In Defense of Geoengineering

EPRI Global Climate Change Research Seminar
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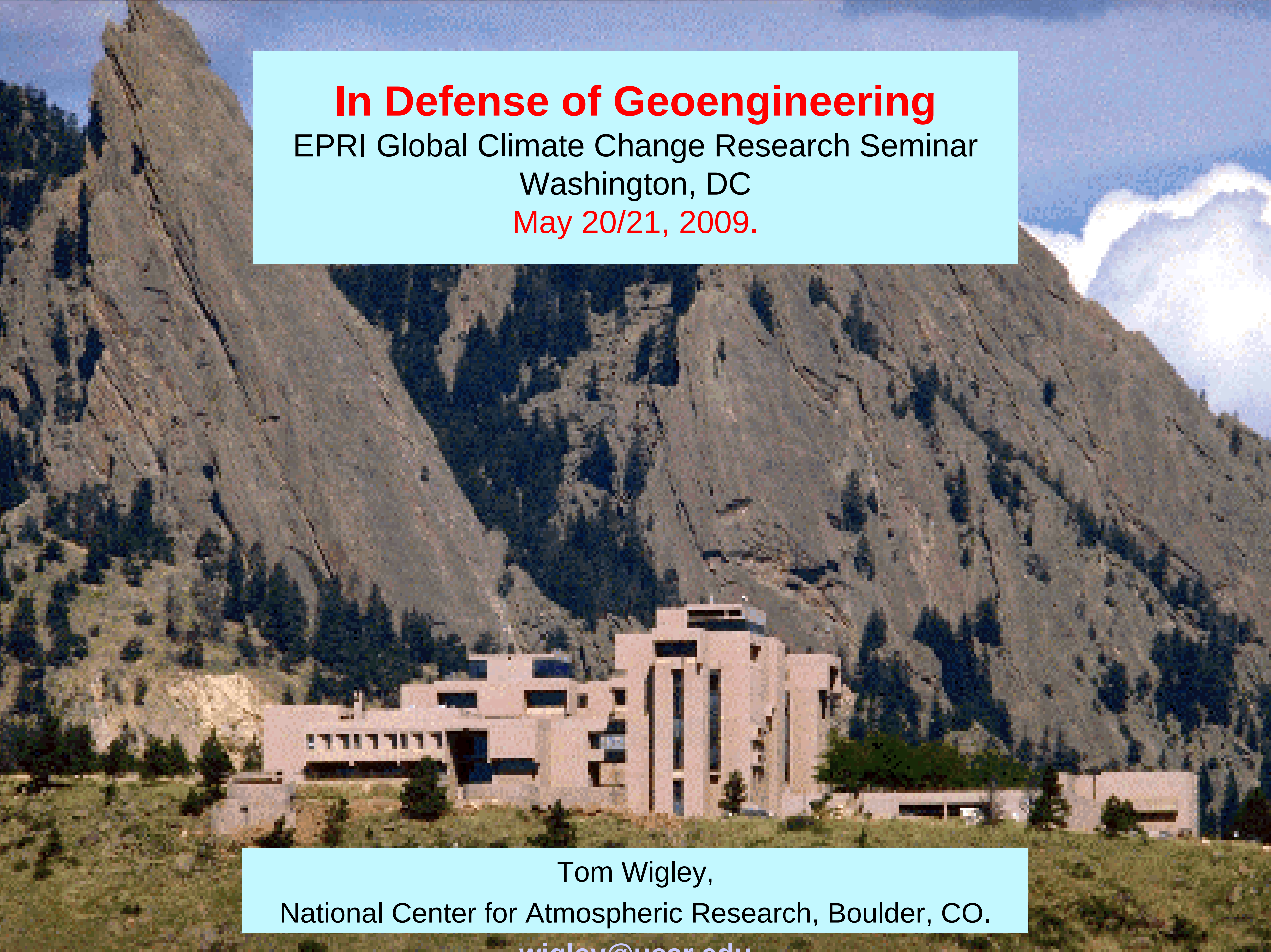

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Outline

- Introduction: Definitions (Mitigation, Adaptation, Climate Engineering). Reasons for revived interest.
- Climate Engineering using stratospheric sulfate aerosols
- Combined climate engineering/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 ocean fertilization.
- **Adaptation:** Making social systems less sensitive to climate change in order to reduce impacts.
- **Climate Engineering:** Deliberate modification of the Earth's short-wave radiation budget to reduce the magnitude of climate change. (Also referred to as Geoengineering and Solar Radiation Management.)

It is generally believed that both mitigation and adaptation are necessary. It is possible that climate engineering may also be necessary – in addition to mitigation and adaptation, NOT as a replacement for either.

WHY HAS CLIMATE ENGINEERING BECOME A HOT TOPIC RECENTLY?

THREE MAIN REASONS …

1. A paper on the subject by Nobel prize winner Paul Crutzen
2. The fact that recent changes in climate appear to be happening faster than expected
3. The realization that the technology challenge of transitioning to a carbon-neutral economy may be very difficult

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Climatic Change article by Paul Crutzen (August, 2006)

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ALBEDO ENHANCEMENT BY STRATOSPHERIC SULFUR INJECTIONS: A CONTRIBUTION TO RESOLVE A POLICY DILEMMA?

An Editorial Essay

Fossil fuel burning releases about 25 Pg of CO_2 per year into the atmosphere, which leads to global warming (Prentice et al., 2001). However, it also emits 55 Tg S as SO_2 per year (Stern, 2005), about half of which is converted to sub-micrometer size sulfate particles, the remainder being dry deposited. Recent research has shown that the warming of earth by the increasing concentrations of CO_2 and other greenhouse gases is partially countered by some backscattering to space of solar radiation by the sulfate particles, which act as cloud condensation nuclei and thereby influence the micro-physical and optical properties of clouds, affecting regional precipitation patterns, and increasing cloud albedo (e.g., Rosenfeld, 2000; Ramanathan et al., 2001; Ramaswamy et al., 2001). Anthropogenically enhanced sulfate particle concentrations thus cool the planet, offsetting an uncertain fraction of the anthropogenic increase in greenhouse gas warming. However, this fortunate coincidence is "bought" at a substantial price. According to the World Health Organization, the pollution particles affect health and lead to more than 500,000 premature deaths per year worldwide (Nel, 2005). Through acid precipitation and deposition, SO_2 and sulfates also cause various kinds of ecological damage. This creates a dilemma for environmental policy makers, because the required emission reductions of SO_2, and also anthropogenic organics (except black carbon), as dictated by health and ecological considerations, add to global warming and associated negative consequences, such as sea level rise, caused by the greenhouse gases. In fact, after earlier

Climatic Change **77** (3-4), 211-220, 2006.

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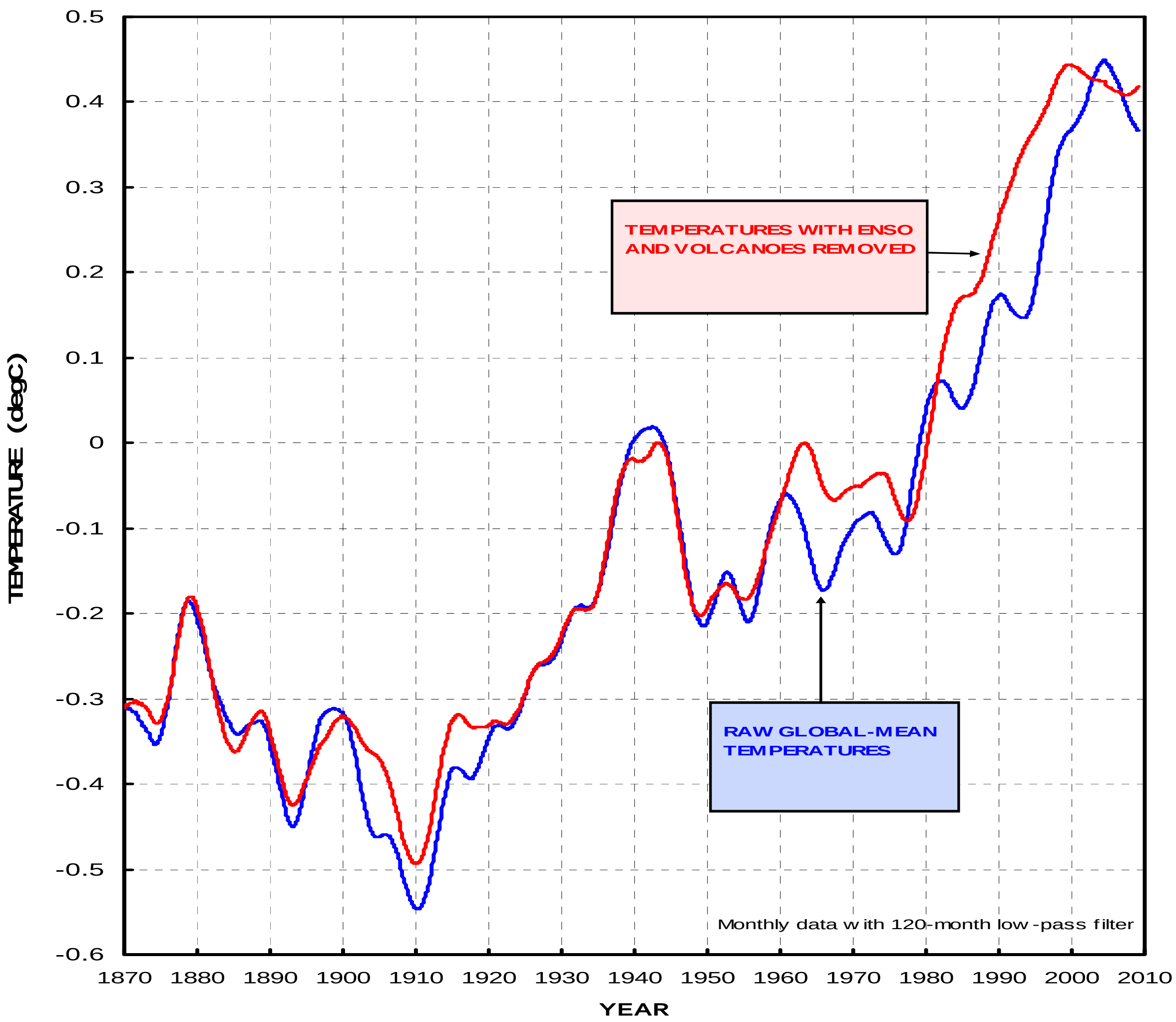
Observed global-mean temperatures

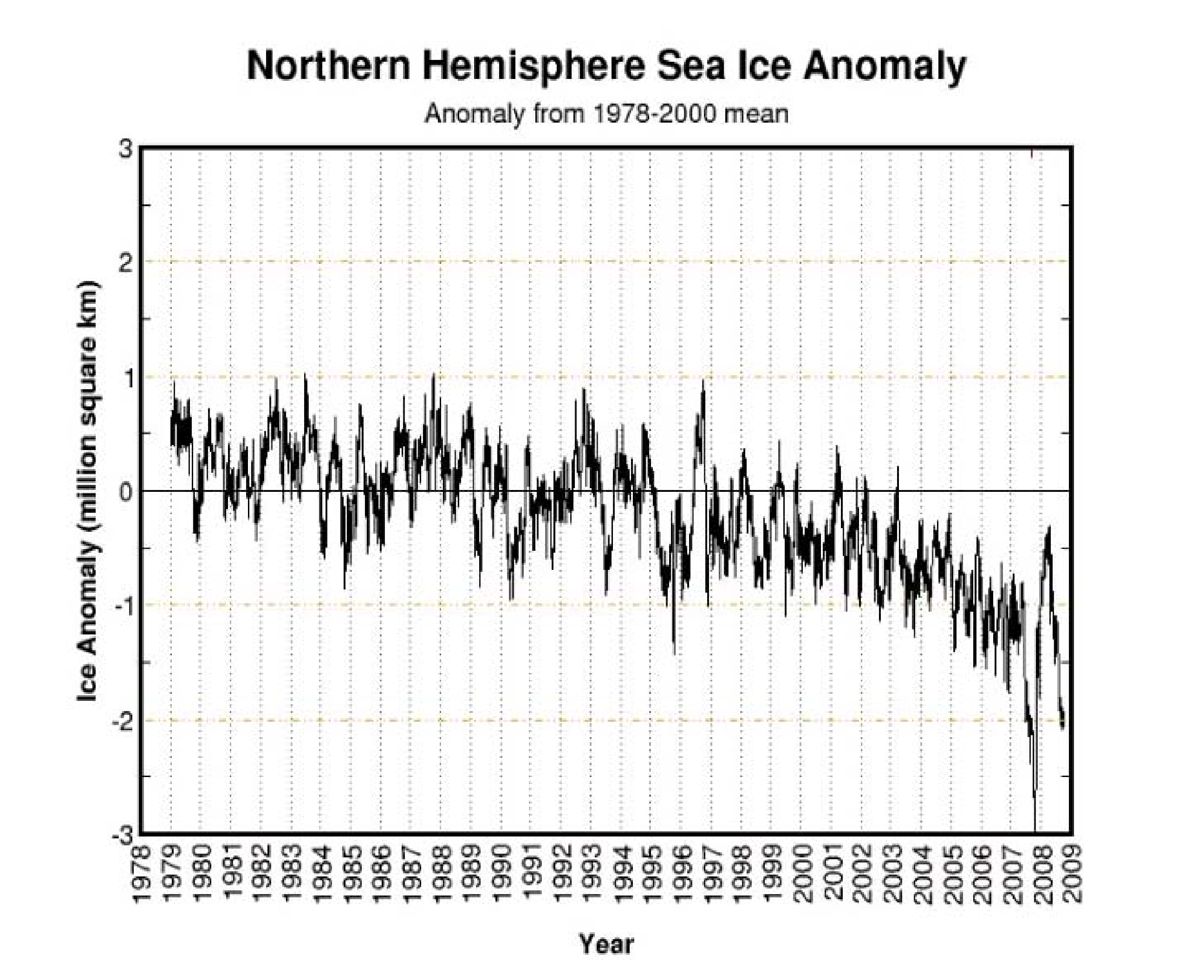


News from the Arctic and Antarctica

Arctic sea ice extent has reduced rapidly

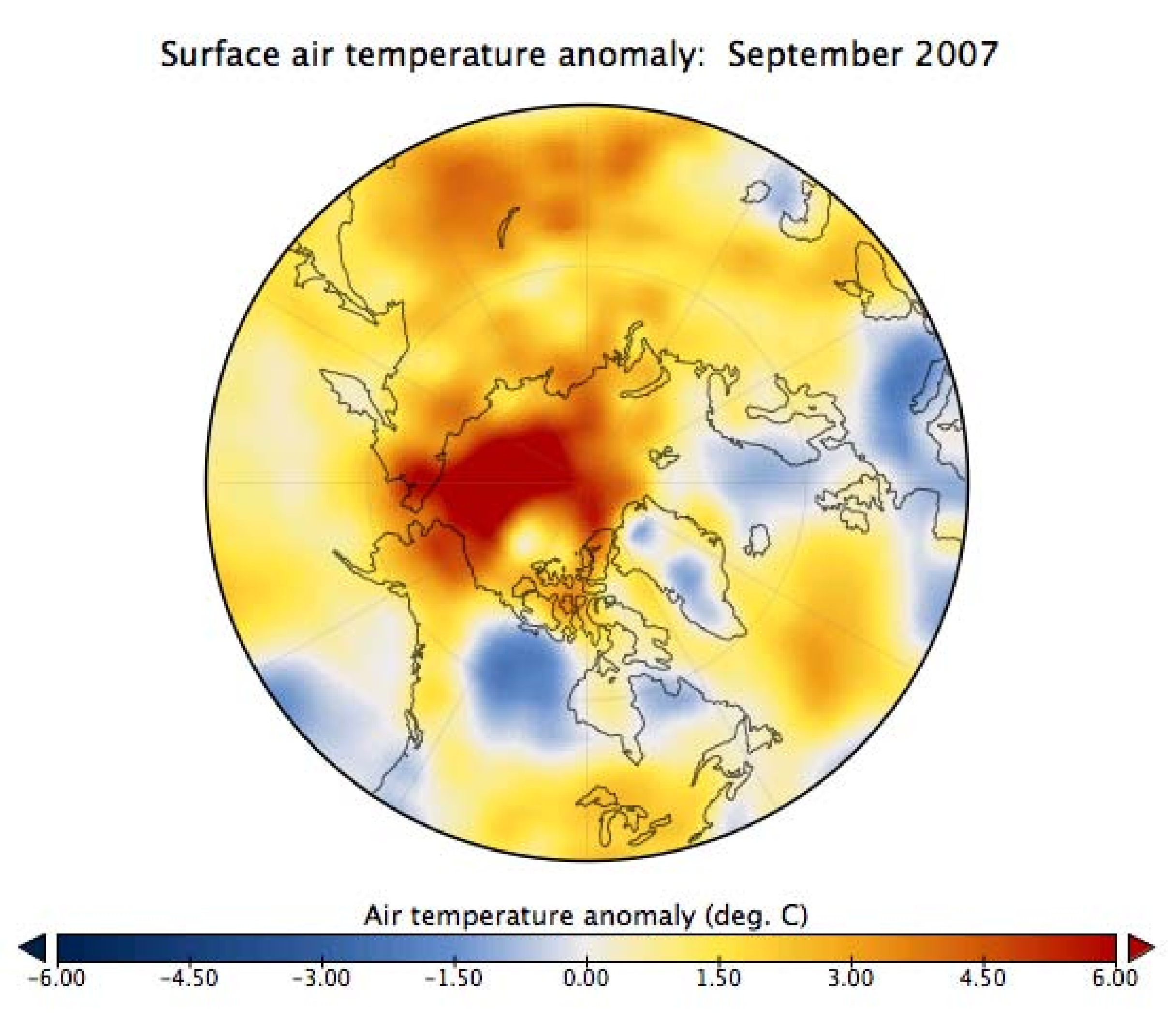
From National Snow and Ice Data Center

Arctic sea ice changes



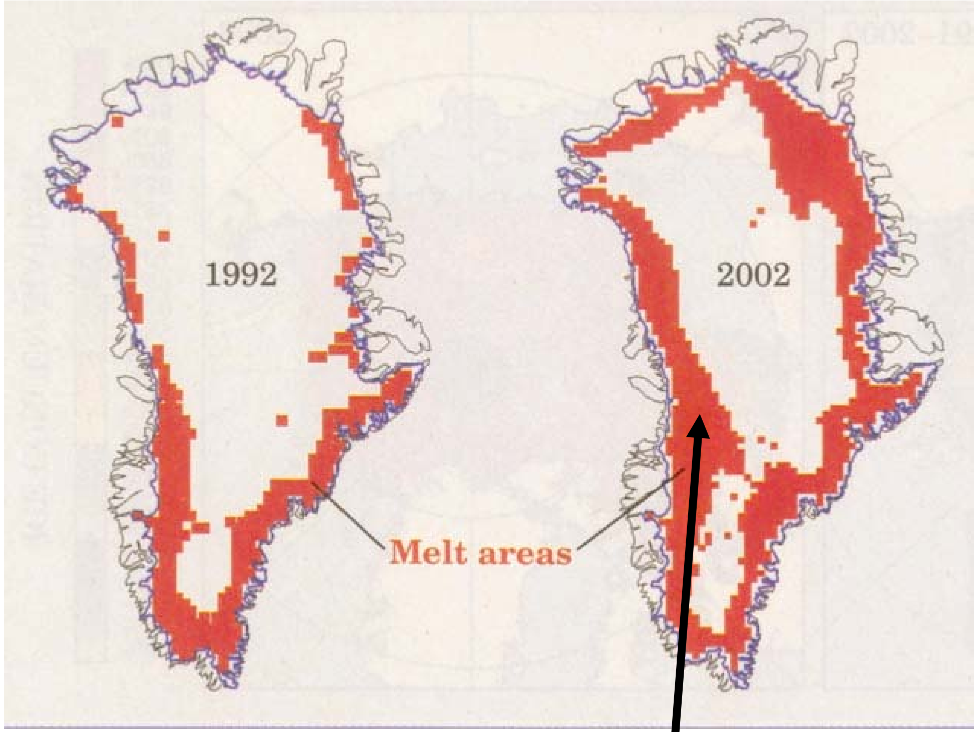
From http://arctic.atmos.uiuc.edu/cryosphere/

Arctic temperatures have been much warmer than usual



From http://arctic.atmos.uiuc.edu/cryosphere/

Increased melt in Greenland



70 meters thinning in 5 years

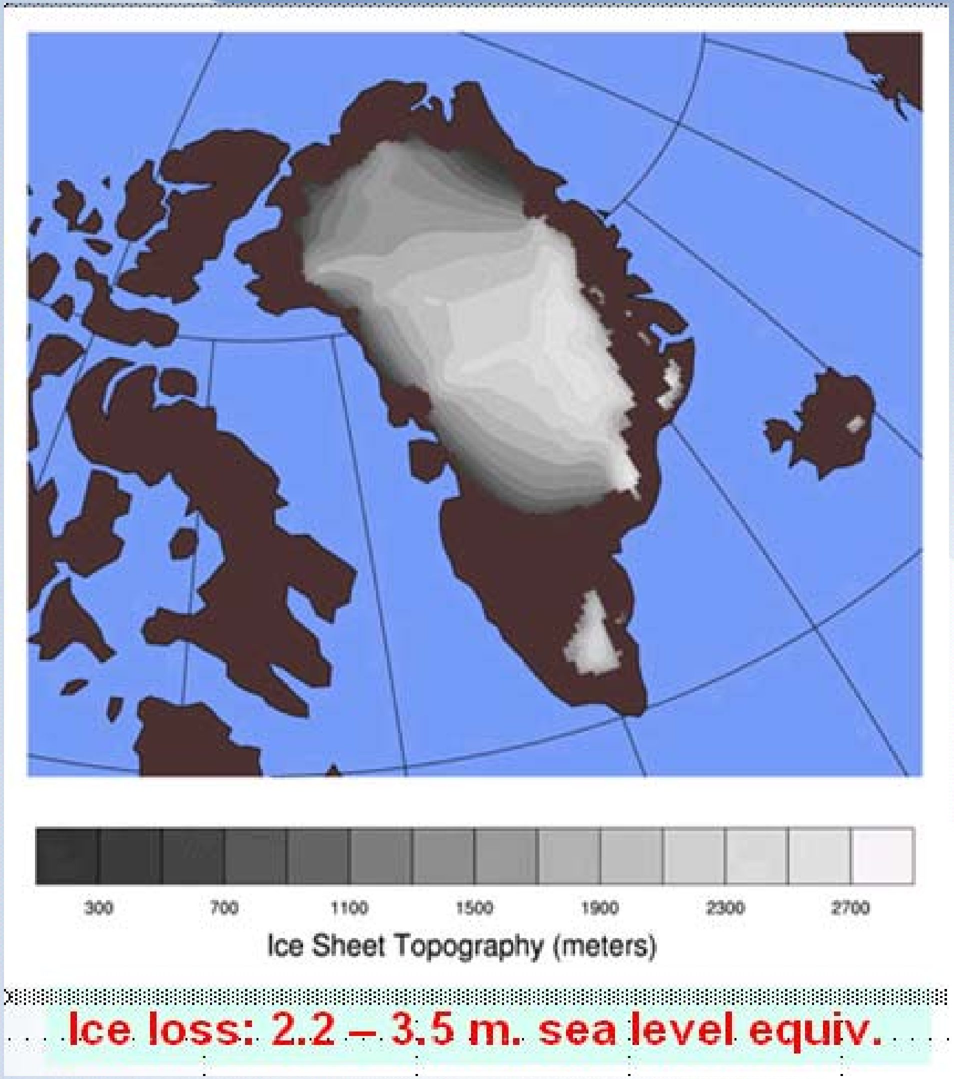
Source: Waleed Abdalati, Goddard Space Flight Center.

Increased melt in Greenland

Melt descending into a moulin, a vertical shaft carrying water to ice sheet base.

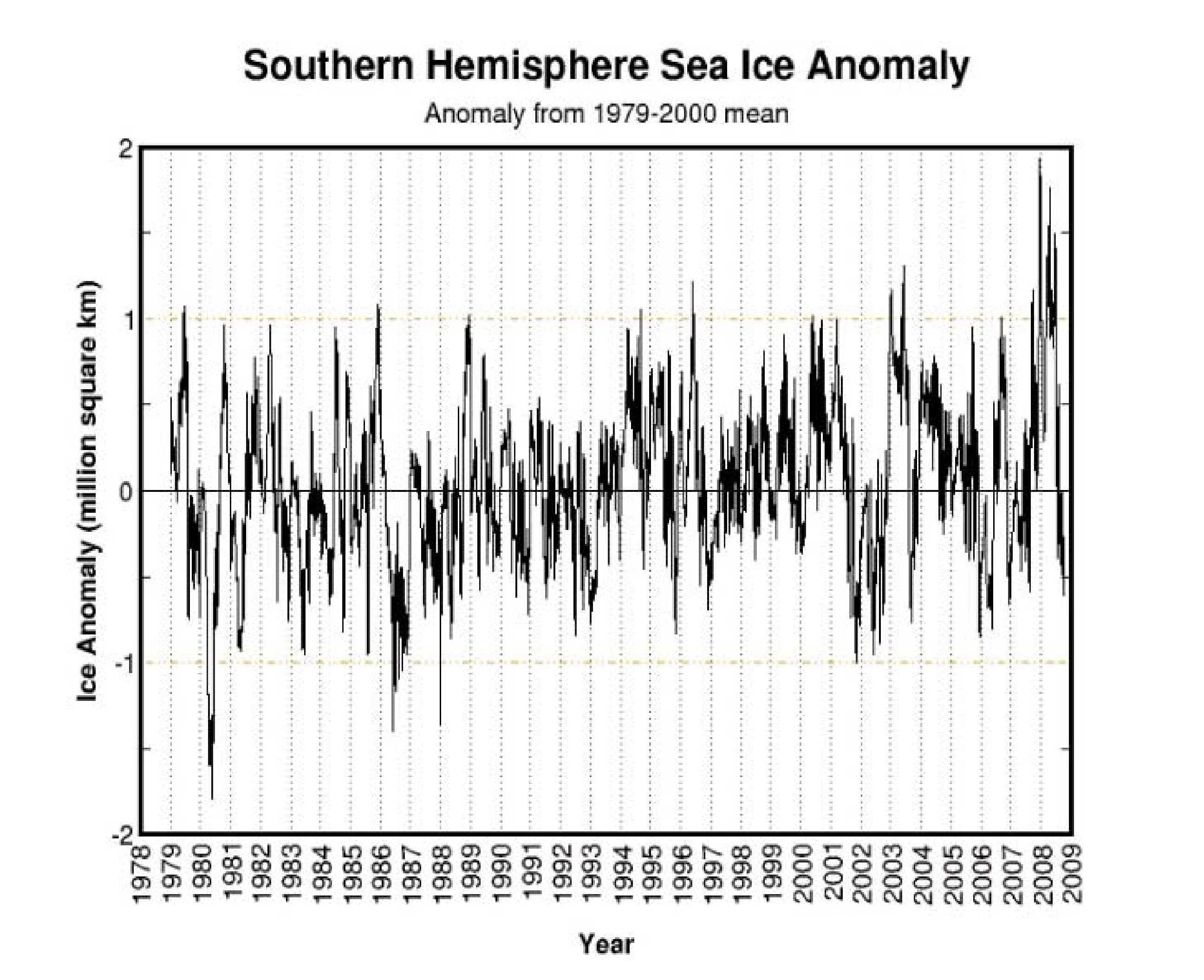
Source: Roger Braithwaite, University of Manchester (UK)

Greenland ice sheet, last interglacial (120Kyr BP)



Simulation from NCAR.

Antarctic sea ice changes



From http://arctic.atmos.uiuc.edu/cryosphere/

CONCLUSION:

Some aspects of the climate system are changing more rapidly than anyone expected just a few years ago.

WHY HAS CLIMATE ENGINEERING BECOME A HOT TOPIC RECENTLY?

THREE MAIN REASONS …

1. A paper on the subject by Nobel prize winner Paul Crutzen
2. The fact that recent changes in climate appear to be happening faster than expected
3. The realization that the technology challenge of transitioning to a carbon-neutral economy (in order to meet the goal of Article 2 of the U.N. Framework Convention on Climate Change) may be very difficult

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ARTICLE 2 OF THE UNFCCC

The objective is …

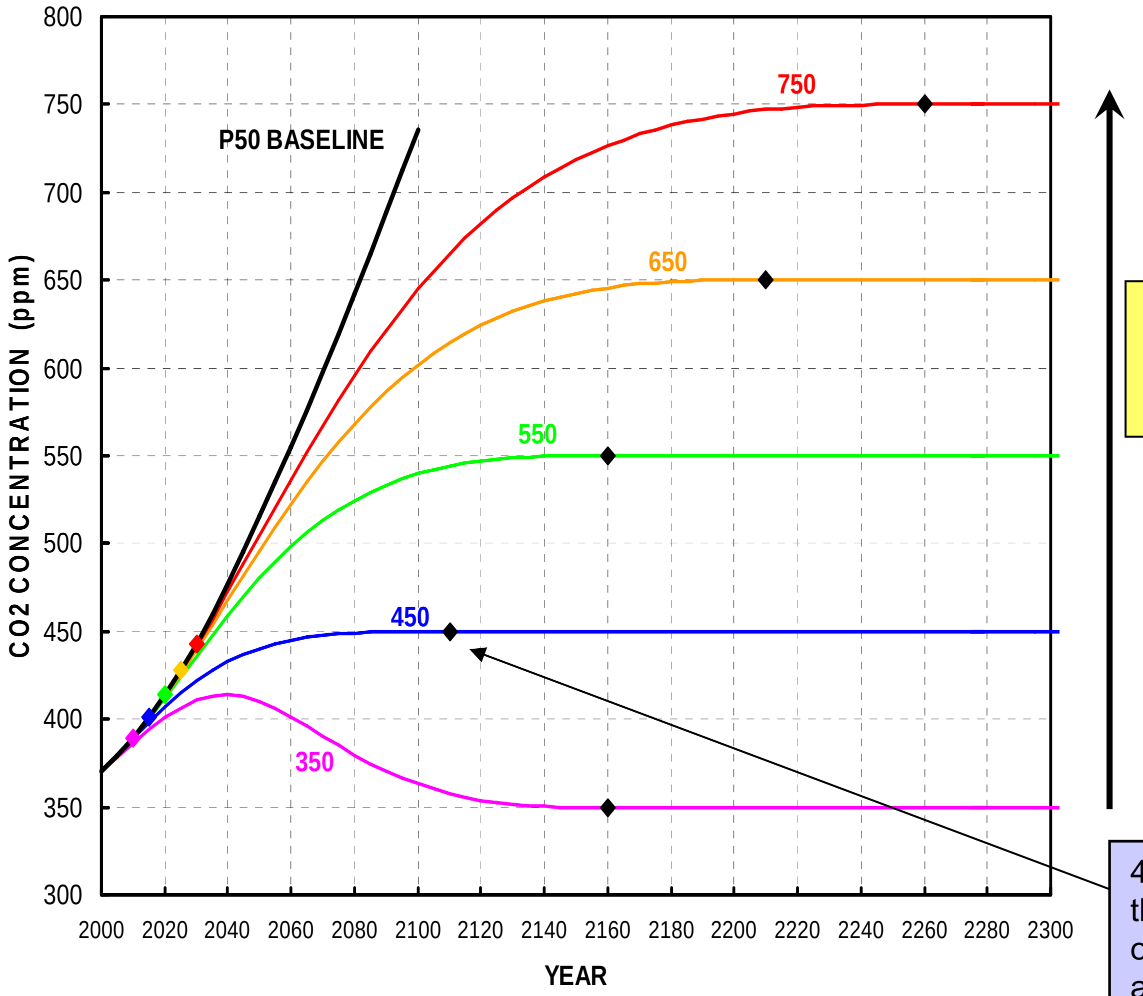
"stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system ….. within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner".

KEY ISSUES

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

Standard concentration pathways to stabilization: the WRE profiles.

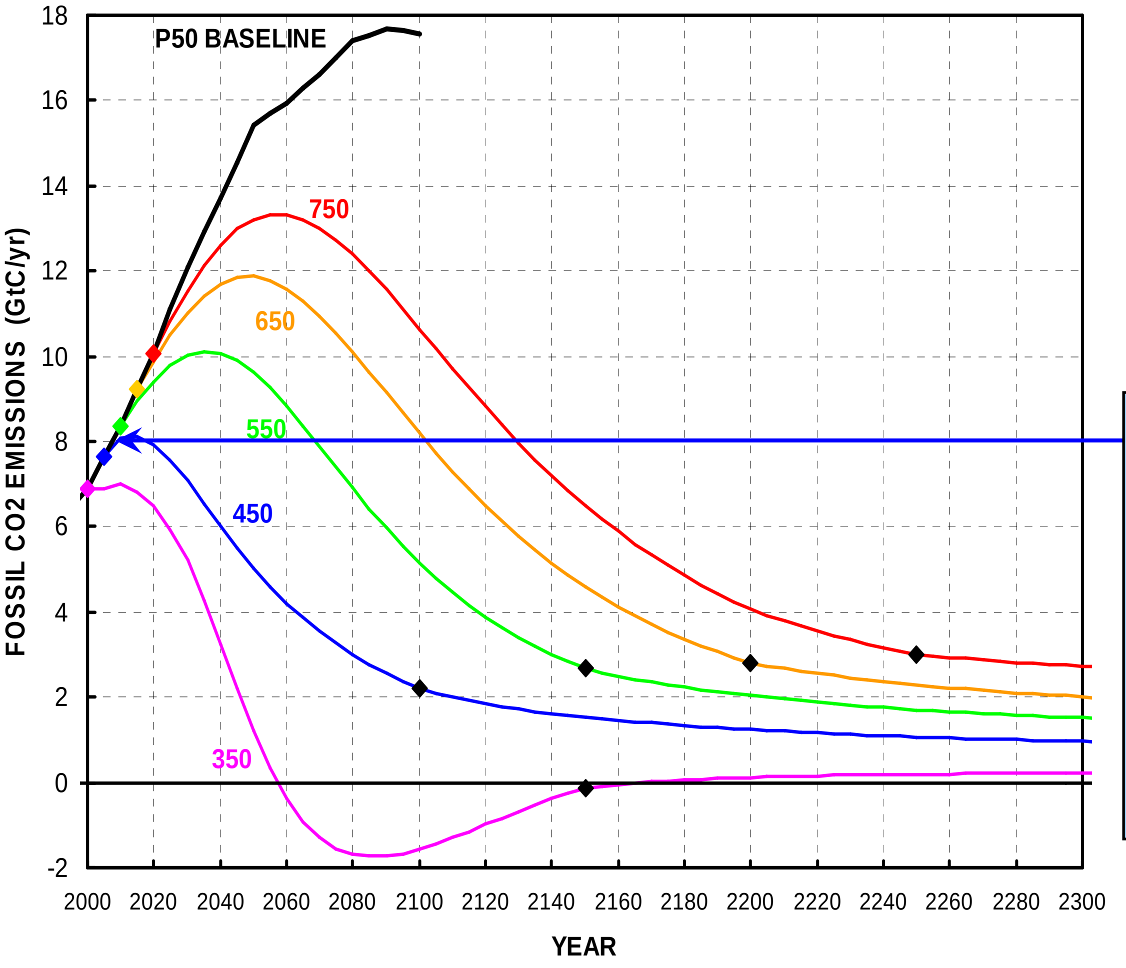
WRE concentration stabilization profiles



Increasing ocean acidity and increasing climate change

450 ppm is often given as a target that would have a high probability of meeting the UNFCCC goal of avoiding dangerous interference …

Emissions for WRE profiles



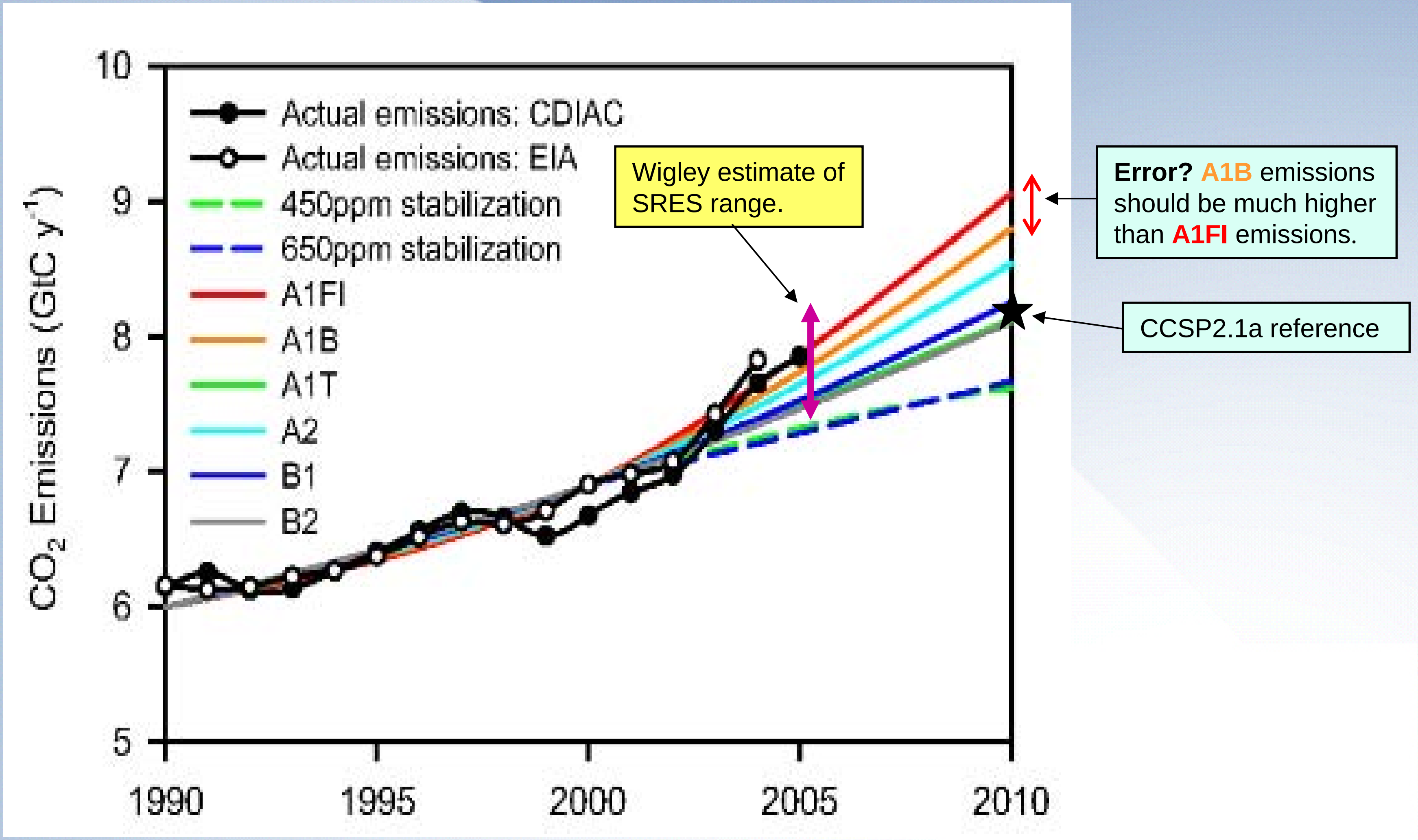
2005 level: 8 GtC/yr.

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

Is this emissions pathway achievable?

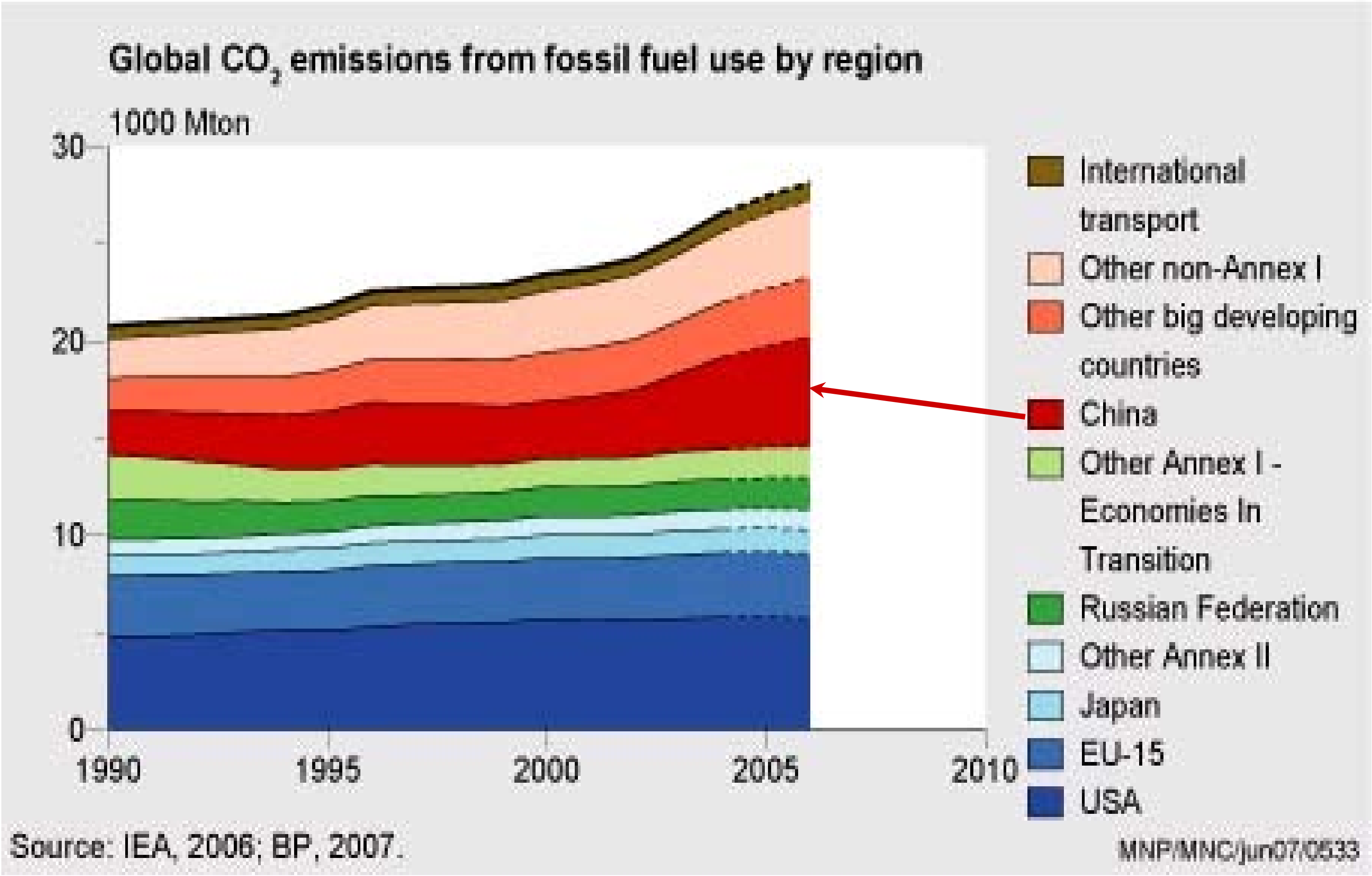
Are we making any progress towards meeting the goal of the UNFCCC?

CO2 emissions may have been rising faster than expected



From Raupach et al., *PNAS* **104**, 10288-10293, 2007

Unprecedented (and unexpected) emissions growth in China



http://www.mnp.nl/en/dossiers/Climatechange/moreinfo/Chinanowno1inCO2emissionsUSAinsecondposition.html

Opinions of leading economists

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 …” (in Scientific American, 2008)

Key points

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(1) We may have underestimated the rate and magnitude of future climate change

(2) We may have underestimated the technological (and political) challenges required to stabilize the climate at a level that would avoid “dangerous anthropogenic interference with the climate system”

CLIMATE ENGINEERING/GEOENGINEERING

Why should we consider climate engineering?

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- 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 already at around 385ppm, 100ppm above the pre-industrial level.
- Two crucial questions therefore are: is 450ppm achievable? and, is 450ppm low enough?
- **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?
- **What if we find that a target of less than 450ppm is required** in order to avoid “dangerous interference”?

Climate engineering as a last resort

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A number of climate scientists say that geoengineering should only be considered as a "last resort"

The usual concept of "last resort" 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 probably 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: climate engineering to gain time

- 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 carbon-neutral technologies.

- Climate engineering 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.

Climate engineering strategy

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- We should seriously consider the possibility of **using climate engineering 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 climate engineering/mitigation strategy** with the same long-term concentration goals as in a “pure” mitigation strategy.
- The magnitude of climate engineering required with this approach would be much less than if climate engineering were used as the sole climate-change reduction method.

Examples of climate engineering

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- Changing the net amount of incoming solar radiation by orbiting solar reflectors, by injection of aerosols or aerosol precursors into the stratosphere, or by managing the level of tropospheric sulfate aerosols.
- 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 I will also say a little about the cloud albedo method, which may be a useful complement.

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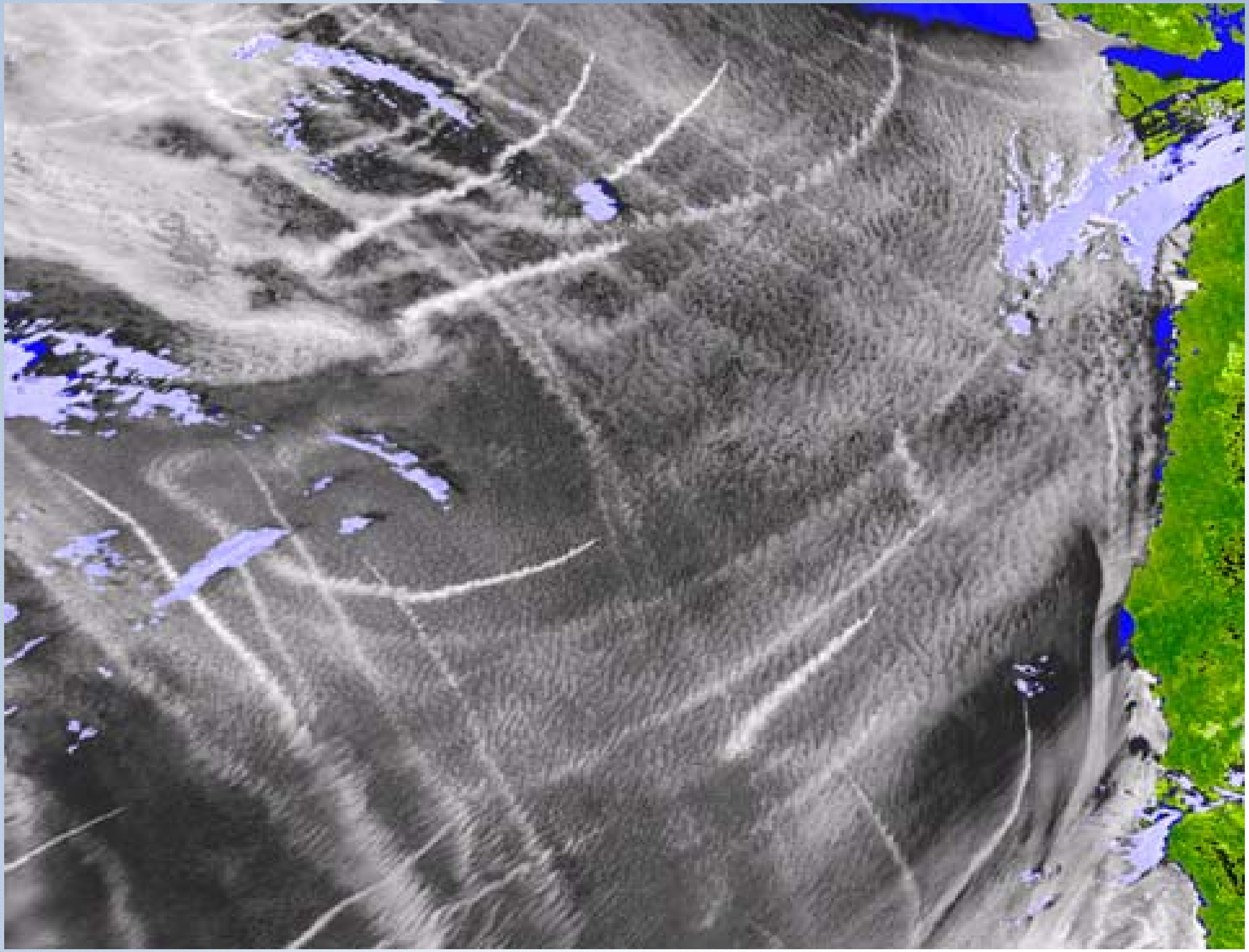
Climate engineering by modifying cloud albedo

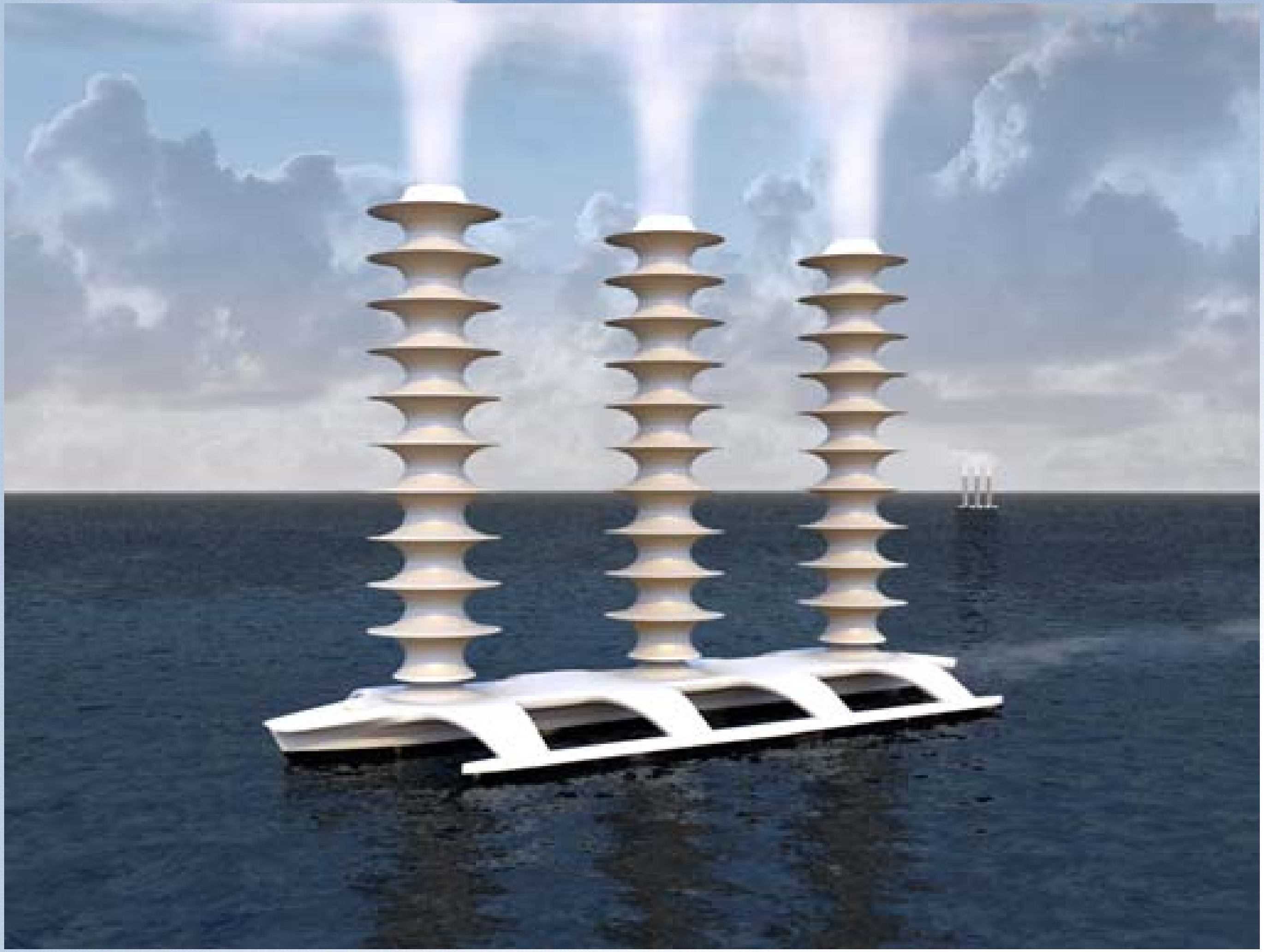
Method: injection of cloud condensation nuclei into the lower troposphere

Originally proposed by John Latham, "Control of global warming?", *Nature* **347**, 339-340, 1990.

Ship tracks show that increased numbers of condensation nuclei make clouds more reflective.



Salter's droplet injection ship



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Climate engineering using stratospheric sulfate aerosols

Method: Injection of aerosols or aerosol precursors into the stratosphere

Estimated cost (from Crutzen): $50bn/year (but recently revised downward by Crutzen to $10bn/year)

This idea was first mentioned in Rusin, N. and Flit, L., 1960: *Man Versus Climate*. (Peace Publishers, Moscow), 175 pp, and elaborated in Budyko, M. I., 1974: *Climate and Life.* (Academic Press, New York, NY), 508 pp.

We know this method works – volcanic eruptions cause substantial global cooling

Mt. Pinatubo eruption: June 1991.

Climate engineering using sulfate aerosols

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CRUCIAL POINT:

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

I will consider a **joint mitigation/climate engineering scenario:** designed specifically to give additional time for the development and implementation of carbon-neutral technologies.

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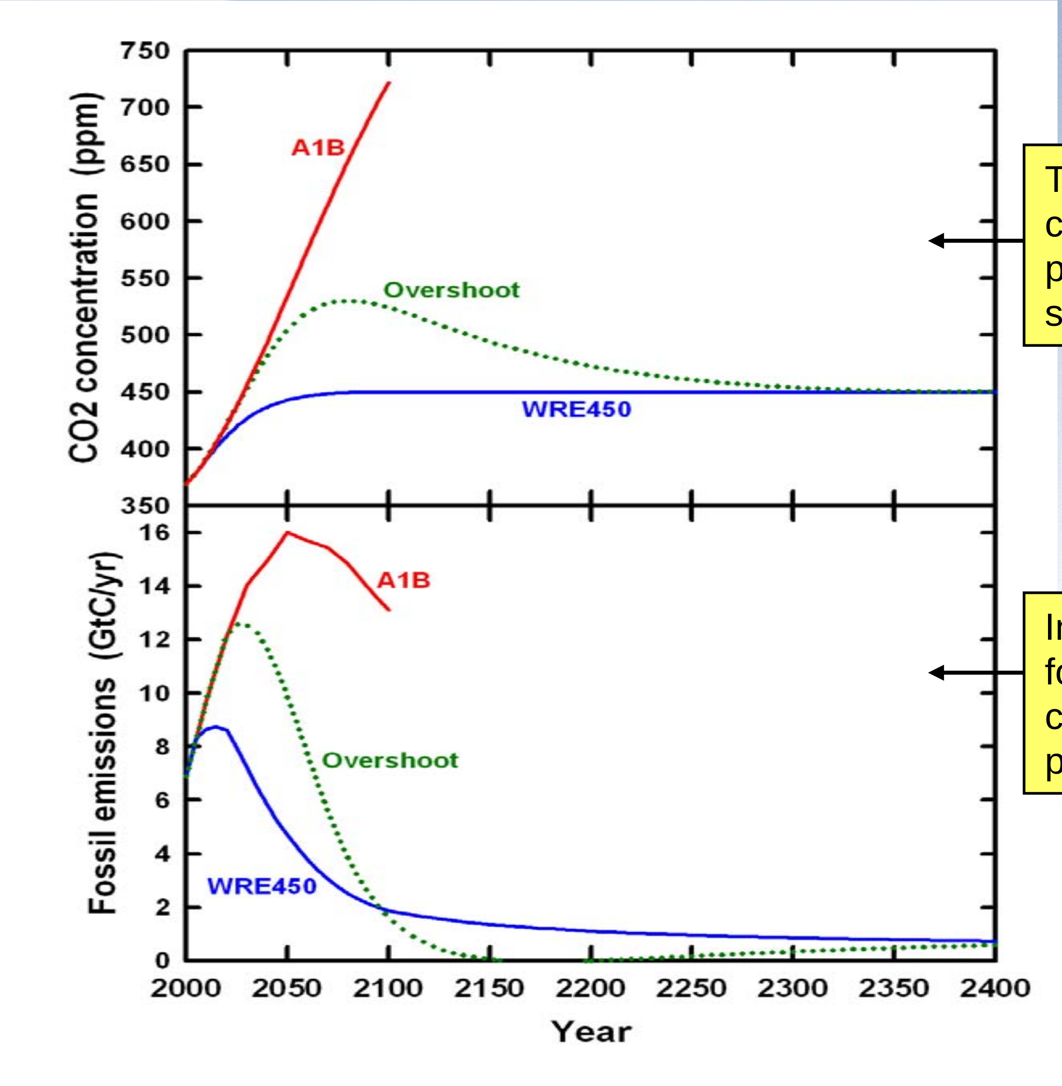
Combined climate engineering and mitigation scenarios.

Baseline (A1B) and CO_2 stabilization scenarios

Overshoot is the case that is used in conjunction with climate engineering.

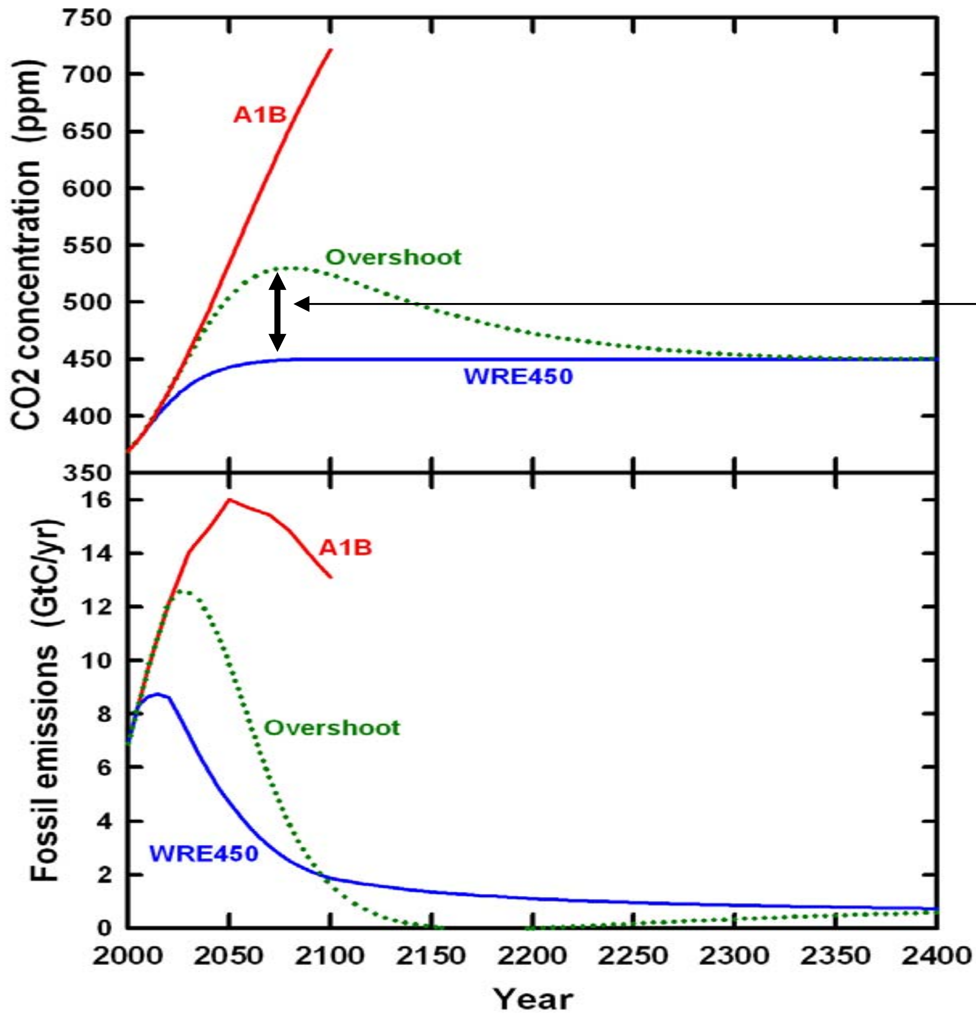
Overshoot delays departure from the emissions baseline for 15 years allowing more time to develop and deploy carbon-neutral technologies.



Two alternative concentration pathways to stabilization.

Implied emissions for the alternative concentration pathways.

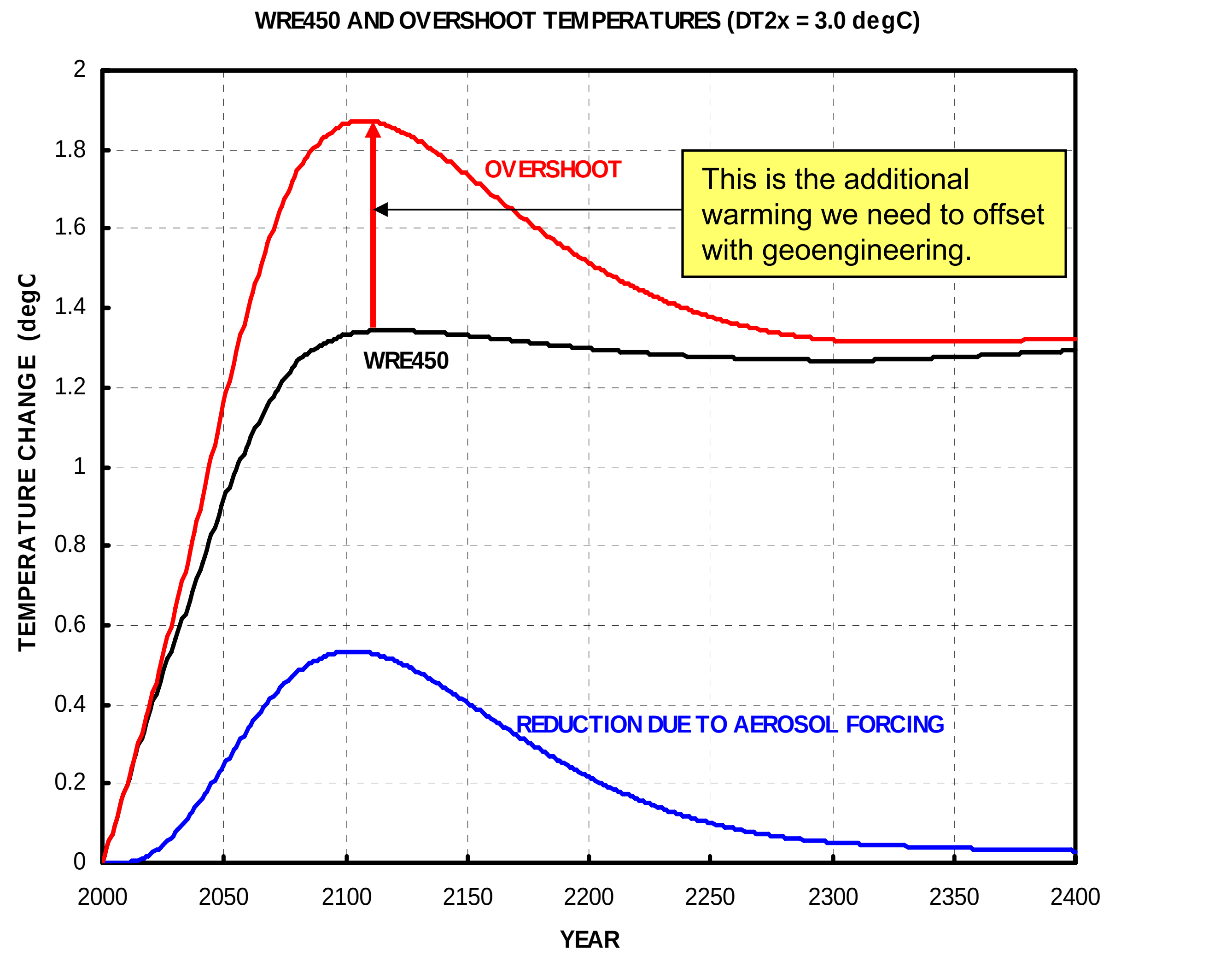
Baseline (A1B) and CO_2 stabilization scenarios



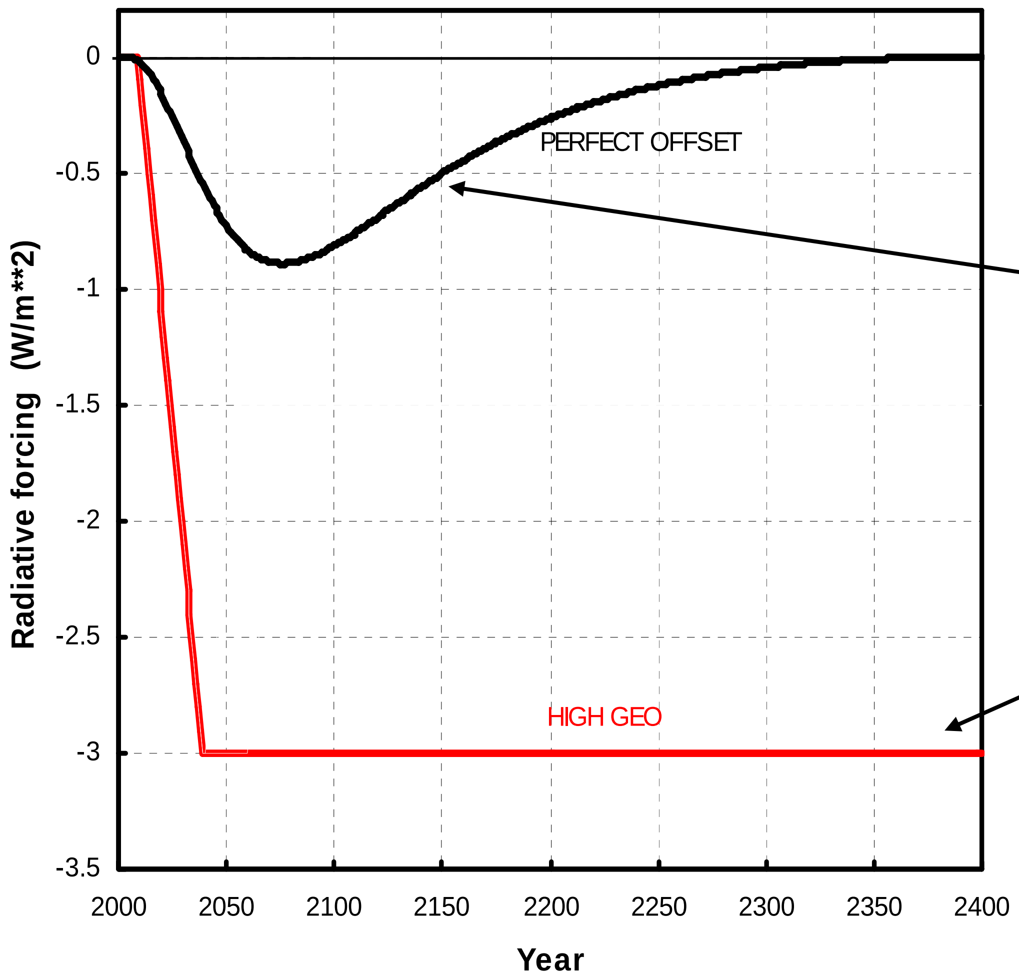
Goal: To offset the forcing due to the Overshoot/WRE450 concentration difference.

(Note, ΔpH = 0.07)

Temperature projections



Forcing required to offset the additional overshoot warming



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.

This scenario would offset all future global warming without the need for mitigation – but it would pose significant risks.

INITIAL CONCLUSION

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A relatively small amount of geoengineering would be enough to offset the effects of a substantial CO_2 concentration/ warming overshoot.

This would allow the departure of CO_2 emissions from a no-climate-policy baseline to be much slower than would otherwise be the case, and so allow significantly more time to develop the necessary carbon-neutral technologies.

Possible risks associated with climate engineering

Benefits and risks

All climate engineering options have both benefits and risks.

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

Some scientists believe that climate engineering 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.

Another argument is that, if we begin to use climate engineering as a means to reduce climate change, this will take the emphasis off mitigation.

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

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

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

Climate engineering 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.** Cancellation of global-mean warming will not necessarily lead to cancellation of regional climate changes.
- Effects of a rapid shutoff of stratospheric injection.

Potential risks associated with stratospheric SO_2 emissions

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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 in the joint mitigation scenario the maximum loading of aerosols in the stratosphere occurs around 2080, by which time the ozone layer has largely "healed".]

- **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. These results, however, have only considered the "climate engineering alone" case, so may not be relevant to the joint mitigation/engineering case.]

Effects on precipitation

A few recent papers* have pointed out that the effect on precipitation of a short-wave radiation change (i.e., climate engineering using stratospheric aerosols) is greater than the effect of the same change in long-wave (i.e., CO_2-induced) radiation. The claim is therefore made that climate engineering will lead to droughts.

This claim is false. It is based on model experiments by Robock et al. in which all future climate change is offset by climate engineering. If the joint mitigation/engineering strategy is employed, then the resulting precipitation changes in the climate engineering case are likely to be less, and less disruptive, than if a mitigation-only strategy were employed.

Suppose T450(t) is the warming following the WRE450 mitigation pathway, Tover(t) is the warming following the overshoot pathway, and Tdiff = Tover – T450. Suppose also that, for long-wave forcing (CO_2) the % change in global-mean precipitation is 2% per degree global-mean warming, a fairly representative value.

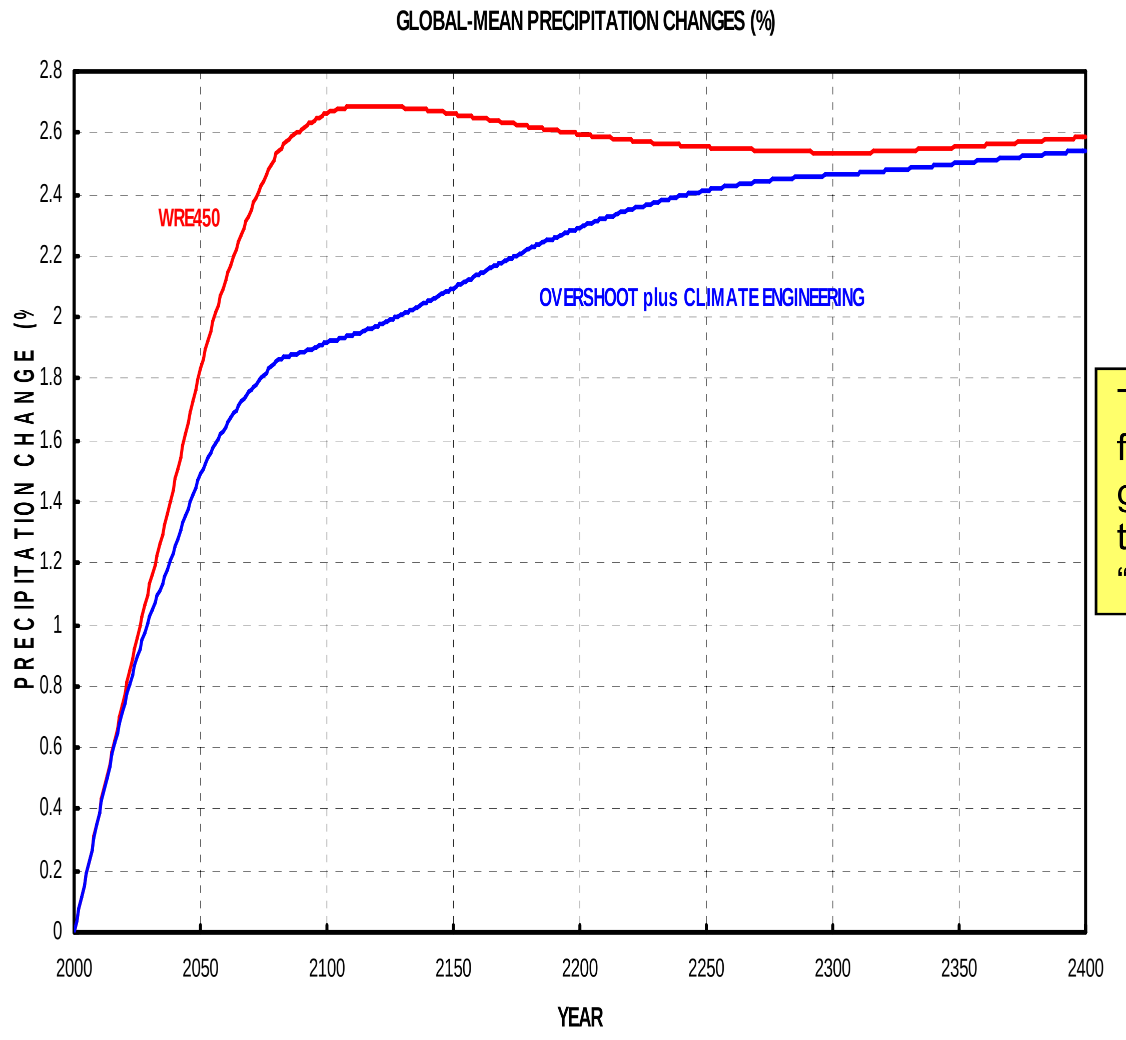
The short wave amplification is a factor of 1.5 to 1.7 based on recent model results, so the corresponding result for short-wave forcing (stratospheric aerosols) is about 3.4% per degree global-mean warming. Hence …

For WRE450, the % precipitation change is R450 = 2(T450), and …
for overshoot plus climate engineering the change is Rgeo = 2(Tover) – 3.4(Tdiff) = 2(T450) – 1.4(Tdiff).

So the climate engineering case must always give a smaller global-mean precipitation change – as shown on the next slide.

* e.g., Bala, G., Duffy, P.B. and Taylor, K.E., 2008: Impact of geoengineering schemes on the global hydrological cycle. *Proc. Nat. Acad. Sciences* **105**, 7664 – 7669.

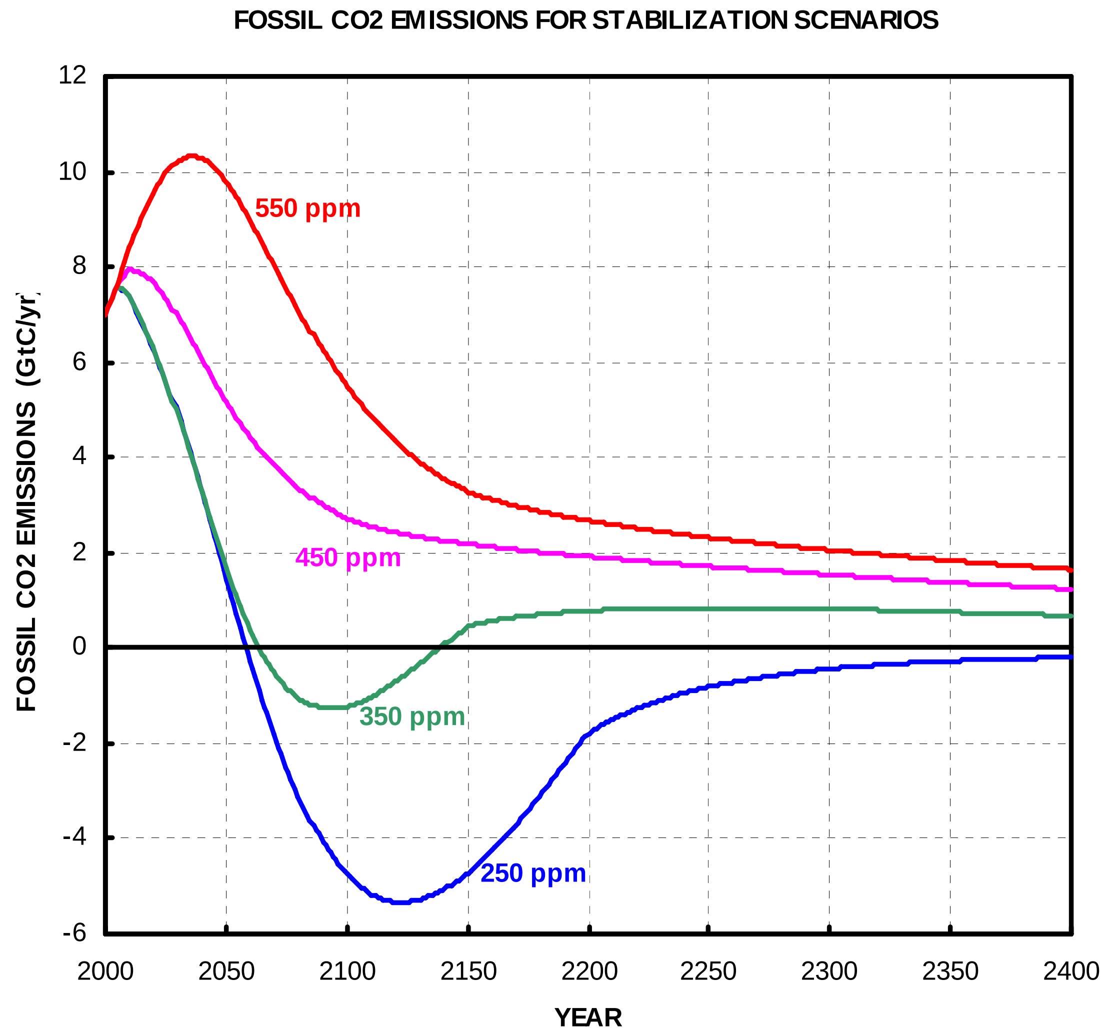
Precipitation projections



The precipitation change for the case involving geoengineering is less than for the corresponding “pure” mitigation case.

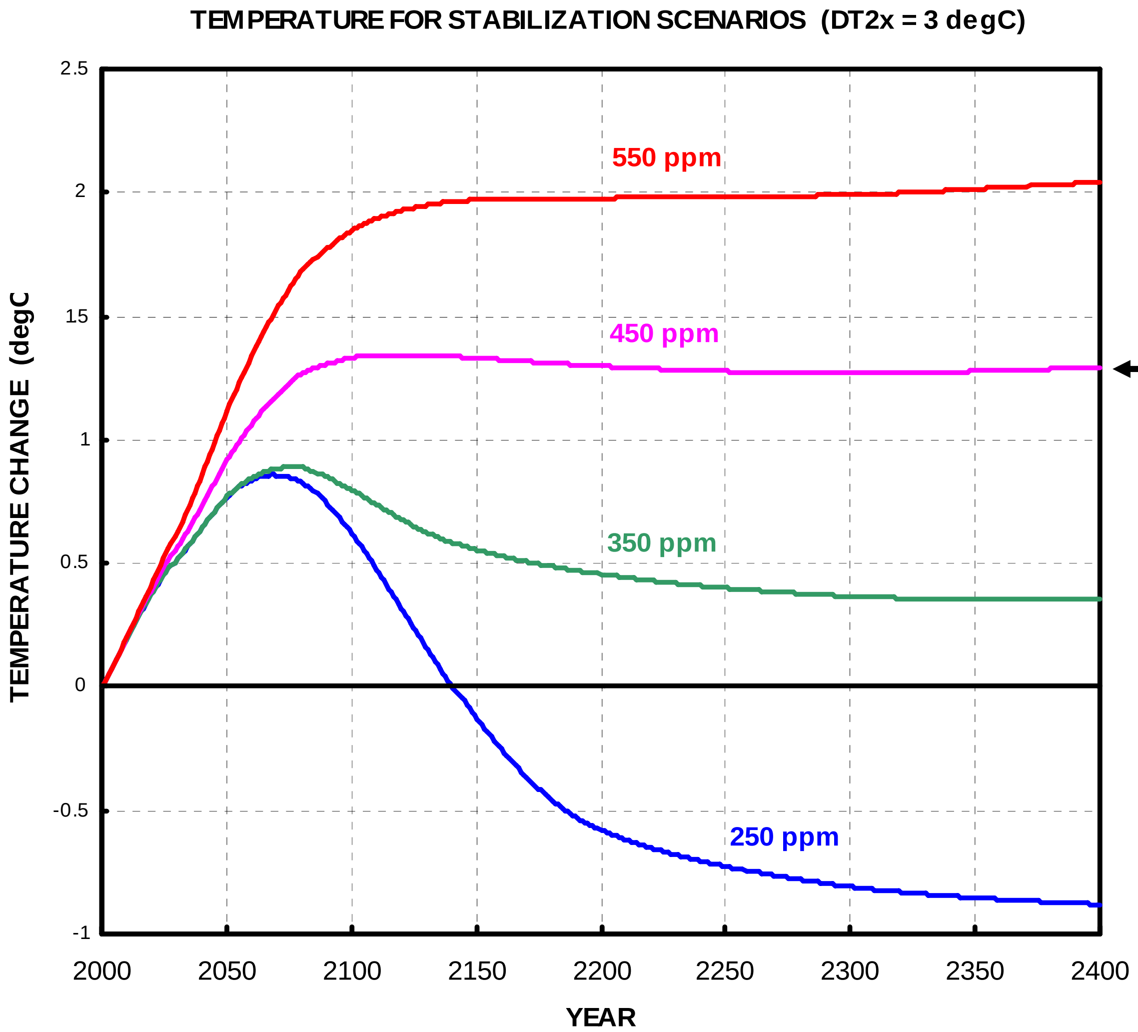
An additional consideration: the challenge of stabilizing sea level rise.

Fossil CO2 emissions requirements for stabilization



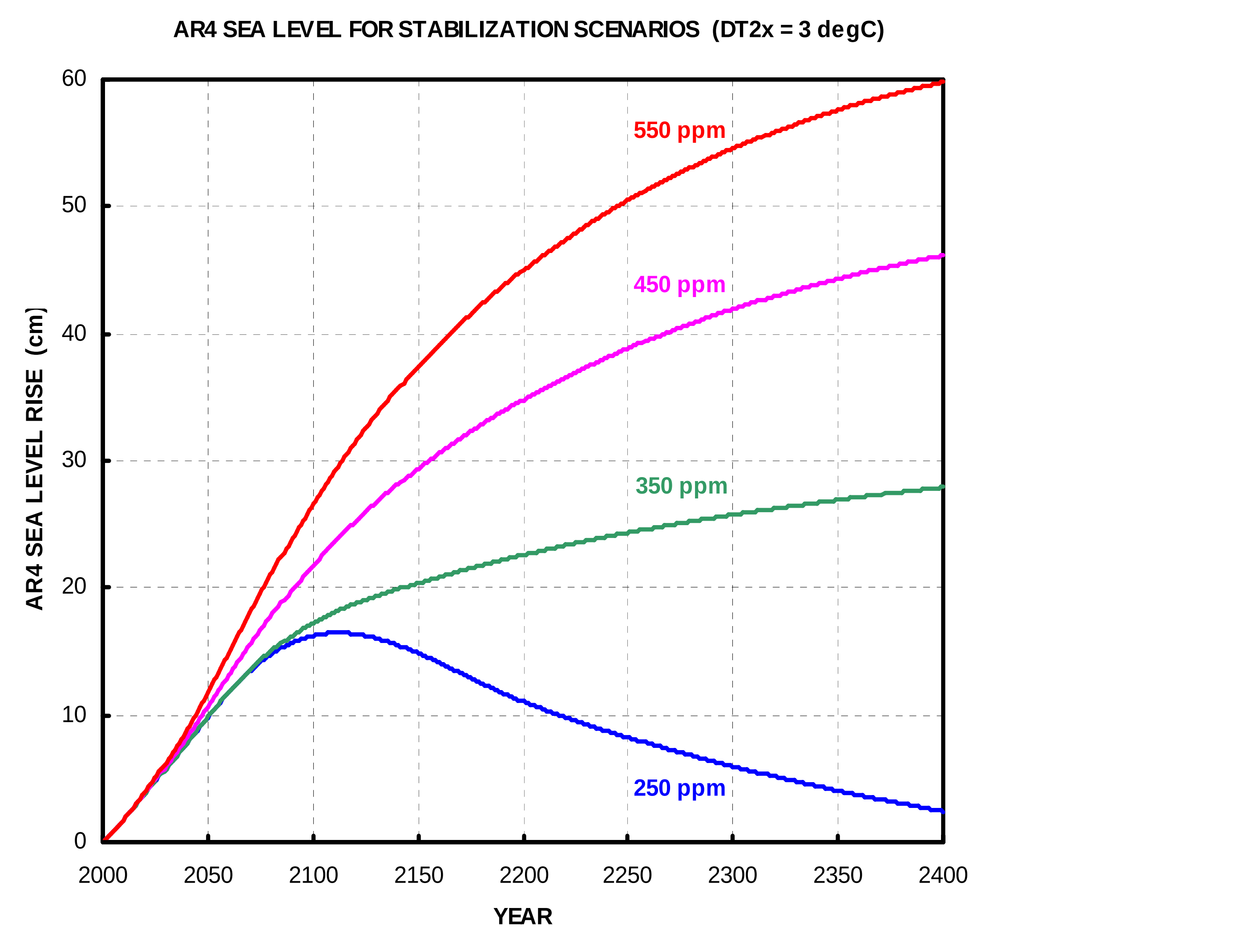
For non-CO2 gases (including aerosols) I use an extended version of the CCSP2.1a Level 1 stabilization scenario.

Temperature projections: Central estimates



Note: This corresponds to a warming of about 2 degC from pre-industrial times, often given as a target that would probably avoid dangerous interference with the climate system.

Sea level projections: Central estimates



Conclusions for sea level stabilization

Stabilizing sea level would require going back to around 300 ppm CO_2.

Sea level would end up at about +15cm relative to today (peak around +19cm).

Global-mean temperature would end up at about –0.3degC relative to today (peak around +0.8degC).

A long period of substantial negative CO_2 emissions would be required from 2060 onwards, up to 3 GtC/yr (currently we are adding CO_2 at about 8 GtC/yr). This may be impossible, so …..

Perhaps the only way to stabilize sea level is through climate engineering?

Conclusions

- Injection of 1 TgS per year, ramping up over 70 years to this as a **maximum** rate 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, about 18 months worth of current emissions of SO_2 from fossil fuel combustion).]

- Mitigation combined with climate engineering 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 about 300ppm over the next few centuries, which may be technologically impossible.

Unresolved issues

- Development of sulfur injection technologies (note that the scenarios considered here assume a 20+ 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 climate engineering versus the economic benefits of changed mitigation timing.

- Assessment of the effects on stratospheric ozone and climate for realistic combined climate engineering/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 climate engineering 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.


Thankyou

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