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

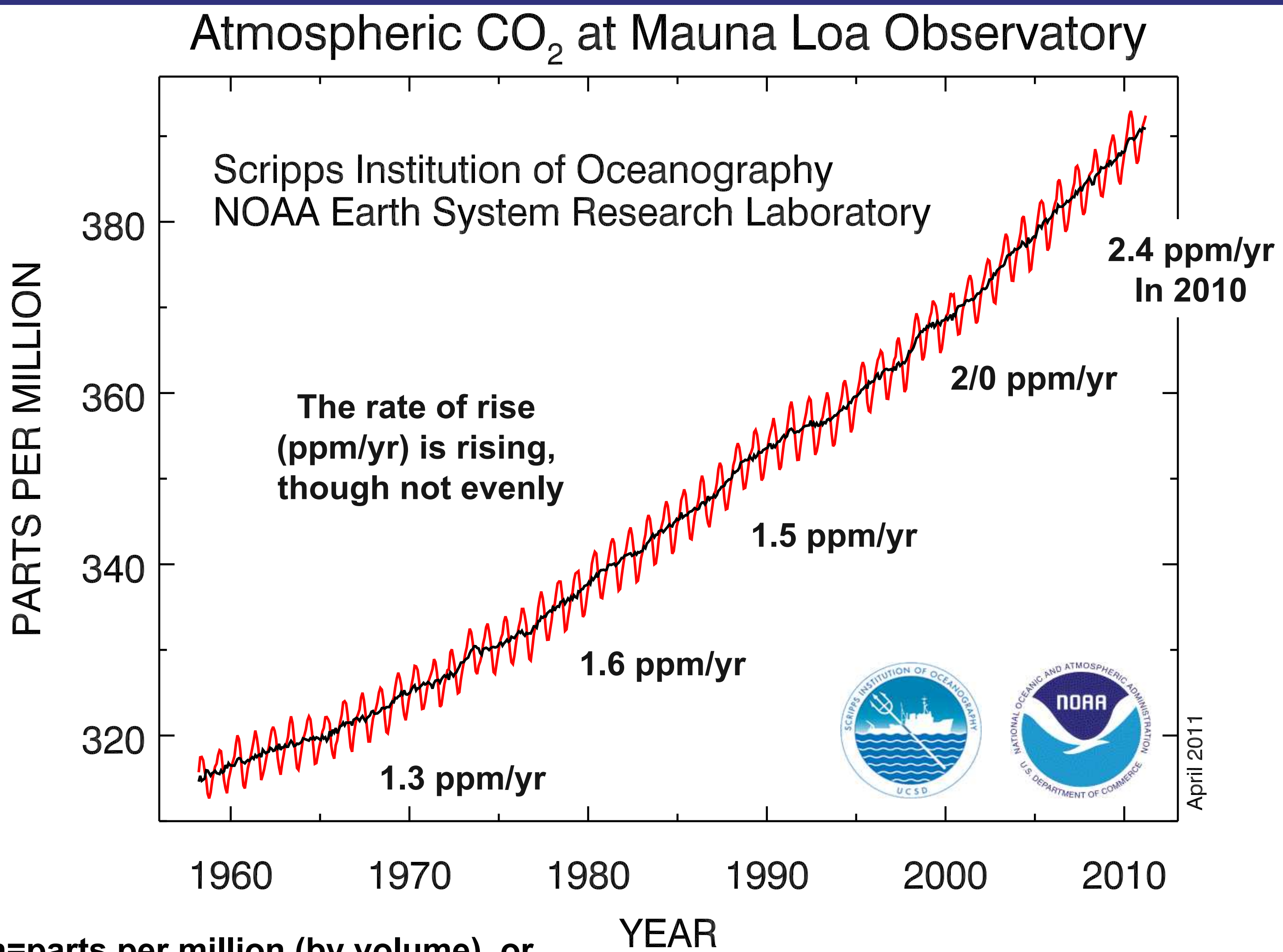
Outline of talk

- 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



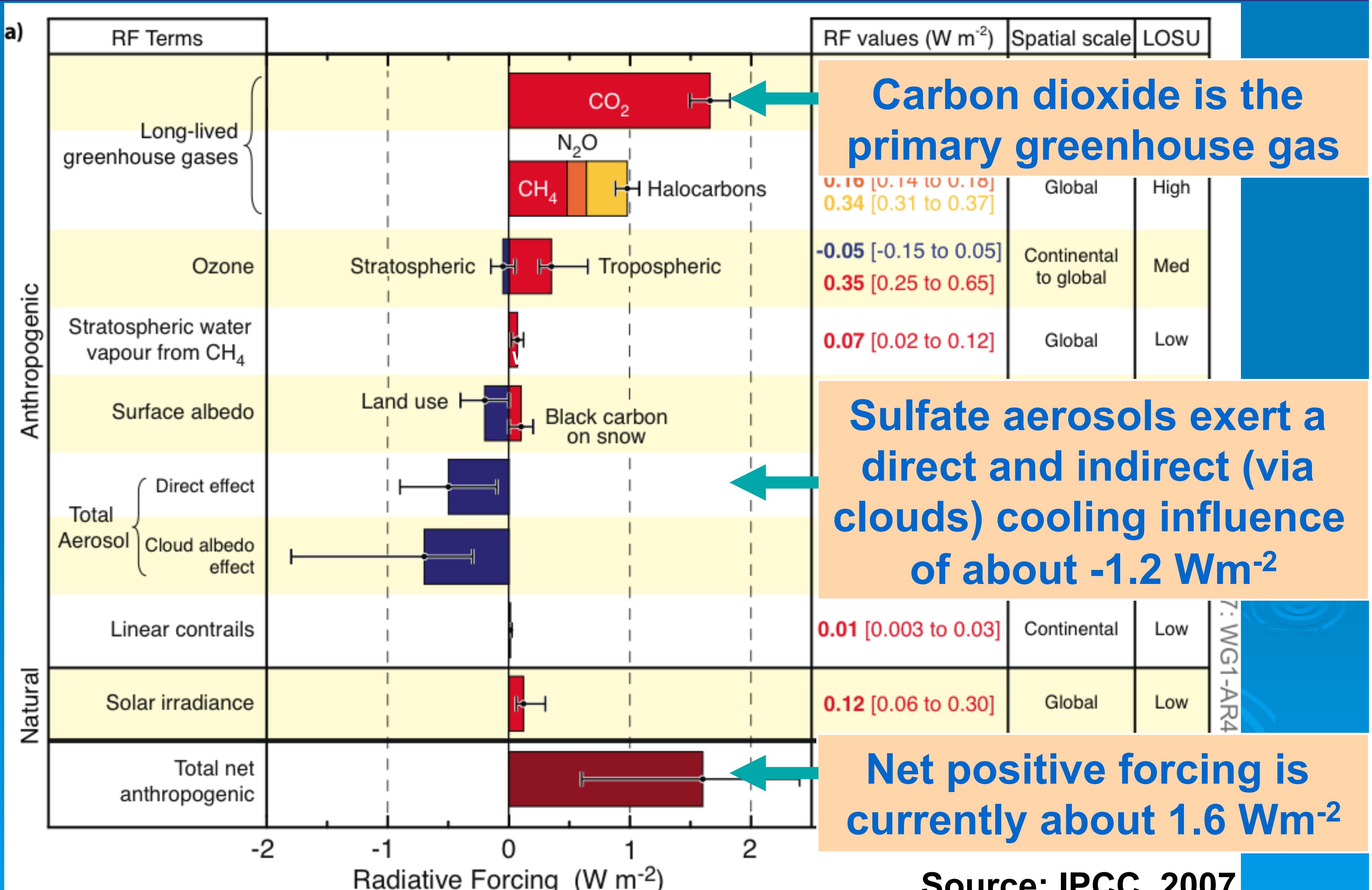
The present concentration is ~390 ppm, about 24% above the value of 315 ppm in 1957 (when C. David Keeling began very careful measurements) and about 40% above the preindustrial concentration

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

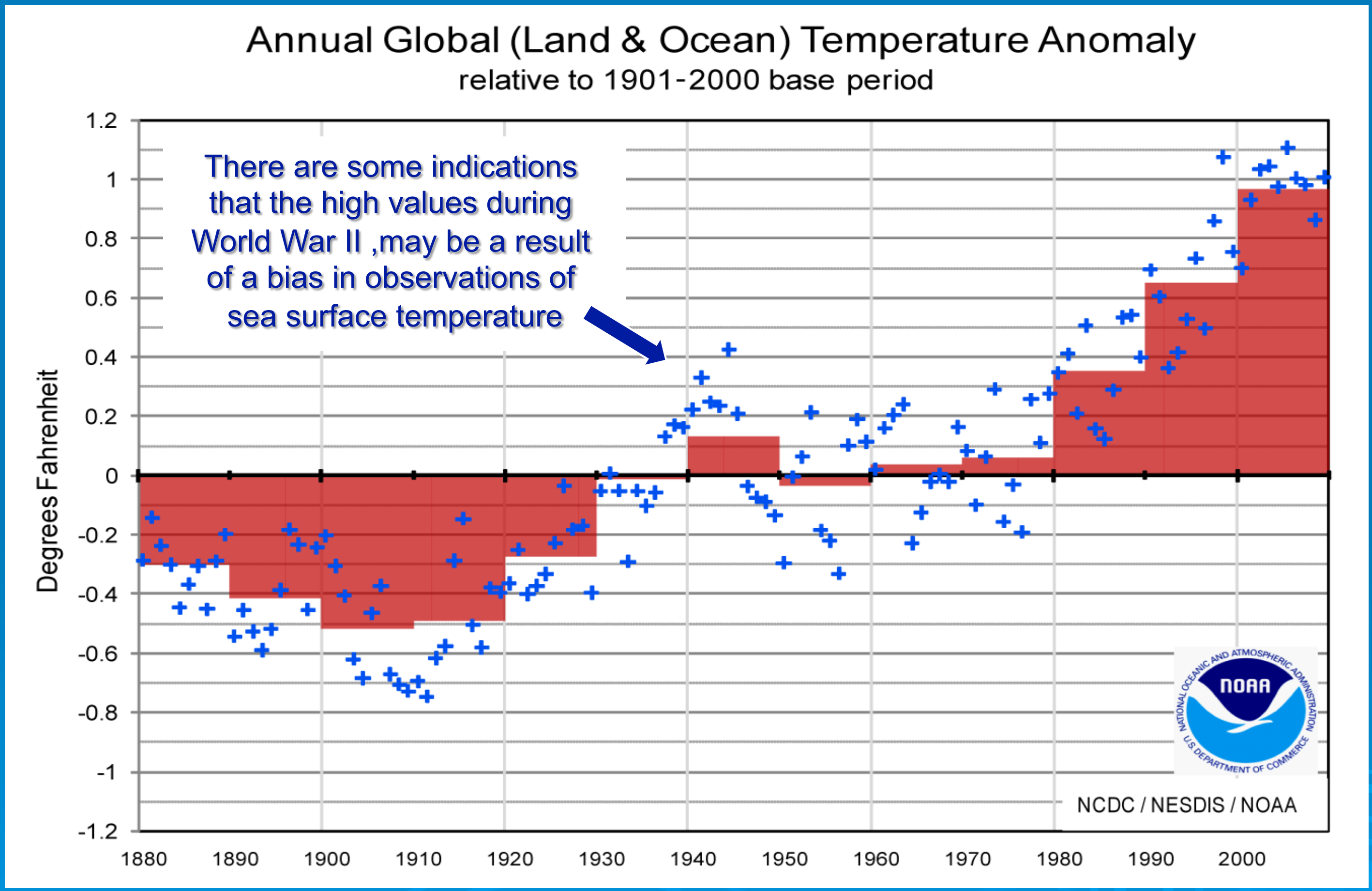
The increasing concentrations of radiatively active gases and aerosols are altering the fluxes of visible and infrared radiation, exerting a "radiative forcing" on climate



Source: IPCC, 2007

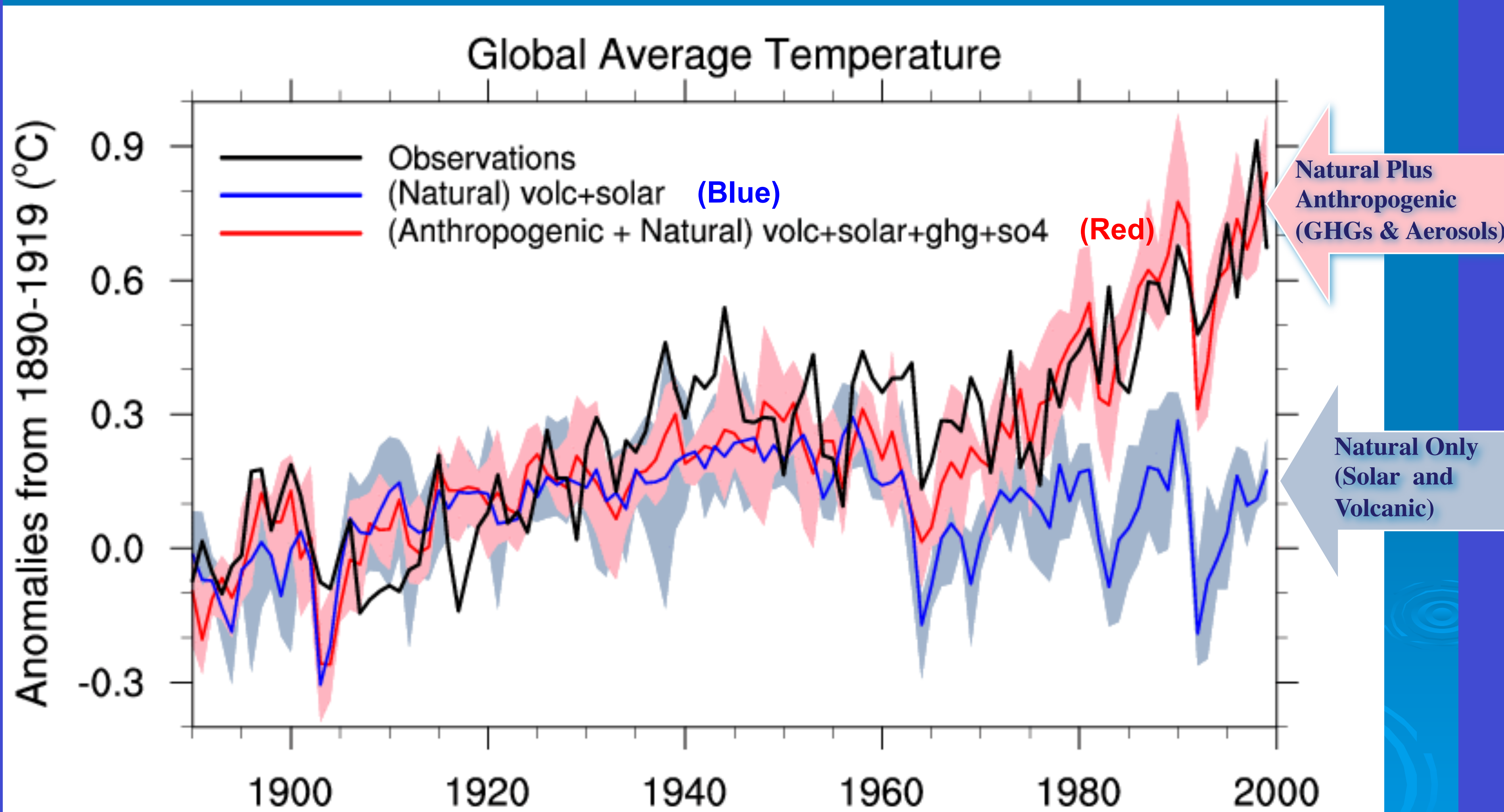
On a decadal-average basis, the world has experienced relatively steadily warming over the last few decades

Global Temperature Anomalies



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

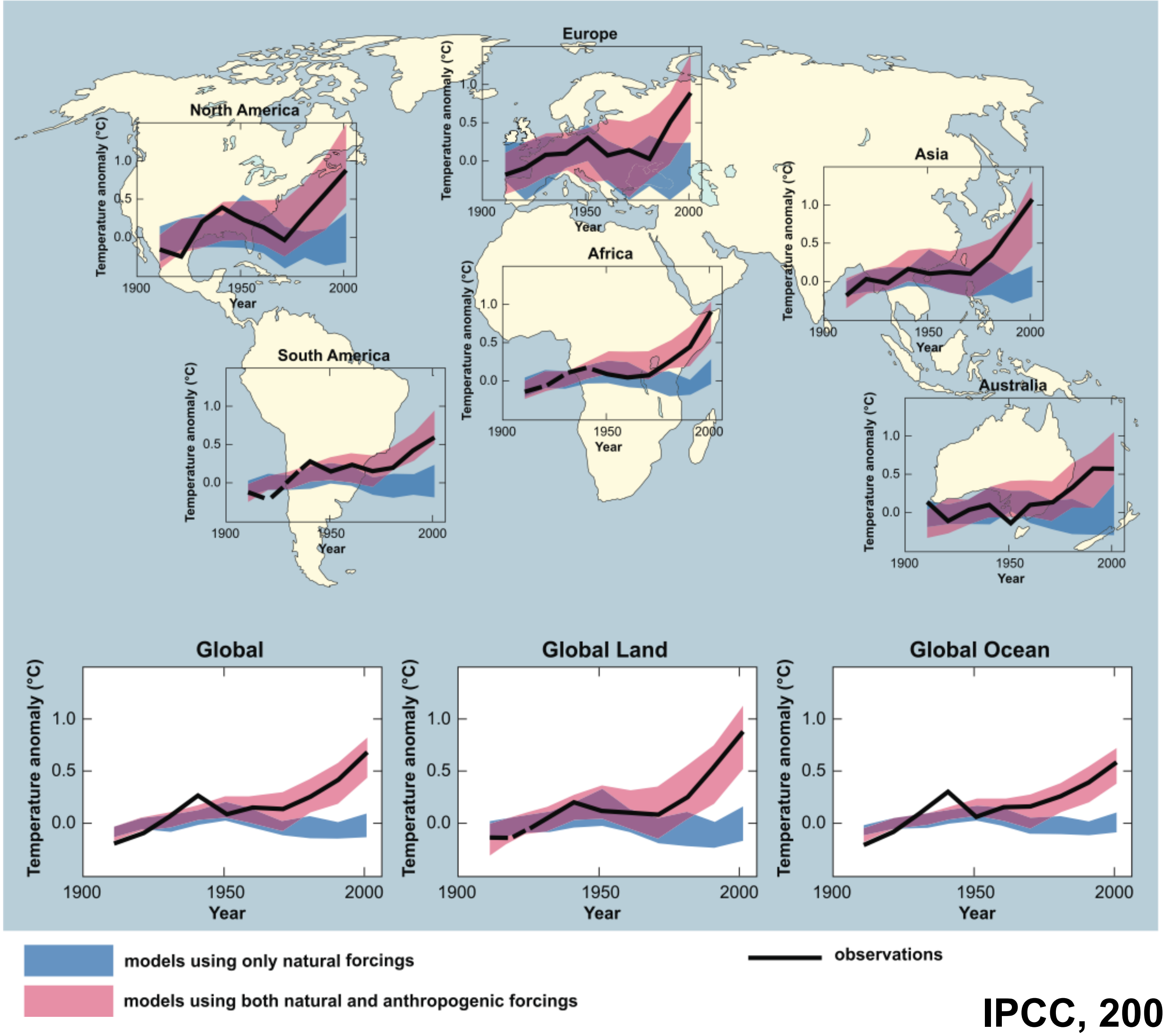
Only when the effects of both natural and human forcings are included do the models reasonably represent climate change over the last 100 years



NCAR Climate Simulations

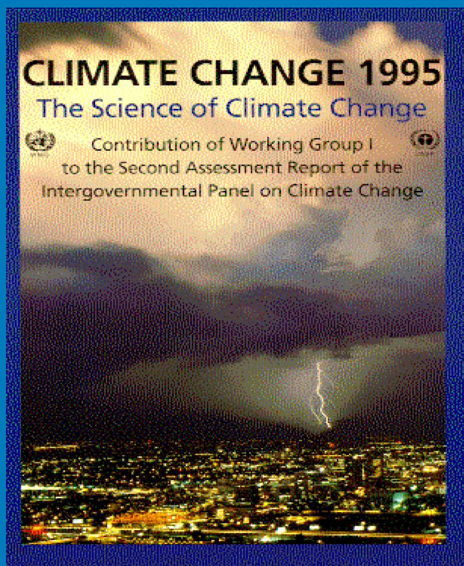
Comparisons show both global and regional agreement of 20th century observations with model simulations including all forcings (pink), but not with just natural forcings (blue)

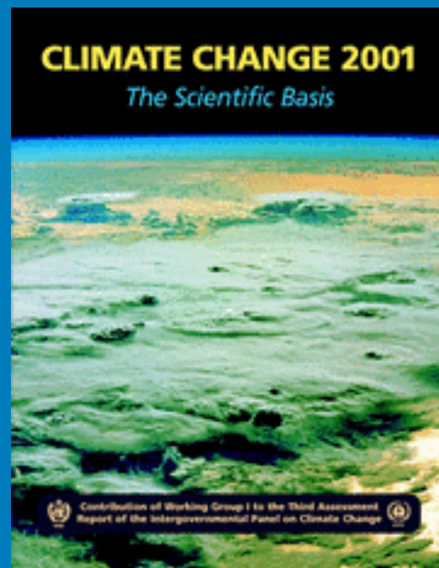
The model results appear as a band because (1) the results are for multiple models, and (2) the model simulations account for the natural variability of the climate, unlike the observations which, although averaged over a decade, represent a single pass through climatic history. Observations also include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

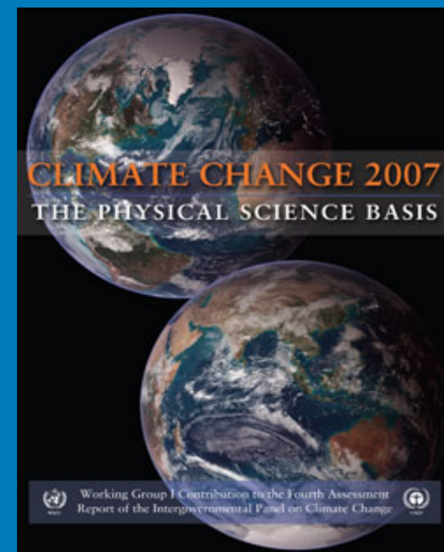


IPCC, 2007

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



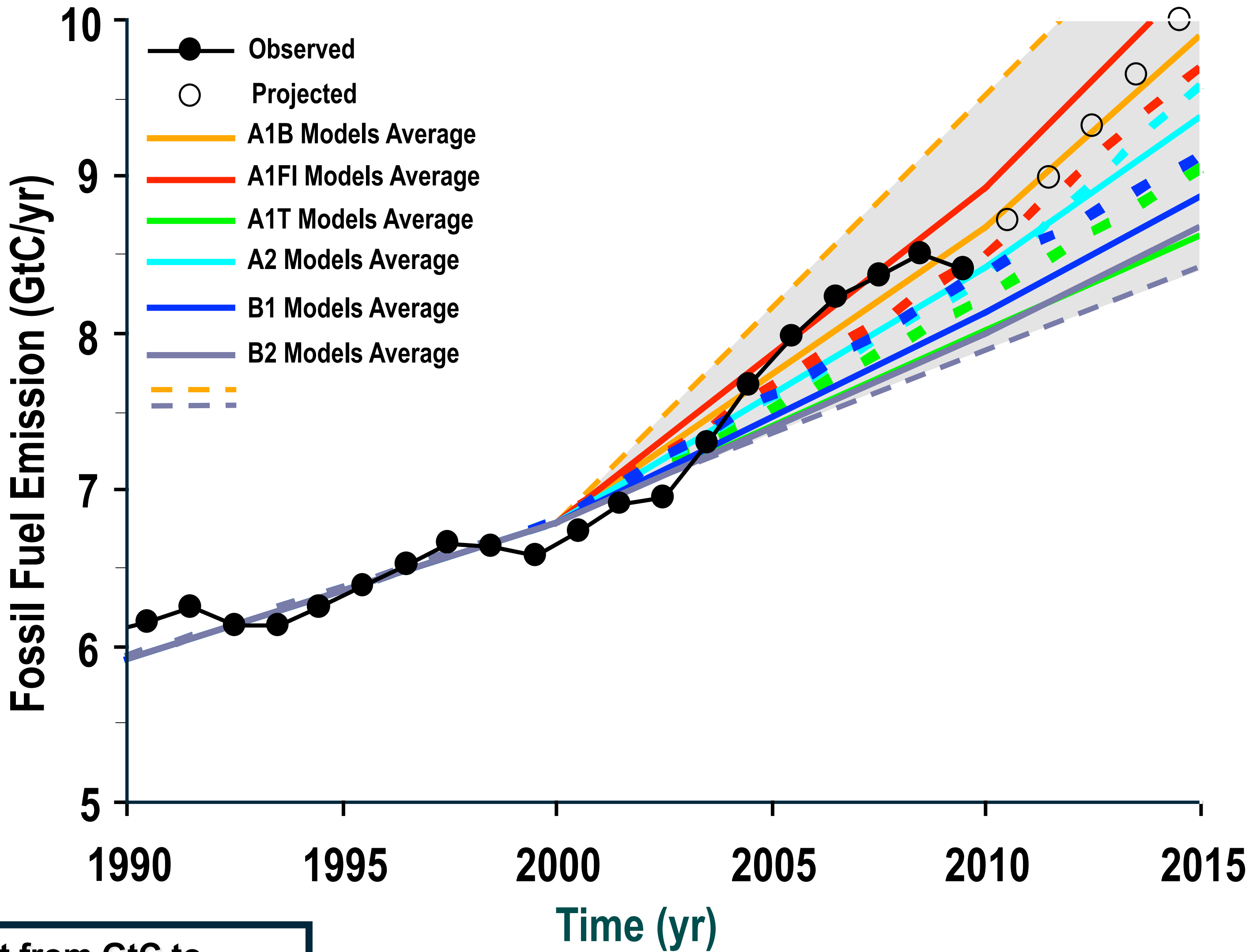




IPCC's summary conclusions, which require full international concurrence, tend to be cautious rather than cutting edge. That they are nonetheless so very disturbing should be reason for significant attention and concern

"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."

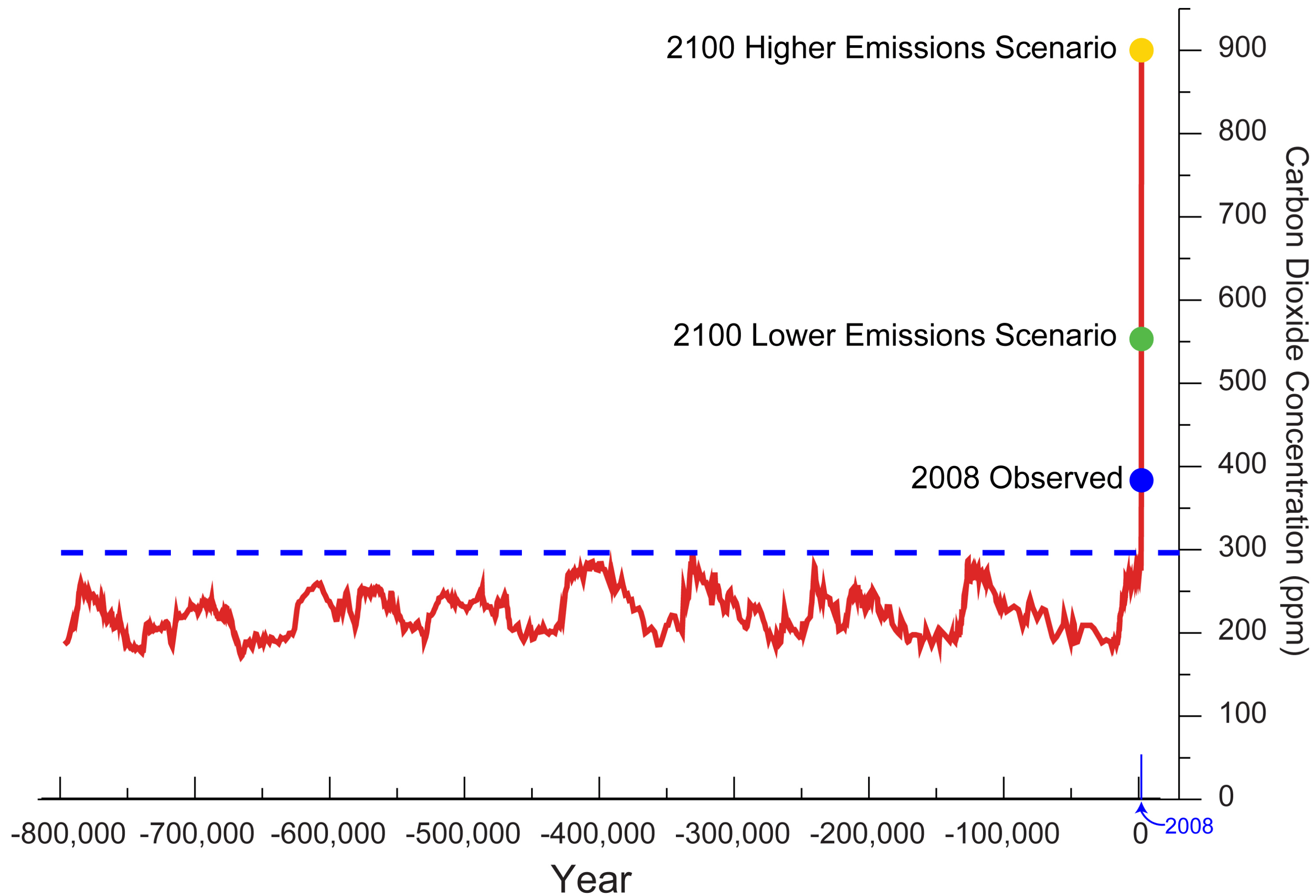
Looking to the future, fossil fuel emissions have been rising as rapidly as the highest IPCC scenario proposed in 2000



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

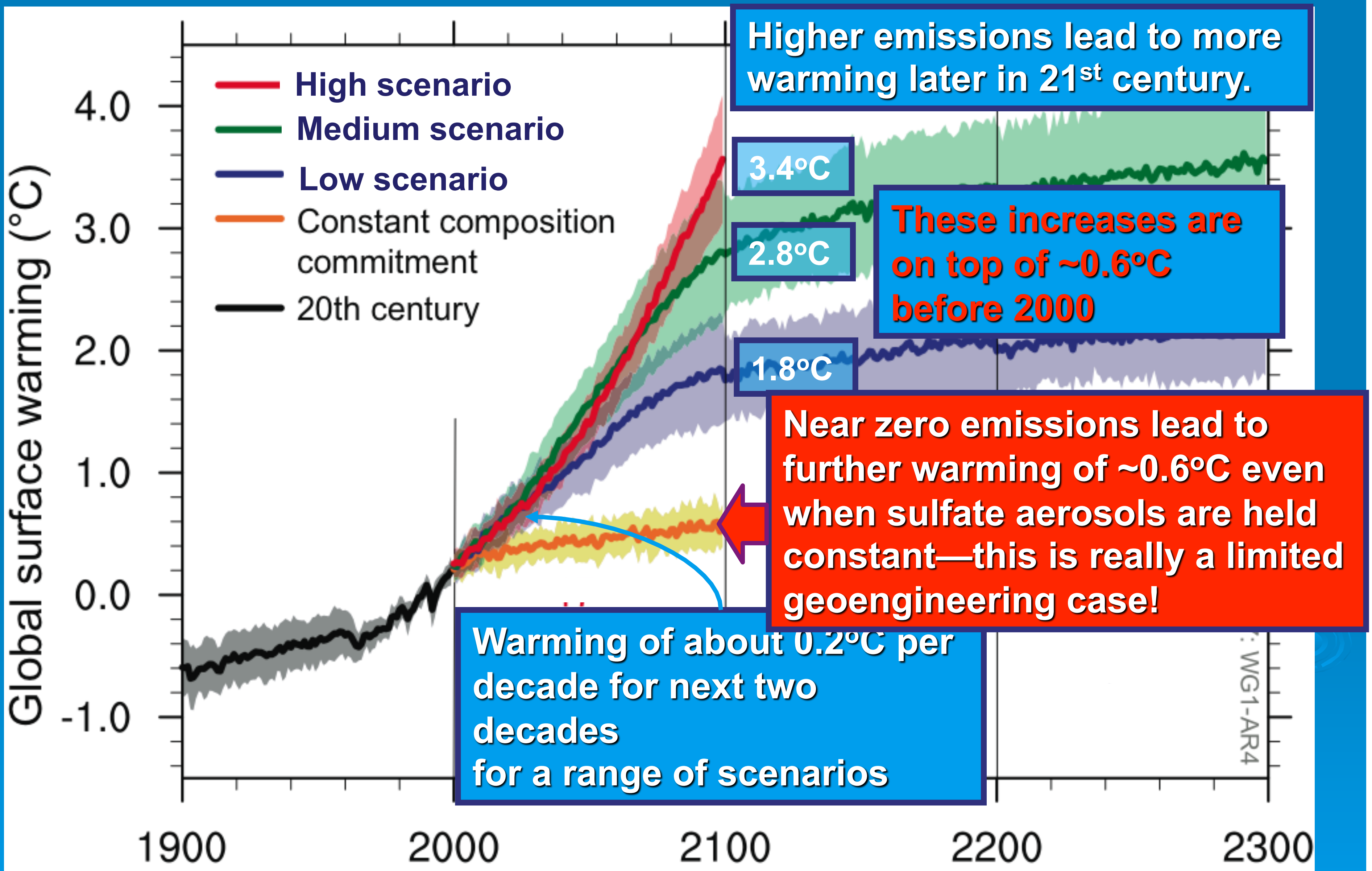
Slide from Global Carbon Project, 2010. Content updated from Raupach et al. 2007, PNAS; Data: Gregg Marland, Thomas Boden-CDIAC 2010; International Monetary Fund 2010

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

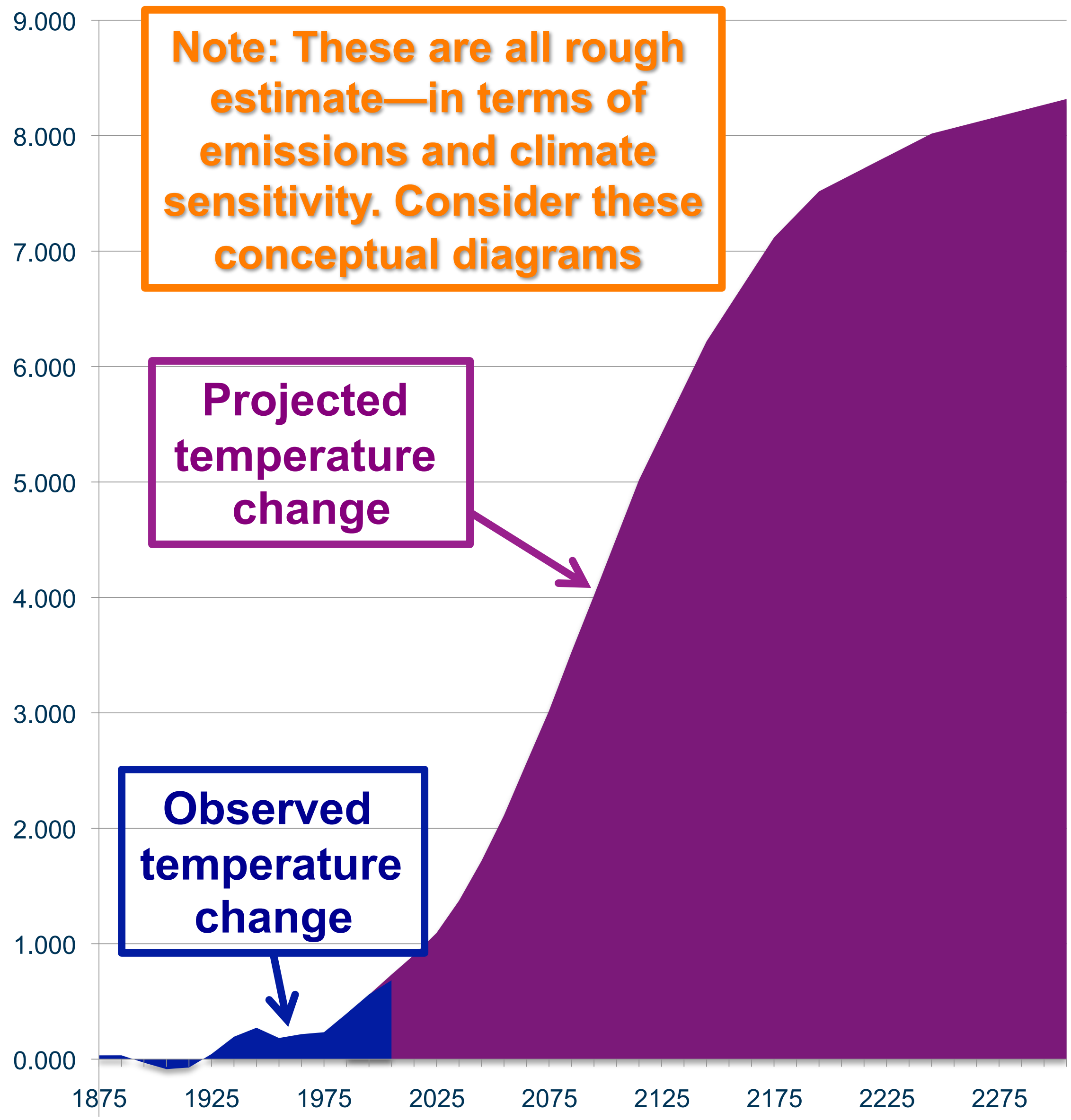


800,000 year ice-core record of the CO_2 concentration

Projections of global average warming after 2000 for different assumptions about emissions of GHGs



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

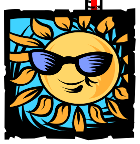
Observed Temp Change over 1750 (1880-2110)

Climate change is likely to lead to a range of important environmental and societal impacts

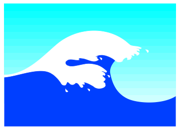
Adapted from EPA

Carbon Dioxide and Climate Changes

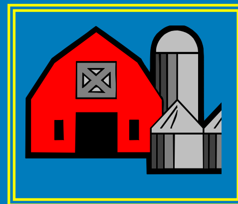

CO_2 and GHGs

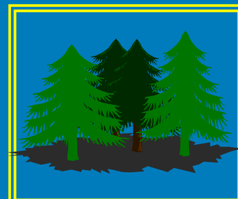

Temperature


Precipitation

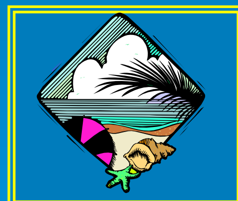

Sea Level Rise

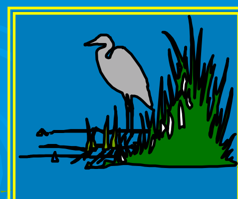

Health Impacts
Weather-related mortality/heat stress
Infectious diseases
Air quality-induced respiratory effects


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

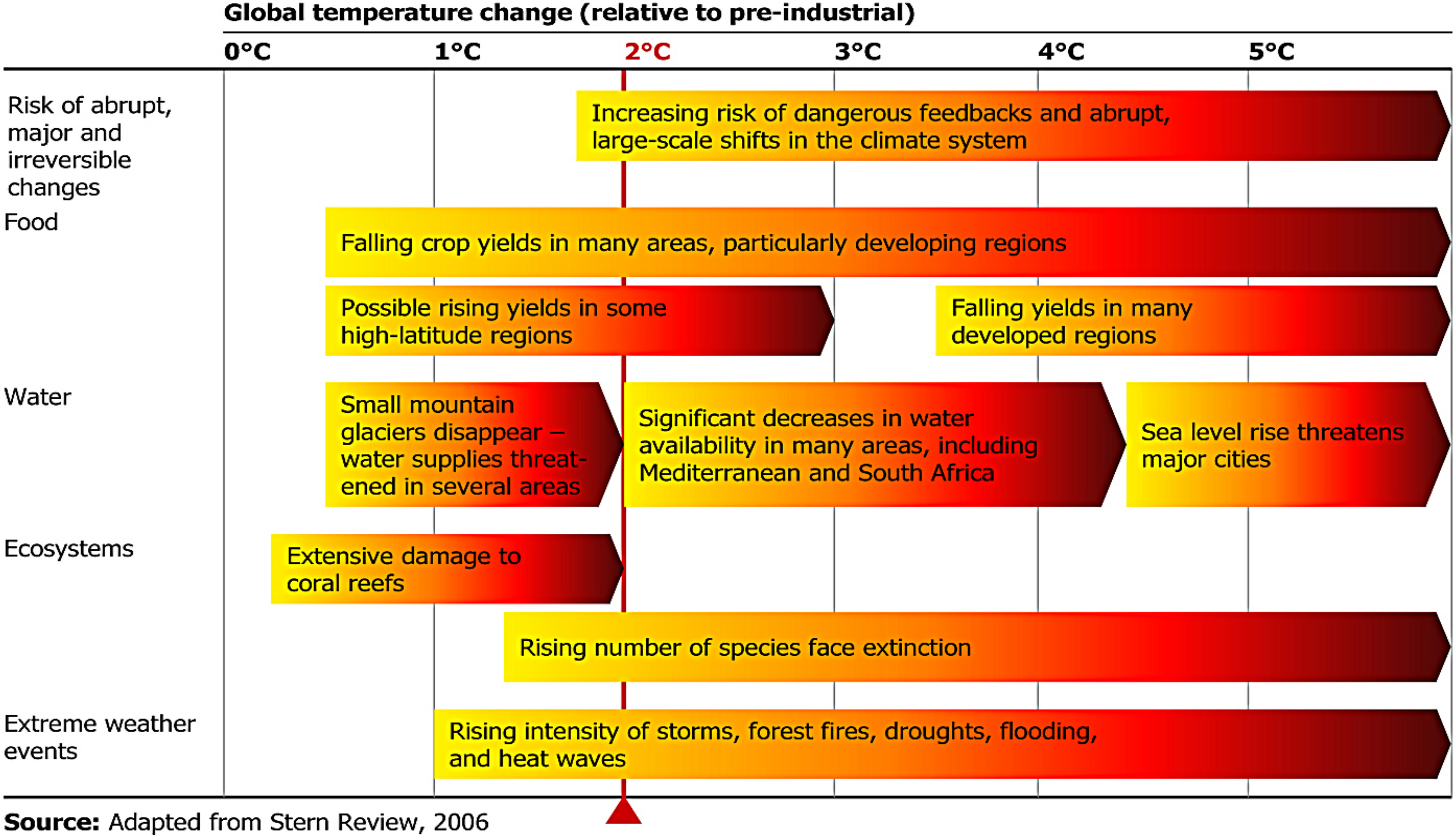

Water Resource Impacts
Changes in water supply and timing
Water quality
Increased competition for water


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

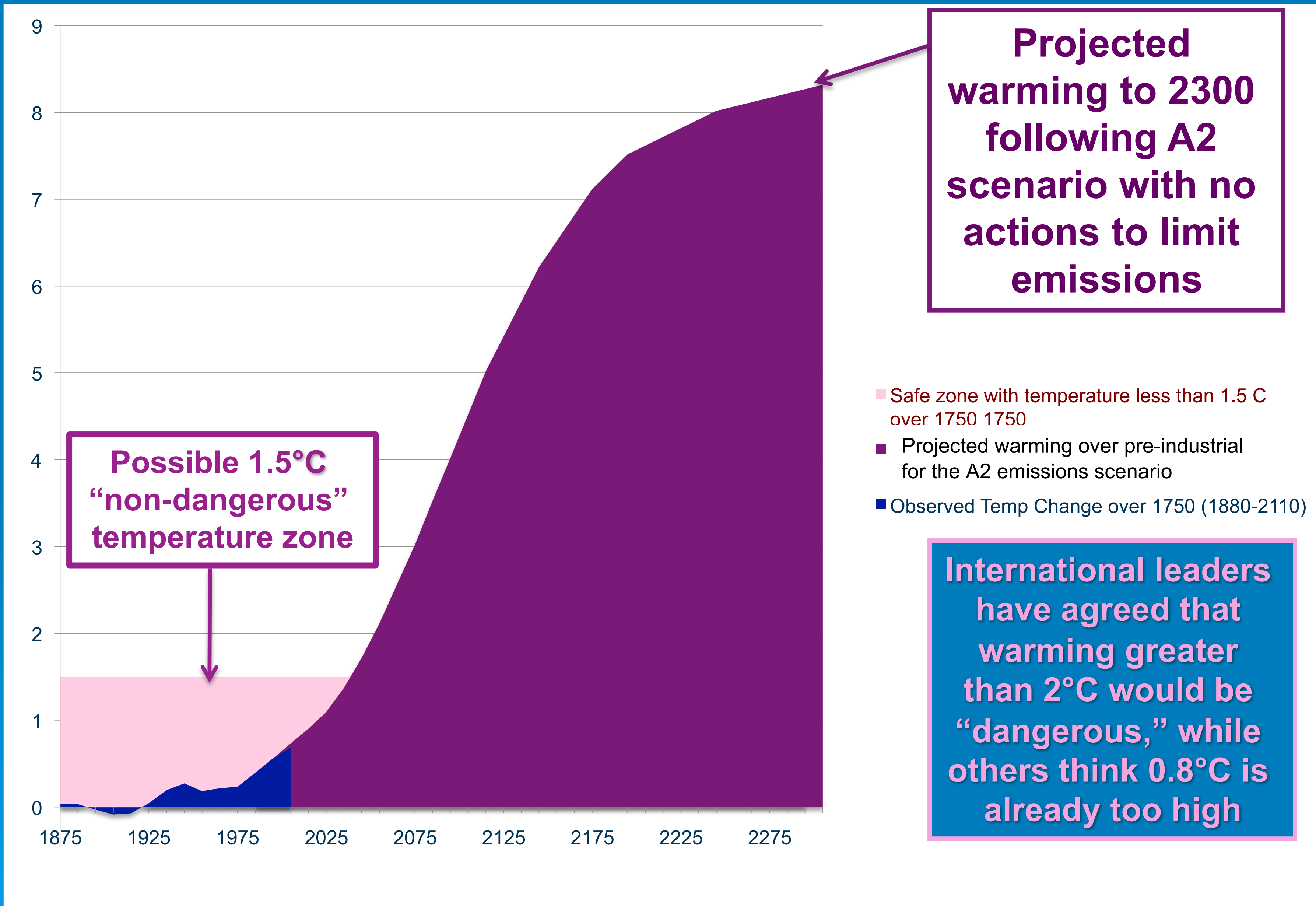

Societal Impacts
Indigenous peoples and developing nations
Exacerbated impacts on the poor
Dramatically different situation for future generations

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



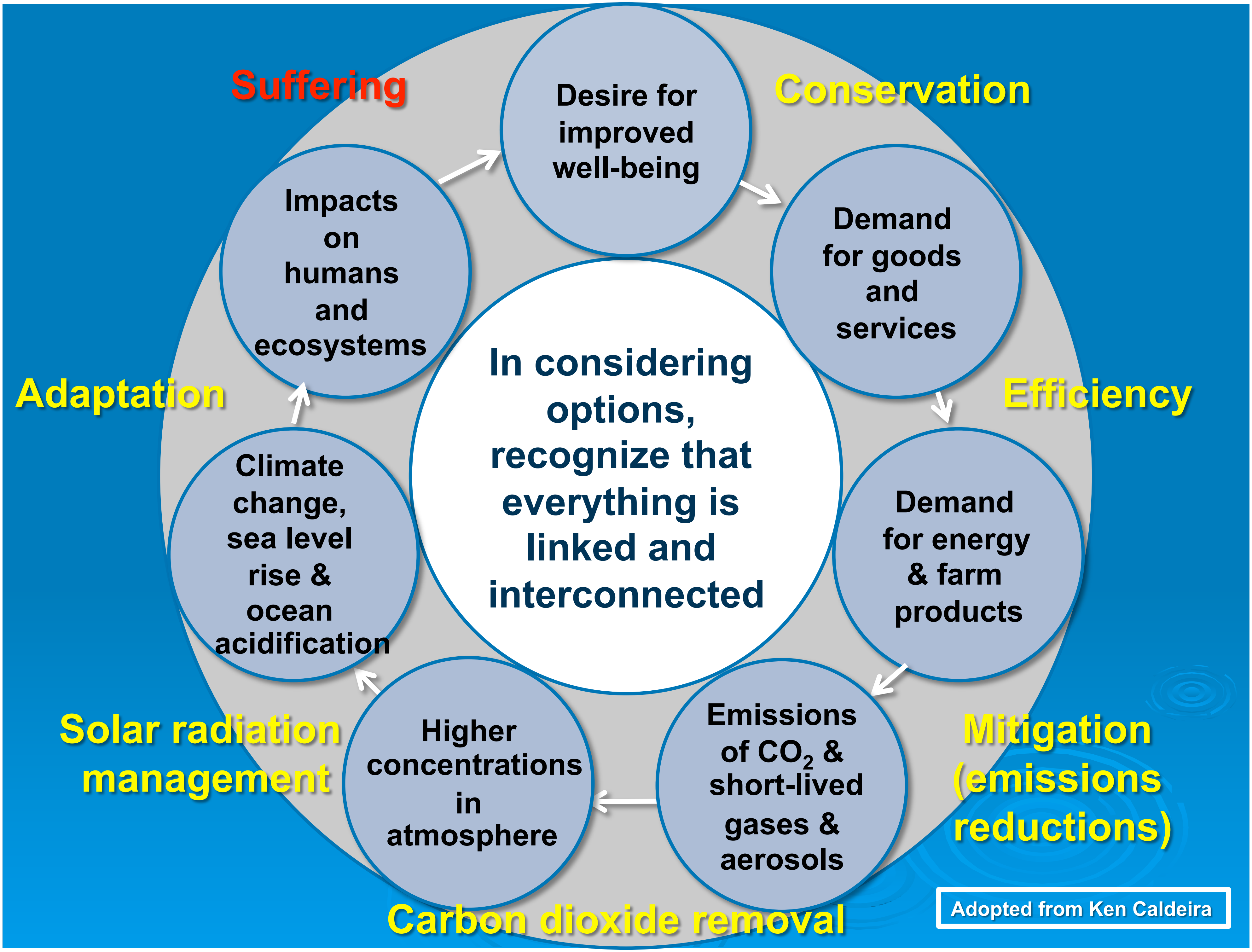
Source: Adapted from Stern Review, 2006

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

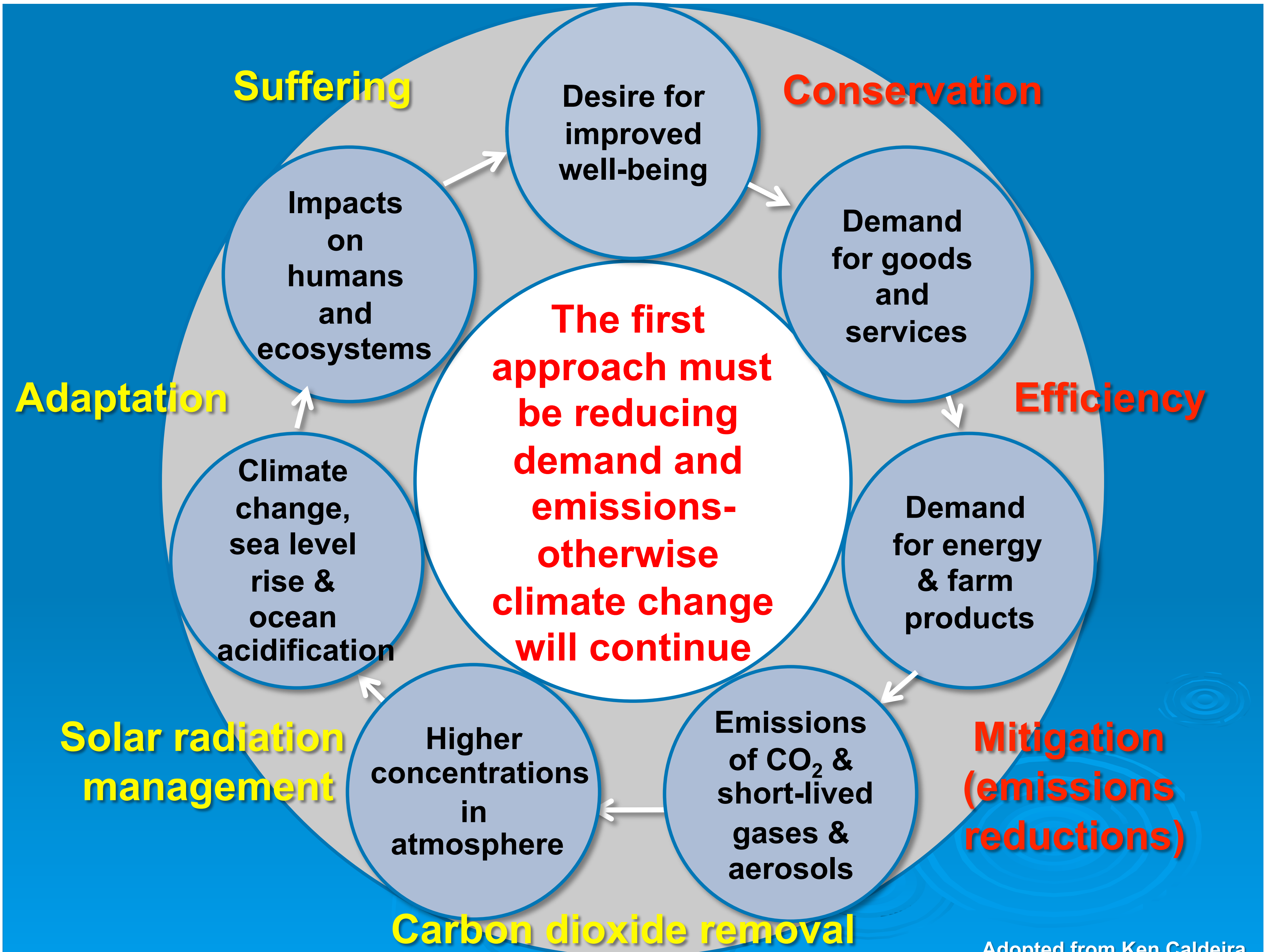


We cannot take away their hope!

**So, is there a feasible path forward,
or is climate catastrophe inevitable,
almost no matter what we do?**



Suffering
Desire for improved well-being
Conservation
Impacts on humans and ecosystems
Demand for goods and services
In considering options, recognize that everything is linked and interconnected
Adaptation
Efficiency
Climate change, sea level rise & ocean acidification
Demand for energy & farm products
Solar radiation management
Higher concentrations in atmosphere
Emissions of CO_2 & short-lived gases & aerosols
Mitigation (emissions reductions)
Carbon dioxide removal
Adopted from Ken Caldeira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Demand for goods and services
The first approach must be reducing demand and emissions- otherwise climate change will continue
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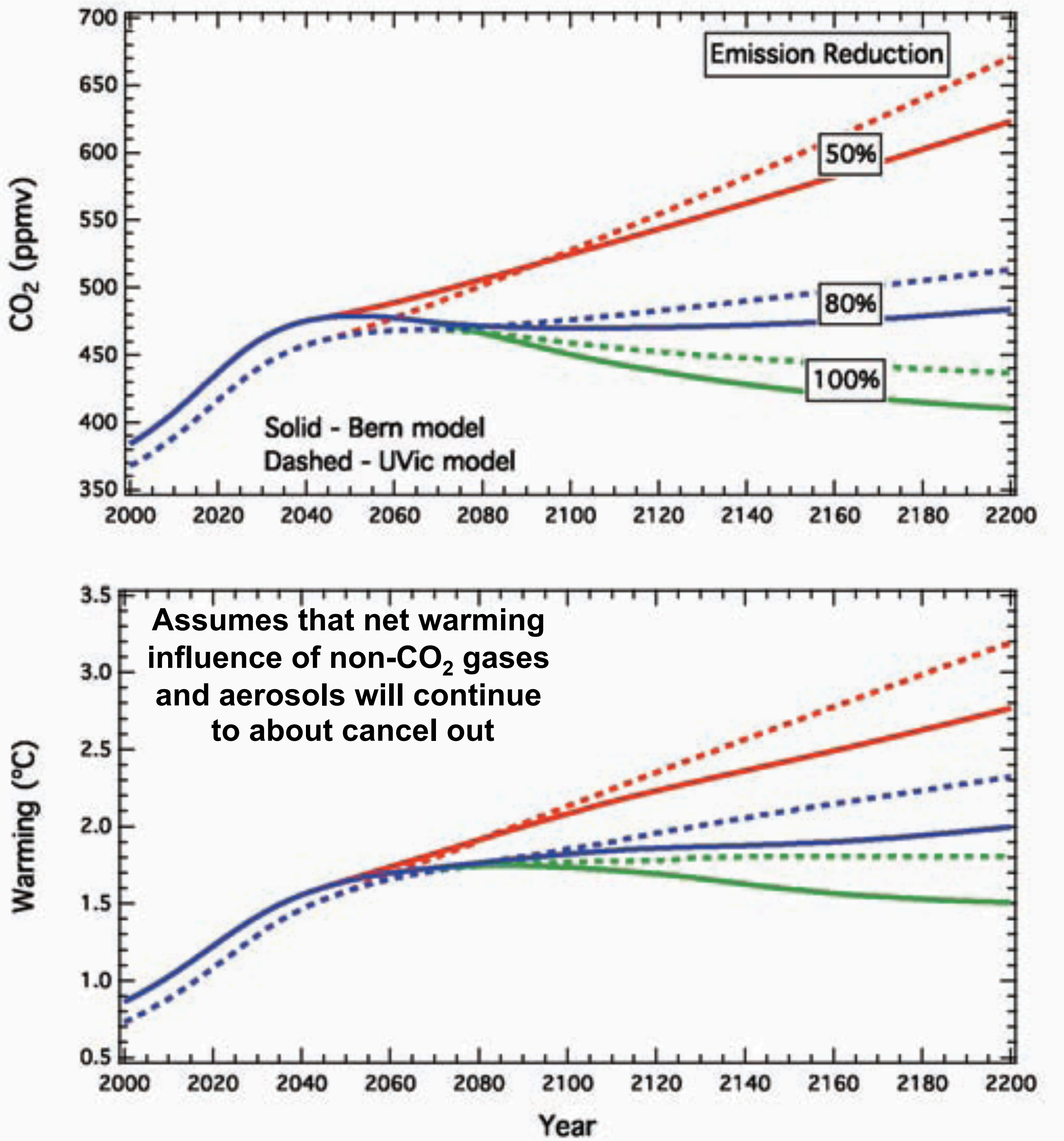
There are several major components to reduce the intensification of the climate change problem by human activities

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)

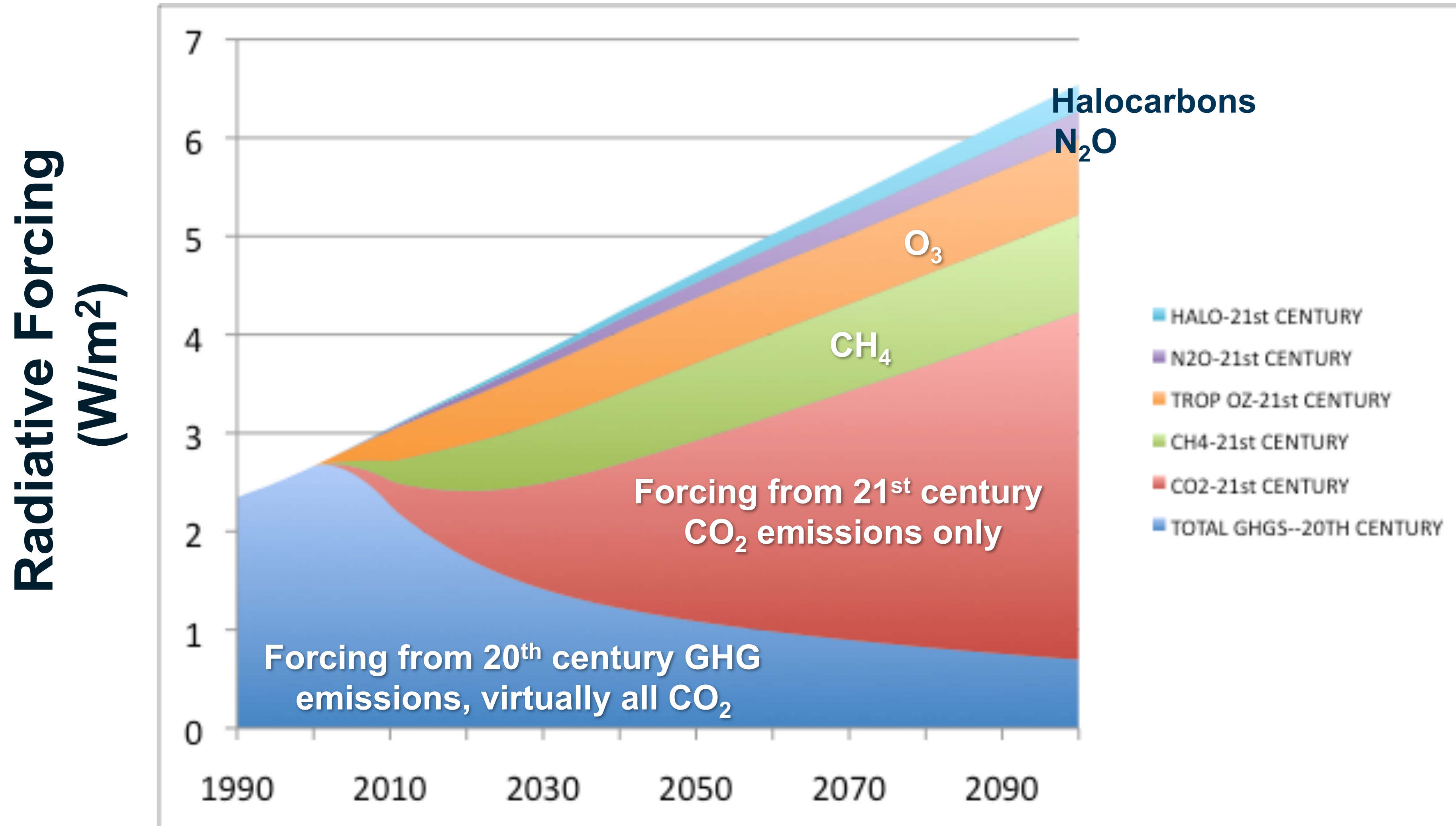


Source: "Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia" by the National Research Council, 2011

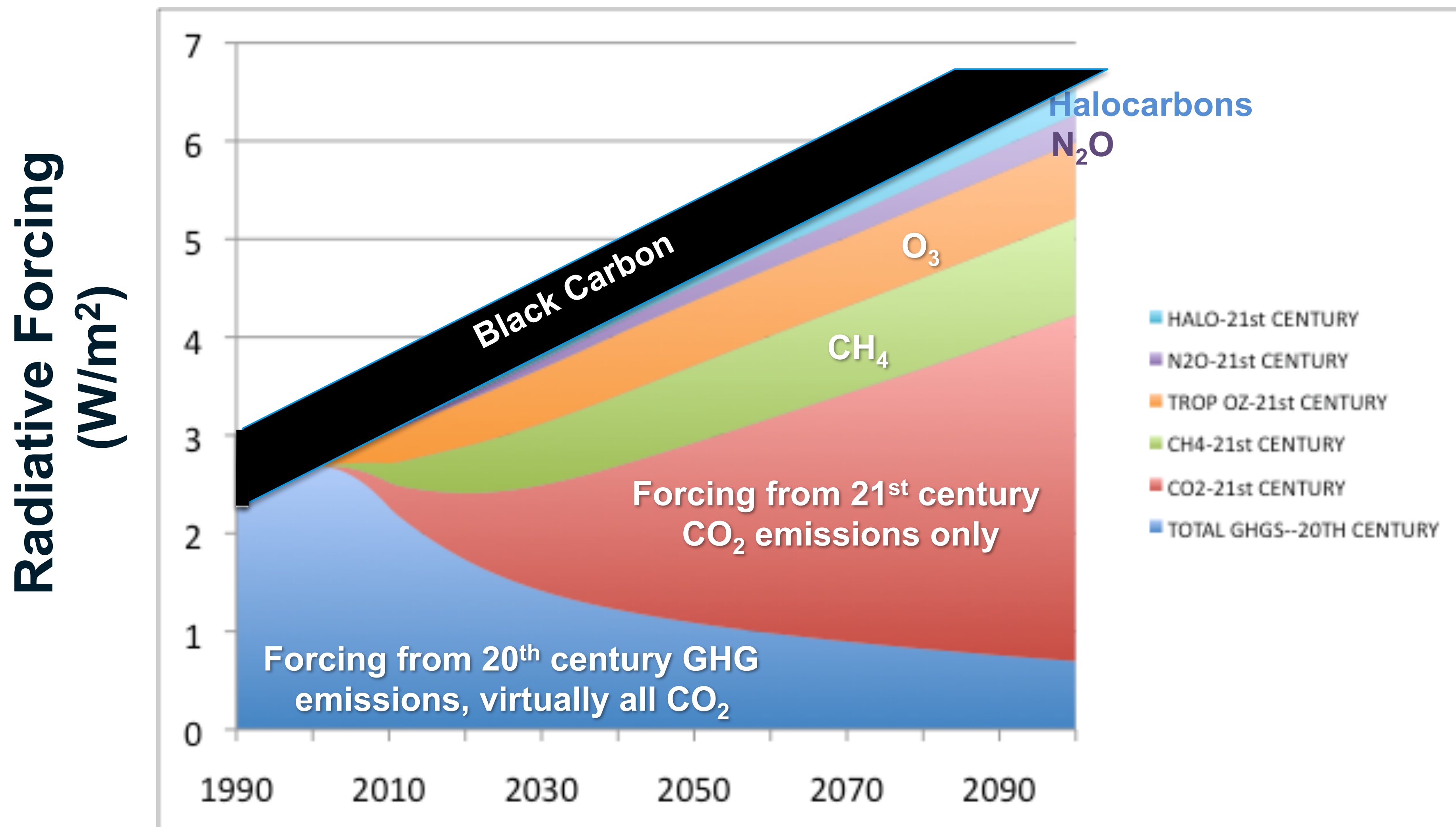
Separately considering the climatic effects of different greenhouse gases offers some hope

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

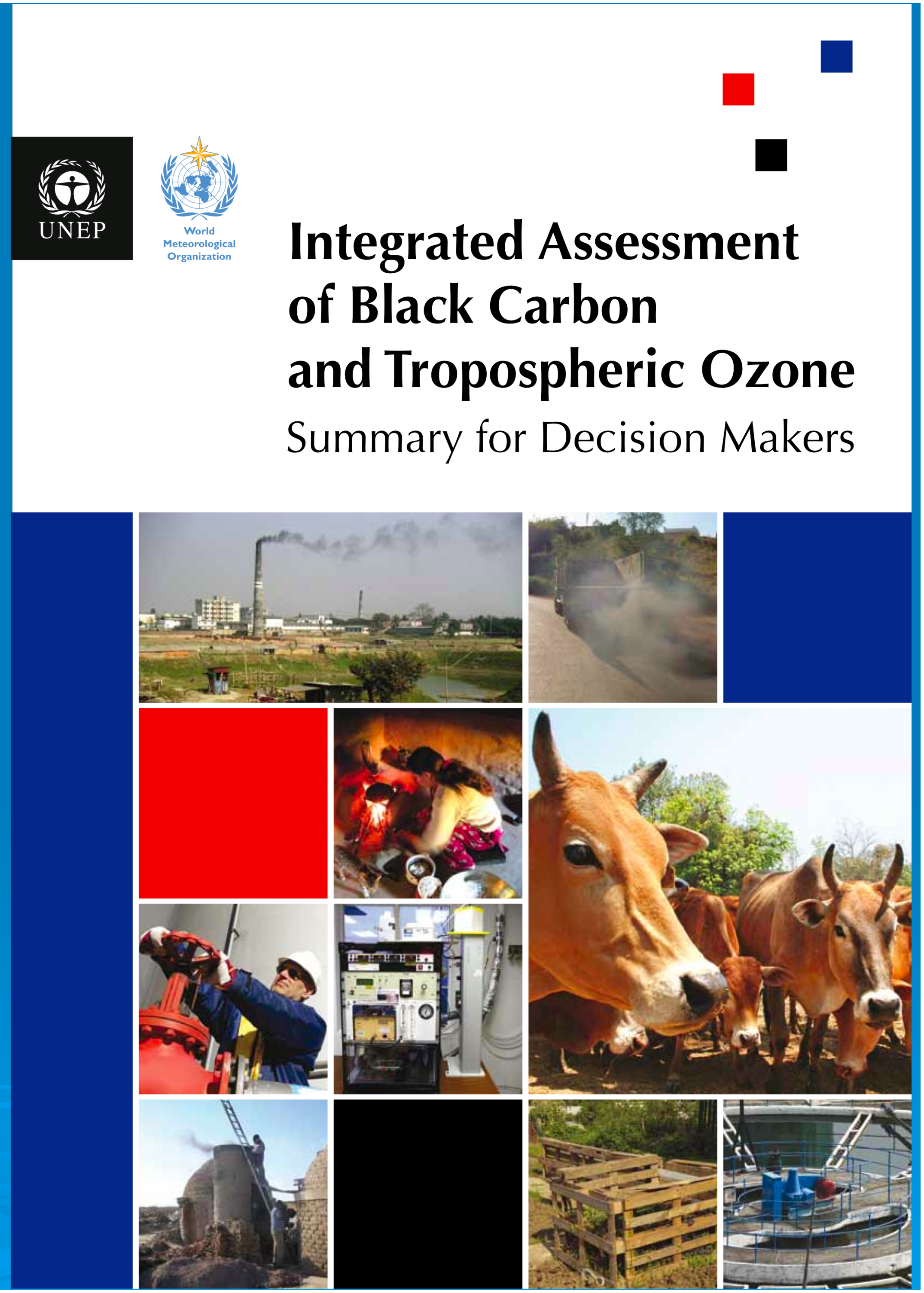
Decomposing the warming influence of each of the gases, the warming influence of CH_4 and tropospheric O_3 makes clear that their influence will be very significant this century



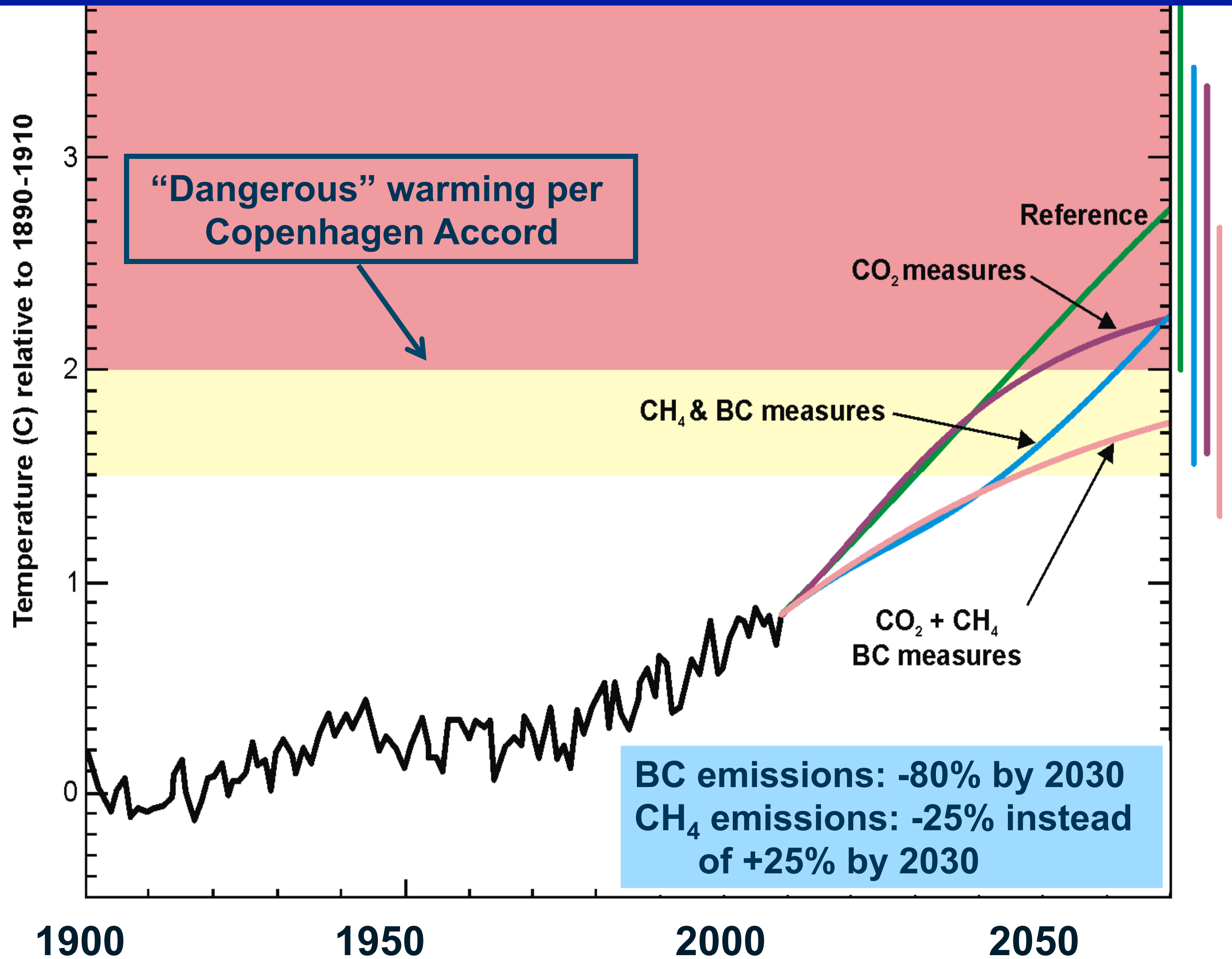
Adding the somewhat uncertain warming influence of black carbon emissions makes clearer that cutting emissions of short-lived species will reduce near-term warming



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

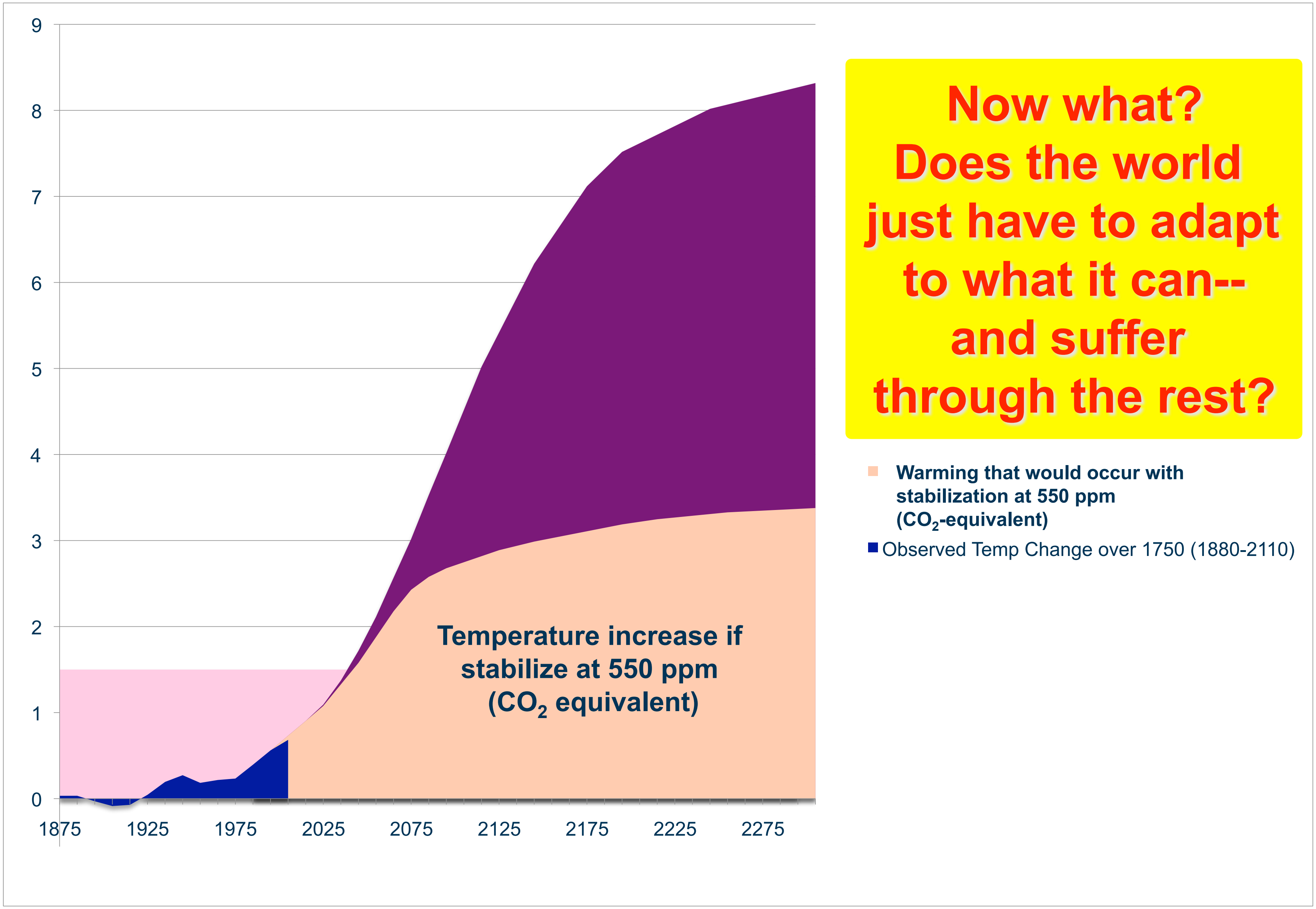
To limit long-term climate change, global emissions of CO_2 must be cut sharply:

- 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

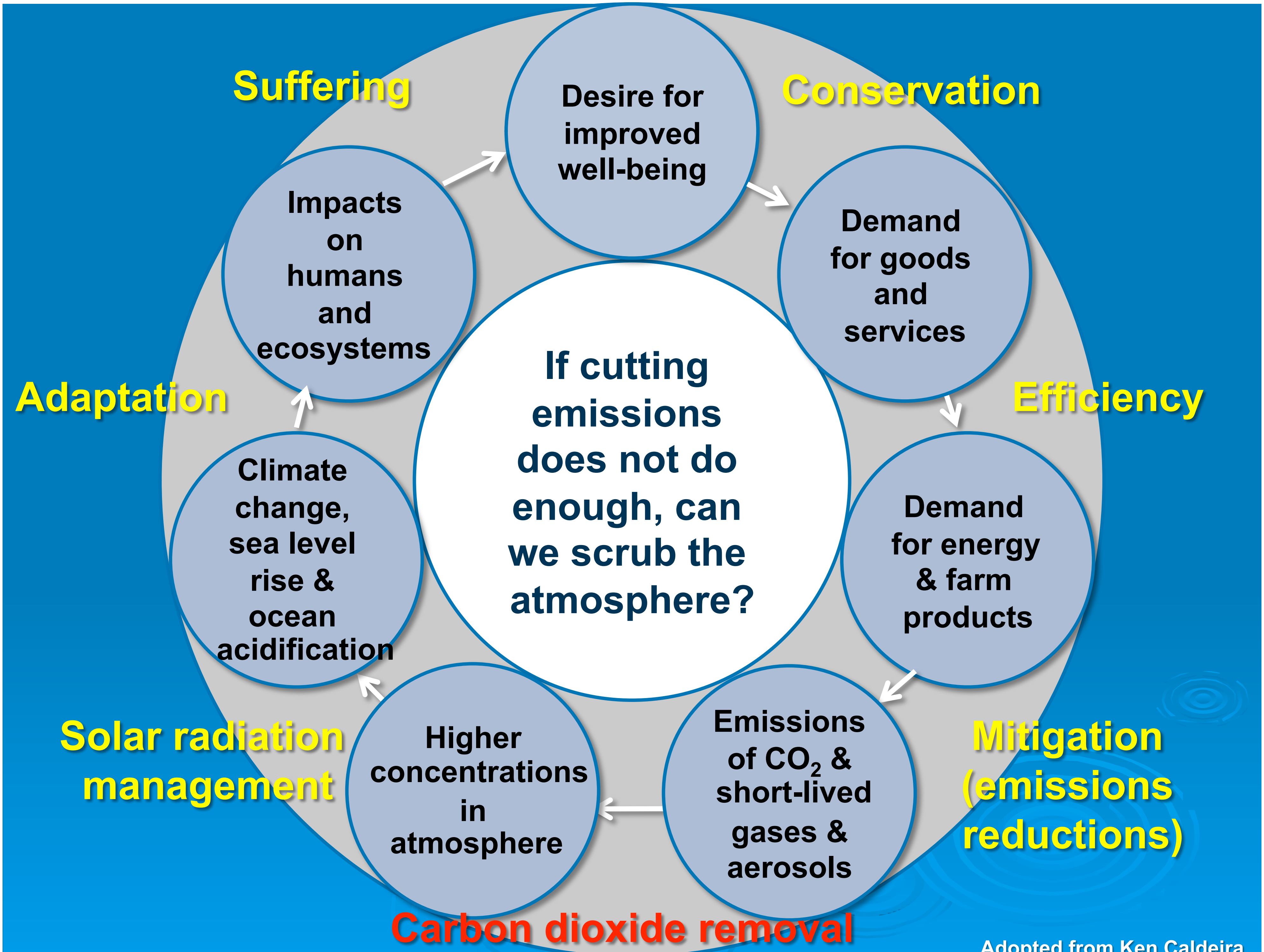
To slow the rate of climate change over the next several decades, *all nations* need to sharply reduce emissions of CH_4, O_3 precursors, and black carbon:

- 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



Now what? Does the world just have to adapt to what it can-- and suffer through the rest?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If cutting emissions does not do enough, can we scrub the atmosphere?
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Emissions of CO_2 & short-lived gases & aerosols
Mitigation (emissions reductions)
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 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

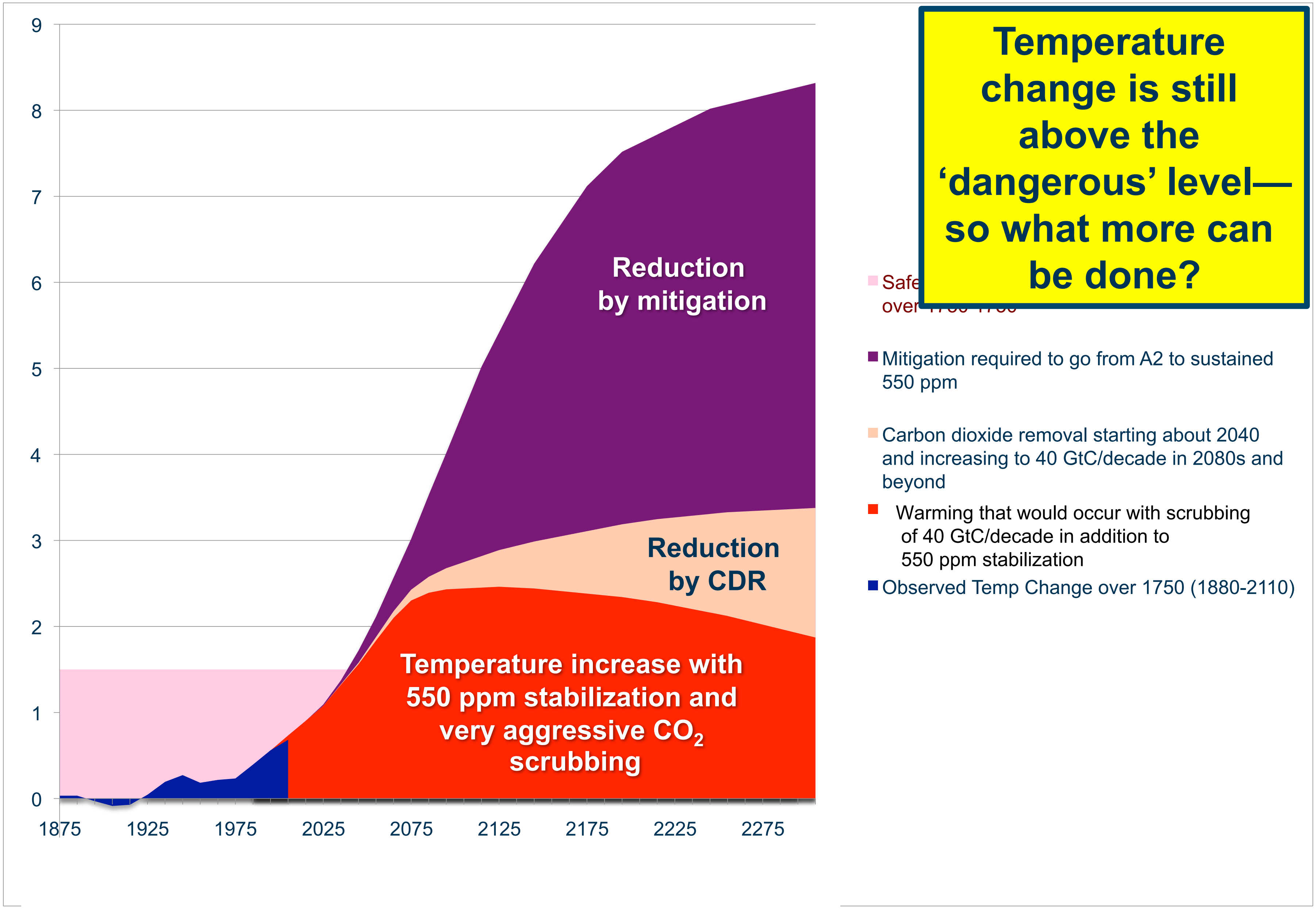
Research makes clear that keeping the CO_2 level below 450 ppm to limit global warming and ocean acidification will be very difficult without both aggressive mitigation and carbon dioxide removal

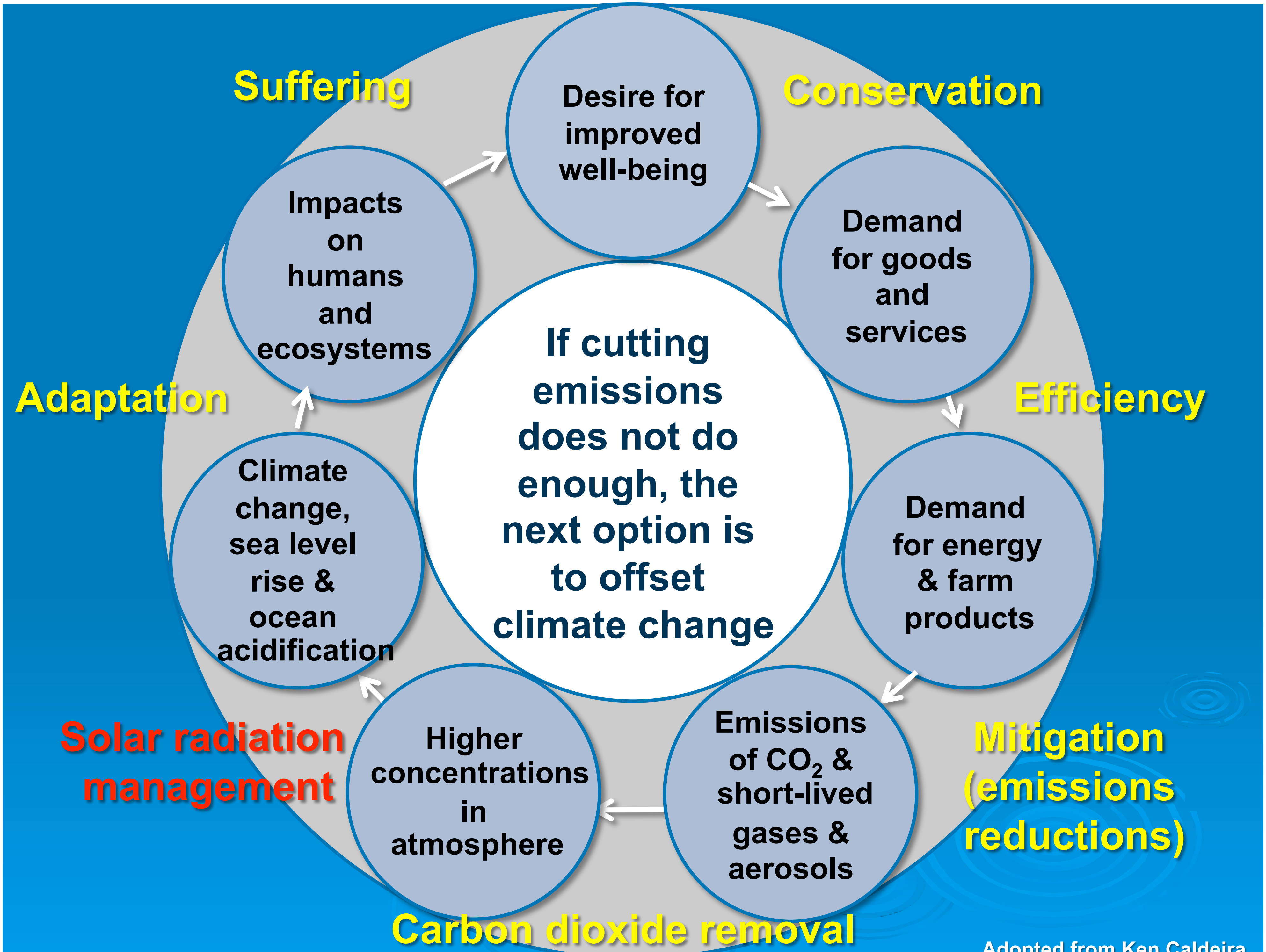
Removing a significant amount of CO_2 from the atmosphere will be very challenging until emissions are greatly reduced

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

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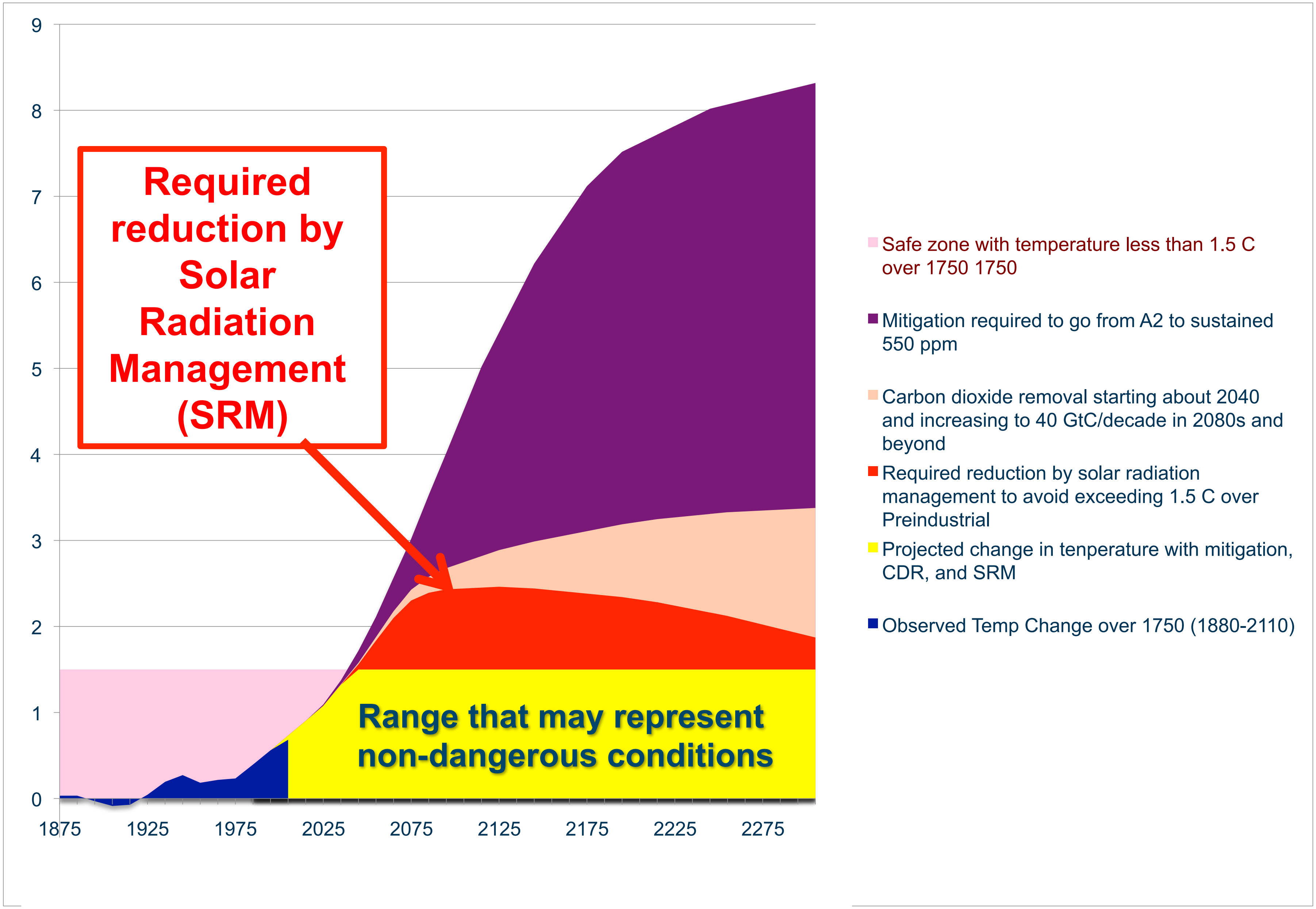
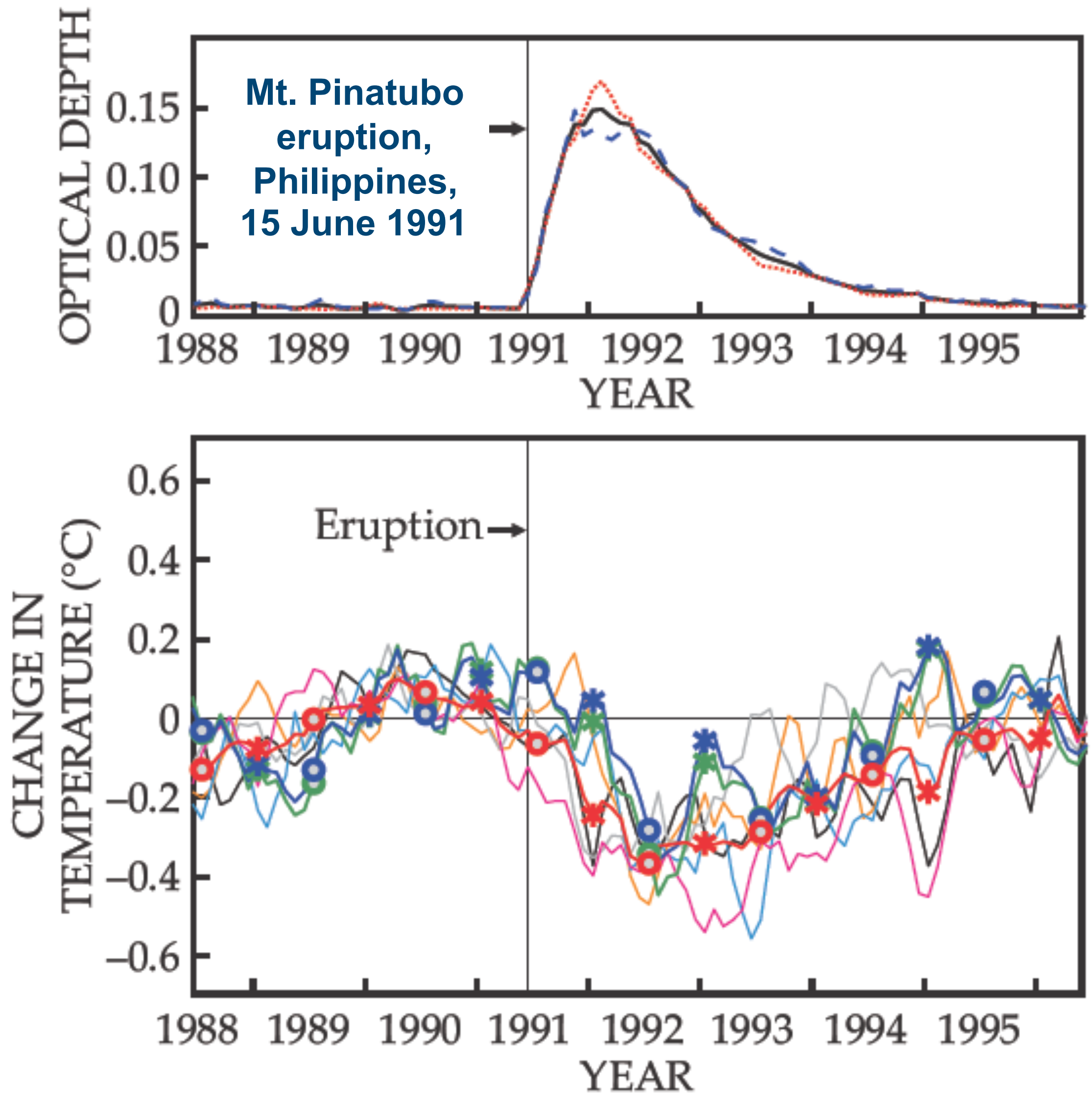
If cutting emissions does not do enough, the next option is to offset climate change
Adopted from Ken Caldeira

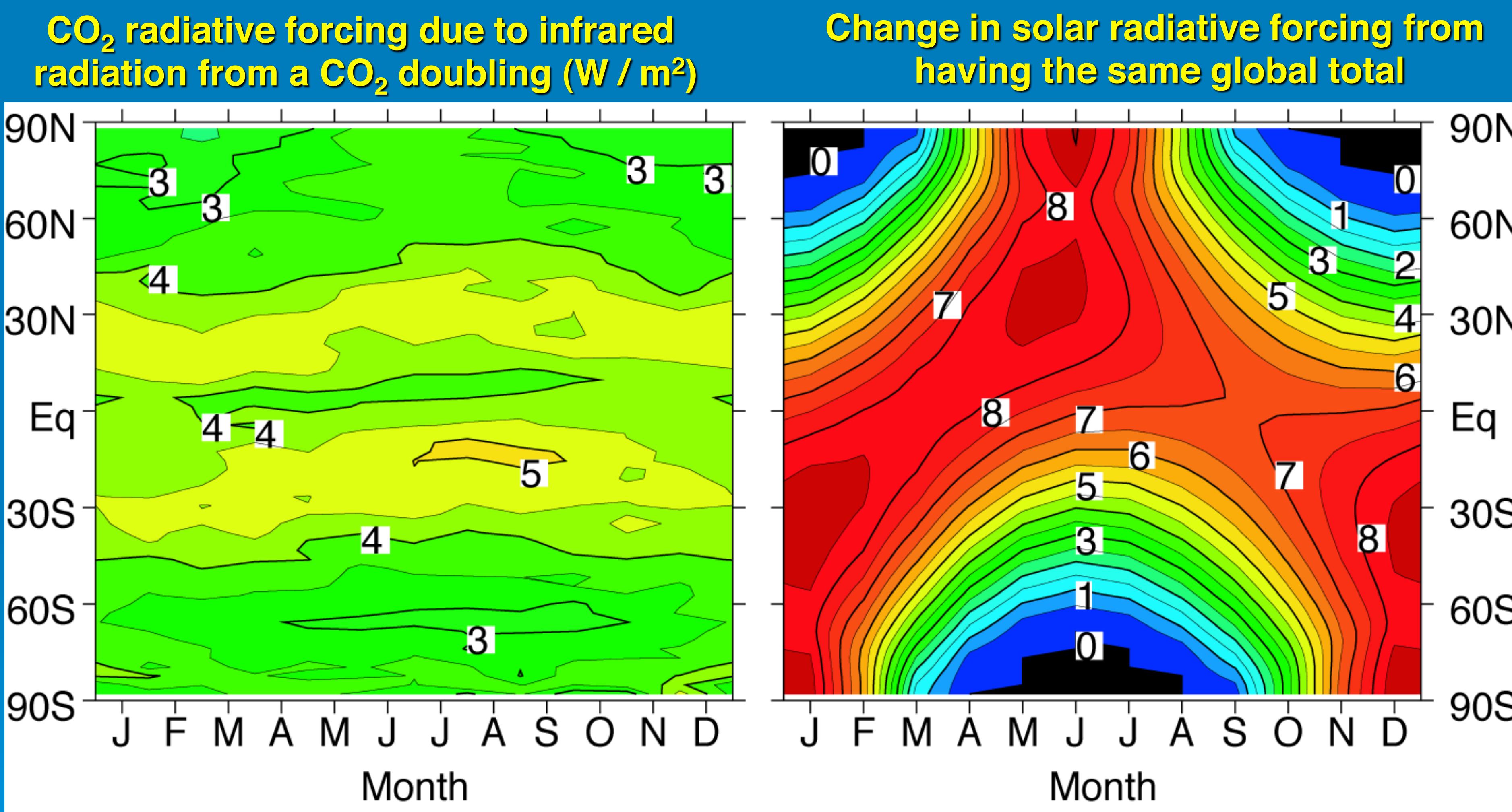
To the extent mitigation and scrubbing cannot limit warming, solar radiation management will be needed



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

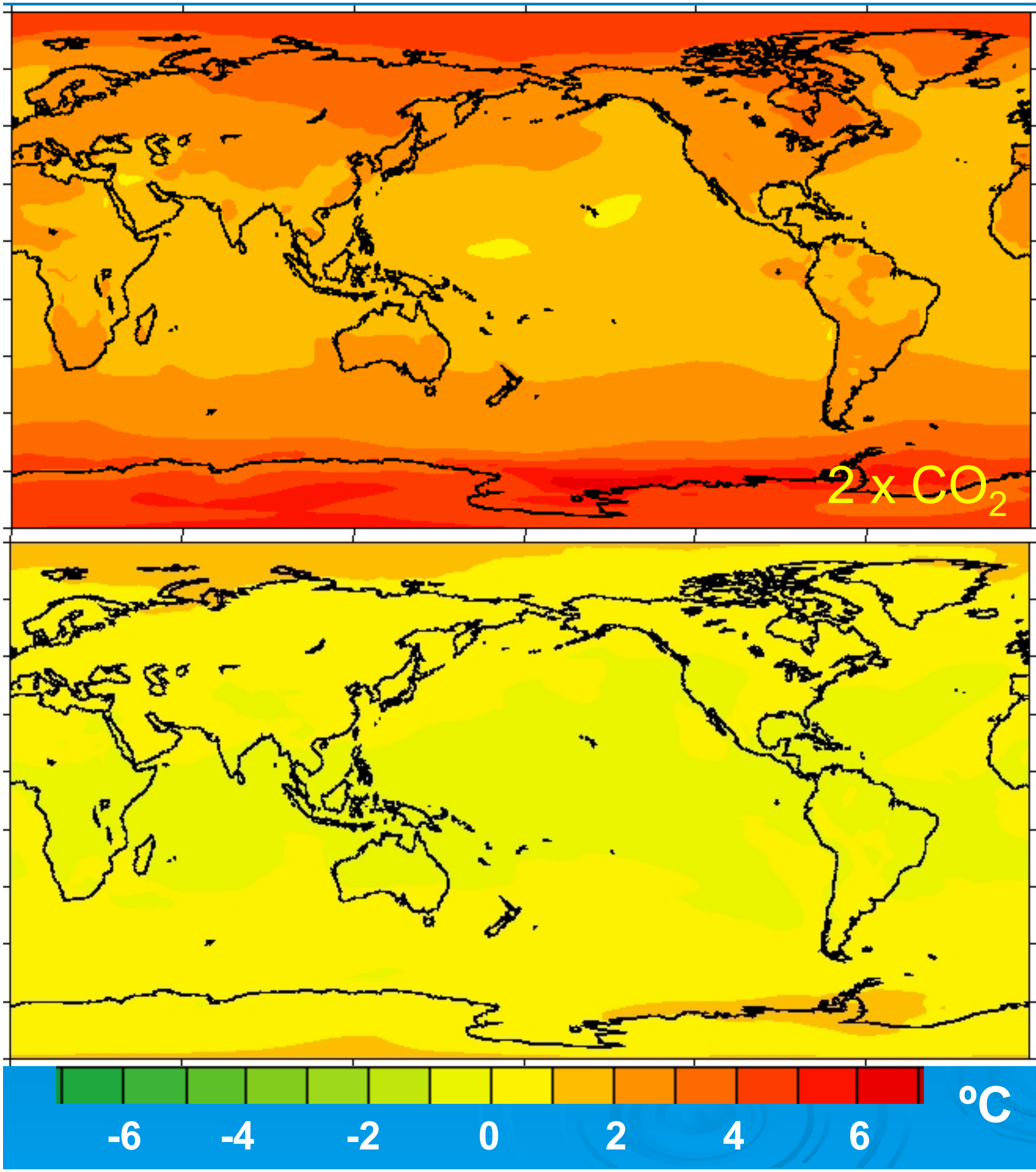


In practice, Solar Radiation Management may be made difficult by the differing patterns of influence



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

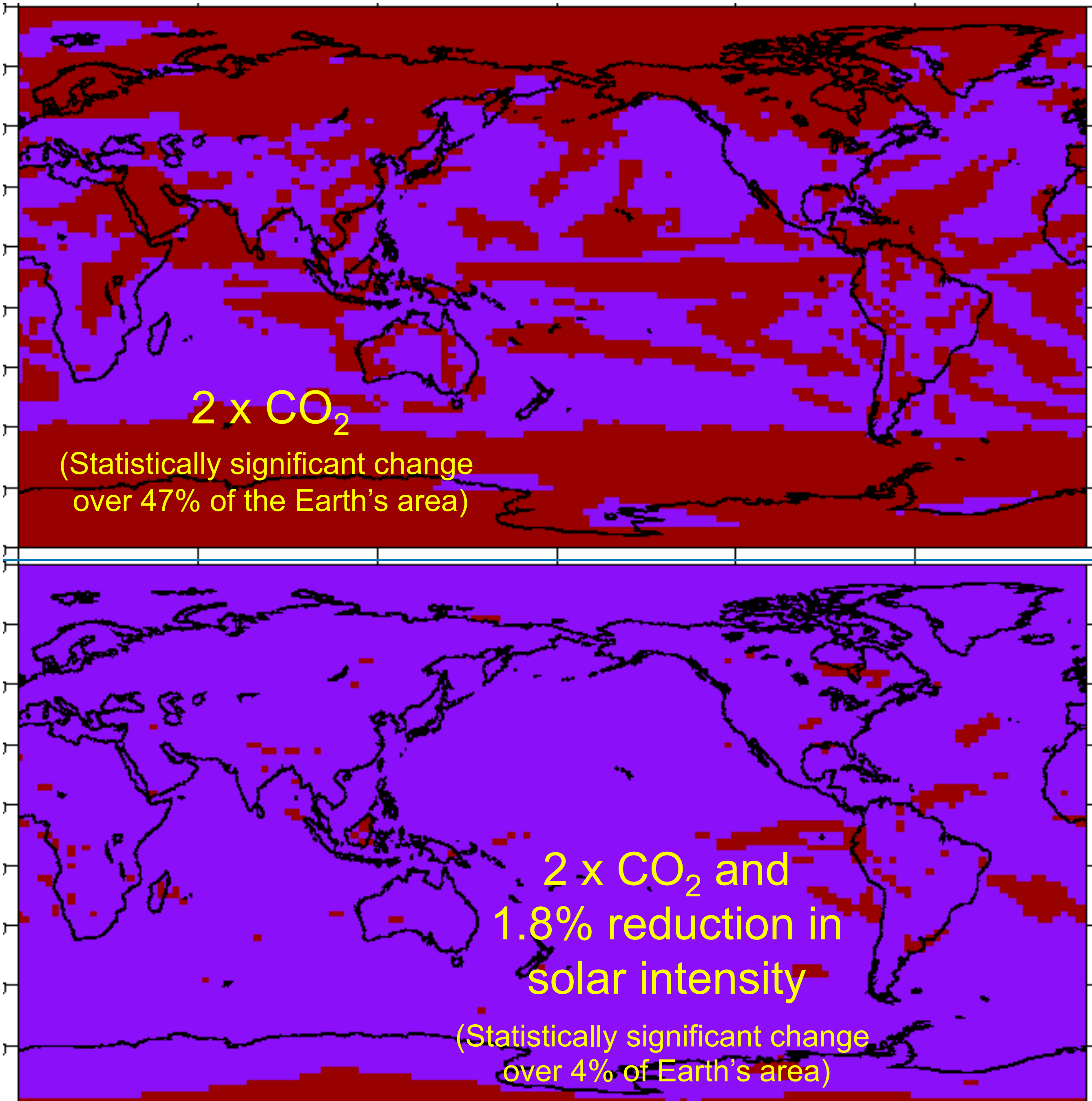
Govindasamy and Caldeira, GRL, 2000



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



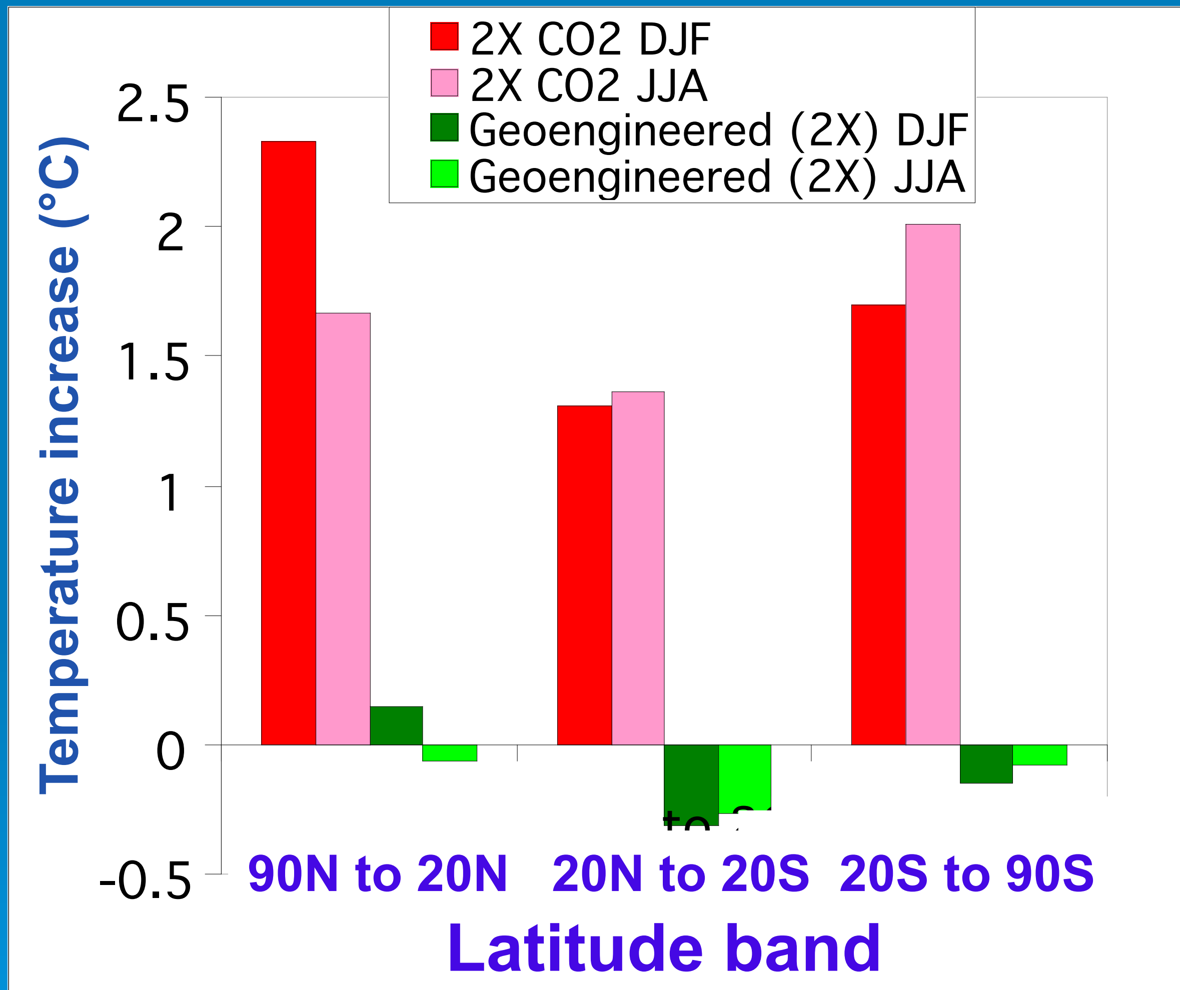
Model results also suggest that the change in precipitation from a CO_2 doubling can largely be offset by reducing incoming solar radiation by about 1.8%

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 a seasonal and latitudinal basis

Seasonal and latitudinal temperature change

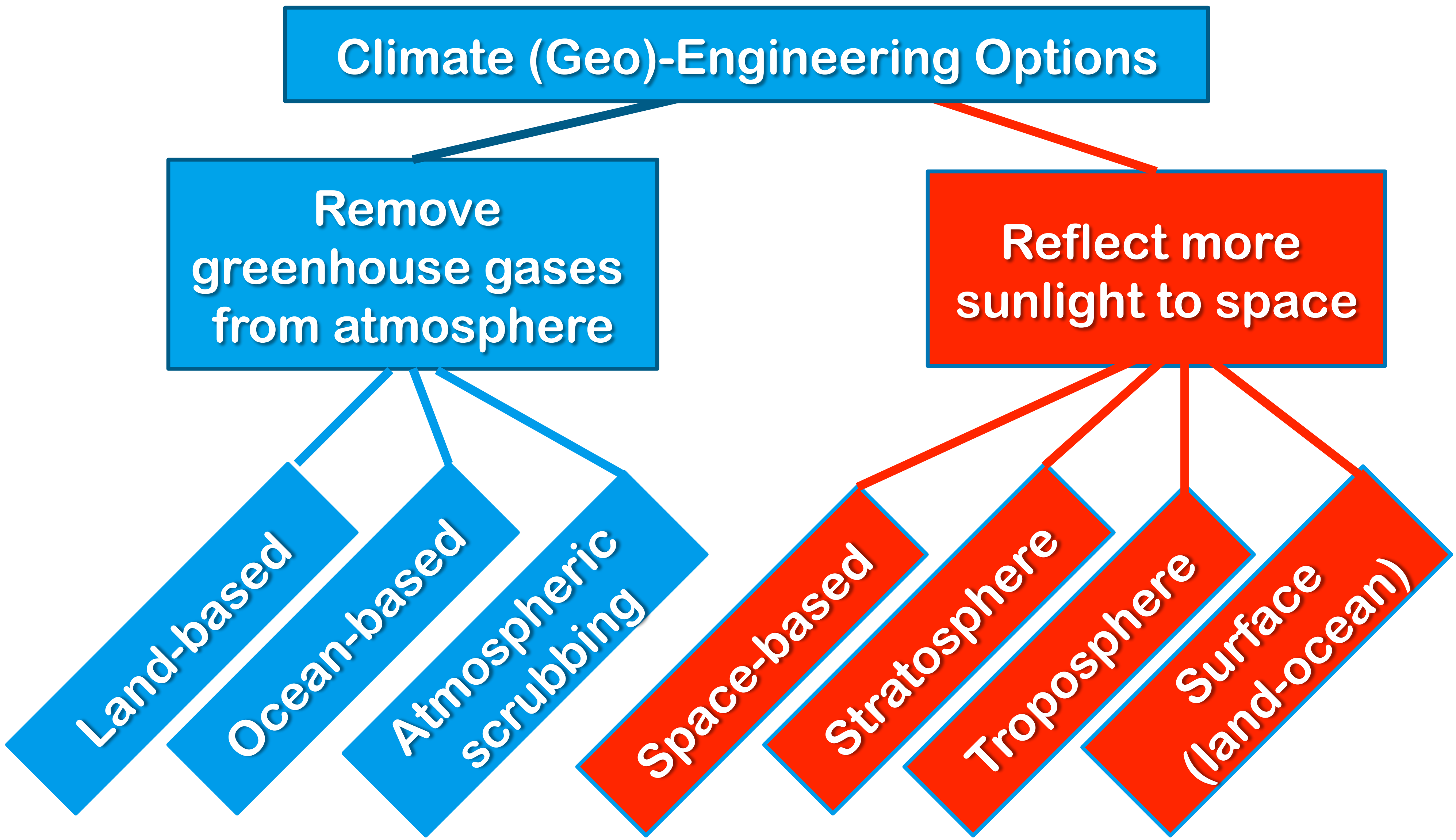


Govindasamy and Caldeira 2000

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

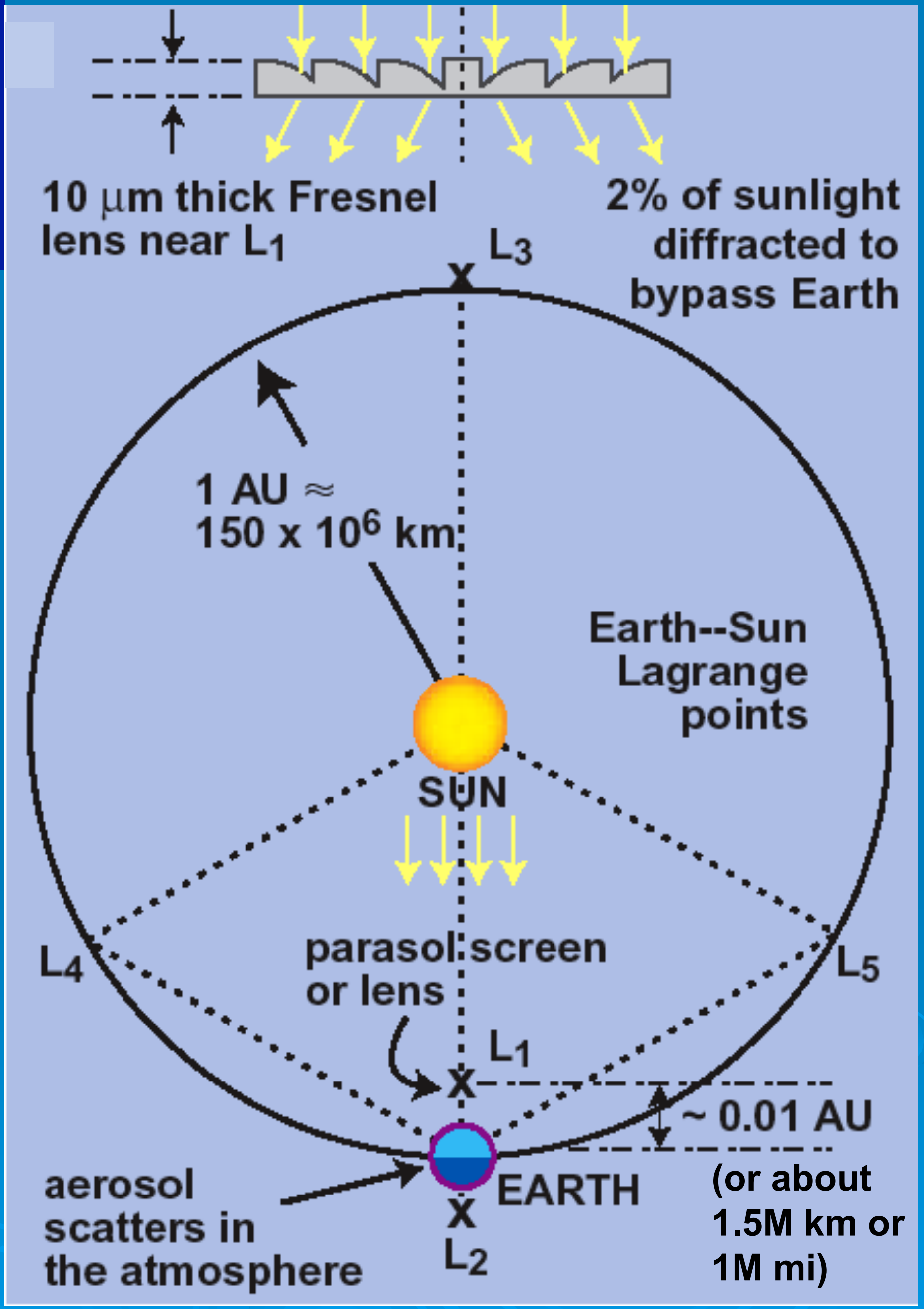
A number of options have been suggested for reducing incoming solar radiation to counter-balance global warming



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

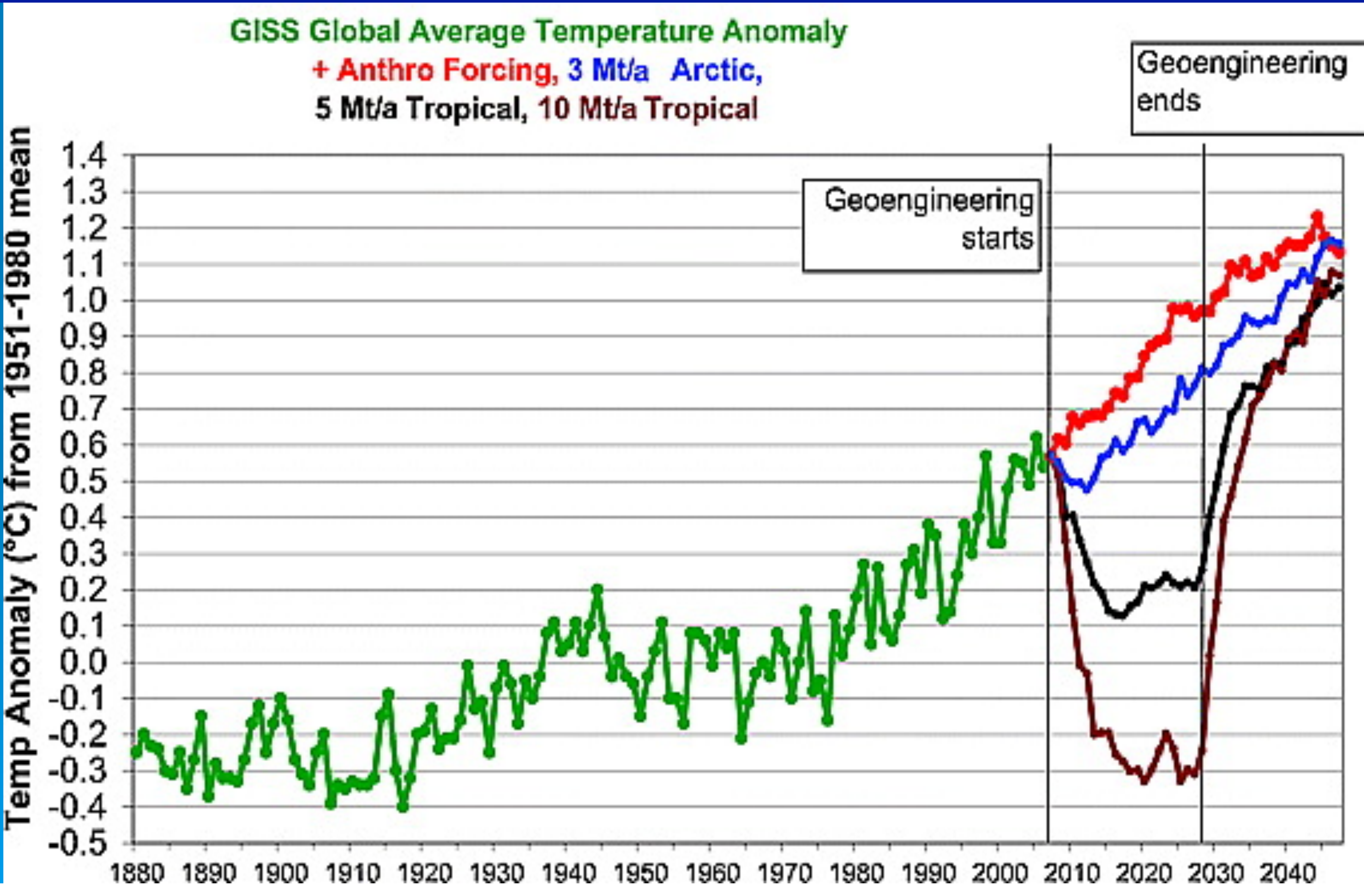
Injecting reflective materials into the stratosphere has the advantage of them remaining aloft for 1-2 years

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

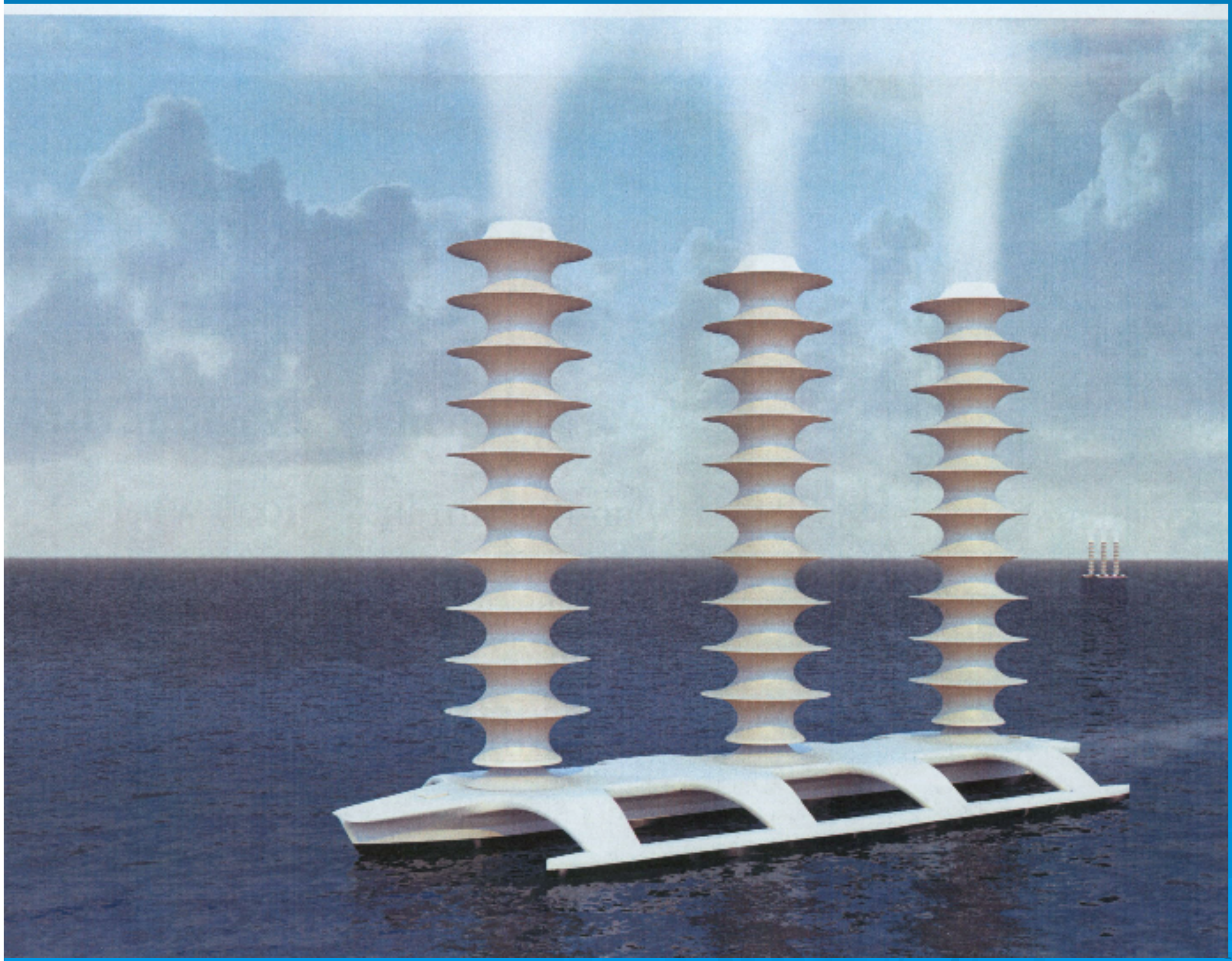
Robock et al. have looked at the reductions in temperature that could be achieved if required due to the need to reverse an abrupt or nonlinear acceleration



Although the interventions would require ongoing injections, there are 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

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

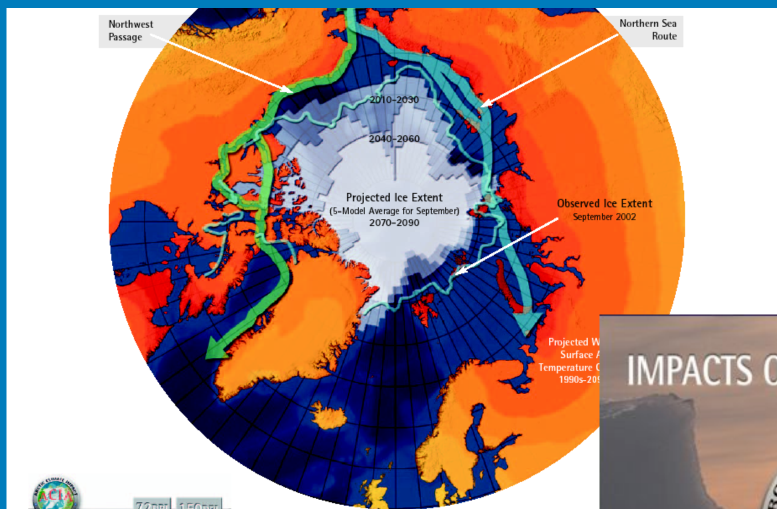
Particular objectives for which it might well make sense to determine if approaches exist to attempt:

- 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

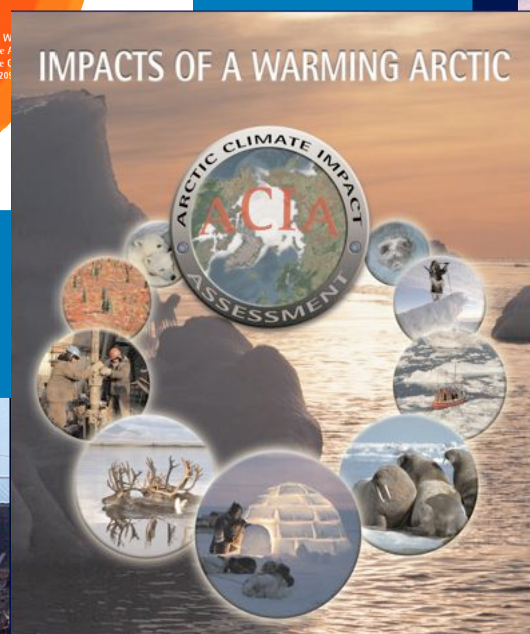
An aggressive research program is needed to determine if there really are possibilities

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

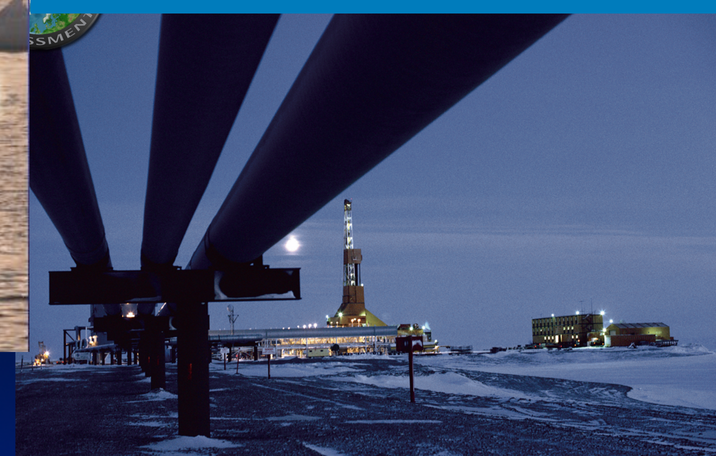


Sea ice loss allows increased coastal erosion, which will force relocation of ~150 Indigenous communities



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

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.

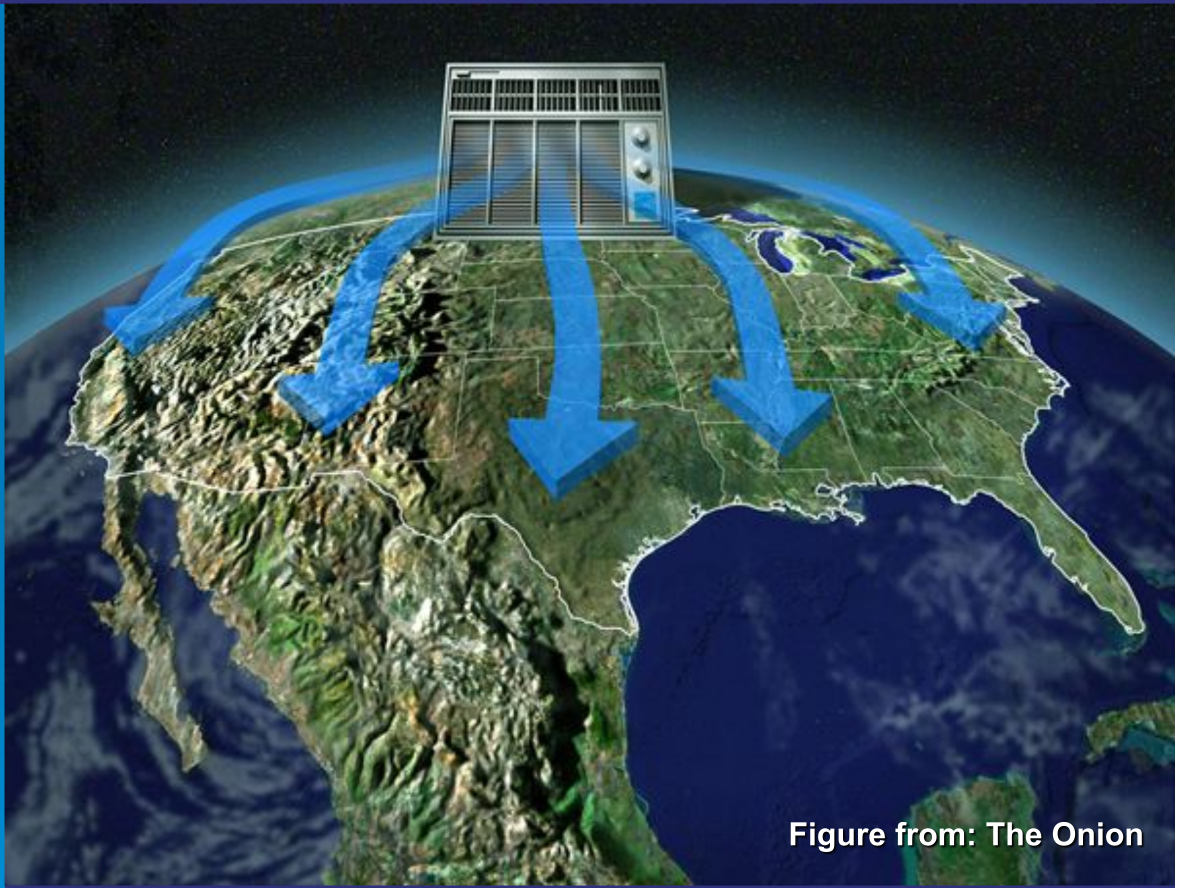
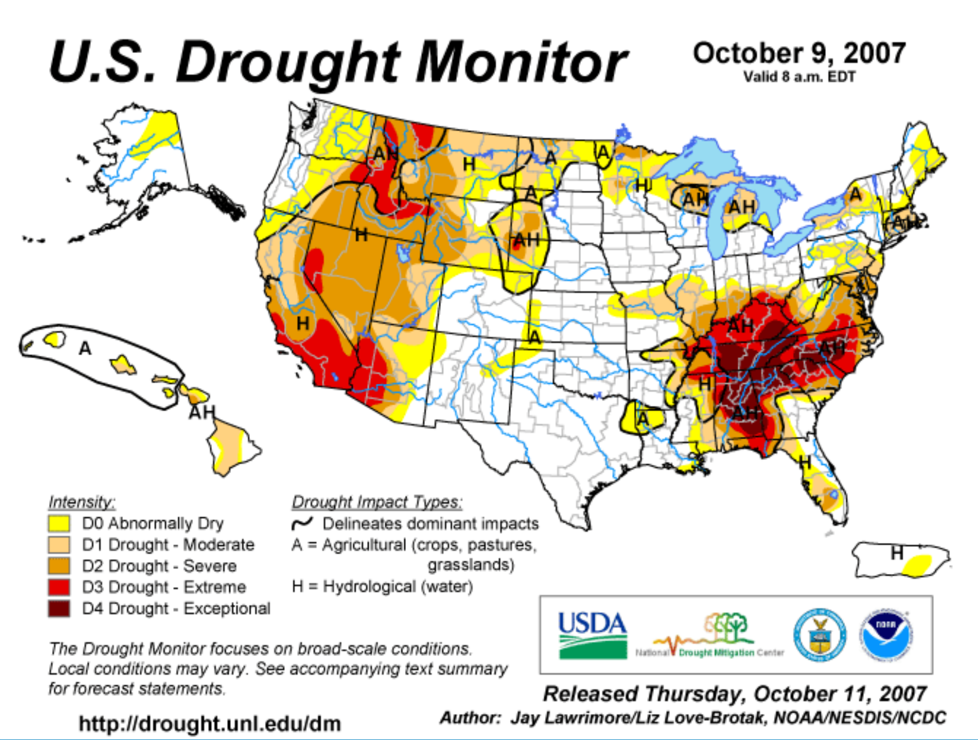


Figure from: The Onion

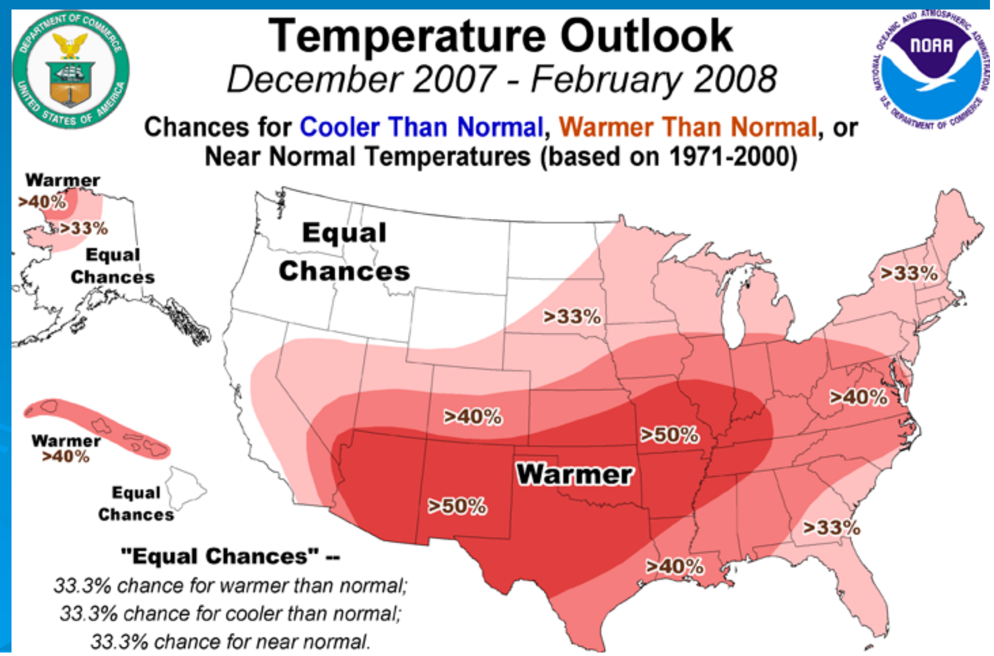
For interesting discussions of the unusual weather, go to the blog of Stu Ostro, senior meteorologist for The Weather Channel

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.

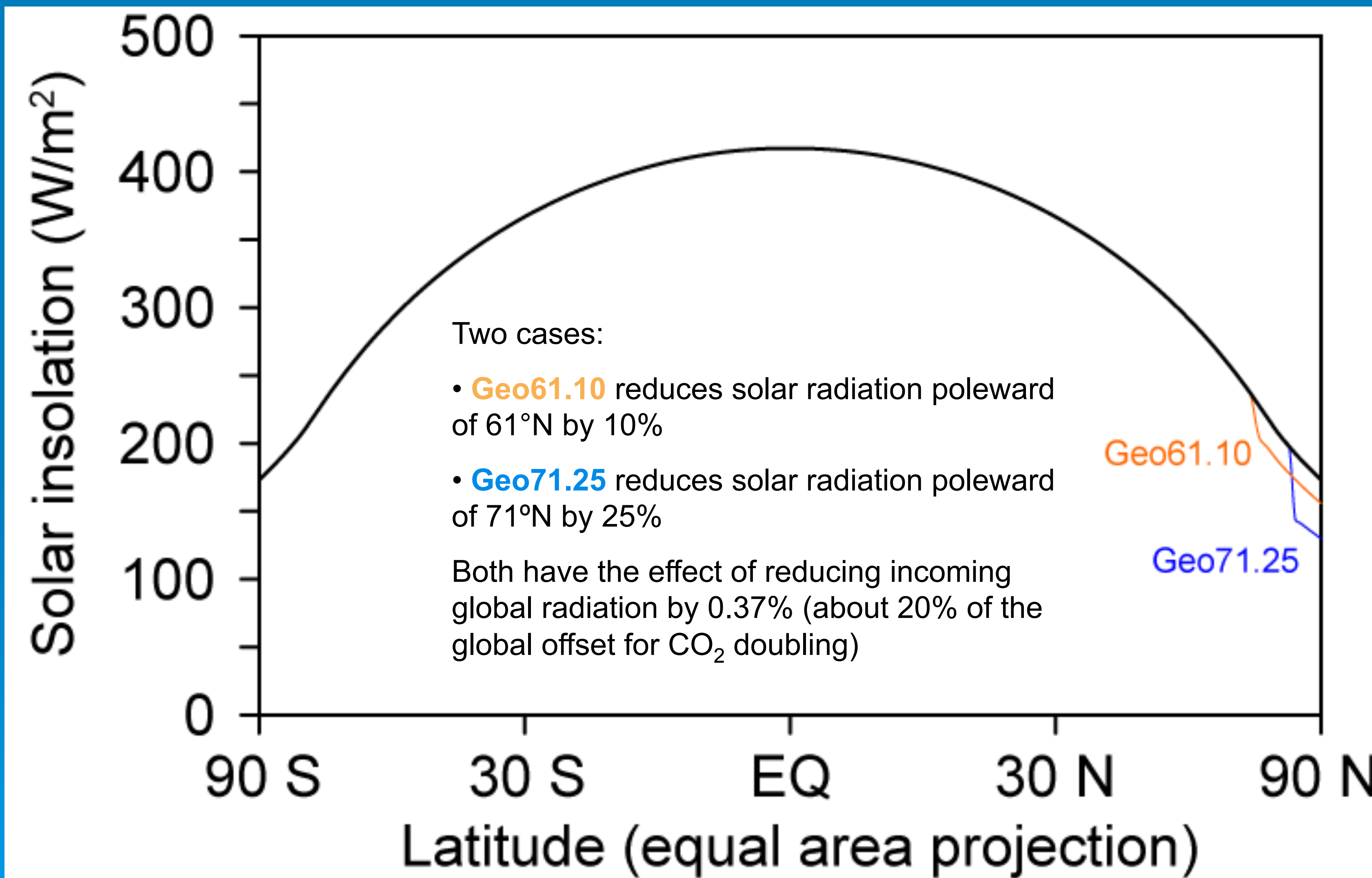
Until Arctic sea ice 1-2 meters thick insulates the air from the ocean, really cold winter air masses cannot form and warm, moist air pushes north into the US; the resulting clash can yield violent weather



Reversing Arctic warming might be possible, with many benefits (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

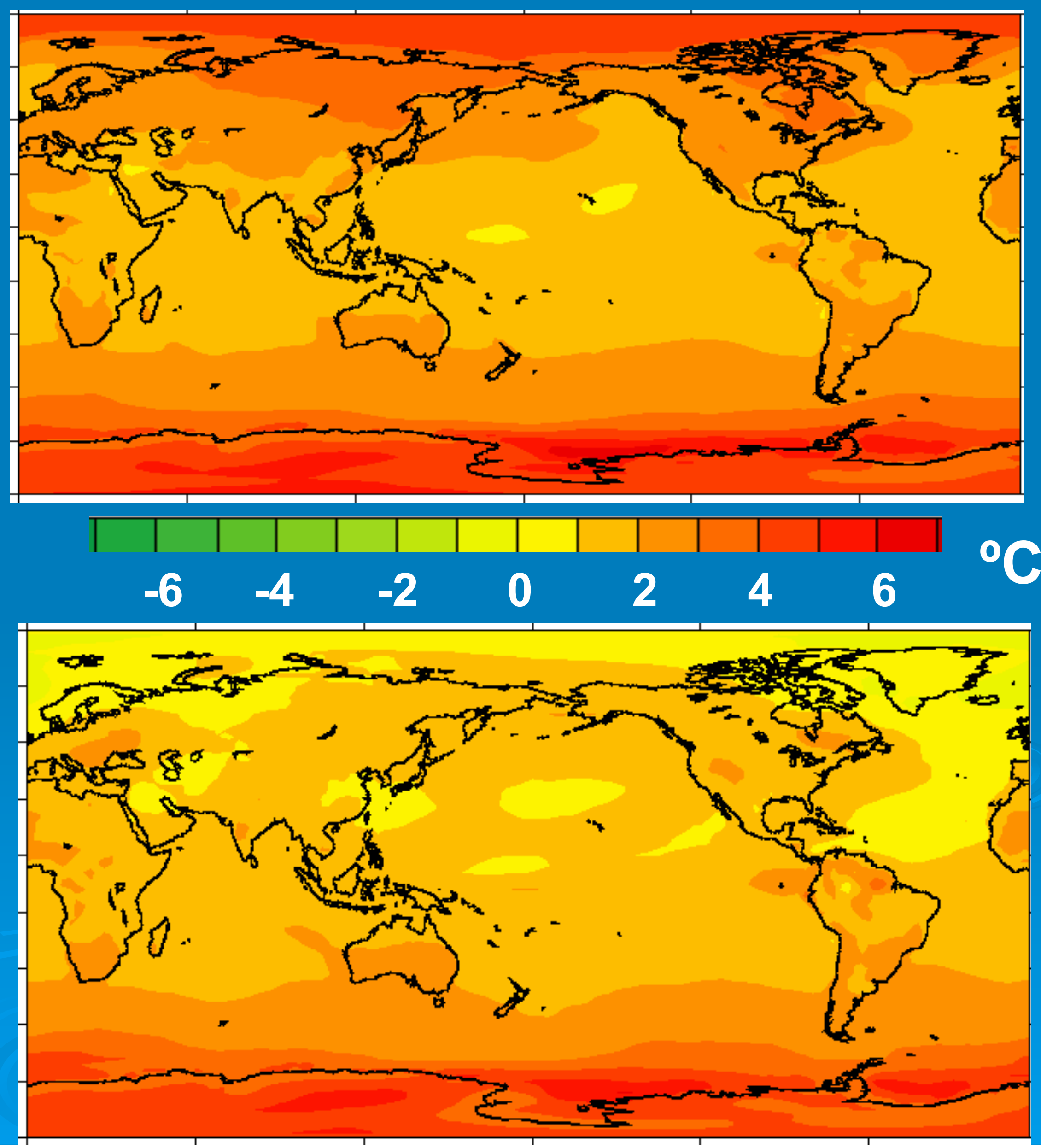
Reducing solar radiation only in the Arctic would avoid a number of adverse consequences of global Solar Radiation Management



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

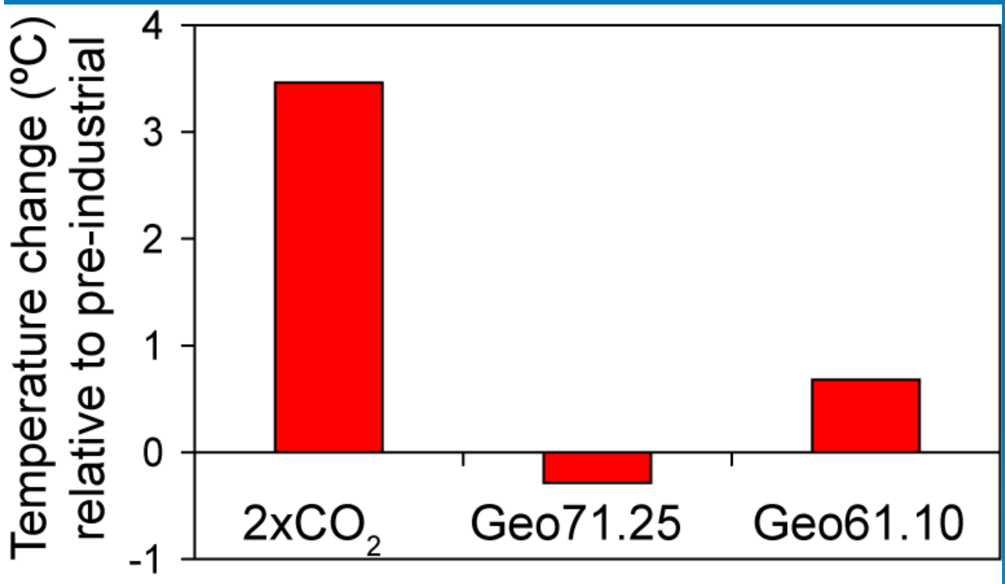
560 ppm CO_2, normal solar radiation

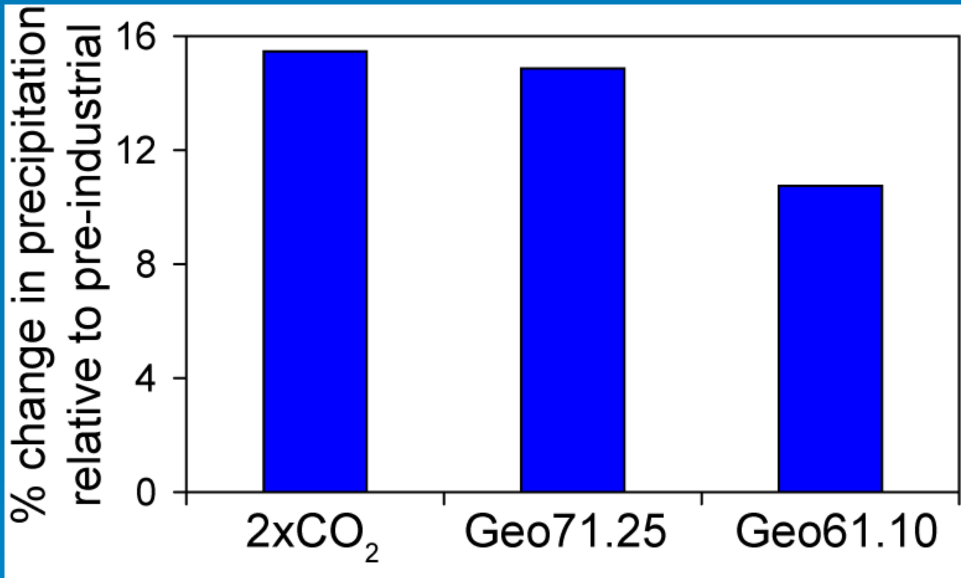
560 ppm CO_2, 10% solar reduction north of 61ºN



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:

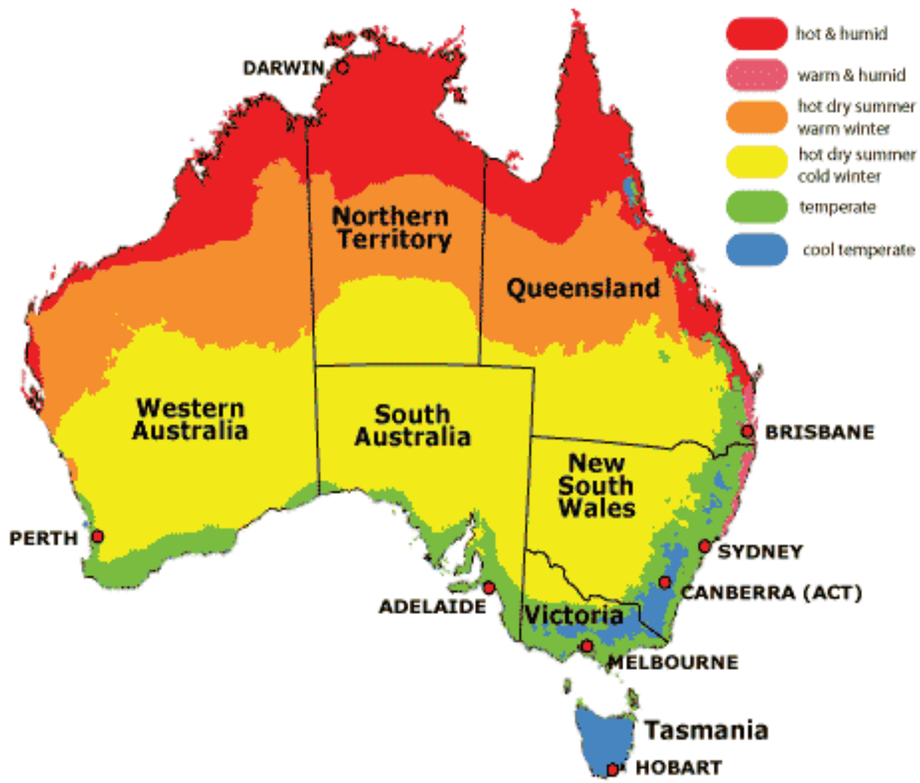
- Ocean temperatures are increasing in the areas where storms intensify:
  - The warming adds energy to each passing storm
  - Waters remain warm enough to power later storms in season
- A larger fraction of storms is in the most intense categories
- Integrated energy dissipation per storm is increasing
- 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

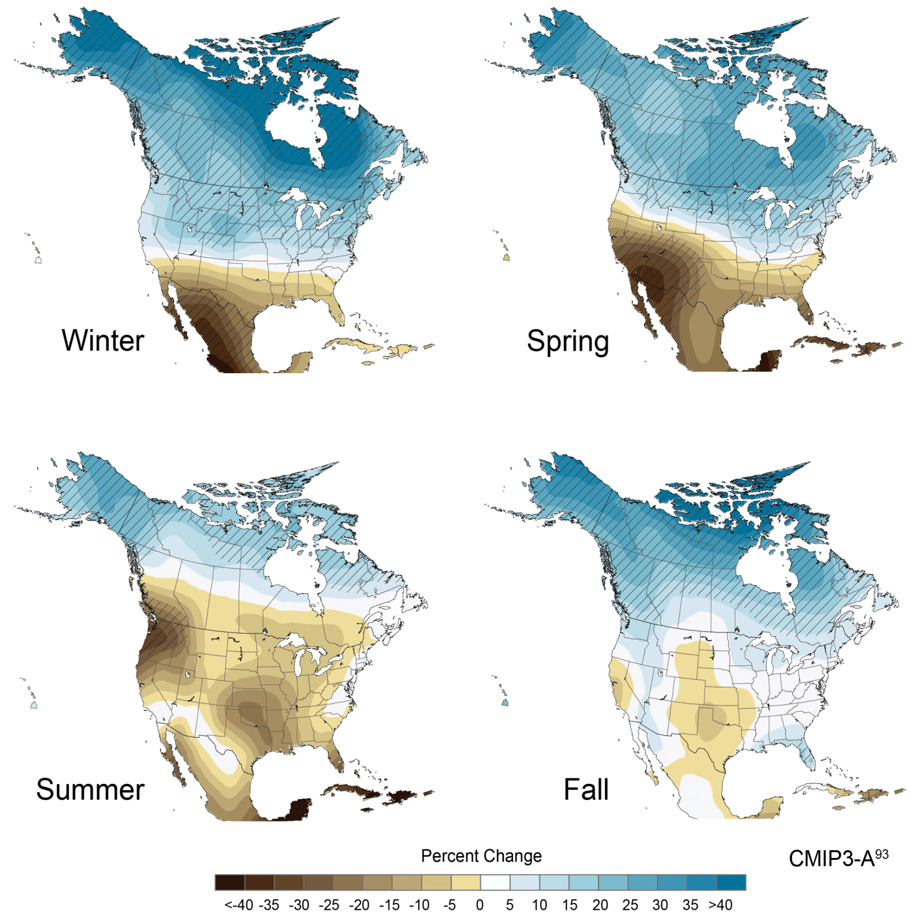
- Individual storms likely have too much energy to modify over a few days in a confident way (but perhaps not)
- Spreading energy limitation over time could reduce likelihood of storm intensification:
  - Increase cloud albedo by aerosol injection (cloudy sky)
  - Increase surface albedo or reduce the 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



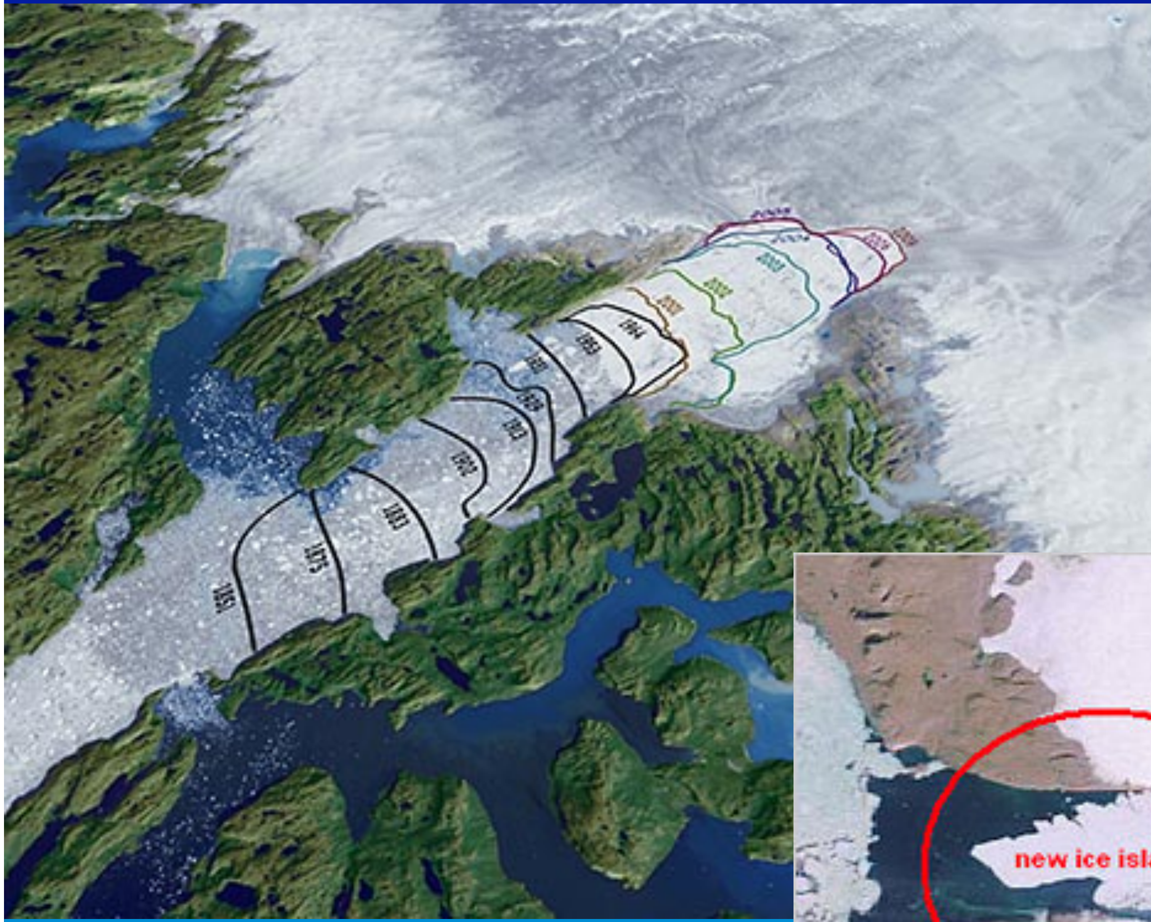
Projected change in precipitation by 2080-90s compared to present



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



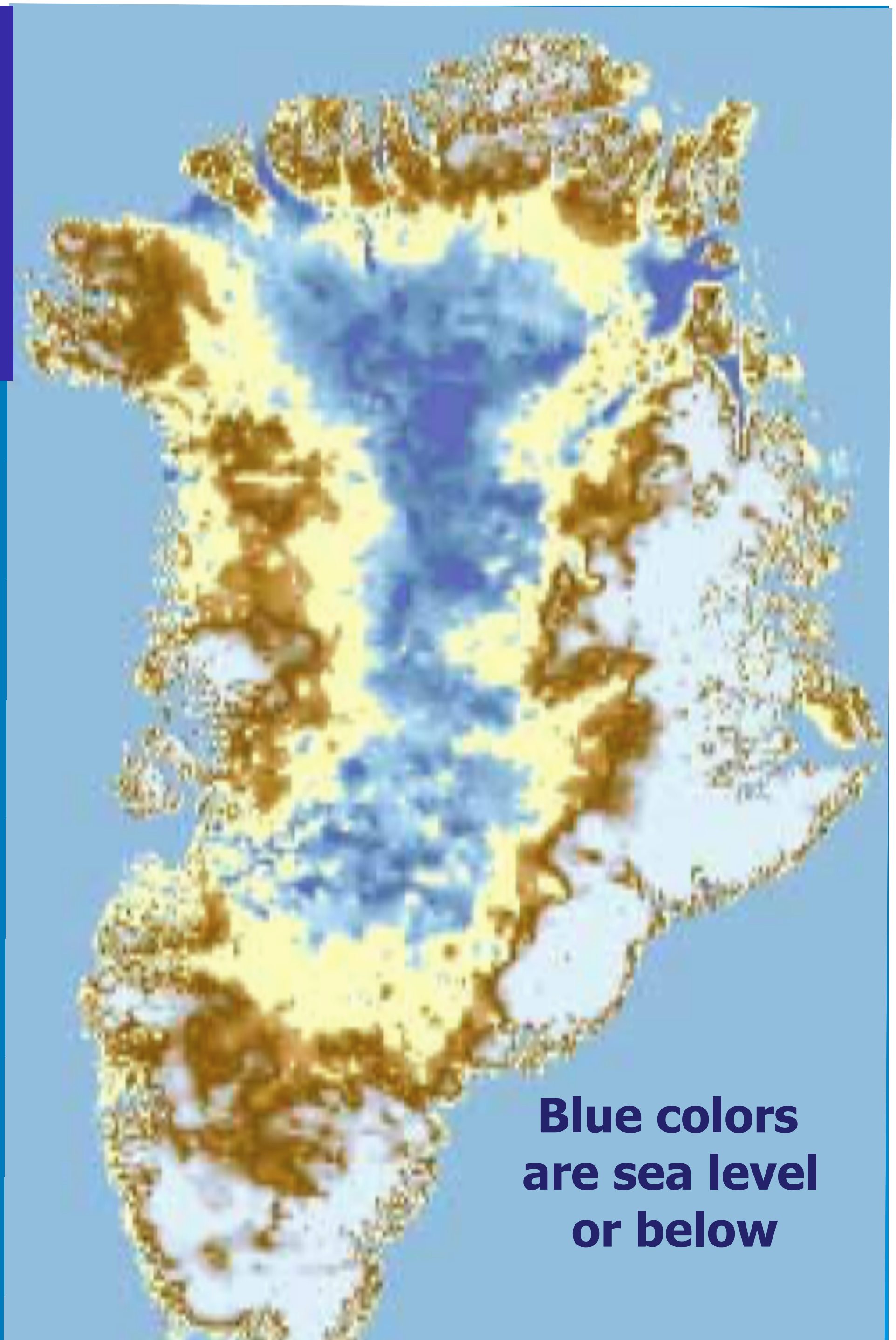
Possible approaches:

- 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

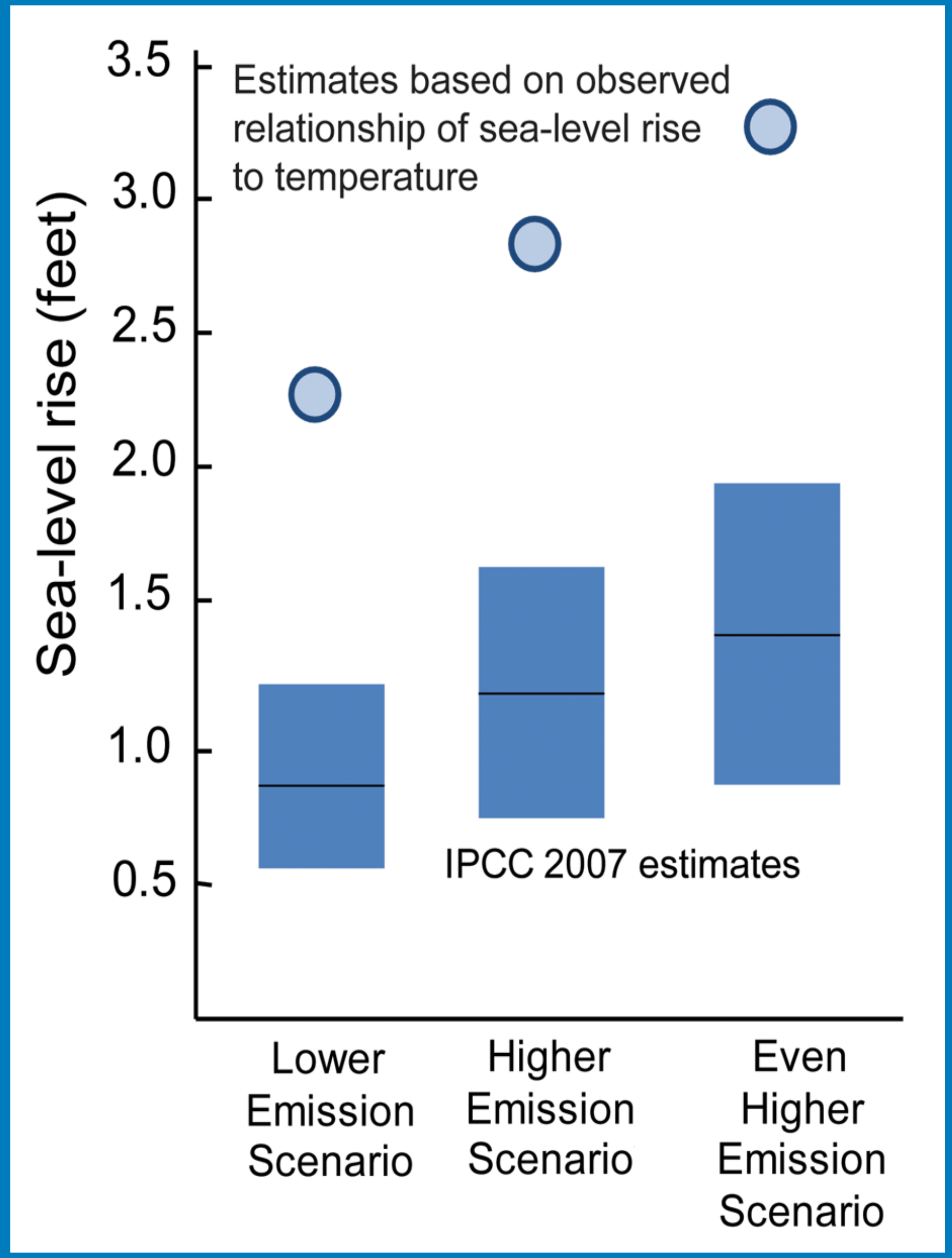


Source: Konrad Steffen, NSIDC data

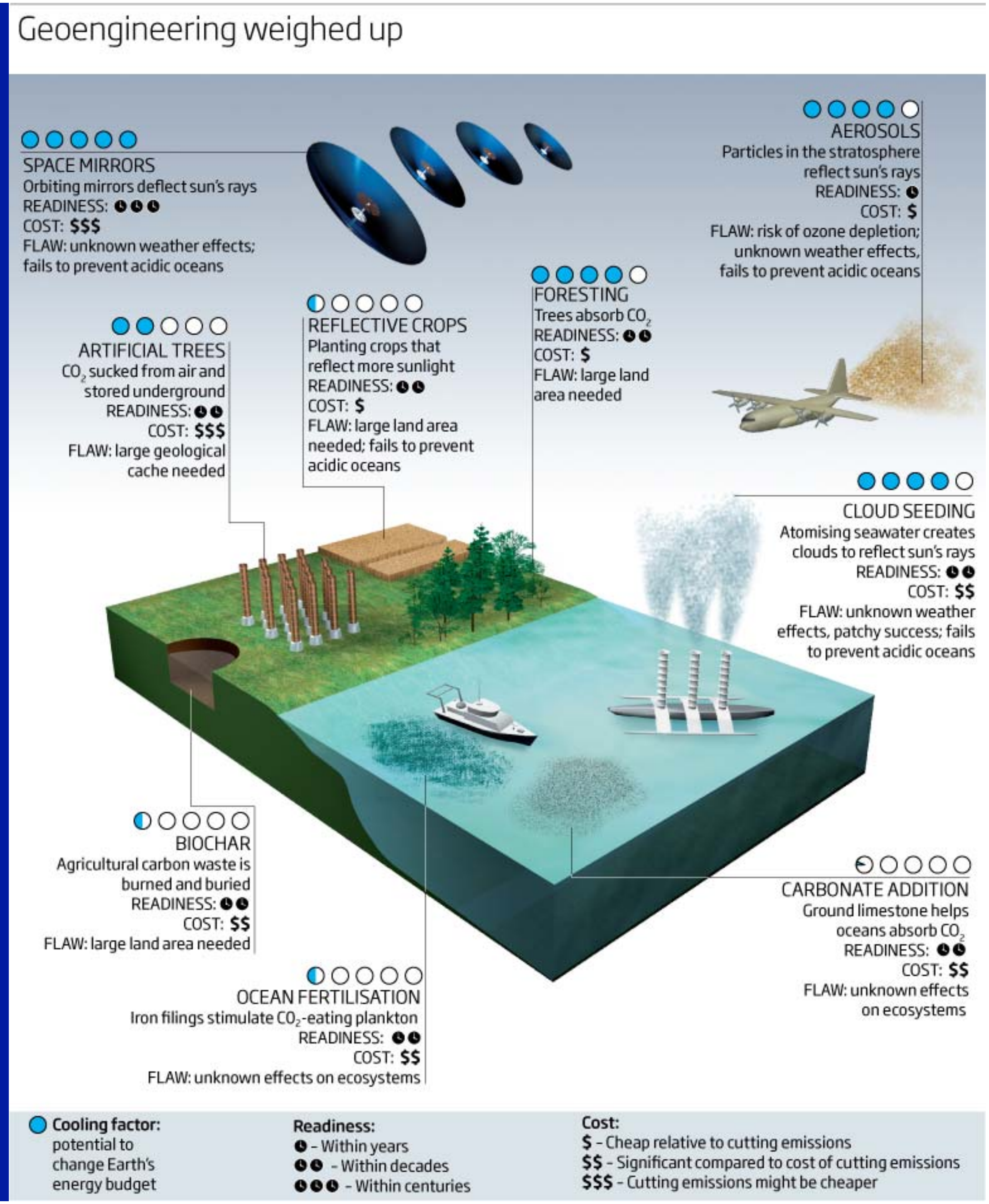
There is significant uncertainty in projections of future sea level rise—the IPCC 2007 estimates were at the lower end due to limited understanding about a key process

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

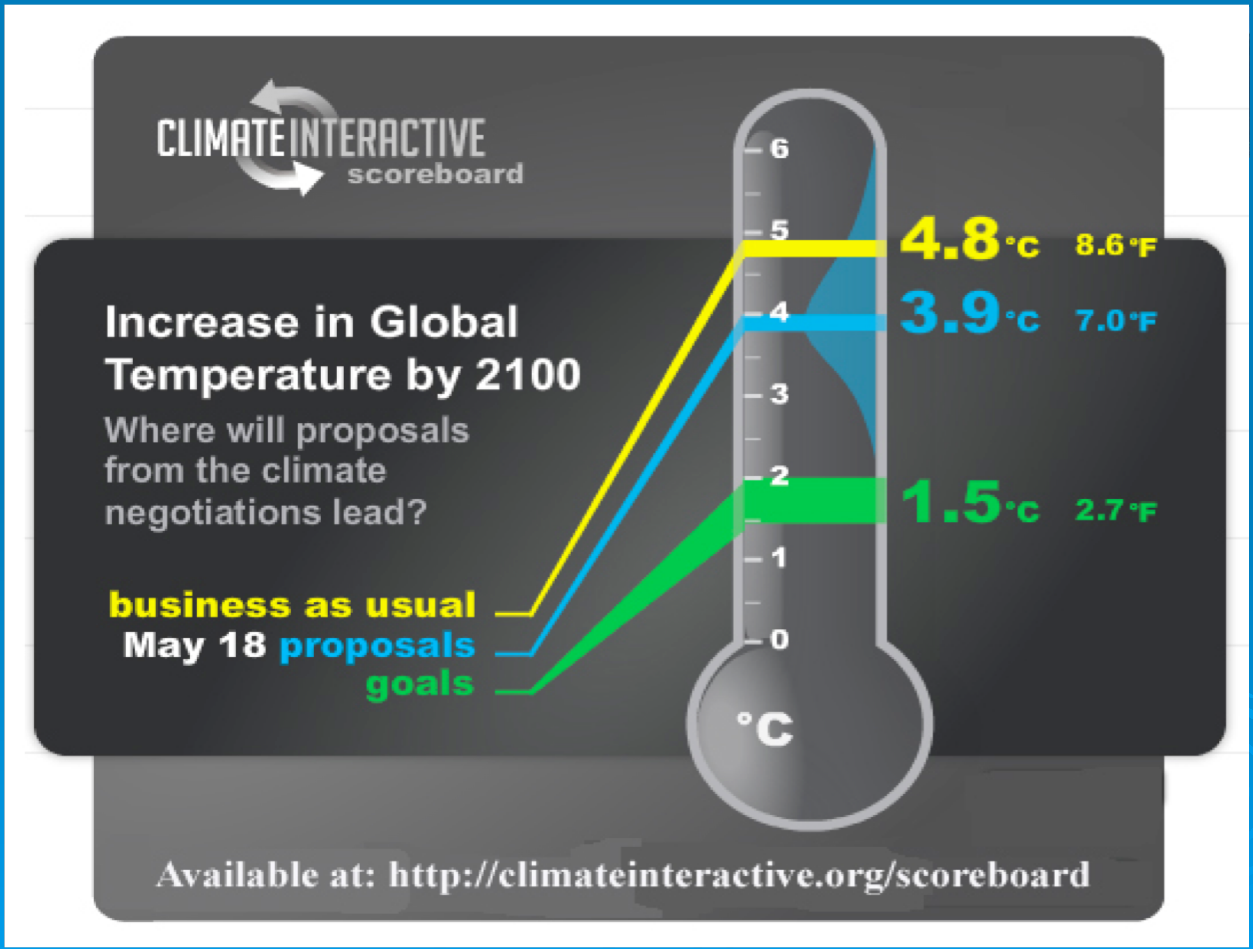
Projected Sea-Level Rise by 2100



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



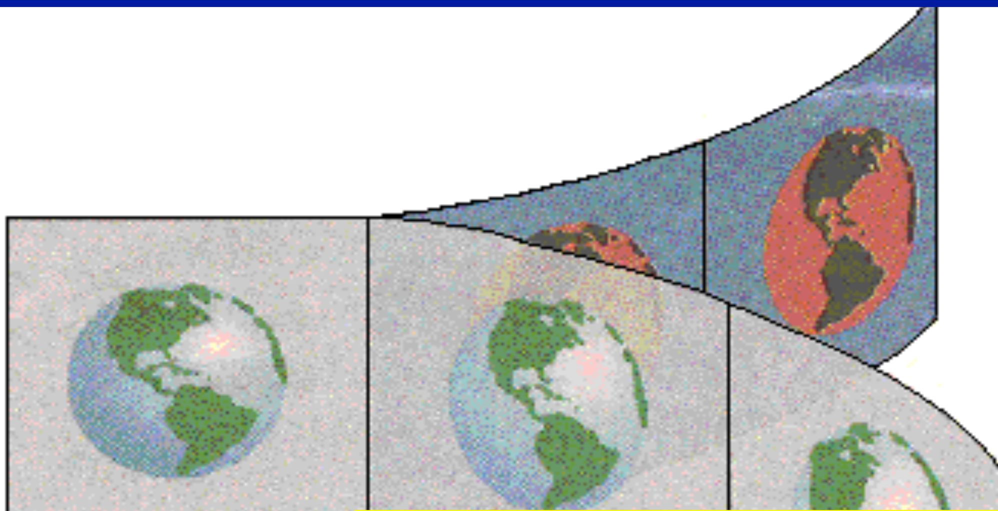
Climate engineering may be able to limit the worst impacts, BUT, there is no such thing as a "free lunch"

- **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 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

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
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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].