Finding a Path to Stopping and then Reversing Climate Change

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Society for Conservation Biology

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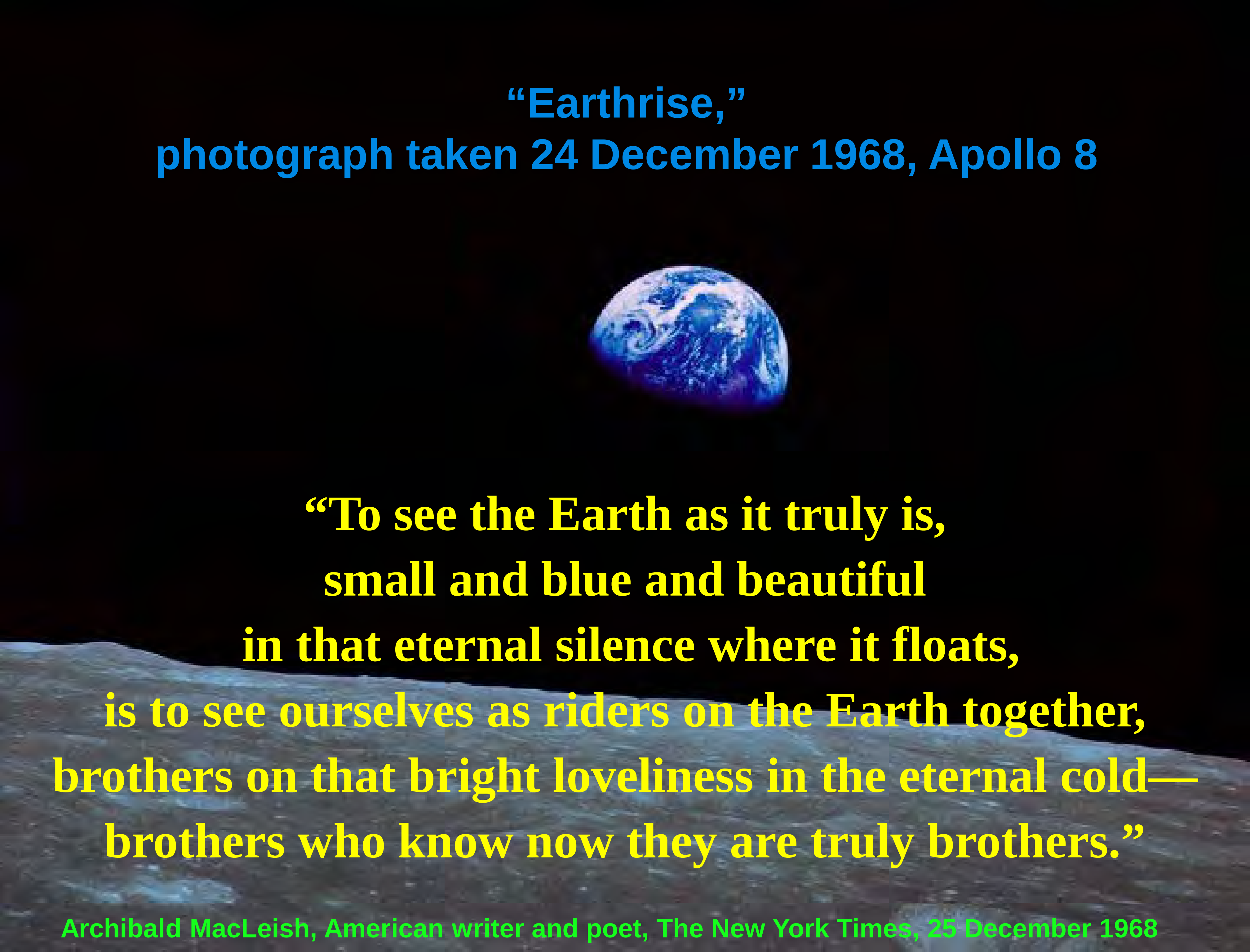
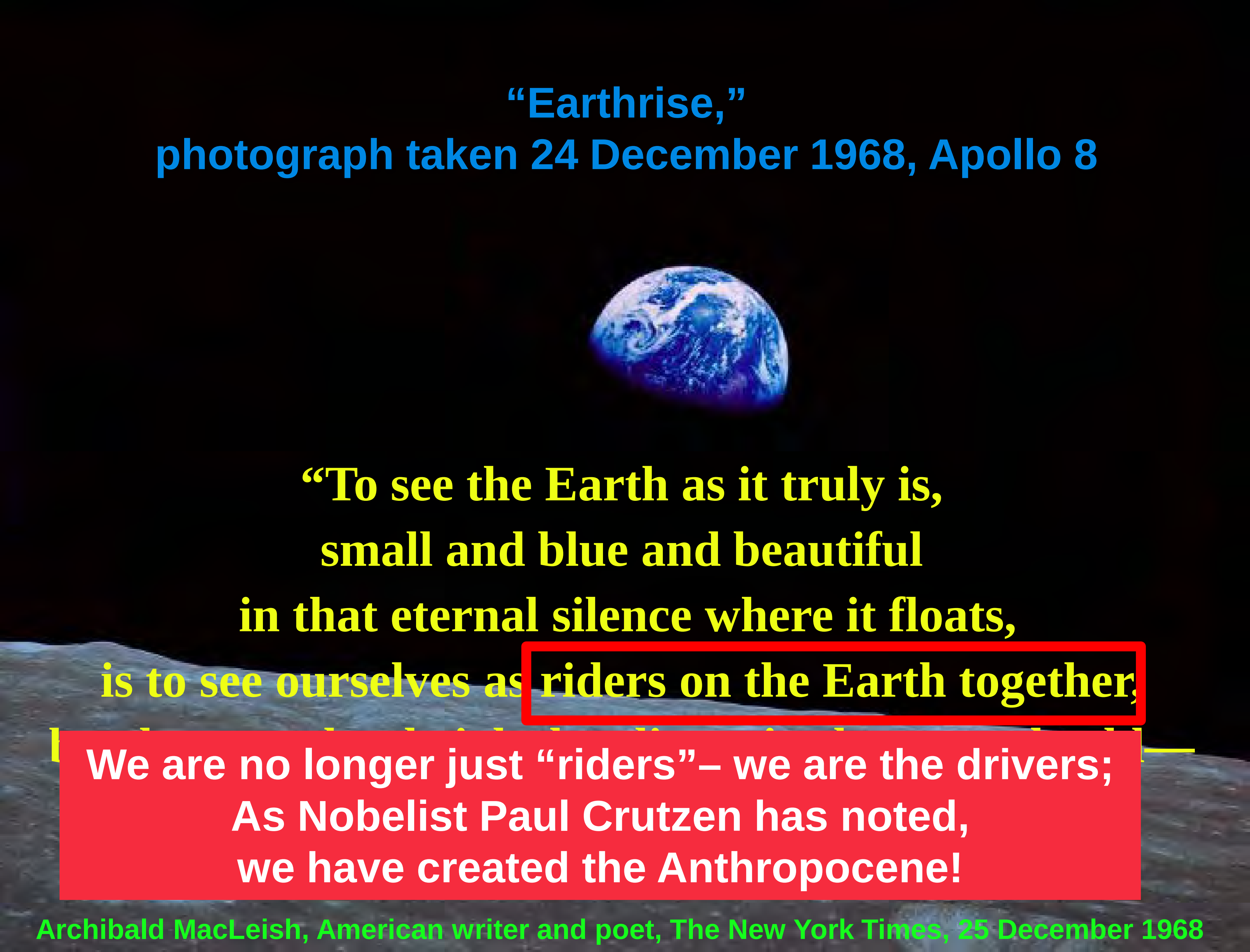
“Earthrise,”
photograph taken 24 December 1968, Apollo 8



“To see the Earth as it truly is,
small and blue and beautiful
in that eternal silence where it floats,
is to see ourselves as riders on the Earth together,
brothers on that bright loveliness in the eternal cold—
brothers who know now they are truly brothers.”

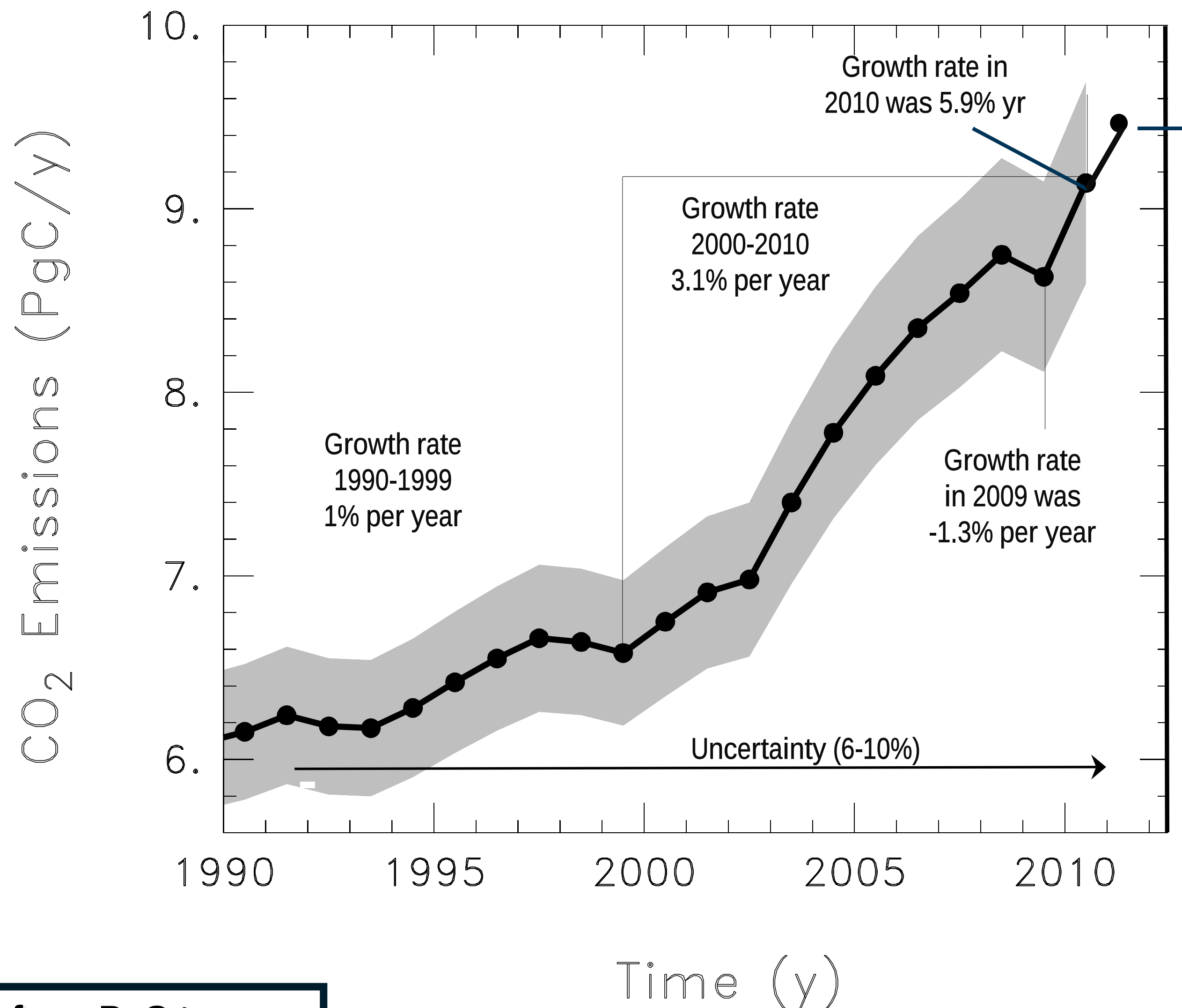
Archibald MacLeish, American writer and poet, The New York Times, 25 December 1968


"Earthrise,"
photograph taken 24 December 1968, Apollo 8
"To see the Earth as it truly is,
small and blue and beautiful
in that eternal silence where it floats,
is to see ourselves as riders on the Earth together,
We are no longer just "riders"– we are the drivers;
As Nobelist Paul Crutzen has noted,
we have created the Anthropocene!
Archibald MacLeish, American writer and poet, The New York Times, 25 December 1968

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 lead to ‘dangerous’ impacts**
  - **Sea level rise (glacier and ice sheet loss)**
  - **Ocean acidification**

Emissions of CO_2 from fossil fuel combustion and cement have been rising as rapidly as the highest IPCC scenario proposed in 2000

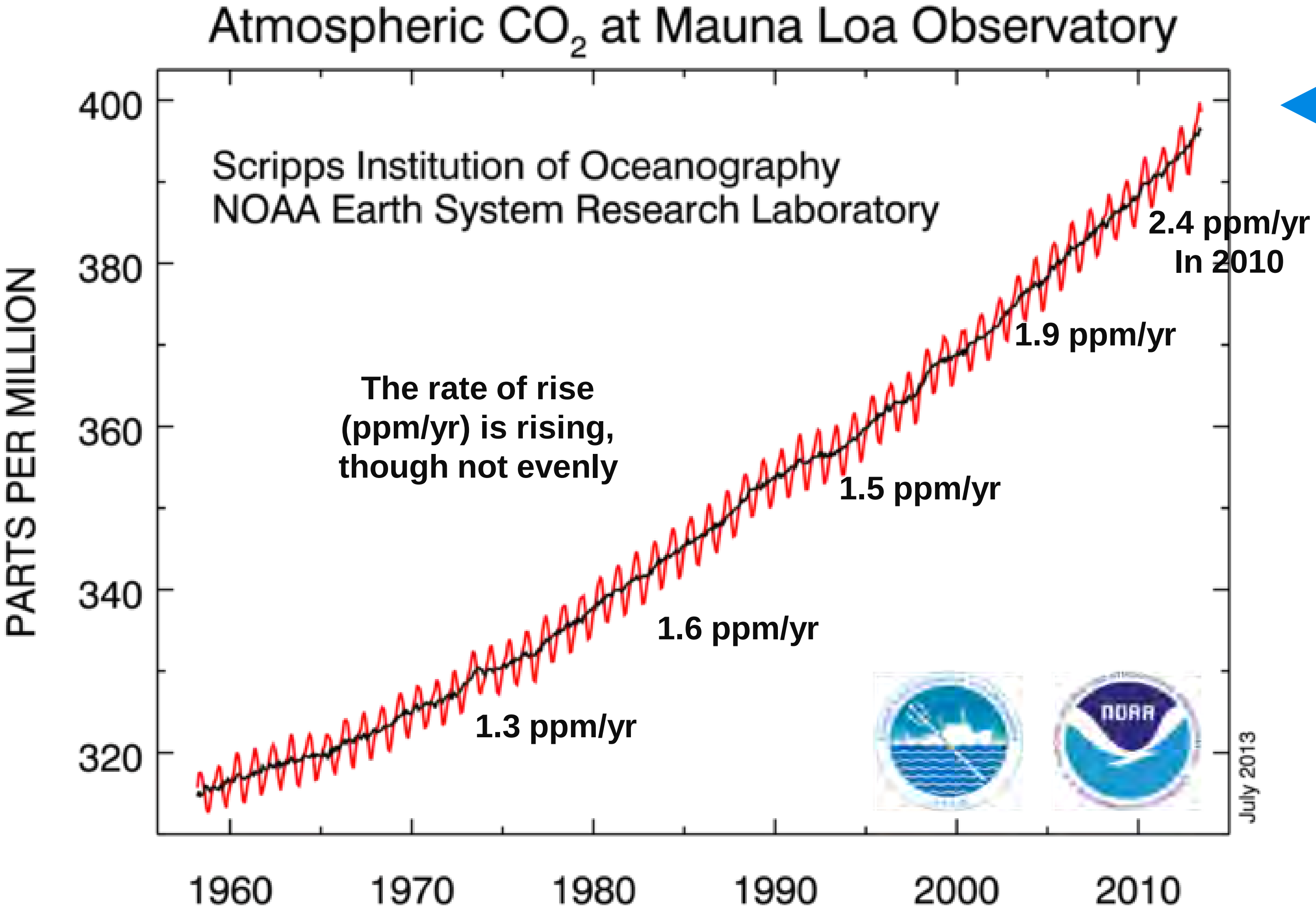


Growth rate in 2011 was 3.2% per year—totaling now about 38.2 billion tons of CO_2 per year

To convert from PgC 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; IEA 2011

Increasing emissions are causing an increase in the rate of increase of the atmospheric CO_2 concentration



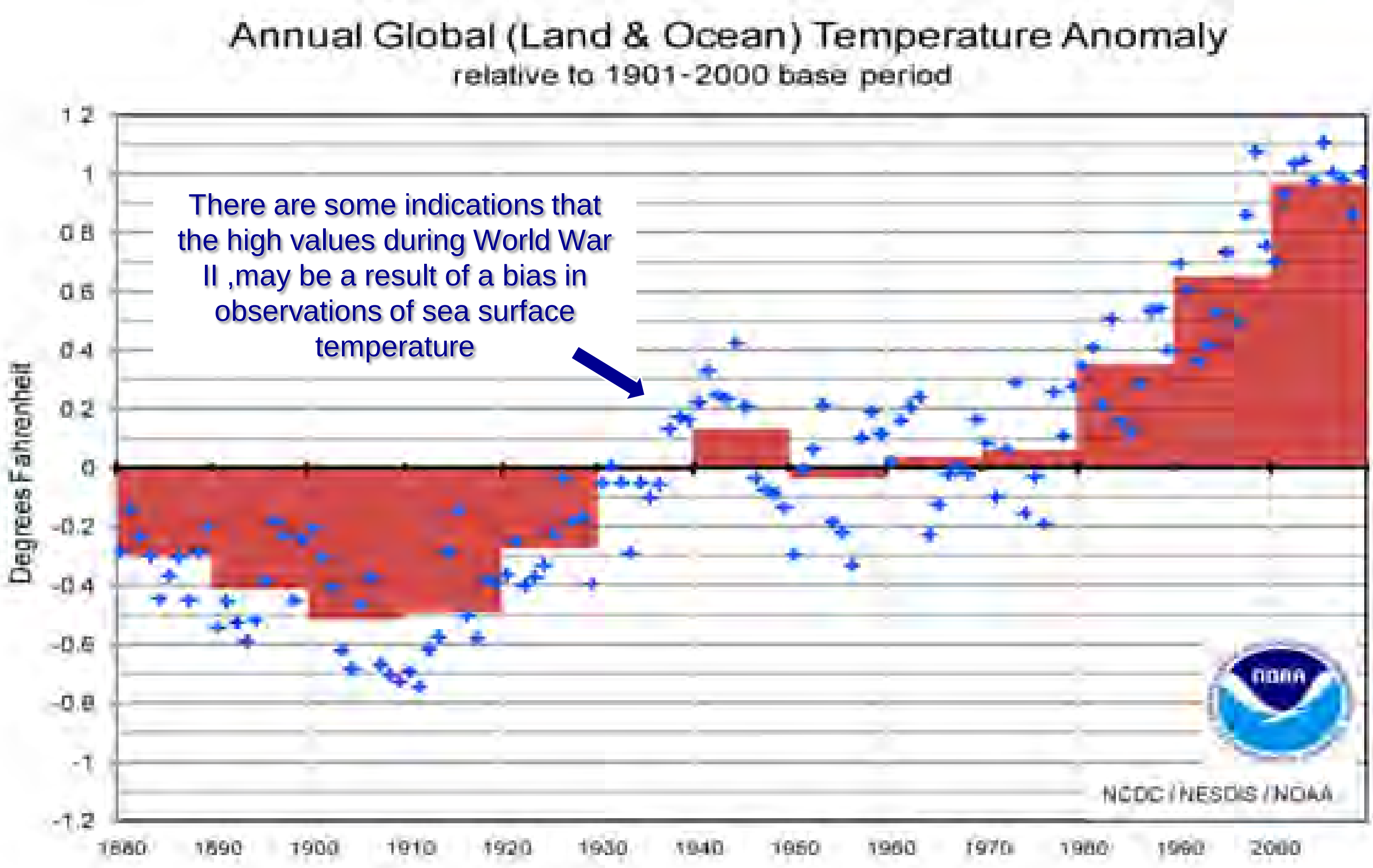
The present concentration is nearing 400 ppm, ~27% above the value of 315 ppm in 1957 (when C. David Keeling began very careful measurements) and ~43% above the preindustrial concentration

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

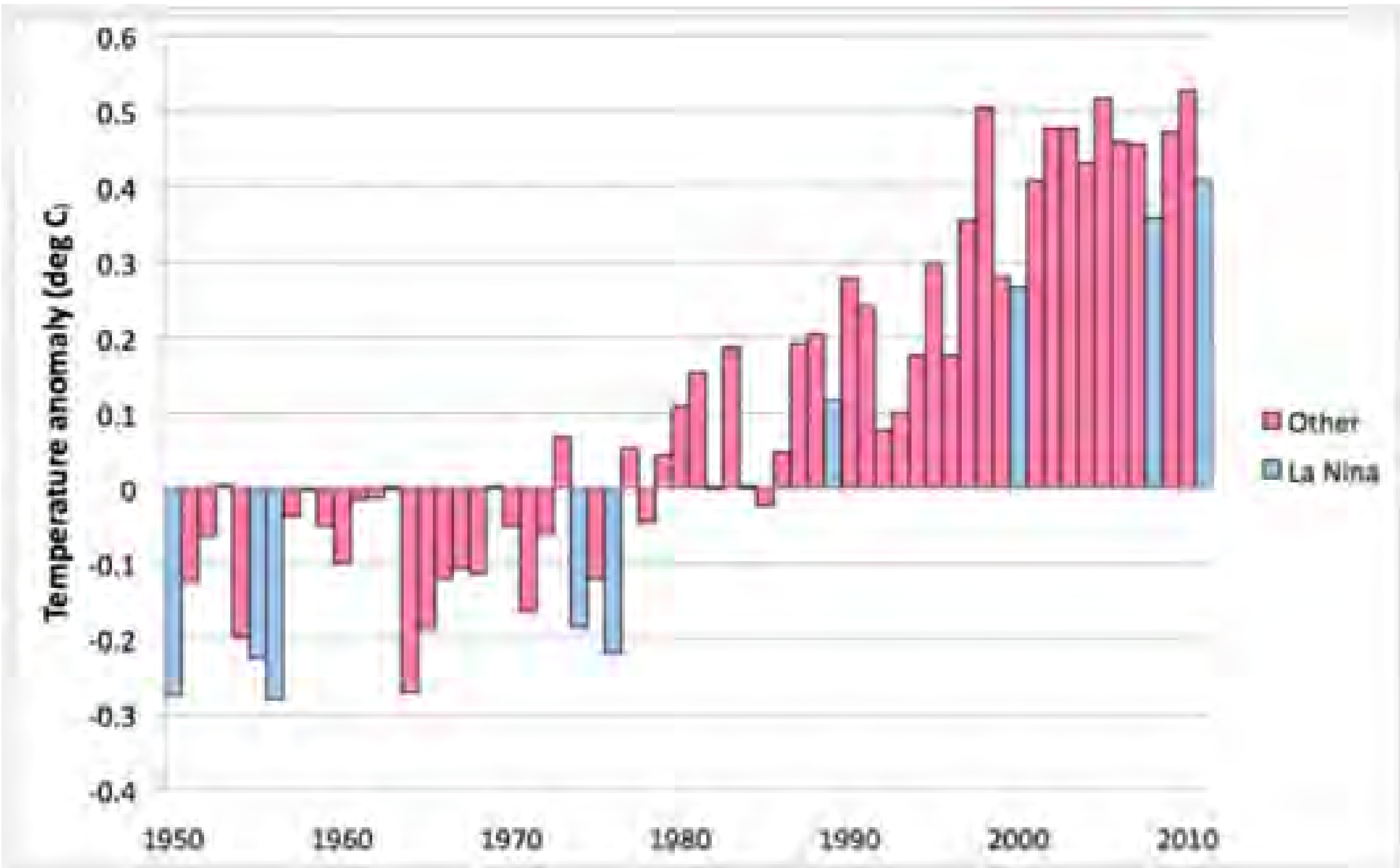
While year-to-year conditions vary, the world has experienced relatively steady warming over the last several decades



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

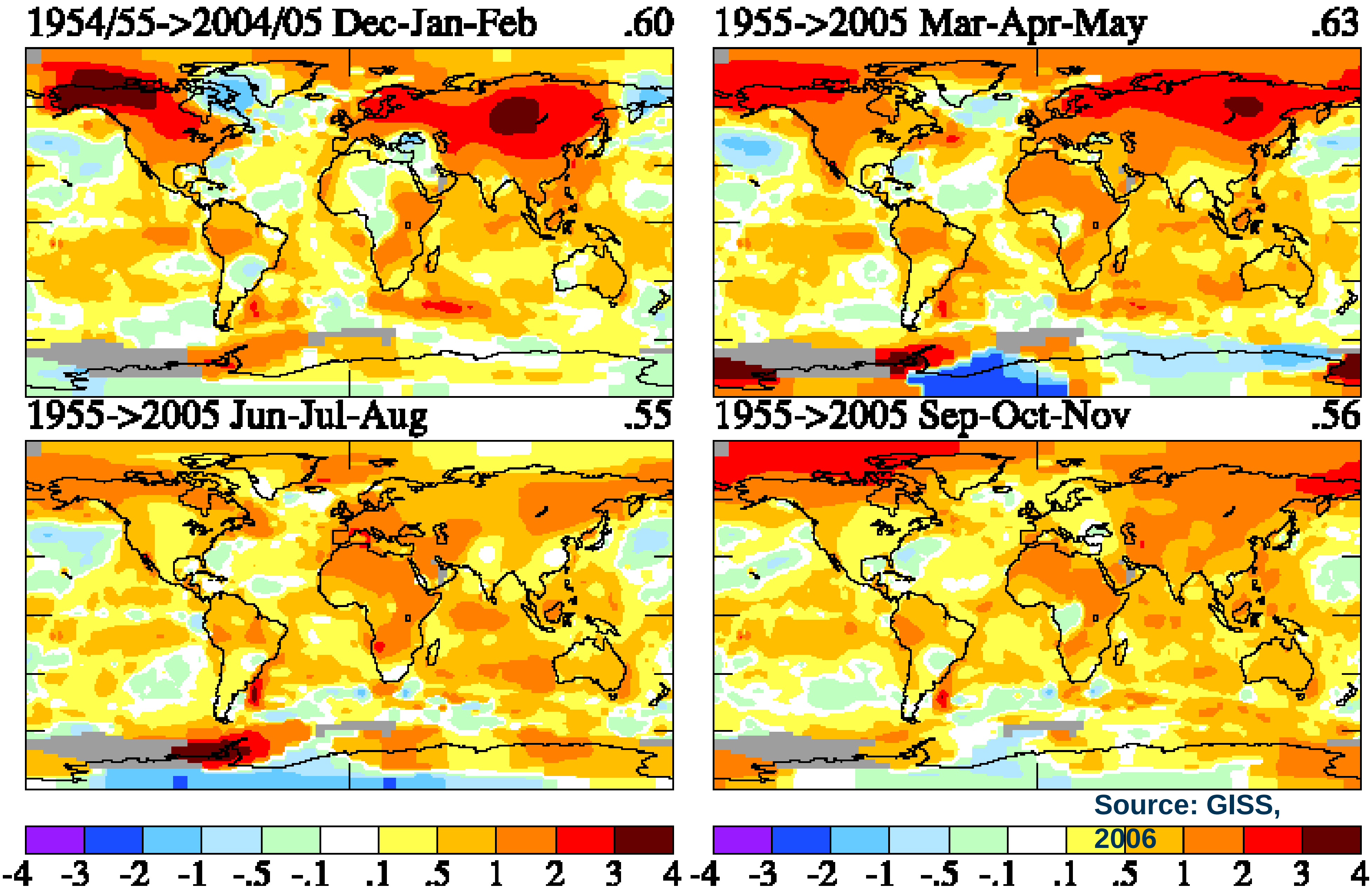
Year-to-year variations can occur due to the ENSO cycle, and apparent pauses can occur due to ocean heat uptake or other natural variations and the effects of other forcings (e.g., sulfate aerosols, volcanic eruptions)

Even if the rate of warming has slowed, the GHG forcing term is increasing and will show eventually



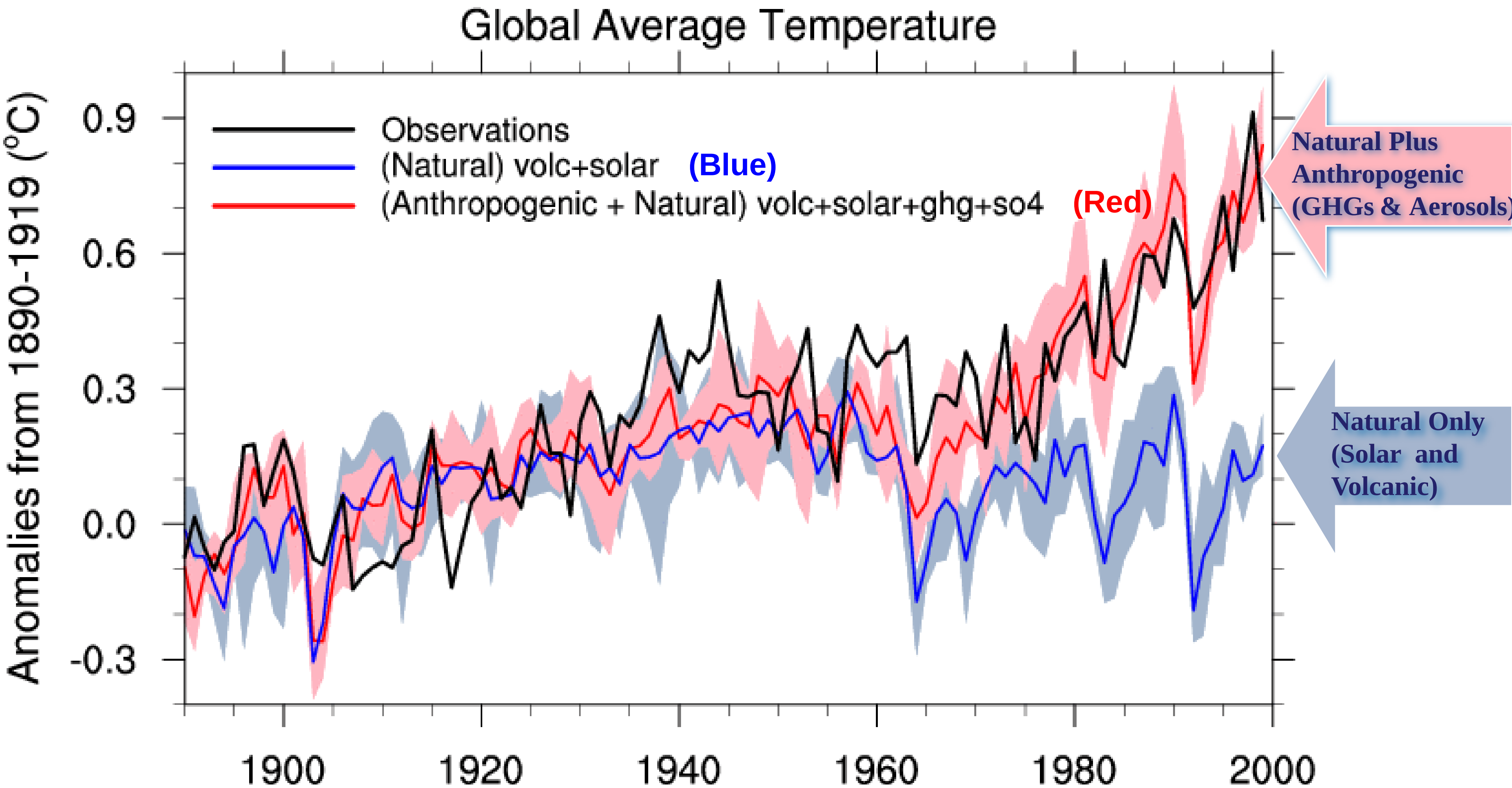
Source: http://mpe2013.org/images/climate-data-global-temp-anom/

Significant warming has been occurring over the past several decades, especially in high latitudes



Source: GISS, 2006

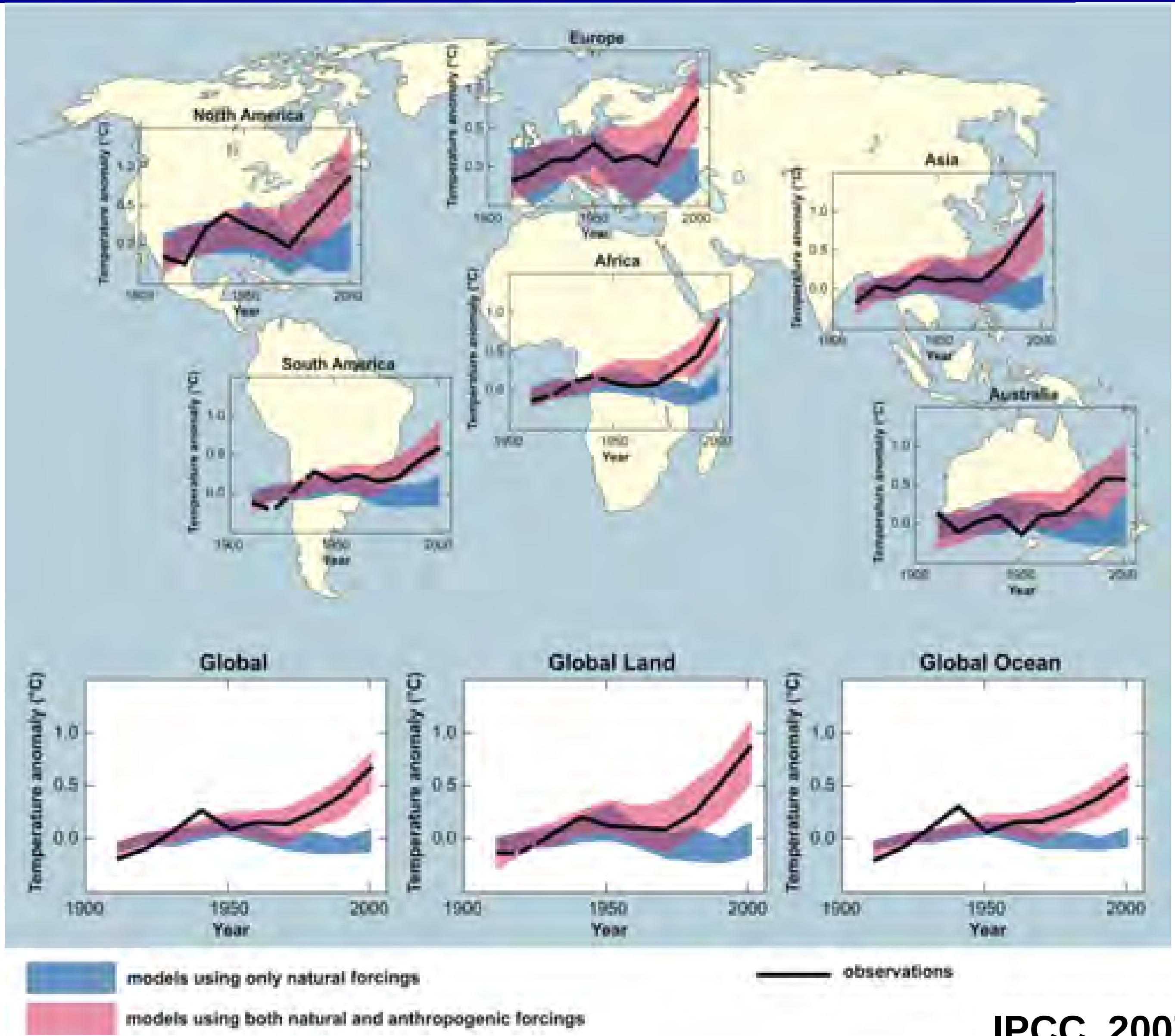
When the effects of both natural and human forcings are included, the models reasonably represent climate change over the last 100 years



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)

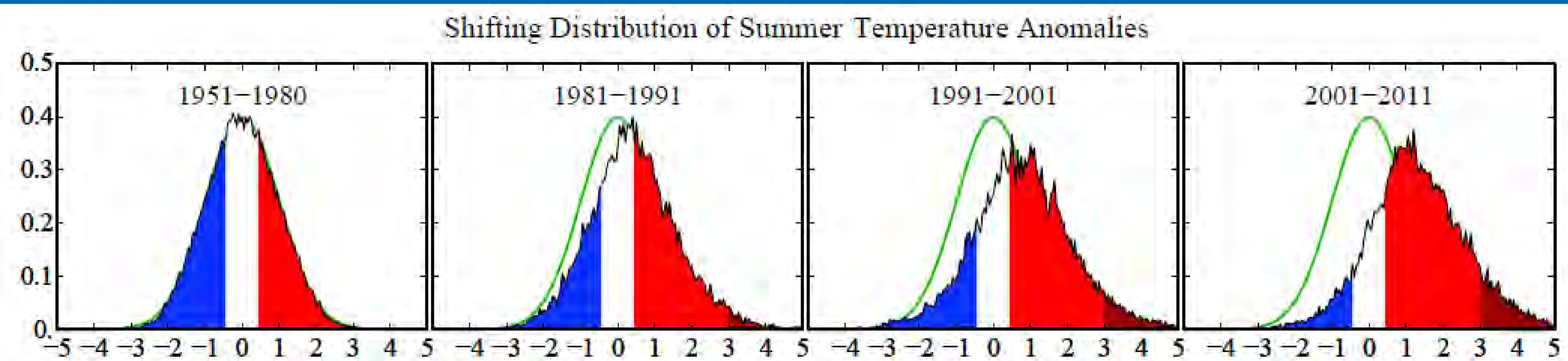
The model results appear as a band because (1) the results are for multiple models, and (2) the model simulations account for the natural variability of the climate, unlike the observations which, although averaged over a decade, represent a single pass through climatic history. Observations also include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



IPCC, 2007

Climate change is "loading the climate dice" [per Jim Hansen] and sharply increasing the likelihood of unusual and extreme weather events

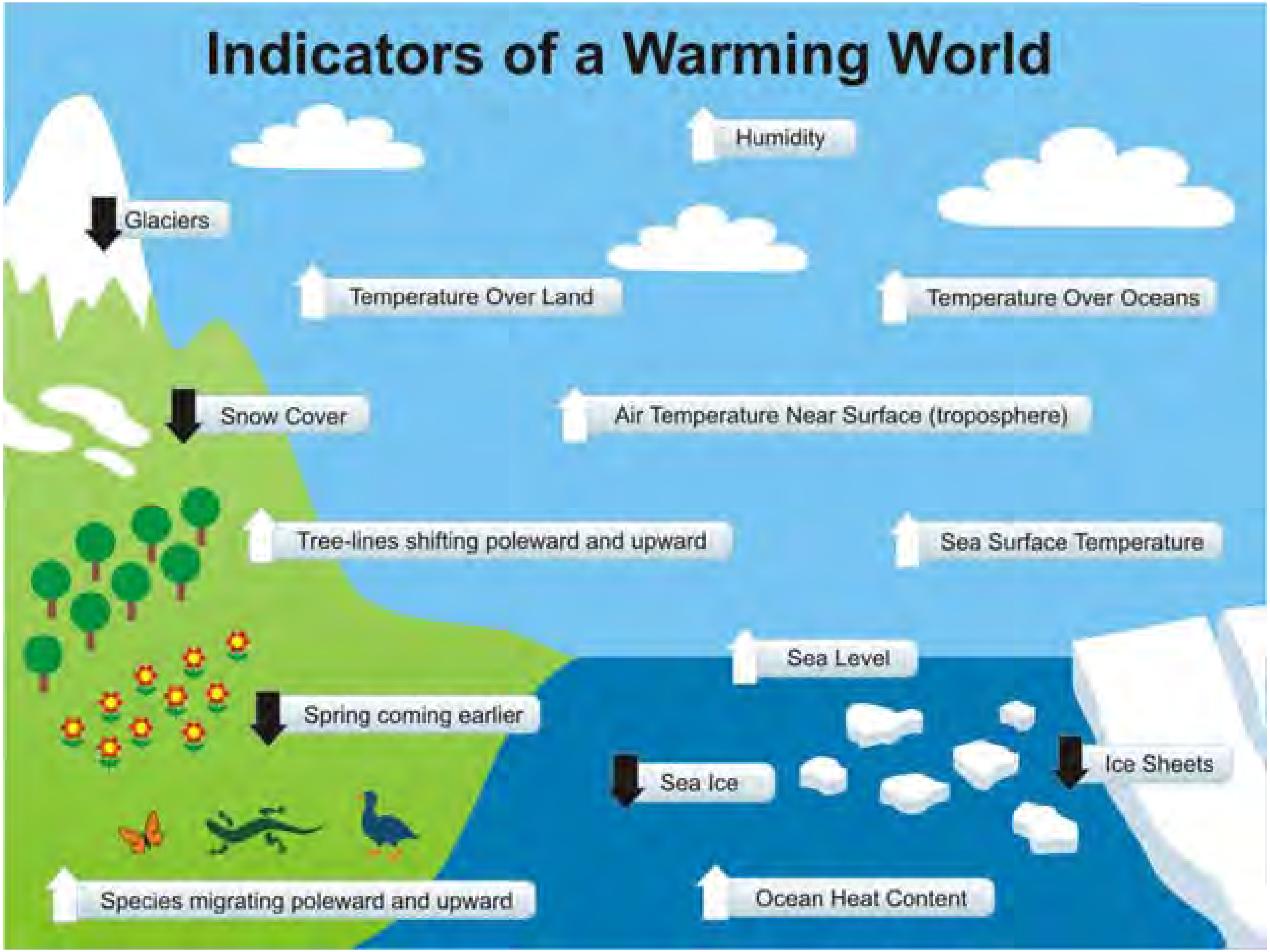
[extreme summer heat now covers 10% of land area, up from 0.2%]



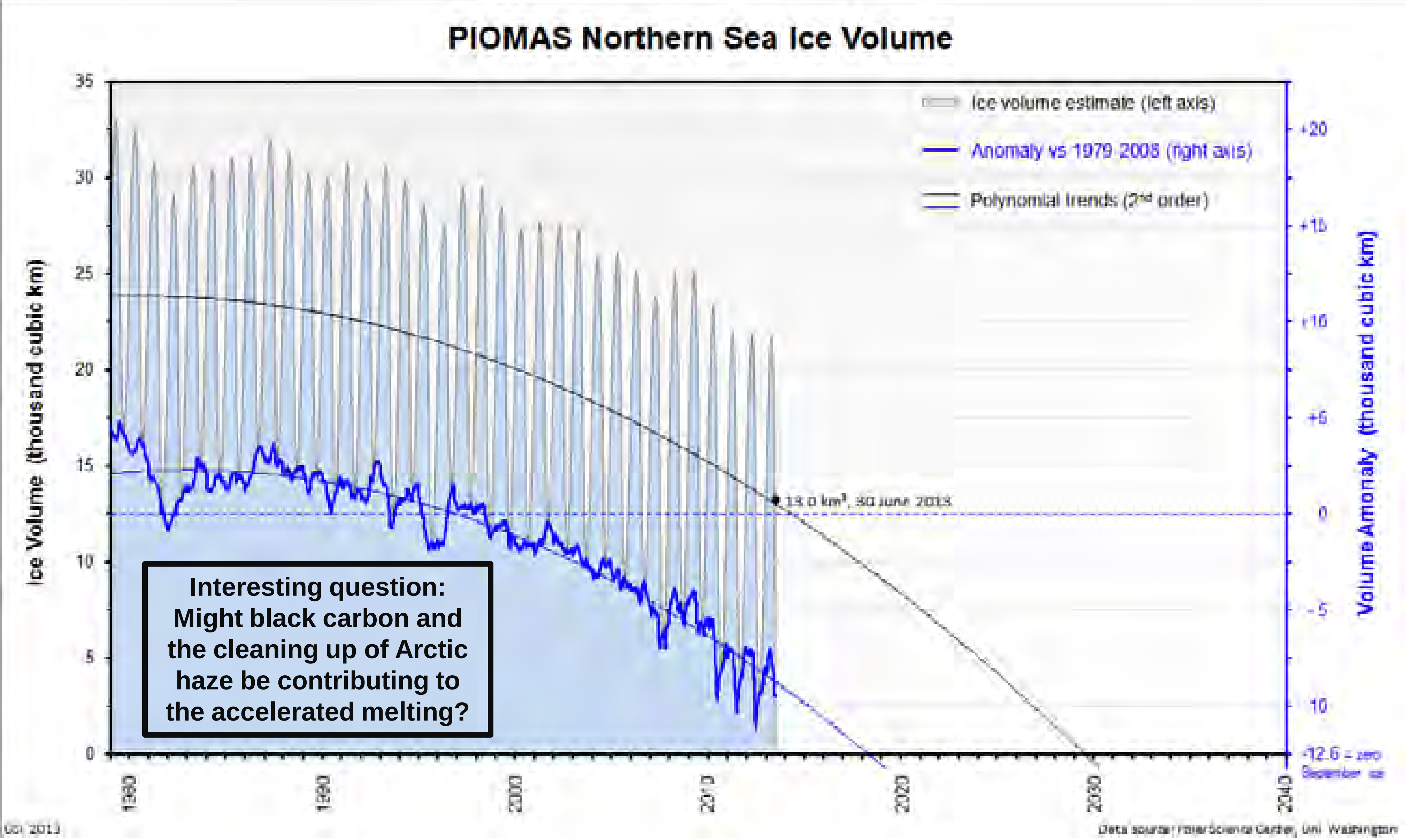
The frequency of occurrence (vertical axis) of local June-July-August temperature anomalies (relative to 1951-1980 mean) for Northern Hemisphere land areas is plotted versus the magnitude of the anomaly (horizontal axis, in units of local standard deviation). Temperature anomalies in the baseline period 1951-1980 closely match the normal distribution ("bell curve", shown in green), which is used to define unusually cold (blue), typical (white) and hot (red) seasons, each with probability 33.3%. The distribution has shifted to the right as a result of the global warming over the past three decades, such that cool summers now cover only half of one side of a six-sided die, white covers one side, red covers four sides, and an extremely hot (red-brown) anomaly covers half of one side.

Source: Hansen, J., Sato, M., and Ruedy, R., Proc. Natl. Acad. Sci., 2012.

In addition to the observed global warming, a lot of other indicators make clear that the climate is changing in a manner consistent with a strong human influence

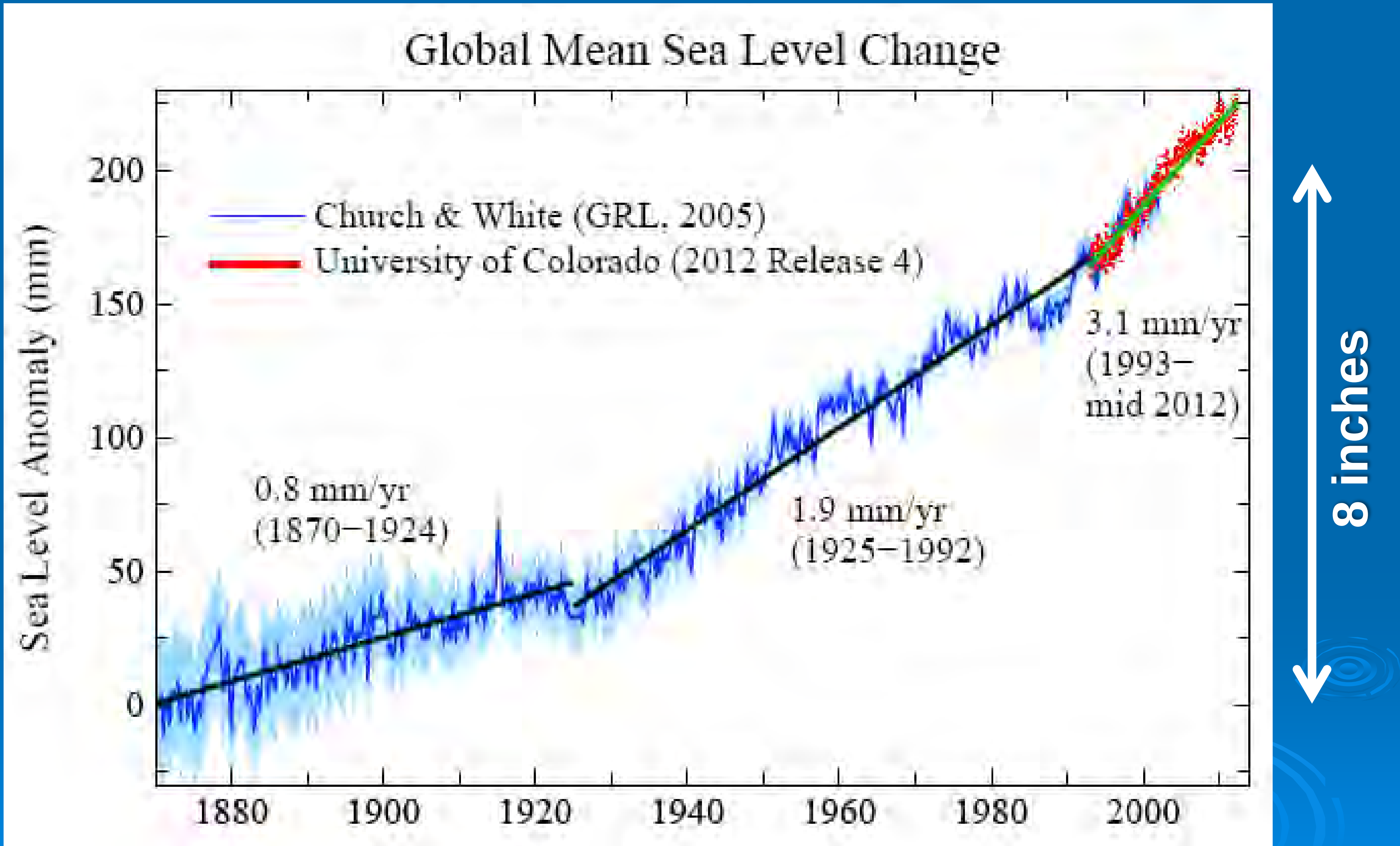


Arctic sea ice is proving to be particularly vulnerable, with both the area and the volume shrinking rapidly over the past few decades

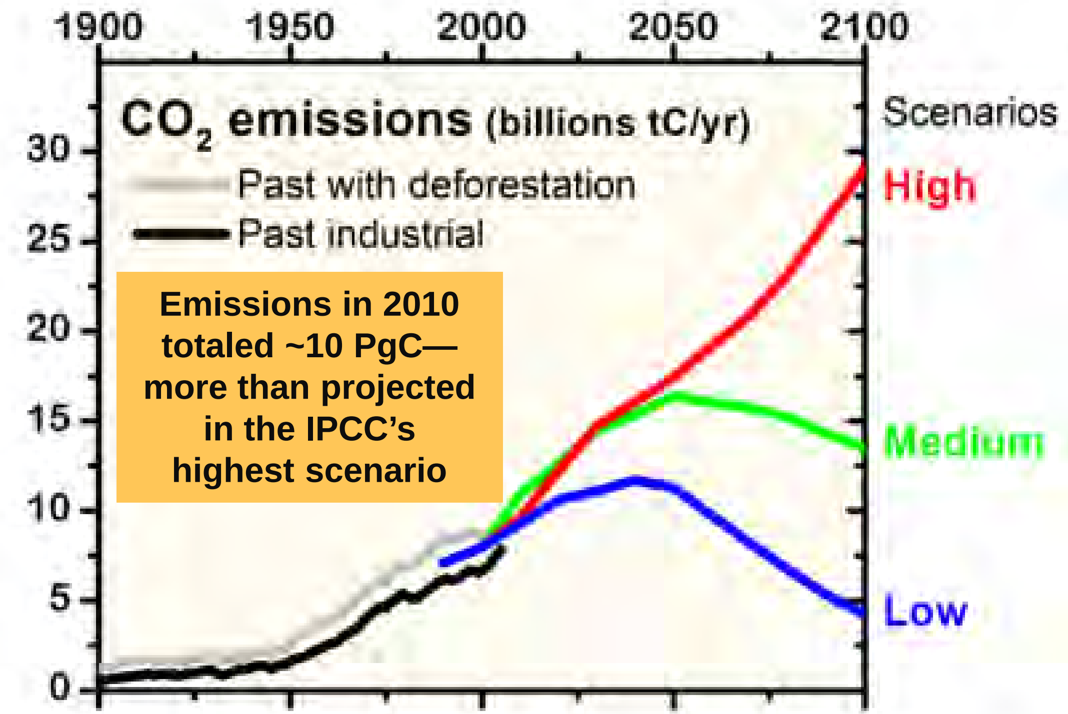


Interesting question: Might black carbon and the cleaning up of Arctic haze be contributing to the accelerated melting?

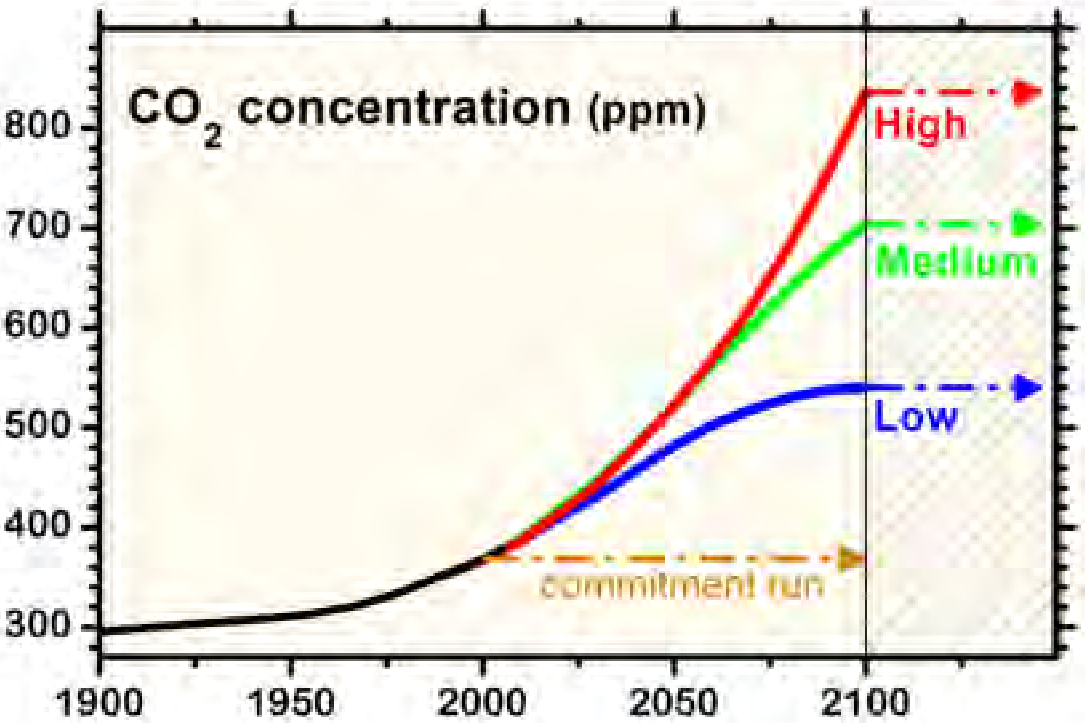
After relatively little change for several thousand years, global sea level has started to increase at an accelerating rate



Source of slide: modified from James Hansen
Blue: Sea level change from tide-gauge data ***(Church J.A. and White N.J., Geophys. Res. Lett. 2006; 33: L01602)***
Red: Univ. Colorado sea level analyses in satellite era ***(http://www.columbia.edu/~mhs119/SeaLevel/)*****.**

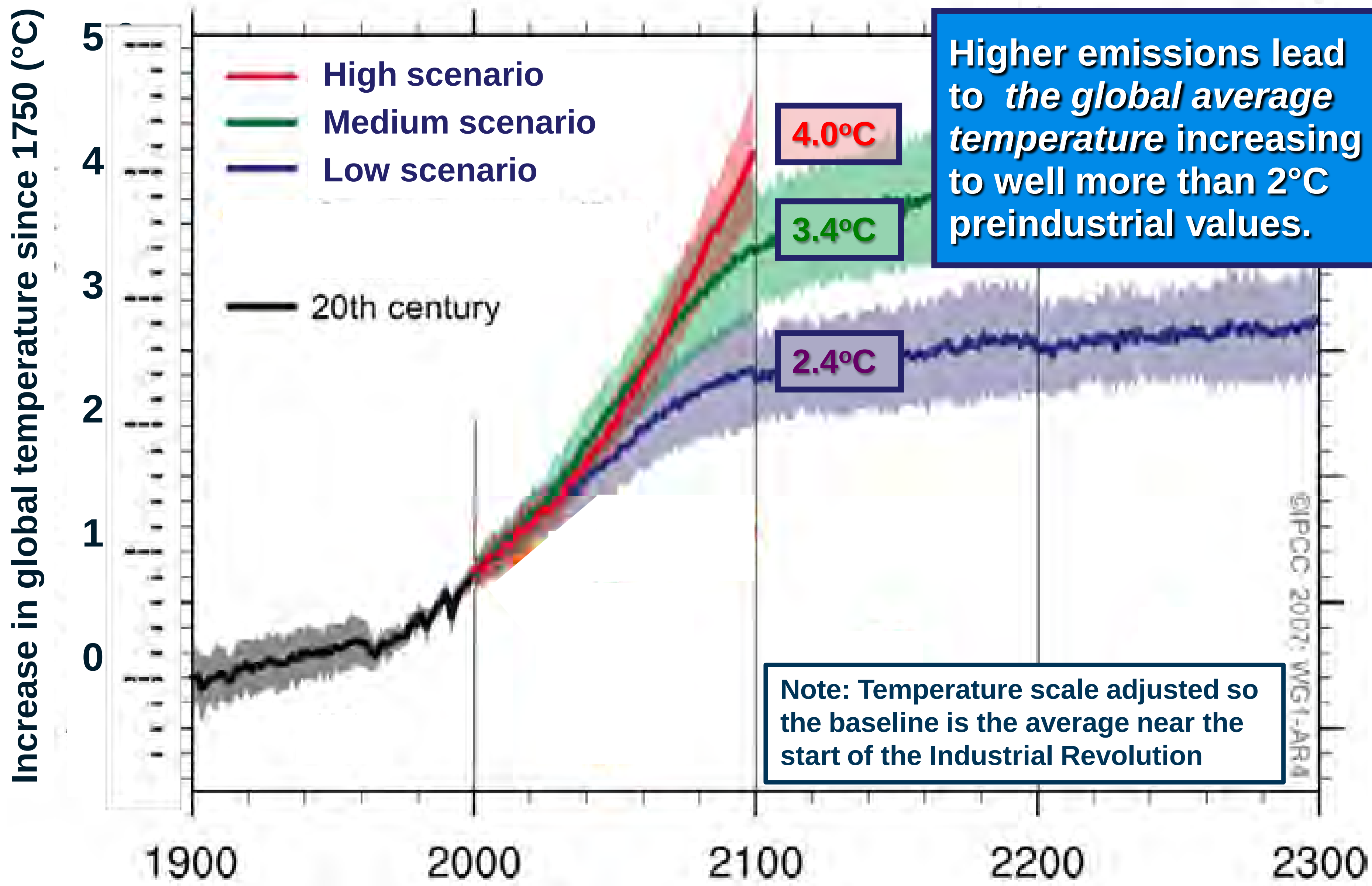


Without policies to limit emissions, the continued increase in global population and rising standard of living are projected to lead to substantial increases in global CO_2 emissions

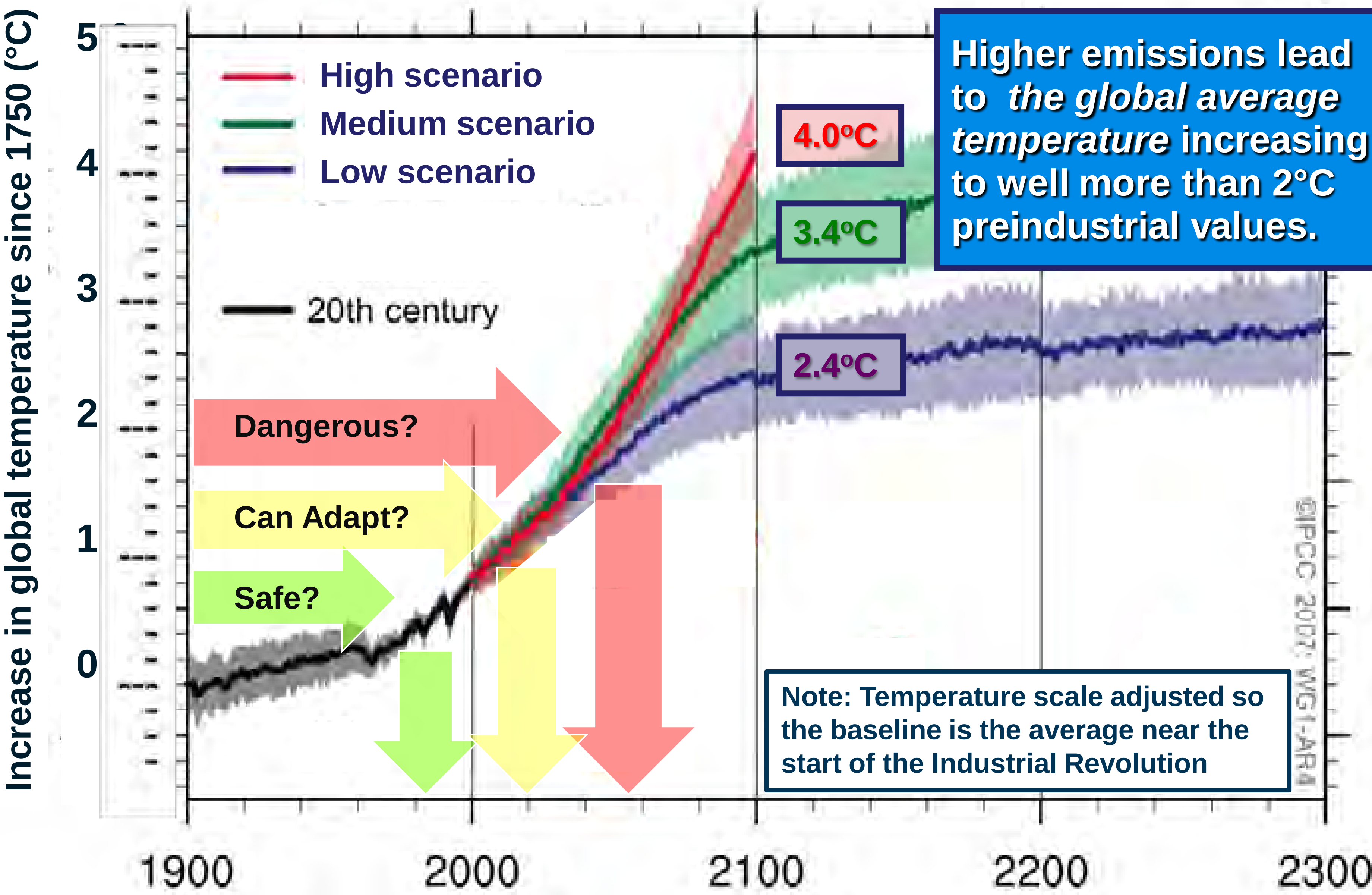


As a result, the atmospheric CO_2 concentration is projected to rise from its current value of ~400 ppm to at least 2 to 3 times the preindustrial value of 280 ppm by 2100, and possibly go higher thereafter

Without emissions controls, driving the climate with projected emissions of CO_2, the warming that began during the 20th century is calculated to continue for the next several centuries



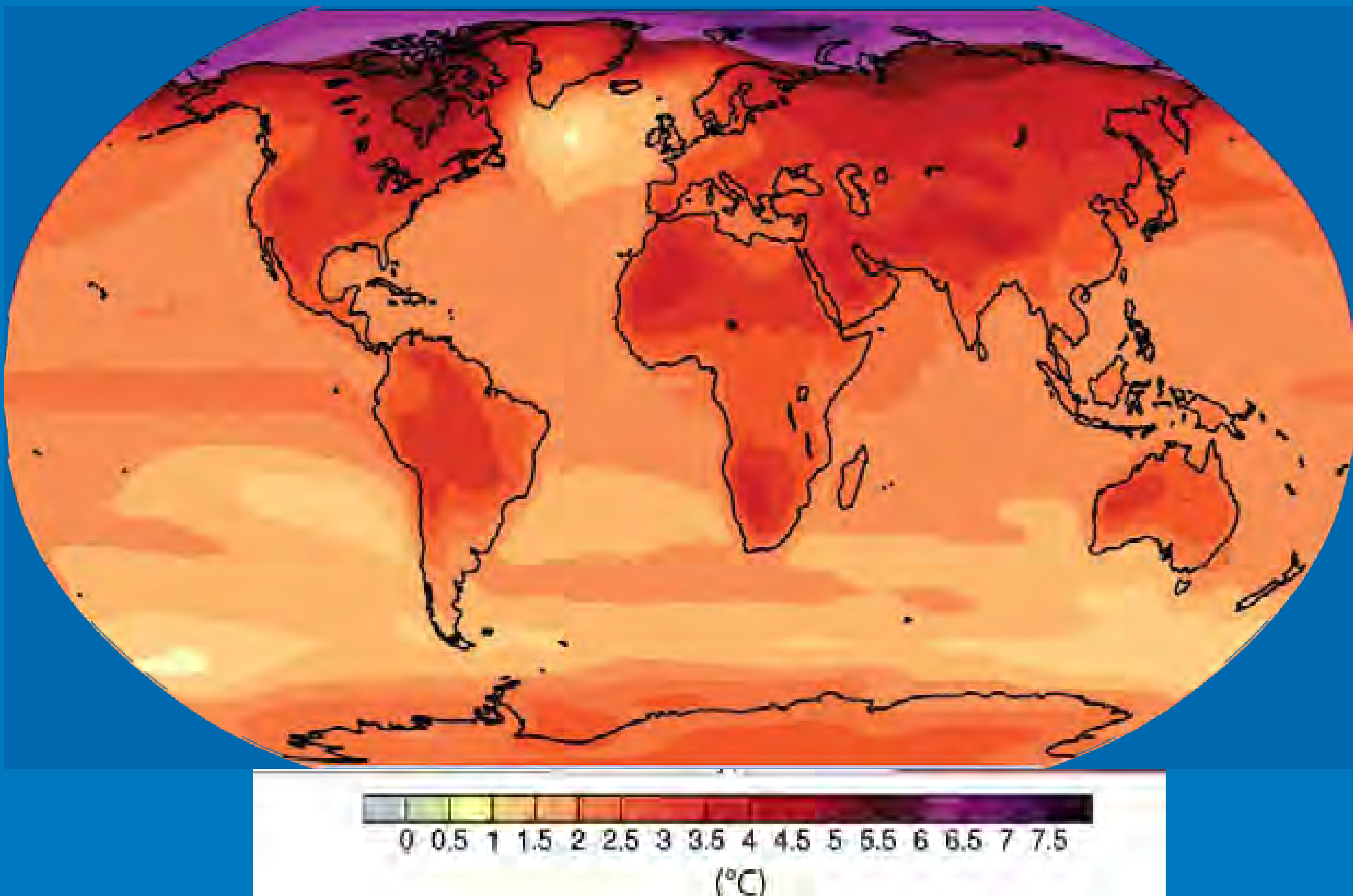
Global average warming is likely to significantly exceed 2° C over preindustrial level, which international leaders have set as the goal for avoiding "dangerous interference" (UNFCCC)



Higher emissions lead to *the global average temperature* increasing to well more than 2°C preindustrial values.

Note: Temperature scale adjusted so the baseline is the average near the start of the Industrial Revolution

Warming is projected to be greatest at high latitudes, over land, during winter, and at night, except where land dries out in summer. Over oceans and low latitudes, evaporation buffers warming

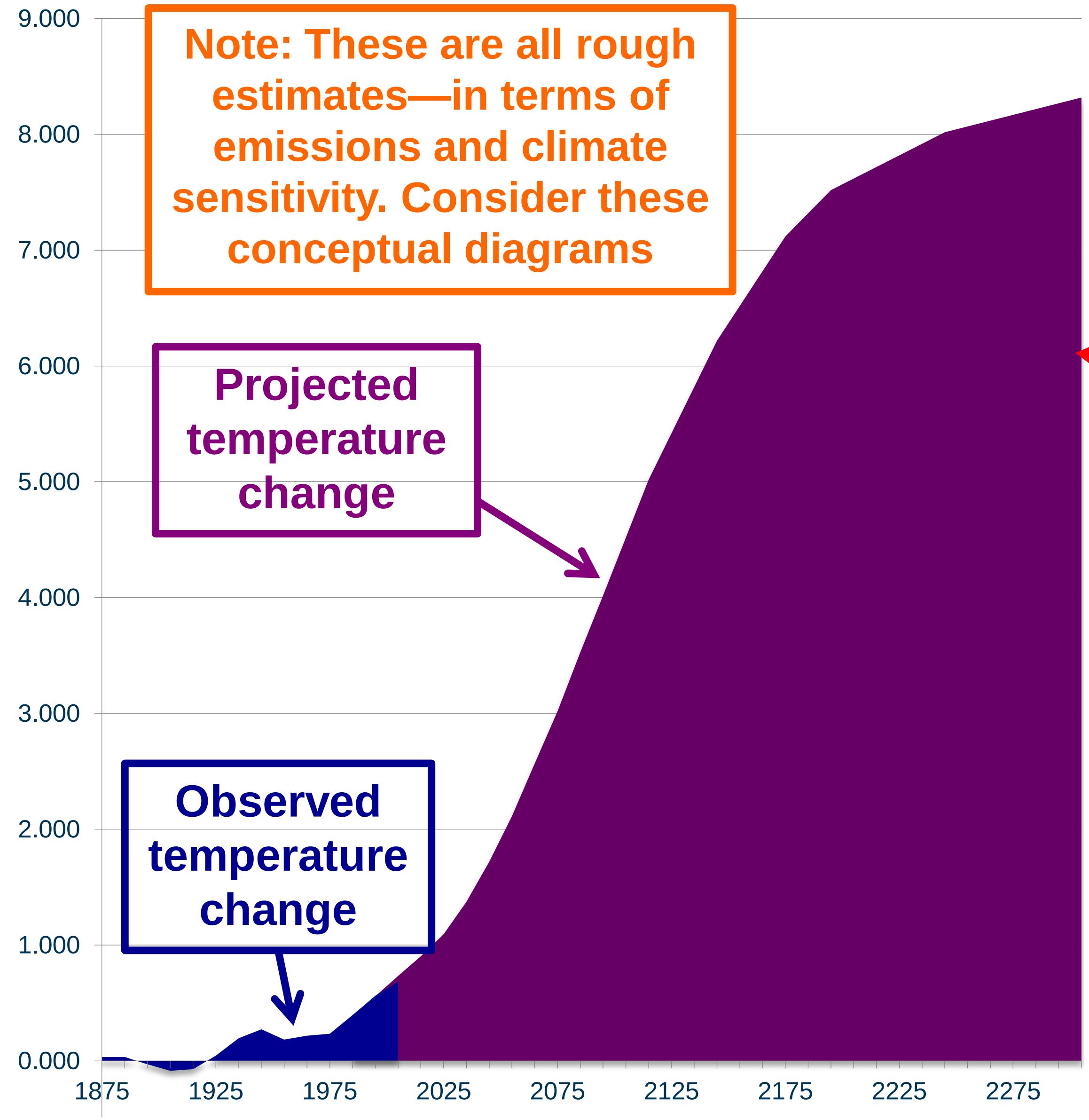


Much of land area warms by ~3-5°C (~5-10°F); Arctic warms by more

"Global warming" is shorthand for a wide array of potential changes in the climate

- **Warming** is very likely to be greater in high than low latitudes, greater in winter than in summer, and greater over land than over the oceans
- **Total evaporation** is very likely to increase, more rapidly leading to dry soil conditions and drought
- **Total global precipitation** is very likely to increase, coming especially in relatively intense events that could increase flood likelihood in some regions.
- The highest percentage increase in precipitation is likely to occur in **mid- to high-latitudes**.
- **The potential for an increase in climate extremes and unexpected changes** is increasing as balancing influences are disrupted and thresholds are exceeded

For perspective on the potential options, consider the projected multi-century increase in global temperature over pre-industrial for a mid-range scenario



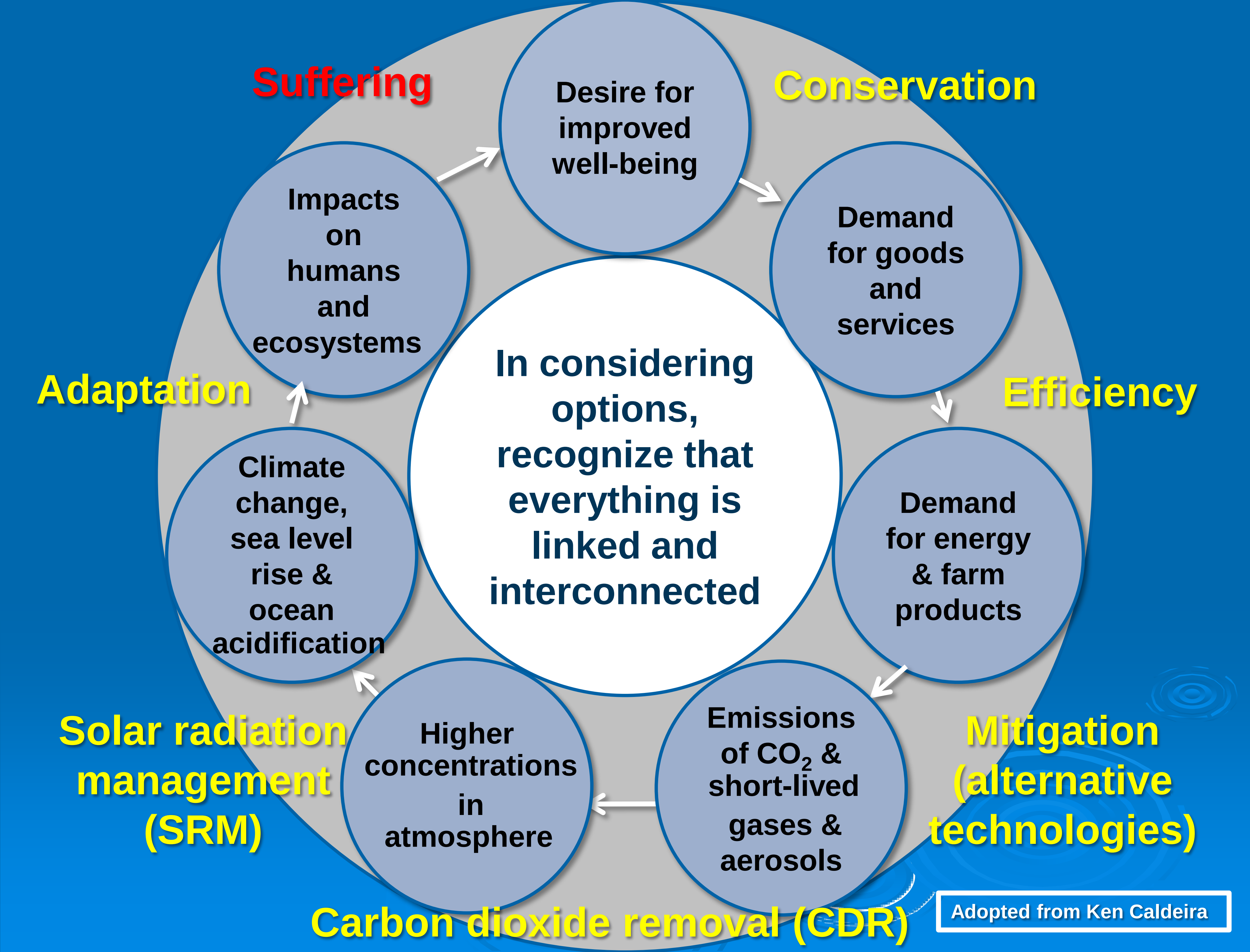
The A2 scenario assumes a fragmented world:

- Regional self-reliance
- Continuously increasing global population
- Economic development and income vary regionally
- Technological change fragmented and slow

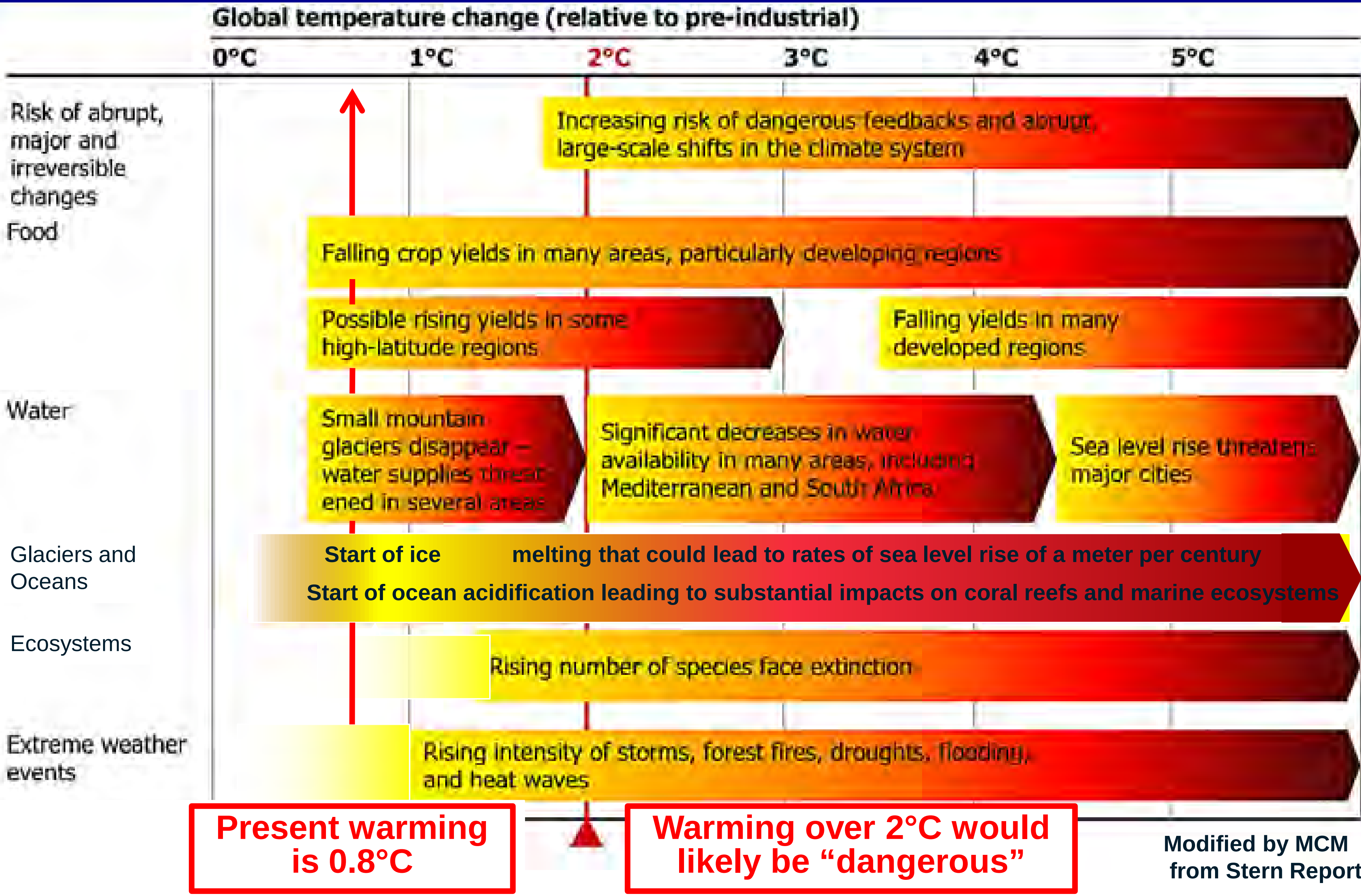
This extension assumes the CO2 concentration rises to over 1000 ppm

The glacial-to-interglacial and the interglacial-to-Cretaceous transitions are both estimated to be about 6°C—so the projected changes are very large and very rapid in the context of Earth's climatic history

So, what can we do to limit climate change?

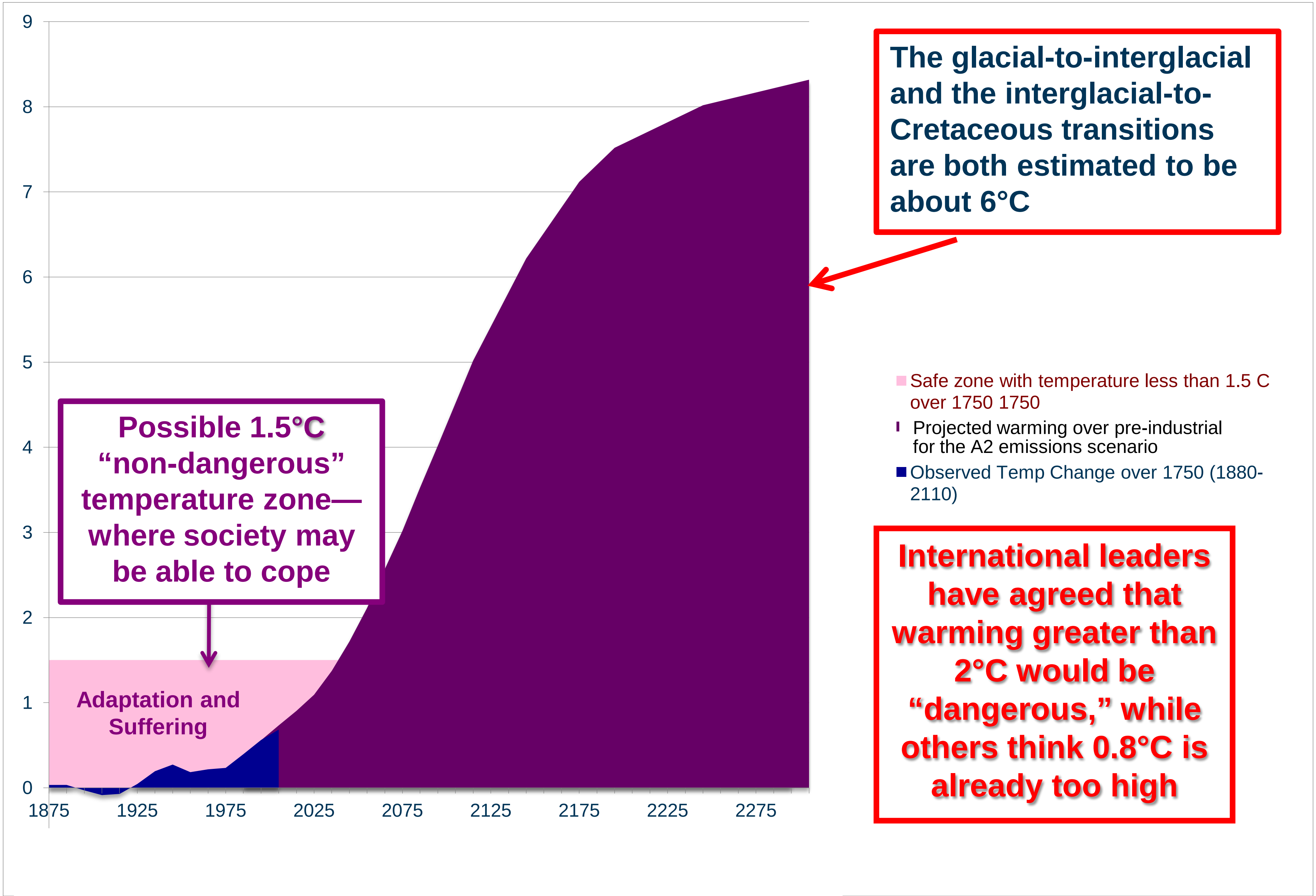

Suffering
Conservation
Desire for improved well-being
Demand for goods and services
Efficiency
Demand for energy & farm products
Emissions of CO_2 & short-lived gases & aerosols
Mitigation (alternative technologies)
Higher concentrations in atmosphere
Carbon dioxide removal (CDR)
Solar radiation management (SRM)
Climate change, sea level rise & ocean acidification
Adaptation
Impacts on humans and ecosystems
In considering options, recognize that everything is linked and interconnected
Adopted from Ken Caldeira

Climate change is starting to cause serious impacts NOW, and much more disruptive impacts lie ahead, especially if the global average temperature rises above 1-2° C



Modified by MCM from Stern Report

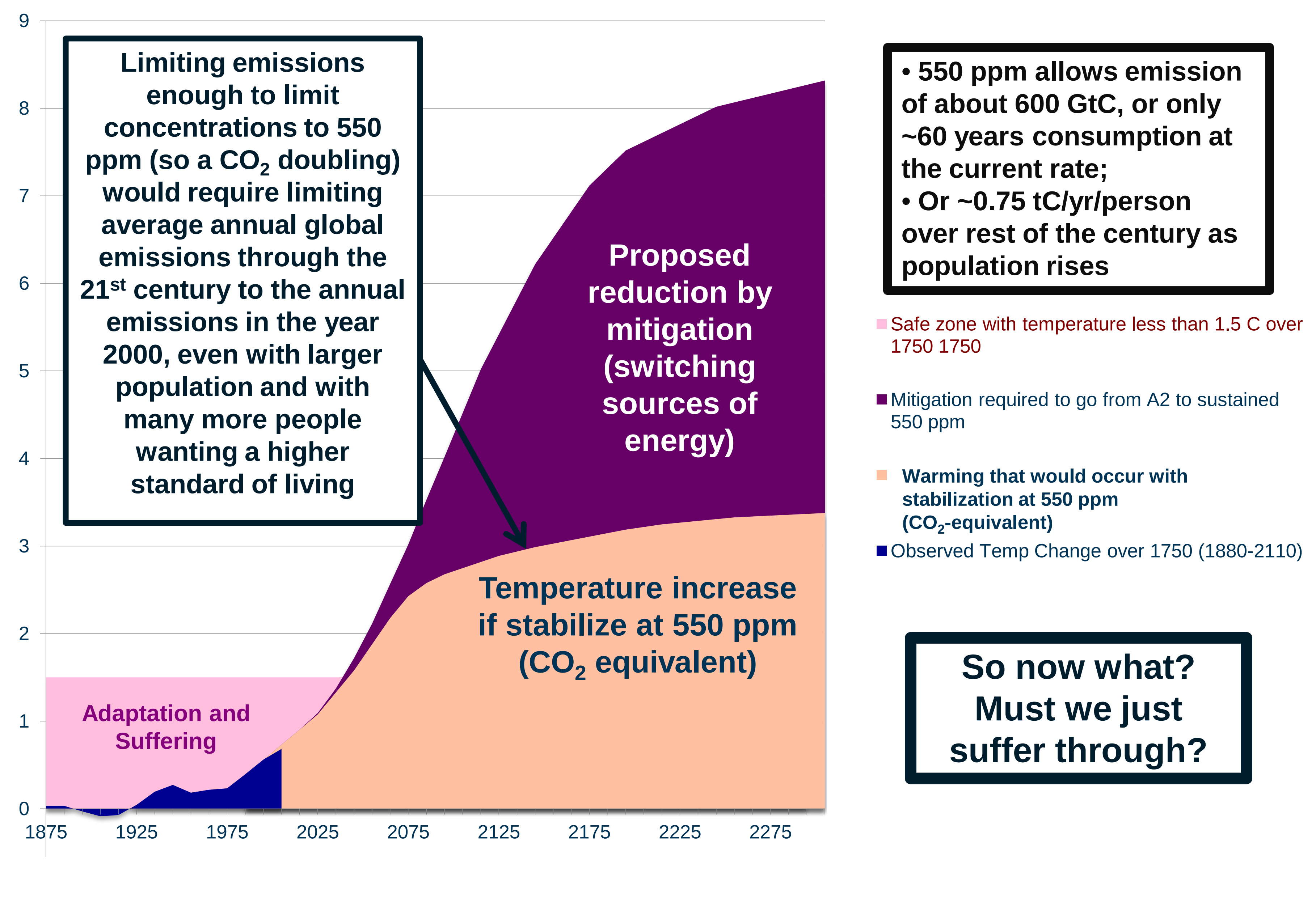
The world thus faces a very serious dilemma--- the projected warming is far above what might be considered a “safe” temperature zone of 1-2° C over pre-industrial



There is certainly potential for reducing emissions, and 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, for example:
     1. Methane
     2. Precursors to tropospheric ozone (e.g., nitrogen oxides, CO)
     3. Black carbon
     4. Hydrofluorocarbons (the replacements for CFCs)

Strong mitigation efforts have the potential to limit the peak in the CO_2 concentration to roughly 550 ppm



- 550 ppm allows emission of about 600 GtC, or only ~60 years consumption at the current rate;
- Or ~0.75 tC/yr/person over rest of the century as population rises

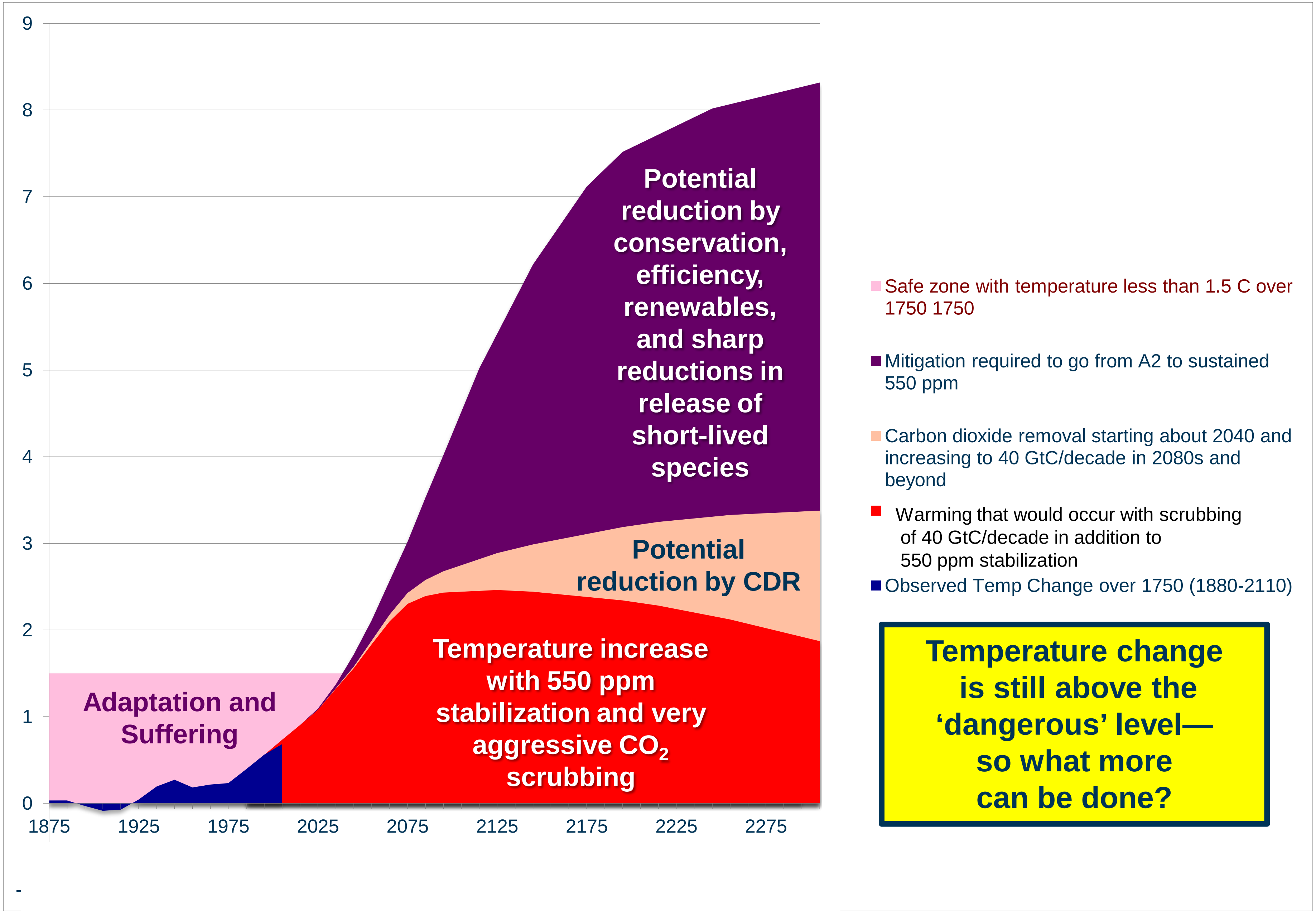
So now what? Must we just suffer through?

Increasing carbon removal from the atmosphere offers some hope, but tends to be slow-acting, long-term, and costly

- **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 is limited by the low CO_2 concentration (compared to power plant flue gas), the amount to be processed, and locations for storage

At present, the biosphere is a net contributor to atmospheric CO_2, so we first need to stop those emissions before Carbon Dioxide Removal can play a useful role

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



Beyond mitigation, CO_2 removal, and adaptation, the only choice, other than suffering, is to consider Radiation Management (RM)

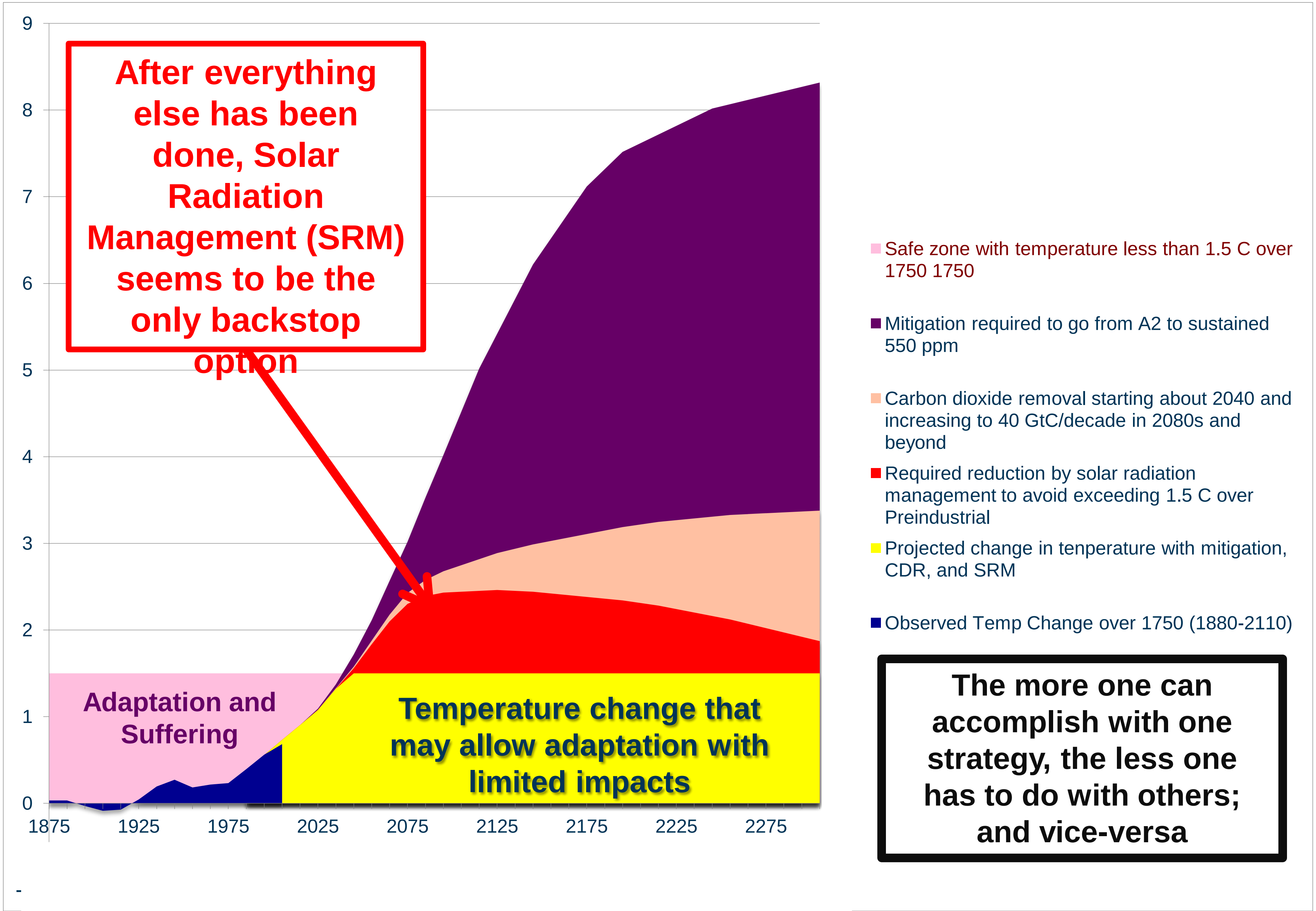
The options are:

1. **Solar Radiation Management (SRM):** Reduce the amount of solar radiation being absorbed by the Earth system; and/or
2. **Infrared Radiation Management (IRM):** Reduce the effectiveness of the infrared trapping by clouds

Suggested approaches, most involving solar reductions, include:

- Mirrors in space (very expensive and long-time to do)
- **Brightening the stratosphere** or higher, via aerosols or engineered particles (imitating a volcano; may affects ozone; aerosols have 1-2 year lifetime)
- **Brightening tropospheric clouds**, potentially with a sea salt mist (imitating ship tracks; regionally inhomogeneous; CCN have quite short lifetime)
- **Brightening clear skies**, possibly with sulfates over ocean areas (imitating air pollution; potential health and environmental impacts if persistent/widespread)
- **Dispersing cirrus clouds**, seeding ice nuclei (imitating 9/11 jet travel cessation)
- Brightening the land surface (imitating bright surfaces; competes with other needs for land; limited effectiveness since below cloud level)
- Brightening the ocean surface, possibly with microbubbles (imitating ship wakes; very difficult to sustain over large areas)

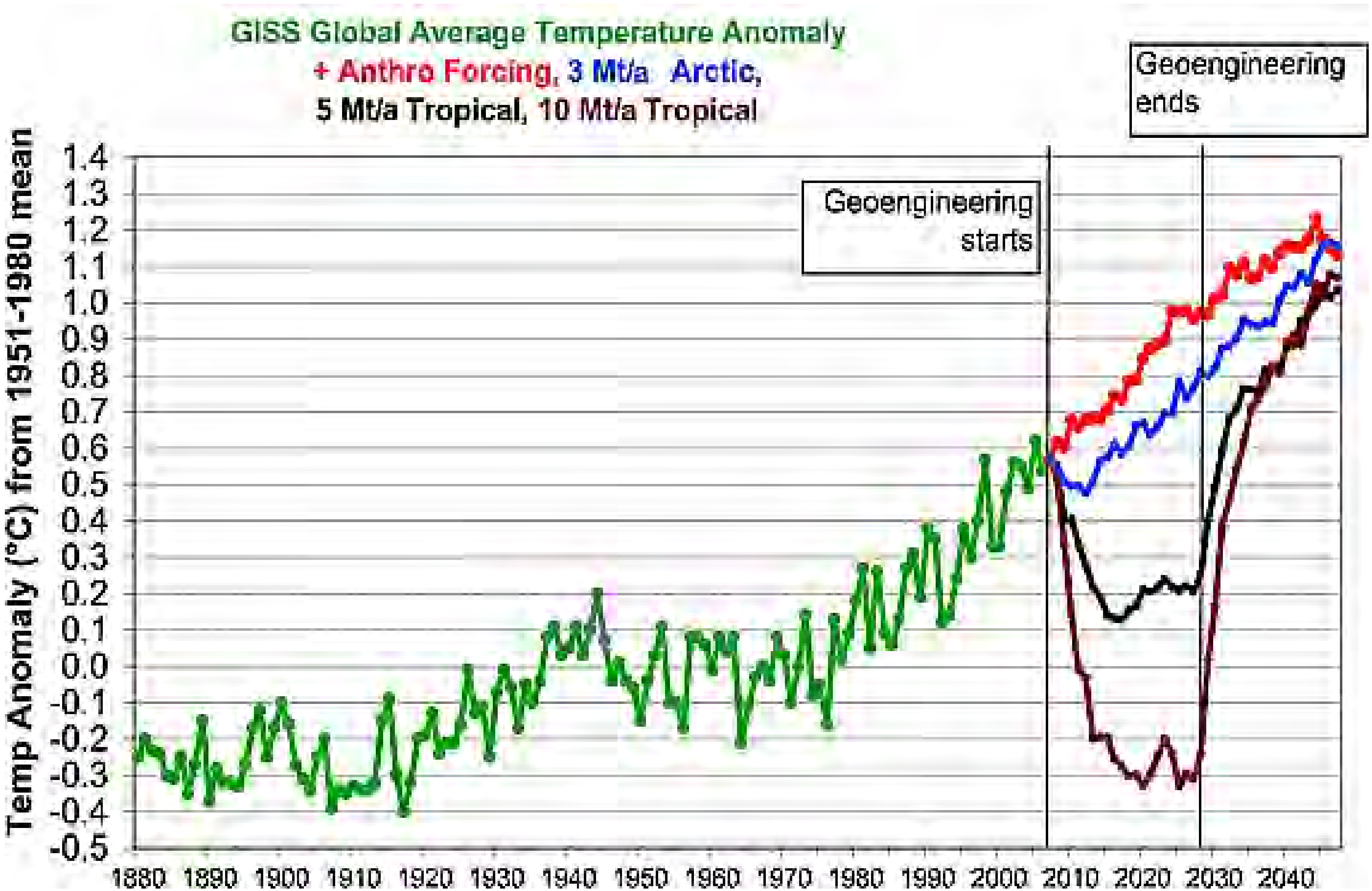
To the extent mitigation and scrubbing cannot limit warming, solar radiation management becomes the only option



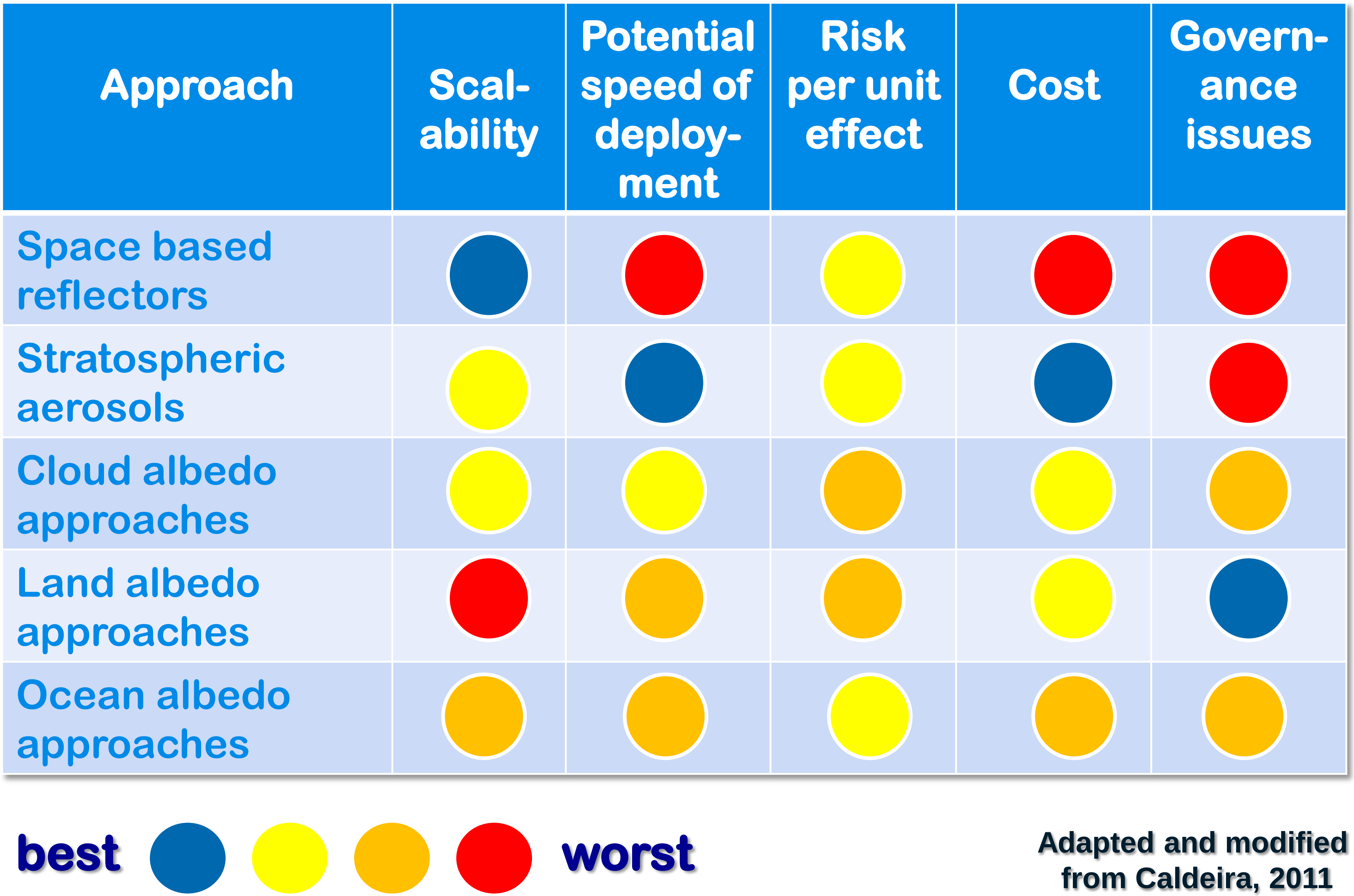
Global climate engineering poses a number of challenges, both scientific and governmental

- While volcanic eruptions demonstrate that a large reduction in the amount of absorbed solar radiation can cause a relatively rapid cooling, there are a number of scientific, ethical, legal, and governmental challenges, including:
  - The techniques are unproven and testing at scale is difficult to imagine (generally, volcanoes and other natural analogs are of only limited use);
  - The spatial and temporal patterns of forcing do not match that of increased greenhouse gases, although ocean inertia may somewhat moderate the effects of the mismatch;
  - The SRM approach cannot counter all impacts of fossil-fuel consumption, doing nothing, for example, for ocean acidification;
  - Potential slippery slope because estimates of the cost of implementation are small compared to the cost of cutting emissions, leading some to think of it as an alternative to mitigation instead of a last-resort complement;
  - SRM would need to be maintained for centuries and longer, imposing an obligation on future generations;
  - The need for global agreement and public acceptance seems conceivable only in response to an emergency situation affecting all in the world.
  - Application of SRM as an emergency measure may not work in the face of accelerated warming, ice sheet loss, etc. because it requires being able to identify an emergency before it is irreversible and ready to act quickly;

Robock et al. (2008) considered reductions in temperature that could be achieved with a stratospheric injection of SO_2 (although it continued year-round and spread in latitude)



A speculative comparison of possible approaches to global-scale Solar Radiation Management



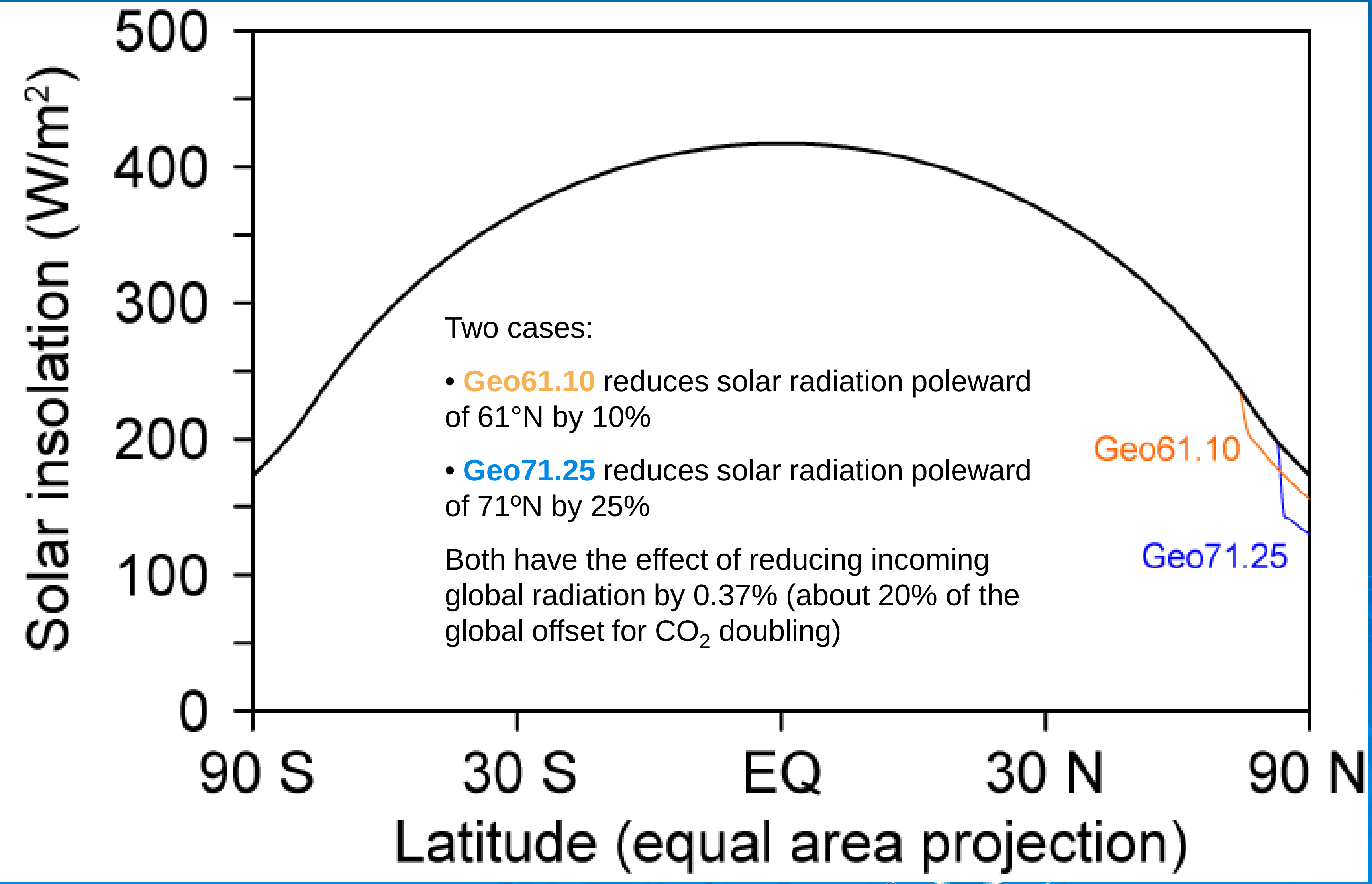
Adapted and modified from Caldeira, 2011

Might focused regional climate engineering have the potential to moderate specific global-warming impacts, possibly with reduced adverse side effects?

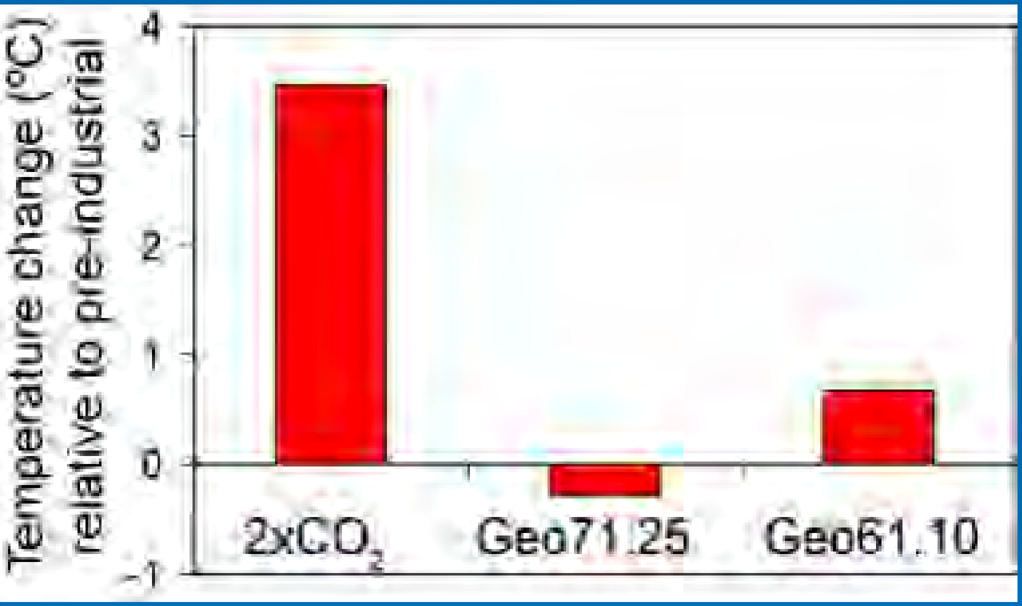
Particular objectives for which it might well make sense to determine if climate engineering technologies exist:

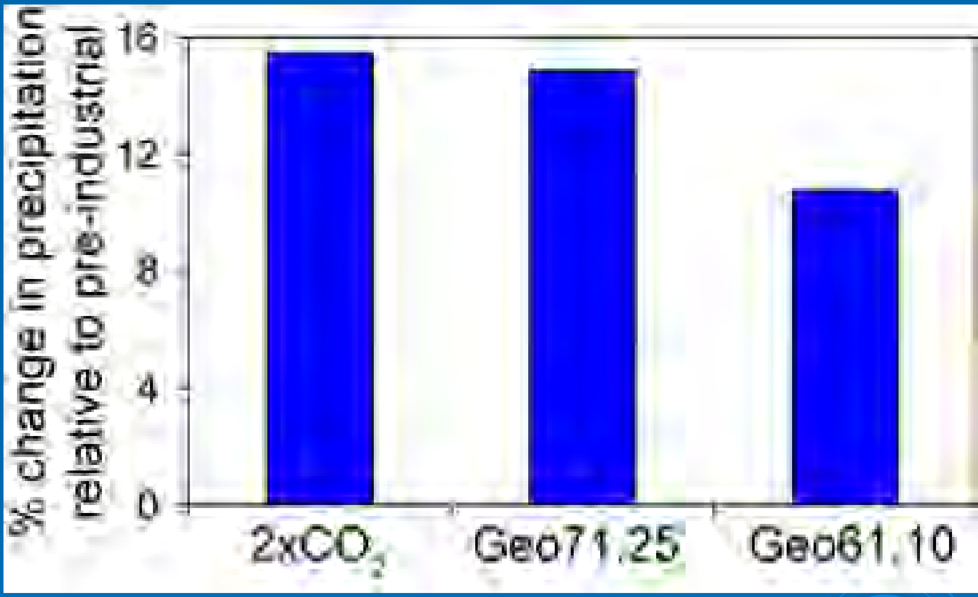
- **Moderating Arctic (and/or Antarctic) warming** (and/or permafrost thawing)
- **Moderating the intensification of tropical cyclones** and hurricanes
- **Nudging storm tracks** toward areas experiencing extreme drought
- **Sustaining (or enhancing) the cooling offset** of aerosols as SO_2 emissions decrease
- **Slowing the rate of retreat of outlet ice streams**
- Other ideas?

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



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





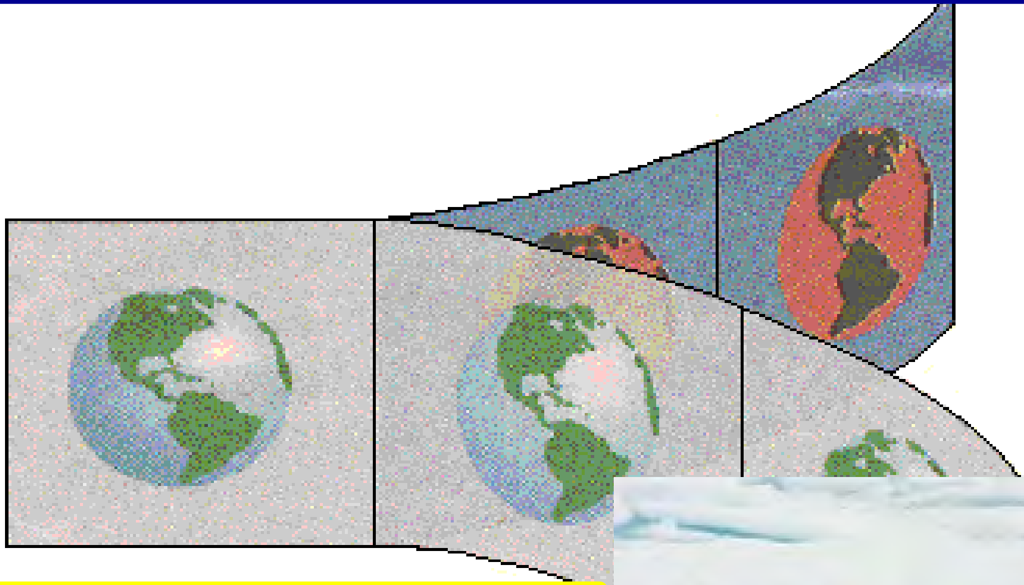
Model experiments are underway to look at similar reductions in the Southern Hemisphere, and how these together might limit global warming

Caldeira and Wood, 2008.

Given the pace of climate change, even with aggressive mitigation, an aggressive research program would seem to be justified to determine if there really are possibilities

- **Most approaches to geoengineering are based on imitating natural processes** in an amplified and directed manner, so not generally introducing unfamiliar physical or chemical processes;
- **The solar radiation management approaches that are proposed are difficult to sustain**; natural atmospheric cleansing works to shut them down quickly (unlike biological interventions);
- **The intent of proposed geoengineering approaches is to keep the climate near conditions of the recent past**, and not allow much warmer conditions, about which uncertainties are quite large (but still low enough to justify giving up fossil fuels);
- **The appropriate risk-benefit analysis is for global warming with or without geoengineering**, not for geoengineering alone;
- **There is the potential that geoengineering could reduce the incentive for aggressive mitigation**, letting impacts like ocean acidification become even worse; and
- **There are quite complex questions of ethics, equity, liability, and governance**, but there are also global interests in preventing rapid sea level rise, uncontrolled global warming, and increasingly disruptive and extreme weather.

Whether climate engineering might be used to counterbalance CO_2-induced climate change will be up to society …



… continued global warming with ever increasing environmental risk

. . . Or, aggressive emissions reductions, probably expensive adaptation, and even, with its many implications, some degree of climate (geo-)engineering approaches to slow global warming

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

Modified from Ken Caldeira