The Potential for Climate (Geo-)Engineering to Help to Limit Global Warming to 2°C Over Pre-Industrial

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Monitoring of Geo-Engineering Impacts and their Natural and Anthropogenic Analogues

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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
Outline of talk

- The reasons for even considering climate engineering
- The expectations and possibilities of mitigation
- Conceptual approaches for carbon dioxide removal (CDR) and solar radiation management (SRM)
  - Counterbalancing global climate change
  - Moderating regional and specific impacts
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.

The rate of rise (ppm/yr) is rising, though not evenly:
- 1.3 ppm/yr
- 1.5 ppm/yr
- 1.6 ppm/yr
- 2.0 ppm/yr
- 2.4 ppm/yr

In 2010

ppm=parts per million (by volume), or number of CO$_2$ molecules in a million molecules of air

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.

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

Annual Global (Land & Ocean) Temperature Anomaly
relative to 1901-2000 base period

There are some indications that the high values during World War II may be a result of a bias in observations of sea surface temperature.

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.
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.

"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."

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.
Looking to the future, fossil fuel emissions have been rising as rapidly as the highest IPCC scenario proposed in 2000.

To convert from GtC to MMTCO₂ used in negotiations, multiply by 3670.
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.
Projections of global average warming after 2000 for different assumptions about emissions of GHGs

- **High scenario**: 3.4°C
- **Medium scenario**: 2.8°C
- **Low scenario**: 1.8°C

Higher emissions lead to more warming later in 21st century.

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.
One example of the projected increase in global temperature over pre-industrial for mid-range scenario

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)

Note: These are all rough estimate—in terms of emissions and climate sensitivity. Consider these conceptual diagrams.
Climate change is likely to lead to a range of important environmental and societal impacts

Carbon Dioxide and Climate Changes
- CO₂ and GHGs
- Temperature
- Precipitation
- Sea Level Rise

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

Societal Impacts
- Indigenous peoples and developing nations
- Exacerbated impacts on the poor
- Dramatically different situation for future generations

Adapted from EPA
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”

<table>
<thead>
<tr>
<th>Global temperature change (relative to pre-industrial)</th>
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<tbody>
<tr>
<td>0°C</td>
</tr>
<tr>
<td>Risk of abrupt, major and irreversible changes</td>
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<tr>
<td>Food</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Ecosystems</td>
</tr>
<tr>
<td>Extreme weather events</td>
</tr>
</tbody>
</table>

**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 conditions.

![Graph showing temperature changes over time.](Image)

- **Safe zone with temperature less than 1.5°C over 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?
In considering options, recognize that everything is linked and interconnected.

- **Desire for improved well-being**
- **Demand for goods and services**
- **Demand for energy & farm products**
- **Impacts on humans and ecosystems**
- **Climate change, sea level rise & ocean acidification**
- **Higher concentrations in atmosphere**
- **Emissions of CO₂ & short-lived gases & aerosols**

**Adaptation**
- Solar radiation management

**Conservation**
- Efficiency
- Mitigation (emissions reductions)

**Suffering**
- Carbon dioxide removal

Adopted from Ken Caldeira
The first approach must be reducing demand and emissions—otherwise climate change will continue.
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 CO₂ emissions.

Even starting today, the projections indicate that cuts in CO₂ emissions would not start to reduce the warming rate for several decades (this delay is serving as a reason for not acting now).

Assumes that net warming influence of non-CO₂ gases and aerosols will continue to about cancel out.

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.

“Dangerous” warming per Copenhagen Accord

BC emissions: -80% by 2030
CH₄ emissions: -25% instead of +25% by 2030

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

To limit long-term climate change, global emissions of CO₂ must be cut sharply:

- Fossil fuel emissions of CO₂ need to be cut by 80% to 90%
- Developed nations need to demonstrate a 21st century economy can prosper on low CO₂ emissions
- Deforestation needs to be reversed in developing nations
- Atmospheric scrubbing of CO₂ 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 CH₄, O₃ precursors, and black carbon:

- Cutting CH₄ 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.

Now what? Does the world just have to adapt to what it can—and suffer through the rest?

- Warming that would occur with stabilization at 550 ppm (CO$_2$-equivalent)
- Observed Temp Change over 1750 (1880-2110)
If cutting emissions does not do enough, can we scrub the atmosphere?

Desire for improved well-being

Demand for goods and services

Demand for energy & farm products

Emissions of CO₂ & short-lived gases & aerosols

Higher concentrations in atmosphere

Climate change, sea level rise & ocean acidification

Impacts on humans and ecosystems

Adaptation

Efficiency

Suffering

Conservation

Mitigation (emissions reductions)

Solar radiation management

Carbon dioxide removal

Adopted from Ken Caldeira
Carbon Dioxide Removal (CDR) is, in essence, 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 CO₂ from the atmosphere
   a. Enhance natural sinks, expand forests, etc.
   b. Scrub CO₂ 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 CO₂ 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 CO₂ from the atmosphere and underground sequestration

Research makes clear that keeping the CO₂ 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

<table>
<thead>
<tr>
<th>Source/Sink</th>
<th>As billions of tons of carbon (units scientists use)</th>
<th>As millions of tons of CO$_2$ (3670 x GtC) (units negotiators use)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil Fuel Emissions</td>
<td>8–9 GtC/yr</td>
<td>30,000-33,000 MMT/yr</td>
</tr>
<tr>
<td>Deforestation, etc.</td>
<td>1-2 GtC/yr</td>
<td>4,000-7,000 MMT/yr</td>
</tr>
<tr>
<td>Standing forests/grasslands</td>
<td>600 GtC (~63 GtC/yr)</td>
<td>2,100,000 MMT</td>
</tr>
<tr>
<td>Soil detritus, etc.</td>
<td>~2100 GtC (~60 GtC/yr)</td>
<td>7,700,000 MMT</td>
</tr>
<tr>
<td>Fertilization of global ocean</td>
<td>1 GtC/yr (max)</td>
<td>4,000 MMT/yr (max)</td>
</tr>
<tr>
<td>Reforestation, afforestation,</td>
<td>1 GtC/yr</td>
<td>4,000 MMT/yr</td>
</tr>
<tr>
<td>Biochar and biofuels</td>
<td>maybe a few by 2100</td>
<td>maybe 10-20,000 MMT/yr</td>
</tr>
<tr>
<td>Carbon scrubbing</td>
<td>1 GtC/yr</td>
<td>4,000 MMT/yr</td>
</tr>
</tbody>
</table>

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

Temperature change is still above the ‘dangerous’ level—so what more can be done?

- Safe zone with temperature less than 1.5°C over 1750
- Mitigation required to go from A2 to sustained 550 ppm
- Carbon dioxide removal starting about 2040 and increasing to 40 GtC/decade in 2080s and beyond
- Warming that would occur with scrubbing of 40 GtC/decade in addition to 550 ppm stabilization
- Observed Temp Change over 1750 (1880-2110)
If cutting emissions does not do enough, the next option is to offset climate change.
To the extent mitigation and scrubbing cannot limit warming, solar radiation management will be needed.

- Safe zone with temperature less than 1.5°C over 1750-1750
- Mitigation required to go from A2 to sustained 550 ppm
- Carbon dioxide removal starting about 2040 and increasing to 40 GtC/decade in 2080s and beyond
- Required reduction by solar radiation management to avoid exceeding 1.5°C over Preindustrial
- Projected change in temperature with mitigation, CDR, and SRM
- Observed Temp Change over 1750 (1880-2110)
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 may be made difficult by the differing patterns of influence.

**CO₂ radiative forcing due to infrared radiation from a CO₂ 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.
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%.
The counter-balancing also seems to work on a seasonal and latitudinal basis.

Seasonal and latitudinal temperature change

- 90N to 20N
- 20N to 20S
- 20S to 90S

Temperature increase (°C)

- 2X CO2 DJF
- 2X CO2 JJA
- Geoengineered (2X) DJF
- Geoengineered (2X) JJA

Govindasamy and Caldeira 2000
## Solar Radiation Management

### has both potential advantages and disadvantages compared to Carbon Dioxide Removal

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

Climate (Geo)-Engineering Options

Remove greenhouse gases from atmosphere
- Land-based
- Ocean-based
- Atmospheric scrubbing

Reflect more sunlight to space
- Space-based
- Stratosphere
- Troposphere
- Surface (land-ocean)
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 also approaches applicable for the troposphere and surface

- Tropospheric injection of sulfur dioxide to increase its current cooling influence in clear and cloudy skies (sulfate lifetime ~10 days)
- Injection of cloud condensation nuclei to make clouds brighter (CCN lifetime ~few days?)
- 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 lifetime of low-level maritime clouds

- The ships are wind-powered (Flettner rotors)
- 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

<table>
<thead>
<tr>
<th>Approach</th>
<th>Scalability</th>
<th>Potential speed of deployment</th>
<th>Risk per unit effect</th>
<th>Cost</th>
<th>Governance issues</th>
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</thead>
<tbody>
<tr>
<td>Space based reflectors</td>
<td><img src="#" alt="Blue" /></td>
<td><img src="#" alt="Red" /></td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Red" /></td>
<td><img src="#" alt="Red" /></td>
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<tr>
<td>Stratospheric aerosols</td>
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<td><img src="#" alt="Blue" /></td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Blue" /></td>
<td><img src="#" alt="Red" /></td>
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<tr>
<td>Cloud albedo approaches</td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Yellow" /></td>
<td><img src="#" alt="Yellow" /></td>
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<tr>
<td>Land albedo approaches</td>
<td><img src="#" alt="Red" /></td>
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<td><img src="#" alt="Red" /></td>
<td><img src="#" alt="Yellow" /></td>
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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.
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.

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

U.S. Drought Monitor

October 9, 2007
Valid 8 a.m. EDT

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.

Temperature Outlook
December 2007 - February 2008
Chances for Cooler Than Normal, Warmer Than Normal, or Near Normal Temperatures (based on 1971-2000)

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 (and some unintended consequences)

- 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.

Two cases:
- **Geo61.10** reduces solar radiation poleward of 61°N by 10%
- **Geo71.25** reduces solar radiation poleward of 71°N by 25%

Both have the effect of reducing incoming global radiation by 0.37% (about 20% of the global offset for CO₂ doubling).
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

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.

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.
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.

Source: Konrad Steffen, NSIDC data
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.
Thus, there is an array of possible approaches, each having a different potential cooling influence, readiness, and cost—all are in need of further research if they are to become potential options.
Without significantly more emissions cuts, the world is headed toward a quite different state, with serious impacts.

Increase in Global Temperature by 2100

Where will proposals from the climate negotiations lead?

- **business as usual**
- **May 18 proposals**
- **goals**

Available at: http://climateinteractive.org/scoreboard
Climate engineering may be able to limit the worst 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 CO₂ 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
Resolving governance may be a significant challenge; 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 will be up to Society …

... 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


