitigation controversial
4. Some options for carbon dioxide emission reduction and the wedge concept of Socolow and Pacala
5. What about emissions of other warming agents?
The World Has Warmed

Last ten years: warmest decade since at least the late 1800s

Widespread warming has occurred. Globally averaged, the planet is about 0.75°C warmer than it was in 1880, based upon dozens of high-quality long records using thermometers worldwide, including land and ocean.

Increases in long-lived greenhouse gases (GHGs)

Radiative forcing efficiencies and atmospheric lifetimes differ among different gases.

Methane lives for about 10 years in our atmosphere.

Nitrous oxide lives for about 100 years.

Carbon dioxide is uniquely long-lived. Some of what we emit today (about 20%) will still be here in a thousand years.

Scattering and absorption of sunlight by aerosols

Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.1 and 2.11. Cambridge University Press. Used with permission.
Unprecedented Increases in Carbon Dioxide

- A critical ‘greenhouse gas’ that absorbs energy and is the largest single driver of current warming

- Increases change the Earth’s energy budget, ‘forcing’ climate to change and acidifying the oceans

*IPCC WG1 (2007) ch 2*
Consider a scenario in which the concentration of CO₂ in the atmosphere gradually rises to 400 ppm, about 8% higher than the level in 2000, then stabilizes by the year 2100, as shown here:

Sketch your estimate of future net CO₂ removal and anthropogenic emissions for this 400 ppmv stabilization scenario.

Anthropogenic emissions versus time, and current net removal

Images by MIT OpenCourseWare.

Sterman, Science, 2007
A typical response to the climate stabilization task.
Future emissions are erroneously correlated with atmospheric CO₂. Purple dashed line indicates the correct emissions path to stabilize CO₂ given the subject’s estimate of net removal.
The Amount of Carbon in The Bathtub

Stabilization of CO$_2$ concentrations globally would require at least 50% emissions reductions.

What if the gas was methane?
What if it was HCFC-123?

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Image courtesy of CD/AC, BP and USGS.
What drives carbon emissions?

The Kaya identity (8, 9) expresses the global $F$ as a product of four driving factors:

$$F = P \left( \frac{G}{P} \right) \left( \frac{E}{G} \right) \left( \frac{F}{E} \right) = Pgef,$$

Where $P$ is global population, $G$ is world GDP of gross world product, $E$ is global primary energy consumption, $g = G/P$ is the per-capita world GDP, $e = E/G$ is the energy intensity of world GDP, and $f = F/E$ is the carbon intensity of energy. Upper- and lowercase symbols distinguish extensive and intensive variables.

One way of considering factors involved (not the only way): population, GDP per capita, energy required per unit GDP, emissions per unit energy. --> Population, wealth, efficiency, cleanliness

Carbon emission is integral to all of the world’s economies

Learn more by reading Raupach et al., PNAS, 2007
Carbon Dioxide Emission From Fossil Fuel Burning

The human side of climate change.

Who?

Source: Energy Information Agency, DOE
Why: Going, Doing, Making, Being Comfortable…..

In short, just about everything.
On average, the 6 B people now in the developing world emit about 5x less fossil CO₂ per person than the 1B in the developed world.

What about those people’s future?

Image courtesy of DOE.

Source: Energy Information Administration, US DOE 2006
The Amount of Carbon in The Bathtub

Can we mitigate carbon emissions at the same time that the world’s poor countries develop and increase their energy needs?

• 6/7 of the people emit about 5x less per person than 1/6
What about total emissions, not per capita? Let’s add it up by country…..

Recent increases in wealth in China

What’s fair?

Should China pay more to develop than we did? Should Africa?
Carbon Intensity of the Global Economy

• ≈ -50% globally since 1970 but flattening out recently (can you guess why?)

Image by MIT OpenCourseWare.
Infrastructure Commitments

Power plants, homes ~50 years

Cars ~10 years

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The next few decades…it’s up to us.

Past and future emissions from ‘stuff’ we already have (leads to about 1-1.4°C warming)

See Davis et al., Science, 2010

What will be built: power plants, cars, planes, trains, appliances, homes, etc….. (leads to about 3-7°C warming by 2100).

Our joint choices on what ‘stuff’ to build matter a great deal.

Blade runner or star trek?

See Davis et al., Science, 2010
Emissions past and future

- Typical scenarios
- A1FI, A1B, etc show plausible futures with no additional climate policy; note uncertainties even with no policy.
- Stabilization at 450 would require large emissions reductions within the next several decades; 650 would imply reduced rate of growth soon, and bigger reductions by 2050.

Image by MIT OpenCourseWare.
Information and implications:

- units here are tC not tCO₂
- ≈75% of the total accumulated CO₂ in the atmosphere came from developed countries during 1860-1990.
- The integrated per capita contribution of developed countries to today’s fossil fuel CO₂ burden is about 20x larger than that of developing countries. The current annual contribution is about 5x.
- Stabilization at e.g., 550 suggests future DC share less than 1tC per person/yr, many times lower throughout the 21st century than what it took for the developed world to develop.
- Gridlock at UN level: developed and developing....
- Role of science and tech?

Political Matters:
numbers; north-south
issues, connections

(1) the times are difficult

(2) The numbers at the
table are large

(3) Equity issues?

Never before has there
been a greater need
for a joint and well-
informed societal
choice, or a more
difficult one.
A Very Few Words About Impacts and Adaptation

Table 4.1. Selected examples of planned adaptation by sector.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Adaptation option/strategy</th>
<th>Underlying policy framework</th>
<th>Key constraints and opportunities to implementation (Normal font = constraints; italics = opportunities)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water [WGII, 5.5, 16.4; Tables 3.5, 11.6, 17.1]</td>
<td>Expanded rainwater harvesting; water storage and conservation techniques; water reuse; desalination; water-use and irrigation efficiency</td>
<td>National water policies and integrated water resources management; water-related hazards management</td>
<td>Financial, human resources and physical barriers; integrated water resources management; synergies with other sectors</td>
</tr>
<tr>
<td>Agriculture [WGII 10.5, 13.5; Table 10.6]</td>
<td>Adjustment of planting dates and crop variety; crop relocation; improved land management, e.g. erosion control and soil protection through tree planting</td>
<td>R&amp;D policies; institutional reform; land tenure and land reform; training; capacity building; crop insurance; financial incentives, e.g. subsidies and tax credits</td>
<td>Technological and financial constraints; access to new varieties; markets; longer growing season in higher latitudes; revenues from 'new' products</td>
</tr>
<tr>
<td>Infrastructure/ settlement (including coastal zones) [WGII 3.6, 11.4; Tables 6.11, 17.1]</td>
<td>Relocation; seawalls and storm surge barriers; dune reinforcement; land acquisition and creation of marshlands/wetlands as buffer against sea level rise and flooding; protection of existing natural barriers</td>
<td>Standards and regulations that integrate climate change considerations into design; land-use policies; building codes; insurance</td>
<td>Financial and technological barriers; availability of relocation space; integrated policies and management; synergies with sustainable development goals</td>
</tr>
<tr>
<td>Human health [WGII 14.6, Table 10.8]</td>
<td>Heat-health action plans; emergency medical services; improved climate-sensitive disease surveillance and control; safe water and improved sanitation</td>
<td>Public health policies that recognise climate risk; strengthen health services; regional and international cooperation</td>
<td>Limits to human tolerance (vulnerable groups); knowledge limitations; financial capacity; upgraded health services; improved quality of life</td>
</tr>
<tr>
<td>Tourism [WGII 12.5, 15.5, 17.5; Table 17.1]</td>
<td>Diversification of tourism attractions and revenues; shifting ski slopes to higher altitudes and glaciers; artificial snow-making</td>
<td>Integrated planning (e.g. carrying capacity; linkages with other sectors); financial incentives, e.g. subsidies and tax credits</td>
<td>Appeal/marketing of new attractions; financial and logistical challenges; potential adverse impact on other sectors (e.g. artificial snow-making may increase energy use); revenues from 'new' attractions; involvement of wider group of stakeholders</td>
</tr>
<tr>
<td>Transport [WGII 7.6, 17.2]</td>
<td>Realignment/relocation; design standards and planning for roads, rail and other infrastructure to cope with warming and drainage</td>
<td>Integrating climate change considerations into national transport policy; investment in R&amp;D for special situations, e.g. permafrost areas</td>
<td>Financial and technological barriers; availability of less vulnerable routes; improved technologies and integration with key sectors (e.g. energy)</td>
</tr>
<tr>
<td>Energy [WGII 7.4, 16.2]</td>
<td>Strengthening of overhead transmission and distribution infrastructure; underground cabling for utilities; energy efficiency; use of renewable sources; reduced dependence on single sources of energy</td>
<td>National energy policies, regulations, and fiscal and financial incentives to encourage use of alternative sources; incorporating climate change in design standards</td>
<td>Access to viable alternatives; financial and technological barriers; acceptance of new technologies; stimulation of new technologies; use of local resources</td>
</tr>
</tbody>
</table>

Note:
Other examples from many sectors would include early warning systems.
Past Emissions

Billion of Tons of Carbon Emitted per Year

Historical emissions

After Socolow and Pacala
The Stabilization Triangle

Historical emissions

Currently projected path = "ramp"

Billion of Tons of Carbon Emitted per Year

1955 → 2005 → 2055

After Socolow and Pacala
Beat doubling or accept tripling

Billion of Tons of Carbon Emitted per Year

Historical emissions

Currently projected path = “ramp”

Stabilization Triangle

Flat path

Interim Goal

Easier CO₂ target
~850 ppm

Tougher CO₂ target
~500 ppm

What is a wedge and does it help us think about this problem?
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.

Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years.

A “solution” to the CO₂ problem should provide at least one wedge.

After Socolow and Pacala
Billion of Tons of Carbon Emitted per Year

About a dozen "wedges"

Historical emissions

Flat path

After Socolow and Pacala
There are no silver bullets but there is much silver buckshot. Why do some economists object to the wedge concept? What will it take to realize a few wedges?

After Socolow and Pacala
<table>
<thead>
<tr>
<th>Sector</th>
<th>Key mitigation technologies and practices currently commercially available.</th>
<th>Policies, measures and instruments shown to be environmentally effective.</th>
<th>Key constraints or opportunities.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Supply [WGIII 4.3, 4.4]</td>
<td>Improved supply and distribution efficiency; fuel switching from coal to gas; renewable power; nuclear power; combined heat and power; early applications of carbon dioxide capture and storage (CCS) (e.g., storage of removed CO₂ from natural gas); CCS for gas, biofuels and coal-fired electric generating facilities; advanced nuclear power; advanced renewable energy, including tidal and wave energy, concentrating solar, and solar photovoltaics</td>
<td>Reduction of fossil fuel subsidies; taxes or carbon charges on fossil fuels; Feed-in tariffs for renewable energy technologies; renewable energy obligations; producer subsidies</td>
<td>Resistance by vested interests may make it difficult to implement. May be appropriate to create markets for low-emissions technologies.</td>
</tr>
<tr>
<td>Transport [WGIII 5.4]</td>
<td>More fuel-efficient vehicles; hybrid vehicles; cleaner diesel vehicles; biofuels; modal shifts from road transport to rail and public transport systems; non-motorised transport (cycling, walking); land-use and transport planning; second generation biofuels; higher efficiency aircraft; advanced electric and hybrid vehicles with more powerful and reliable batteries</td>
<td>Mandatory fuel economy; biofuel blending and CO₂ standards for road transport; Taxes on vehicle purchase, registration, use and motor fuels; road and parking pricing</td>
<td>Partial coverage of vehicle fleet may limit effectiveness. Effectiveness may drop with higher incomes.</td>
</tr>
<tr>
<td>Buildings [WGIII 6.5]</td>
<td>Efficient lighting and day lighting; more efficient electrical appliances and heating and cooling devices; improved cook stoves, improved insulation; passive and active solar design for heating and cooling; alternative refrigeration fluids, recovery and recycling of fluorinated gases; integrated design of commercial buildings, including technologies, such as intelligent meters that provide feedback and control; solar photovoltaics integrated in buildings</td>
<td>Appliance standards and labelling</td>
<td>Partly appropriate for countries that are building up their transportation systems.</td>
</tr>
<tr>
<td>Industry [WGIII 7.5]</td>
<td>More efficient end-use electrical equipment; heat and power recovery; material recycling and substitution; control of non-CO₂ gas emissions; and a wide array of process-specific technologies; advanced energy efficiency; CCS for cement, ammonia, and iron manufacture; inert electrodes for aluminum manufacture</td>
<td>Building codes and certification; Demand-side management programmes; Public sector leadership programmes, including procurement; Incentives for energy service companies (ESCOs).</td>
<td>Periodic revision of standards needed. Attractive for new buildings. Enforcement can be difficult.</td>
</tr>
<tr>
<td>Agriculture [WGIII 6.4]</td>
<td>Improved crop and grazing land management to increase soil carbon storage; restoration of cultivated paddy soils and degraded lands; improved rice cultivation techniques and livestock and manure management to reduce CH₄ emissions; improved nitrogen fertilizer application techniques to reduce N₂O emissions; dedicated energy crops to replace fossil fuel use; improved energy efficiency; improvements of crop yields</td>
<td>Provision of benchmark information; performance standards; subsidies; tax credits</td>
<td>May be appropriate to stimulate technology uptake. Stability of national policy important in view of international competitiveness.</td>
</tr>
<tr>
<td>Forestry/forests [WGIII 6.4]</td>
<td>Afforestation; reforestation; forest management; reduced deforestation; harvested wood product management; use of forestry products for bioenergy to replace fossil fuel use; tree species improvement to increase biomass productivity and carbon sequestration; improved remote sensing technologies for analysis of vegetation/soll carbon sequestration potential and mapping land-use change</td>
<td>Tradable permits; Voluntary agreements</td>
<td>Predictable allocation mechanisms and stable price signals important for investments.</td>
</tr>
<tr>
<td>Waste [WGIII 10.4]</td>
<td>Landfill CH₄ recovery; waste incineration with energy recovery; composting of organic waste; controlled wastewater treatment; recycling and waste minimisation; bioenergy and biogas to optimise CH₄ oxidation</td>
<td>Financial incentives for improved waste and wastewater management</td>
<td>May encourage synergy with sustainable development and with reducing vulnerability to climate change, thereby overcoming barriers to implementation.</td>
</tr>
</tbody>
</table>

Daily Energy Use Comparison (220 liter refrigerators)

- E U A
- E U A++
- China MEPS03
- China MEPS07
- Std 2010
- Std 2015

Image by MIT OpenCourseWare.
# U.S. Renewable Resources

Current ≈ 3000 GW

<table>
<thead>
<tr>
<th>Resource</th>
<th>Solar PV/CSP</th>
<th>Wind</th>
<th>Geothermal</th>
<th>Water Power</th>
<th>Biopower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>206,000 GW</td>
<td>8,000 GW (onshore)</td>
<td>39 GW (conventional)</td>
<td>140 GW</td>
<td>78 GW</td>
</tr>
<tr>
<td>Potential</td>
<td>(PV)</td>
<td>2,200 GW (offshore to 50 nm)</td>
<td>520 GW (EGS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11,100 GW (CSP)</td>
<td></td>
<td>4 GW (co-produced)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Image courtesy of DOE.
Variable Renewable Resources

Image courtesy of DOE.
Meeting all of U.S. demand with current PV technologies would require about 100-200 m² per person (average).

Variable source

Storage?

SmartGrid?

(With biomass, it requires 7000-9000 m²/person, or about 50% of the state area). What other factors make biomass controversial?
Need for carbon capture and storage?

**Central estimate of the potential for warming of the different fossil-fuel resources**
The red line indicates the limit of 2.0 °C warming from pre-industrial times agreed to under the Copenhagen Accord. Note, that here we only consider the effects of anthropogenic carbon dioxide. The potential for warming associated with proven Alberta oil-sand reserves is indicated as a barely visible sub-component (shown in blue) of unconventional oil (global). The potential warming of the total Alberta oil-sands oil-in-place (OIP) is shown in orange. *The carbon-climate response method is not valid for emissions above about 20x10^{17} g C, so these figures are not valid climate change estimates, but are included for comparison.*
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Snake Oil or Solution?

Olivine beaches everywhere?

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Source: Figure 1 in http://www.pnas.org/content/105/45/17295.figures-only.
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Figure 2.1. (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004.\textsuperscript{5} (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of $CO_2$-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of $CO_2$-eq. (Forestry includes deforestation.) [WGIII Figures TS.1a, TS.1b, TS.2b]

Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2.1, IPCC, Geneva, Switzerland. Used with permission.
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Clean-burning stoves: benefits for health and air quality as well as climate
‘Methane Only’: Technical measures for methane emissions

1. Extended recovery of coal mine gas
2. Extended recovery and flaring (instead of venting) of associated gas from production of crude oil and natural gas
3. Reduced gas leakage at compressor stations in long-distance gas transmission pipelines
4. Separation and treatment of biodegradable municipal waste through recycling, composting and anaerobic digestion
5. Upgrading primary wastewater treatment to secondary/tertiary treatment with gas recovery and overflow control
6. Control of methane emissions from livestock, mainly through farm-scale anaerobic digestion of manure from cattle and pigs with liquid manure management
7. Intermittent aeration of continuously flooded rice paddies
‘BC Tech’: Technical measures for black carbon

1. Replacing traditional coke ovens with modern recovery ovens, including the improvement of end-of-pipe abatement measures (in developing countries)

2. Replacing traditional brick kilns with vertical shaft kilns and Hoffman kilns where considered feasible (in developing countries)

3. Diesel particle filters for road vehicles and off-road mobile sources (excluding shipping)

4. Particle control at stationary engines

5. Improved stoves in developing countries in residential sector
Let’s discuss…

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12.340 Global Warming Science
Spring 2012

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