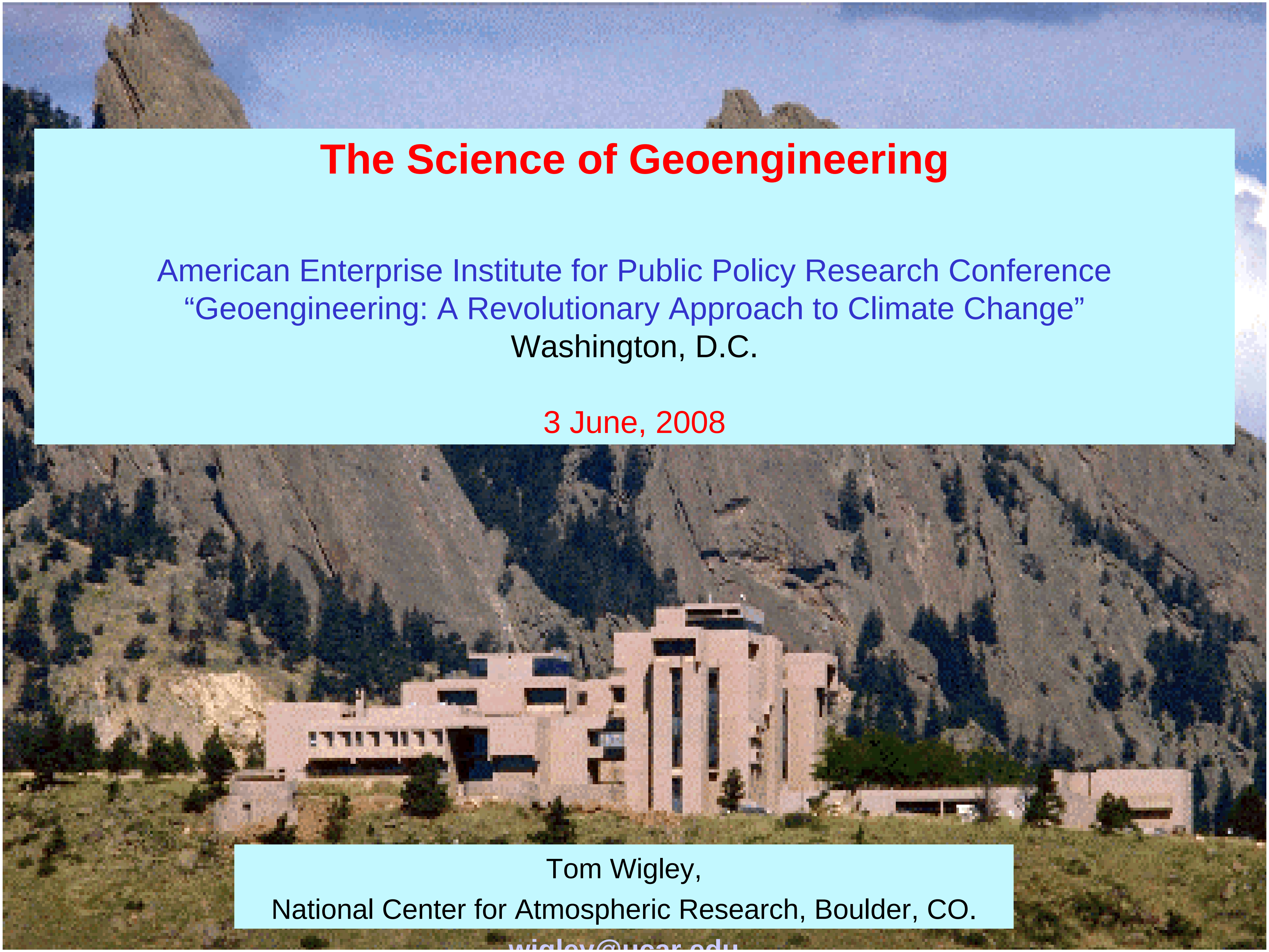

The Science of Geoengineering

American Enterprise Institute for Public Policy Research Conference
“Geoengineering: A Revolutionary Approach to Climate Change”
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Outline

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- Introduction: Definitions (Mitigation, Adaptation, Geoengineering), Examples, Why might we need geoengineering?, Benefits and risks.
- **Geoengineering using stratospheric sulfate aerosols**
- Mitigation (CO_2 emissions reduction) issues
- Combined geoengineering/mitigation strategies
- Implications for global-mean temperature and sea level.
- Conclusions

Definitions

The responses to climate change may be divided into …

- **Mitigation:** Reduction of net greenhouse gas emissions. This includes CCS (carbon capture and storage) and (possibly) ocean fertilization.
- **Adaptation:** Making social systems less sensitive to climate change in order to reduce impacts.
- **Geoengineering:** Deliberate modification of the Earth's short-wave radiation budget to reduce the magnitude of climate change. (Also referred to as Solar Radiation Management – SRM.)

It is generally believed that both mitigation and adaptation are necessary. It is possible that geoengineering may also be necessary – in addition to mitigation and adaptation, rather than as a replacement for either.

Examples of geoengineering responses

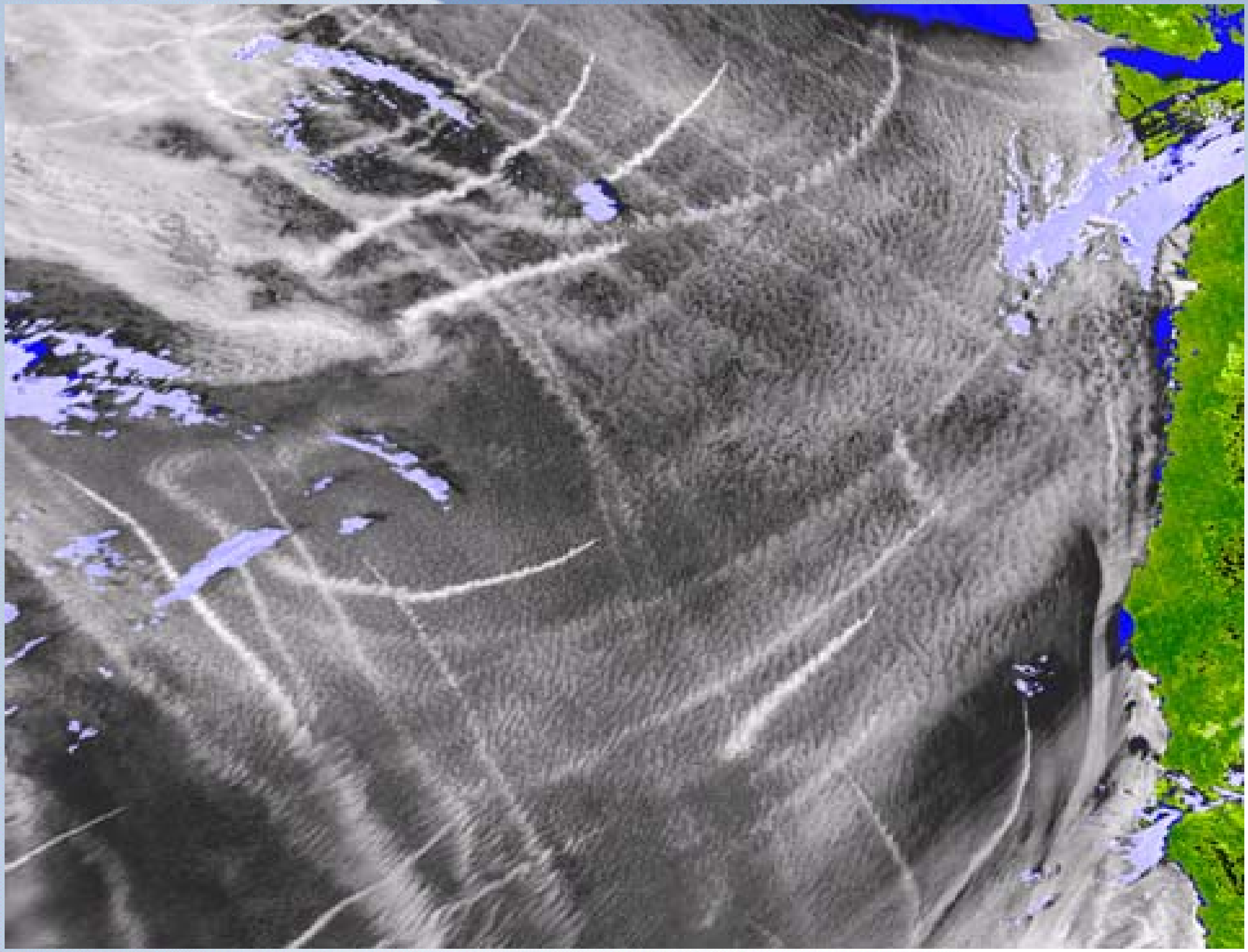
- Changing the net amount of incoming solar radiation using orbiting solar reflectors, or by injection of aerosols or aerosol precursors into the stratosphere.

- Changing the albedo (reflectivity) of clouds by increasing the numbers of cloud condensation nuclei.

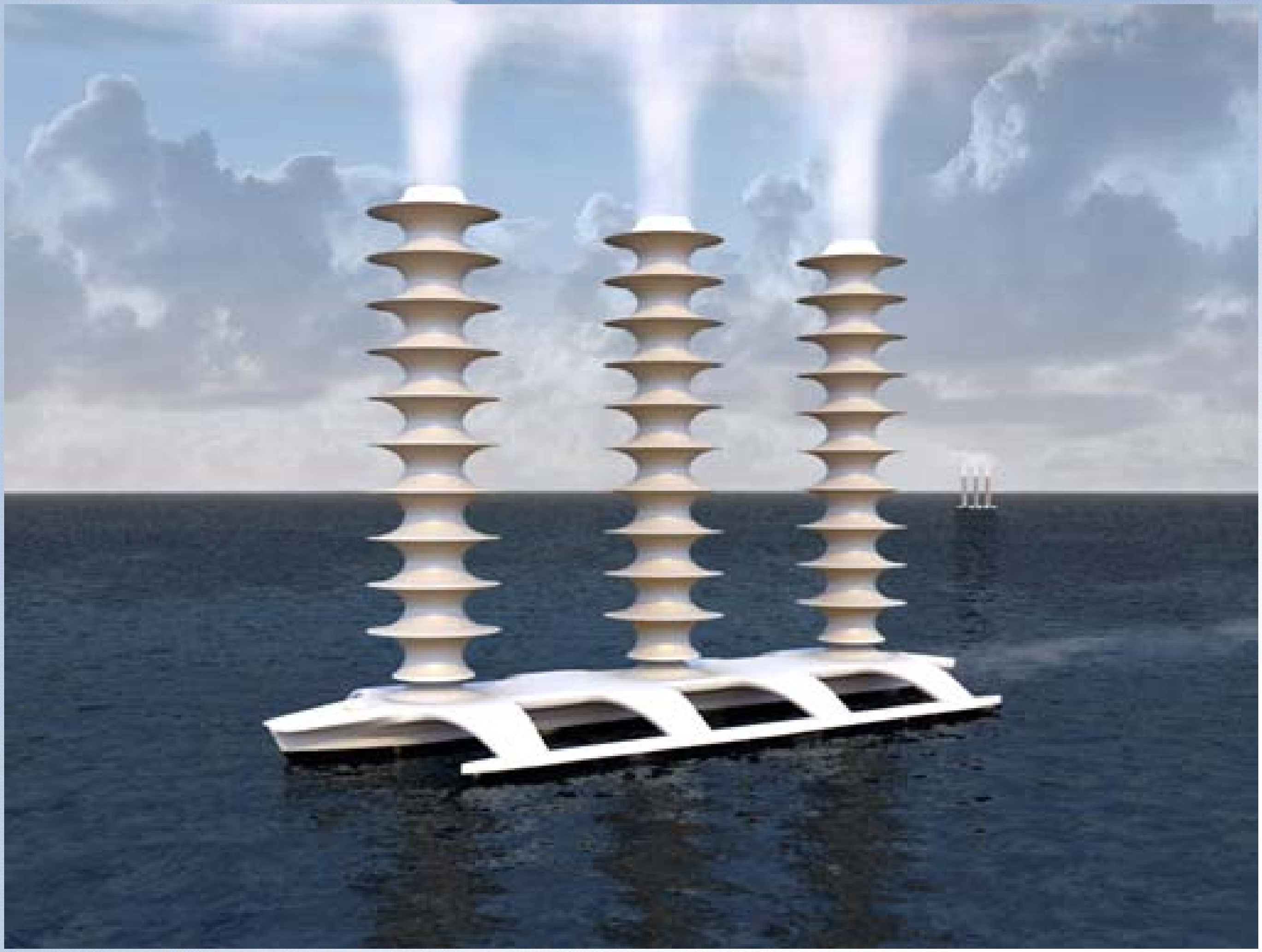
- Changing surface albedo through (e.g.) painting roofs white, vegetation modification, changing desert surfaces, etc.

This talk will concentrate on the stratospheric aerosol method, but first I will say a little about the cloud albedo method, which may be a useful complement.

Ship tracks show that increased CCNs do make clouds more reflective.



Salter's droplet injection ship



Why should we consider geoengineering?

- In an ideal world we would hope to minimize the climate change problem solely through mitigation and adaptation.

- Mitigation targets are guided by Article 2 of the UN Framework Convention on Climate Change -- which has, as its goal, stabilization of greenhouse gas concentrations at a level that will avoid dangerous interference with the climate system.

- A common stabilization target for CO_2 is 450ppm. We are currently at around 385ppm, 100ppm above the pre-industrial level.

- Two crucial questions therefore are: is 450ppm achievable? and, is 450ppm low enough?

Why should we consider geoengineering?

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- **What if we find that 450ppm is not achievable**, or that it can only be achieved through a pathway that exceeds this limit before declining – an overshoot pathway?
- **What if we find that a target of less than 450ppm is required** in order to avoid "dangerous interference"?
- **These are the circumstances under which geoengineering might become necessary. We may not know whether these circumstances prevail for a number of decades, so, as an insurance policy, we should consider the politics, ethics, legal aspects, technology and science of geoengineering now.**

Benefits and Risks

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All geoengineering options have both benefits and risks.

Any decision to use geoengineering must weigh the benefits (of reduced global-mean warming) against the risks of anticipated or unanticipated negative environmental consequences.

Some scientists believe that geoengineering should not be used under any circumstances. They say that, because we are already altering the planet in an inadvertent and largely uncontrolled manner, it would be foolish to tamper further with the system deliberately.

Other scientists say that geoengineering should only be used as a last resort – as a safety valve.

I am in the second group – but my view is that we may have already reached the "last resort" stage.

Nevertheless, before embarking on a geoengineering strategy (**as a complement to mitigation**) we need to assess the risks better.

Geoengineering using stratospheric sulfate aerosols

Method: injection of aerosols or aerosol precursors into the stratosphere

Estimated cost (from Crutzen): $50bn/year

How do we get the aerosols up there?
Aircraft ceilings

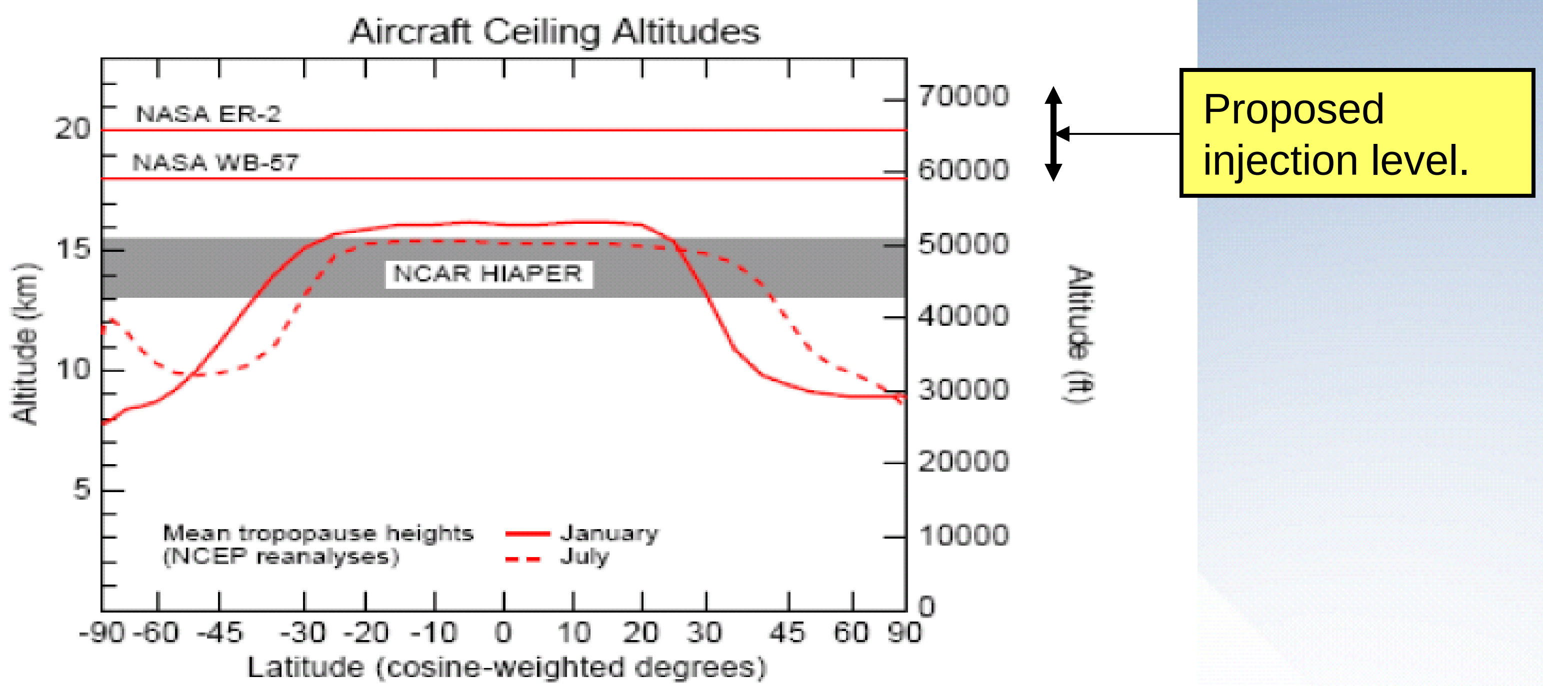

Figure 1. Nominal ceiling altitudes of the HIAPER and NASA high-altitude aircraft operating for long distances with substantial payloads. The ceiling altitude range of the HIAPER reflects payload weight. To achieve the upper limit altitude, the payload must be reduced by about 60% from that available at the lower limit altitude. Note that the horizontal axis is cosine weighted to yield a display of equal areas on the globe. Data courtesy of W. Randel and F. Wu (NCAR).

Geoengineering using sulfate aerosols

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CRUCIAL POINT:

Geoengineering cannot replace mitigation. CO_2 emissions reduction is necessary to minimize CO_2-induced ocean acidification. However, geoengineering can provide additional time to develop and implement carbon-neutral energy technologies.

I will consider a number of geoengineering scenarios. These are, necessarily, **joint mitigation/geoengineering scenarios.** They are designed specifically to give additional time for the development and implementation of carbon-neutral technologies.

Geoengineering using sulfate aerosols

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POSSIBLE RISKS:

- **Increased tropospheric sulfate loading** and surface deposition due to flux of aerosols into the troposphere.
- Possible effects on **cirrus clouds**.
- Slowdown of **recovery of the ozone layer**.
- **Uncertain changes in the patterns of climate change.**
- Effects of a rapid shutoff of stratospheric injection.

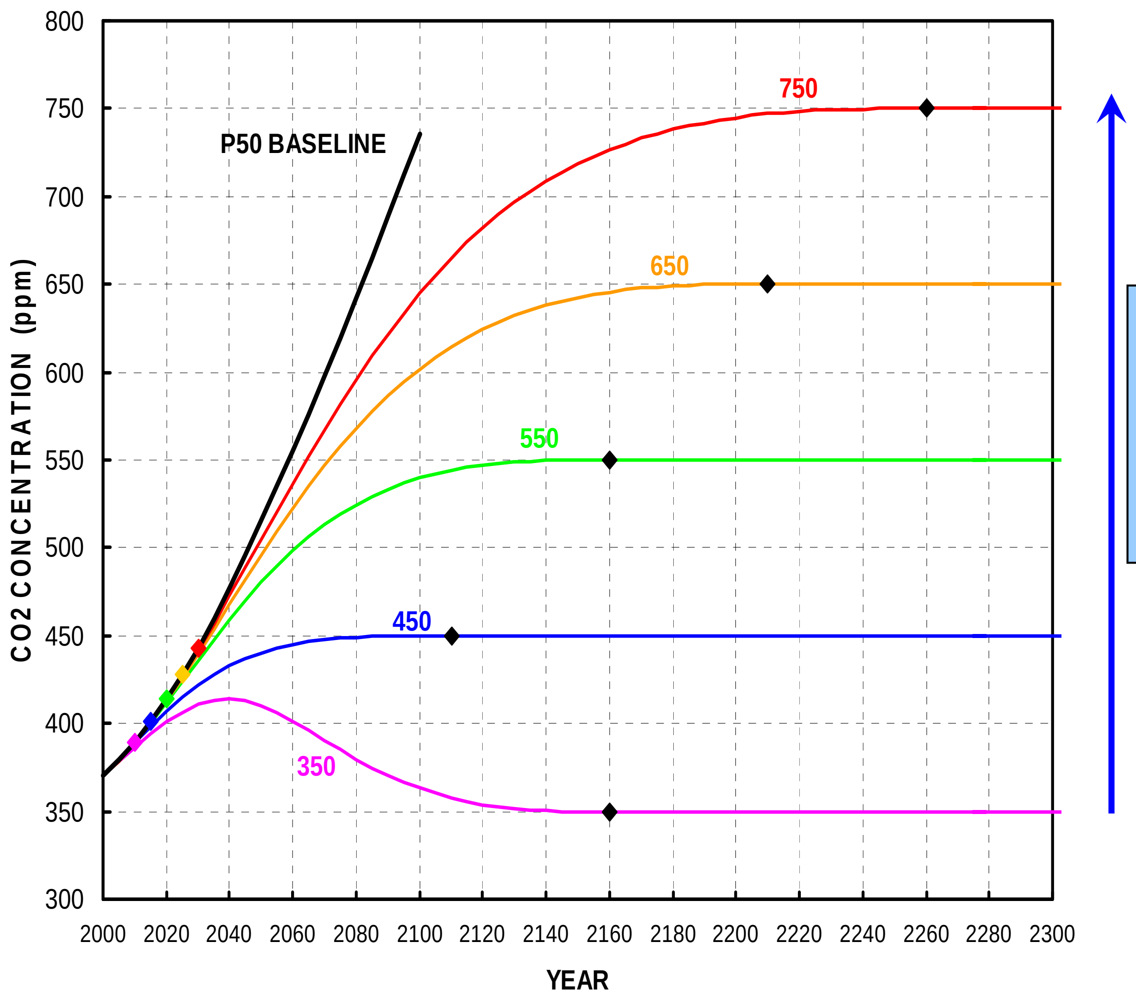
MITIGATION: Reduction of CO_2 emissions with a goal of CO_2 concentration stabilization.

KEY ISSUES

- **What should the stabilization target be?**
- **Concentration stabilization is not the same as emissions stabilization.**

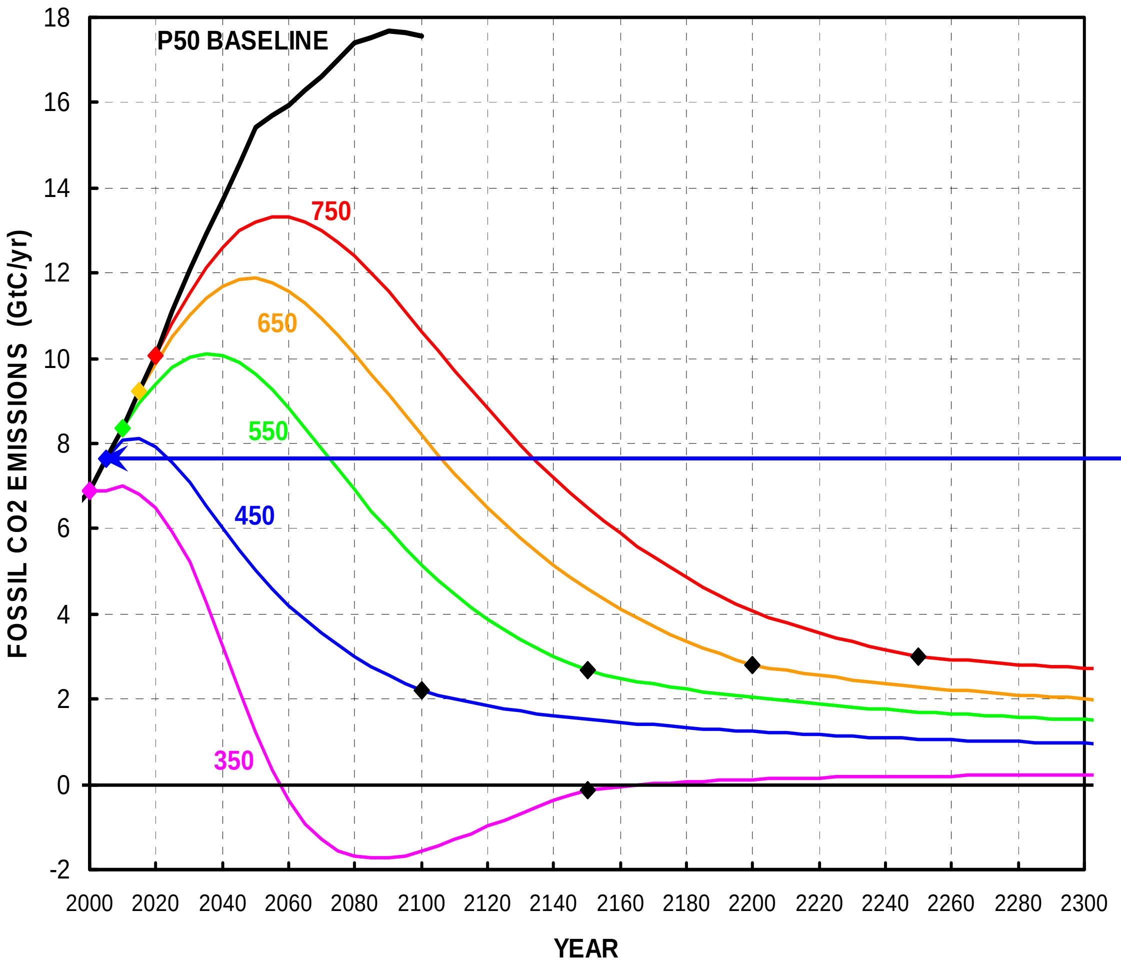
Standard pathways to concentration stabilization: the WRE profiles.

WRE concentration stabilization profiles



Increasing ocean acidity and increasing climate change

Emissions for WRE profiles



2005 level: 7.53 GtC/yr.

Note that the 450ppm pathway requires an immediate departure from the baseline.

Is this emissions pathway achievable?

The stabilization challenge

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- For stabilization at 450ppm we require an almost immediate reduction of emissions below the 'no-climate-policy' baseline, while at the same time maintaining a global economic growth rate of around 2% per year.
- Reductions required relative to today: 2030, –11%; 2050, –37%; 2070, –54%.
- Reductions required relative to baseline: 2030, –42%; 2050, –68%; 2070, –79%.
- **Reductions made this rapidly would require all new power plants to have zero net CO_2 emissions.** This sudden change in current energy sources would almost certainly have serious economic consequences.
- Furthermore, **we do not have the technology** required to make this rapid change in our energy structure – so concentration stabilization is essentially a technology challenge.
- To make matters worse, the standard 'no-climate-policy' baselines already have very large amounts of carbon-neutral technologies built into them, assumed to occur spontaneously. The true technology challenge must include the challenge of developing these technologies as well as the additional technologies required to meet a concentration stabilization target.

The technology challenge

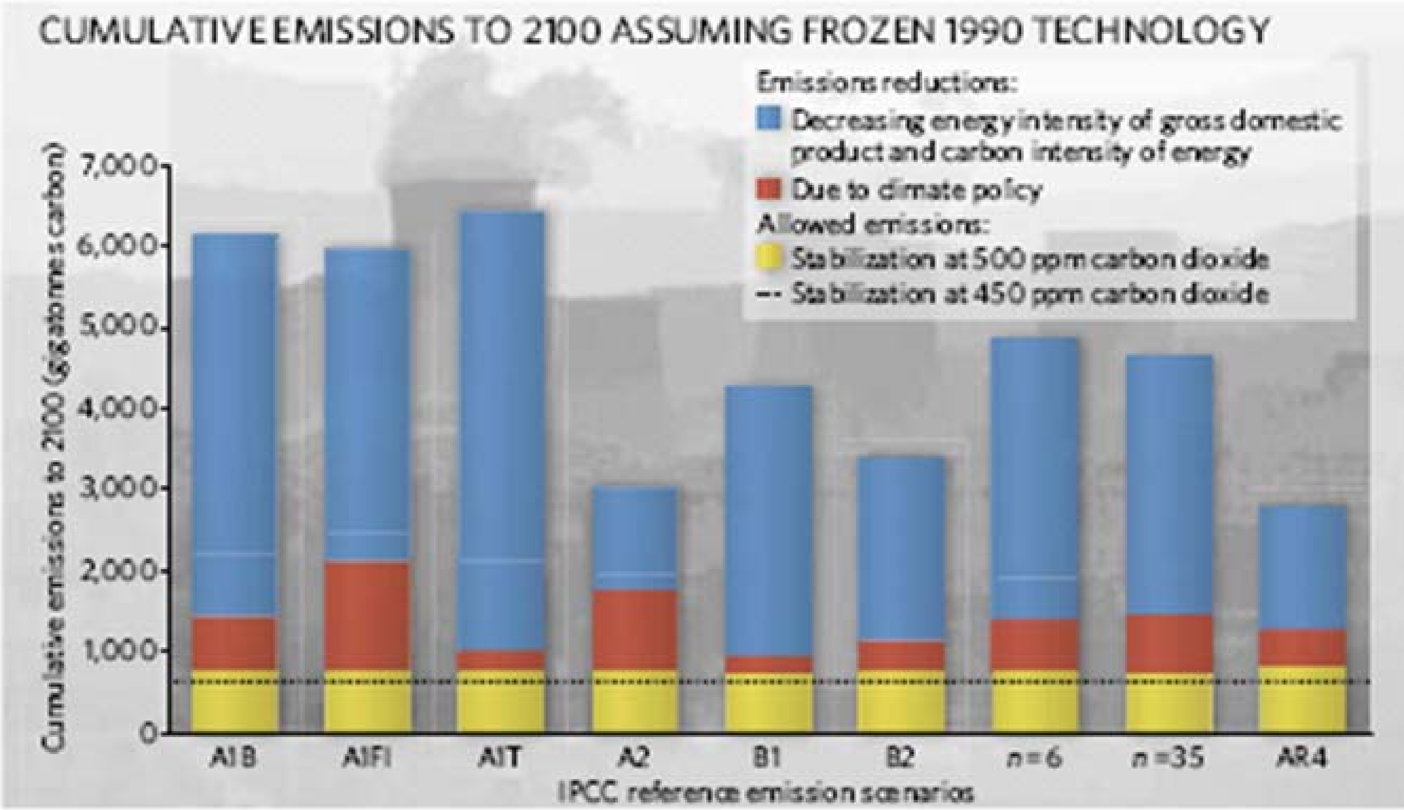

Figure 1 | Cumulative emissions. A range of 'built-in' emissions reductions (blue) in the scenarios used by the Intergovernmental Panel on Climate Change (IPCC). Total cumulative emissions to 2100 associated with a frozen-technology baseline are shown for: six individual scenarios, the means of these scenarios, and for all 35 IPCC scenarios, and the median of the scenario set (AR4). Additional reductions will have to be achieved by climate policy (red), assuming carbon-dioxide stabilization at about 500 parts per million (ppm), leaving allowed emissions for this stabilization target (yellow).

Blue bars: Emissions reductions due to increases in carbon-neutral technologies that are assumed to occur spontaneously.

Red bars: Further reductions in emissions that must be policy driven.

Pielke et al., Nature (2008)

Opinions of leading economists

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From Carmen Difiglio: IEA's 450 Scenario … requires a complete transformation of investment in the electric power sector by 2012. … To quote the *World Energy Outlook 2007*, p. 191: "exceptionally strong and immediate policy action would be essential for [the 450 Scenario] to happen and the associated costs would be very high."

From Jeffrey Sachs: "… current technologies cannot support both a decline in carbon dioxide emissions and an expanding global economy. If we try to restrain emissions without a fundamentally new set of technologies, we will end up stifling economic growth …" (*Scientific American*, April, 2008)

Conclusions re technology

- The magnitude of the technological challenge is not generally appreciated.
- To meet this challenge requires a Manhattan Project effort to develop and deploy the huge amounts of carbon-neutral technologies that are required to simultaneously sustain rapid economic growth and reduce emissions.
- There is no such effort ongoing or planned.

Geoengineering as a “last resort”.

What does “last resort” mean?

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The usual concept of this term considers only aspects of **climate** change. For example, changes in Arctic sea ice and melting of the Greenland ice sheet have been more rapid than previously anticipated, and **some scientists believe that we are already close to a “last resort” climate threshold.**

An equally valid interpretation is in terms of energy **technology**. Carbon-neutral technologies are not being developed or implemented fast enough, and the challenge of developing these technologies is greater than previously anticipated. Thus, we may not be able to avoid dangerous interference with the climate system through changes in energy technology. **We may therefore already be close to a “last resort” technology threshold.**

The **political situation** is, so far, not encouraging, with countries like the USA, Russia, China, India, etc. unwilling to consider emissions targets and timetables. Most signatories of the Kyoto Protocol are unlikely to meet their targets.

A possible solution: geoengineering to gain time

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- A slower departure from the "no-climate-policy" CO_2 emissions baseline would reduce the economic burden and give more time to develop the required zero-net-carbon technologies.

- Climate geoengineering would allow a slower departure from the baseline – but it does not solve the ocean acidity problem and so does not avoid the need to eventually stabilize CO_2 levels at some level close to today.

Geoengineering strategy

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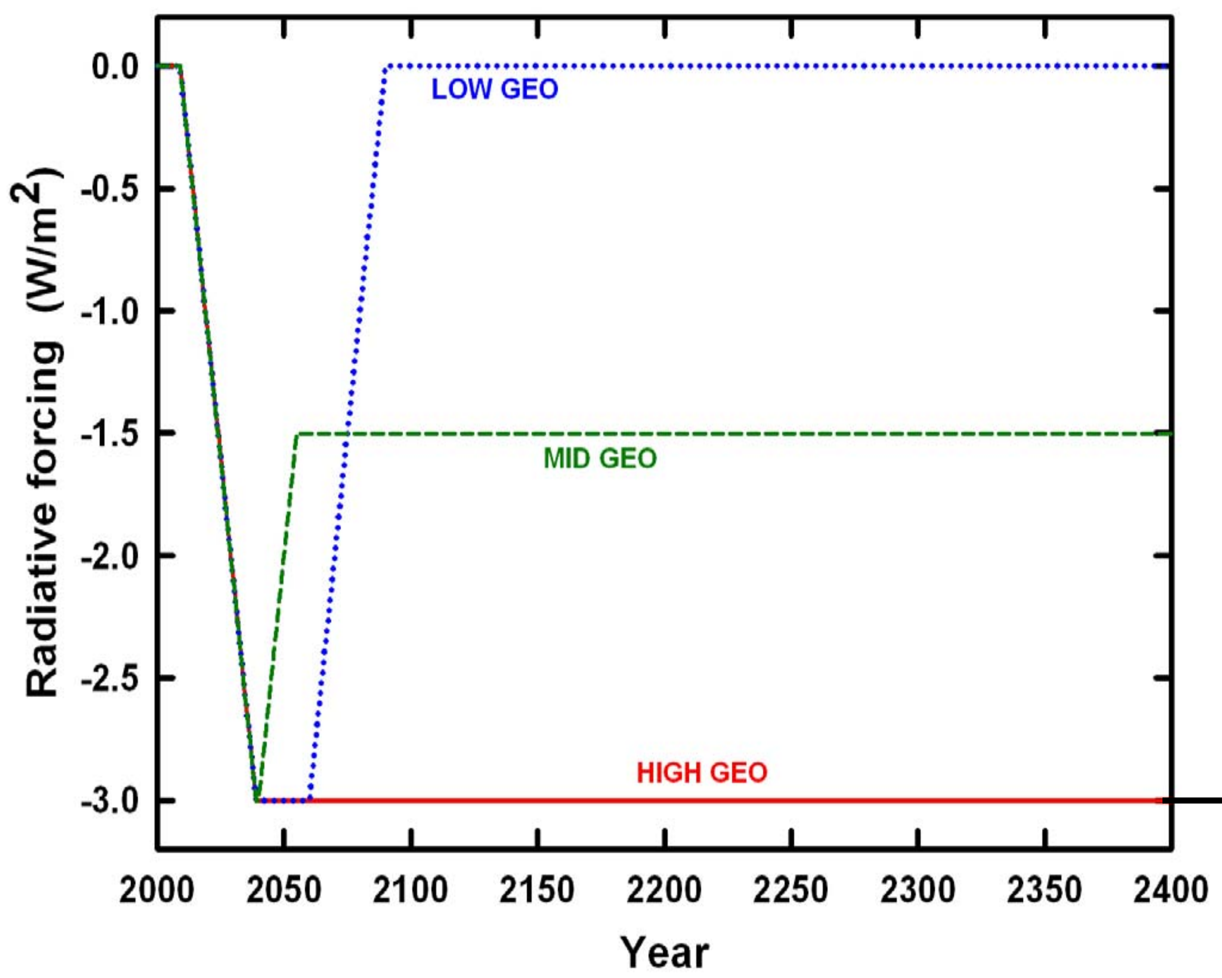
- We should seriously consider **using geoengineering to gain time** to implement mitigation measures (CO_2 emissions reductions) cost-effectively and to develop carbon-neutral energy technologies at the scale required.
- This would require a **combined geoengineering/mitigation strategy** with the same long-term concentration goals as in a “pure” mitigation strategy.
- The magnitude of geoengineering required with this approach (and any associated risks) would be much less than if geoengineering were used as the sole climate-change reduction method.

Combined geoengineering and mitigation scenarios.

Results from Wigley, 2006: A combined mitigation/geoengineering approach to climate stabilization**.** *Science* **314**, 452–454.

Possible geoengineering scenarios



3 W/m² equals one Pinatubo every two years (approx.)

Without geoengineering: Baseline and CO_2 stabilization scenarios

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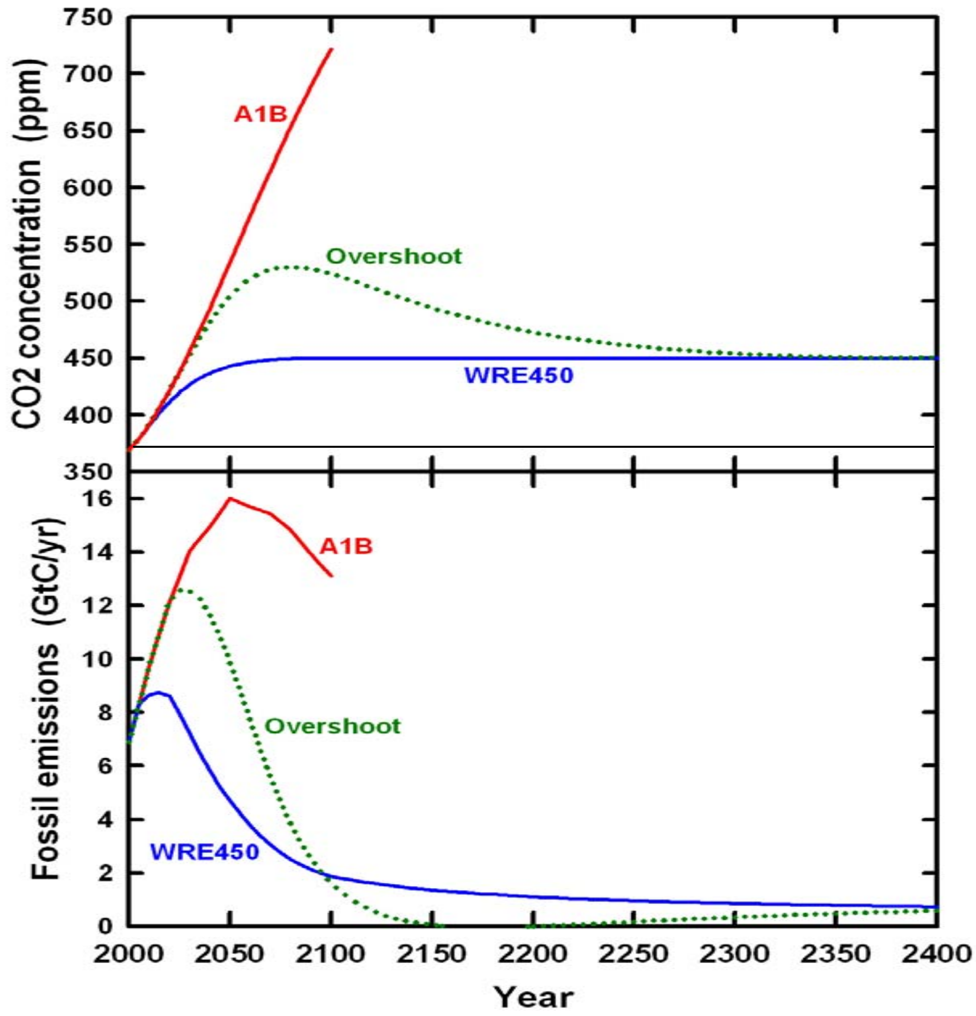
Overshoot is the case that is used in conjunction with the three geoengineering scenarios.

Overshoot delays departure from the emissions baseline for 15 years allowing more time to develop and deploy carbon-neutral technologies.



Combined mitigation/geoengineering scenarios

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Comparing no-geoengineering scenarios with combined scenarios.

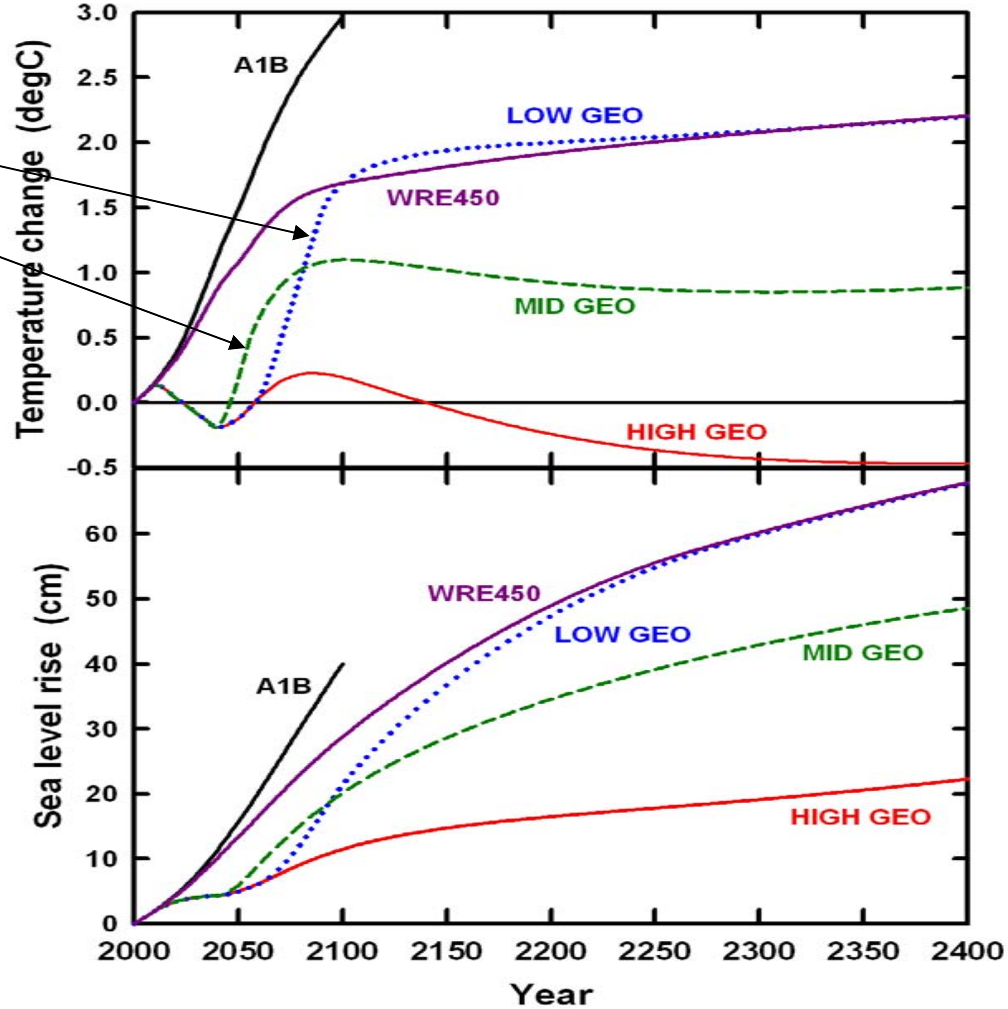
(1) Baseline ('no policy') scenario (A1B).

(2) Mitigation only (WRE450).

(3) Overshoot (less rapid, but probably more realistic mitigation) plus LOW, MID and HIGH amounts of geoengineering.

Global-mean temperature and sea level consequences

Rapid warming if geoengineering turned off – but no more rapid than A1B.



KEY

- A1B = no-climate-policy baseline
- WRE450 = mitigation only
- LOW/MID/HIGH GEO = less rapid mitigation plus geoengineering

ΔT2x = 3 degC: mid ice melt parameters for sea level rise from IPCC TAR.

Potential risks associated with stratospheric SO_2 emissions (1)

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- Increased tropospheric SO_2 loading, and surface deposition.
- Effects on cirrus clouds.
- Effects on stratospheric ozone – slowdown of ozone layer recovery.
- Uncertain patterns of climate change. Cancellation of global-mean warming will not necessarily lead to cancellation of regional climate changes.

Potential risks associated with stratospheric SO_2 emissions (2)

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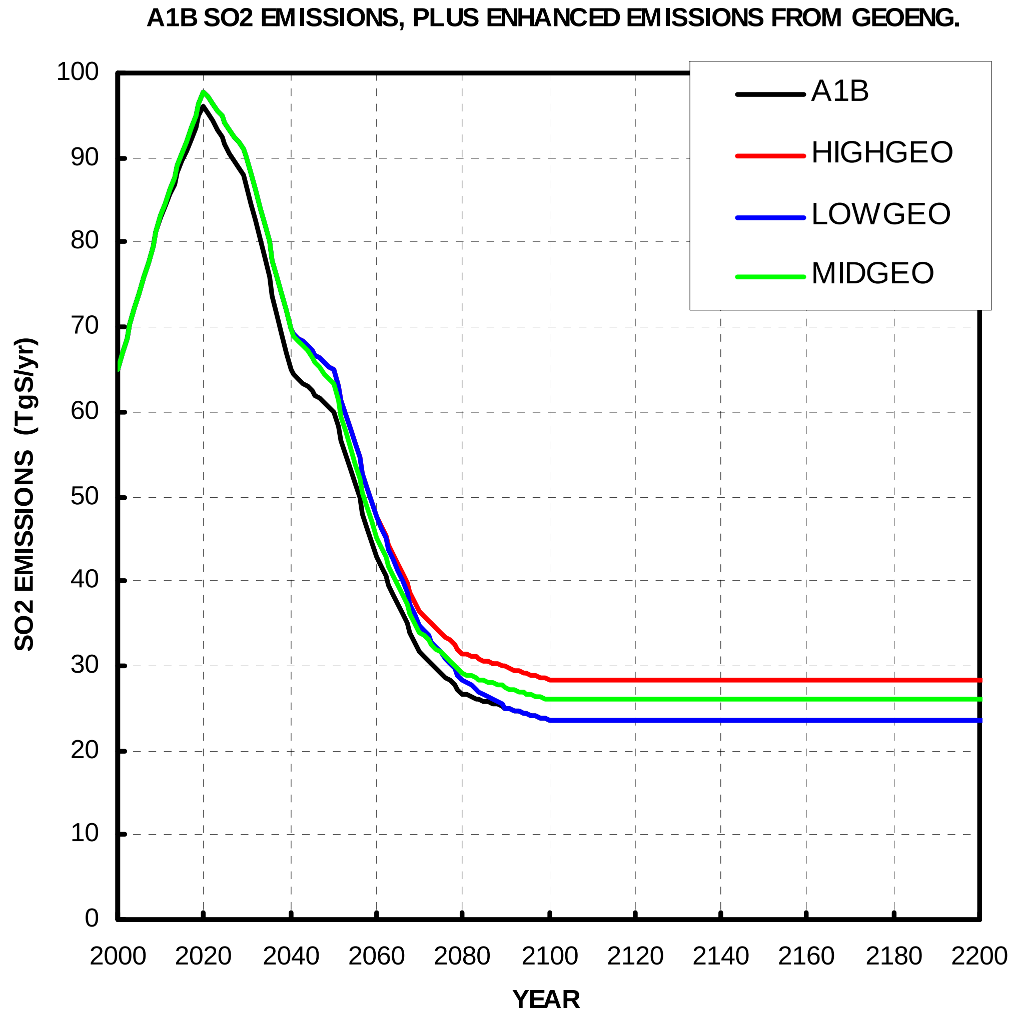
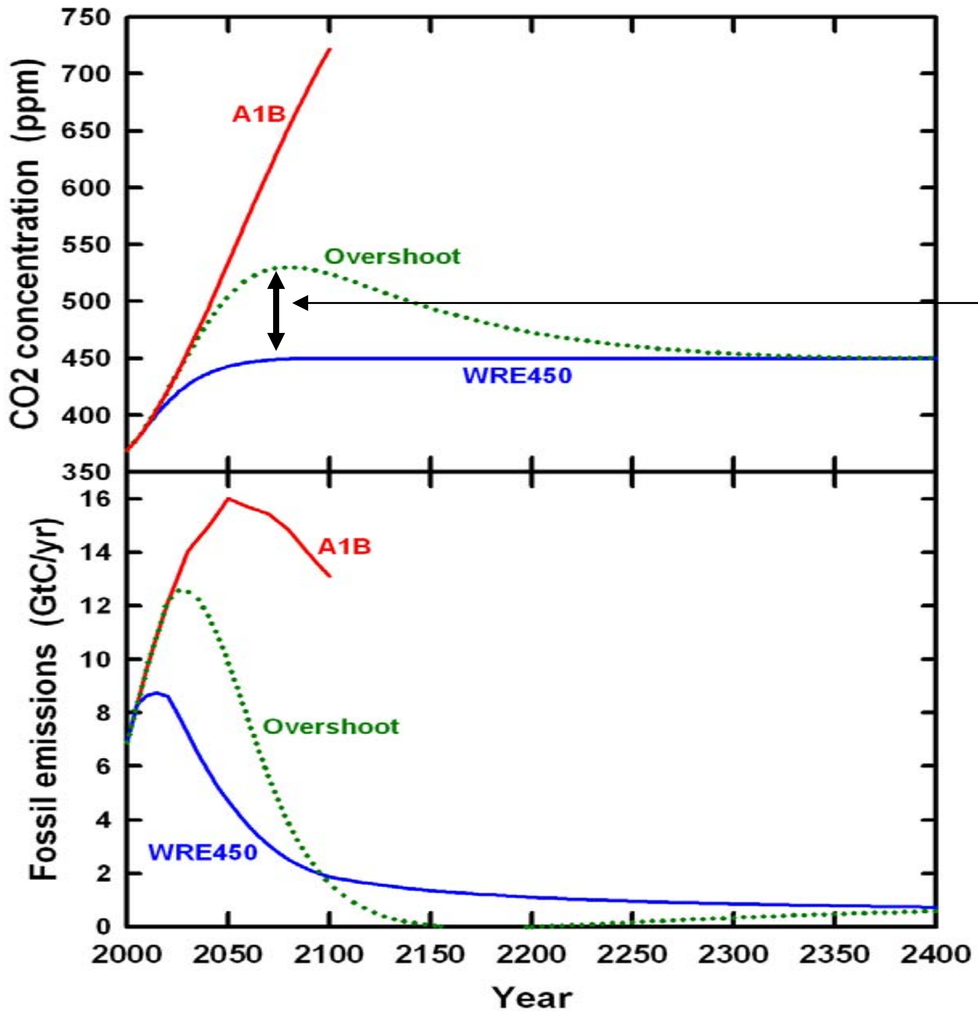
- Increased tropospheric SO_2 loading, and surface deposition. [But only by a few percent globally compared to current emissions from coal combustion.]
- Effects on cirrus clouds. [Uncertain, but probably small and may have a net cooling effect (Abbatt et al., 2006).]
- Effects on stratospheric ozone – slowdown of ozone layer recovery. [Uncertain, but would probably delay recovery of the ozone hole by only a few decades for the scenarios considered here.]
- Uncertain patterns of climate change. Cancellation of global-mean warming will not necessarily lead to cancellation of regional climate changes. [Overall, a perfect balancing of global-mean temperature would cause a global-mean reduction in precipitation because precipitation changes are more sensitive to short-wave (aerosol) forcing than long-wave (greenhouse-gas) forcing. Further, perfect global-mean balancing would probably leave residual high-latitude warming and over-compensating cooling in the tropics.]

Effect on tropospheric SO2



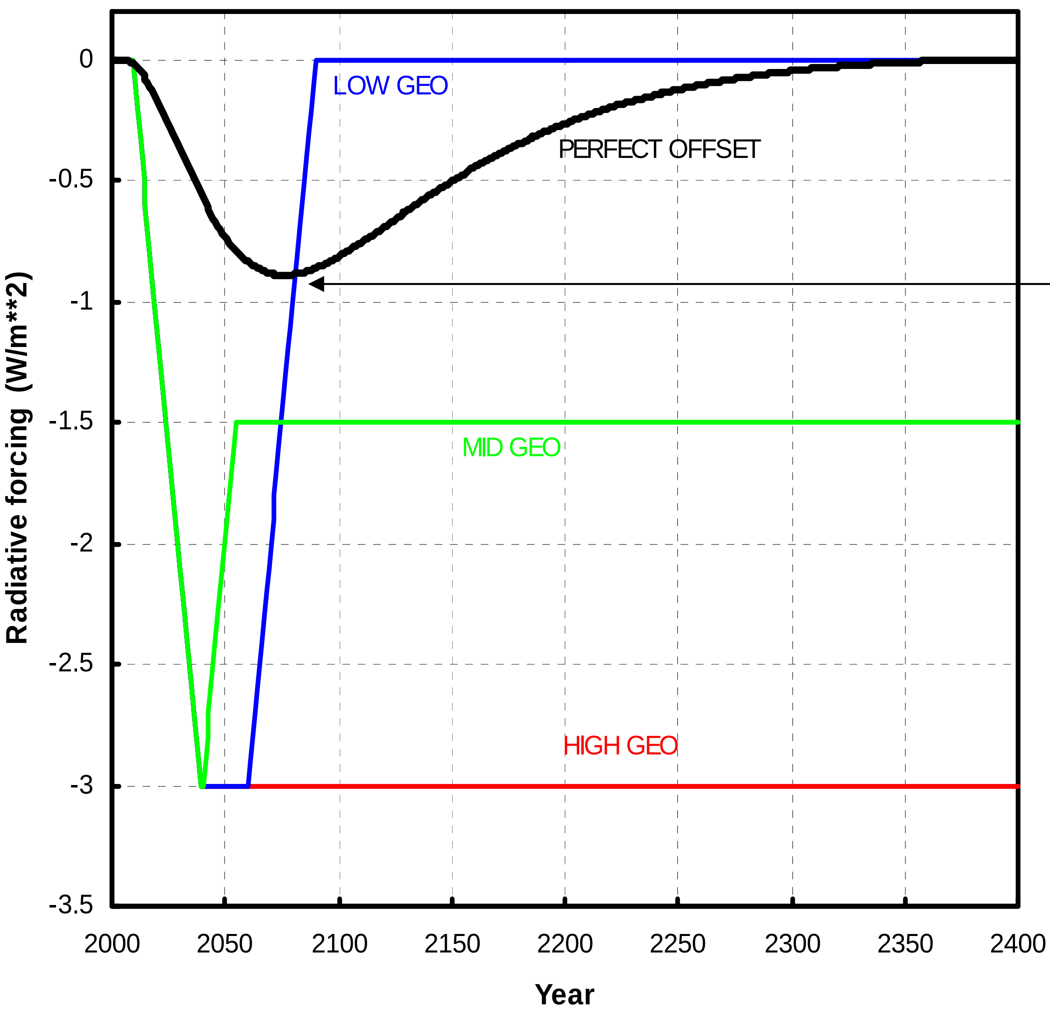
An optimized geoengineering scenario. What if all we want to do is offset the additional forcing produced by an overshoot mitigation pathway?

Overshoot scenario



Goal: To offset the forcing due to the Overshoot/WRE450 concentration difference.

Forcing required to fully offset additional overshoot forcing



For volcanic-sized aerosols, this corresponds to a peak injection rate of a little over 1TgS/yr, equivalent to one Pinatubo eruption every 7 years.

Based on recent modeling results (Robock, Rasch, Tilmes) the negative effects on climate and ozone would be negligible.

Conclusions

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- Injection of up to about 1 TgS per year, ramping up to this maximum rate over 70 years and then slowly declining to zero, could allow an extra two decades to develop the technology for, and allow us to implement mitigation cost-effectively. [Total injection = 100TgS.]

- Mitigation combined with continuous geoengineering at a higher level could eliminate future global warming, and keep sea level rise below 20 cm for many centuries.

- This may be the only practical way to keep long-term sea level rise within acceptable levels. To do so through greenhouse-gas reductions alone would require reducing CO_2 concentrations to below 250ppm over the next few centuries. On longer time scales there are still potential problems.

Unresolved issues

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- Development of sulfur injection technologies (note that the scenarios considered here assume a 30+ year development period).

- Assessment of alternative types of aerosol – as suggested by Teller.

  Smaller and/or more optically efficient aerosols would require smaller emissions/mass loadings to produce the same amount of global-mean cooling. But smaller aerosols also have larger ozone effects.

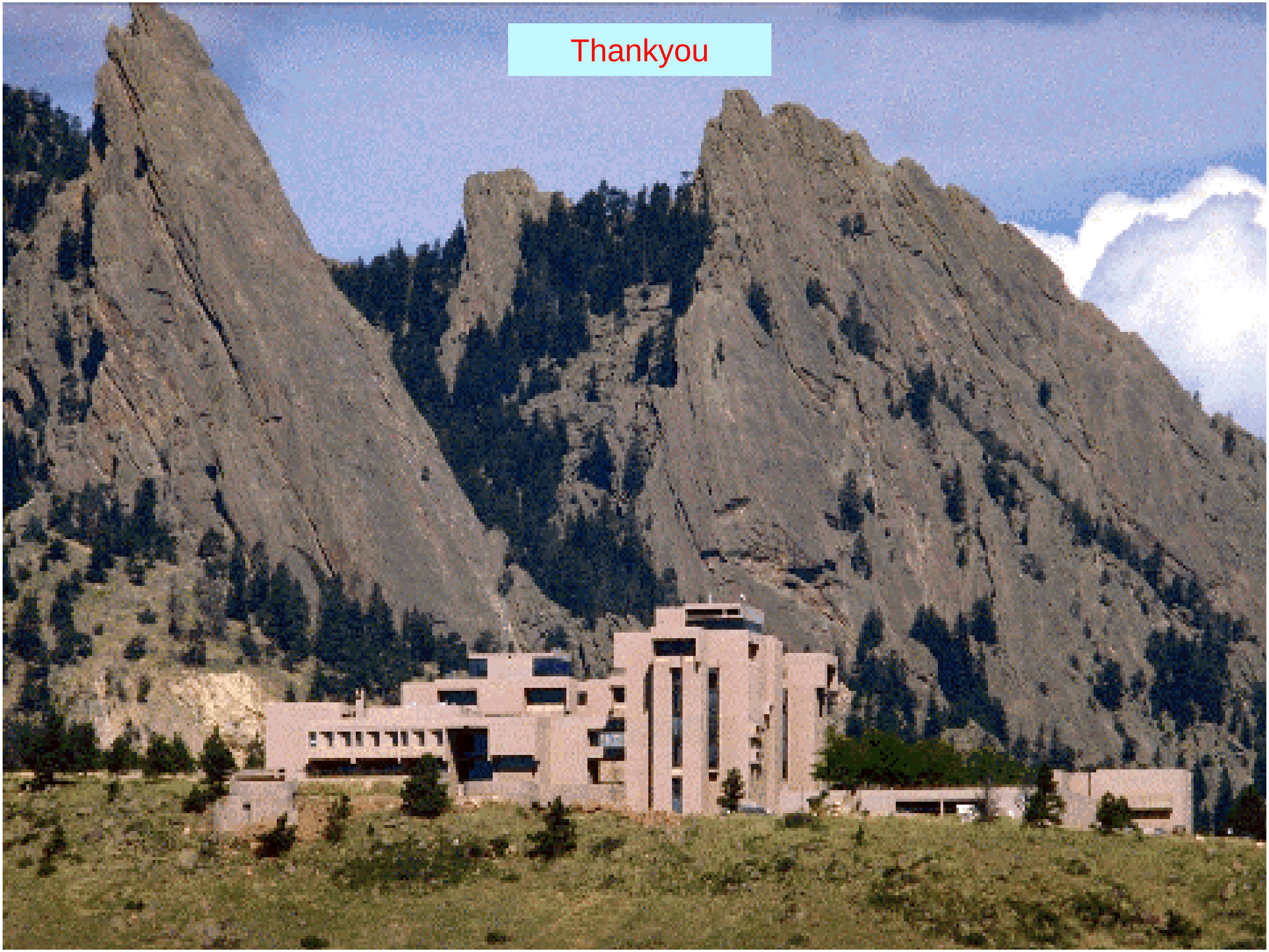
- Assessment of the costs of geoengineering versus the economic benefits of changed mitigation timing.

- Assessment of the effects on stratospheric ozone and climate for realistic combined geoengineering/mitigation scenarios.

Summary

- My main concern is that, even with the best of good intentions and global political co-operation, we may not be able to avoid dangerous interference with the climate system through mitigation and adaptation strategies alone, either because future climate changes and/or impacts will be larger than current central estimates, and/or because the rate of development and implementation of appropriate carbon-neutral energy technologies will be too slow.

- Because of these concerns, my judgment is that geoengineering should be considered seriously as a “fall back” option – and that research into its technical challenges, costs, benefits and risks should be a high priority item.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