World Academy
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Intentional intervention in the climate system

Climate science and perspectives on deployment

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Geoengineering

What does it mean?

Facts

Knowledge ⟷ Speculation

Values

Various perspectives

"We should never under any circumstances consider albedo geoengineering."

"We should consider albedo geoengineering only as a last resort emergency response."

"We should consider albedo geoengineering as a normal component in an optimized portfolio of climate change response options."

"We should consider albedo geoengineering as an alternative to CO_2 emissions reduction."

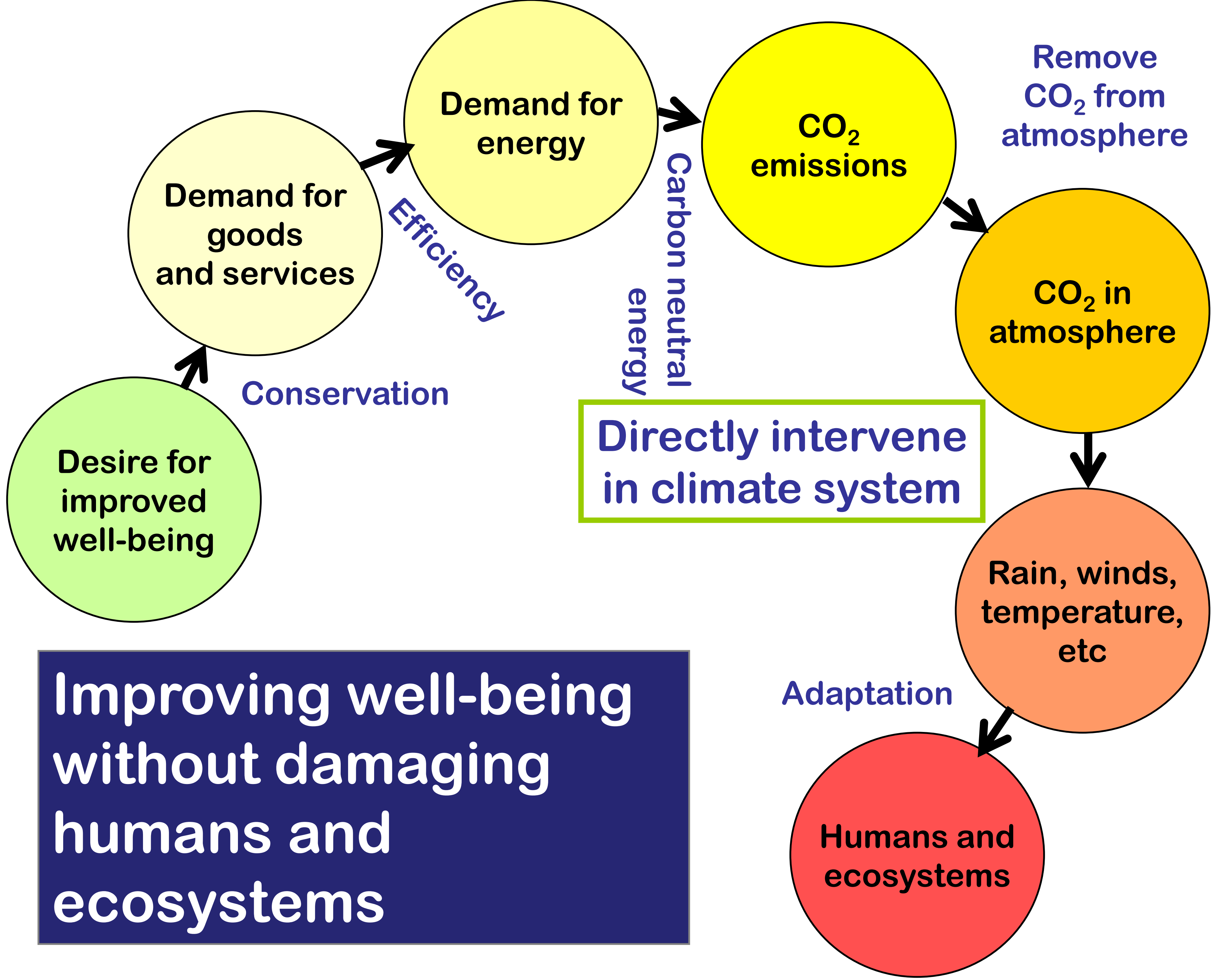
My Perspective

In some circumstances, some geoengineering approaches may have the potential to diminish risk.

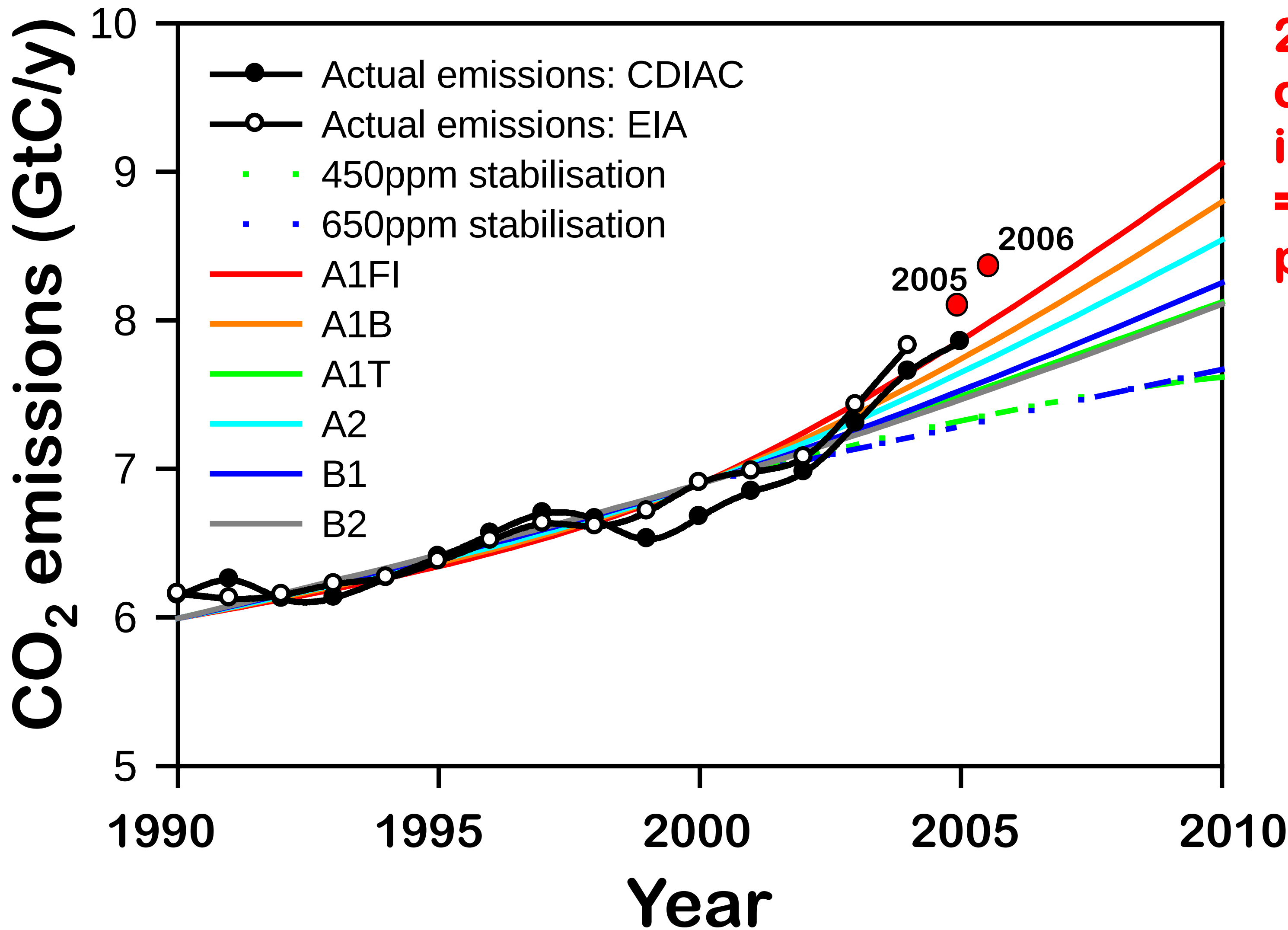
Therefore, we should establish whether, how, and under what circumstances these approaches could contribute to risk reduction.

My Perspective

Nothing known about geoengineering gives us any reason to work less hard to limit greenhouse gas emissions and increase our adaptive capacity in the face of climate change.


Desire for improved well-being
Conservation
Demand for goods and services
Efficiency
Demand for energy
Carbon neutral energy
CO2 emissions
Remove CO2 from atmosphere
CO2 in atmosphere
Directly intervene in climate system
Rain, winds, temperature, etc
Adaptation
Humans and ecosystems
Improving well-being without damaging humans and ecosystems

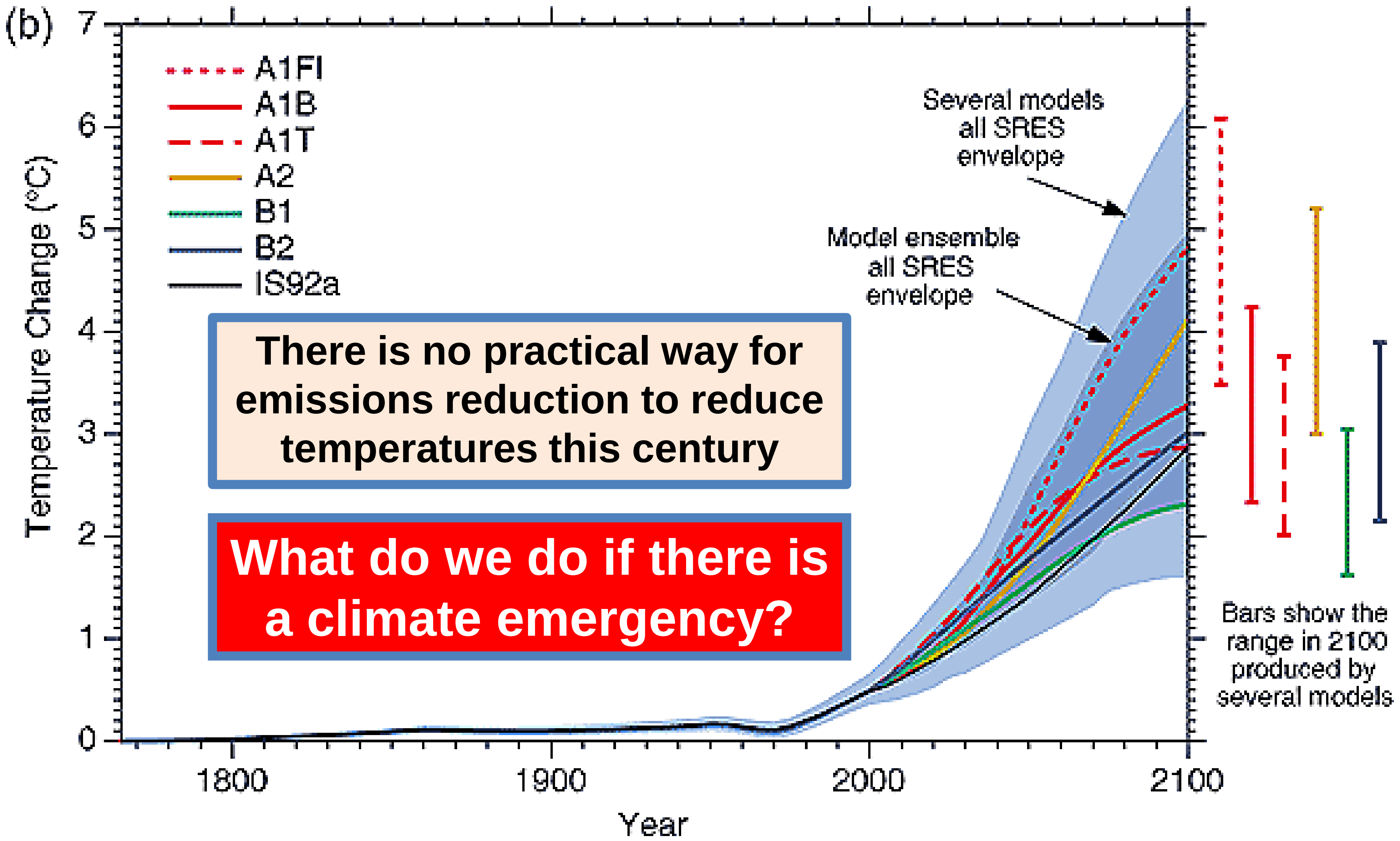
Fossil-fuel CO_2 emissions exceed all expectations



2000-2006 observed increase = 3.3% per year

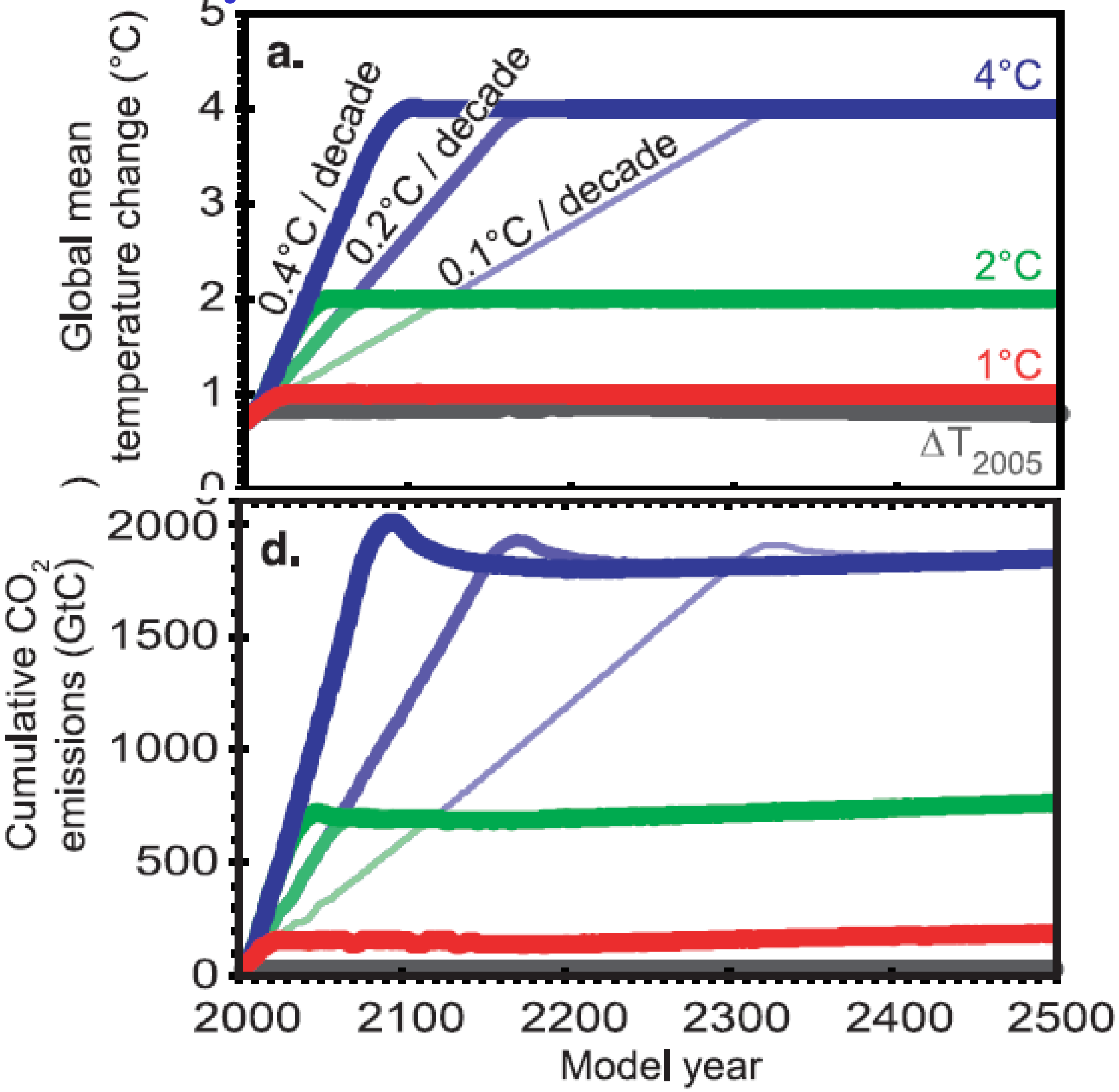
Repatch et al. 2007, PNAS

Temperatures continue to increase throughout this century in every plausible emissions scenario



IPCC TAR

Preventing further warming requires near-zero emissions

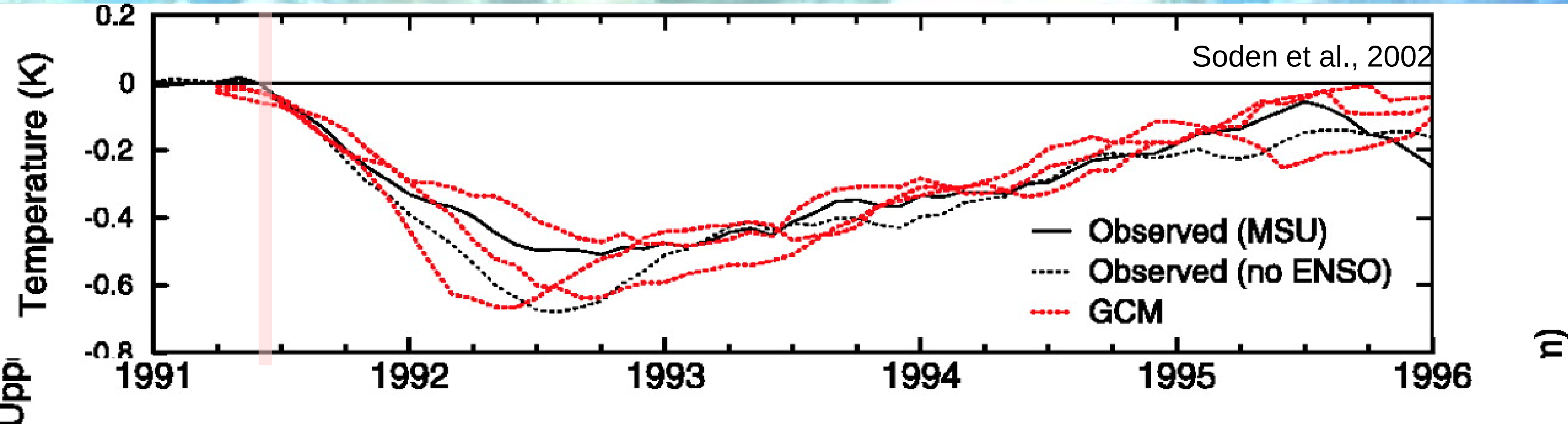


Temperature stabilization scenarios

Required cumulative emissions

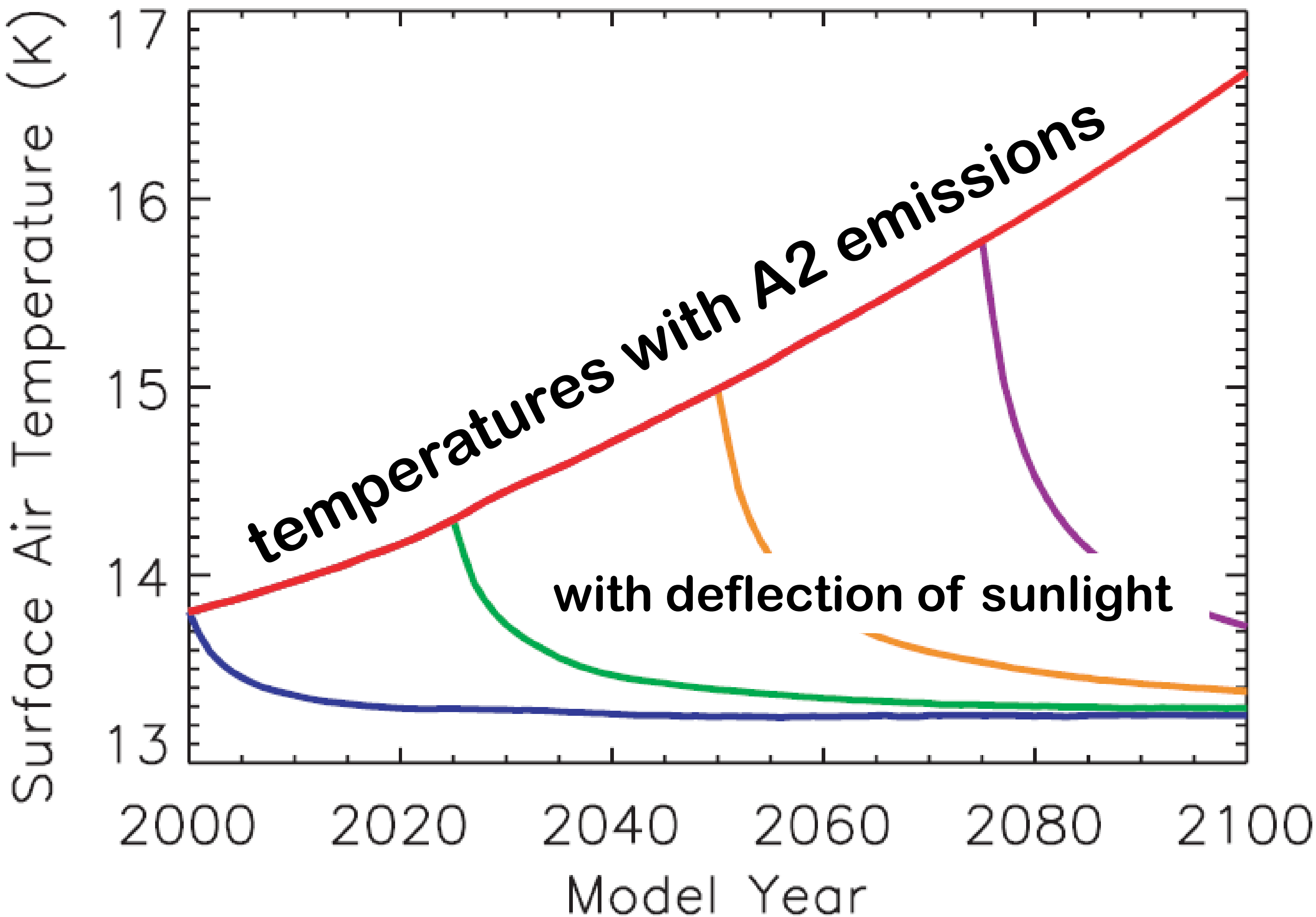
Matthews and Caldeira 2008

Mt. Pinatubo, 1991

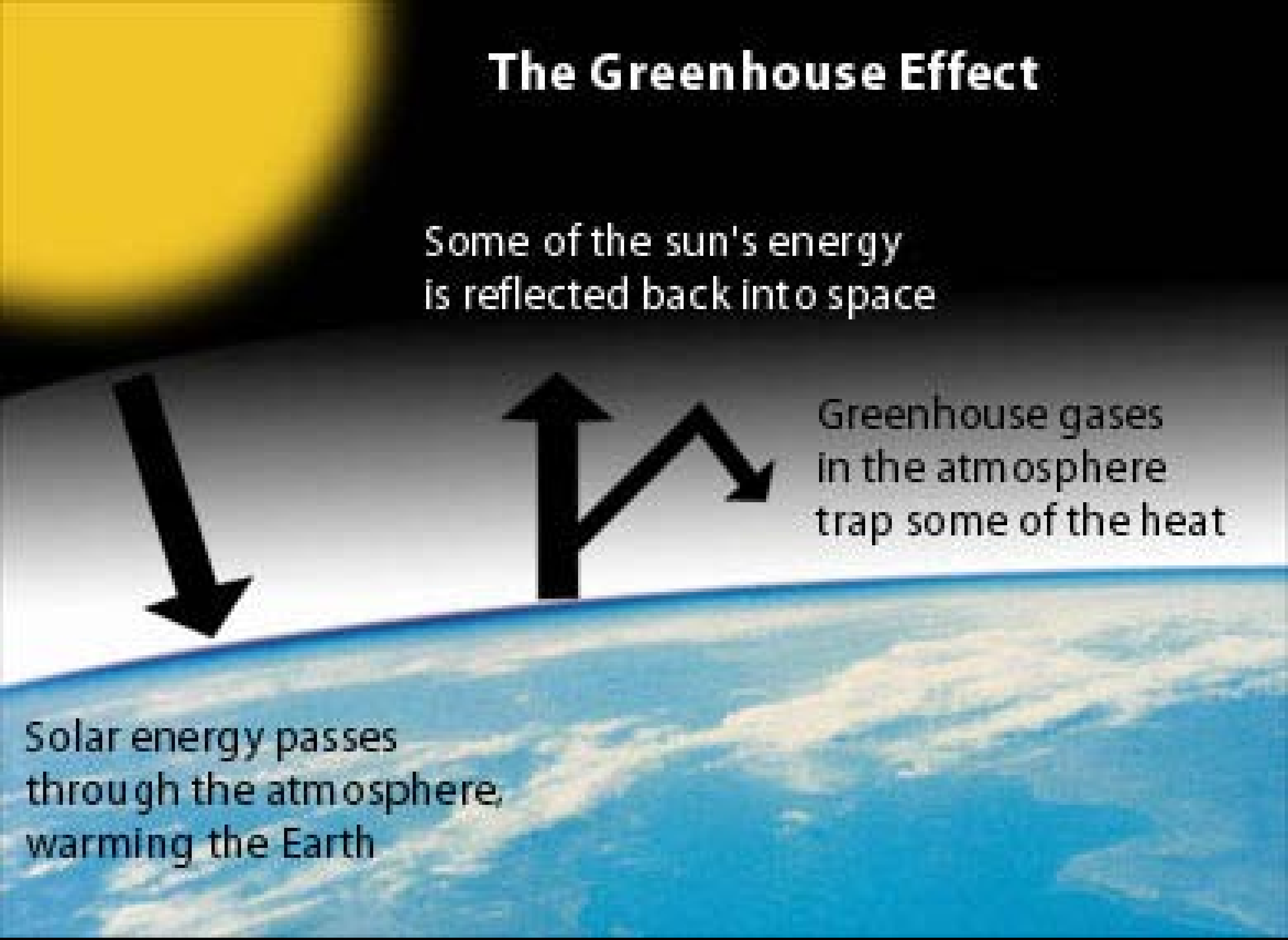


Henning
Wagenbreth

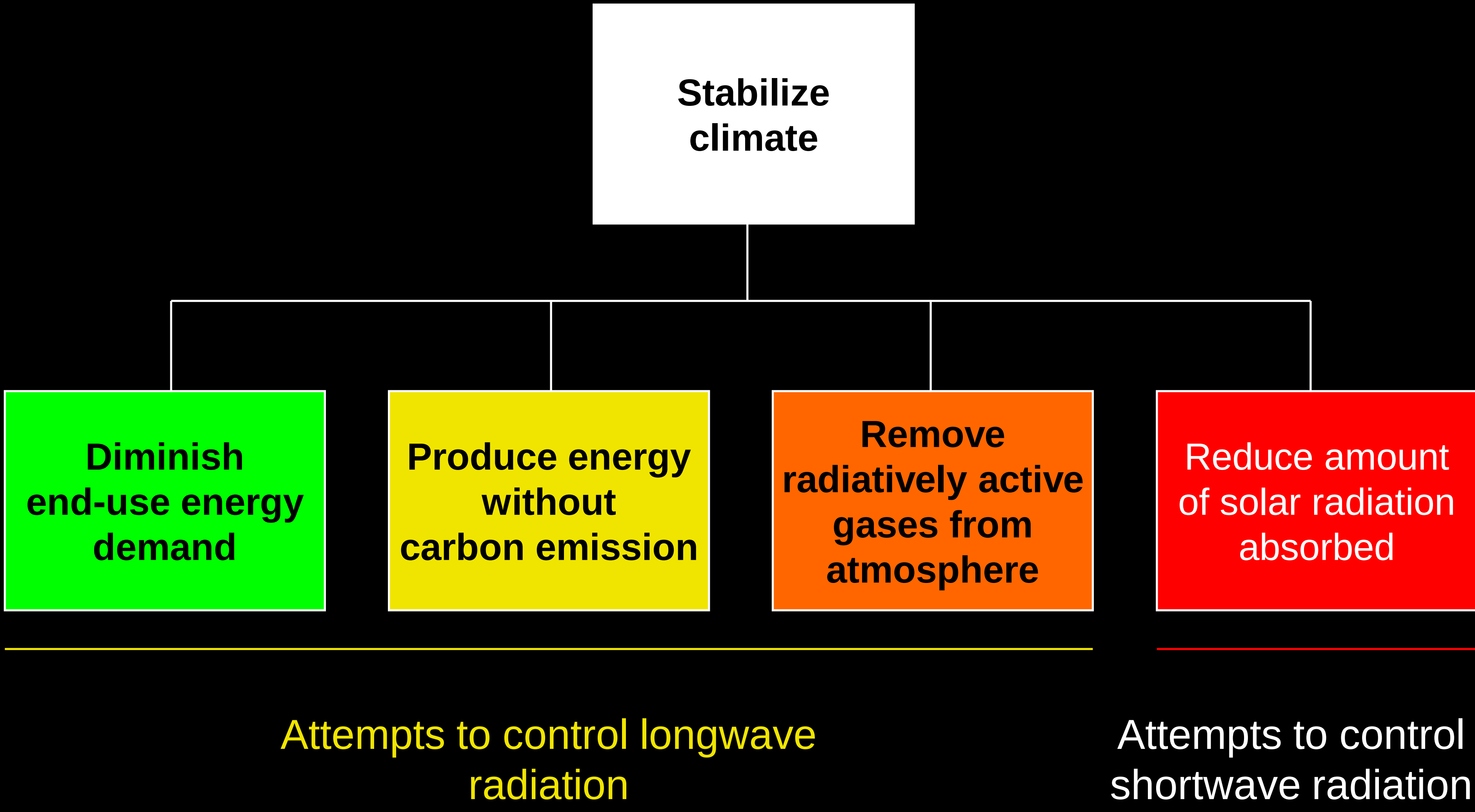
Direct intervention approaches could cool Earth within years



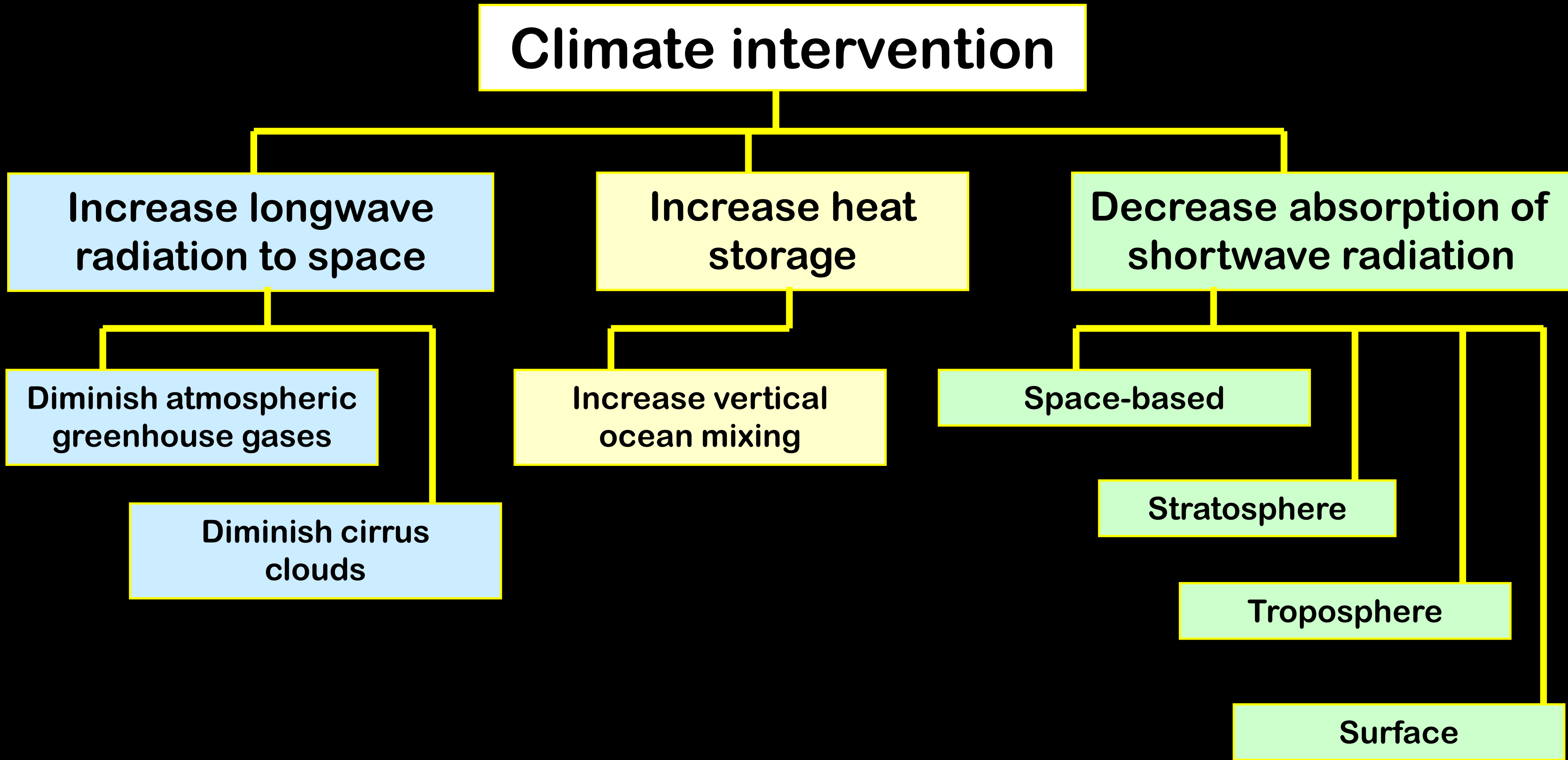
Matthews and Caldeira (2007)


The Greenhouse Effect
Some of the sun's energy
is reflected back into space
Greenhouse gases
in the atmosphere
trap some of the heat
Solar energy passes
through the atmosphere,
warming the Earth

Strategies to climate stabilization



A taxonomy of climate intervention options



Back-of-envelope example: land albedo change

- ¤ Radiative forcing from $2xCO_2$ = 4 W m^{-2}
- ¤ Area of Earth = 5 x 10^{14} m^2

- Total radiative forcing = 2 x 10^{15} W

- ¤ Top-of-atmosphere land albedo change = 0.1
- ¤ Top-of-atmosphere sunlight = 340 W m^{-2}

- Area needed = 0.6 x 10^{14} m^2

- ¤ Total land area = 1.6 x 10^{14} m^2

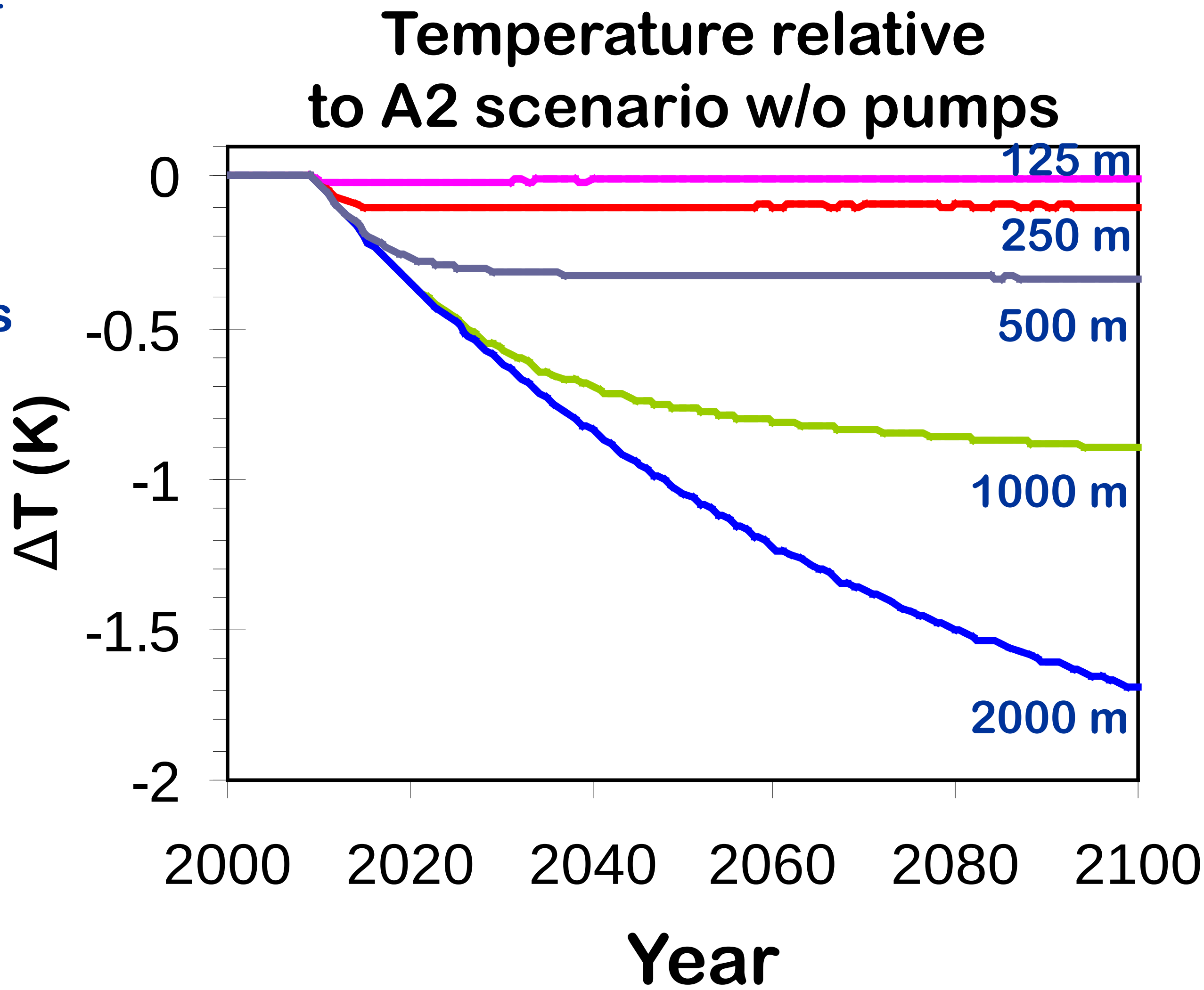
- Percentage of land area required = 37%

But could be low-cost, possible co-benefits, tractable governance issues, etc

Vertical pumping in the ocean
Effect of depth and pumping rates

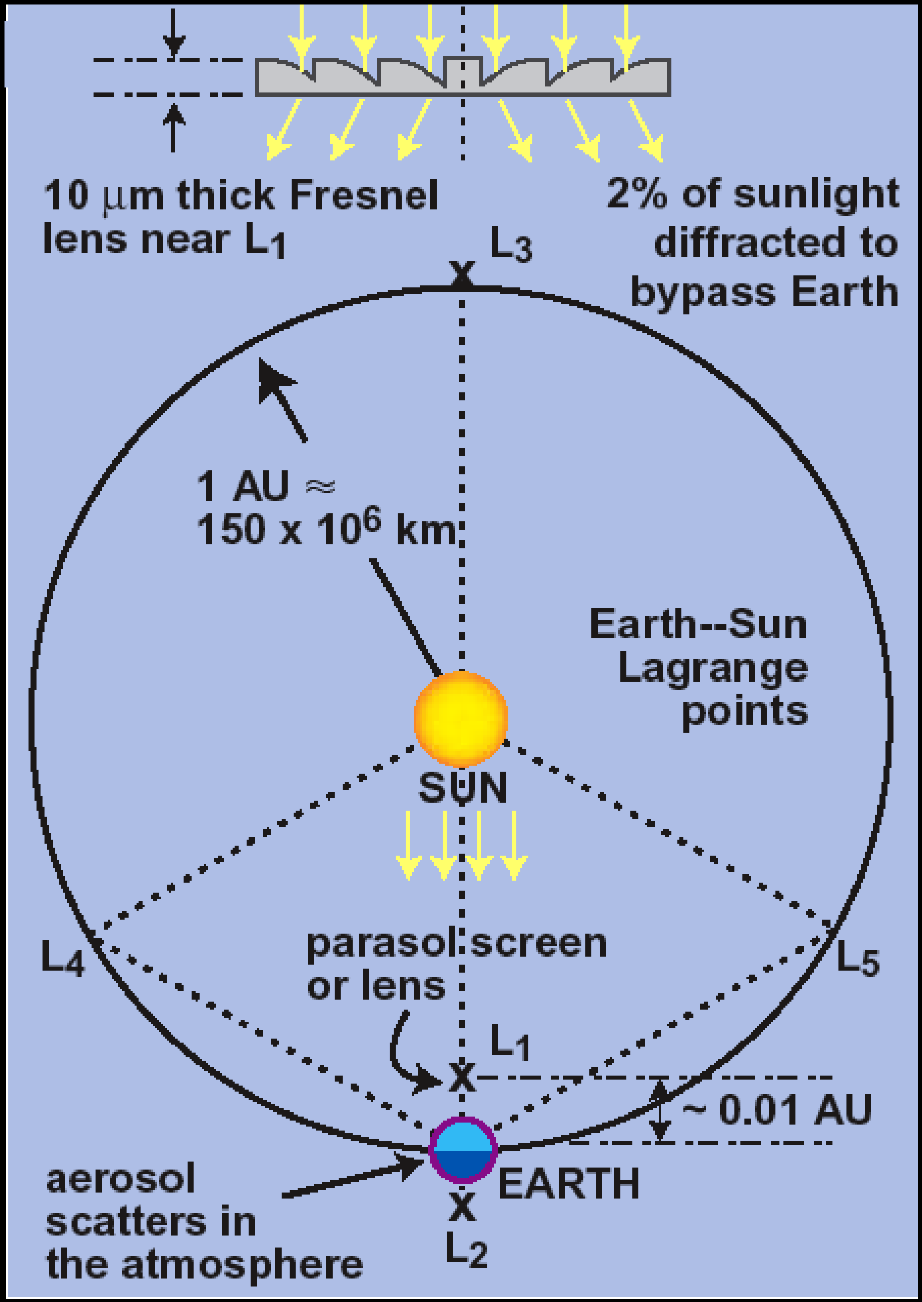
Pumping depth of 2000, 1000, 500, 250, 125 m

Mixed-layer removal = 10 years



Cao and Caldeira, in prep.

Spaced-based and atmosphere-based options



Hoffert et al., 2002

What fraction of incident sunlight would you need to block to compensate for a doubling of CO_2

- Each doubling of CO_2 traps ~2×10^{15} W

- Total sunlight absorbed by Earth
  $= A (1\text{-}a) S_0 = 1.2 \times 10^{17}$ W

- Fraction of sunlight $= (2 \times 10^{15}\ \text{W}) / (1.2 \times 10^{17}\ \text{W})$
  $= 1.7\ \%$
  - 1.7% of Earth's spherical area $= 8.5 \times 10^{6}\ \text{km}^2$
  - 1.7% of Earth's disk area $= 2.1 \times 10^{6}\ \text{km}^2$

Rate of radiative forcing increase

- Each doubling of CO_2 traps ~2×10^{15} W
- If this doubling occurs over 100 years, radiative forcing increases at a rate of 2×10^{13} W yr^{-1}
  - Increases at a rate of about 600 kW s^{-1}

How fast would we need to build a space-based system to compensate for rate of increase of greenhouse gases?

- Average solar radiation absorption per unit *disk area* normal to direction of sun = $(1 – a)\ S_0 = 940\ W\ m^{-2}$

- Need to increase at rate of $2 \times 10^{13}\ W\ yr^{-1}$ normal to direction of sun

$= 2{,}000\ km^2\ yr^{-1}$
$= 2.4\ km^2\ hr^{-1}$
$= 670\ m^2\ s^{-1}$

Thin/small is the answer

- To compensate for a CO_2 doubling,
  - Disk area (out in space)
    - you need 2×10^6 km^2 area
      volume @1 mm = 2 km^3
      volume @ 0.1 μm = 0.0002 km^3

  - Spherical area (in atmosphere)
    - you need 8×10^6 km^2 area
      volume @ 1 mm = 8 km^3
      volume @ 0.1 μm = 0.0008 km^3

This is equivalent to a cube of less than 100 m on a side.

Approximately ½ the volume of sulfur put into stratosphere by Mt. Pinatubo

Back-of-envelope example: stratospheric aerosols

- ¤ Top-of-atmosphere sunlight = 340 W m^{-2}
- Area needed to block 2 x 10^{15} W = 6 x 10^{12} m^2

- ¤ Particle size = 10^{-7} m
- Volume needed = 6 x 10^5 m^3

- ¤ Residence time in stratosphere = 3 x 10^7 s
- Injection rate = 0.02 m^3 s^{-1}

But presents major governance issues, more easily turned off rapidly, etc

A small amount of dust can stop global warming

- 10's of kg per second
- Most injected dust remains in the stratosphere remains about a year

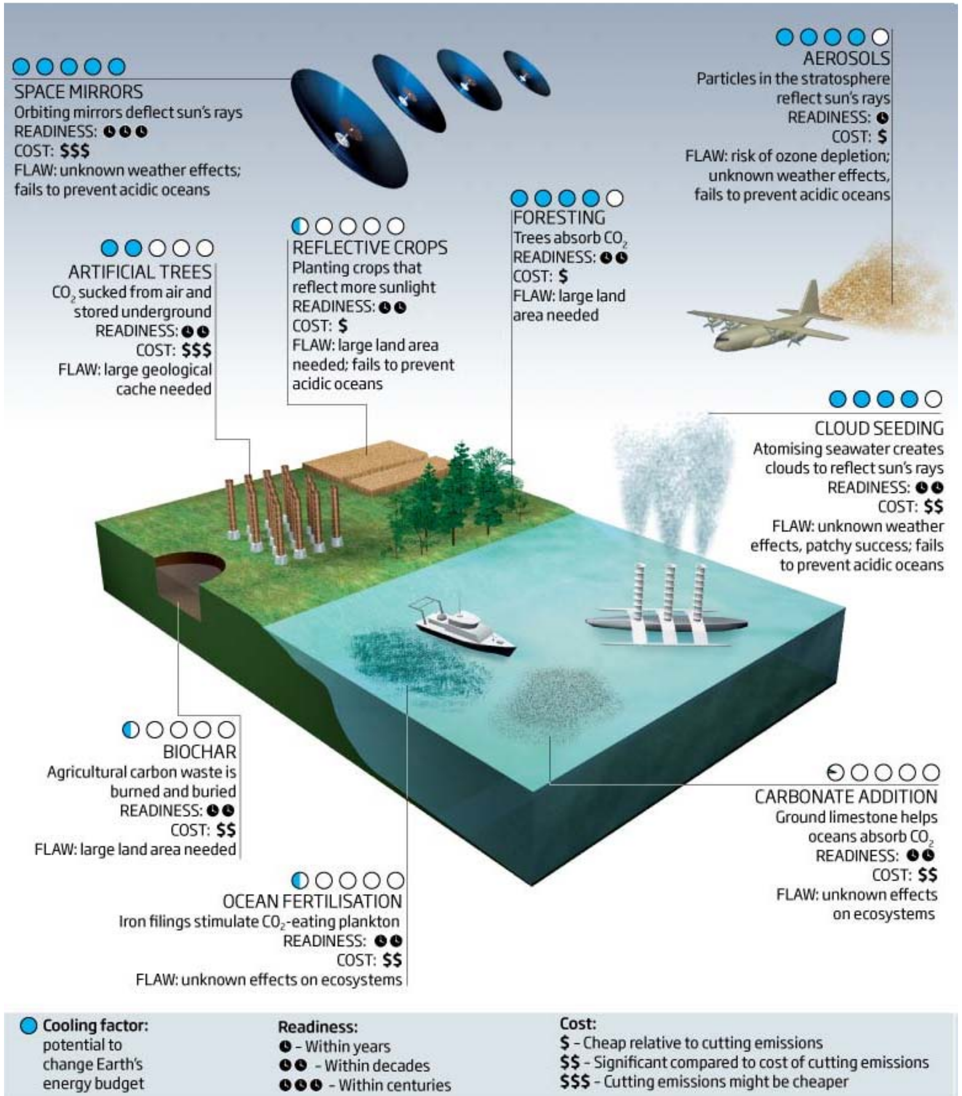
Engineering options for placing aerosols in stratosphere

- "Smokestack 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 ceilings
- Other options
  - Anthropogenic (mini-)volcanoes
  - Tethered (set-of-)lifting-body – a high-tech kites

Courtesy Lowell Wood

There are a range of strategies

Geoengineering weighed up



Stratospheric dust

From volcanoes, we know it basically works

From volcanoes, we know it doesn't cause an immediate global disaster

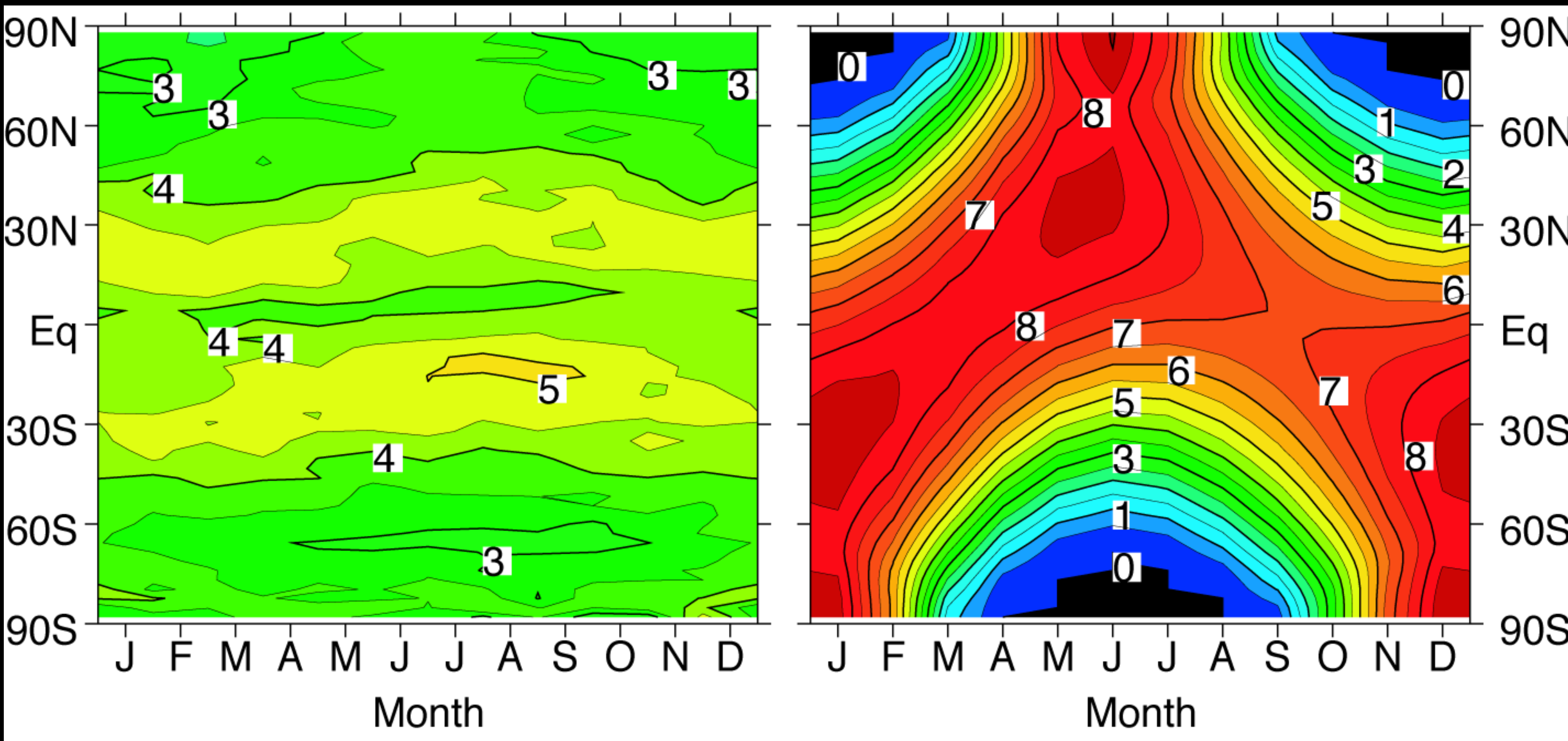
Could be deployed cheaply without any leaps in technology

Scalable to high amounts of cooling

Can these cancel?

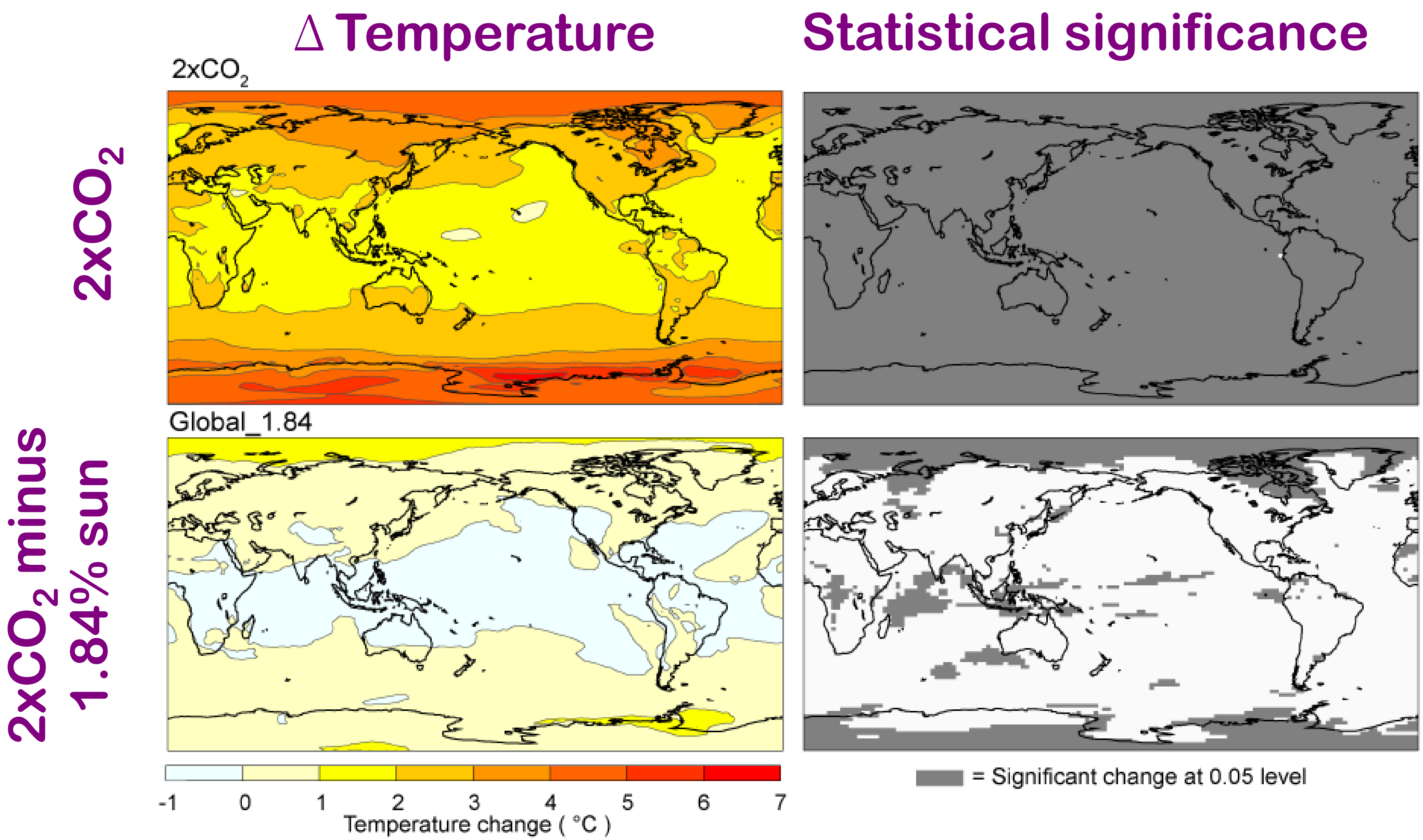
CO_2 radiative forcing from a CO_2 doubling (W / m^2)

Radiative forcing from 1.8% reduction in solar intensity (W / m^2)



Govindasamy and Caldeira, GRL, 2000

Model results for temperature



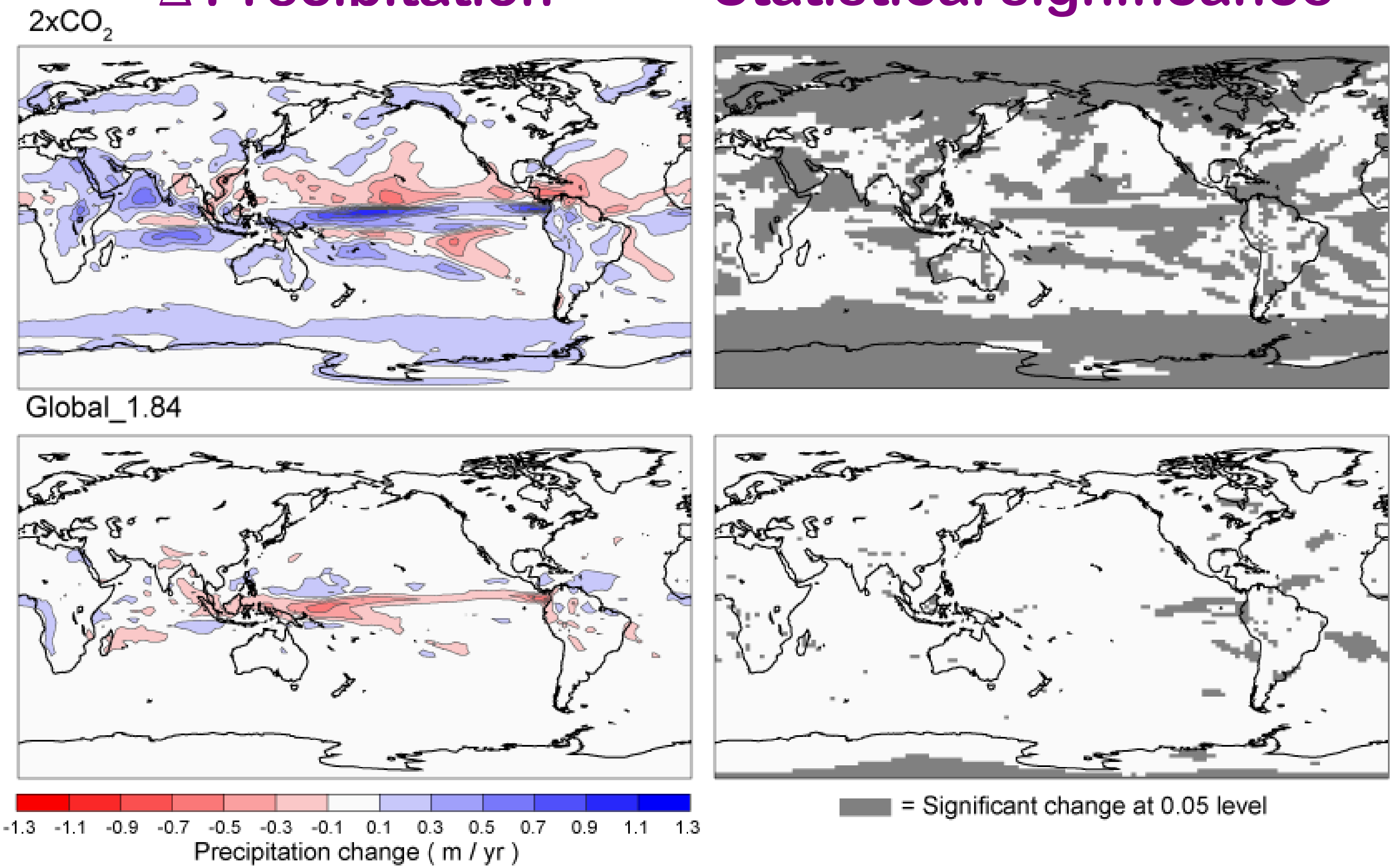
Caldeira and Wood, 2008

Model results for precipitation

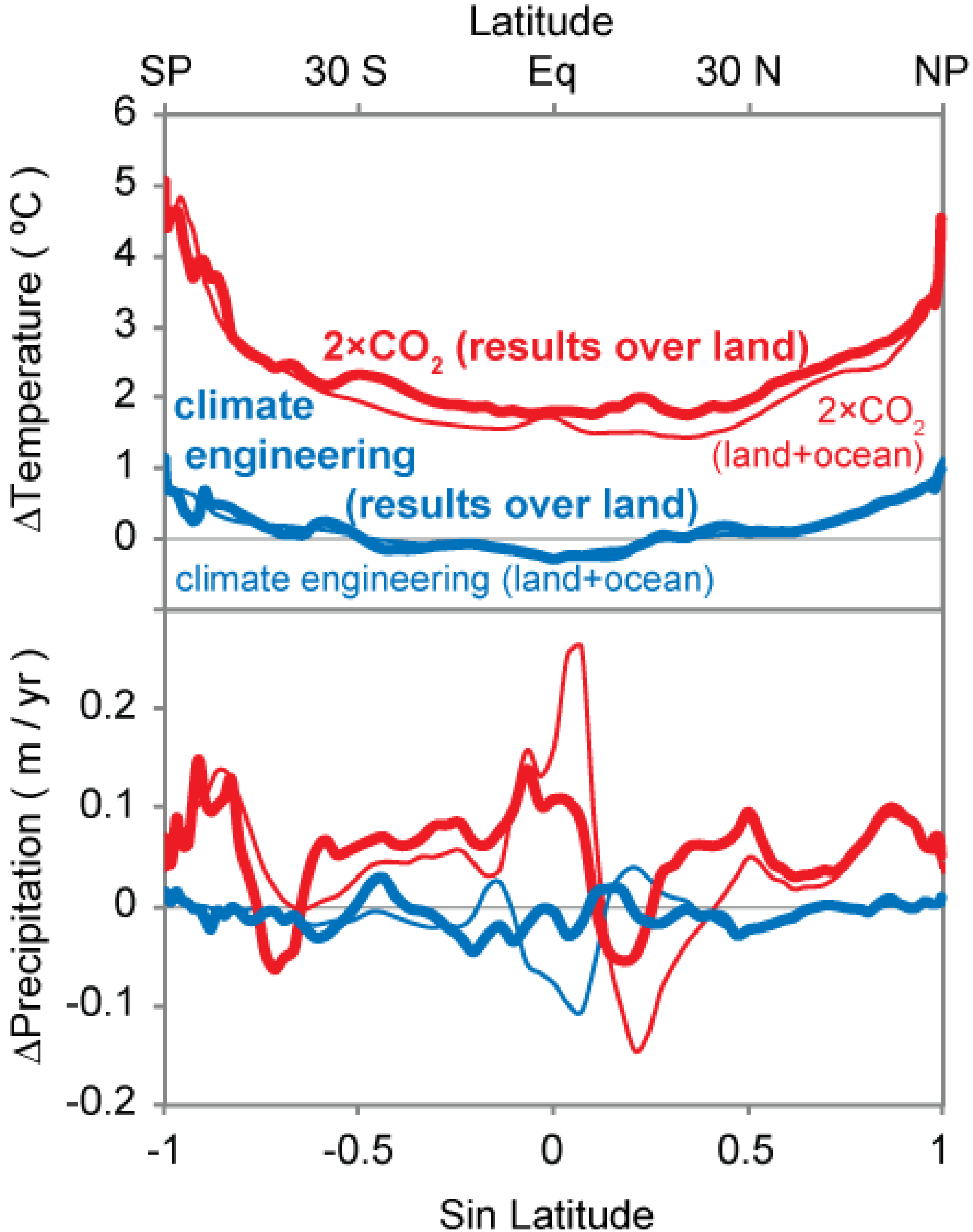
Δ Precipitation | **Statistical significance**

$2xCO_2$

$2xCO_2$ minus 1.84% sun



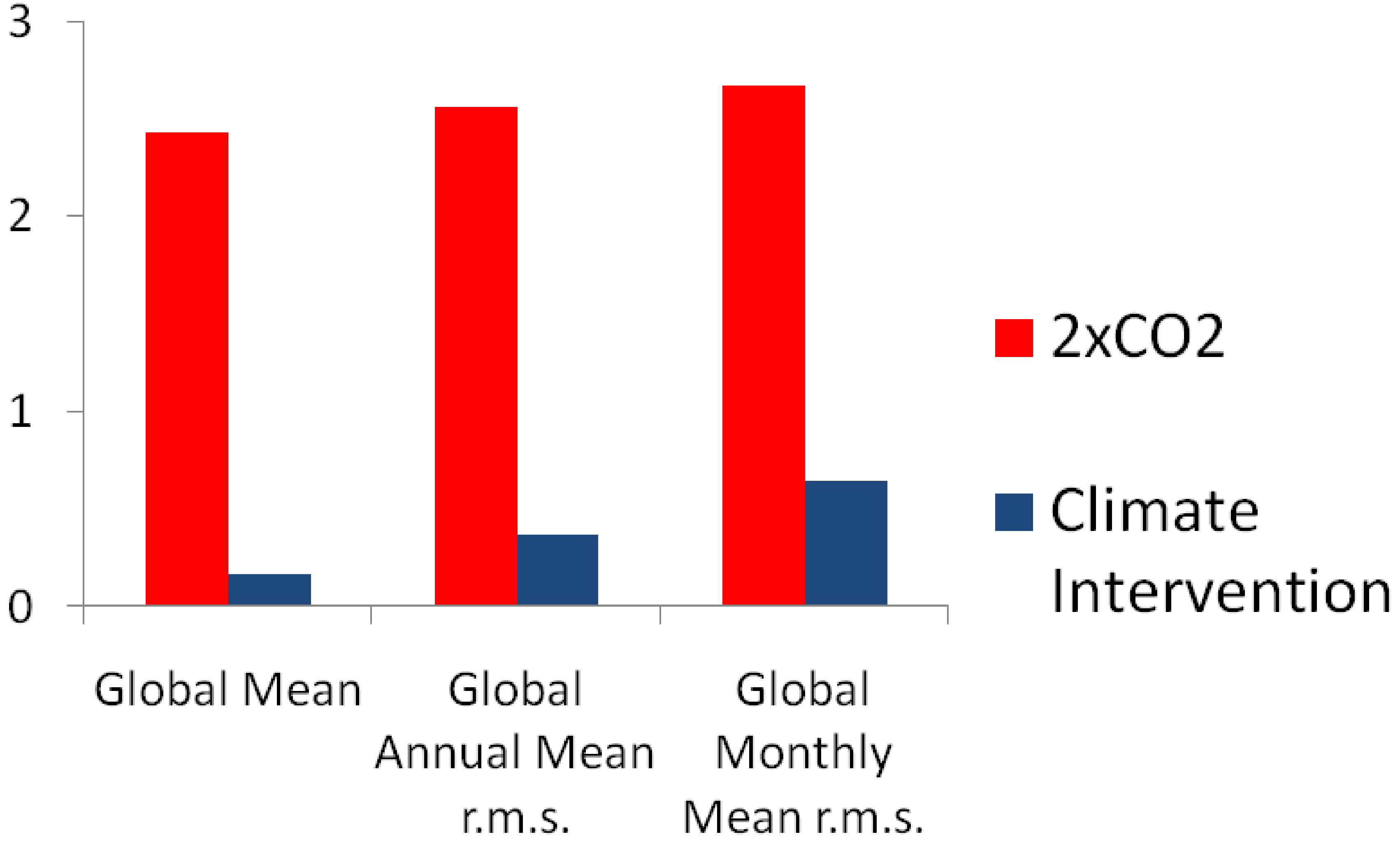
Caldeira and Wood, 2008



Deflecting 1.8% of sunlight reduces but does not eliminate simulated temperature and precipitation change caused by a doubling of atmospheric CO_2 content

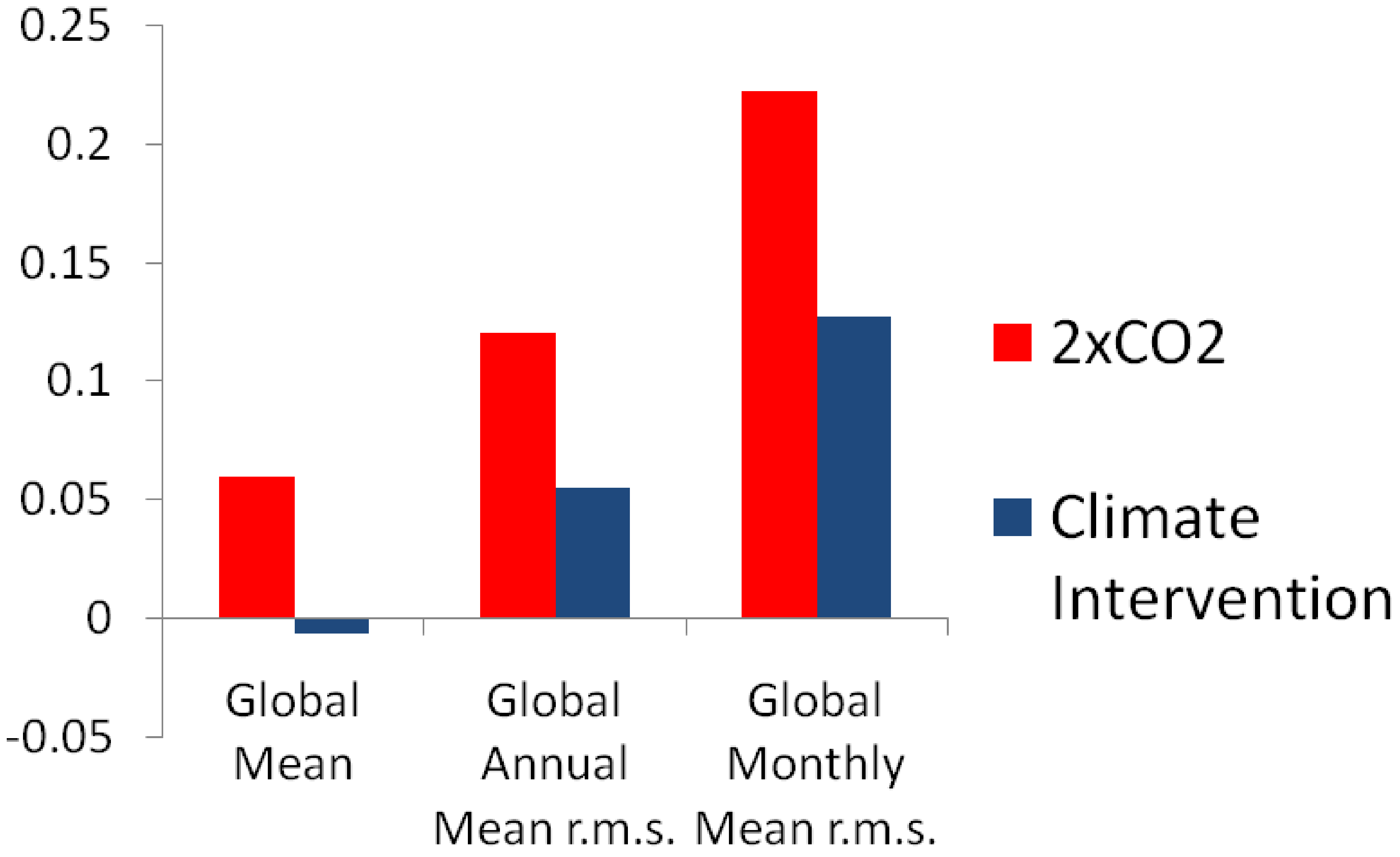
Caldeira and Wood, 2008

Temperature changes over land (°C)



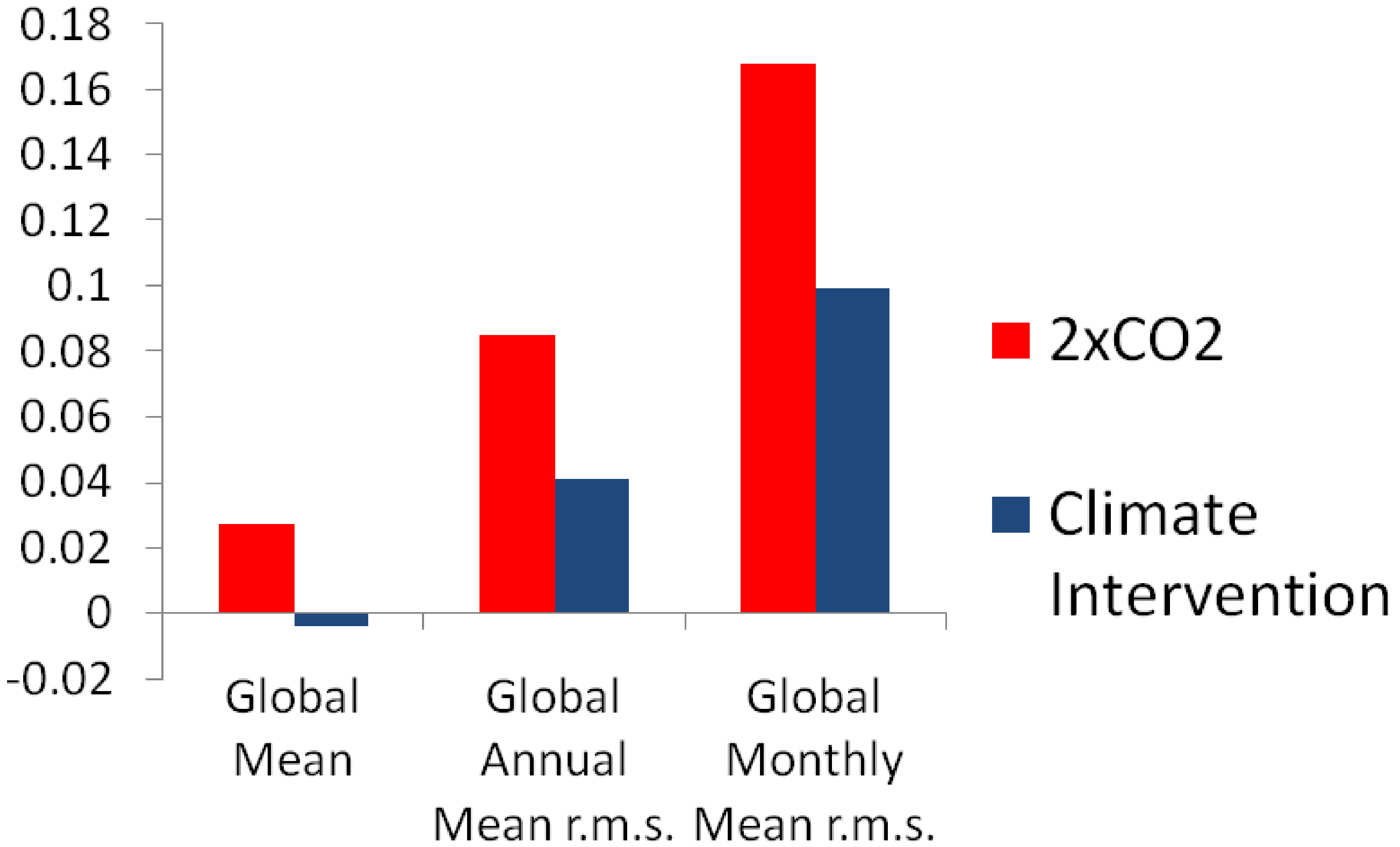
Caldeira and Wood, 2008

Precipitation changes over land (m/yr)



Caldeira and Wood, 2008

Runoff changes over land (m/yr)



Caldeira and Wood, 2008

What could be achieved with an optimized system?

But won’t the reduction in solar radiation hurt the biosphere?

Geoengineering and plant growth

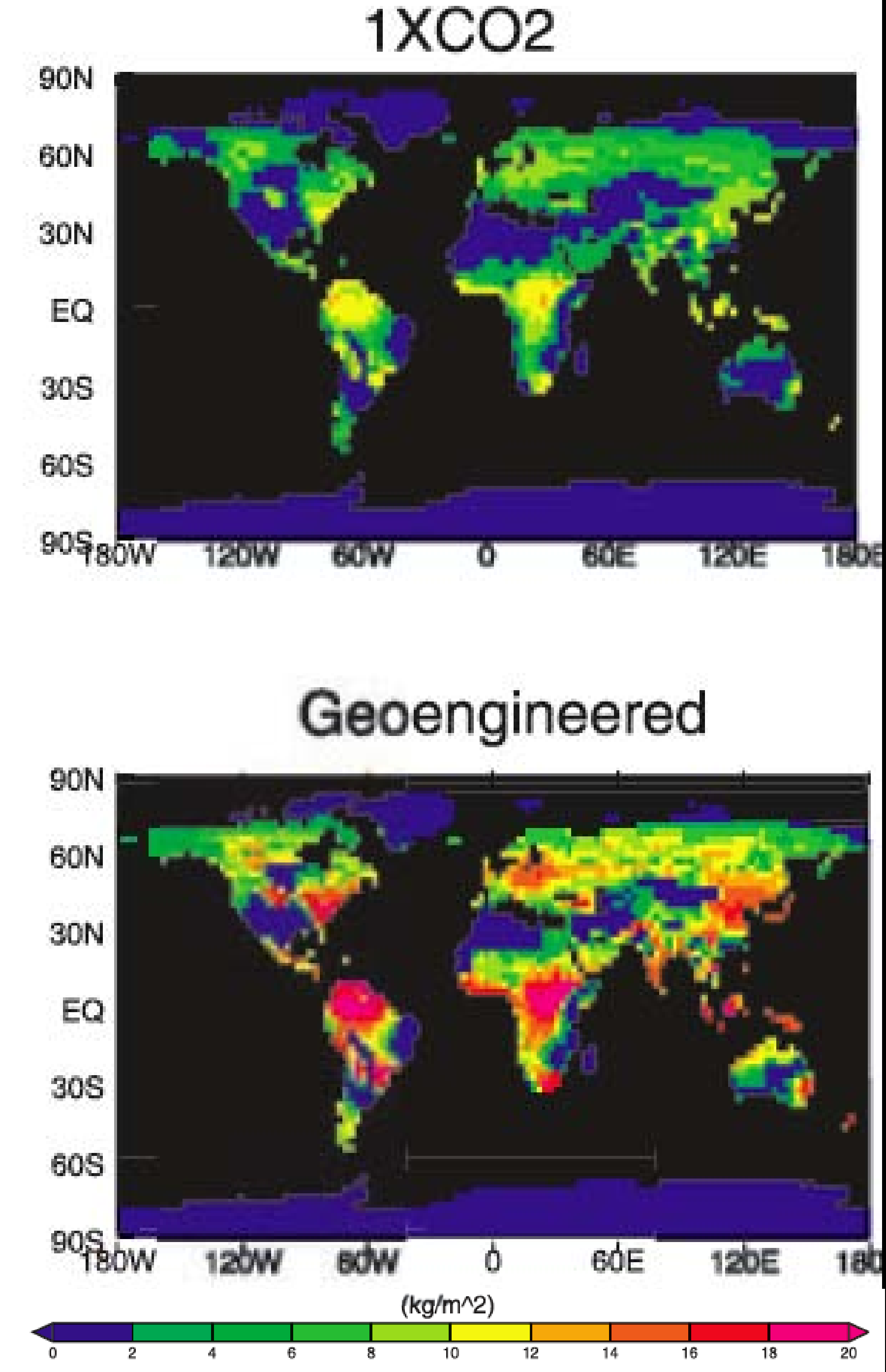


Figure 1. Total annual mean biomass simulated by IBIS in

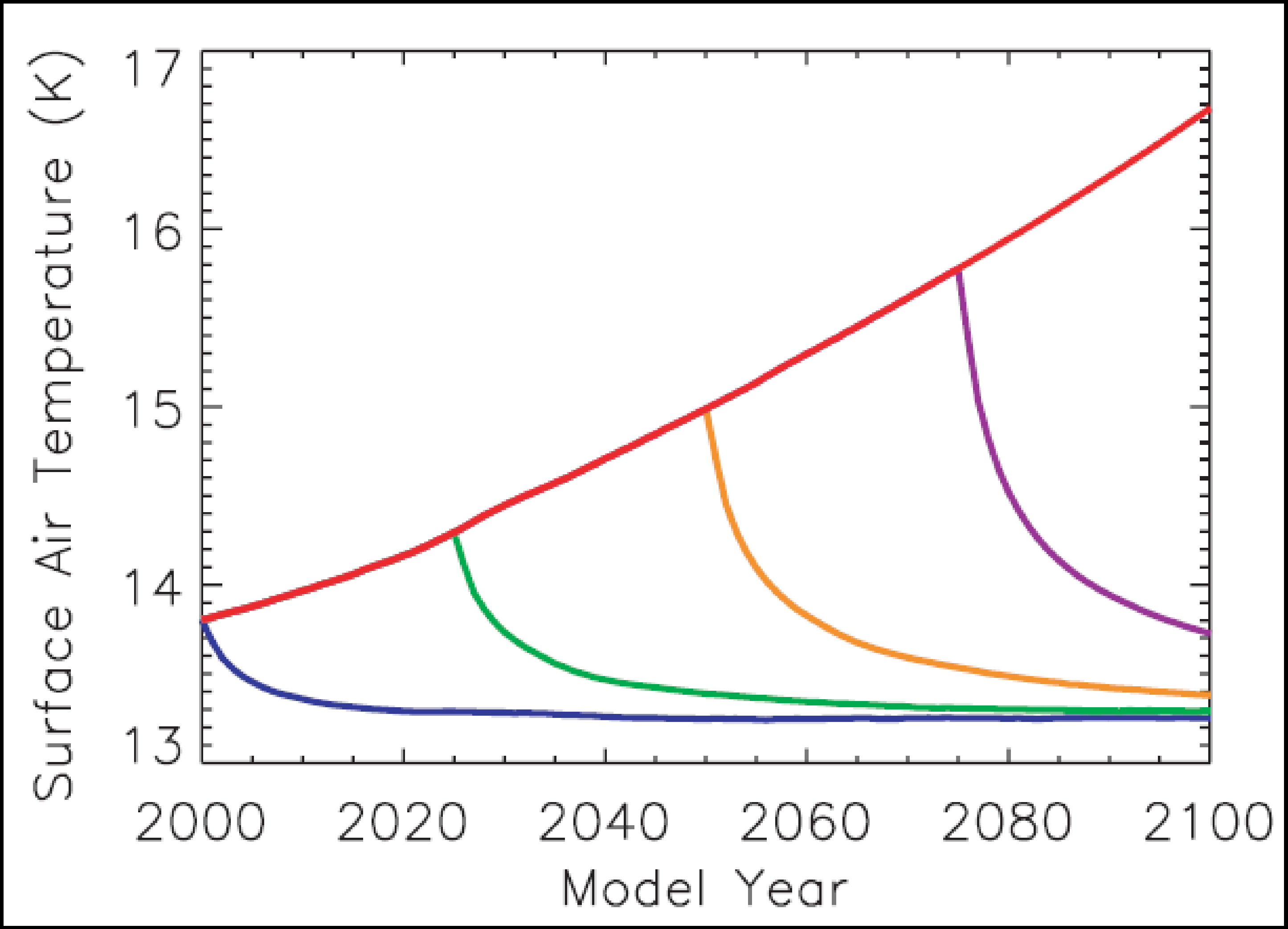
In the model, plants grow much better in the geoengineered world than in the natural world.

Geoengineering results in CO_2 fertilization without the increased heating that leads to increased plant respiration

Govindasamy et al., 2002

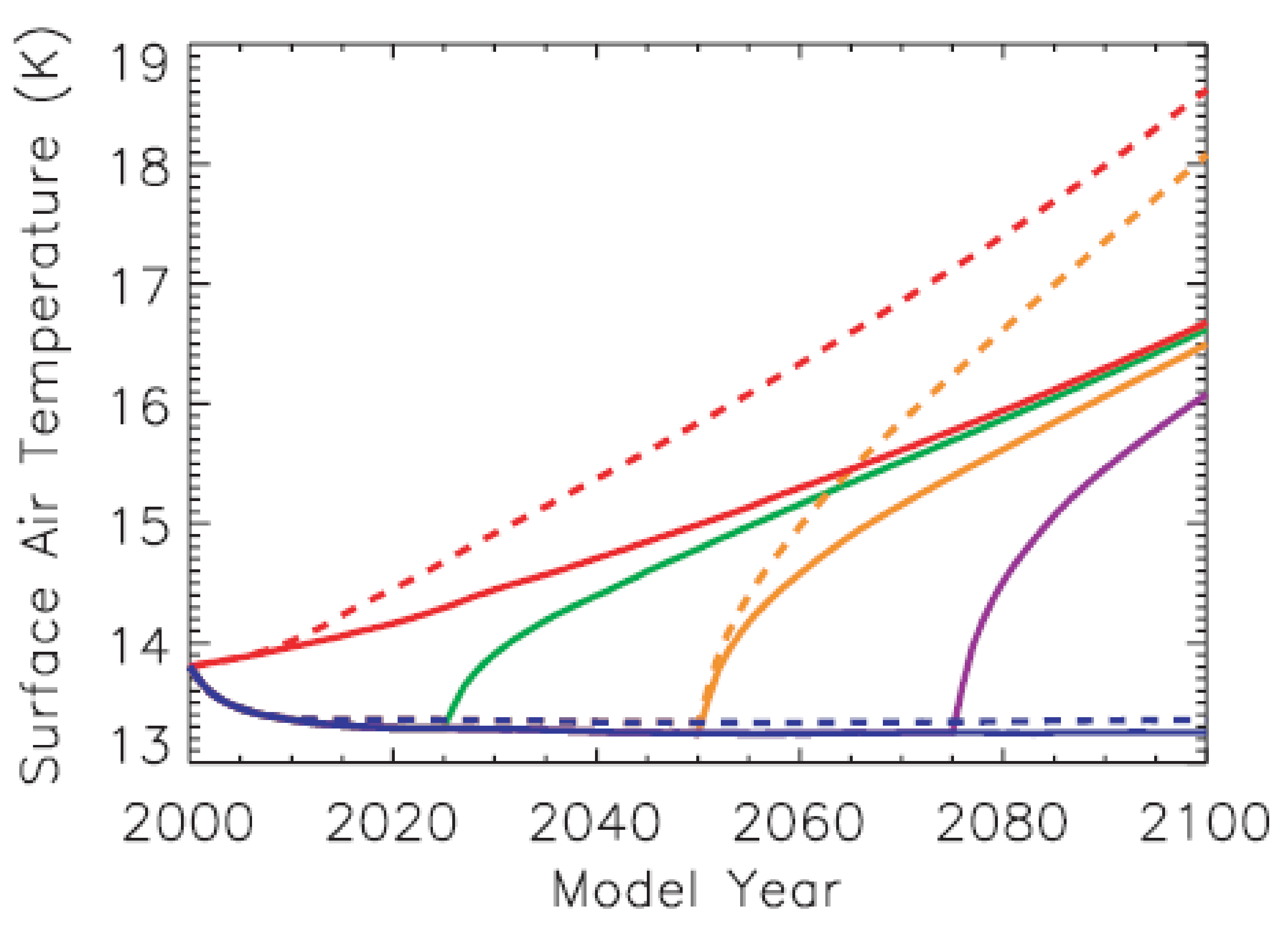
How fast would we feel the climate effects?

"Turning on" geoengineering suddenly has big effects on decadal time scale



Matthews and Caldeira, 2007

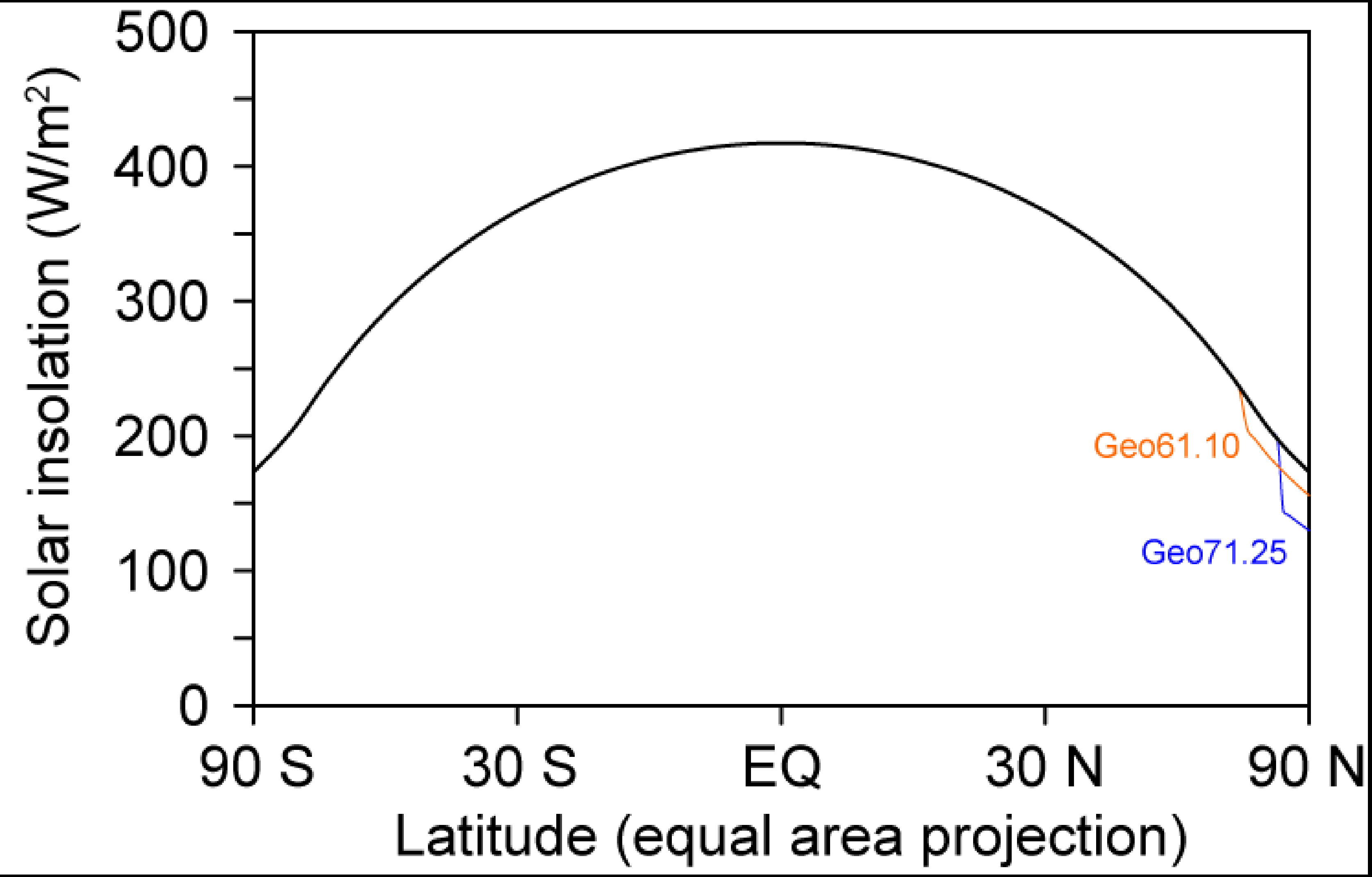
"Turning off" geoengineering suddenly has big effects on decadal time scale



Matthews and Caldeira, 2007

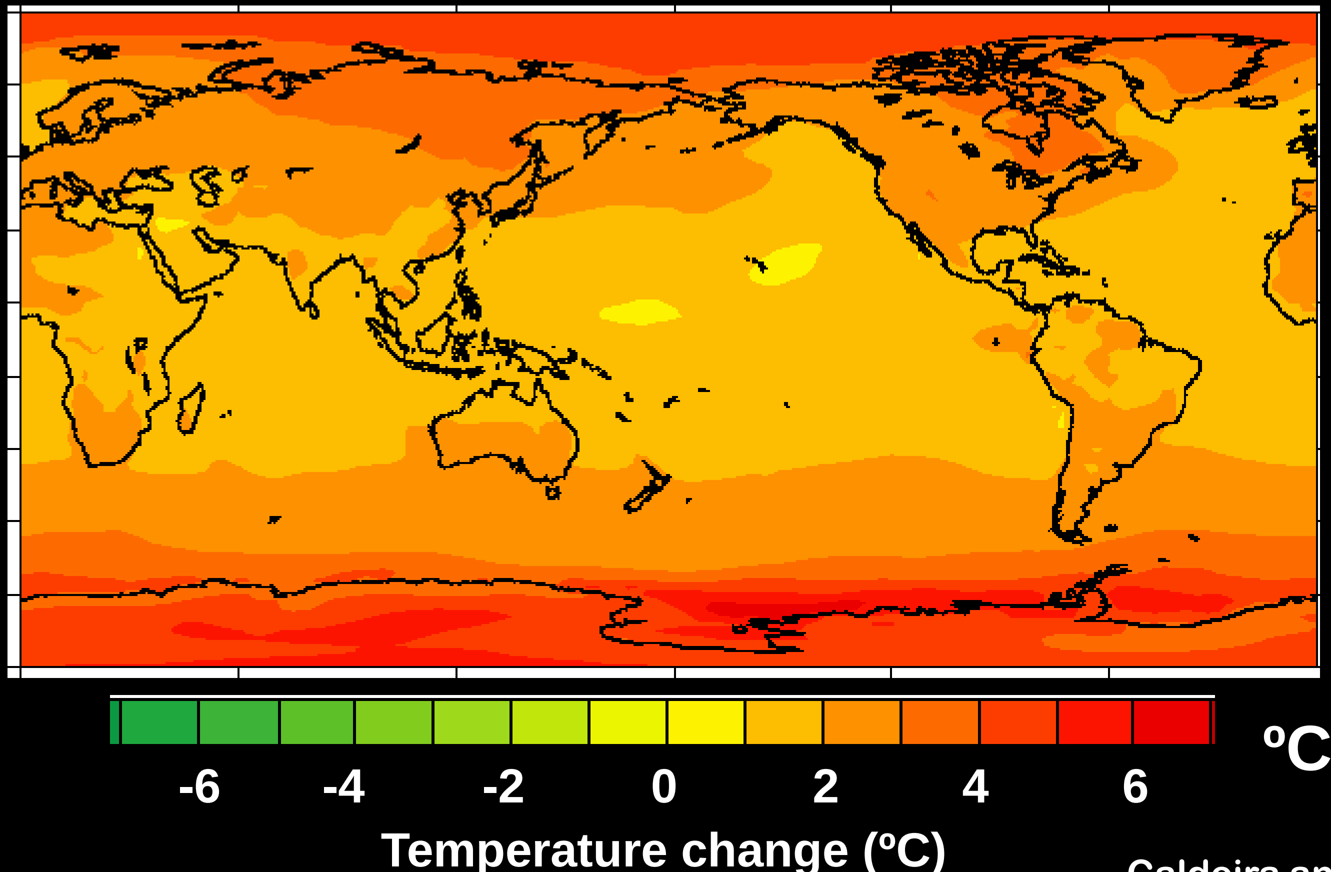
Would regional-scale climate intervention be possible?

Both geoengineering cases remove ~0.37% of total solar insolation



Annual mean temperature response

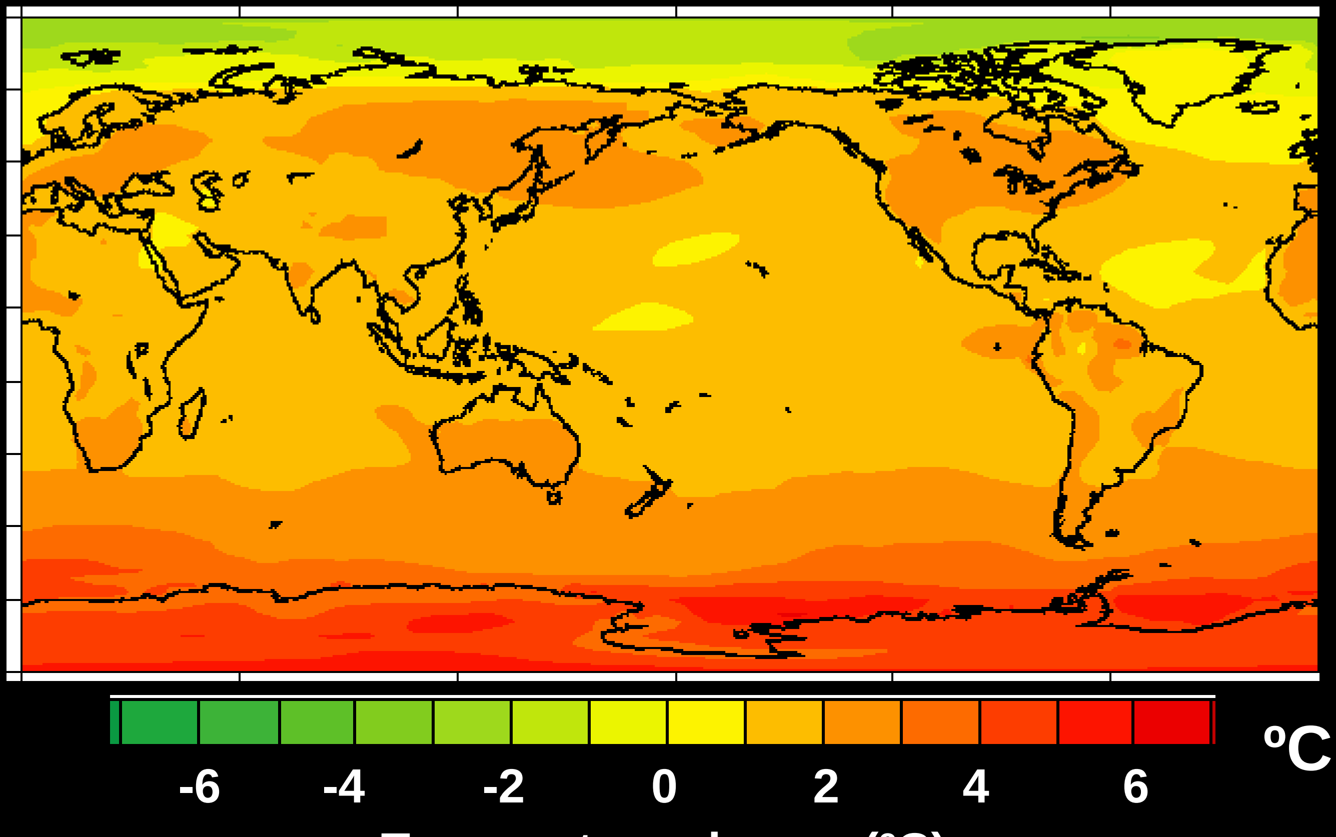
- $2xCO_2$
  - 560 ppm CO_2, normal solar radiation



Caldeira and Wood, 2008

Annual mean temperature response

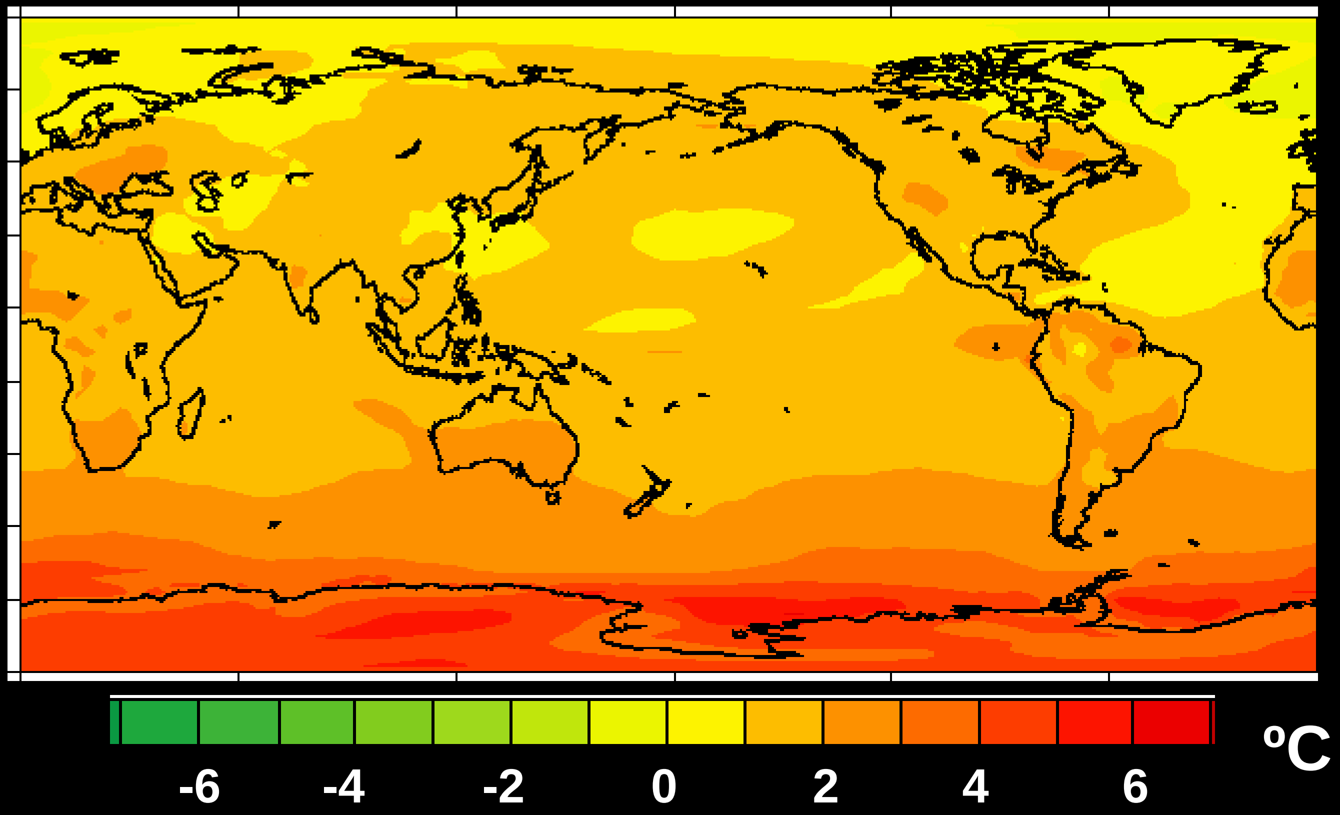
- Geo71.25
  - 560 ppm CO_2, 25% solar reduction north of 71ºN



Caldeira and Wood, 2008

Annual mean temperature response

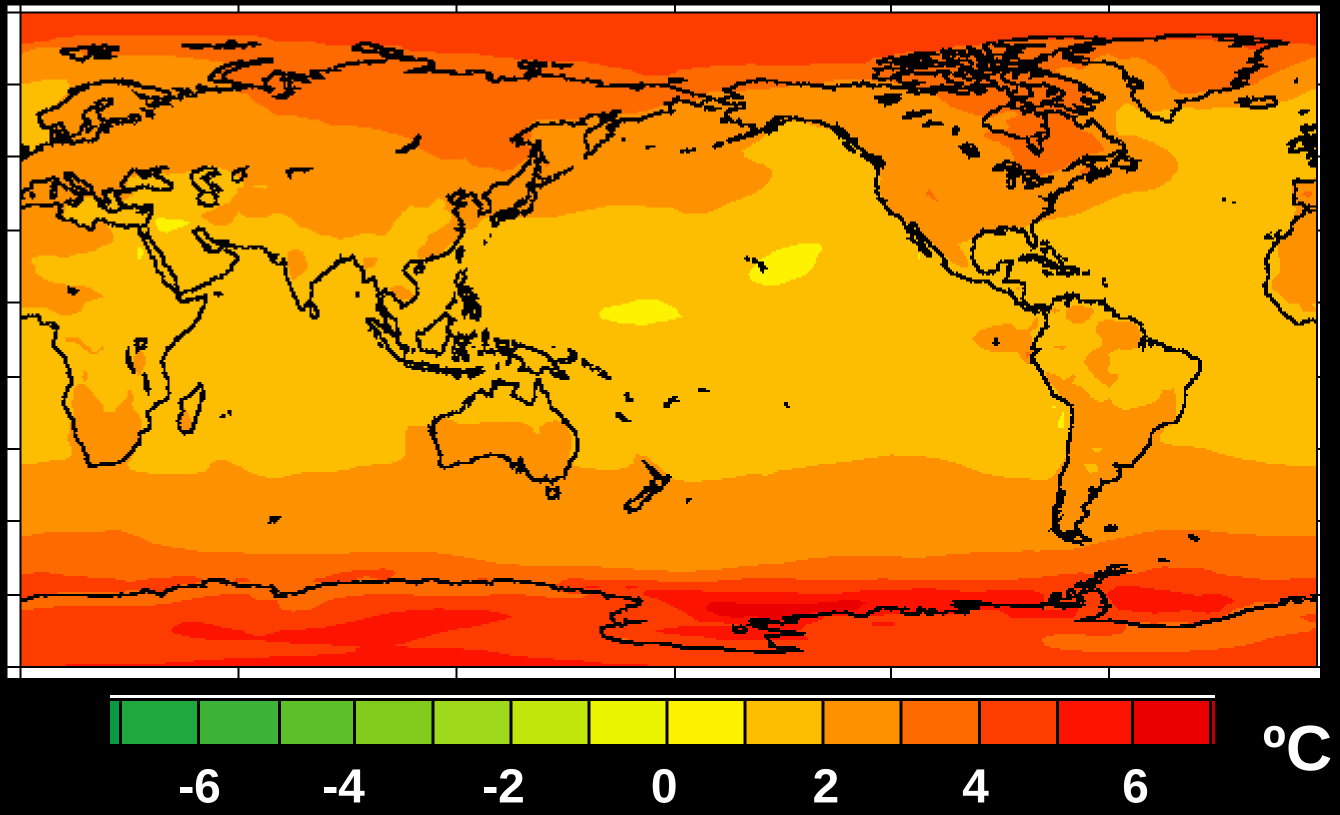
- Geo61.10
  - 560 ppm CO_2, 10% solar reduction north of 61ºN



Caldeira and Wood, 2008

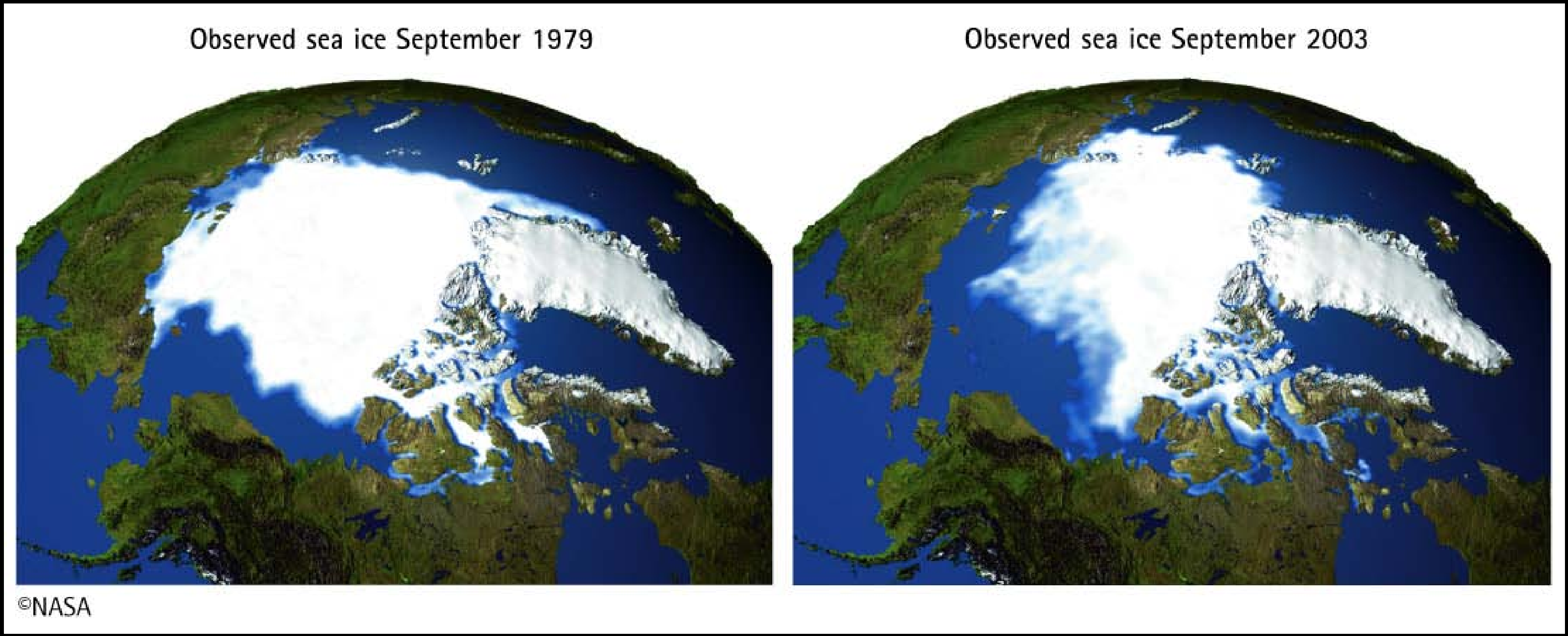
Annual mean temperature response

- $2xCO_2$
  - 560 ppm CO_2, normal solar radiation



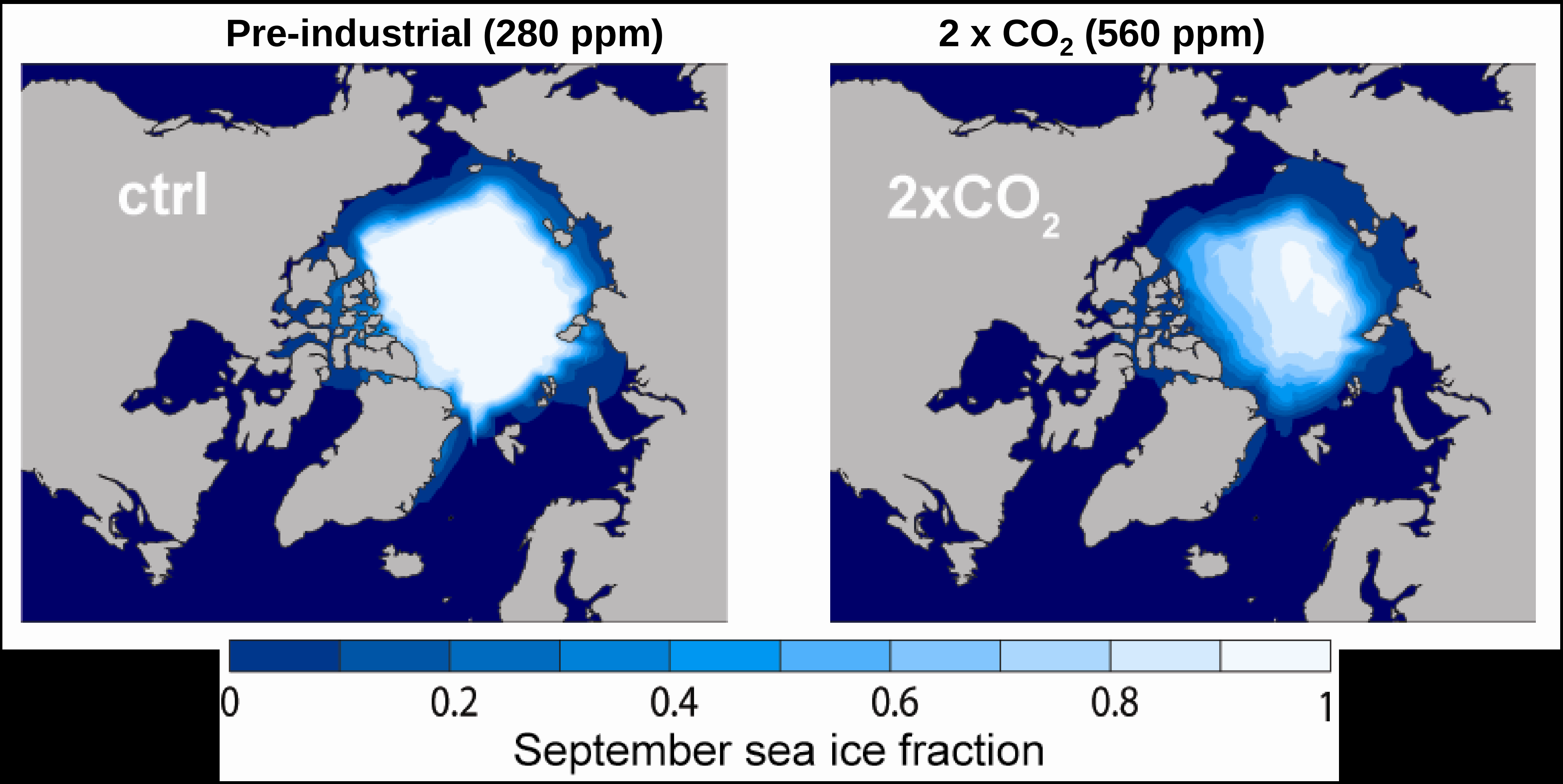
Caldeira and Wood, 2008

Observed September sea-ice

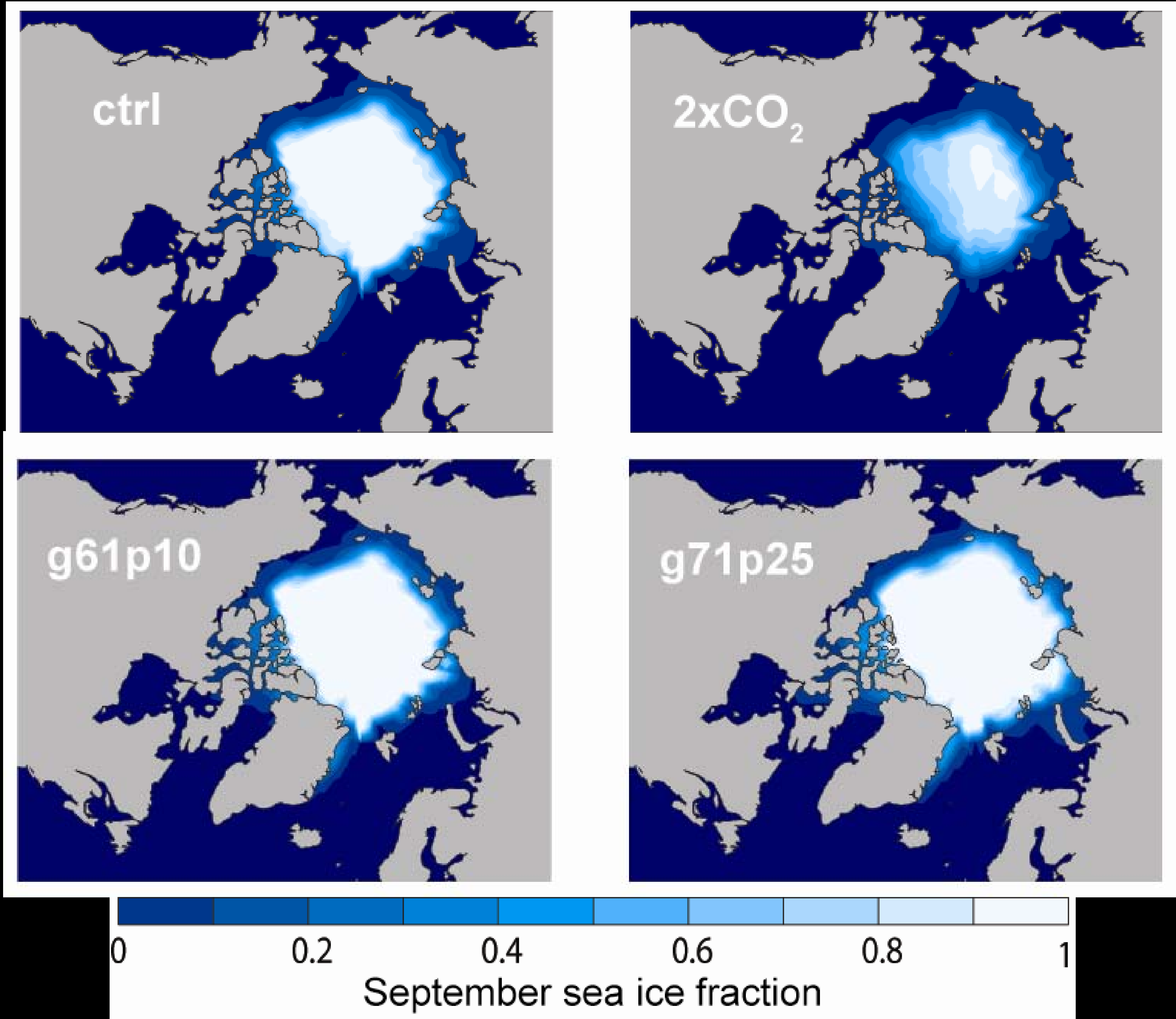


NASA

Modeled September sea-ice



Caldeira and Wood, 2008



Caldeira and Wood, 2008

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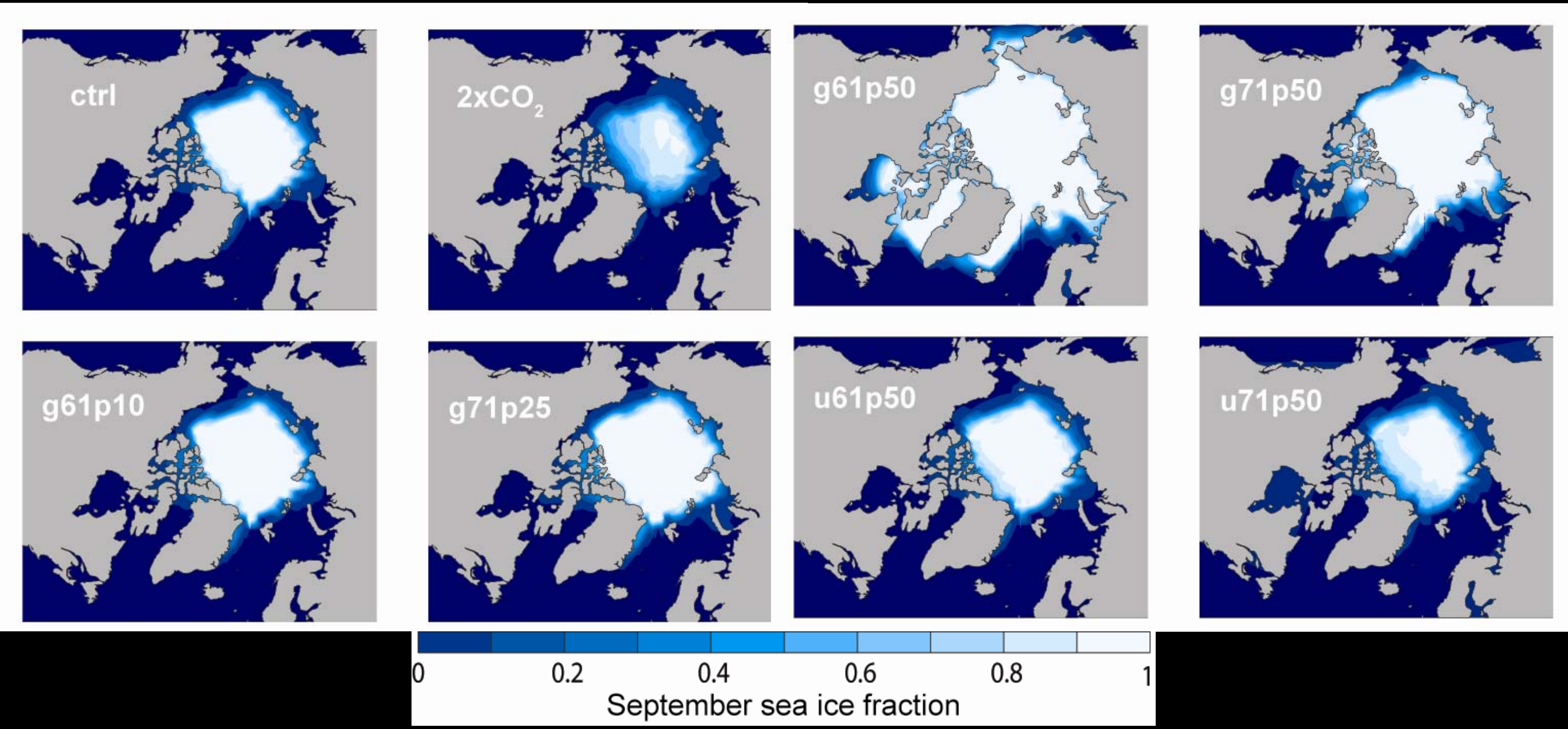
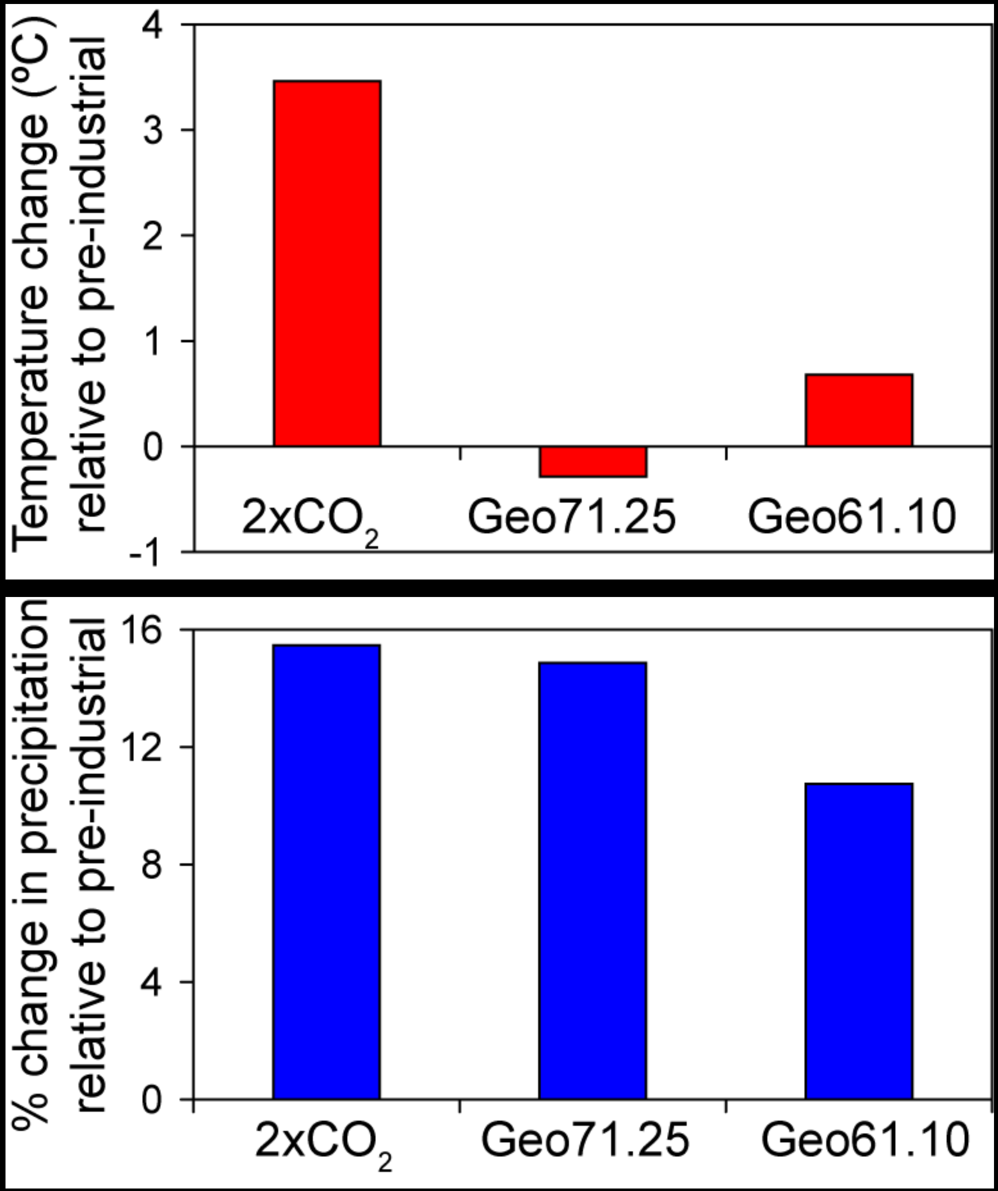


Caldeira and Wood, 2008

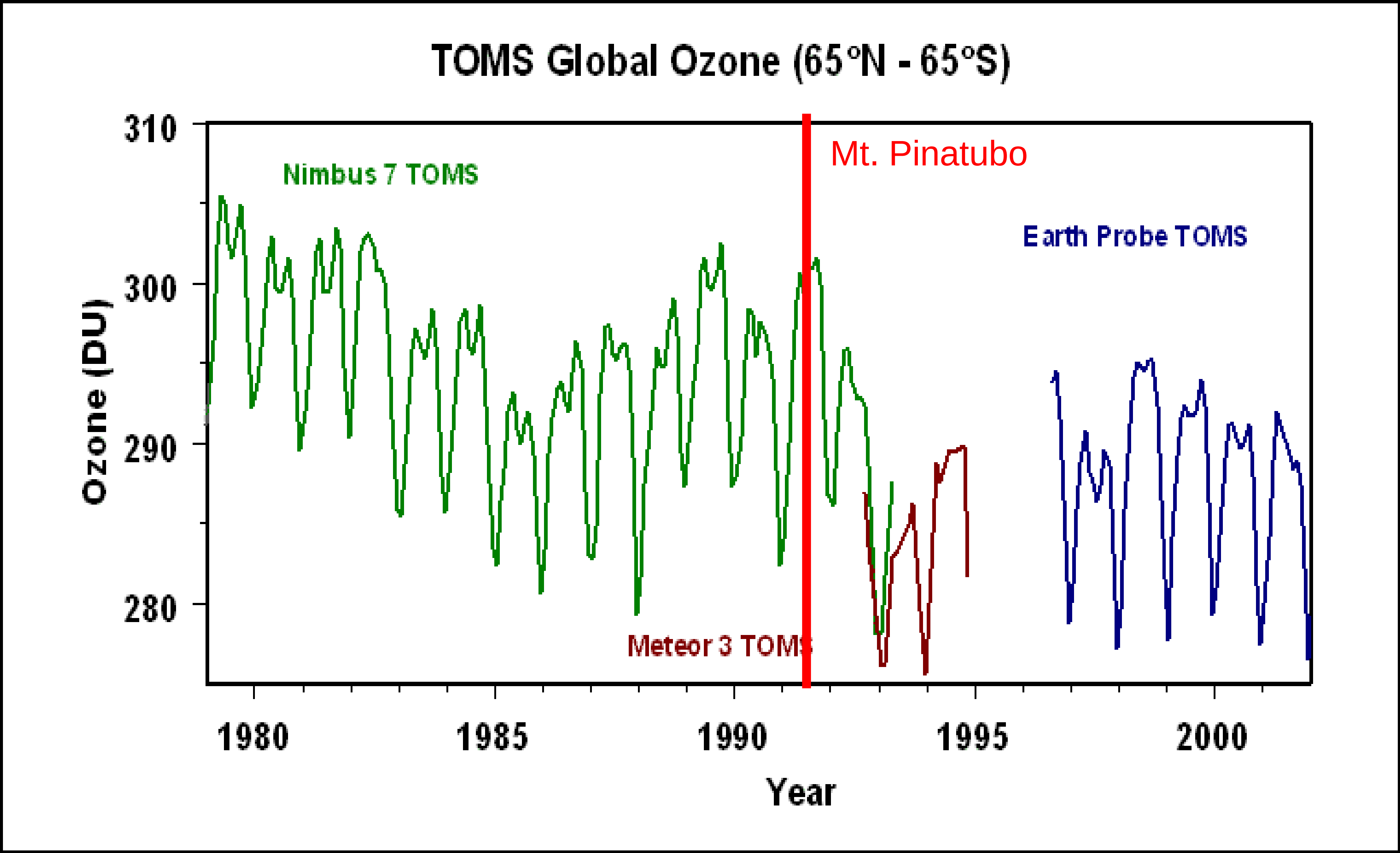
Arctic geoengineering reverses temperature effects but not increased precipitation



Caldeira and Wood, 2008

Ozone

Mt. Pinatubo and global ozone



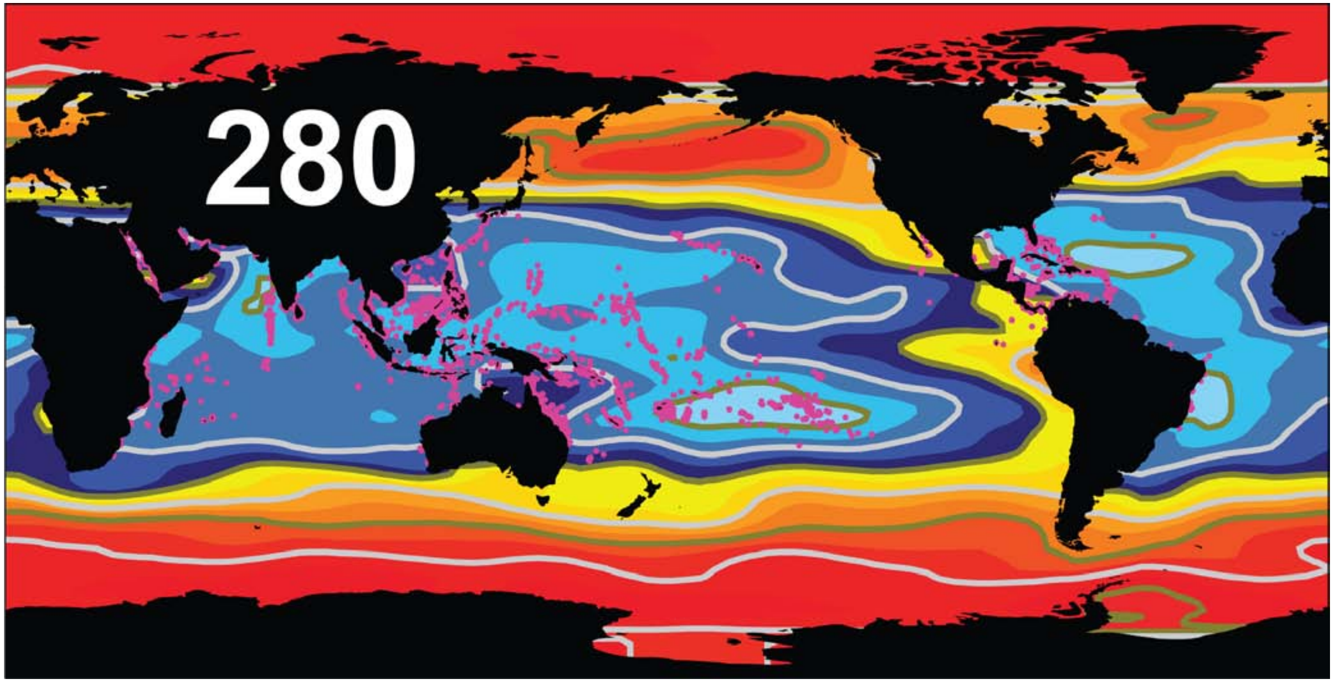
Unanticipated outcomes

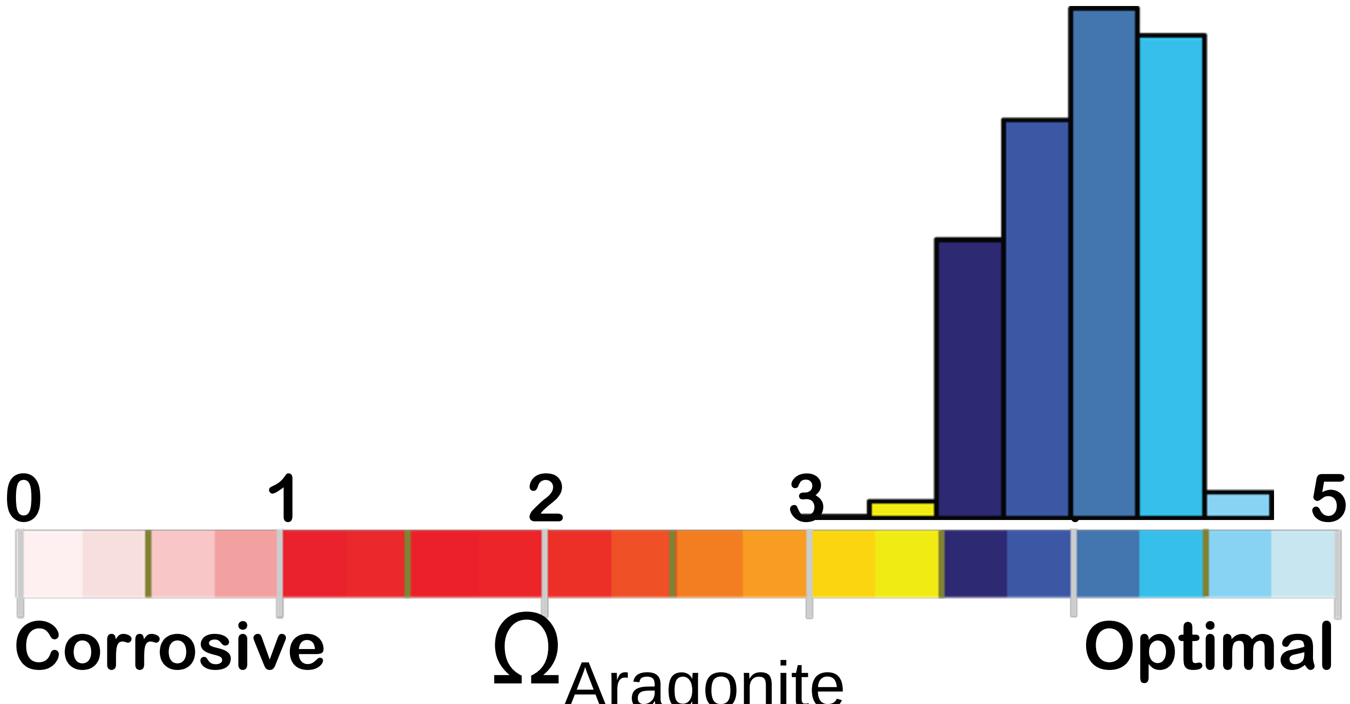

Little knowledge
Great risks
Great potential

Carbon dioxide level,

Coral reef distribution,

and chemical conditions helping drive reef formation





Cao and Caldeira, 2008

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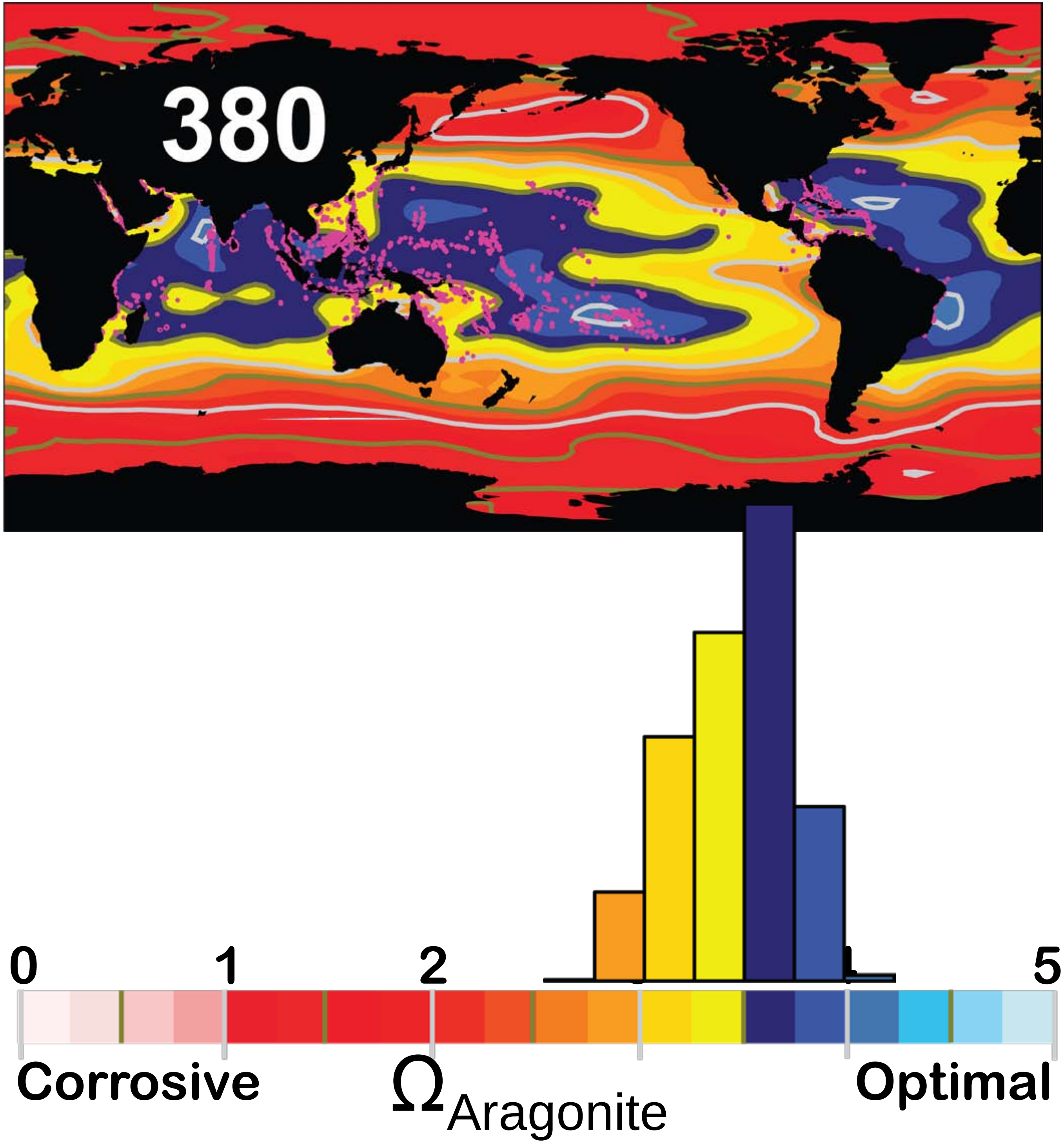

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Carbon dioxide level,

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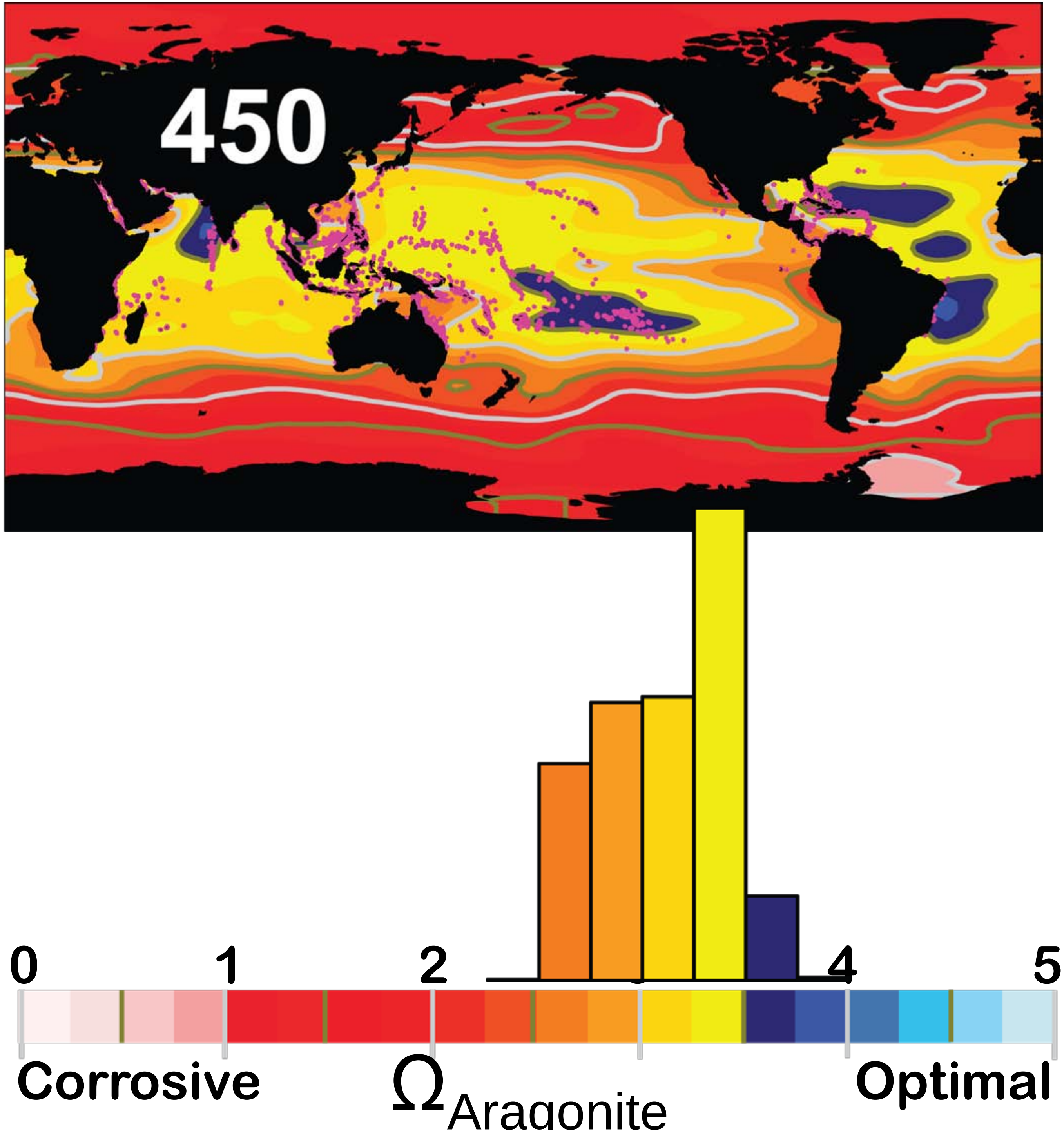

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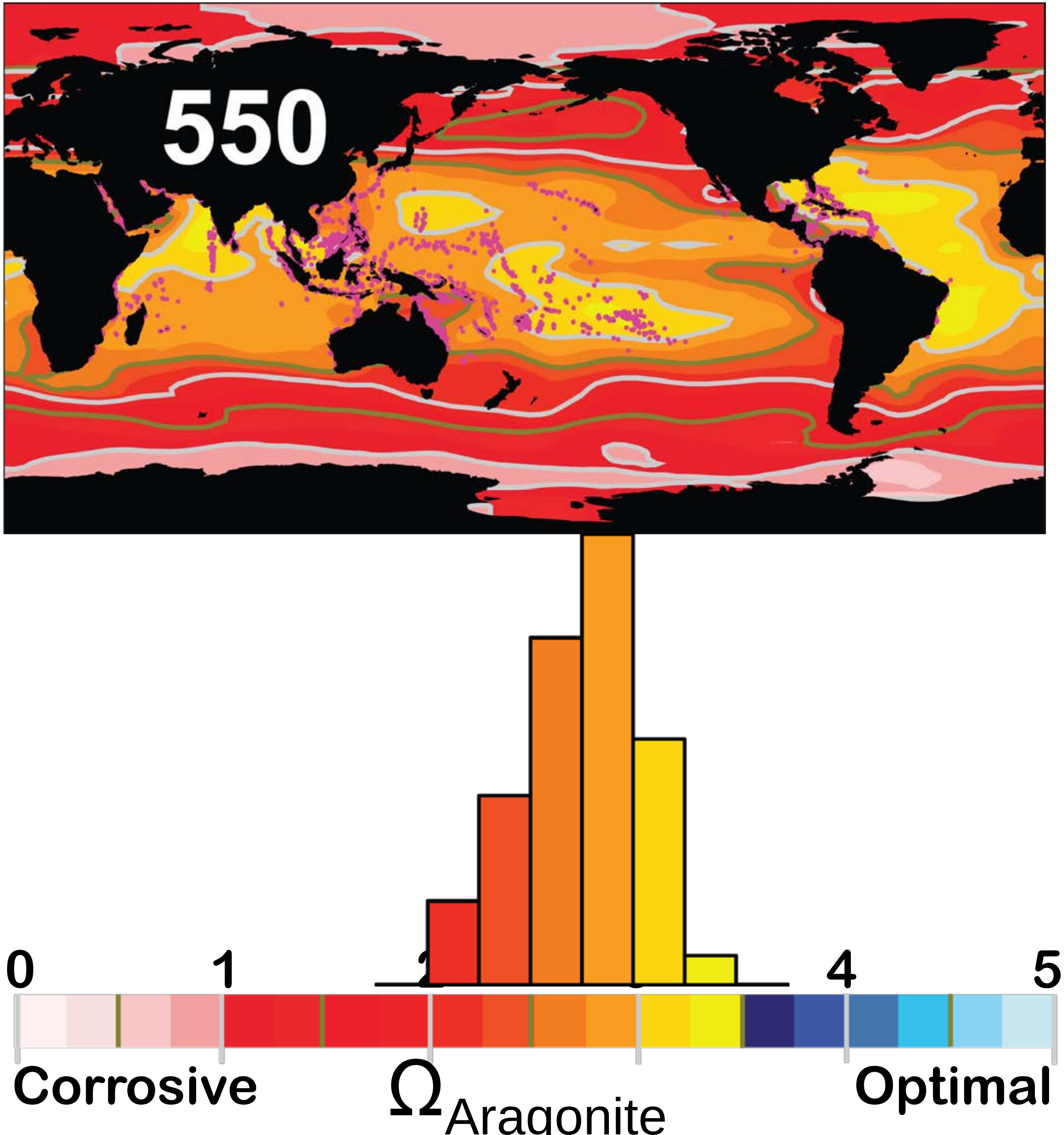

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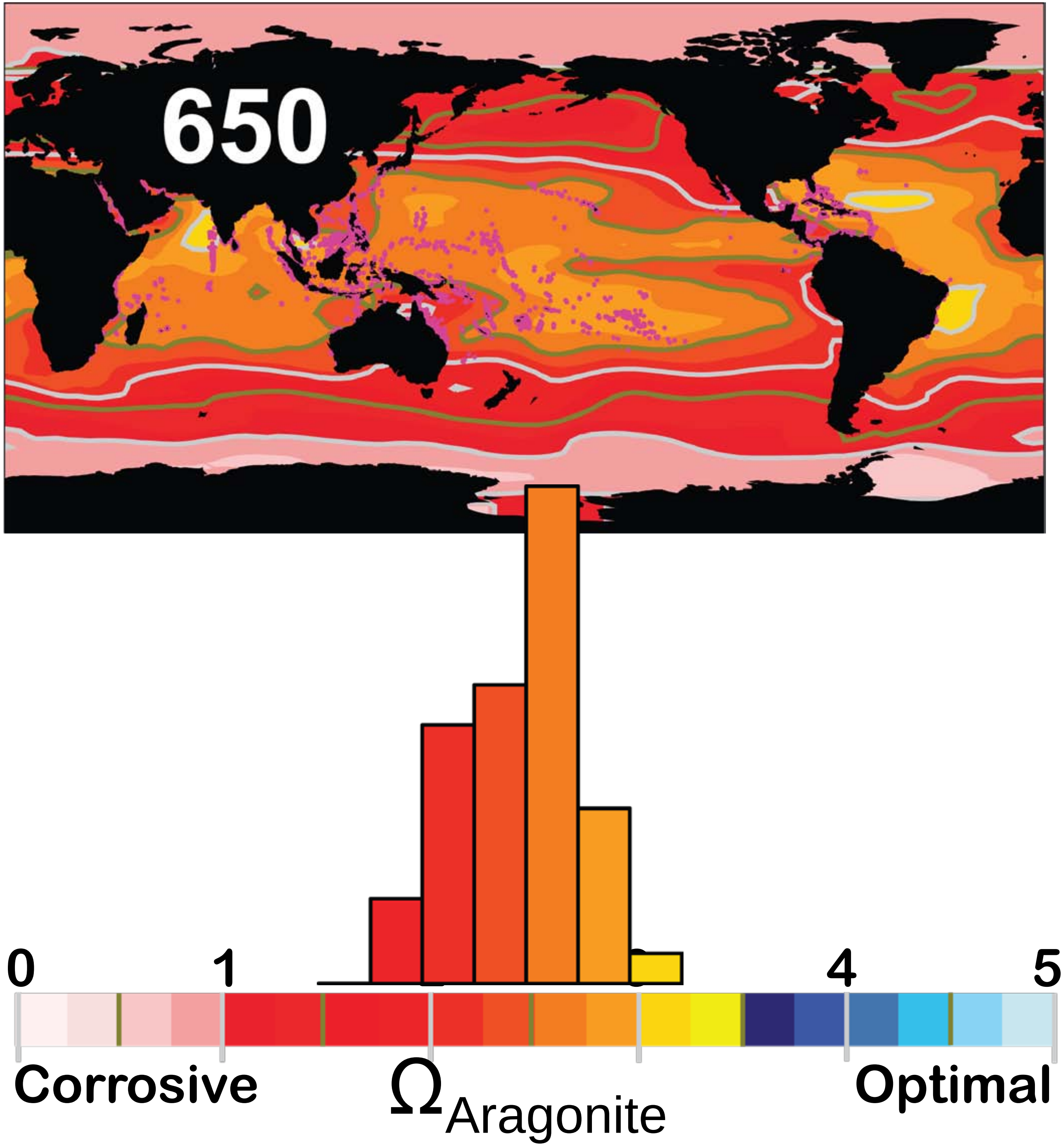

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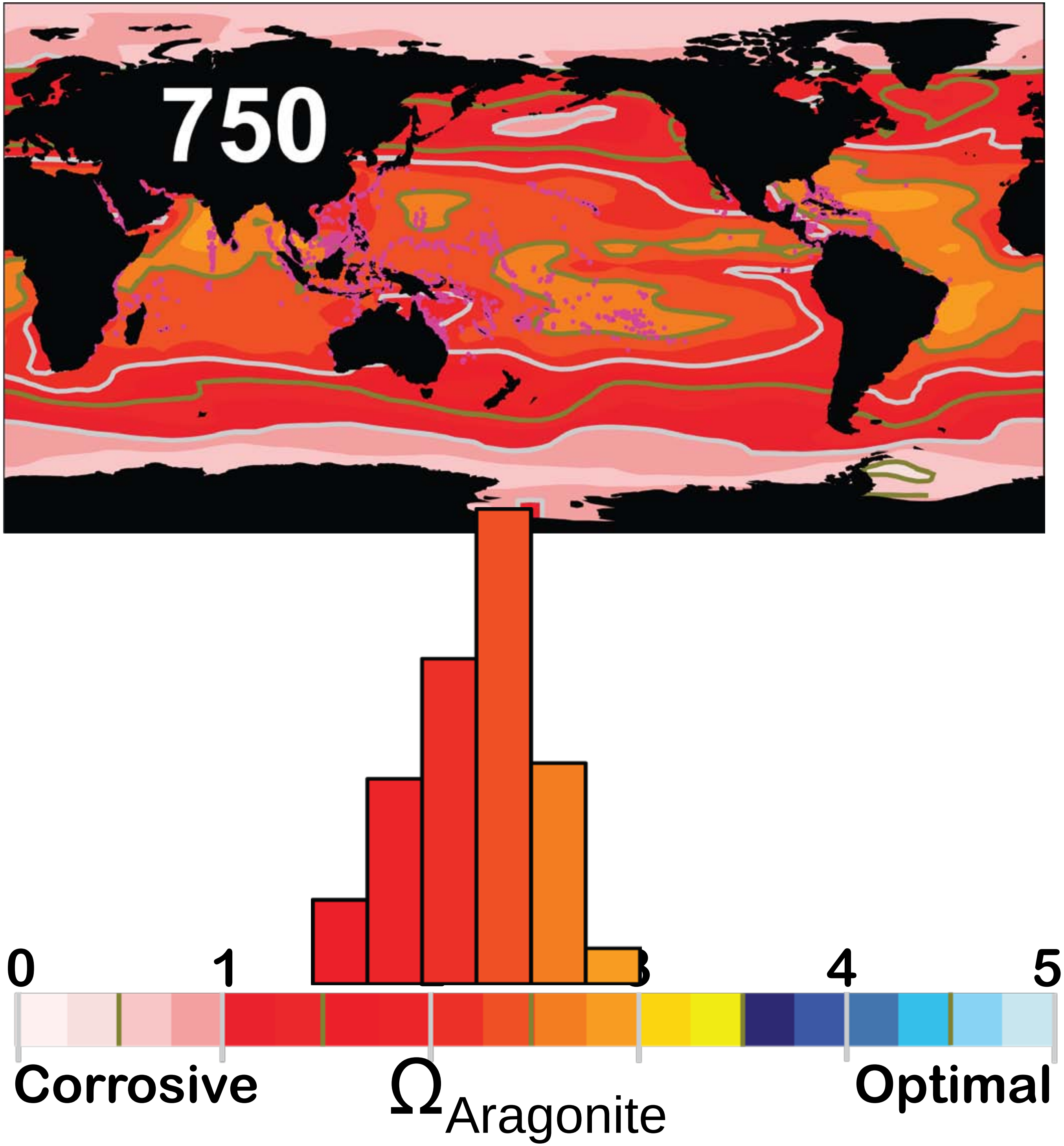

Cao and Caldeira, 2008

Questions

- What are the range of possible feasible means of intervening in the climate system?
  - What are the advantages and disadvantages of each method?

Questions

- How can science and technology be advanced to rapidly and cost-effectively provide useful assessments for people who will need to make decisions about intentional climate intervention?

Questions

- How could one predict the effects of large-scale geoengineering attempts, and what new science is required to improve these predictions?
  - To what extent can small-scale geoengineering pilot studies provide useful information about the impacts of large-scale geoengineering efforts?

Questions

- How long would it take to fully understand the extent to which a geoengineering attempt does in fact affect the climate?
  - What can be done to counteract adverse effects of climate interventions?

Issues

- Governance and regulation
  - National level
  - International level

- Research and development
  - Lab tests and computer modeling
  - Field tests

two online discussion groups

- http://groups.google.com/group/geoengineering
  - Broad ranging discussion involving interested public
- http://groups.google.com/group/climateintervention
  - More focused discussion, oriented towards academics

Conclusions

- Investigation of the climate effects of various climate intervention approaches is in its infancy
- Preliminary results indicate that a high-CO_2 world with climate intervention would be more similar to the pre-industrial world than would be a high-CO_2 world without geoengineering
- The Earth System is notoriously complex, and one can assume that tinkering with it on a global scale will produce unanticipated outcomes