Ethics and Issues Surrounding Geo-Engineering to Mitigate Climate Change

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May 12, 2011
Osher Lifelong Learning Institute
F803 Climate Change: Impacts, Solutions and Perceptions

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[Adjusted Title] Incentives, Options, Issues and Ethics Surrounding Potential Use of Climate Engineering to Mitigate/Counterbalance Climate Change

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Definitions and terminology are fluid and evolving

Geo-engineering: The large-scale modification of the natural environment. Examples include:

- Intentional (for human benefit)
  - International agricultural production of food
  - Water storage and supply systems
- Unintentional (impacting the environment)
  - Air and water pollution (nitrogen and phosphorus)
  - Global climate change from fossil fuel emissions

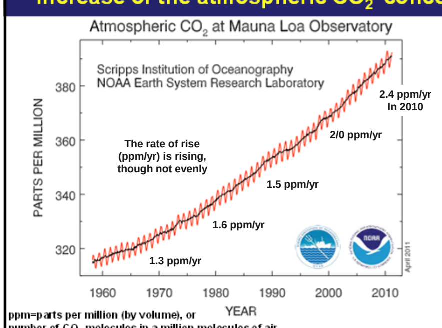
Climate-engineering: The intentional, large-scale modification of the natural environment to moderate or counter-balance human-induced global climate change:

- Carbon Dioxide Removal (CDR) to increase the loss of trapped heat from the Earth
- Solar Radiation Management (SRM) to reduce the Earth's uptake of solar heating

As the lectures in this course have made clear, the world faces a very challenging dilemma

- Fossil fuels provide tremendous benefits to society
  - Supply >80% of global energy (excluding rural biomass)
  - Global infrastructure is in place
  - Relatively inexpensive
  - Relatively abundant supply (particularly coal)
  - Very transportable and easy to store
  - Available day and night, on demand
- Fossil fuels have major impacts on the environment
  - Air pollution (photochemical smog, health and visibility/welfare impacts)
  - Acidification of precipitation
  - Agriculture and ecosystem impacts (and some benefits)
  - Climate change that could be 'dangerous'
  - Sea level rise (glacier and ice sheet loss)
  - Ocean acidification

Increasing emissions are increasing the rate of increase of the atmospheric CO_2 concentration



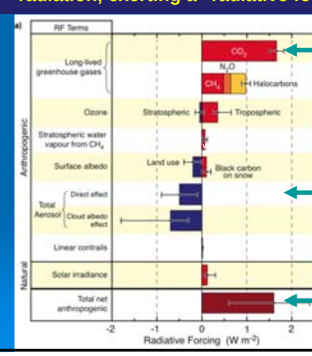
The present concentration is ~390 ppm, about 24% above the value of 315 ppm in 1957 (when C. David Keeling began very careful measurements) and about 40% above the preindustrial concentration

ppm=parts per million (by volume), or number of CO_2 molecules in a million molecules of air

Source: NOAA http://www.esrl.noaa.gov/gmd/ccgg/trends/#mlo_full

That the magnitude of the seasonal cycle has increased suggests that, even with a reduced amount of vegetation, the higher CO_2 concentration is enhancing the seasonal growth of global vegetation

The increasing concentrations of radiatively active gases and aerosols are altering the fluxes of visible and infrared radiation, exerting a "radiative forcing" on climate



Carbon dioxide is the primary greenhouse gas

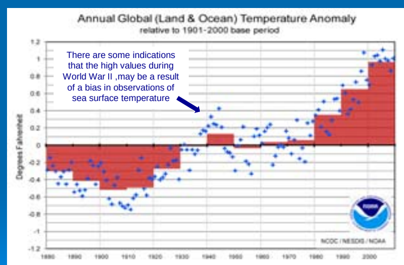
Sulfate aerosols exert a direct and indirect (via clouds) cooling influence of about -1.2 Wm^{-2}

Net positive forcing is currently about 1.6 Wm^{-2}

Source: IPCC, 2007

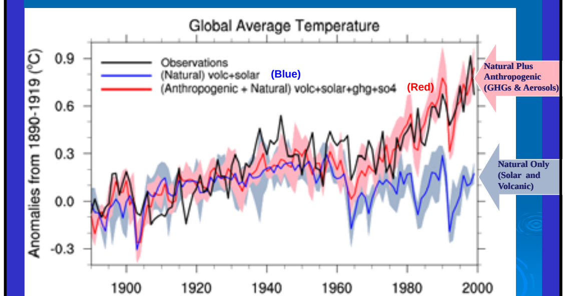
On a decadal-average basis, the world has experienced relatively steadily warming over the last few decades

Global Temperature Anomalies



Blue dots—annual global anomalies
Red bars—decadal-average anomalies

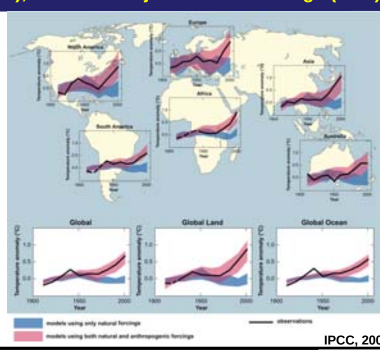
Only when the effects of both natural and human forcings are included do the models reasonably represent climate change over the last 100 years



NCAR Climate Simulations

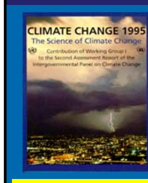
Comparisons show both global and regional agreement of 20th century observations with model simulations including all forcings (pink), but not with just natural forcings (blue)

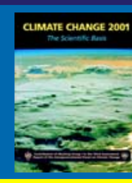
The model results appear as a band because (1) the results are for multiple models, and (2) the model simulations account for the natural variability of the climate, unlike the observations which, although averaged over a decade, represent a single pass through climatic history. Observations also include biases due to changing spatial coverage and measurement errors.



IPCC, 2007

Over its series of assessments, the IPCC has concluded that the evidence for human influences on climate is getting stronger

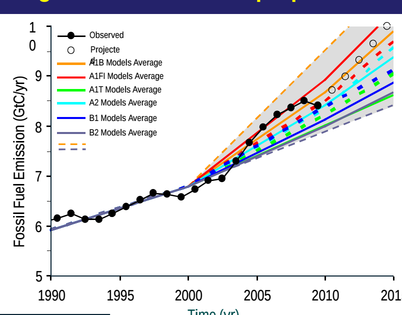




IPCC's summary conclusions, which require full international concurrence, tend to be cautious rather than cutting edge. That they are nonetheless so very disturbing should be reason for significant attention and concern

"Warming of the climate system is unequivocal.... Most of the observed increase in globally-averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."

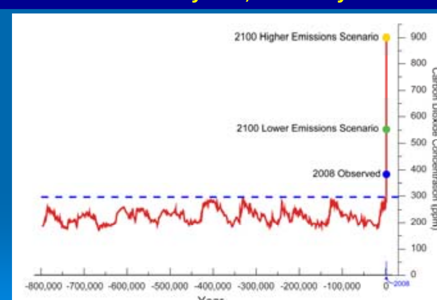
Fossil fuel emissions have been rising as rapidly as the highest IPCC scenario proposed in 2000



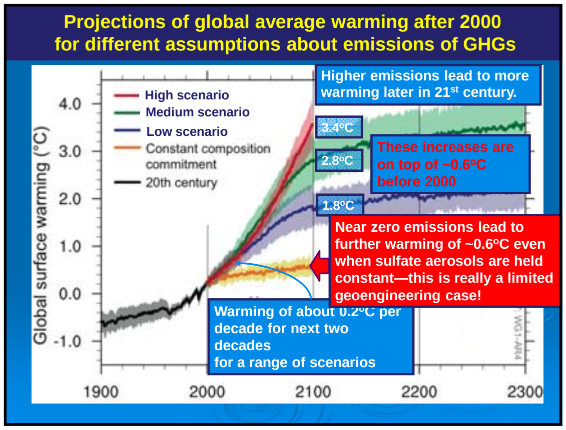
To convert from GtC to $MMTCO_2$ used in negotiations, multiply by 3670

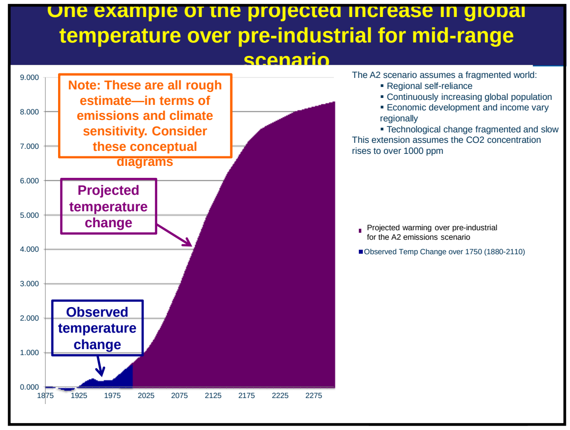
Slide from Global Carbon Project, 2010. Content updated from Raupach et al. 2007, PNAS; Data: Gregg Marland, Thomas Boden-CDIAC 2010; International Monetary Fund 2010

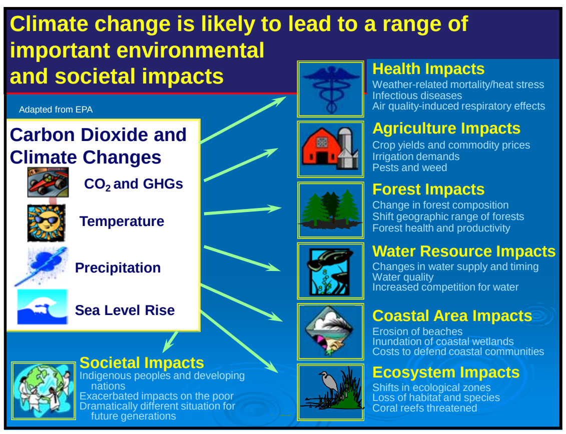
Plausible emissions scenarios would cause the CO_2 concentration to rise to far above its value over at least the last 800K years, and likely much longer

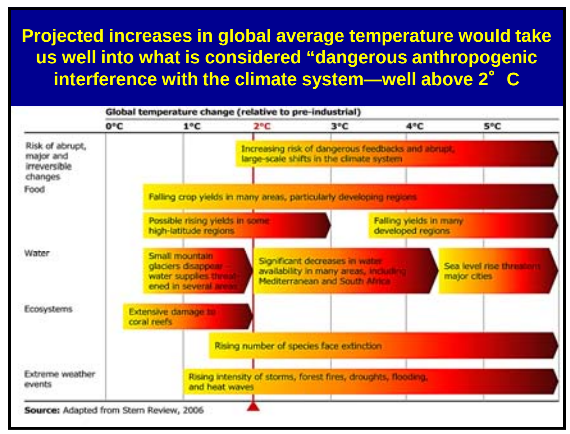


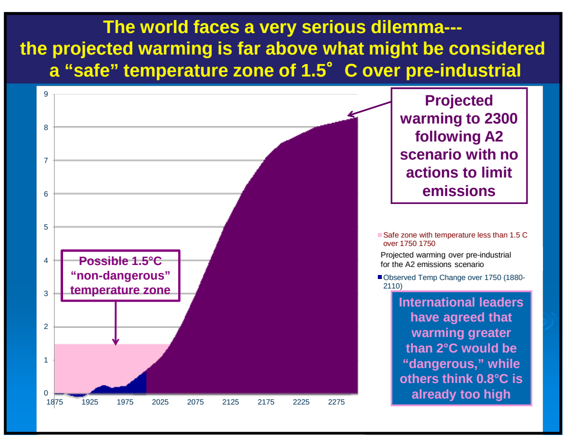
800,000 year ice-core record of the CO_2 concentration


Projections of global average warming after 2000 for different assumptions about emissions of GHGs
Higher emissions lead to more warming later in 21st century.
High scenario
Medium scenario
Low scenario
Constant composition commitment
20th century
Global surface warming (°C)
3.4°C
2.8°C
1.8°C
These increases are on top of ~0.6°C before 2000
Near zero emissions lead to further warming of ~0.6°C even when sulfate aerosols are held constant—this is really a limited geoengineering case!
Warming of about 0.2°C per decade for next two decades for a range of scenarios
1900
2000
2100
2200
2300

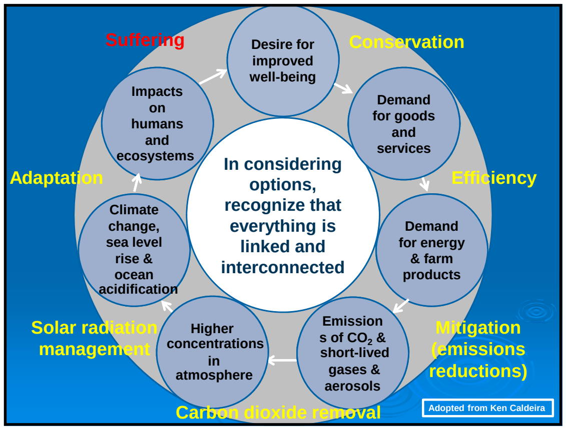

One example of the projected increase in global temperature over pre-industrial for mid-range scenario
Note: These are all rough estimate—in terms of emissions and climate sensitivity. Consider these conceptual diagrams
Projected temperature change
Observed temperature change
The A2 scenario assumes a fragmented world:
Regional self-reliance
Continuously increasing global population
Economic development and income vary regionally
Technological change fragmented and slow
This extension assumes the CO2 concentration rises to over 1000 ppm
Projected warming over pre-industrial for the A2 emissions scenario
Observed Temp Change over 1750 (1880-2110)

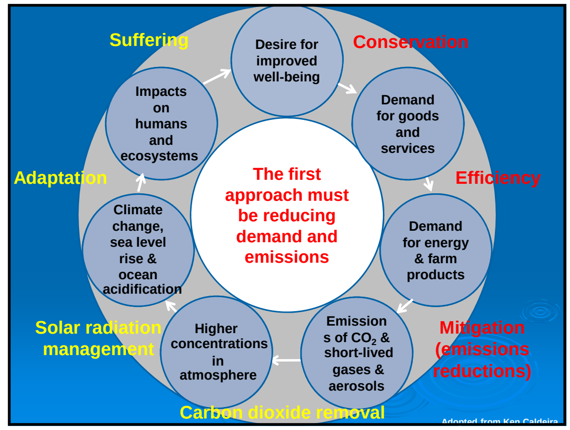

Climate change is likely to lead to a range of important environmental and societal impacts
Adapted from EPA
Carbon Dioxide and Climate Changes
CO2 and GHGs
Temperature
Precipitation
Sea Level Rise
Societal Impacts
Indigenous peoples and developing nations
Exacerbated impacts on the poor
Dramatically different situation for future generations
Health Impacts
Weather-related mortality/heat stress
Infectious diseases
Air quality-induced respiratory effects
Agriculture Impacts
Crop yields and commodity prices
Irrigation demands
Pests and weed
Forest Impacts
Change in forest composition
Shift geographic range of forests
Forest health and productivity
Water Resource Impacts
Changes in water supply and timing
Water quality
Increased competition for water
Coastal Area Impacts
Erosion of beaches
Inundation of coastal wetlands
Costs to defend coastal communities
Ecosystem Impacts
Shifts in ecological zones
Loss of habitat and species
Coral reefs threatened


Projected increases in global average temperature would take us well into what is considered "dangerous anthropogenic interference with the climate system—well above 2° C
Global temperature change (relative to pre-industrial)
0°C
1°C
2°C
3°C
4°C
5°C
Risk of abrupt, major and irreversible changes
Increasing risk of dangerous feedbacks and abrupt, large-scale shifts in the climate system
Food
Falling crop yields in many areas, particularly developing regions
Possible rising yields in some high-latitude regions
Falling yields in many developed regions
Water
Small mountain glaciers disappear
Significant decreases in water availability in many areas, including Mediterranean and South Africa
Sea level rise threatens major cities
Ecosystems
Extensive damage to coral reefs
Rising number of species face extinction
Extreme weather events
Rising intensity of storms, forest fires, droughts, flooding, and heat waves
Source: Adapted from Stern Review, 2006


The world faces a very serious dilemma--- the projected warming is far above what might be considered a "safe" temperature zone of 1.5° C over pre-industrial
Projected warming to 2300 following A2 scenario with no actions to limit emissions
Possible 1.5°C "non-dangerous" temperature zone
Safe zone with temperature less than 1.5 C over 1750 1750
Projected warming over pre-industrial for the A2 emissions scenario
Observed Temp Change over 1750 (1880-2110)
International leaders have agreed that warming greater than 2°C would be "dangerous," while others think 0.8°C is already too high


We cannot take away their hope!
So, is there a feasible path forward, or is climate catastrophe inevitable, almost no matter what we do?



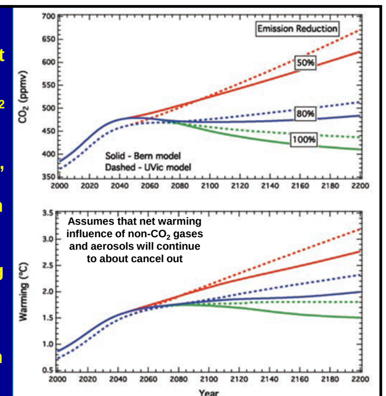


There are several major components to reduce the intensification of the climate change problem by human activities

1. Conservation: Reduce per capita demand for energy services and products
2. Efficiency: Provide the required products and services with less energy
3. Mitigation: Reduce greenhouse gas intensity by switching to low- or non-carbon emitting energy technologies and other technological improvements
   A. Reduce emissions of long-lived species to limit the ultimate warming

It is proving difficult to even get started reducing global CO_2 emissions.

Even starting today, the projections indicate that cuts in CO_2 emissions would not start to reduce the warming rate for several decades (this delay is serving as a reason for not acting now)

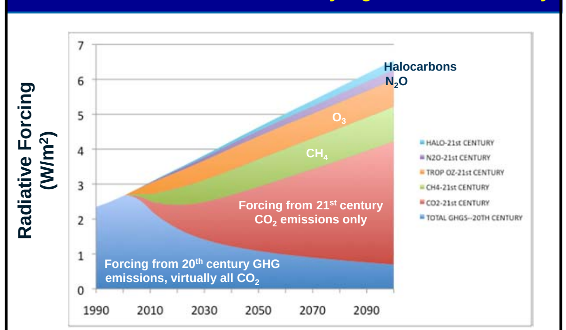


Source: "Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia" by the National Research Council, 2011

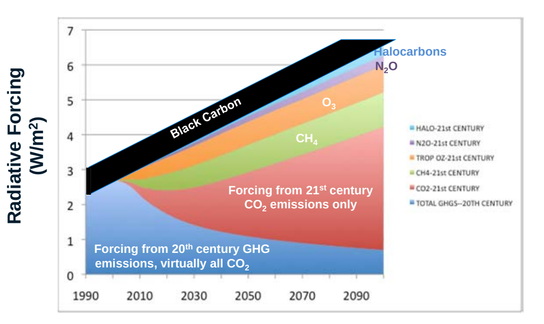
Separately considering the climatic effects of different greenhouse gases offers some hope

1. Conservation: Reduce per capita demand for energy services and products
2. Efficiency: Provide the required products and services with less energy
3. Mitigation: Reduce greenhouse gas intensity by switching to low- or non-carbon emitting energy technologies and other technological improvements
   A. Reduce emissions of long-lived species to limit the ultimate warming
   B. Reduce emissions of short-lived species to slow the rate of warming over the next several decades

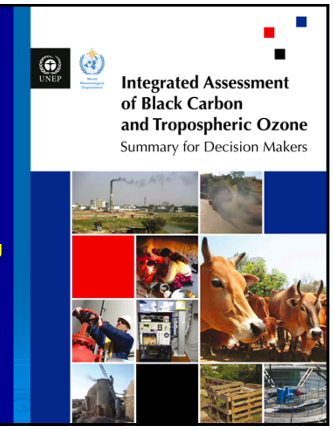
Decomposing the warming influence of each of the gases, the warming influence of CH_4 and tropospheric O_3 makes clear that their influence will be very significant this century



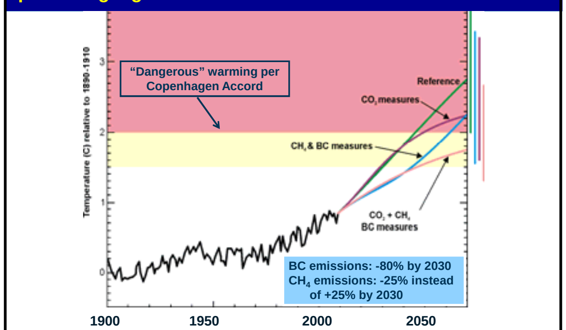
Adding the somewhat uncertain warming influence of black carbon emissions makes clearer that cutting emissions of short-lived species will reduce near-term warming



The United National Environment Programme (UNEP) and the World Meteorological Organization (WMO) have recently completed an assessment looking at the slowing of warming that can be achieved by limiting air pollutant (i.e., short-lived) emissions



The report describes the potential for limiting near-term climate change and improving air quality, also producing significant health and environmental co-benefits



See http://www.unep.org/dewa/Portals/67/pdf/Black_Carbon.pdf

Aggressively limiting emissions of both near- and long-lived greenhouse gases can thus reduce warming

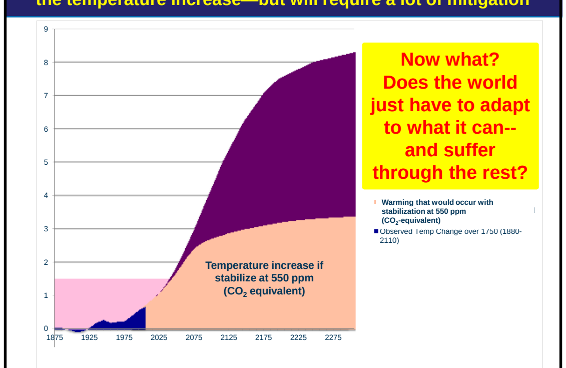
To limit long-term climate change, global emissions of CO_2 must be cut sharply:

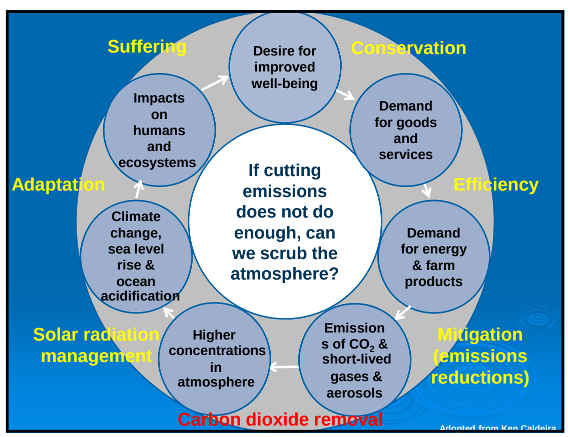
- Fossil fuel emissions of CO_2 need to be cut by 80% to 90%
- Developed nations need to demonstrate a 21st century economy can prosper on low CO_2 emissions
- Deforestation needs to be reversed in developing nations
- Atmospheric scrubbing of CO_2 will likely be needed to limit ocean acidification

To slow the rate of climate change over the next several decades, *all nations* need to sharply reduce emissions of CH_4, O_3 precursors, and black carbon:

- Cutting CH_4 emissions saves energy and reduces air pollution
- Cutting air pollutant emissions improves health and air quality
- Cutting black carbon emissions improves health, air quality, energy efficiency, and reduces the cutting of trees and forest loss

Stabilization at 550 ppm (CO_2-equivalent) would significantly limit the temperature increase—but will require a lot of mitigation





Carbon Dioxide Removal (CDR) is an extension of mitigation, and one of the two major approaches to (geo)engineering the global climate

1. **Conservation:** Reduce per capita demand for energy services and products
2. **Efficiency:** Provide the required products and services with less energy
3. **Mitigation:** Reduce greenhouse gas intensity by switching to low- or non-carbon emitting energy technologies and other technological improvements
   A. Reduce emissions of long-lived species to limit the ultimate warming
   B. Reduce emissions of short-lived species to slow the rate of warming over the next several decades
4. **Carbon dioxide removal:** Pull CO_2 from the atmosphere
   A. Enhance natural sinks, expand forests, etc.
   B. Scrub CO_2 from the atmosphere by industrial processes

Carbon removal technologies tend to be slow-acting, long-term, and resource-intensive

- **Reforestation and afforestation** are limited by the rate of forest growth, the areas of land available, the need for adequate nutrients and water resources, etc.—and are far less than current fossil fuel emissions;
- **Gathering of excess biomass and underground sequestration** (e.g., as biochar) is limited by available amounts and uses of the biomass, but may enhance soil quality
- **Using biofuels** in conjunction with sequestration of CO_2 from coal-fired power plants requires geological storage of carbon
- **Enhancing oceanic uptake** of carbon dioxide is limited by need for added nutrients, prospective impacts on existing ecosystems, and difficulty of achieving deep sea transfer
- **Scrubbing CO_2 from the atmosphere** and underground sequestration

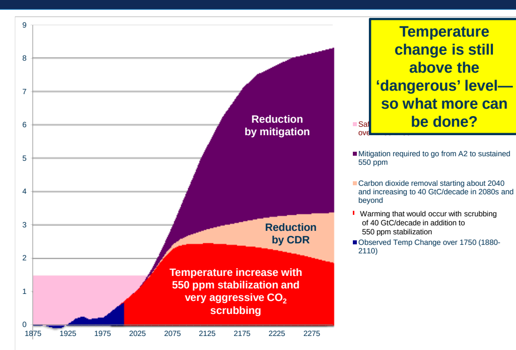
Research makes clear that keeping the CO_2 level below 450 ppm to limit global warming and ocean acidification will be very difficult without both aggressive mitigation and carbon dioxide removal

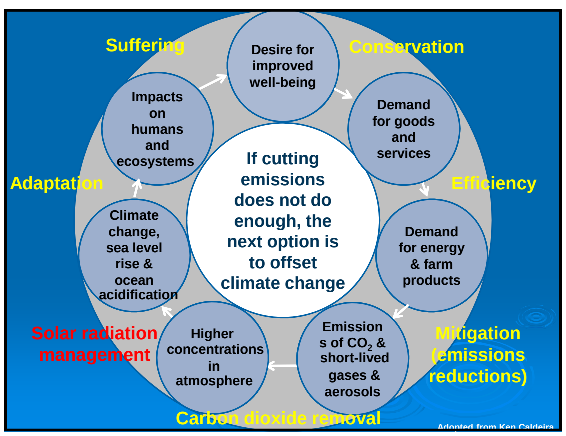
Removing a significant amount of CO_2 from the atmosphere will be very challenging until emissions are greatly reduced

Source/Sink	As billions of tons of carbon (units scientists use)	As millions of tons of CO_2 (3670 x GtC) (units negotiators use)
Fossil Fuel Emissions	8–9 GtC/yr	30,000-33,000 MMT/yr
Deforestation, etc.	1-2 GtC/yr	4,000-7,000 MMT/yr
Standing forests/grasslands Soil detritus, etc.	600 GtC (~63 GtC/yr) ~2100 GtC (~60 GtC/yr)	2,100,000 MMT 7,700,000 MMT
	Maximum of ~ 4 GtC/yr	
Fertilization of global ocean	1 GtC/yr (max)	4,000 MMT/yr (max)
Reforestation, afforestation, Biochar and biofuels	1 GtC/yr maybe a few by 2100	4,000 MMT/yr maybe 10-20,000 MMT/yr
Carbon scrubbing	1 GtC/yr	4,000 MMT/yr

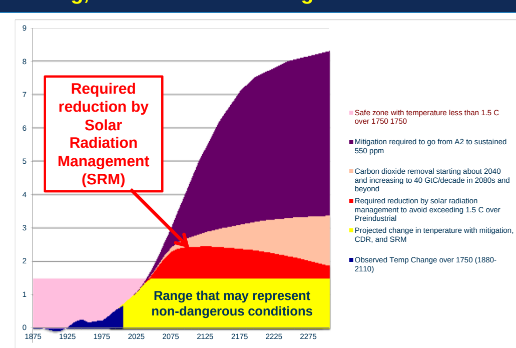
Source: Very rough estimates; similar to Royal Society, 2009

Building up to scrubbing out 4 GtC/year (in addition to mitigation!) would help—but still not enough

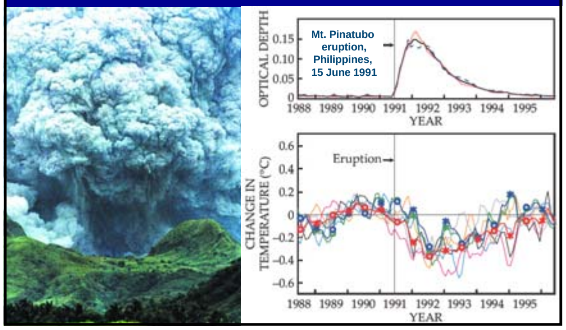




To the extent mitigation and scrubbing cannot limit warming, solar radiation management will be needed



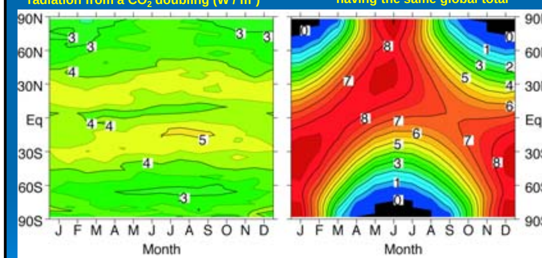
Conceptually, Solar Radiation Management is simple: Reduce the incoming solar radiation (e.g., as volcanoes do) and cooling will result



In practice, Solar Radiation Management is made difficult by the differing patterns of influence

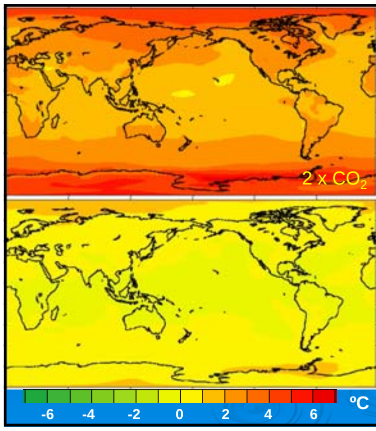
CO_2 radiative forcing due to infrared radiation from a CO_2 doubling (W / m²)

Change in solar radiative forcing from having the same global total



Key Question: Will the changes in climate from these very different forcings be essentially the same?

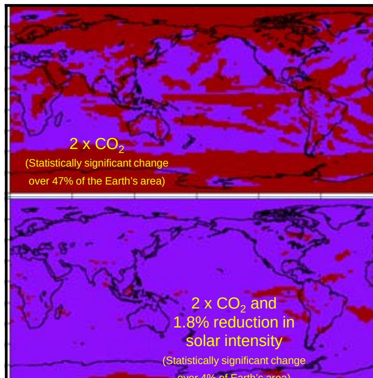
Govindasamy and Caldeira, GRL, 2000



Model results suggest that the warming from a CO_2 doubling can largely be offset by reducing incoming solar radiation by about 1.8%

2 x CO_2 along with a 1.8% reduction in solar intensity

Caldeira and Wood, 2008



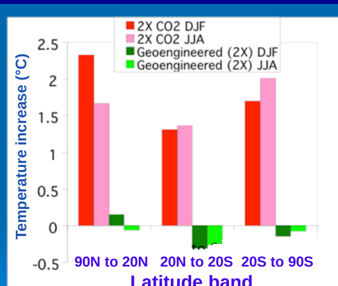
Model results also suggest that the change in precipitation from a CO_2 doubling can largely be offset by reducing incoming solar radiation by about 1.8%

Area where change is significant at 0.05 level based on 30-yr climatology

Caldeira and Wood, 2008

The counter-balancing also seems to work on seasonal and latitudinal basis

Seasonal and latitudinal temperature change

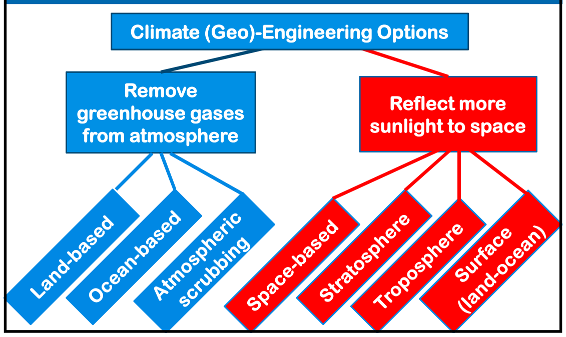


Govindasamy and Caldeira 2000

Solar Radiation Management has both potential advantages and disadvantages compared to Carbon Dioxide Removal

Carbon Dioxide Removal	Solar Radiation Management
Addresses the cause of the problem	Creates a counter-balancing intervention to one component of the problem (e.g., does not address ocean acidification)
Response to intervention takes many decades	Response to intervention occurs over months to years
Requires extensive investment and high sustained cost	Some approaches appear to be relatively inexpensive
Effect insignificant until emissions are substantially reduced	Potentially capable of offsetting significant warming
Relatively few adverse side effects	Potentially significant side effects (e.g., sky whitening, shifts in storms and monsoons, etc.)
Can be undertaken at local to national levels	Gaining international agreement may be difficult
Can be ended without causing a rapid change in the climate	Must be sustained over many decades to avoid climate jump if terminated

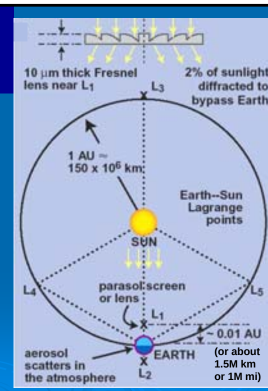
A number of options have been suggested for reducing incoming solar radiation to counter-balance global warming



Locate solar deflector(s) at the L1 Lagrange Point

Options:

1. A single deflector about 1400 km in diameter, manufactured and launched from the Moon (Early, 1989)
2. A cloud of smaller deflectors lofted from Earth over up to a few decades by 20M electro-magnetic launches, each with 800k reflectors, and carried to position by ion propulsion (Angel, 2006)



Hoffert et al., 2002

Lofting mirrors into near-Earth orbit seems totally impractical

- NAS (1992) panel report estimated it would require 55,000 orbiting mirrors, each covering and area of 100 square kilometers:
  - The Sun would be obscured with numerous mini-eclipses
  - Would be hard to deal with space debris
  - Could cut number in half if actively aligned
  - Cost and navigational difficulties would be quite high

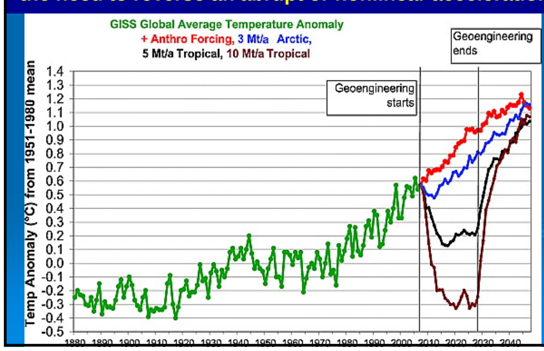
Injecting reflective materials into the stratosphere has the advantage of them remaining aloft for 1-2 years

There are a number of options for stratospheric injections:

- "Hose to the stratosphere"
  - Skinny pipe/hose, ground to ~25 km-high HAA (DoD)
- Artillery (shooting barrels of particles into stratosphere)
  - "…surprisingly practical" – NAS Study, 1992
- High-altitude transport aircraft
  - "Condor/Global Hawk, with a cargo bay"
  - Half-dozen B-747s deploy 10^6 tonnes/year of engineered aerosol; towed lifting-lines/bodies for height-boosting the sprayer-dispenser an additional 5-10 km above normal cruising ceiling
- Other options
  - Anthropogenic (mini-) volcanoes (e.g., created by explosions)
  - Tethered (set-of-) lifting-body – a set of high-tech kites
  - Lofting of balloons into the stratosphere (possibly micro-scale and shaped as corner reflectors to reduce problems of light scattering)
  - Increase release of carbonyl sulfide (COS) from oceans, leading to sulfates after chemical reaction in the stratosphere

Modified from original by Lowell Wood

Robock et al. have looked at the reductions in temperature that could be achieved if required due to the need to reverse an abrupt or nonlinear acceleration



Although the interventions would require ongoing injections, there are approaches applicable for the troposphere and surface

- Tropospheric injection of sulfur dioxide to increase its current cooling influence in clear and cloudy skies
- Injection of cloud condensation nuclei to make clouds brighter
- Increasing reflectivity of the land surface (e.g., by whitening cities, roadways, vegetation, etc.)
- Increasing reflectivity of the ocean surface (e.g., by microbubbles, floating reflectors, etc.)

Latham and Salter propose controlled enhancement of the albedo and longevity of low-level maritime clouds

- The ships are wind-powered
- They loft a spray of very fine sea water that is carried up into clouds, brightening their albedo
- The approach works best in pristine areas
- Ship locations could shift with the season
- The basic effect is to reduce uptake of solar energy by the oceans

A speculative comparison of possible approaches to Solar Radiation Management

Approach	Scal-ability	Potential speed of deploy-ment	Risk per unit effect	Cost	Govern-ance issues
Space based reflectors	blue	red	yellow	red	red
Stratospheric aerosols	blue	blue	yellow	blue	red
Cloud albedo approaches	yellow	yellow	orange	yellow	orange
Land albedo approaches	red	orange	orange	yellow	blue

best (blue) (yellow) (orange) (red) worst

From Caldeira, 2011

Focused (rather than global) interventions may have the potential to moderate specific global-warming impacts, possibly with reduced adverse side effects

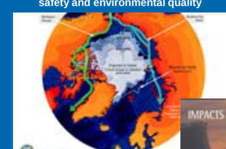
Particular objectives for which it might well make sense to determine if approaches exist to attempt:

- Reverse Arctic (and/or Antarctic) warming
- Moderate the intensification of tropical cyclones and hurricanes
- Shift storm tracks
- Sustain (or enhance) the cooling offset of aerosols as precursor emissions decrease

An aggressive research program is needed to determine if there really are possibilities

Reductions in Arctic Sea Ice are already having significant effects within the region

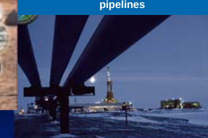
Access to the region will increase, leading to sovereignty claims and challenges for ensuring safety and environmental quality



Adverse impacts on Arctic ecosystems and species (e.g., polar bear)

Sea ice loss allows increased coastal erosion, which will force relocation of ~150 Indigenous communities

Melting of permafrost weakens soils and foundations for buildings and pipelines



The world system is interconnected-- a warmer Arctic will also have significant impacts on mid-latitude weather

- In the fall and early winter, little really cold air can be generated until the sea ice is 1-2 meters thick, letting the warm subtropical air push northward--and can create large, wet snowstorms.
- In the spring and summer, less cool, dry air is generated that can undercut the moist tropical air and trigger thunderstorms, shifting their occurrence further to the north.

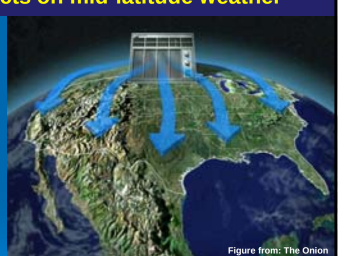
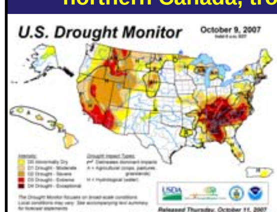


Figure from: The Onion

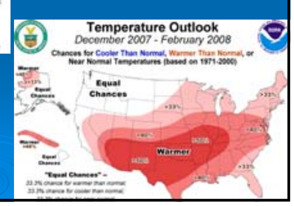
For interesting discussions of the unusual weather, go to the blog of Stu Ostro, senior meteorologist for The Weather Channel

With less cold air coming out of the Arctic and northern Canada, tropical air pushes north



Warm season thunderstorms require the presence of warm, moist air, plus a trigger such as a cool front from northern Canada. Weak fronts get blocked by the Appalachians, leaving their southeastern side drier--and the area hoping for hurricane rains.

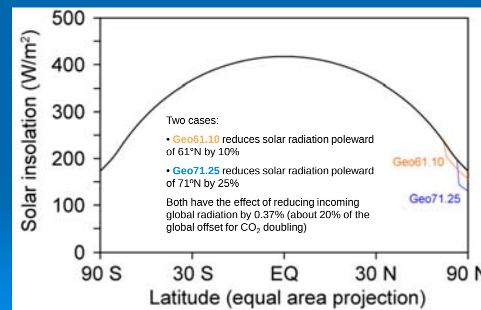
Until Arctic sea ice 1-2 meters thick insulates the air from the ocean, really cold winter air masses cannot form and warm, moist air pushes north into the US; the resulting clash can yield violent weather



Reversing Arctic warming might be possible, with many benefits

- Benefits within the Arctic region, many of which would also benefit the rest of the world, include:
  - Sustaining and restoring sea ice, which is essential for sustaining Arctic and migrating species
  - Sustaining and restoring river and coastal ice, which are essential for limiting erosion that is/will be requiring village relocation
  - Sustaining and rebuilding mountain glaciers and ice sheets, thus slowing sea level rise
  - Limiting permafrost thawing, which is destabilizing buildings and causing the release of methane, which will amplify future warming
  - Restoring the chilling of air that influences mid-latitude weather and climate

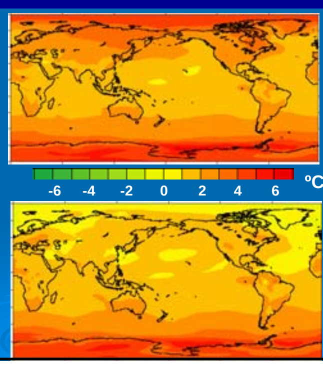
Reducing solar radiation only in the Arctic would avoid a number of adverse consequences of global Solar Radiation Management



Annual mean temperature response to a CO_2 doubling and reduced solar north of 61° N

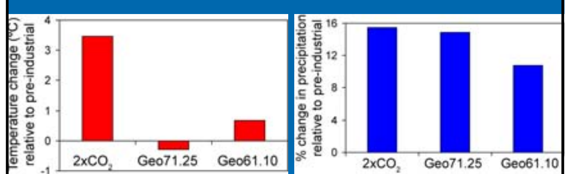
560 ppm CO_2, normal solar radiation

560 ppm CO_2, 10% solar reduction north of 61°N



Caldeira and Wood, 2008.

Model simulations suggest that reducing incoming solar radiation could reverse the polar temperature increase but not reduce the precipitation increase



Model experiments are underway to look at similar reductions in the Southern Hemisphere, and how these together might limit global warming

Caldeira and Wood, 2008.

2. Decreasing the driving force for intensification of tropical cyclones

Damage from intense tropical cyclones is increasing, and is projected to increase more:

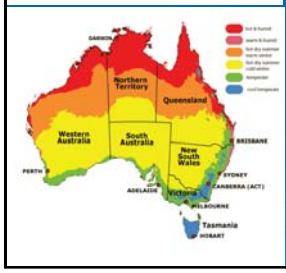
- Ocean temperatures are increasing in the areas where storms intensify:
  - The warming adds energy to each passing storm
  - Waters remain warm enough to power later storms in season
- A larger fraction of storms is in the most intense categories
- Integrated energy dissipation per storm is increasing
- Higher storm surges are augmented by rising sea level
- Increasing coastal populations and more extensive infrastructure are a major contributor to the increasing vulnerability and losses

Limiting ocean energy available is likely more feasible than storm modification

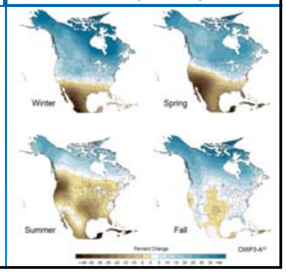
- Individual storms likely have too much energy to modify over a few days in a confident way (but perhaps not)
- Spreading energy limitation over time could reduce likelihood of storm intensification:
  - Increase cloud albedo by aerosol injection (cloudy sky)
  - Increase surface albedo or reduce the air-sea flux via a film
  - Use wave driven pumps to vertically mix ocean waters
  - Use wave driven pumps to enhance evaporative cooling
- While focusing first on ocean regions that promote cyclone intensification, limiting warming in other ocean areas might also provide benefits (e.g., coral reefs)

3. With critical areas drying, it might be possible to modify sea surface temperatures by a few degrees in order to slightly redirect storm tracks, at least in years favoring such possibilities

Australia depends on the storm track striking its southern coastal zones



Projected change in precipitation by 2080-90s compared to present



4. It might be possible to counteract the warming that will result from reducing SO_2 emissions

- IPCC (2007) estimates that fossil fuel generated aerosols (mostly sulfate) exert a strong cooling influence:
  - Direct forcing: -0.5 (± 0.4) W/m^2
  - Indirect (cloud) forcing: -0.7 (-1.1, +0.4) W/m^2
- Using mid-range sensitivity, this is about 1° C cooling influence (at equilibrium)
- SO_2/sulfate has a 5-10 day lifetime compared to centuries to millennia for most GHGs
  - Pollution control and reductions in CO_2 emissions, particularly from cutbacks in coal combustion, will lead to sharp reductions in SO_2 emissions and thus a reduced cooling offset, uncovering a strong additional warming influence

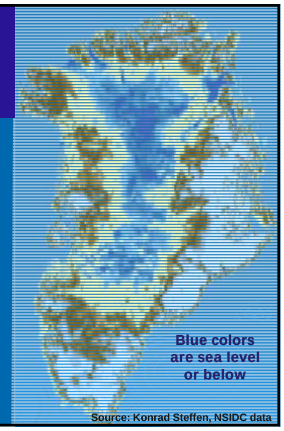
5. It might be possible to slow the ice stream calving that is draining the major ice sheets

Possible approaches:
- Vertical mixing of fjord waters
- Cooling of 'warm' waters entering fjord via surface bubbling, etc.
- Blocking ice berg exit

Greenland's underlying topography suggests the Ice Sheet is very vulnerable

Contrary to earlier understanding, much of the Greenland Ice Sheet in interior areas is grounded below sea level (the land has been depressed by the ice), so ocean waters can flow underneath, thus lifting and heating the ice sheet.

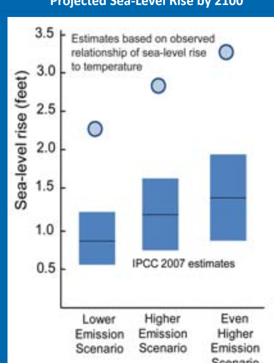
In addition, fjords connect the ice sheet to the surrounding seas along the west and northern coasts, enabling more rapid movement of the ice from the interior to the ocean



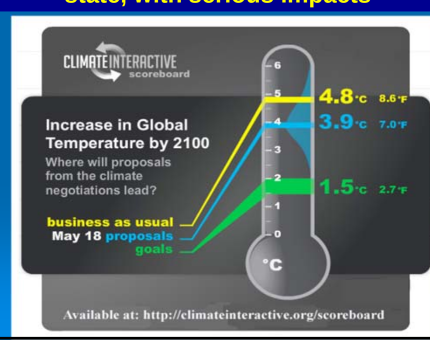
There is significant uncertainty in projections of future sea level rise— the IPCC 2007 estimates were at the lower end due to limited understanding about a key process

Recent estimates suggest that the increase in sea level during the 21st century could be from about 3 ± 1.5 feet by 2100

Projected Sea-Level Rise by 2100



Without significantly more emissions cuts, the world is headed toward a quite different state, with serious impacts



But, there is no such thing as a "free lunch"

- **Emissions Reductions** of 80-90% over the next several decades will require a significant transition of the global energy system that will likely be costly up front, even if paying off over time
- **Impacts and Consequences** are likely to be quite significant, as well as in many situations being adequate, thus requiring abandonment, relocation, misery, and suffering
- **Carbon Dioxide Removal** directly addresses the cause of the problem, but is slow, expensive, and incapable of making a significant difference until emissions are sharply reduced
- **Solar Radiation Management** can likely counter-balance the warming due to CO_2 emissions, but may shift precipitation patterns, modify ozone and sky color, require substantial negotiations, need to be sustained for many decades, and fail to deal with ocean acidification

In addition, both inadvertent and advertent changes to the climate are the subject of International Protocols

- Inadvertent climate change (i.e., caused by fossil-fuel emissions) is governed by the *UN Framework Convention on Climate Change* (and for some nations by the additional *Kyoto Protocol*). The Montreal Protocol also governs emission of some of the greenhouse gases.
- Advertent climate change (i.e., climate engineering) may be subject to the *UN Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques* agreed to in 1978 (and the US ratification was filed on January 17, 1980). Other conventions (e.g., for air pollutants, ocean dumping, etc.) may also apply.

The Choice is up to Society Today …

… continued global warming with ever increasing environmental risk

. . . Or, with its many implications, pursue climate engineering approaches that allow slower changing of the global energy system while likely diminishing environmental risk

But the choice will dramatically affect the natural environment and future generations (raising issues of stewardship and equity)

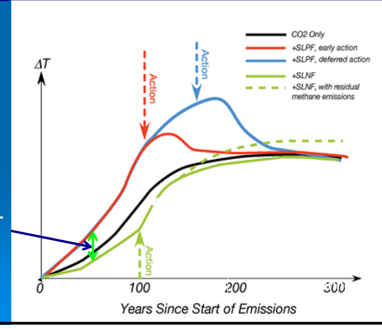
Modified from Ken Caldeira

Additional Information

- Scientific Expert Group on Climate Change (SEG), 2007: *Confronting Climate Change: Avoiding the Unmanageable and Managing the Unavoidable*, Rosina M. Bierbaum, John P. Holdren, Michael C. MacCracken, Richard H. Moss, and Peter H. Raven (eds.), Report prepared for the United Nations Commission on Sustainable Development by Sigma Xi, Research Triangle Park, NC, and the United Nations Foundation, Washington, DC, 144 pp. [downloadable from http://www.unfoundation.org/global-issues/climate-and-energy/sigma-xi.html
- MacCracken, M. C., 2008: Prospects for future climate change and the reasons for early action, *Journal of the Air and Waste Management Association*, 58, 735-786 [downloadable from www.climate.org].
- Moore, F. C., and M. C. MacCracken, 2009: Lifetime-leveraging: An approach to achieving international agreement and effective climate protection using mitigation of short-lived greenhouse gases, *International Journal of Climate Change Strategies and Management* 1, 42-62.
- MacCracken, M. C., 2009: On the possible use of geoengineering to moderate specific climate change impacts, *Environmental Research Letters*, 4 (October-December 2009) 045107 doi:10.1088/1748-9326/4/4/045107 [http://www.iop.org/EJ/article/1748-9326/4/4/045107/erl9_4_045107.html].

The NRC Stabilization report recognizes the importance of reducing short-lived species in order to reduce temperature and impact overshoot

The UNEP/WMO Report focuses on the value and possibility of early reductions in the emissions of short-lived species.



Measures that can reduce methane emissions, both in developing and developed nations

1. Extended pre-mine degasification and recovery of **coal mine** gas
2. Extended recovery and utilization (instead of venting) of associated gas from **production of crude oil and natural gas**
3. Reduced **gas leakage** in long-distance gas transmission pipelines
4. Separation and treatment of biodegradable **municipal waste** through recycling, composting and anaerobic digestion, as well as landfill gas collection
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**

US Methane Emissions: Gas and oil operations (37%); Farm-based (28%); Landfills and wastewater (21%); Coal mines (11%)
There is significant potential for reductions of US emissions, as for other nations

Measures for reducing black carbon emissions in developed and developing nations (Group 1, technical)

1. **Diesel particle filters** for road vehicles and off-road mobile sources (excluding shipping)
2. Replacing coal by **briquettes for cooking and heating** stoves
3. **Pellet stoves and boilers**, using fuel made from recycled waste or sawdust to replace current wood burning technologies in the residential sector in industrialised countries
4. Replacing **traditional brick kilns** with vertical shaft kilns and Hoffman kilns
5. Replacing **traditional coke ovens** with modern recovery ovens, including the improvement of end-of-pipe abatement measures in developing countries

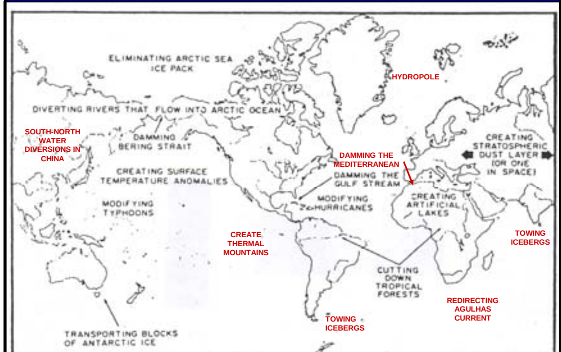
US BC Emissions: Mobile, mainly diesel and tire/brake wear 63%); Biomass burning (27%); Power plants (8%)
Globally, US is near the global average per capita emissions; we need to act as well

Measures for reducing black carbon emissions in developed and developing nations (Group 2, non-technical)

1. Replace **high-emitting vehicles** in road and off-road transport
2. Ban **open burning of agricultural waste**
3. Upgrade/replace **biomass cook stoves** in developing countries

Co-benefits of cutting emissions of BC, CH_4, etc. are very large
- **Avoid 2.4 million premature deaths per year (range 0.7-4.6 million)**
- **Avoid global crop loss of 1-4% caused by air pollution damage (mostly in Asia)**
- **Reduced loss of snowpack and Arctic ice due to black carbon**

Beyond modifying the weather, proposals to 'improve' the climate also emerged in the mid-20th century



From Glantz, after Kellogg & Schneider

The 'Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques' was the prepared and approved in response to military uses

Article I.1. Each State Party to this Convention undertakes not to engage in military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage or injury to any other State Party.

Article I.2. Each State Party to this Convention undertakes not to assist, encourage or induce any State, group of States or international organization to engage in activities contrary to the provisions of paragraph 1 of this article.

Understanding Relating to Article I

It is the understanding of the Committee that, for the purposes of this Convention, the terms, "widespread", "long-lasting" and "severe" shall be interpreted as follows:

- **(a) "widespread": encompassing an area on the scale of several hundred square kilometres;**
- **(b) "long-lasting": lasting for a period of months, or approximately a season;**
- **(c) "severe": involving serious or significant disruption or harm to human life, natural and economic resources or other assets.**
- **It is further understood that the interpretation set forth above is intended exclusively for this Convention and is not intended to prejudice the interpretation of the same or similar terms if used in connexion with any other international agreement.**

Understanding Relating to Article II

- It is the understanding of the Committee that the following examples are illustrative of phenomena that could be caused by the use of environmental modification techniques as defined in Article II of the Convention: earthquakes, tsunamis; an upset in the ecological balance of a region; changes in weather patterns (clouds, precipitation, cyclones of various types and tornadic storms); changes in climate patterns; changes in ocean currents; changes in the state of the ozone layer; and changes in the state of the ionosphere.
- It is further understood that all the phenomena listed above, when produced by military or any other hostile use of environmental modification techniques, would result, or could reasonably be expected to result, in widespread, long-lasting or severe destruction, damage or injury. Thus, military or any other hostile use of environmental modification techniques as defined in Article II, so as to cause those phenomena as a means of destruction, damage or injury to another State Party, would be prohibited.
- It is recognized, moreover, that the list of examples set out above is not exhaustive. Other phenomena which could result from the use of environmental modification techniques as defined in Article II could also be appropriately included. The absence of such phenomena from the list does not in any way imply that the undertaking contained in Article I would not be applicable to those phenomena, provided the criteria set out in that article were met.

[Emphasis added]

However: Understanding Relating to Article III

- It is the understanding of the Committee that this Convention does not deal with the question whether or not a given use of environmental modification techniques for peaceful purposes is in accordance with generally recognized principles and applicable rules of international law.

Unresolved Questions (in my view):

1. Would this convention be applicable in the case of advertent changes in the climate if some party considers them to have an adverse (hostile) influence on them?
2. Is intentionally not taking an action to limit inadvertent changes in the climate subject to this convention if it has an adverse (hostile) influence on another party?