Fall Term – 2011
Woodrow Wilson School 585b

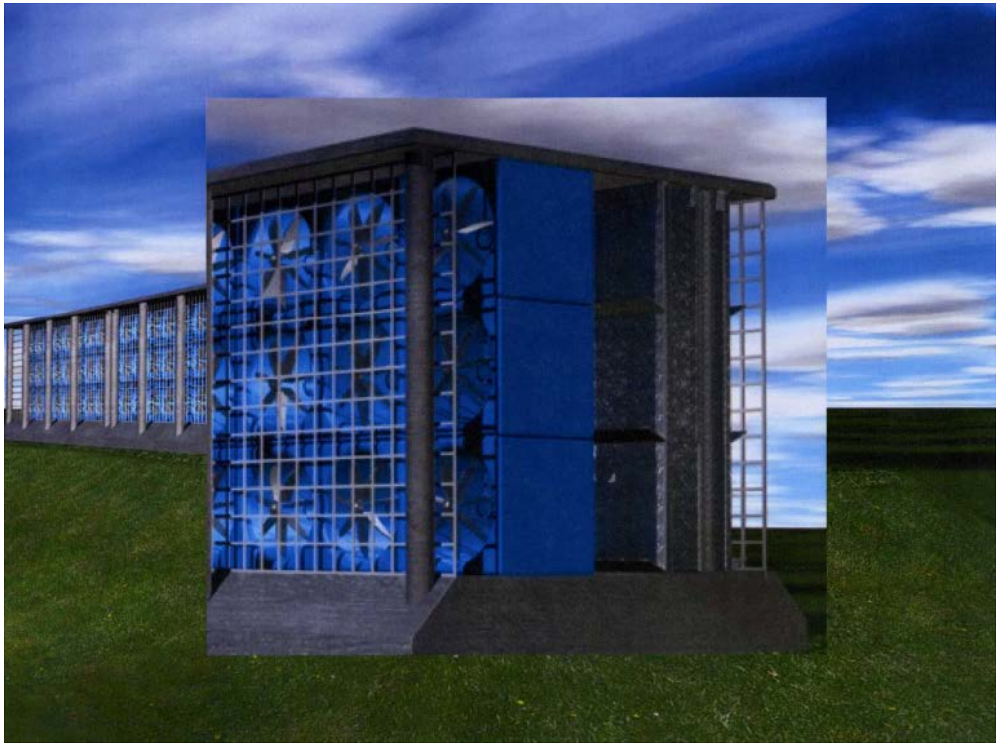
Living in a Greenhouse: Technology and Policy

Robert Socolow
Alex Whitworth

Week Ten: November 30, 2011
Geoengineering

Compensatory interventions in the climate system

Direct capture of CO_2 from air



Source: David Keith, MIT talk, Sept. 16, 2008

Injection of reflecting particles into the stratosphere

What if the current technocratic response is not sufficient?

Two possible reasons:

1. The world cannot implement the necessary changes.
   A. Inertia and habit
   B. Shortcomings of the available “solutions”

2. The world does implement the necessary changes, but the low-probability nasty outcomes turn out to be real.

Moral hazard

Geoengineering and traditional mitigation compete, if costs of geoengineering are low enough.

Even knowing that geoengineering *could* work will reduce, and *should* reduce, the level of effort on all other alternatives.

Exaggerating the commercial viability of geoengineering will lead to a flagging of mitigation strategies already known to be workable.

Structure of this lecture

Carbon dioxide removal

Solar radiation management

General considerations

Carbon Dioxide Removal

Carbon Dioxide Removal (CDR)

As emissions reductions founder, desires grow to find a way to undo today's emissions at a later time.

Vocabulary:

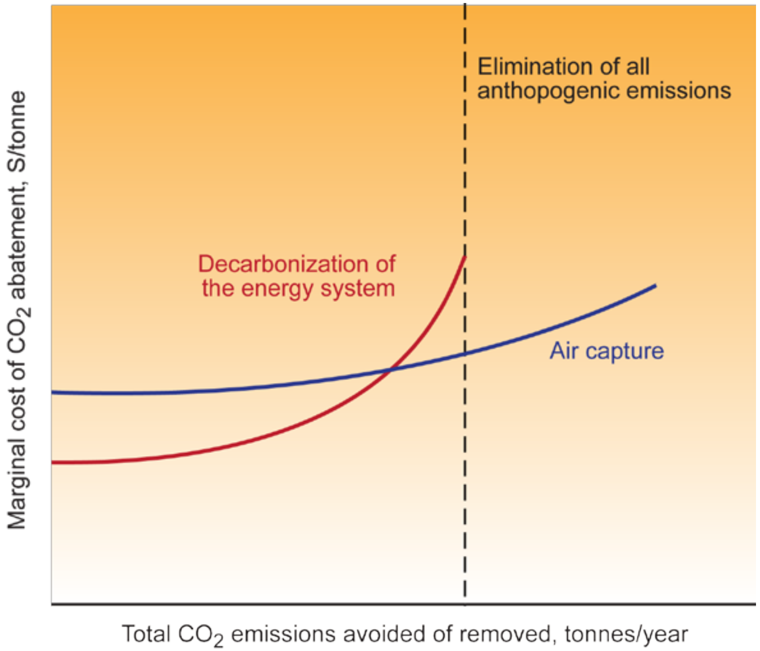
Overshoot trajectories (concentrations rise, then fall)
Net negative emissions
Negative emissions
CO_2 removal (CDR) strategies

Overshoot trajectories

An *overshoot trajectory* rises above some concentration target and then approaches the target from above. It requires sustained negative global emissions at some future time.

Particularly expensive emissions reductions include:

- some vehicle emissions (e.g., aircraft)
- emissions from natural gas infrastructure (e.g., furnaces and boilers in homes)
- the last few percent of emissions from centralized sources.



Royal Society CDR categories

- CDR – Carbon Dioxide Removal
  - Terrestrial Biological (stock augmentation in forests, soils)
  - BECS - Biological Energy with Carbon Storage (energy crops with sequestration)
  - Terrestrial Chemical (self-sustaining weathering of rocks)
  - Ocean (fertilization)
  - Direct Air Capture [POPA study terminology] (chemical capture at industrial scale)
- SRM – Solar Radiation Management

CO_2 removal (CDR) strategies are all doubtful at scale

Direct air capture (DAC) by chemicals: Capture costs exceed the already high costs of capture from flue gas. Requires socially acceptable large-scale CO_2 storage.

Biopower/biofuels with CCS: Formidable land competition. Requires socially acceptable large-scale CO_2 storage.

Bio-stock augmentation in forests and soils: Even more formidable land competition. Possible restoration benefit.

Ocean fertilization: Not yet established in principle.

Enhanced rock weathering: Not yet established in principle.

What would a forester do if only carbon matters?

Suppose you are a forester or an agronomist in a world where the carbon price is very high. You are told that *storing carbon* is your only objective, and that you will be paid handsomely (maybe, you will be given a share of the government payment). What would you do? Establish a monocrop? Pour on fertilizer? Be inventive….

What will go wrong if we move headlong to maximize either global biostocks or global biofuels without conditionalities?

For example, managing a forest exclusively for carbon storage or for biofuel , rather than for multiple objectives, may diminish biodiversity.

What are the right conditionalities?

Now, change roles. You are the policy maker in the same world. What conditionalities would you place on the carbon market for biostorage in the interest of eliciting actions you would welcome and deterring out comes you would decry?

Similarly, if your assignment were to provide a low-carbon fuel.

Expect the private sector to follow the letter of the law and to be “creative” where there are no rules.

Example: Fuel economy in cars and the EPA “driving cycle.”

Panel on Public Affairs (POPA), American Physical Society
Study of Direct Capture of CO_2 by Chemicals

Robert Socolow (Princeton), co-chair

Michael Desmond (BP), co-chair, since Oct 2009

William Brinkman (co-chair, start - 3/09), now Director of the Office of Science, DOE

Arun Majumdar (3/09 – 10/09), now Director of ARPA-E, DOE

Roger Aines (LLNL)

Jason Blackstock (IIASA)

Olav Bolland (NTU, Bergen)

Tina Kaarsberg (DOE)

Nate Lewis (Cal Tech)

Marco Mazzotti (ETH, Zurich)

Allen Pfeffer (Alstom)

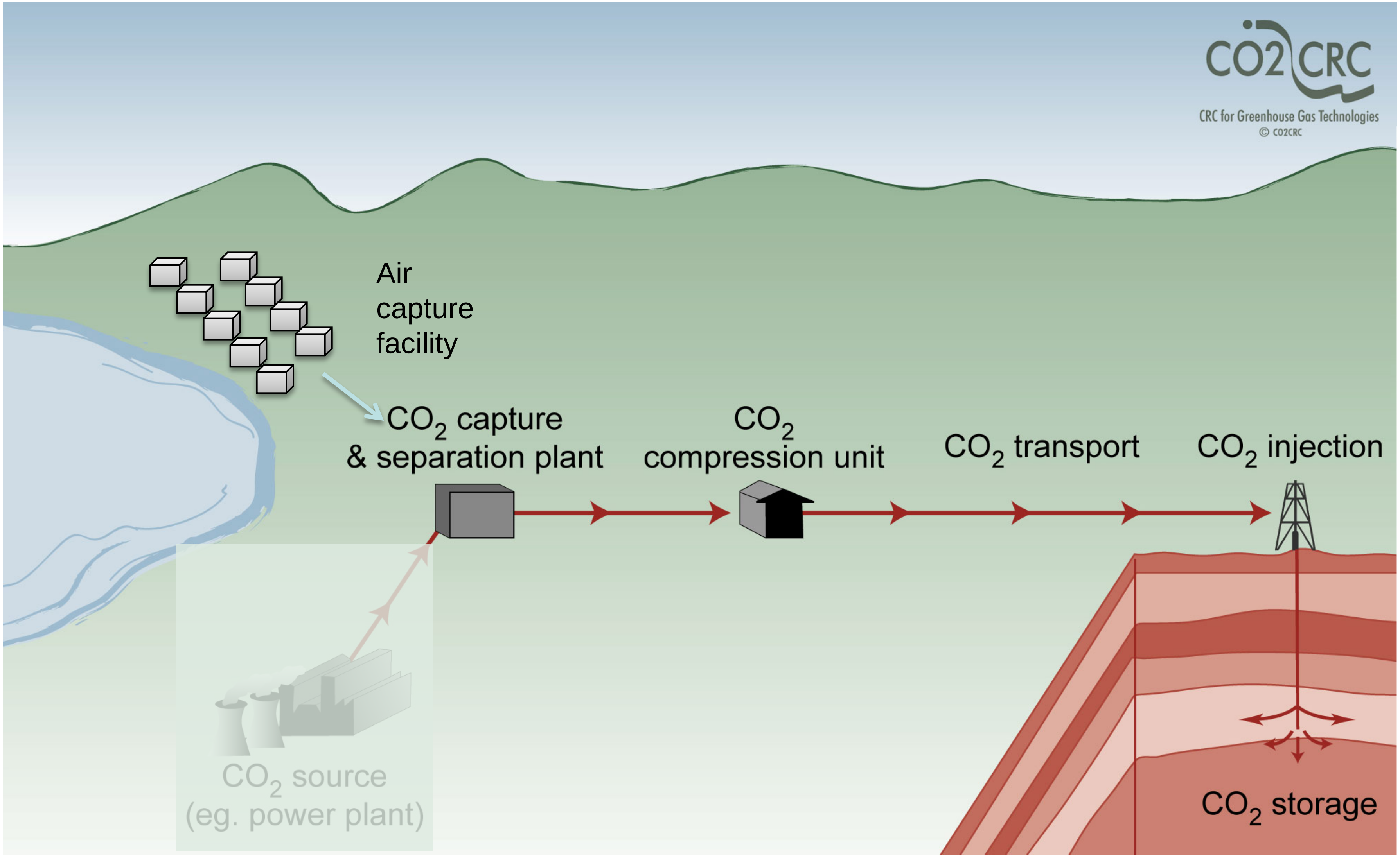
Karma Sawyer (UC Berkeley)

Jeffrey J Siirola (Tennessee Eastman)

Berend Smit (UC Berkeley)

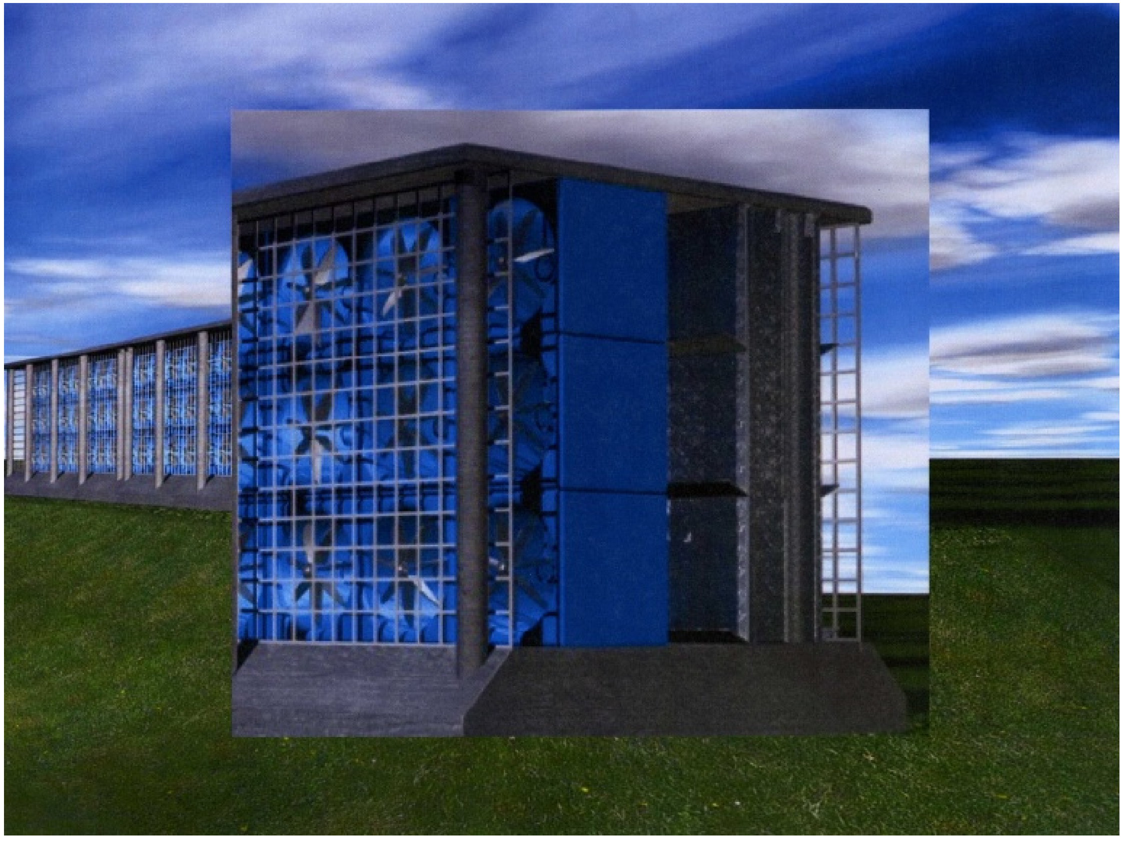
Jennifer Wilcox (Stanford)

Air Capture is a version of CCS



***Credit*: Lawrence Livermore National Laboratory, via Roger Aines**

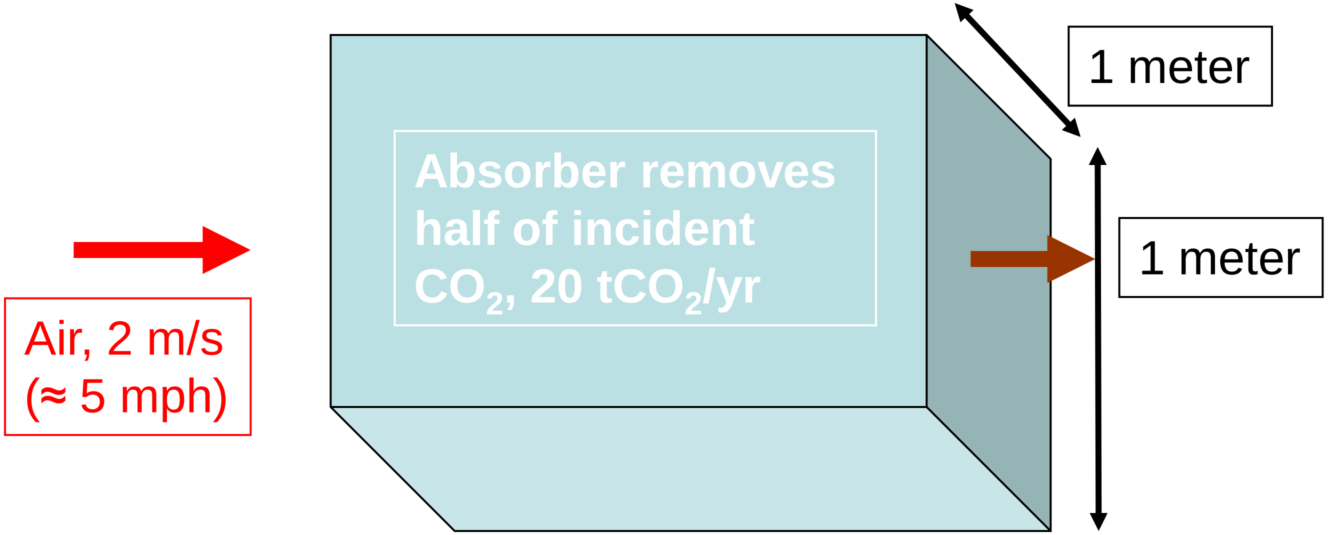
Artist's representation of a direct air capture (DAC) facility



Note, for DAC to be viable the *storage* part of CO_2 capture and storage (CCS) must be socially acceptable and affordable at huge scale.

Source: David Keith, MIT talk, Sept. 16, 2008

Compensating for the average American's emissions requires a contactor with the area of a window



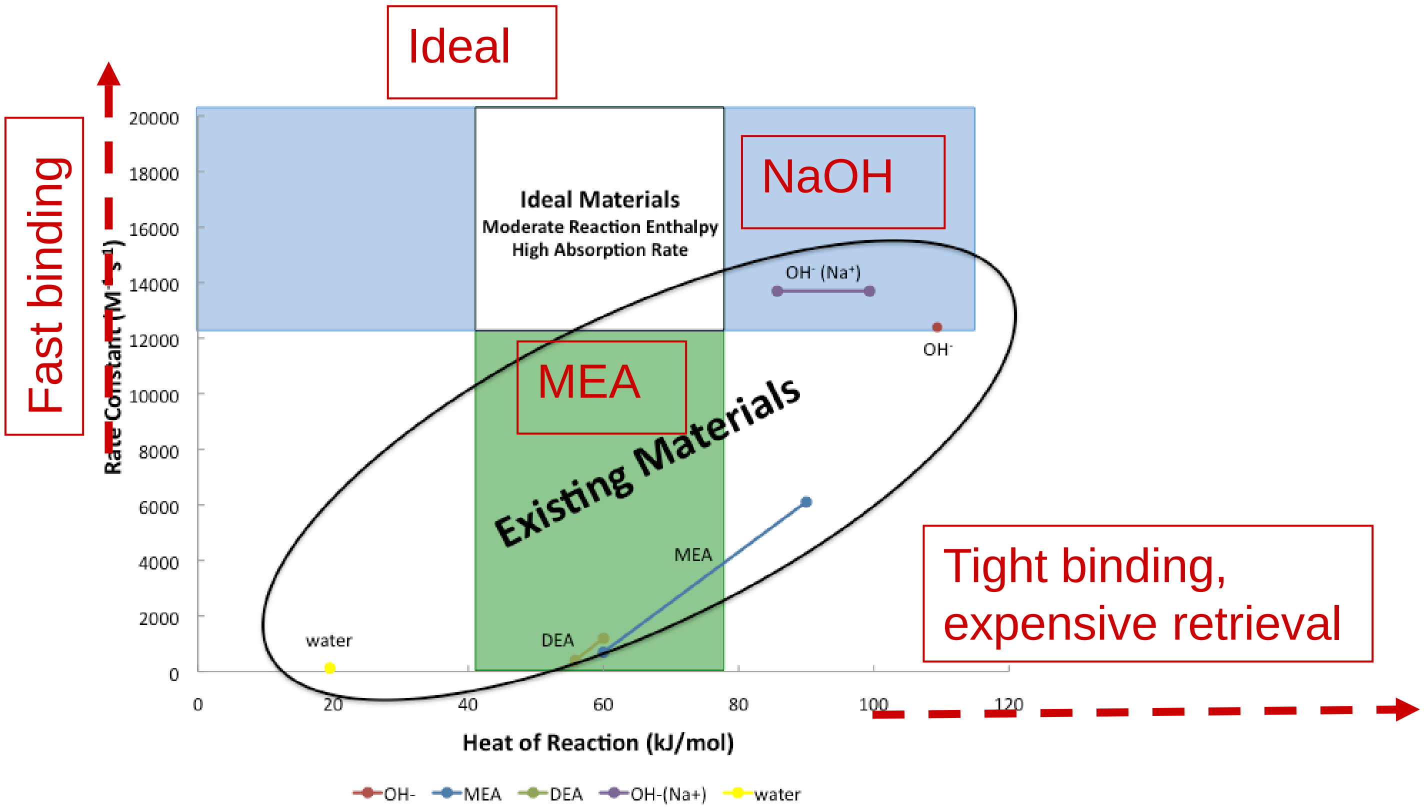
Ambient air flows over a chemical sorbent that selectively removes the CO_2. The CO_2 is then released as a concentrated stream for disposal or reuse, while the sorbent is regenerated and the CO_2-depleted air is returned to the atmosphere.

CO_2 sorption and desorption

Separation at amine contactor towers

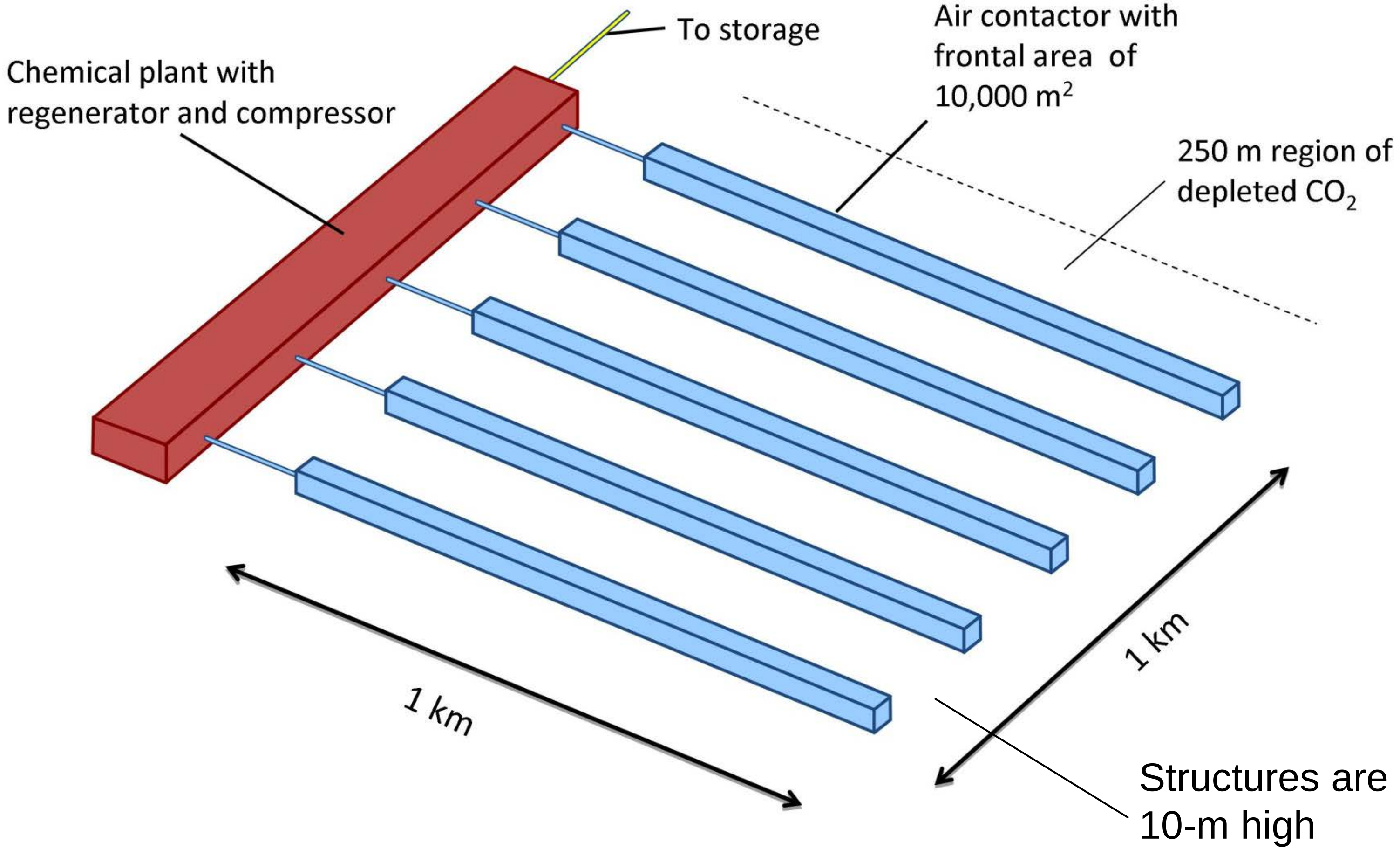
At In Salah, Algeria, natural gas purification by CO_2 removal plus CO_2 pressurization for nearby injection

A sweet spot for chemical sorbents:
Fast kinetics, modest enthalpy of binding



Rate constant (mol-sec/liter)$^{-1}$ vs. reaction enthalpy (kJ/mol)

A 1 $MtCO_2$/yr facility



A 1000 MW coal power plant would require six of these facilities. In all, 30 km of structures 10-m high.

The "net-carbon" challenge

A cost-multiplier, *y*, enters this problem:

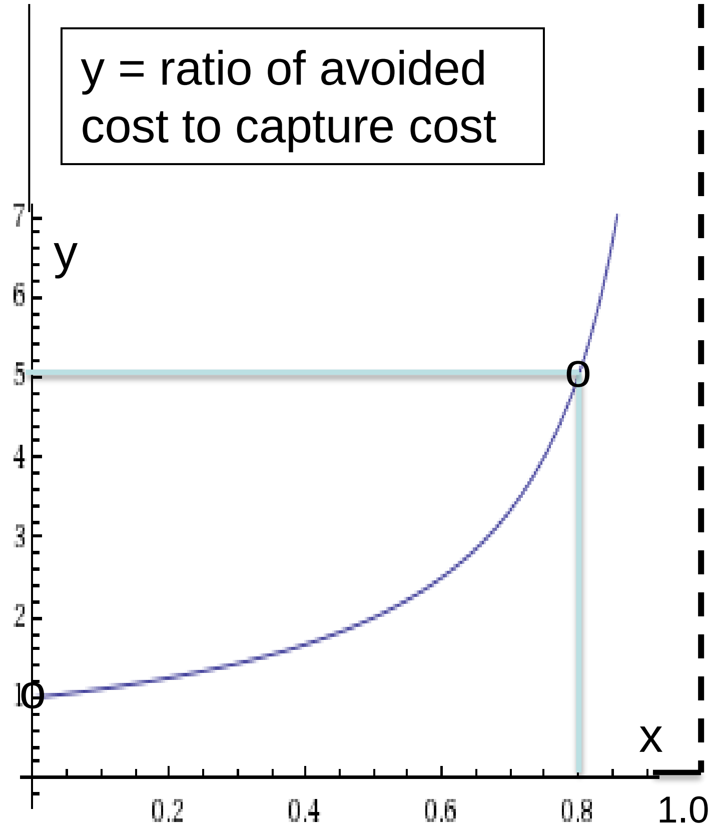
$$y = 1/(1 - x),$$

where *x* is the amount of CO_2 emitted per CO_2 captured.

If the cost per unit of CO_2 *captured* by the system is C_{cap} , then the cost per unit of CO2 reduction in the atmospheric stock (called the avoided cost), C_{avoid}, is given by:

$$C_{avoid} = y*C_{cap}$$

At $x = 1$, one CO_2 is emitted for every CO_2 captured.



x= CO_2 emitted per CO_2 removed

Example: Fan-driven air flow with pressure drop, $\Delta P = 100\ Pa$. Assume coal power (1.0 kgCO_2/kWh), 400 ppm CO_2, 50% capture,100% fan efficiency. Then $\mathbf{x_{fan} = 0.08}$. *Lesson*: Design is tightly constrained if high-C power is required.

Low-carbon leakage

How should a *decarbonized* energy source for DAC be evaluated, while the world still has coal plants venting CO_2? The same decarbonized energy source could have reduced global CO_2 emissions by retiring the coal plant.

N → ~~C~~ + N ***vs.*** N → C + DAC-N

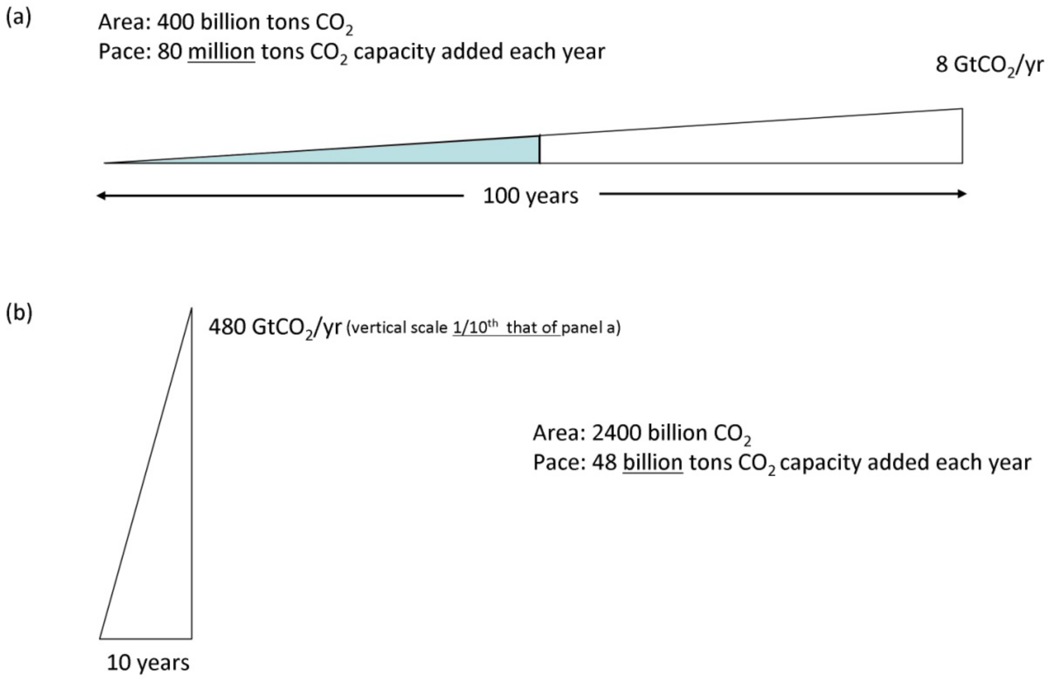
Baseline: Nuclear plant displaces coal plant. No DAC.

Alternative: Nuclear plant powers DAC, coal plant emissions continue.

Relative to baseline, DAC achieves no emissions reductions.

Special situations may show savings.

DAC is not matched to emergencies



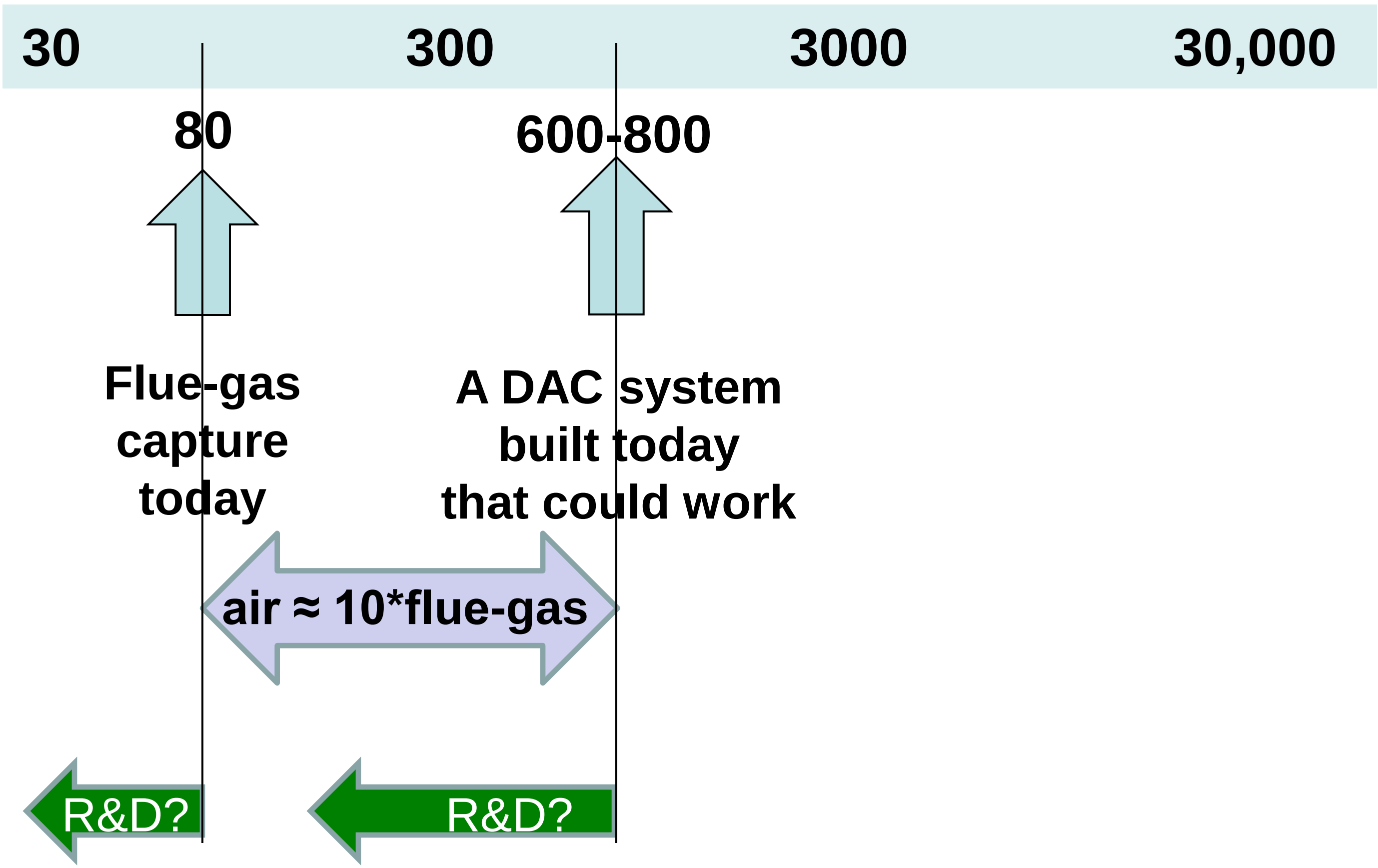
Two CO_2 removal strategies:

(a) In 100 years, down 50 ppm (total removal ≈ 400 $GtCO_2$, reference case)
(b) In 10 years, down 300 ppm (what a crisis might require)

The "pace" (the slope of the triangle) is 600 times larger for *b* than for *a*. Closing down all of the world's current power plants in three months also has a 48 $GtCO_2$/yr pace.

The land and ocean are assumed to be CO_2-neutral (not to outgas as CO_2 is removed).

Cost domains, in $/tonCO$_2$



Increment from Adding \$600/tCO_2 to Fuel and Power Prices

Natural gas	**\$33/1000scf**
Crude oil	**\$260/barrel**
Coal	**\$1400/U.S. ton**
Gasoline	**\$5.20/gallon**
Electricity from coal	**48¢/kWh**
Electricity from nat. gas	**21¢/kWh**

"Indirect" CO_2 emissions associated with production, transport or transmission, and distribution are not included.

Applicability of Direct Air Capture (DAC) for climate: Summary

First things first: Virtually all large-scale industrial CO_2 sources should be decarbonized before DAC is deployed.

DAC may be less expensive than electrification of some distributed fixed sources.

Depending on the availability and impacts of biofuels, DAC may help with transportation emissions.

DAC may be used someday to reduce the atmospheric CO_2 concentration.

A global thermostat

"Global Thermostat" (Eisenberger): Tune the CO_2 concentration (and, thereby, the surface temperature) by air capture.

Drive the concentration as low as desired, e.g., below pre-industrial.

Drive the concentration as high as desired, by storing CO_2 retrievably (parking it) – e.g., to prevent an ice age.

Can the world conceivably negotiate a most desired temperature?

Global thermostat (2 of 2)

Anticipate disputes, if someday the world confronts a choice among end-points of geoengineering.

We should not pretend that the pre-industrial world (the *status quo ante*) will be universally chosen as the end-point, nor any other world.

Nonetheless, there will be a bias toward retrieving the pre-industrial world. We planted crops where the rain fell and built our cities near rivers and coasts. Sea-level rise means moving inland. Sea-level fall means cities without access to the sea.

CO_2 to fuels?

Can CO_2 from air ever become a feedstock for fuels? A similar question arises for CO2 from flue gas.

CO_2 activation can proceed in two ways:

Directly: energy breaks a C-O bond and produces CO.

Indirectly: energy added to water produces H_2, then the “reverse water-gas shift reaction” activates CO_2:

$H_2 + CO_2 \rightarrow H_2O + CO$.

“Fischer-Tropsch” synthesis makes hydrocarbons from CO and H_2.

BREAK

Solar Radiation Management

Imitating Volcanos

On June 15, 1991 (three days after this photo) , Mt. Pinatubo. injected 10 million tons of sulfur into the stratosphere.

The Earth's average surface temperature was 0.5°C cooler six months later, then rebounded.

Sulfur injection: Epinephrine

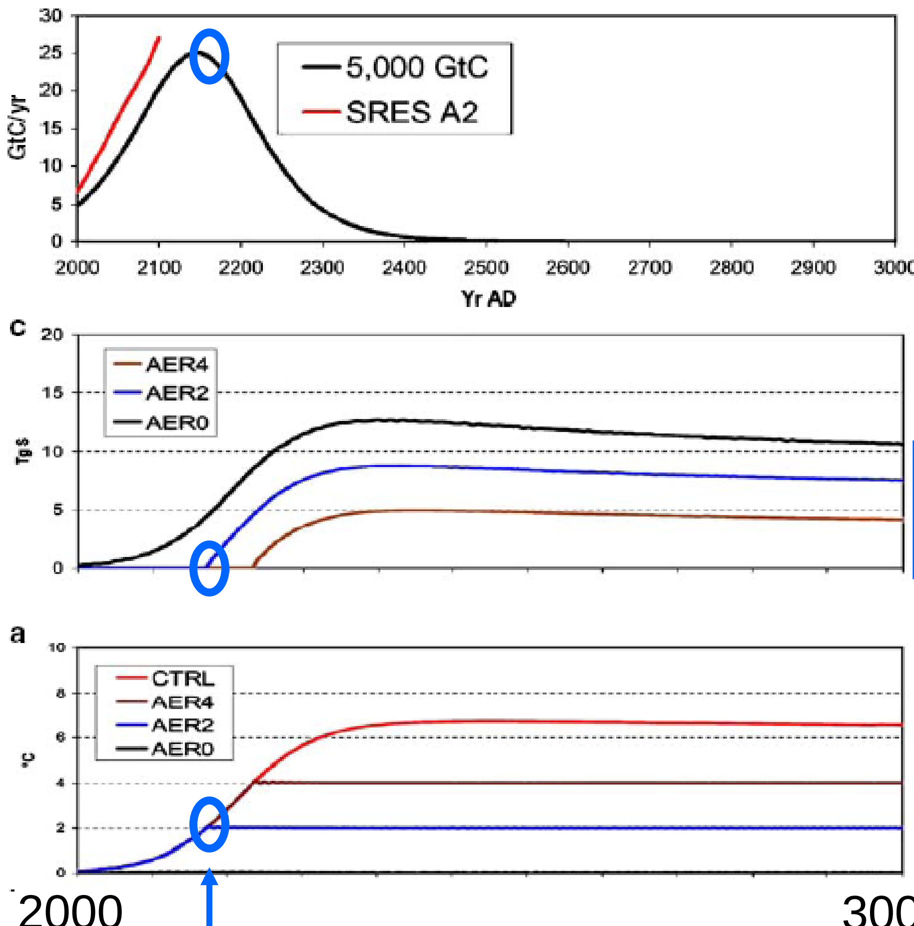
We may someday need “fast geoengineering,” matched to the sudden onset of a crisis. S injection acts quickly.

The analogy here is to the use of epinephrine to treat an acute allergic reaction. It is considered irresponsible for a doctor not to have epinephrine in his or her medicine cabinet.

But geoengineering today is “comparable with 19th century medicine.” (James Lovelock).

**Novim study group*: Steve Koonin (head), David Battisti, Jason Blackstock, Ken Caldeira, Doug Eardley, Jonathan Katz, David Keith, Ari Patrino, Dan Schrag, Robert Socolow.

Compensatory sulfur injection



Fossil fuel burn rate (GtC/yr): 3x today at 2150 peak

Pinatubo injection

Sulfur load (MtS)

Load required to sustain 2°C

Temperature rise (°C)

2°C

Injection to prevent exceeding 2°C begins ≈ 2170

Victor Brovkin, et al., *Climate Change*, 2008

Rapid disengagement

Rapid disengagement from S-injection might be

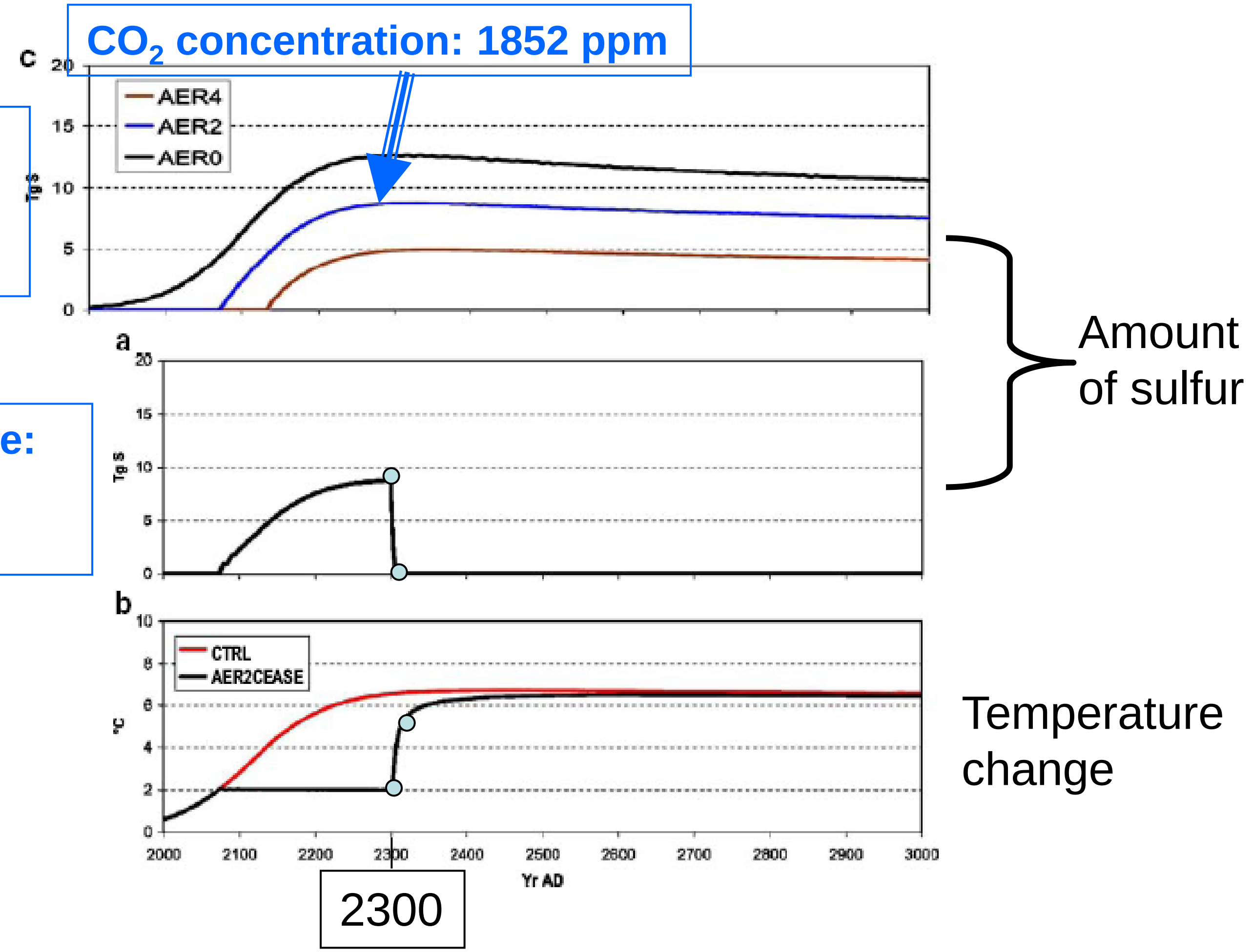
a. deliberate: An adverse side-effect is discovered.

b. unintentional: Loss of capability, political will.

The Sword of Damocles (1)

Sulfur injection succeeds in sustaining 2^{o}C

Whoops: System failure: S loading plummets to zero in 2300



Victor Brovkin, et al., *Climate Change*, 2008

The Sword of Damocles (2)

As a consequence of this interruption of injection, “within a few decades, winter warming in the polar regions exceeds 10^{o}C and summer warming in the northern temperate latitudes will be about 6^{o}C.”

“Coming generations will have to live with the danger of this ‘Sword of Damocles’ scenario, the abruptness of which has no precedent in the geologic history of climate.”

Victor Brovkin, et al., *Climate Change*, 2008

S injection: Deployment engineering

Issues include particle injection (e.g., by guns, balloons, or aircraft), dispersal (coagulation and settling out appears to be a challenge) and monitoring.

Also, alternative aerosols. Recent work (Keith) explores alternatives for particles and their placement that could achieving specificity with respect to wavelengths of reflection and absorption, height and latitude and time of placement, and chemical properties.

S injection: Climate science

Imperfect cancelation: Even if some desired average surface temperature is achieved exactly, there are consequences for regional precipitation, atmospheric and oceanic circulation, interannual variability, net ecological productivity, and other variables.

Stratospheric ozone: Adding particles to the stratosphere appears to read to reduced levels of stratospheric ozone.

Ocean acidification : Particle injection has no effect.

Acid precipitation: Sulfur emissions from S injection are small relative to emissions from coal power plants and smelters: a 10 MtS/yr increment on 50 MtS/yr.

Many ways to enhance albedo

Reflection can be enhanced:

- At the surface on land (white roofs)
- At the surface in the ocean (preserve and enhance floating ice)
- In the troposphere (cloud brightening)
- In the stratosphere (aerosol injection)
- In outer space (solar shields)

General Considerations

The engineered earth

In a fully engineered world:

- Every landscape is simplified
- The well-being of every non-human species is subordinated
- Instrumental values completely dominate.

Ahead are struggles over goals: levels of risk, inter-generational and intra-generational equity, responsibility for ecosystems and other species.

We will also struggle over processes: Who decides?

How strongly will geoengineering be resisted?

There is a widespread assumption that as the public becomes more alarmed, it will acquiesce in CO_2 capture and storage, nuclear power, and geoengineering, probably in that order.

But will rejection dominate? Rejection stems from:

belief in Murphy's Law

unwillingness to cede authority to experts

religious outrage at the prospect of unconstrained human self-determination.

Planetary enhancement

If we succeed in developing geoengineering for insurance, it will allow us to enhance the planet.

The analogy is genetic engineering, valuable for the treatment of many diseases, and also providing a capability to enhance the human species.

Earth enhancement

Genetic engineering now allows enhancement of the human species (prettier, taller, smarter,…)

Geoengineering will allow *enhancement* of the planet – notably, the moderation of extreme events:

warmer winters where people want them
cooler summers where people want them
less severe storms and droughts

} sweet spots

See Michael Sandel, T*he Case Against Perfection*. Enhancement can be pursued to excess. The ability to savor the life we have been “gifted” can be lost, as well as the random, the “unbidden.”

Enhancement *is* problematic

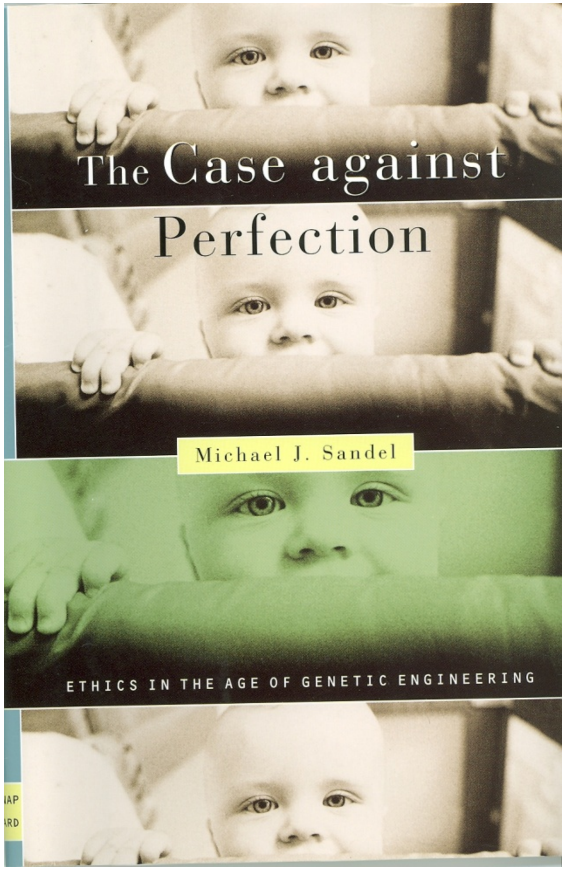
Analogies to medicine:

Michael Sandel sets up a dichotomy to explore modern medicine:

Cure or restore vs. enhance or perfect.

- Fertility and sex selection
- Eugenics
- Steroids and sports
- Cosmetic surgery
- Hyper-parenting

He argues that enhancement can be pursued to excess. He sees a loss of the ability to savor the life we have been “gifted.” He sees value in randomness, the “unbidden.”



“When science moves faster than moral understanding, as it does today, men and women struggle to articulate their unease.”

EXTRA SLIDES

EXTRA SLIDES:

Carbon Dioxide Removal

Terrestrial CDR (1 of 2)

Afforestation

800 Mha at 500 tCO_2/ha

reduces atmospheric CO_2 by 400 $GtCO_2$, or 50 ppm.

is a century-scale project.

can be compared to

today's forests: 1500 Mha tropical, 700 Mha temperate

today's tropical deforestation: 30 Mha/yr, 4 $GtCO_2$/yr.

Other versions of stock augmentation:

Biochar (charcoal) blended into soil

Low-till agriculture.

Fast-growing energy crops, conversion to power or hydrogen, storage of CO_2 (BECS)

These crops can remove ≈ 10 times more CO_2/ha-yr from the atmosphere than the slow-growing trees best suited for building up large stocks of standing biomass over a century, substantially reducing land requirements for equivalent quantities of CDR.

Terrestrial CDR (2 of 2)

Co-benefits

Enhancing the habitats of wildlife

Improving soil productivity

Net-carbon issues

CO_2 associated with planting, fertilizing, harvesting

For BECCS: energy used during energy conversion and CO_2 storage.

“Indirect emissions”: land-use “leakage” from one location to another.

Research questions

Long-term sustainability of very high yields

How to preserve forest benefits when priority is given to carbon storage

How to preserve soil quality and yield while removing nutrients

How to protect biodiversity while introducing new species.

Ocean Iron Fertilization

Idea: Where Fe is a limiting nutrient in the ocean, dump iron filings off the back of a barge. Algal blooms, shell formation up the food chain, and sinking shells will follow (the ocean's "biological pump").

Strong commercial interest. Planktos and Climos

Controversy regarding:

- whether it works at all,
- whether successful capture can be measured,
- how adverse its environmental consequences are.

Direct Air Capture vs. Wind

Compare wind power with the "power" in CO2 removal.*

Suppose all the CO_2 is removed from the wind intercepting 1 m^2 of area at v = 6 m/s.

The flux in this wind is $\frac{1}{2} \rho v^3$ = 140 W/m^2. (Air density is 1.3 kg/m^3.)

The flux of CO_2 in this wind is 580×10^{-6} kg(CO2)/kg(air) * ρv
= $580 \times 7.8 \times 10^{-6}$ kg(CO_2)/m^2-s = 4.5 gCO_2/ m^2-s

A coal plant emits produces about 1 kg(CO_2) per kWh, so the CO_2 in the wind is associated with 4.5 Wh/m^2-s = 16,000 W/m^2.

We observe that capturing the CO_2 carried by an air stream "reduces emissions" about 100 times more than harnessing the kinetic energy in an air stream of equal sweep area.

Several groups are developing adsorption-desorption systems to capture CO_2 from air at this time.

*This calculation was suggested by Klaus Lackner.

The APS Study

Chronology

POPA Energy & Environment Committee recommends study

Authorized by POPA (unanimously), October 3, 2008.

Endorsed by APS Executive Board, November 15, 2008.

Internal review (21 reviewers), April 2010

Manuscript to APS for review, May 17, 2010

APS establishes a review committee chaired by Rob Goldston, two rounds of review. December 2010: 3 to 1 recommendation to approve.

POPA discussion, Feb 4, 2011.

Revised Executive Summary, POPA recommends E-Board approval (vote: 9 to 5, 2 abstentions, 6 not voting), April 2011.

Sponsors

American Physical Society
U.S. Department of Energy
Dreyfus Foundation
Gerry Lenfest
National Commission on Energy Policy

Table of Contents

Three privately funded programs

David Keith – absorption in aqueous NaOH, cross-flow (cooling tower design), regeneration of NaOH.

A pilot project is being prepared, at least for the contactor.

Klaus Lackner – Amine-impregnated solid adsorbents, humidity swing (adsorb dry, desorb wet). Carbonate-bicarbonate cycling.

Proposal: mass-produced, truck-sized units, wind power.

Low humidity required, probable limit to percent CO2 in product.

Peter Eisenberger – Silica-supported hyperbranched amine adsorbents, thermal-swing.

Goal is to cycle at modest temperatures, use “waste heat.”

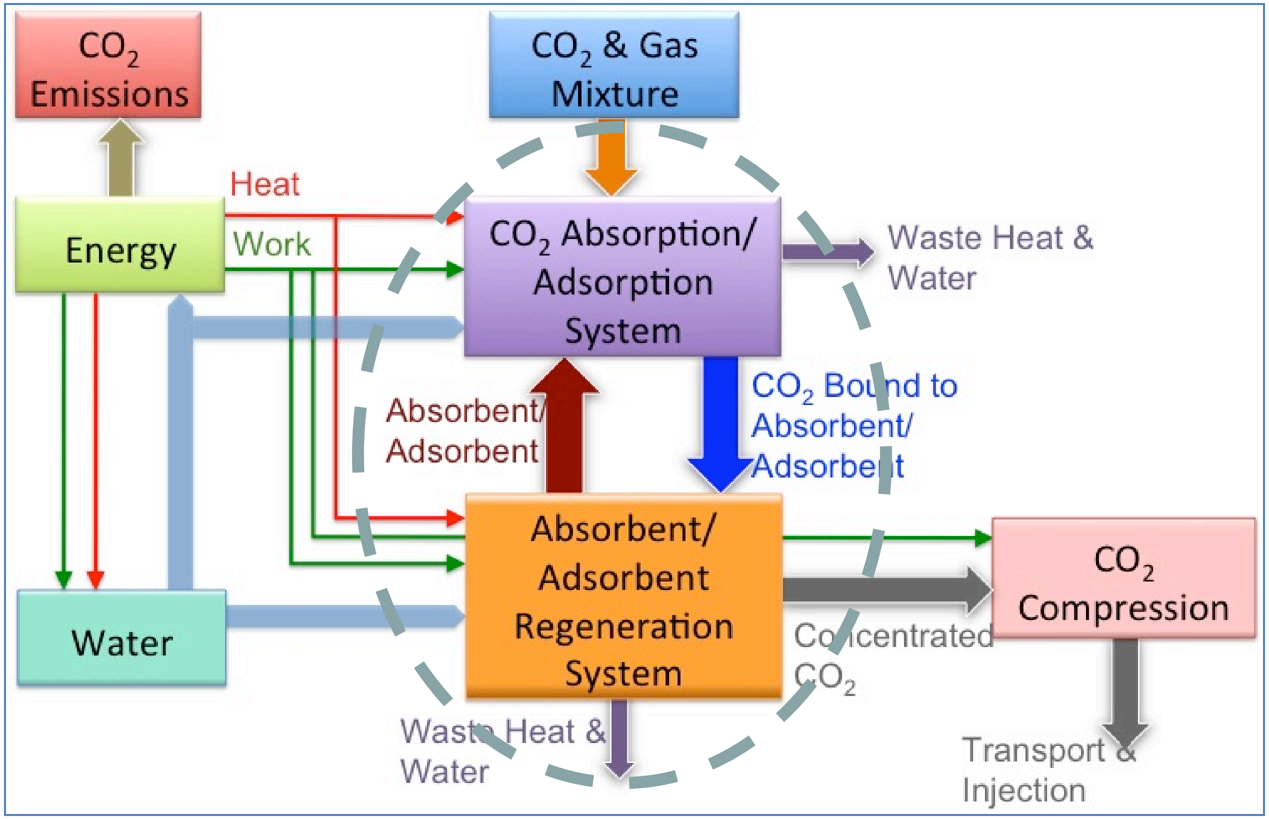
As a matter of policy the APS Committee sought to avoid learning any of their ideas that could not be made public.

Pedagogy

One objective of the report is to enable scientifically literate non-specialists to think independently about DAC, whether they are primarily interested in advancements in DAC technology or in placing DAC in a policy context.

Throughout, the report seeks to demystify, to explain unfamiliar vocabulary, and to work through representative calculations.

Generic CO_2 capture from a gas mixture



The CO_2 concentration in the flue gas at coal plants is 300 times higher than in air. For DAC, 1) huge volumes of air must be moved, and 2) strong sorbents are required, with large regeneration energy costs.

DAC research

Judgments about future roles for DAC and its future costs are necessarily constrained by the near absence, at this time, of experimental results for DAC systems.

A well designed and vigorous PCC-focused research program can address many of the relevant research issues that are critical for both PCC and DAC. Unique characteristics of the DAC research frontier, however, may justify a research program less tightly coupled to post-combustion capture.

Likely public discussion of costs

The value of \$600/tCO_2, reported as an estimate of the minimum cost for any workable and scalable system that could be built today, will be understood to be a wet blanket for air capture. The cost is developed alongside a cost for post-combustion capture, enabling readers to work out for themselves why air capture costs appear greatly to exceed the already high costs of capture from flue gas. The explicit zeroth-order cost methodology will be welcomed.

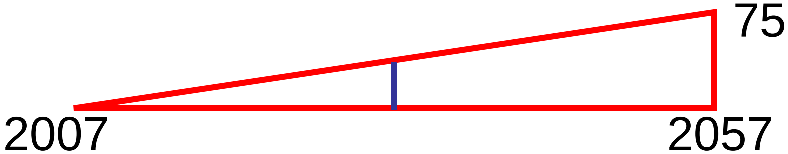
Advocates of DAC, including those pursuing privately funded R&D, will attach the report, because it counters low cost estimates, generally poorly documented, already in play. Key individuals will argue, correctly, that the committee did not assess their approach.

A few critics may attack the report from the opposite direction, claiming that the minimum cost for anything that could be built today is far higher than the cost cited. The counter will be that all three of the industry scientists on the committee, with approximately 100 years of costing under their belts, prefer the estimate in the report.

EXTRA SLIDES:
Solar Radiation Management

A transient wedge

***Transient*: The aerosol wedge is the construction of 700 GW of coal plants over 50 years *along with* compensating aerosol injection.**



75,000 tS/yr as SO_2 (*in 2057, and thereafter!)*

Quadratic: ¼ as much injected in 2032

1 $MtSO_2$ injected, 2007-57.

1 wedge = ramp of avoided CO_2, linear to 1GtC/yr after 50 yrs.

= 25 GtC not in the atmosphere in 2057.

1 GtC ≈ 3,000 tS as SO_2 ≈ .0075 W/m^2 (Keith). 1 year residence time for SO_2.

1 wedge is also a linear ramp for 700 large (1000 MW) nuclear plants or one million large (2 MW) windmills *instead of* 700 GW of coal plants.

Compare the situation after 2057. For nuclear or wind, forcing will not climb. For aerosol injection, the full forcing of the additional 1 GtC will be felt by 2058, unless 75,000 tS is injected that year too, and for hundreds of years after than, until this coal-CO_2 leaves the atmosphere (about 15% of the CO_2 never does). Institutional capabilities for all options persist past 2057.

Undo global warming by diverting sunlight

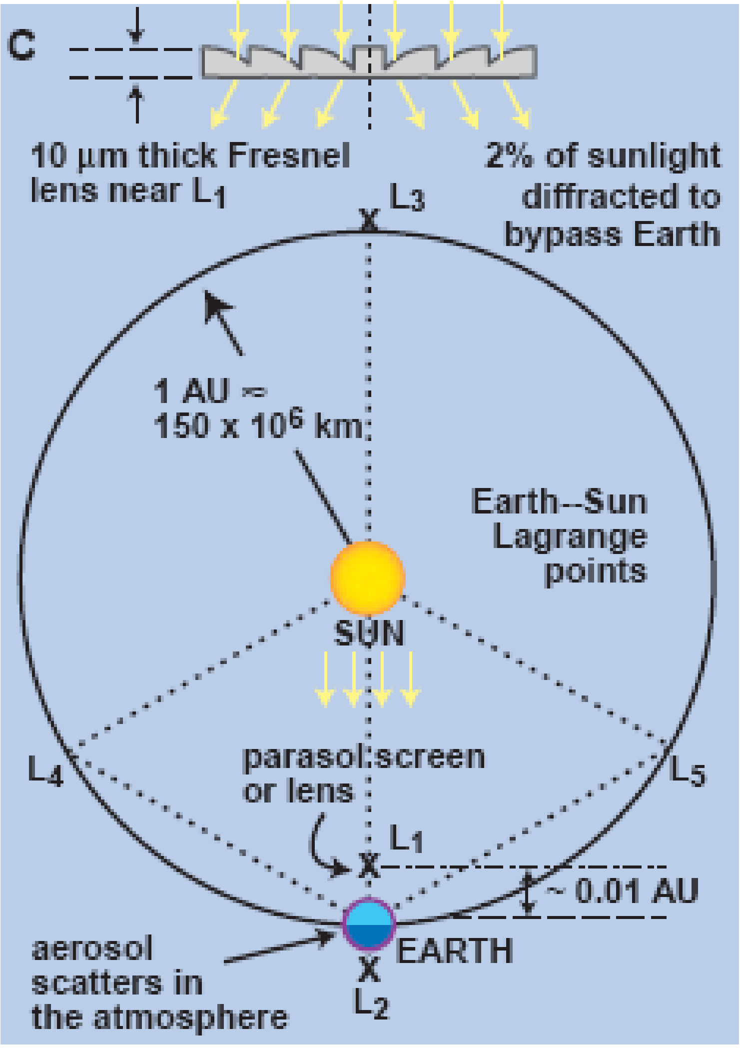
- Lagrange exterior point, L1: 1.5x10^6 km from Earth Moon is 3.84x10^5 km from Earth

- Diameter: 2000 km

- Thickness: 10 µm

- Mass: 10^11 kg.

source: Hoffert, 2002

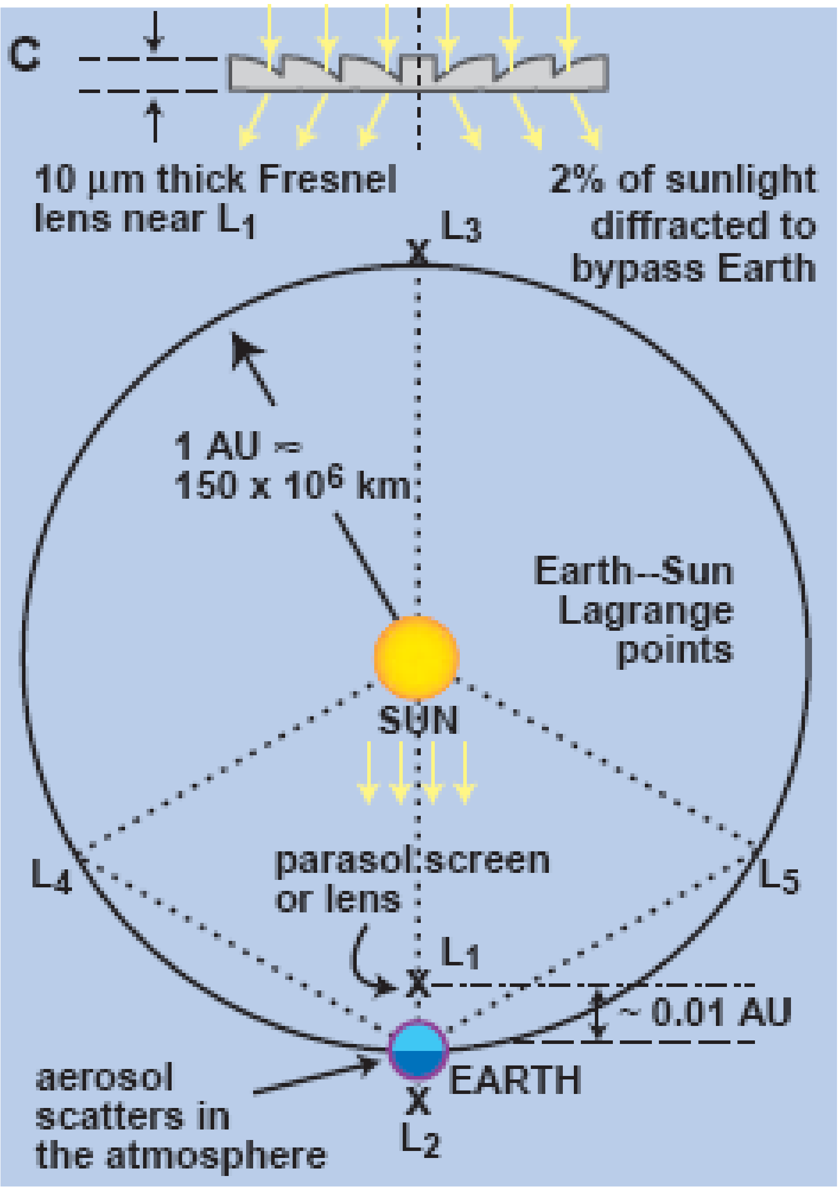


Source, Trenton Franz, this course, 2005

A Reflector in Space

- Lagrange exterior point, L1: 1.5×10^6 km from Earth
  Moon is 3.84×10^5 km from Earth
- Diameter: 2000 km
- Thickness: 10 µm
- Mass: 10^{11} kg.

Source: Hoffert, 2002



Slide by Trenton Franz, CEE, 1G, Dec 2005

Effect of Aerosols

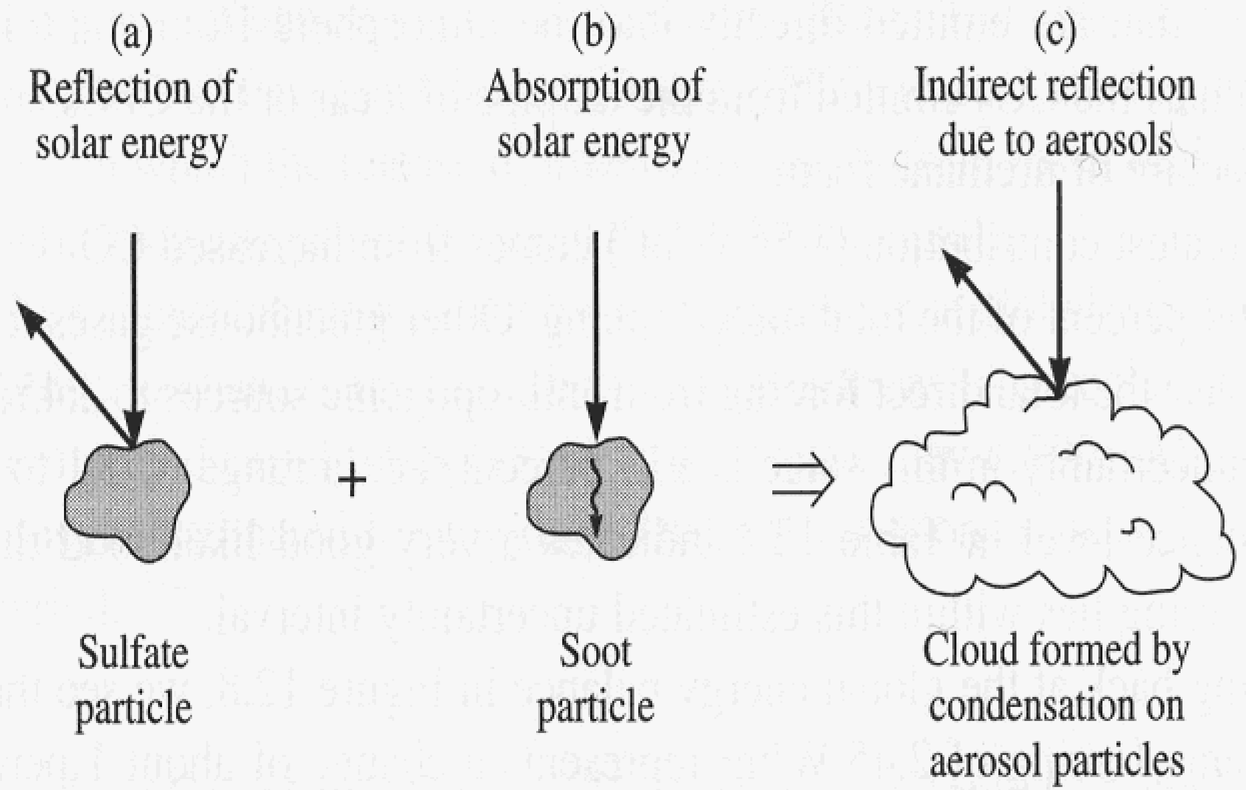


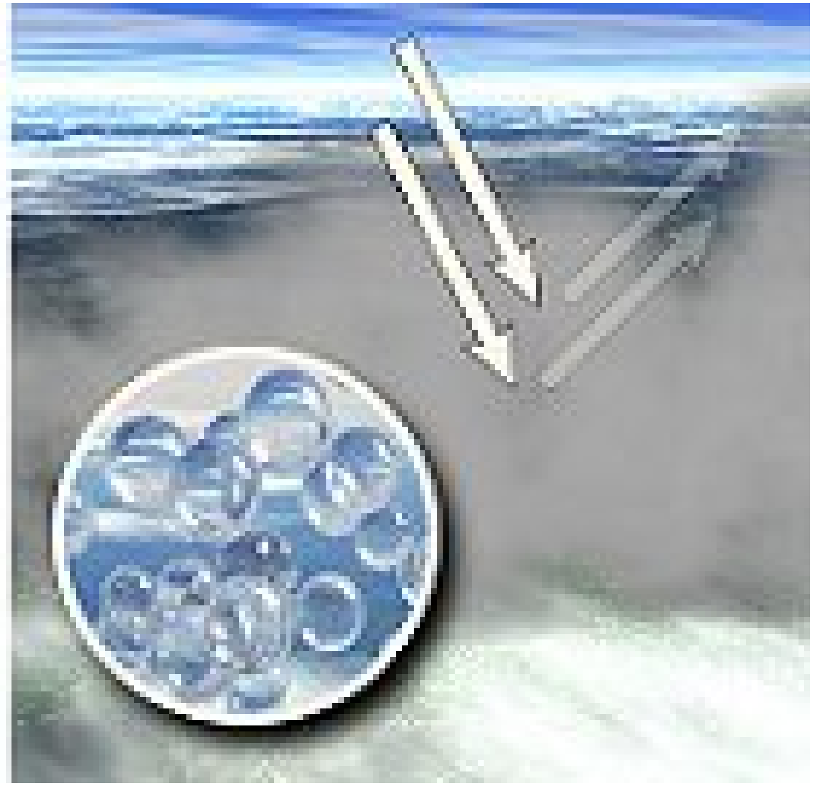
Figure 12.12 Direct and indirect effects of atmospheric aerosols. Most aerosol particles, such as sulfates (a), directly reflect radiation, although some particles, like soot (b), are direct absorbers. Indirect effects are caused by clouds that form as a result of atmospheric aerosols.

Rubin, p. 496

Indirect effects of particles

1st Indirect Effect:

More aerosol (cloud condensation nuclei) → More cloud droplets → *More reflecting clouds* → Less sunlight to surface → Cooling



2nd Indirect Effect:

More aerosol (cloud condensation nuclei) → More, smaller cloud droplets → Less precipitation → *Longer lived clouds* → Cooling

Source: Cynthia Randles, this course, 2005

EXTRA SLIDES:

General Considerations

Boundaries of Geoengineering

We might as well start with Tom Schelling, who received the 2005 Nobel Prize in economics. He proposes three defining characteristics:

Global, not local, in scale.
Intentional, not accidental
Unnatural, not within nature's natural excursions

Global: Sometimes, useful also to discuss large regions: global and regional geoengineering.

Intentional: Keith suggests restricting geoengineering to those intentional actions that are "*countervailing*" actions that compensate for undesired consequences of other actions, and excluding actions that *enhance* desired consequences (pest-resistant crops).

Unnatural: Schelling wishes to exclude reforestation, while Keith considers all sink management to be geoengineering. An example of sink management would be the large-scale extraction and separate sequestration of carbon from intensively irrigated and fertilized genetically modified crops.

What is geoengineering?

A new concept. Not in dictionaries or my spell-checker.

One of many relatively new odd-couple compound words and phrases, a centaur – one part from nature and one part from the human world:

- Eco-tourism
- Industrial ecology
- Green design, Green buildings, Green materials
- Land ethic
- Climate stabilization
- “Earth in the Balance”

Keith comments (p. 277) on “an underlying feeling of abhorrence that many people feel for geoengineering,” an unease about “the eroding distinction between natural and artificial” and about “the biosphere as an artifact.”

The boundaries of the word are not yet well defined, and issues regarding where the boundaries lie are instructive.

What strategies lie beyond CO_2 emissions reductions?

- CO_2 sink enhancements (atmospheric scrubbing)
  - Build up the biological stock of carbon
    - Reforest: increase in carbon intensity of existing forests
    - Build up soil carbon with perennials
    - Enhance the ocean biological pump, e.g., iron fertilization
  - Direct capture from air
- Albedo management (“geoengineering”)
  - A huge mirror near L1
  - Particles in the stratosphere
- Non-CO_2 greenhouse gases (e.g., source reduction and sink enhancement for methane): “CO_{2e}”
- Adaptation (infrastructure, warning systems, health care, insurance) -- a major omission from this course.

The core of geoengineering: Manipulating the albedo and the carbon cycle

Geoengineering highlights two classes of strategies that directly compensate for the global climate change brought about by the increasing atmospheric CO_2 concentration. 1) remove CO_2, and 2) increase the Earth's albedo.

1. Move CO_2 from the atmosphere ("engineered sinks" or "enhanced sinks"):
    a. to the land (reforest, low-till agriculture)
    b. to the deep ocean (fertilize by providing the limiting nutrient, e.g., P, Fe; also, preserve wood by burial or placement in the sea)
    c. by direct capture from the air
2. Increase albedo
    a. via aerosols in the troposphere or stratosphere
    b. via engineered systems placed on land, in the sea, in the stratosphere, or in space
    c. via protecting arctic ice

Geoengineering to undo the *consequences* of climate change

Keith restricts his attention to “climatic geoengineering,” which addresses only the Earth’s energy balance and its energy distribution. Others allow geoengineering to include strategies that undo the *consequences* of climate change. This brings forward strategies that, in combination, might be a credible substitute:

- To counter sea-level rise – **enhance Antarctic snow**
- To counter ocean acidification – **add carbonate ion or remove chloride ion**
- To counter a weakening of the thermohaline circulation – **add salt south of Greenland or redirect arctic fresh water from the Atlantic to the Pacific**
- To weaken hurricanes – **put surfactants on the sea surface to reduce heat transfer**
- To slow the build-up of CO_2 in the atmosphere – **deliberately take CO_2 out**!

Along this continuum (cf. hurricanes) one moves to regional geoengineering, which then is applicable also to environmental problems that are entirely regional. To counter the anoxia at depth in the Baltic Sea due to eutrophication, deliberately inject oxygen at depth. To cool cities, require white roofs and white streets.

Geoengineering manipulates only non-human systems

All authors include in geo-engineering only those strategies that *act directly on non-human systems*.

In addressing hotter climates, manipulating the albedo is included, but not air-conditioning.

In addressing sea level rise, enhancing snow in the Antarctic is included, but not building dikes.

In addressing droughts, rain-making is included, but not canals.

Keith uses this distinction to exclude capture and storage of fossil-energy CO_2 from geoengineering, calling it “industrial carbon management” and locating it between mitigation and geoengineering.

The distinction is not always obvious. Does regional geoengineering include national parks created to preserve wildlife habitat? If not, is that because it is “natural.”

A few problematic issues

- Aren’t we doing geoengineering already?
- Do we know enough?
- How could we get it done? (Who would do what? Who would pay? Who would decide?) Legitimacy.
- Winners and losers? Fairness.
- Separate “prepare” from “deploy”? Slippery slope.
- Moral hazard? Will we become distracted and lazy, or will it catalyze change?
- Are the objectives good ones? Like: When is a war a “just” war?
- How are non-human species to be considered?

Thoughts to add

"Insurance," "catastrophe," "draconian," "tune the planet, direct climate enhancement"

A big new idea: Human influence large enough to modify the planet. The changing atmosphere is just one example. Look at our impacts on forests, fish, groundwater, our oil legacy.

What generated Rio and the Bush I years? There were no dramatic breakthroughs or punctuated moments over the past half century. Closest to such an event are Keeling's first findings and the Russian-French ice cores. Add more indirect influences: seeing the Earth from space and discovering the ozone hole.

Abiotic/biotic; abotanic/botanic. The latter is the right concept for dividing direct capture from air into two groups, because carbonic anhydrase variants are in the same category with absorbents.

When the next big eruption happens, are climate scientists as ready to spring into action, as astronomers are for the next supernova?

Nightmares about Geoengineering

My end-of-meeting talk

The Asilomar International Conference
on Climate Intervention Technologies

March 25, 2010

Nightmares related to:

- Geoengineering science and technology
- Geoengineering policy
- Geoengineering values

Nightmare: SRM runs a while, then is terminated abruptly.

Rapid disengagement from S-injection might be:

a. *deliberate*: An adverse side-effect is discovered.
b. *unintentional*: Loss of capability, political will.

“Coming generations will have to live with the danger of this ‘Sword of Damocles’ scenario, the abruptness of which has no precedent in the geologic history of climate.”

Victor Brovkin, et al., *Climate Change*, 2008

Nightmare: All the climate scientists are working on geoengineering.

Dual Use!

- Clouds and aerosols
- Forest dynamics
- Ocean biology

Wouldn’t it be better to “sell” the needed R&D better as a benefit on the margin of a program addressing the global imperative of improving our understanding of the Earth?

We also need to prepare to learn from the next volcano.

Nightmare: Soon, stratospheric aerosol injection is actually used by a rogue state

… well before international norms are established.

Nightmares related to conventional mitigation and adaptation

1. Nuclear weapons proliferate as global nuclear power expands, due to weak international governance, and there is a nuclear war.

2. After wide deployment of CCS is under way, a major escape of CO_2 from a reservoir undermines public confidence.

3. Human beings, nearly universally today, have defined the good life in terms of self-realization. Zealots take charge and squelch our exuberance (our appetite for variety, our curiosity about other places)

Nightmare: Geoengineering is adopted without debate.

Geoengineering should be greeted with awe. It should not become part of the human agenda before it is linked to the profound existential questions of human purpose and our place in the natural environment. (Leinen)

A geoengineered world bears almost no resemblance to the world desired by environmentalists, who seek to *reduce* the influence of humans on other species and ecosystems.

Nightmare: Geoengineering contributes to the rejection of science as a way of knowing.

Imagine describing environmental problems and formulating and evaluating “solutions” without science.

Cherish the norms of science: open, welcoming of newcomers, cosmopolitan, iterative. These are our jewels.

Anticipate adverse environmental and social impacts of "solutions."

There are no trouble-free ways to manage global carbon: Every wedge strategy can be implemented well or poorly.

Although every wedge has co-benefits that generate alliances and improve the prospects of implementation, every wedge also has a dark side, generating opposition that thwarts implementation.

"Solution science" is emerging: the study of the environmental and social costs and benefits of the stabilization wedges.

A message to those who are drawing up guidelines

Say up front: Geoengineers must not police themselves.

Say this before others say it.

Concede that geoengineering may not be needed.

Muddling through is a legitimate alternative.

Anticipate, imagine what could go wrong.

The norm is good intentions gone awry.

Measure, evaluate, iterate: *Incredibly hard to do*.