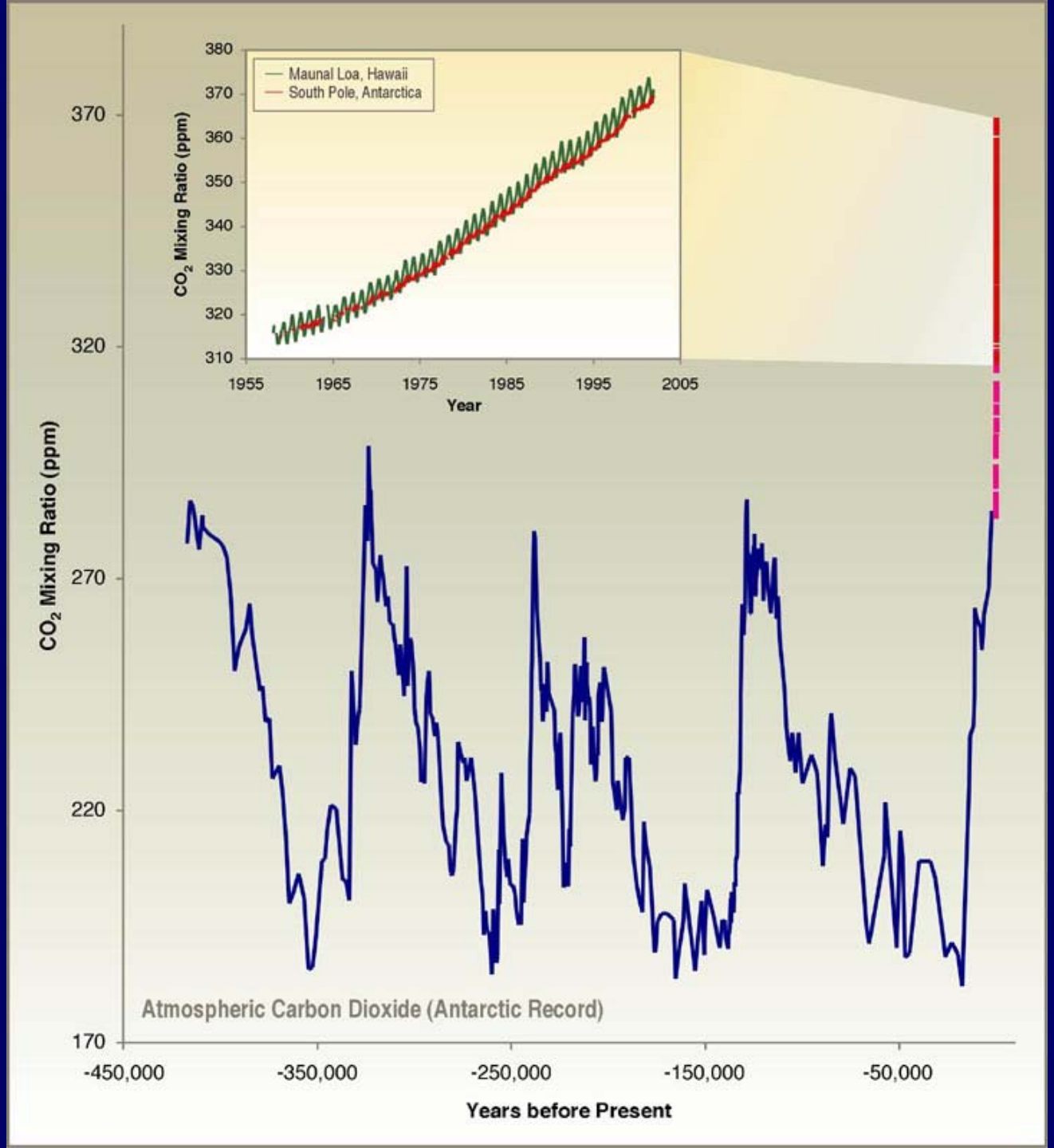
Frontiers in Global Change
PNNL

17 March 2009

Policy-relevant science to help solve the carbon-climate problem

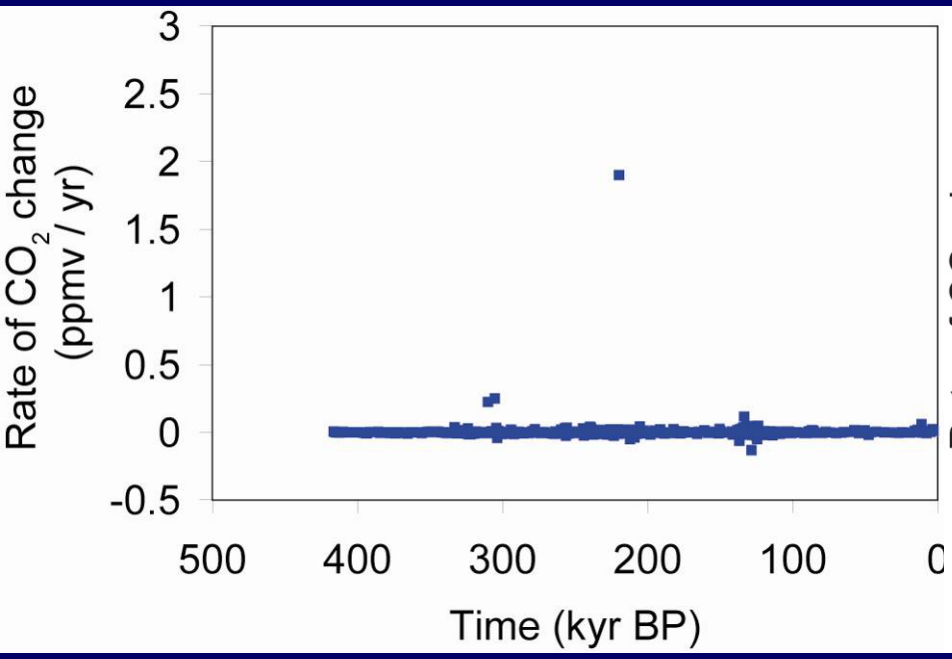
Ken Caldeira
Carnegie Institution Dept of Global Ecology
Stanford, CA
kcaldeira@stanford.edu

Carbon emissions and the scale of the problem

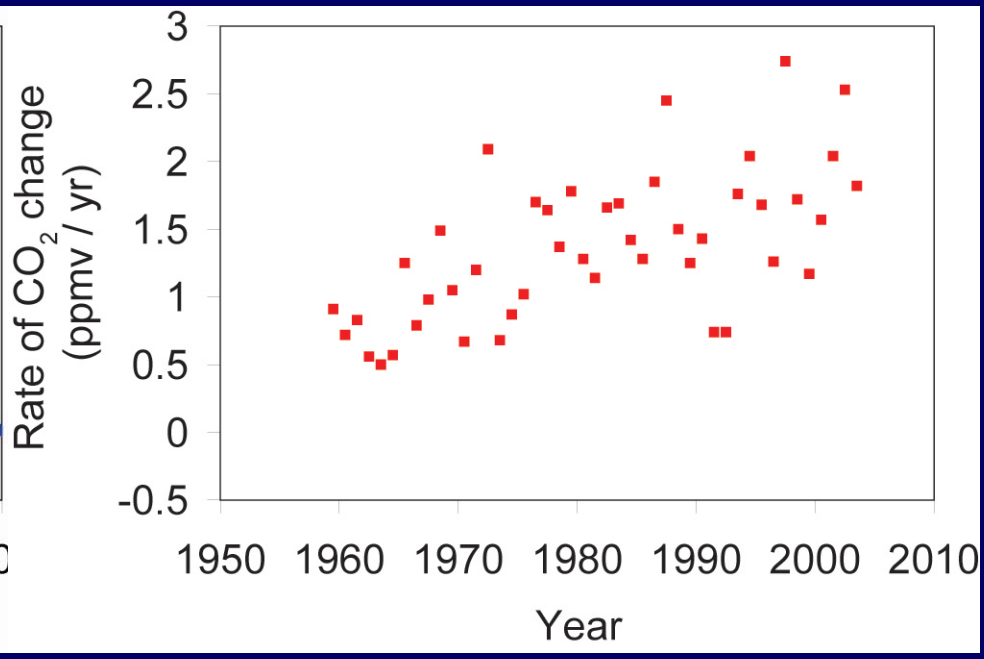

Maunal Loa, Hawaii
South Pole, Antarctica
CO_2 Mixing Ratio (ppm)
380
370
360
350
340
330
320
310
1955
1965
1975
1985
1995
2005
Year
370
320
270
220
170
CO_2 Mixing Ratio (ppm)
Atmospheric Carbon Dioxide (Antarctic Record)
-450,000
-350,000
-250,000
-150,000
-50,000
Years before Present

Rates of atmospheric CO_2 change

Glacial-Interglacial



Recent

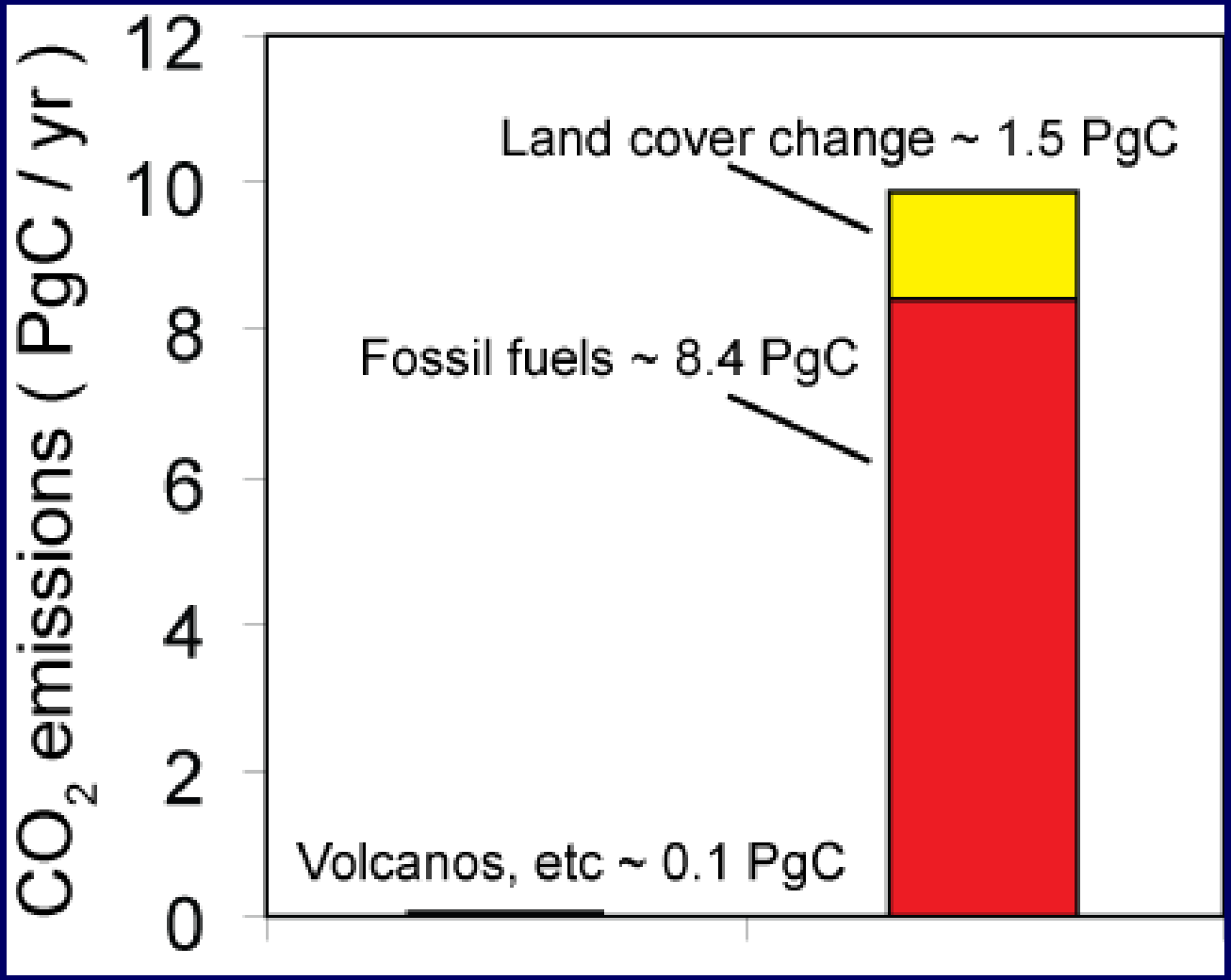


Atmospheric CO_2 is changing ~ 100 times more rapidly than natural variation

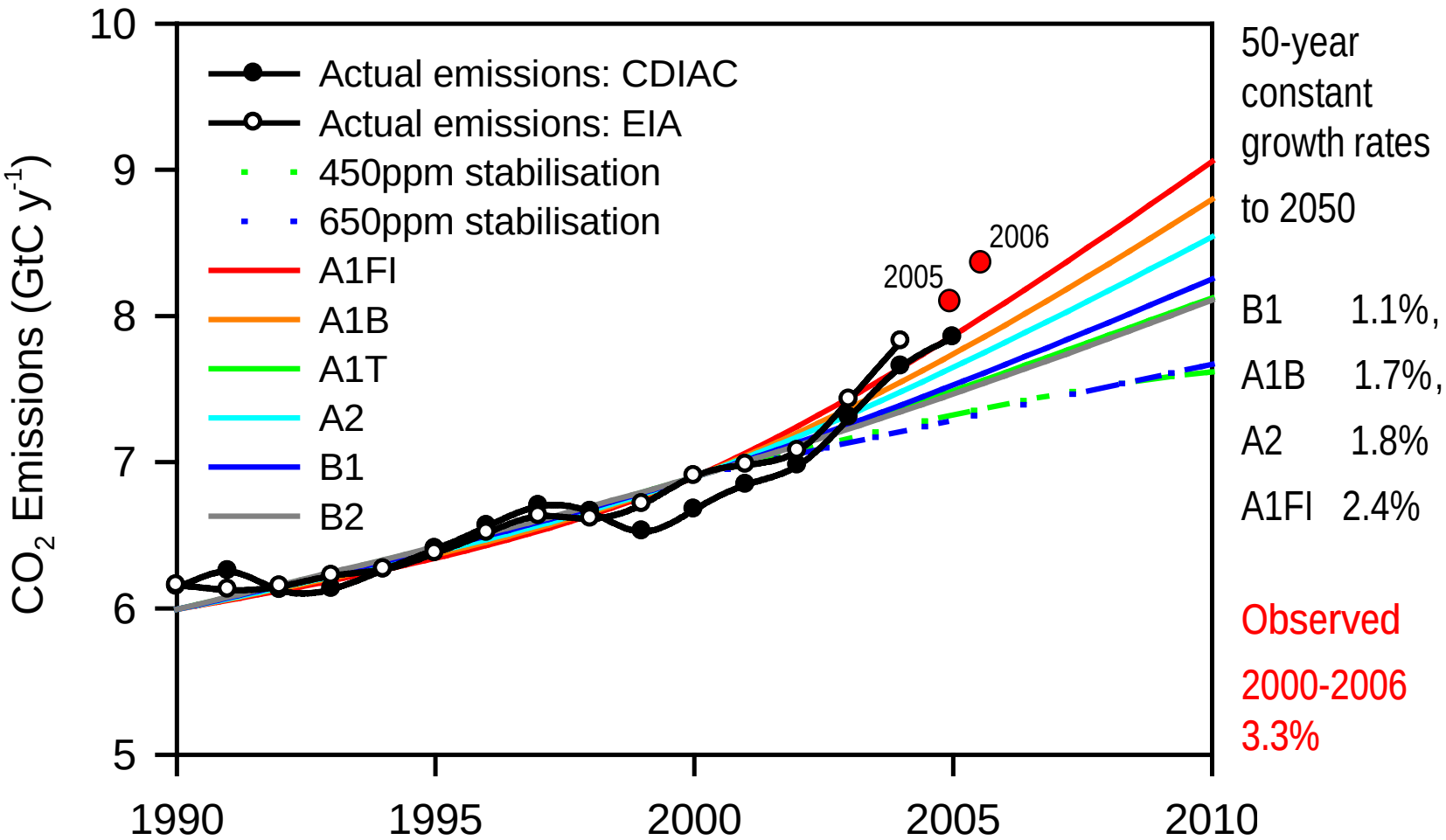
Calculated from Petit et al (1999)

Calculated from Keeling and Whorf (2005)

Anthropogenic CO_2 emissions exceed natural emissions by a factor of about 100



Trajectory of Global Fossil Fuel Emissions



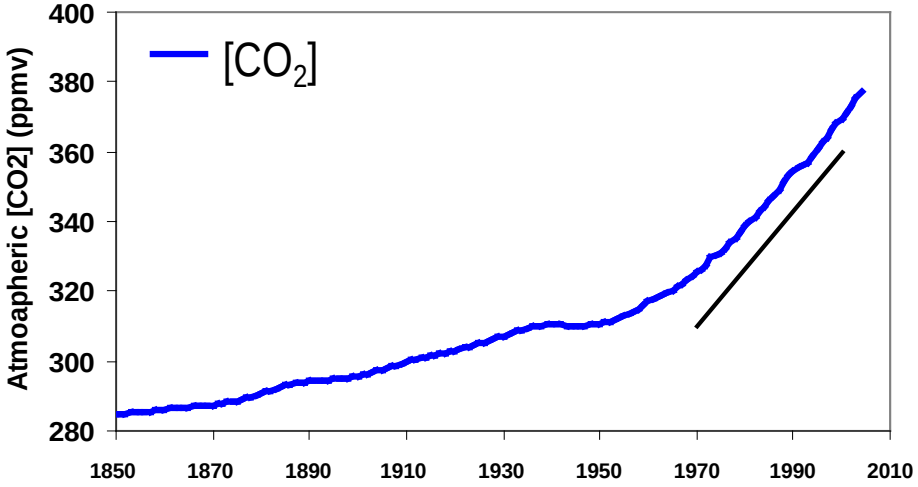
Raupach et al. 2007, PNAS

Atmospheric CO_2 Concentration

Year 2006
Atmospheric CO_2
concentration:

381 ppm

35% above pre-industrial



1970 – 1979: 1.3 ppm y^{-1}
1980 – 1989: 1.6 ppm y^{1}
1990 – 1999: 1.5 ppm y^{-1}

2000 - 2006: 1.9 ppm y^{-1}

NOAA 2007; Canadell et al. 2007, PNAS

Strategies to climate stabilization

Stabilize climate

- **Diminish end-use energy demand**
- **Produce energy without carbon emission**
- **Remove radiatively active gases from atmosphere**
- Reduce amount of solar radiation absorbed

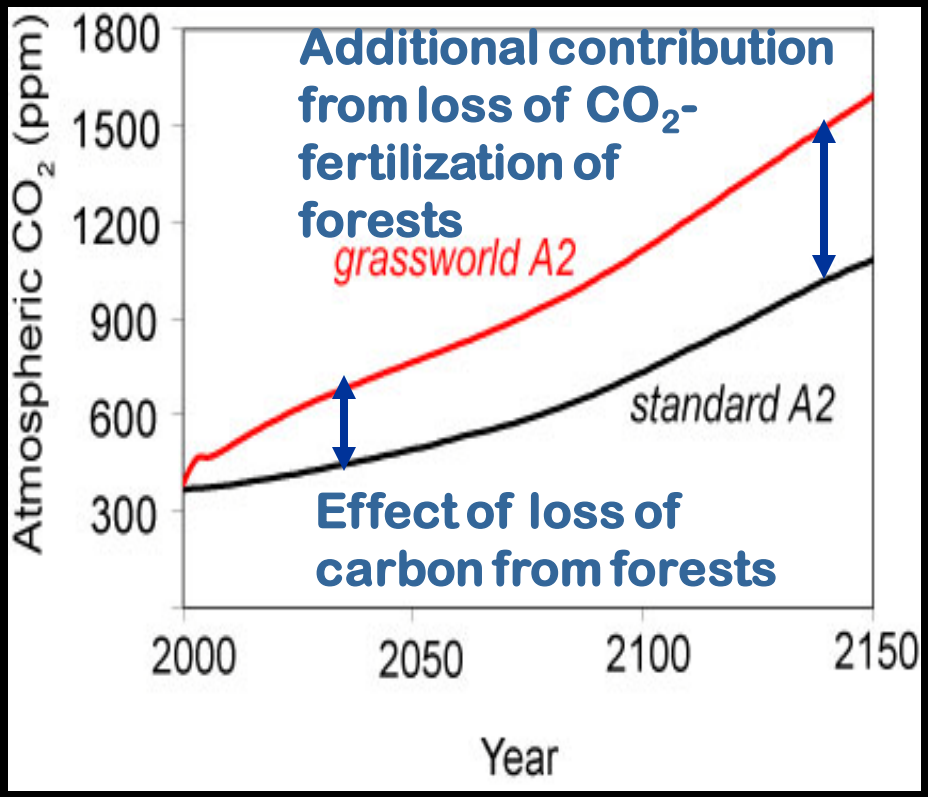
Attempts to control longwave radiation

Attempts to control shortwave radiation

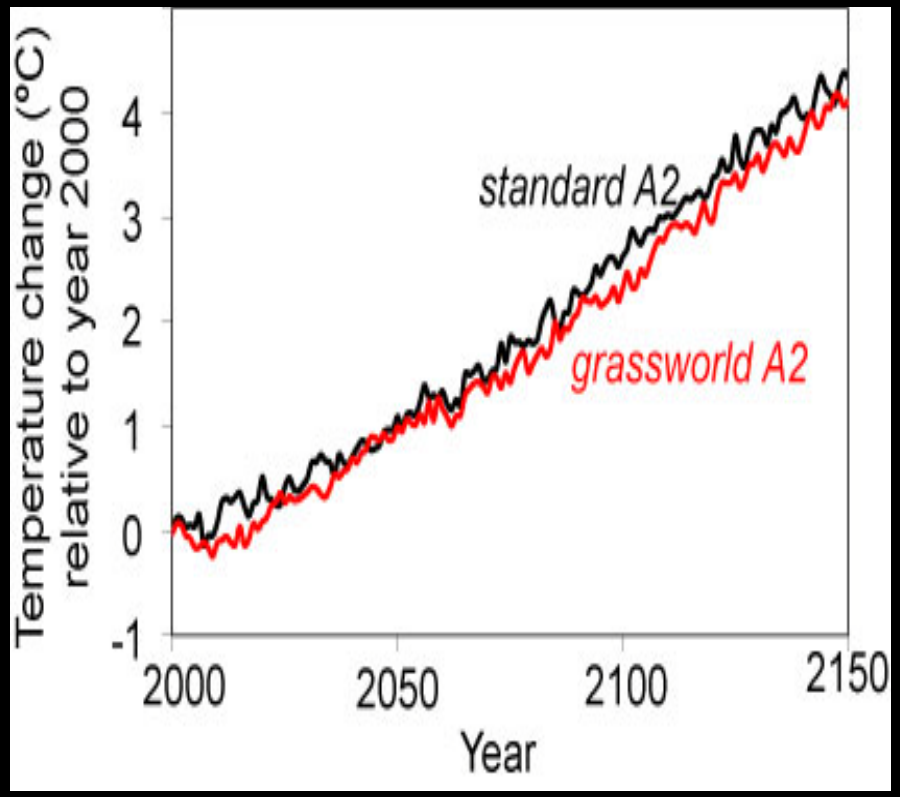
Forests

With deforestation, CO_2 is much higher but temperatures are slightly cooler

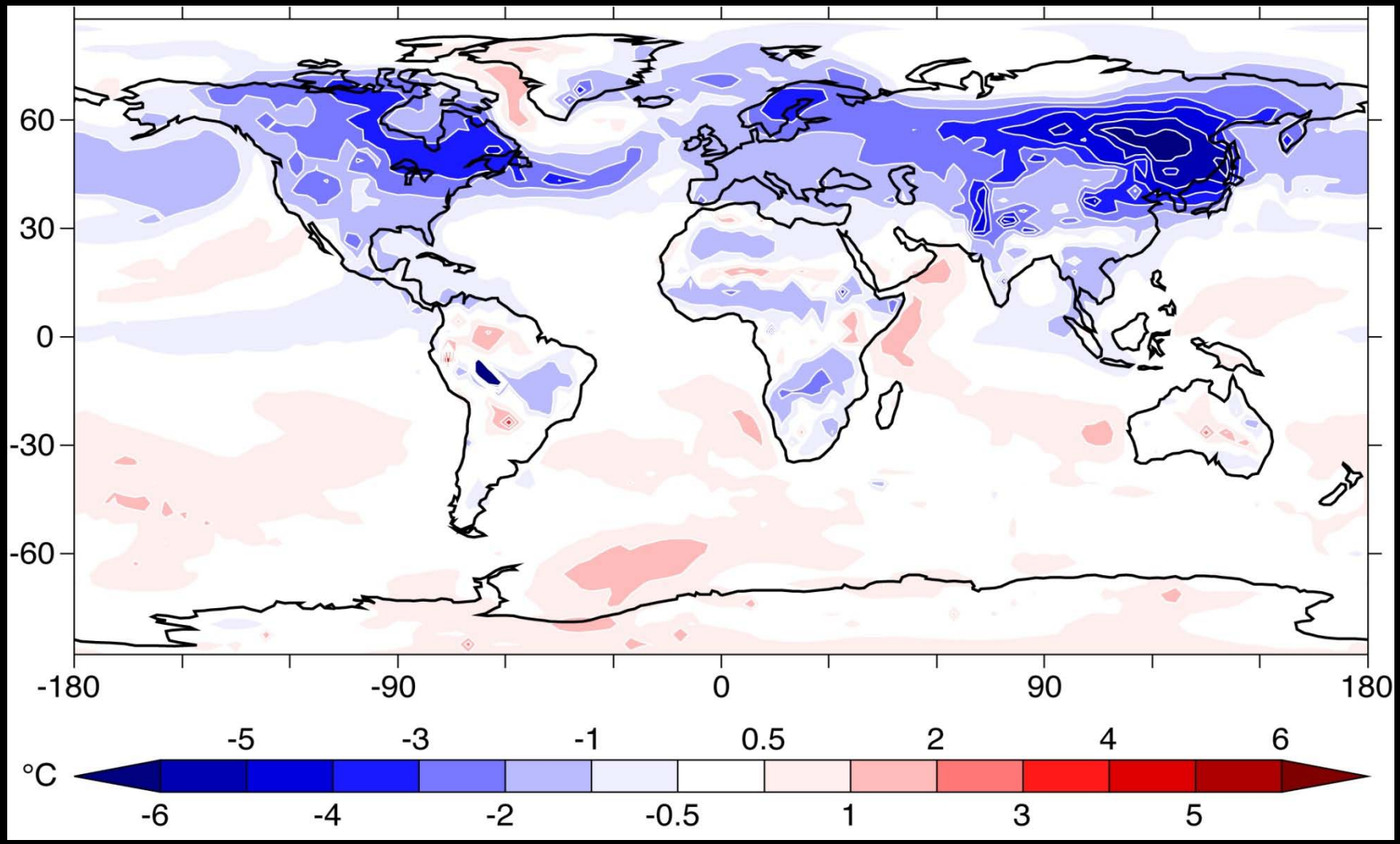
Atmospheric CO_2



Temperature



Global deforestation experiment: net temperature change (CO_2 + biophysical)

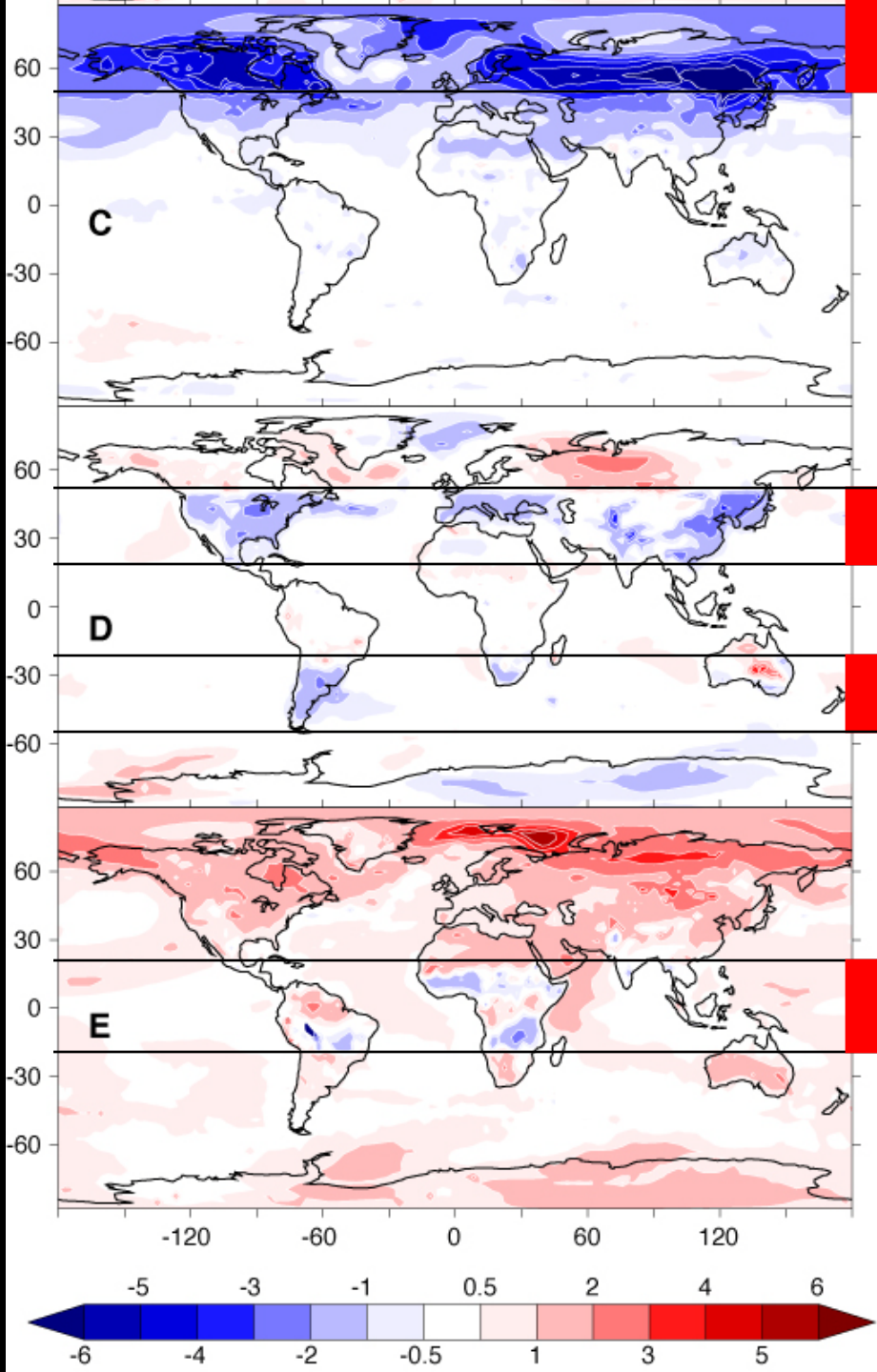


Temperature change predicted in latitude-band deforestation simulations

Boreal

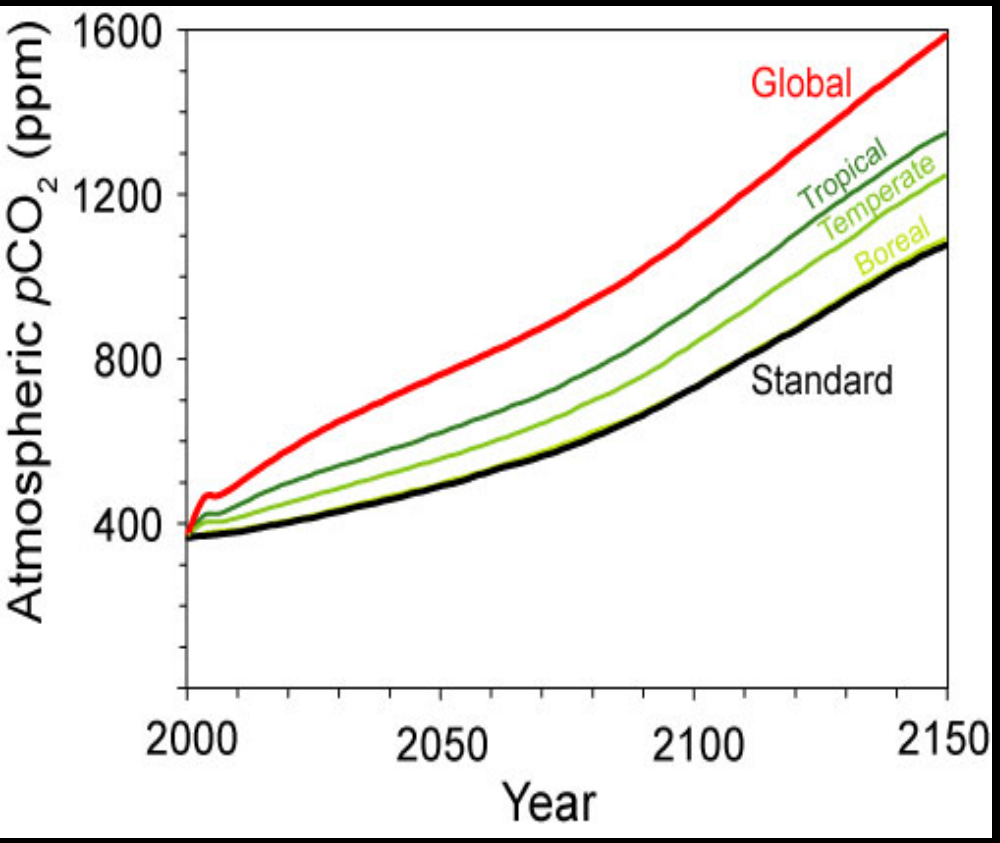
Temperate

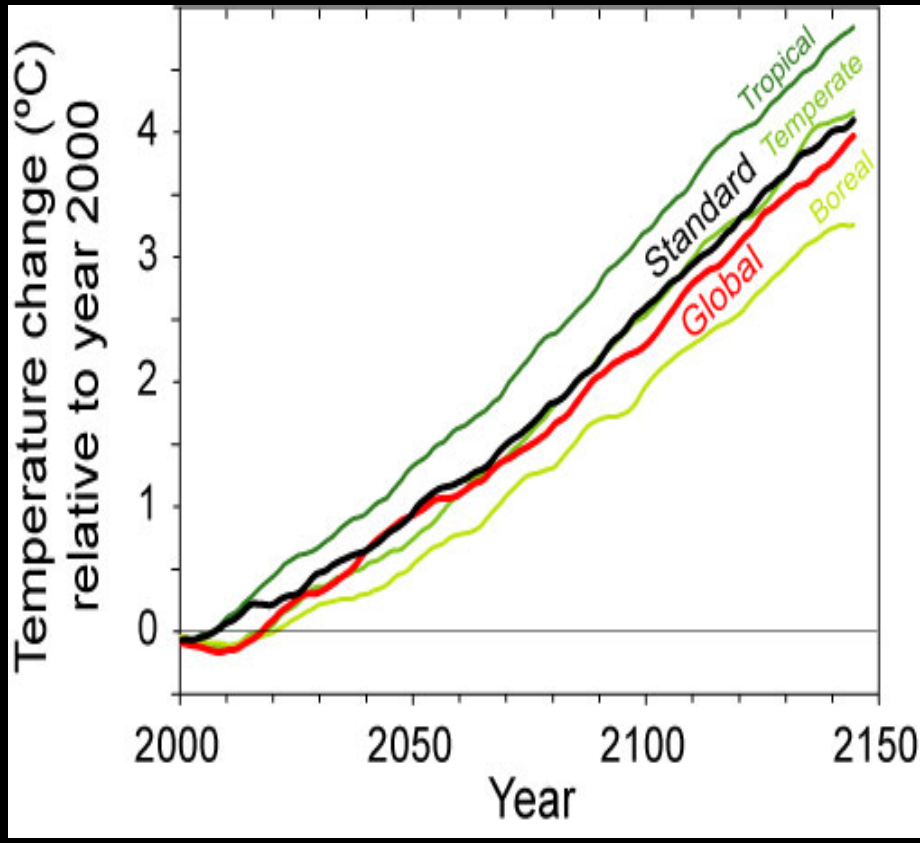
Tropical



Predicted role of forests

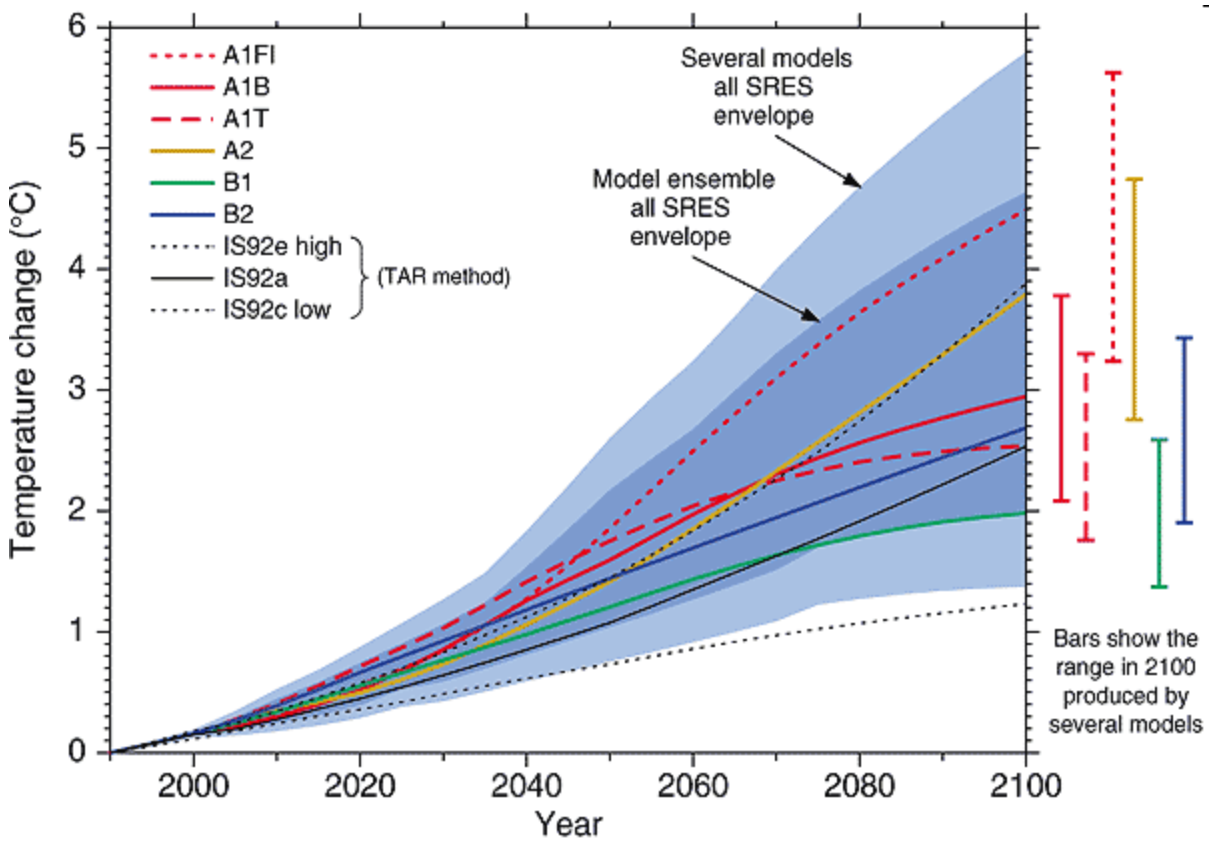
Tropical forests cool the planet
Temperate (mid-latitude) forests do little
Boreal forests warm the planet





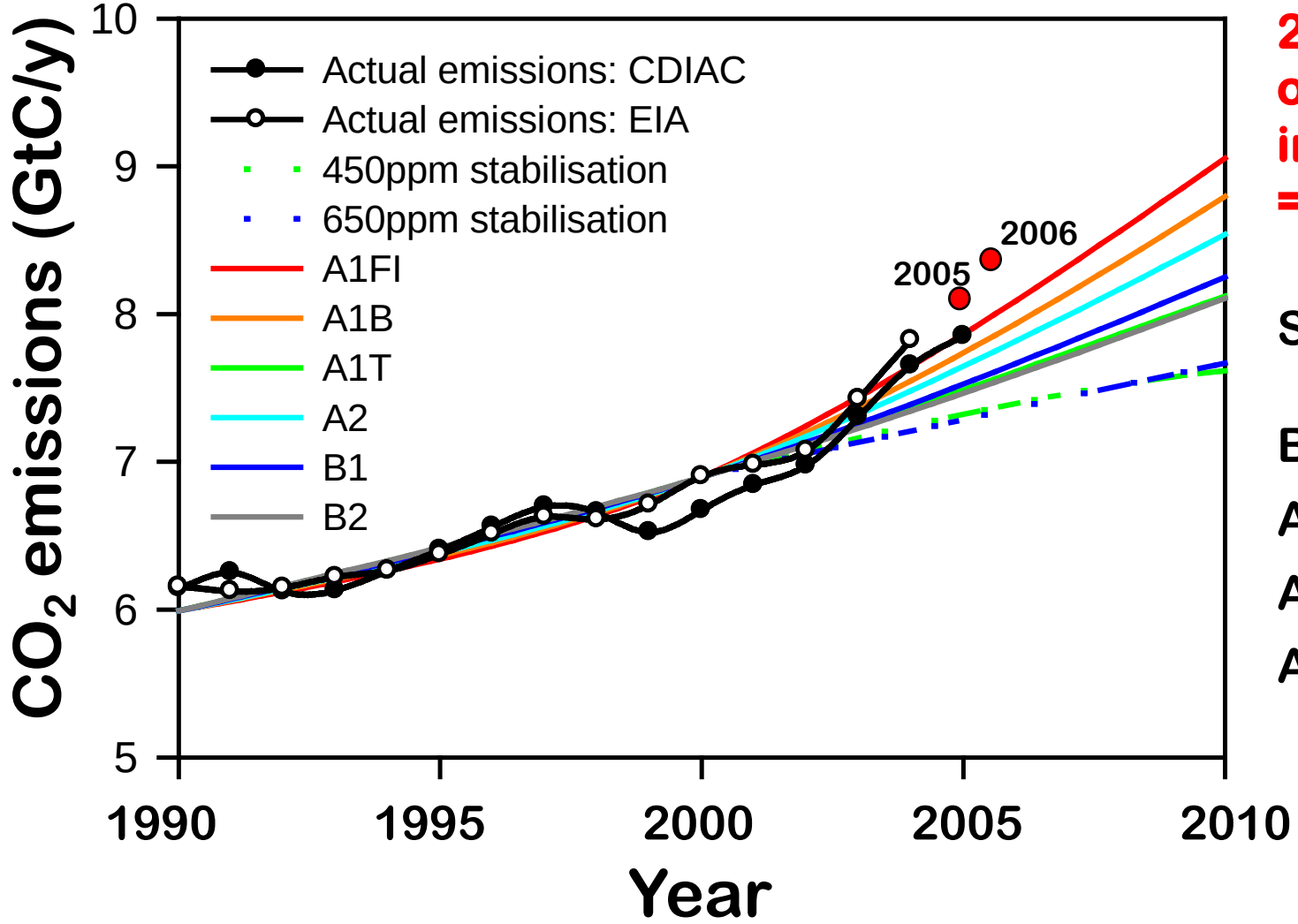
Intentional intervention in the climate system

In all IPCC scenarios, temperatures continue to rise throughout the century



IPCC TAR WG I

Fossil-fuel CO_2 emissions exceed SRES scenarios



2000-2006 observed increase = 3.3%

SRES to 2050

B1 1.1%,

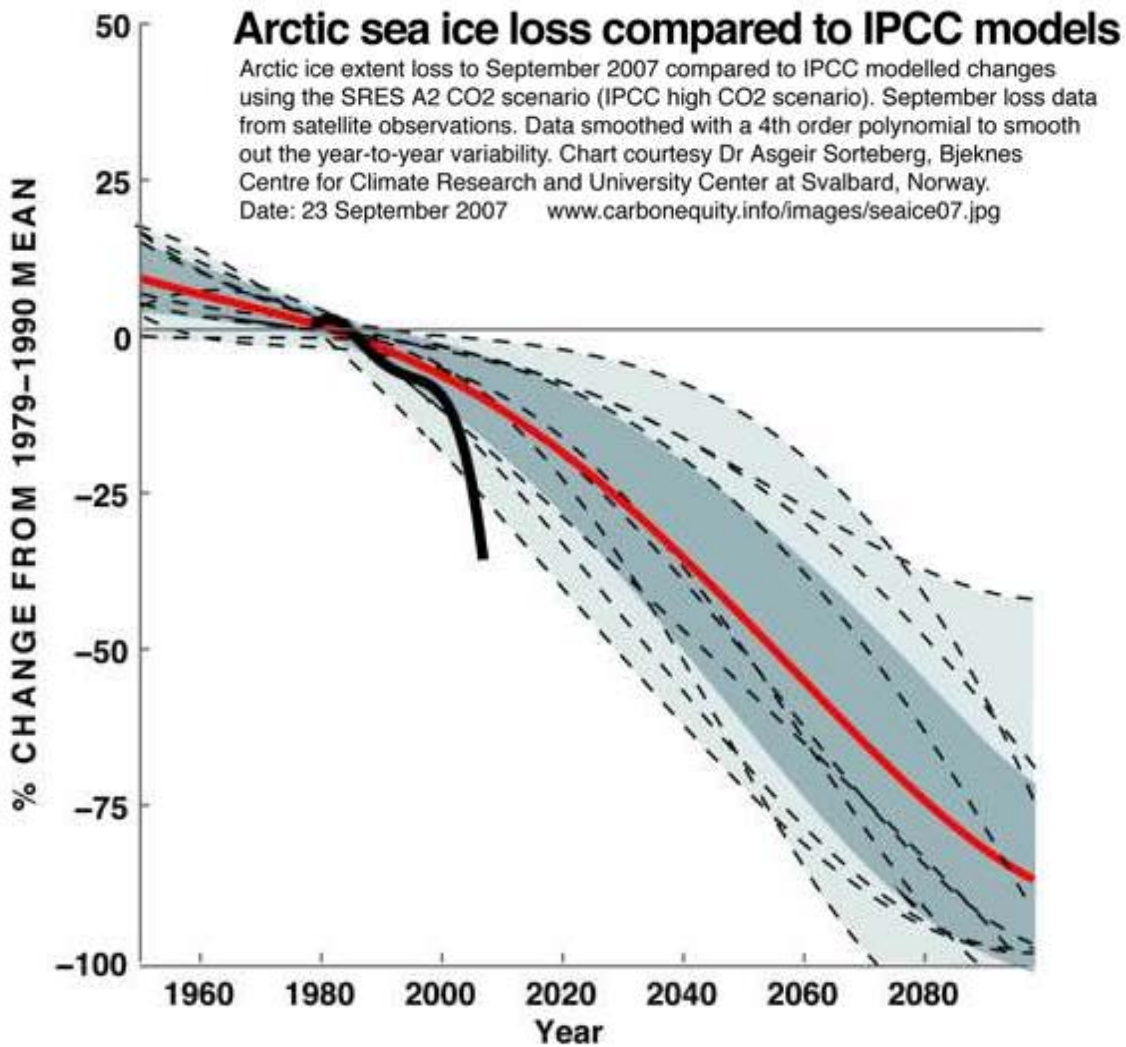
A1B 1.7%,

A2 1.8%

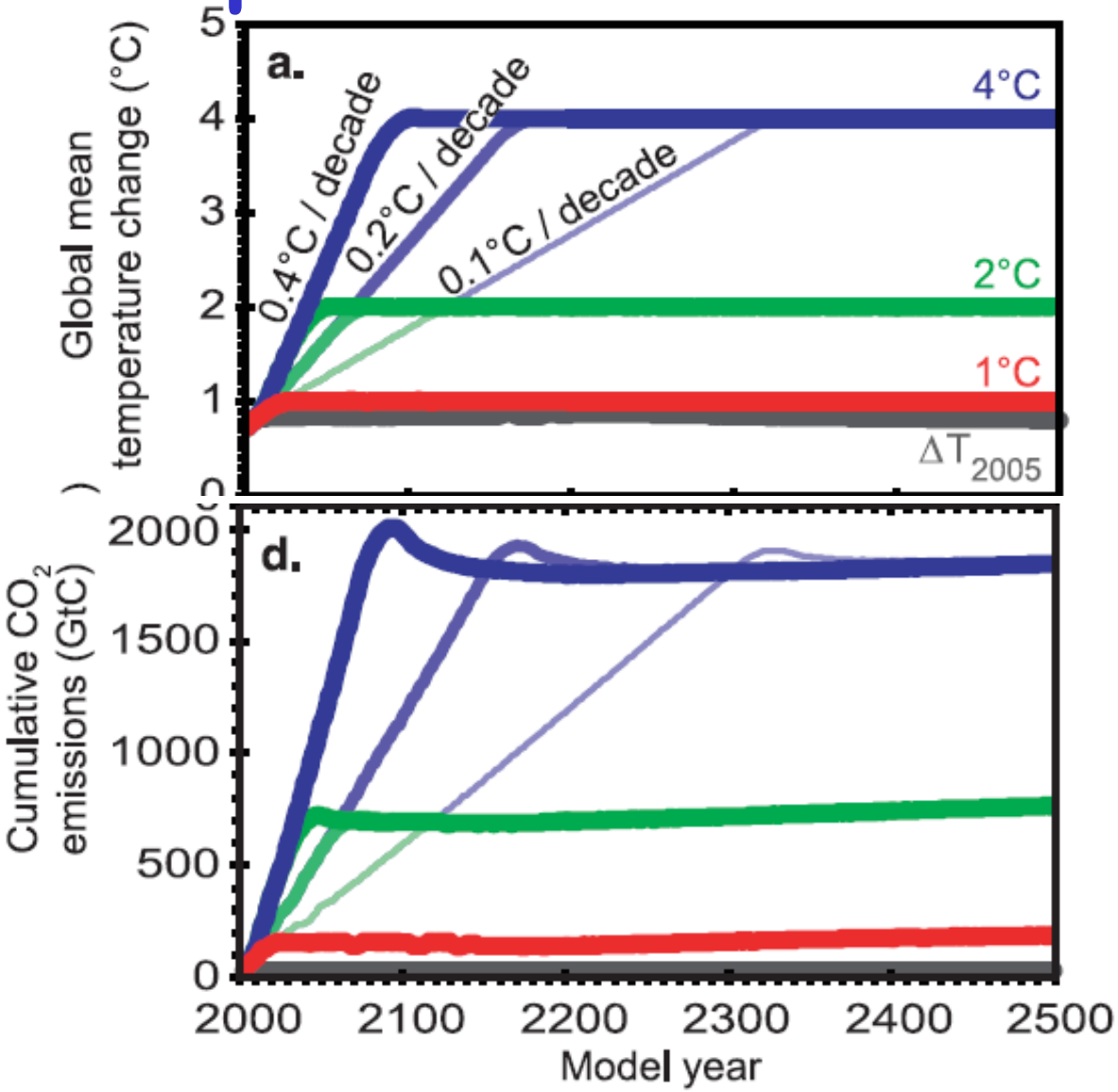
A1FI 2.4%

Raupach et al. 2007, PNAS

What will we do if there is a climate crisis?



Preventing further warming requires near-zero emissions

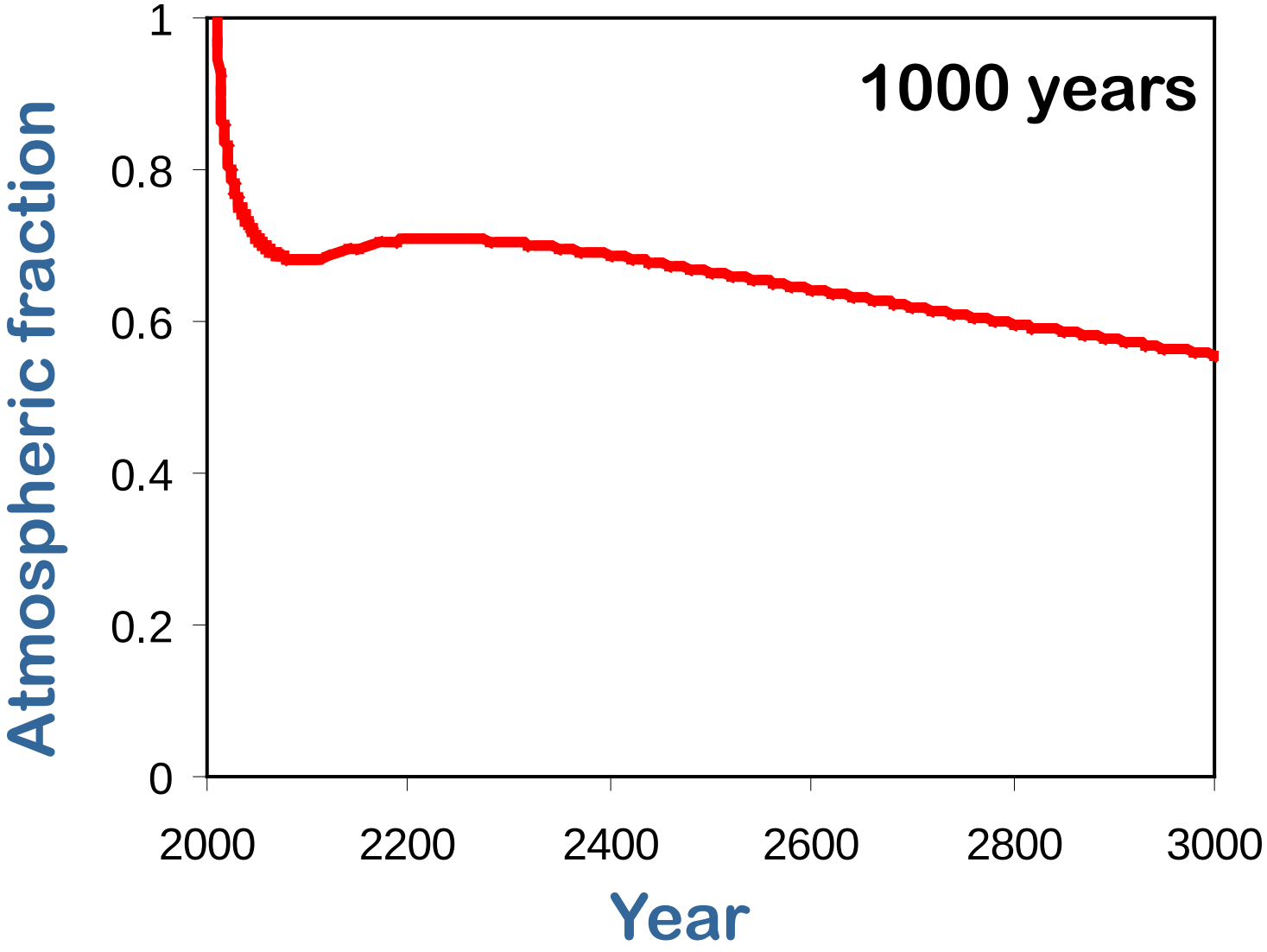


Temperature stabilization scenarios

Required cumulative emissions

Matthews and Caldeira 2008

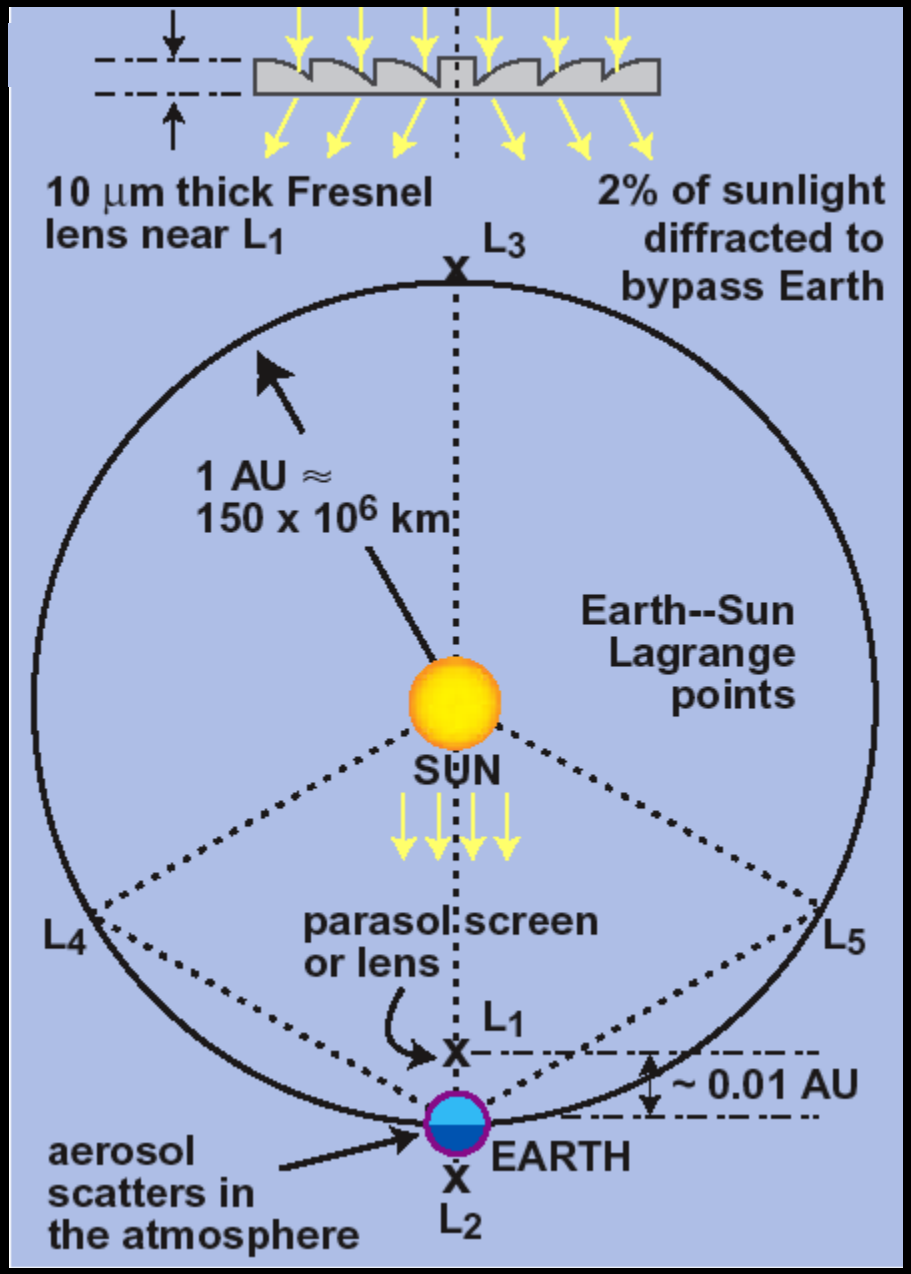
Fraction of an additional CO_2 release remaining in atmosphere



Cao and Caldeira, in prep.

Geoengineering

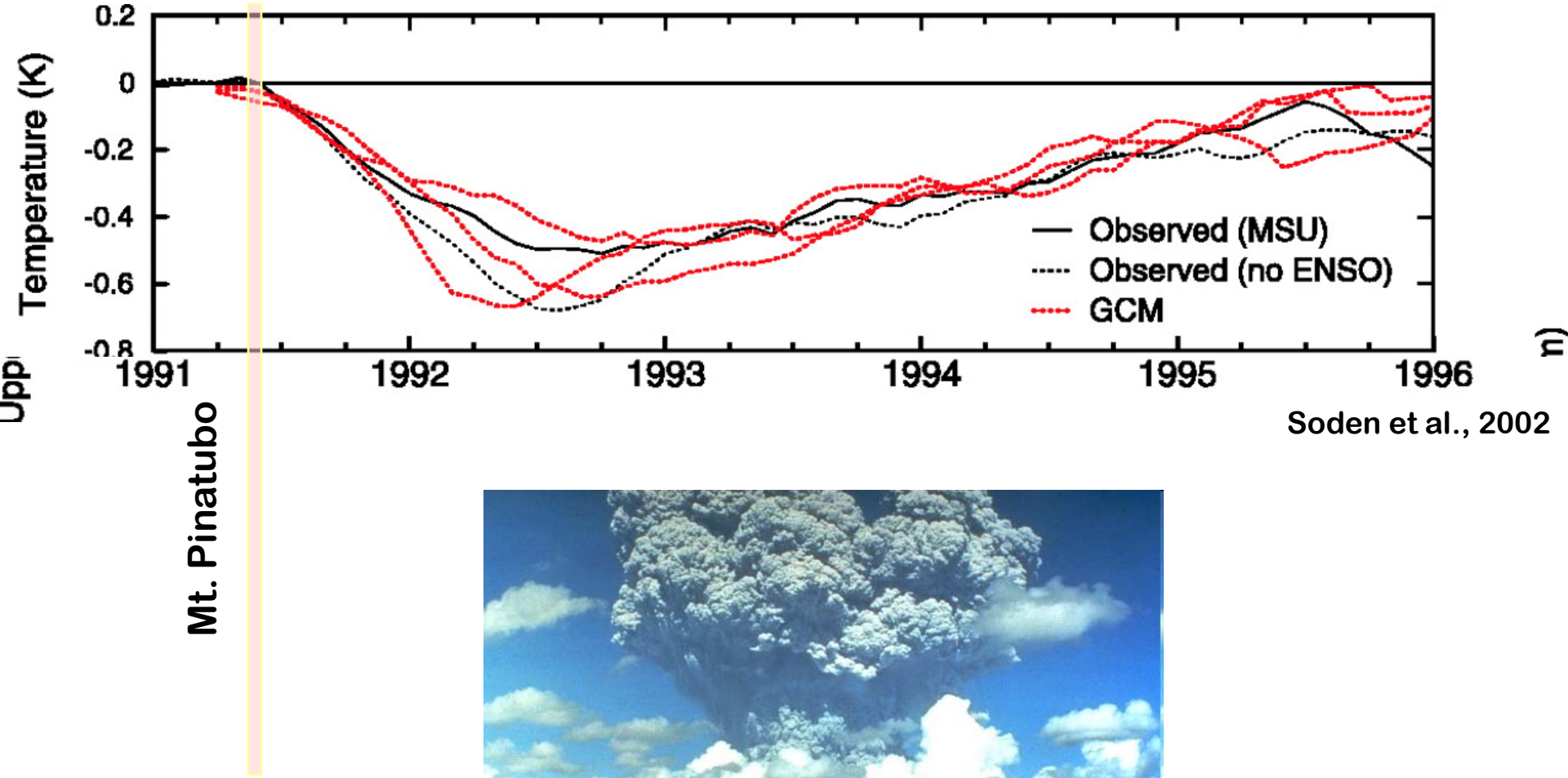
A back-up system, in case transformation of our energy system occurs too slowly to avert irreversible environmental damage?



Hoffert et al., 2002

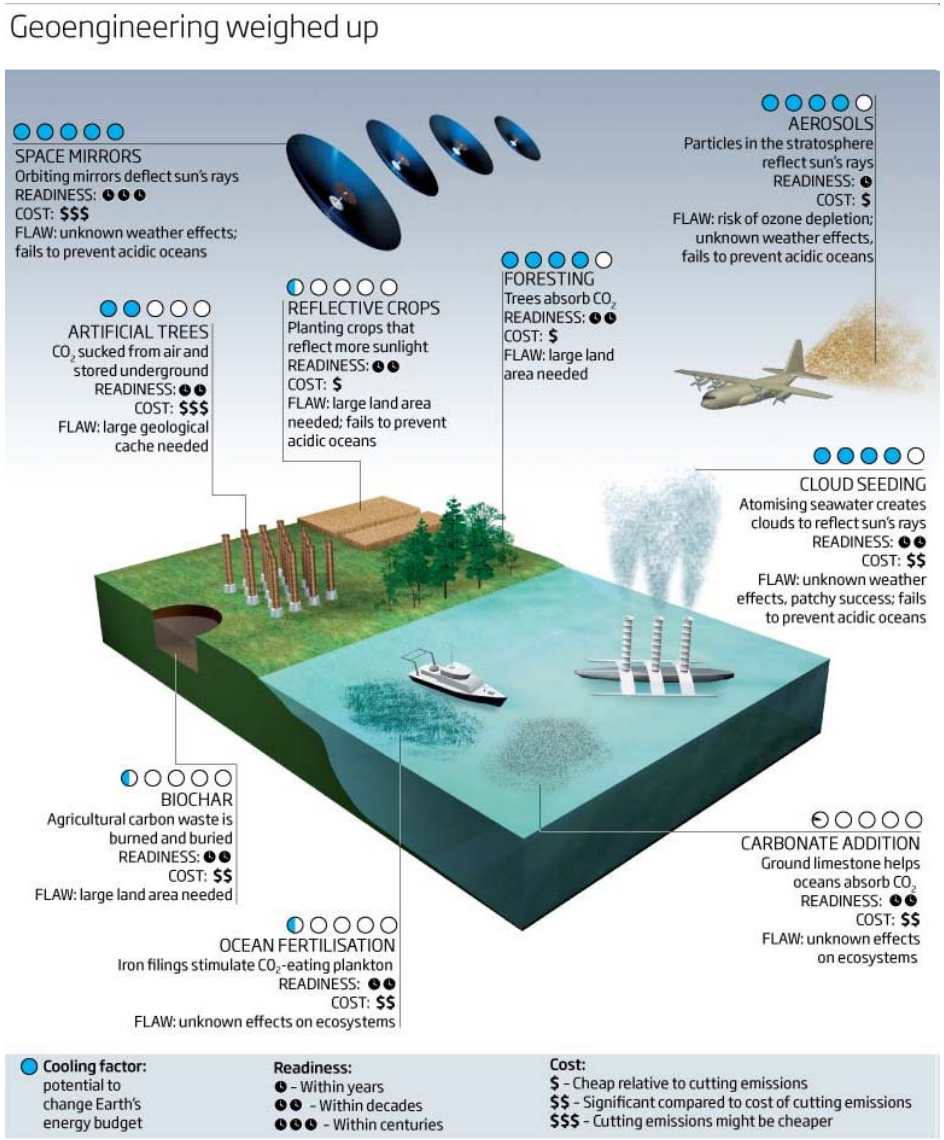
Henning Wagenbr

Volcanoes caused global cooling by putting dust in the stratosphere



Soden et al., 2002

There are a range of strategies



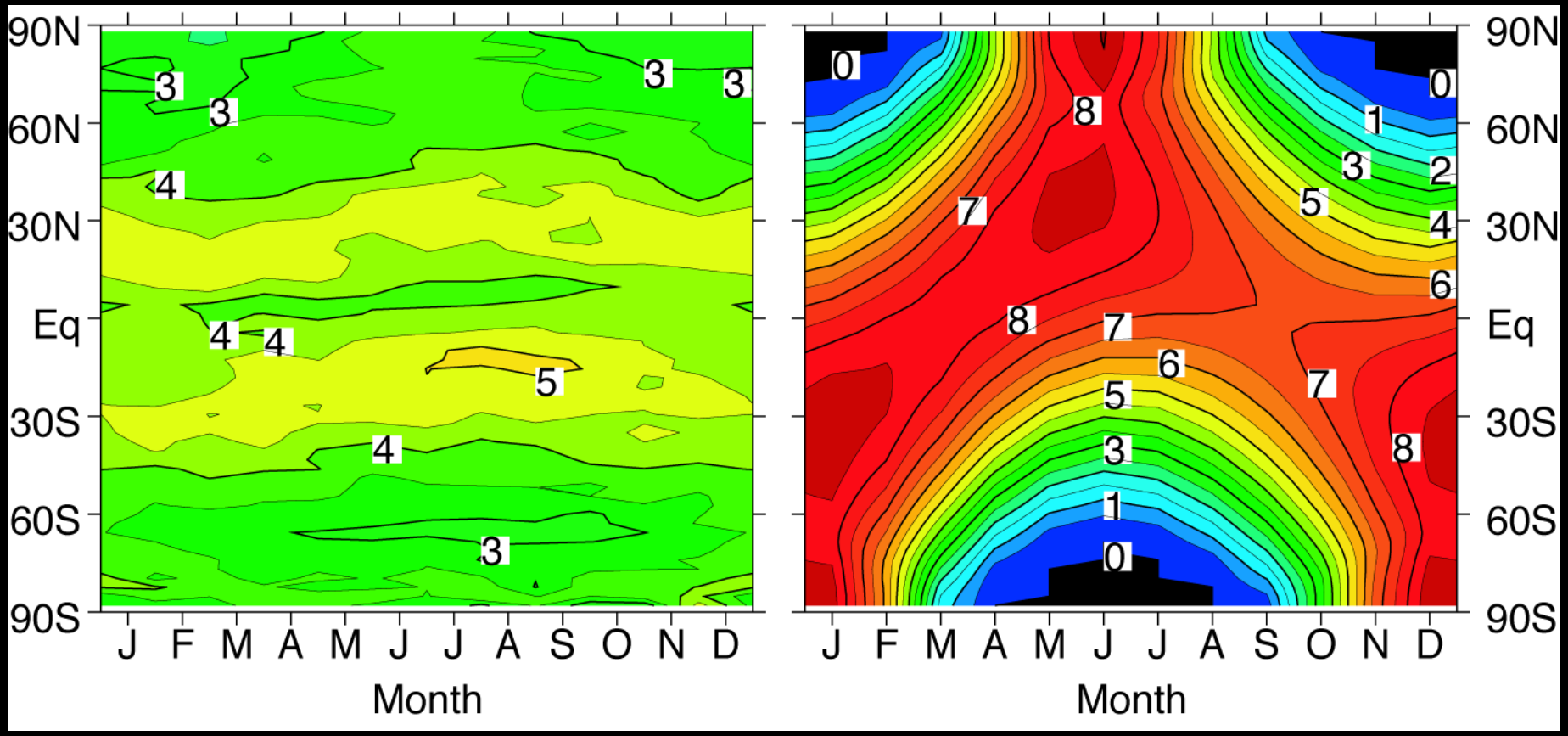
Stratospheric dust

- 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

Geoengineering

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

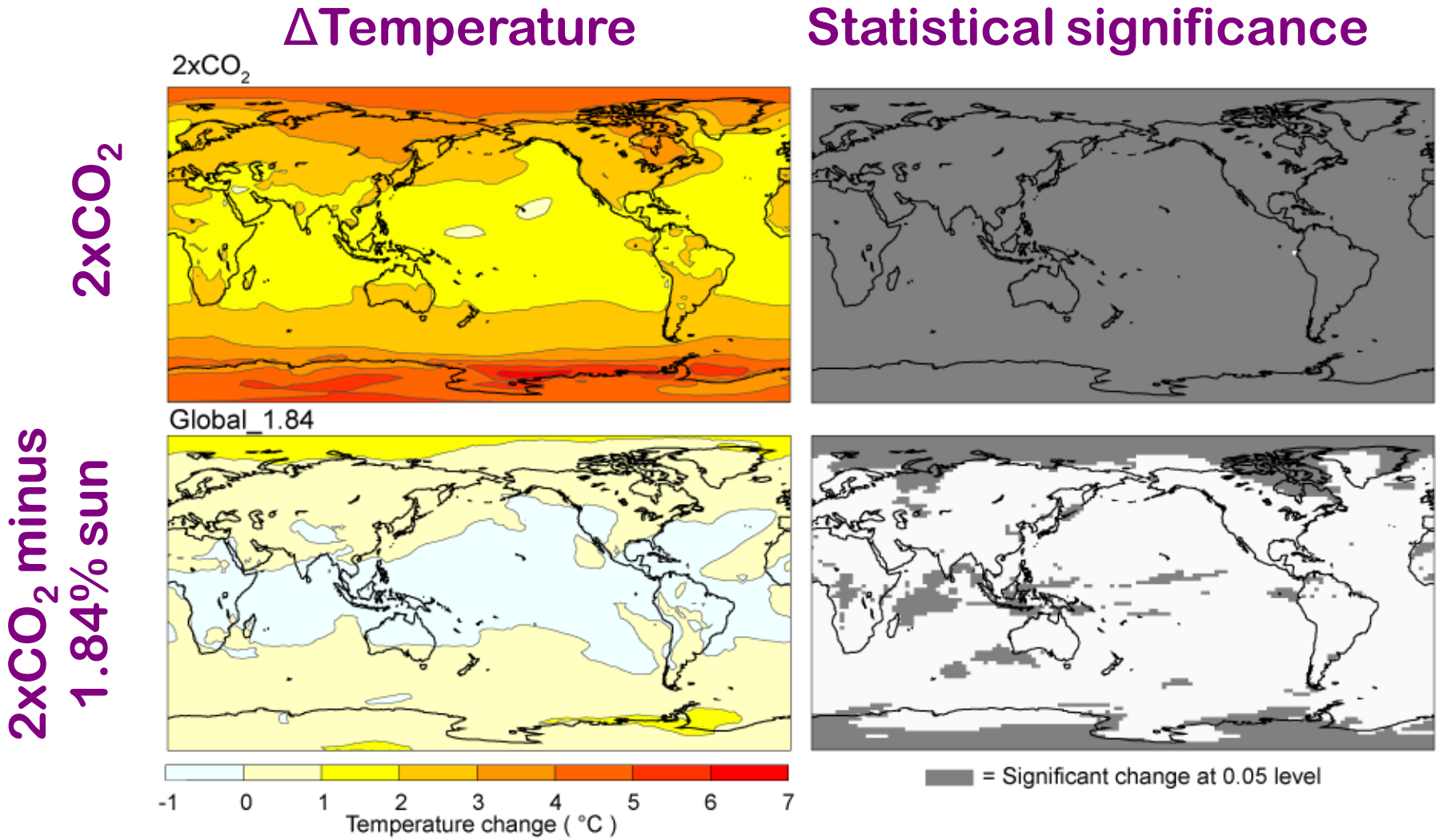
Radiative forcing from 1.8% reduction in solar intensity (W / m^2)



Can these cancel ???

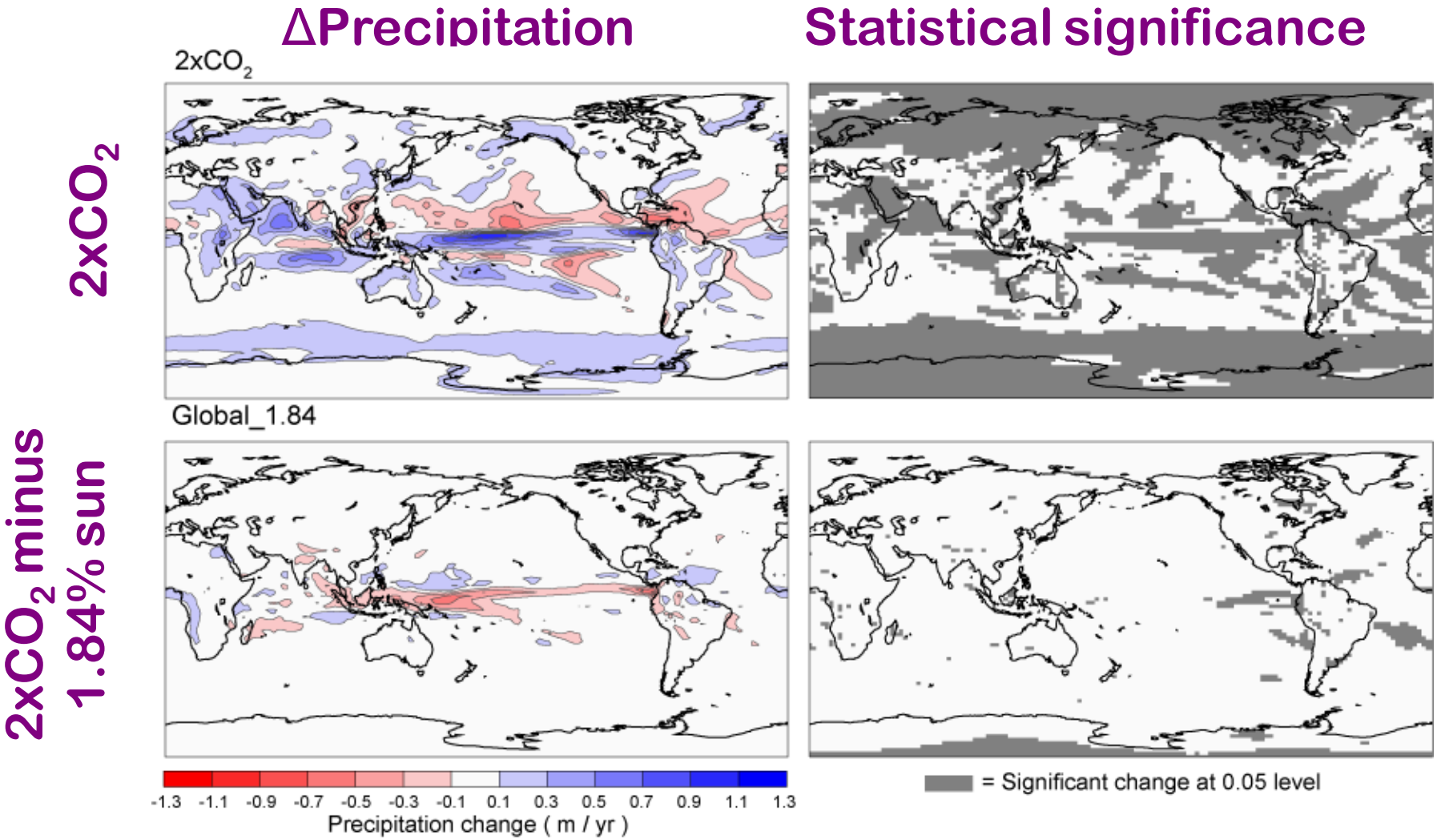
Govindasamy and Caldeira, GRL, 2000

Model results for temperature



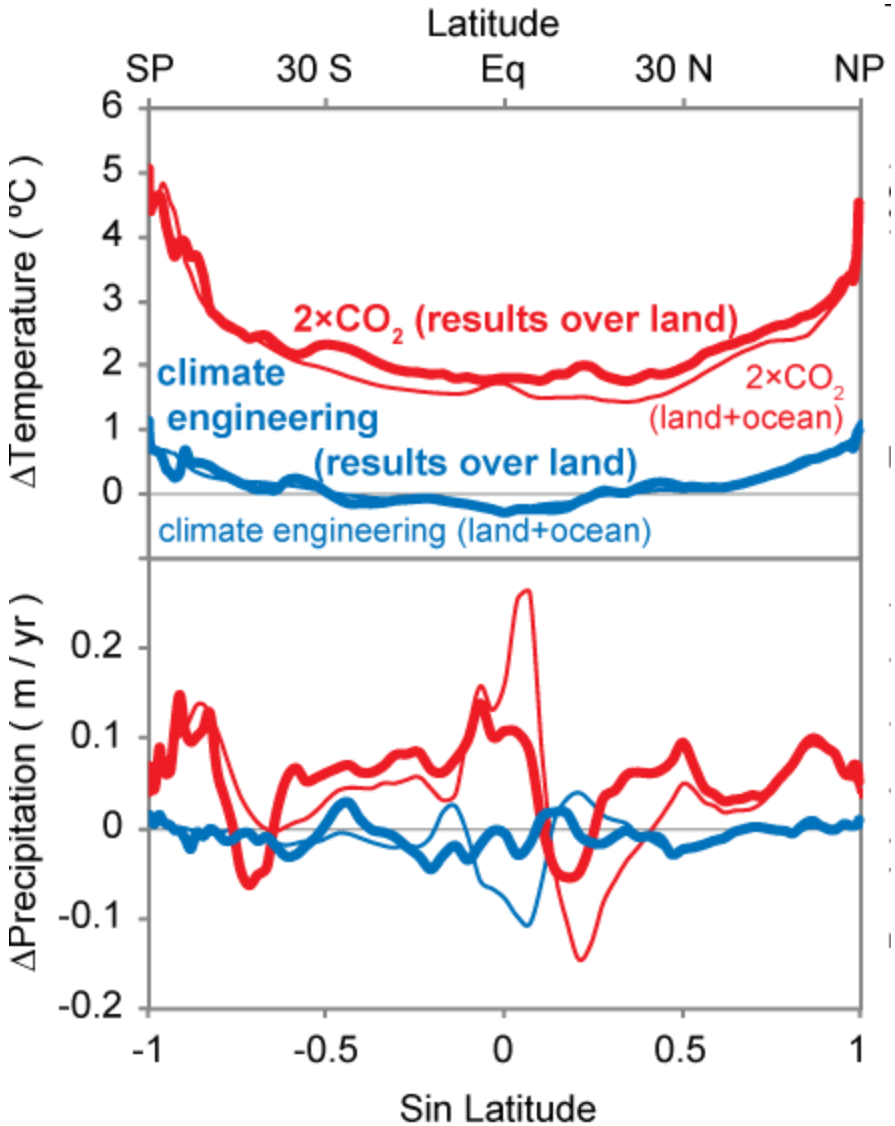
Caldeira and Wood, 2008

Model results for precipitation



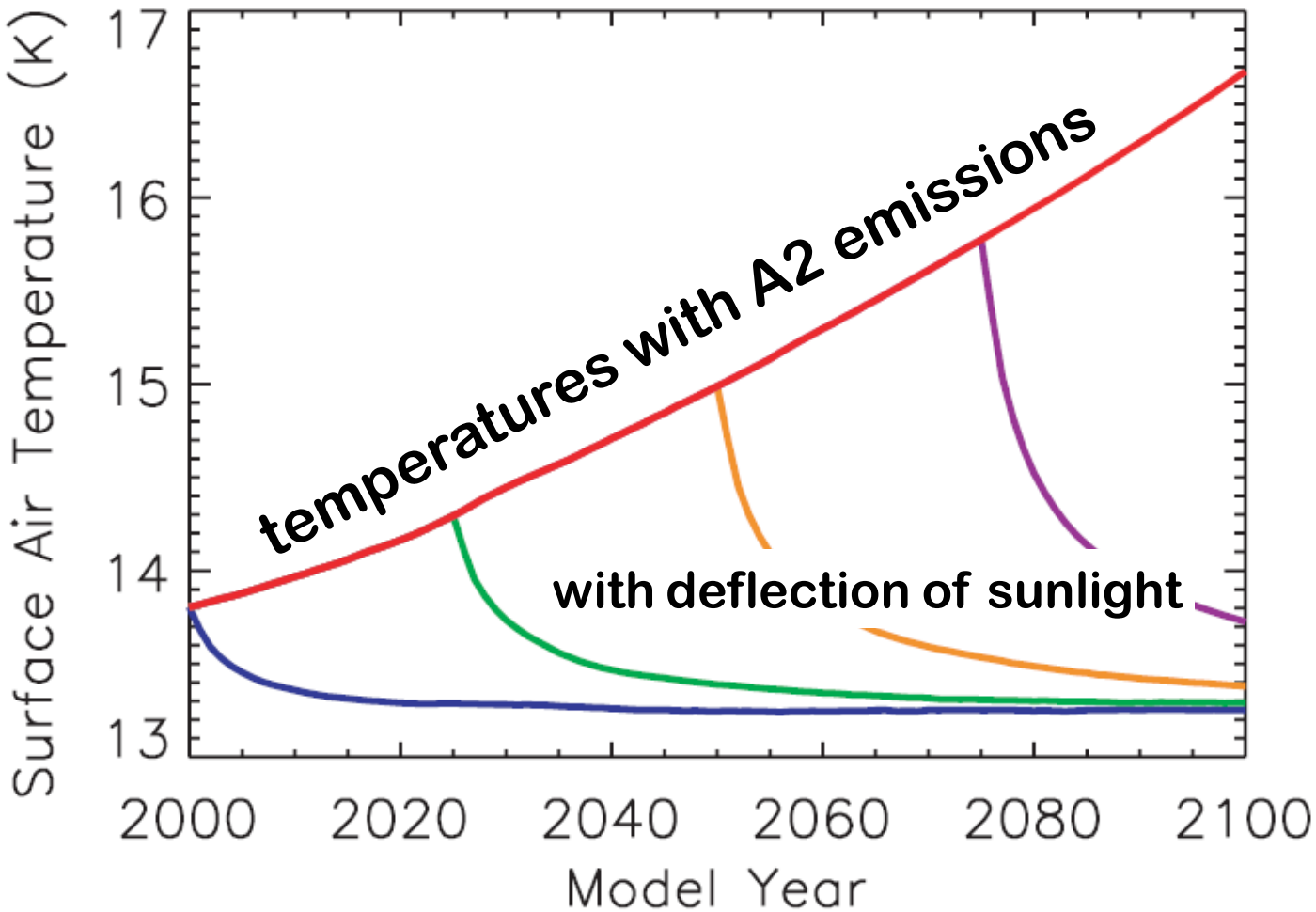
Caldeira and Wood, 2008

Climate model results



Caldeira and Wood, 2008

Direct intervention approaches could cool Earth within years



Matthews and Caldeira (2007)

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

Unanticipated outcomes

Anticipated outcomes

Curse?

May destroy ozone layer, etc

May cause famines, etc

Distracts from emissions reduction

Source of conflict

Ocean acidification

Intrinsically evil

Puts more power in hands of techno-military evil-doers

Risk of irreparable environmental damage

Undermines effort to reduce human footprint on planet

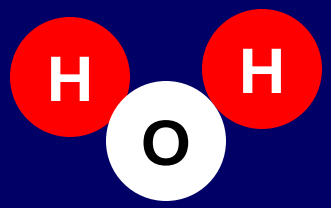
Anti-democratic

Risk reduction

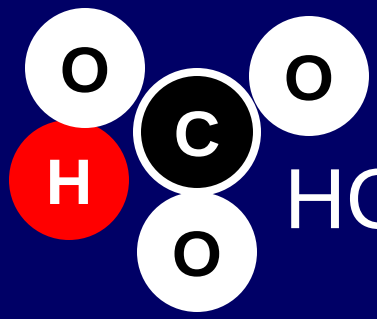
- If you think you may need to intentionally affect Earth's climate
  - it is less risky environmentally to start testing soon
    - Allows test to start small and ramp up cautiously
  - it is more risky politically to start testing soon

Ocean acidification

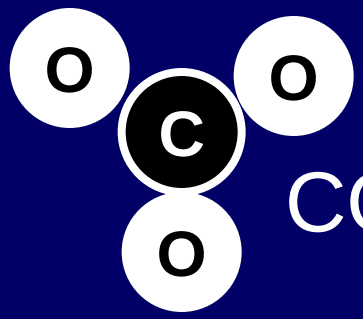
HCO_3^-, CO_3^{2-}, and $CaCO_3$ in H_2O



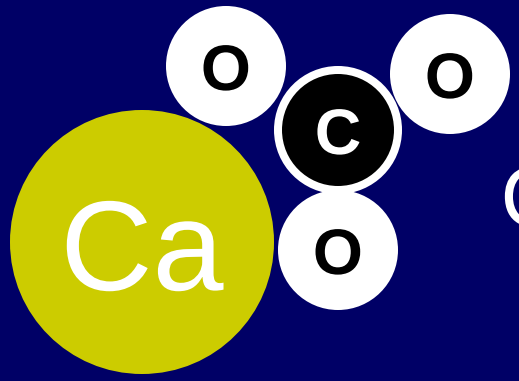
H_2O



HCO_3^-



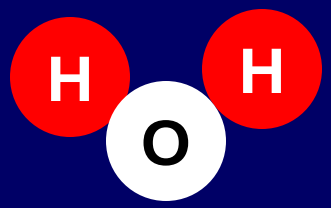
CO_3^{2-}



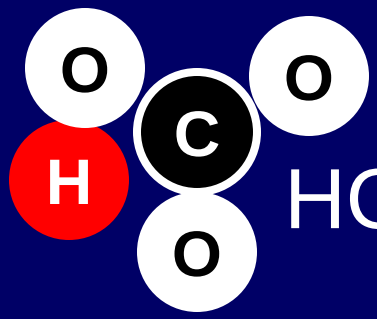
$CaCO_3$ (solid)

Addition of CO_2

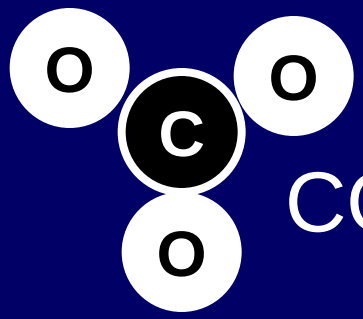
CO_2



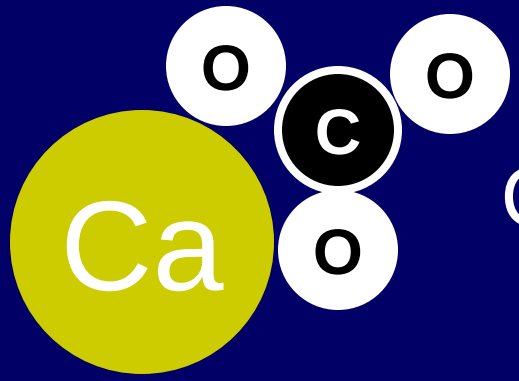
H_2O



HCO_3^-

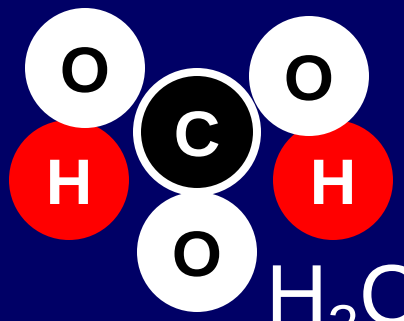


CO_3^{2-}

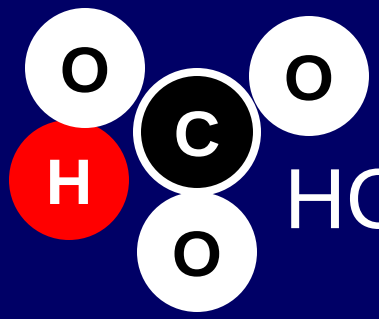


$CaCO_3$ (solid)

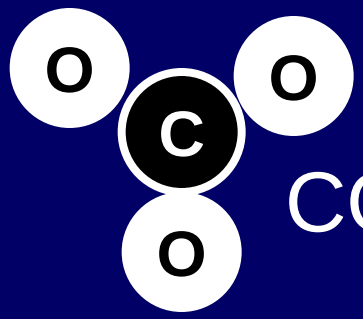
$CO_2 + H_2O \rightarrow H_2CO_3$



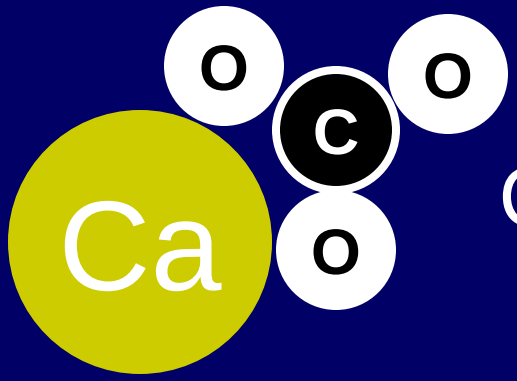
H_2CO_3



HCO_3^-

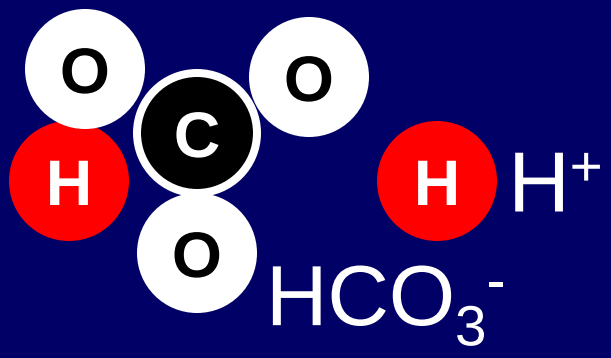


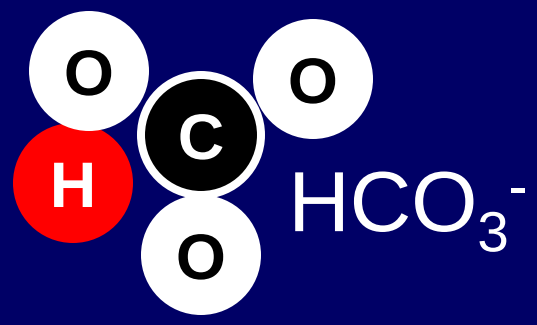
CO_3^{2-}

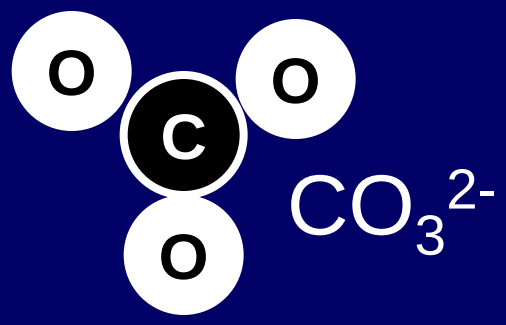


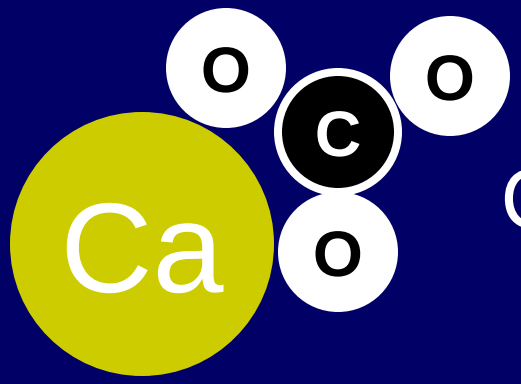
$CaCO_3$ (solid)

$H_2CO_3 \rightarrow H^+ + HCO_3^-$



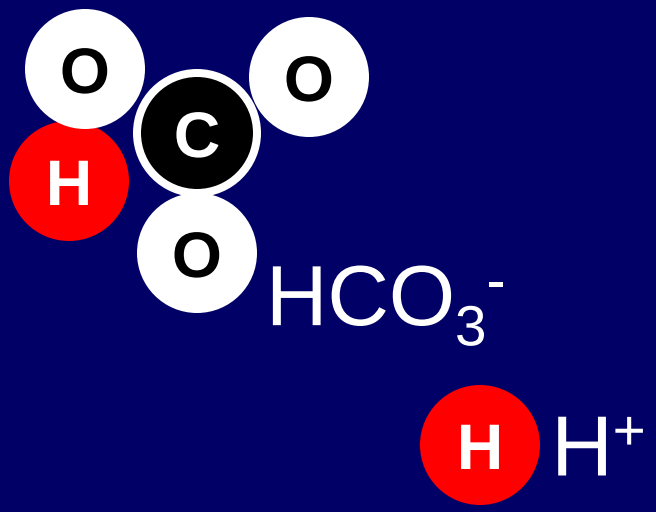


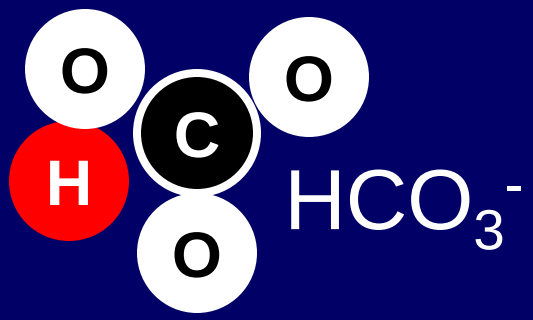


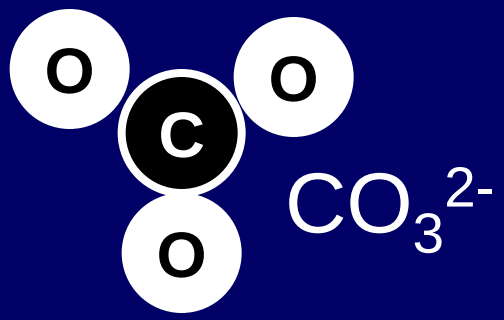


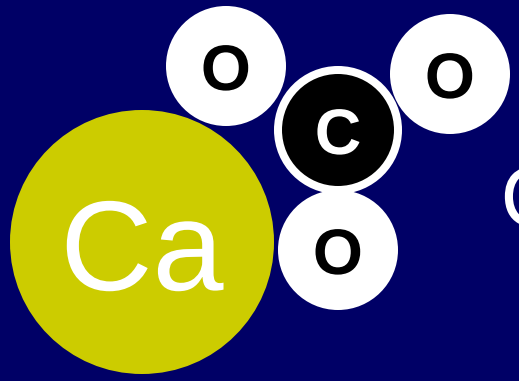
$CaCO_3$ (solid)

$H_2CO_3 \rightarrow H^+ + HCO_3^-$

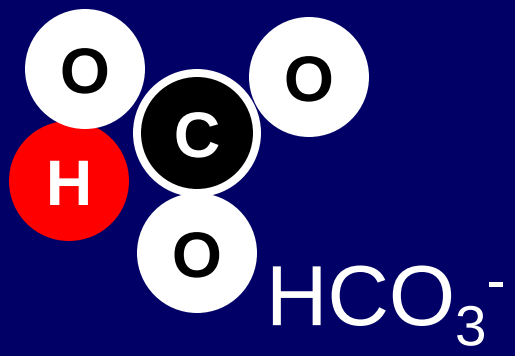


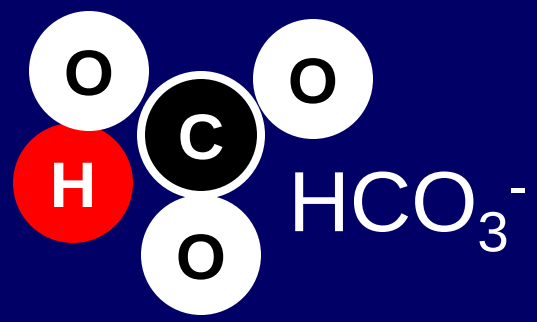


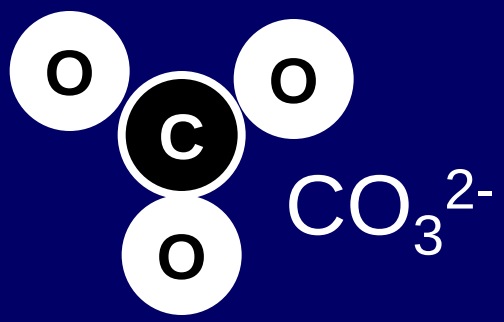


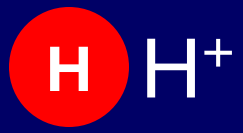


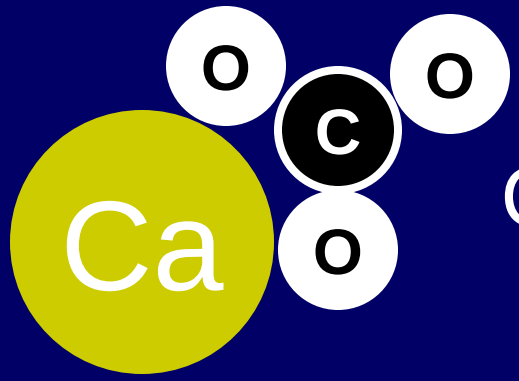
$H^+ + CO_3^{2-} \rightarrow HCO_3^-$



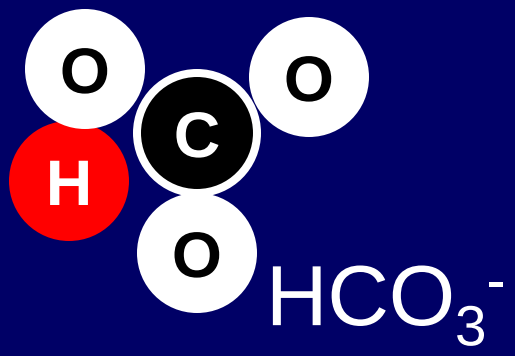


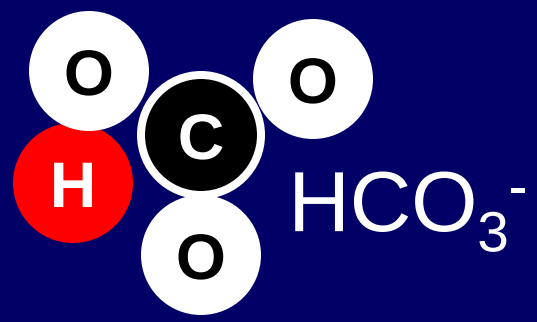


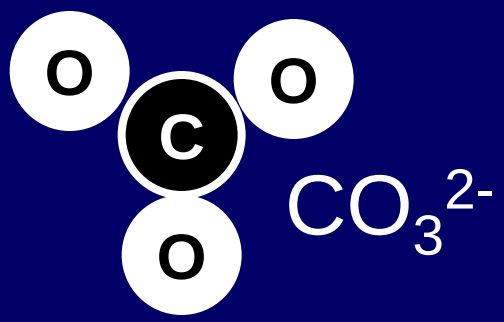


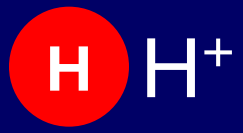


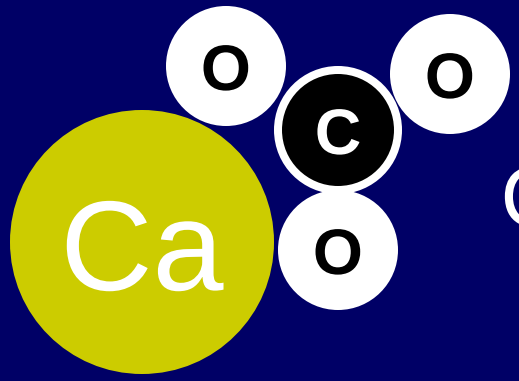
$H^+ + CO_3^{2-} \rightarrow HCO_3^-$



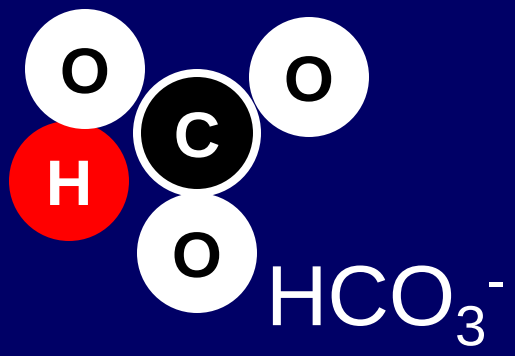


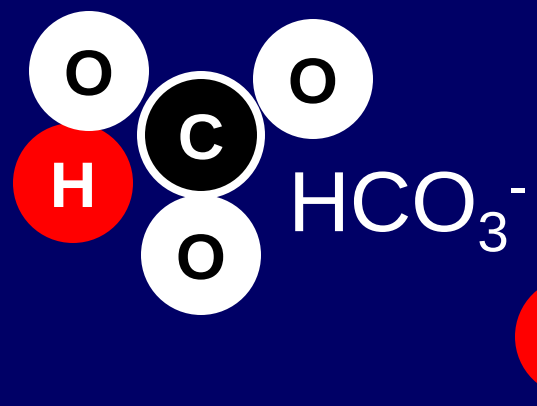


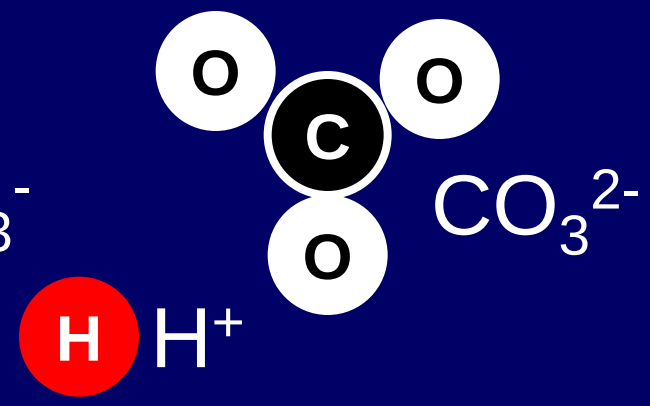


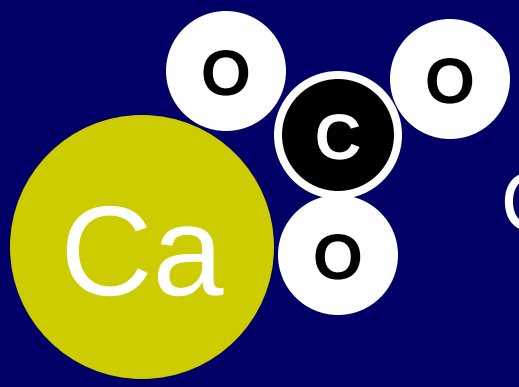


$H^+ + CO_3^{2-} \rightarrow HCO_3^-$



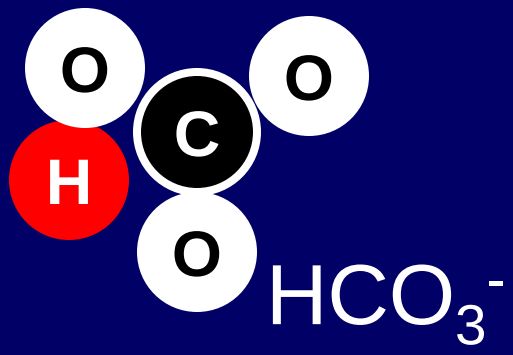


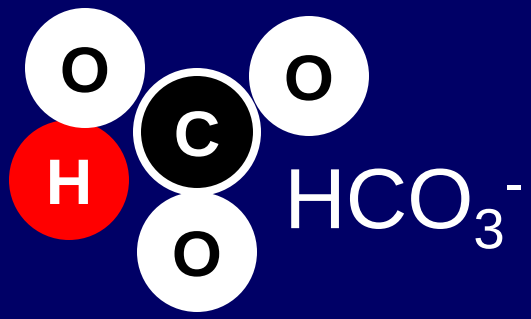


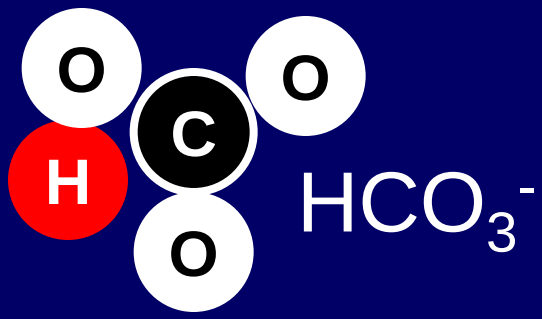


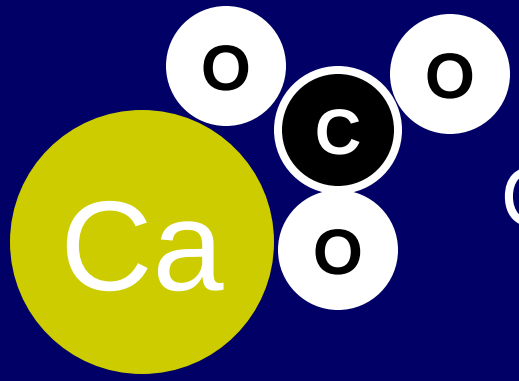
$CaCO_3$ (solid)

$$H^+ + CO_3^{2-} \rightarrow HCO_3^-$$



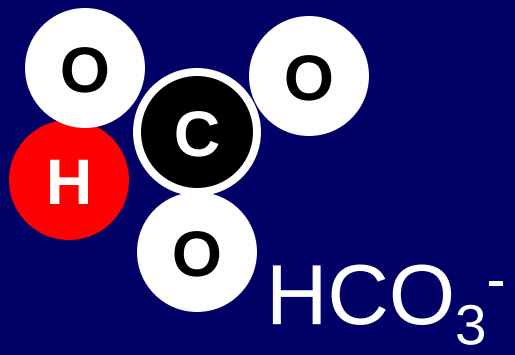


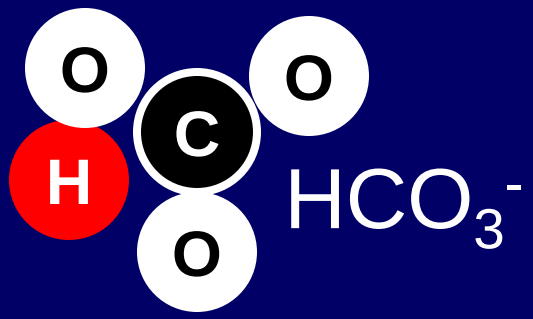


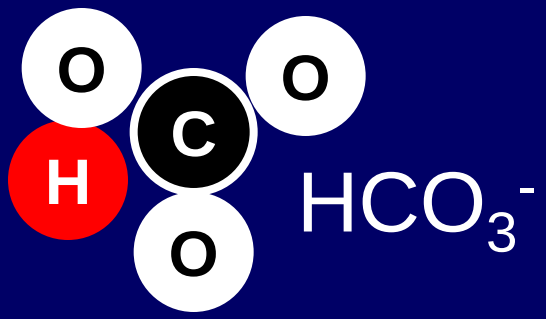


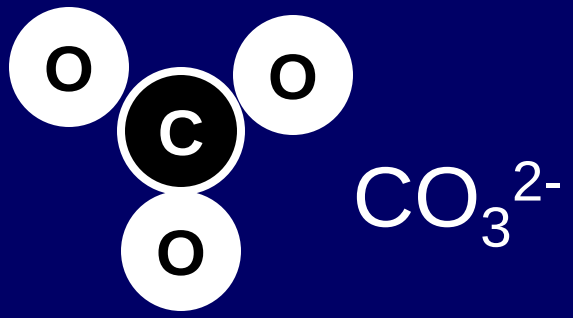
$CaCO_3$ (solid)

$$CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$$



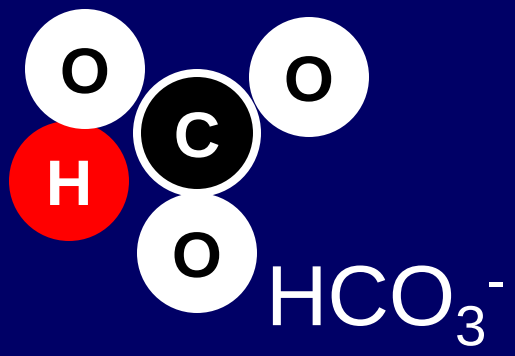


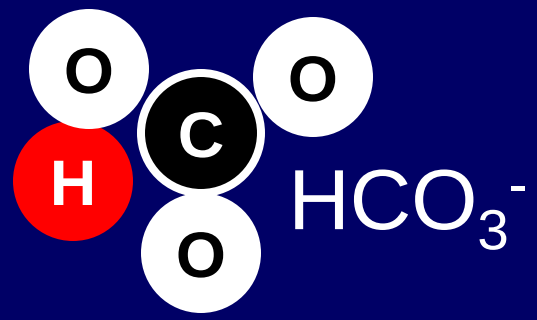


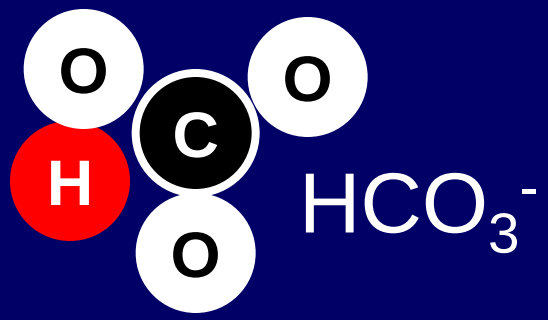


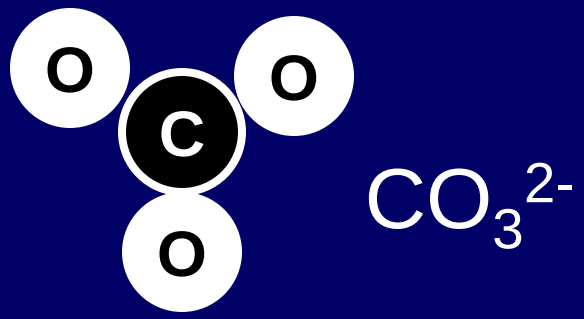
Ca^{2+} (dissolved)

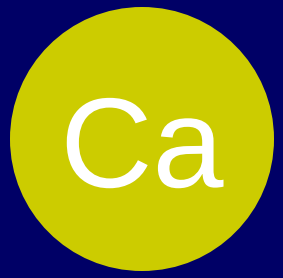
$CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$





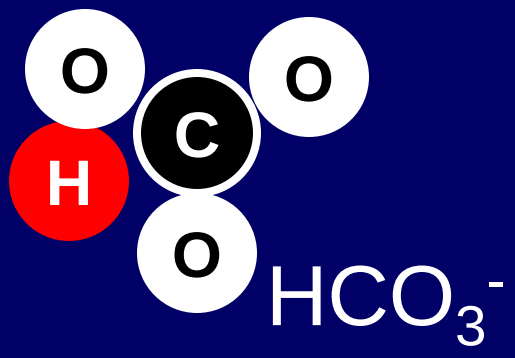


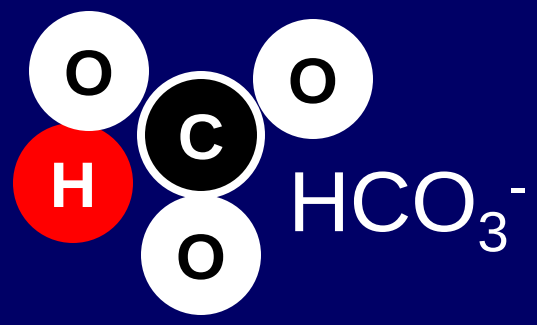


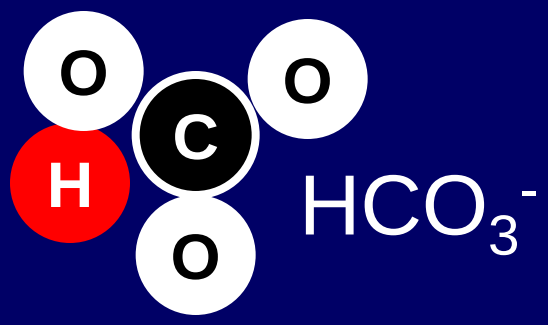


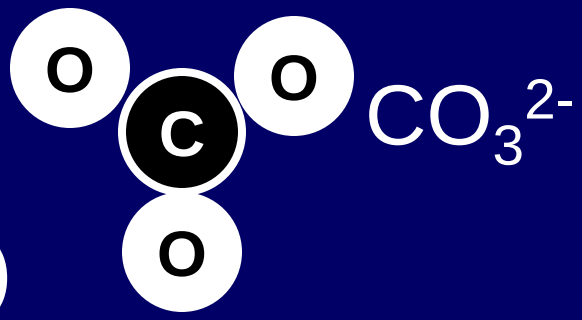
Ca^{2+} (dissolved)

$CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$



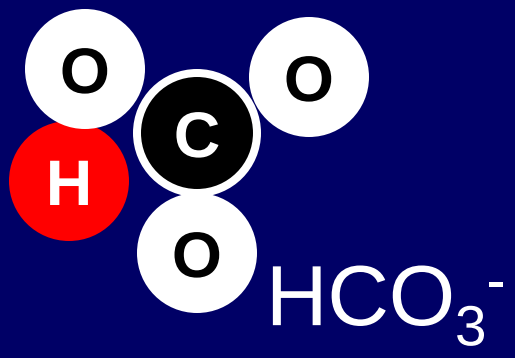


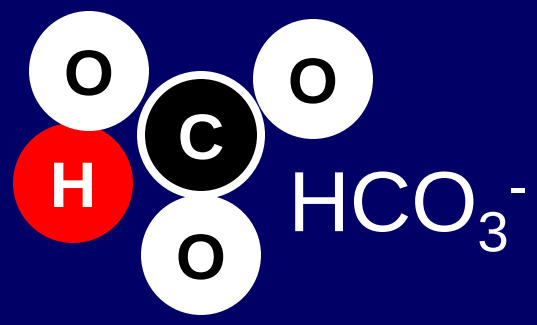


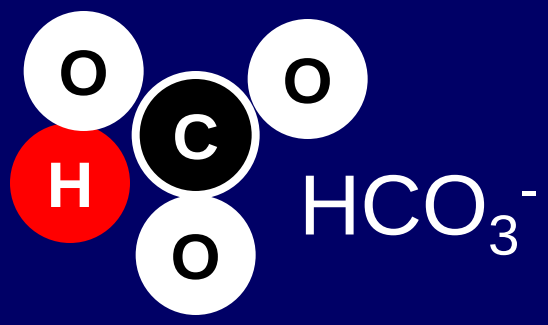


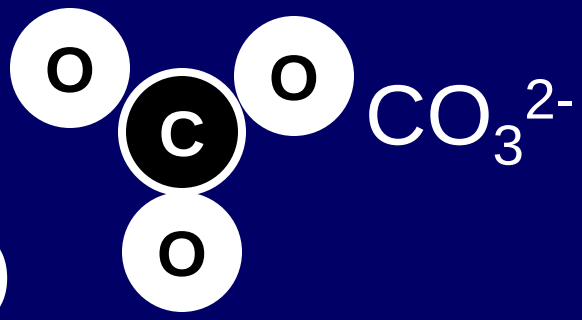
Ca^{2+} (dissolved)

$CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$



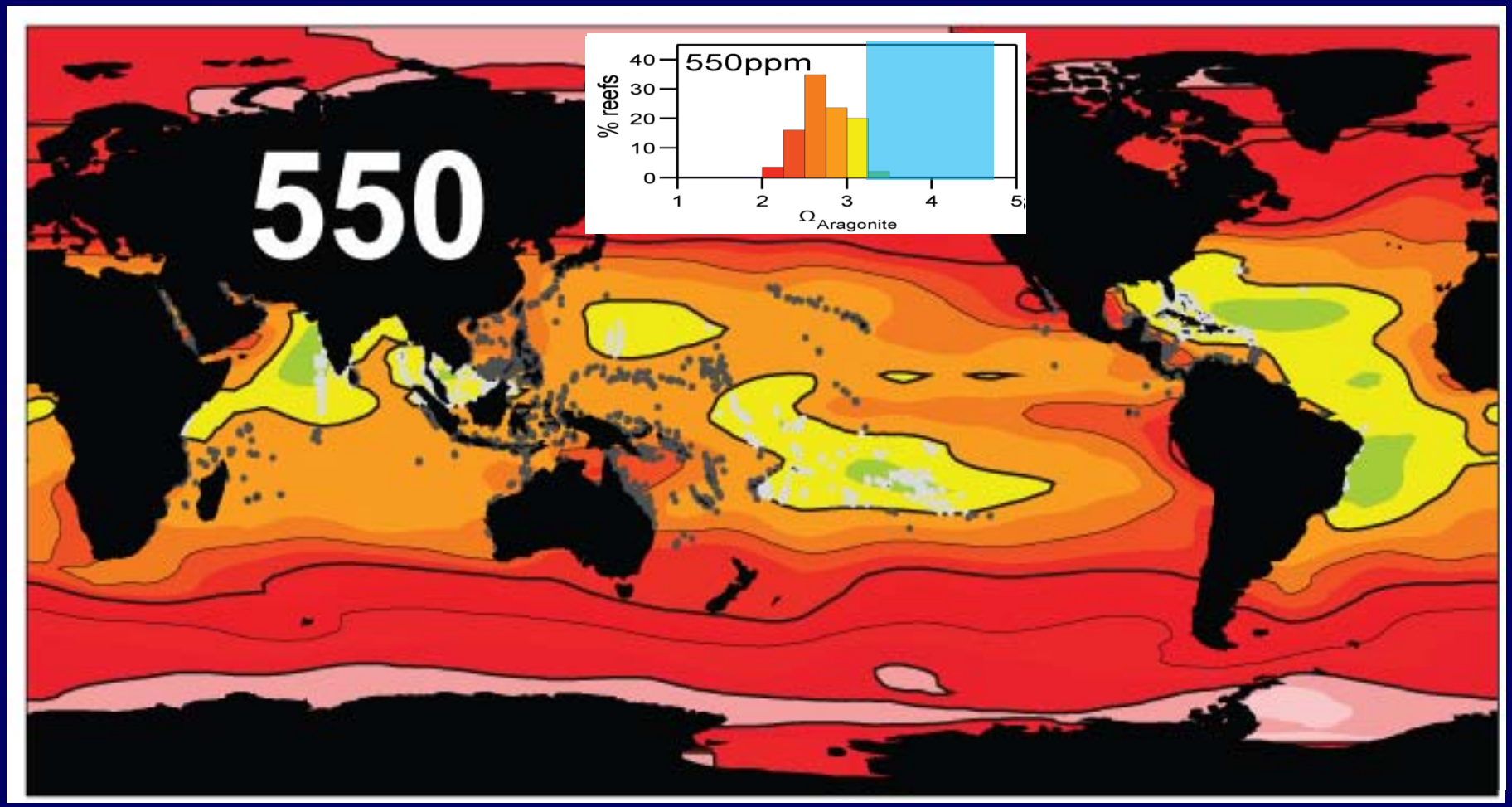






Ca^{2+} (dissolved)

Deteriorating chemical condition for coral reefs



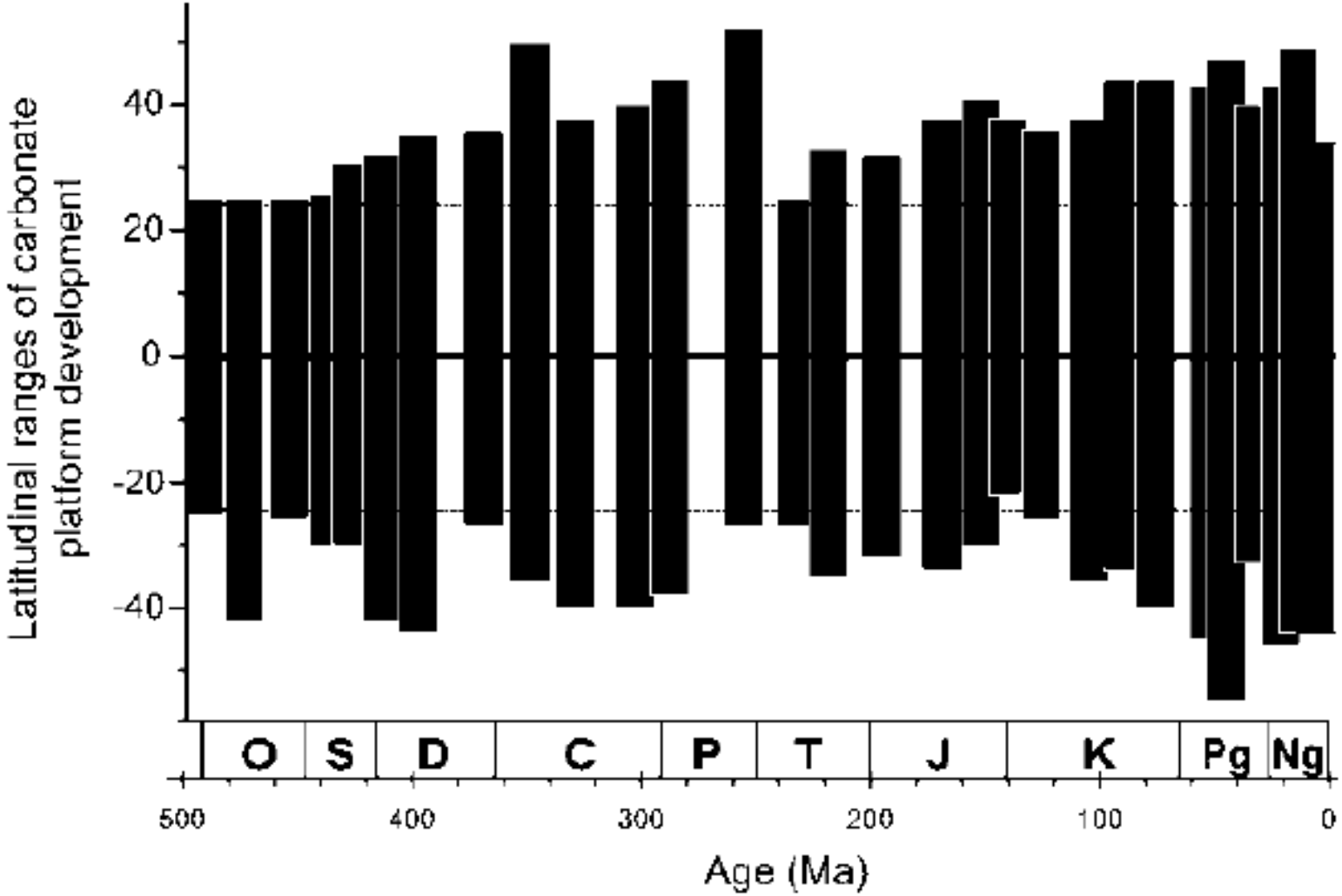
Corrosive to coral reefs

$\Omega_{aragonite}$

Optimal for coral reefs

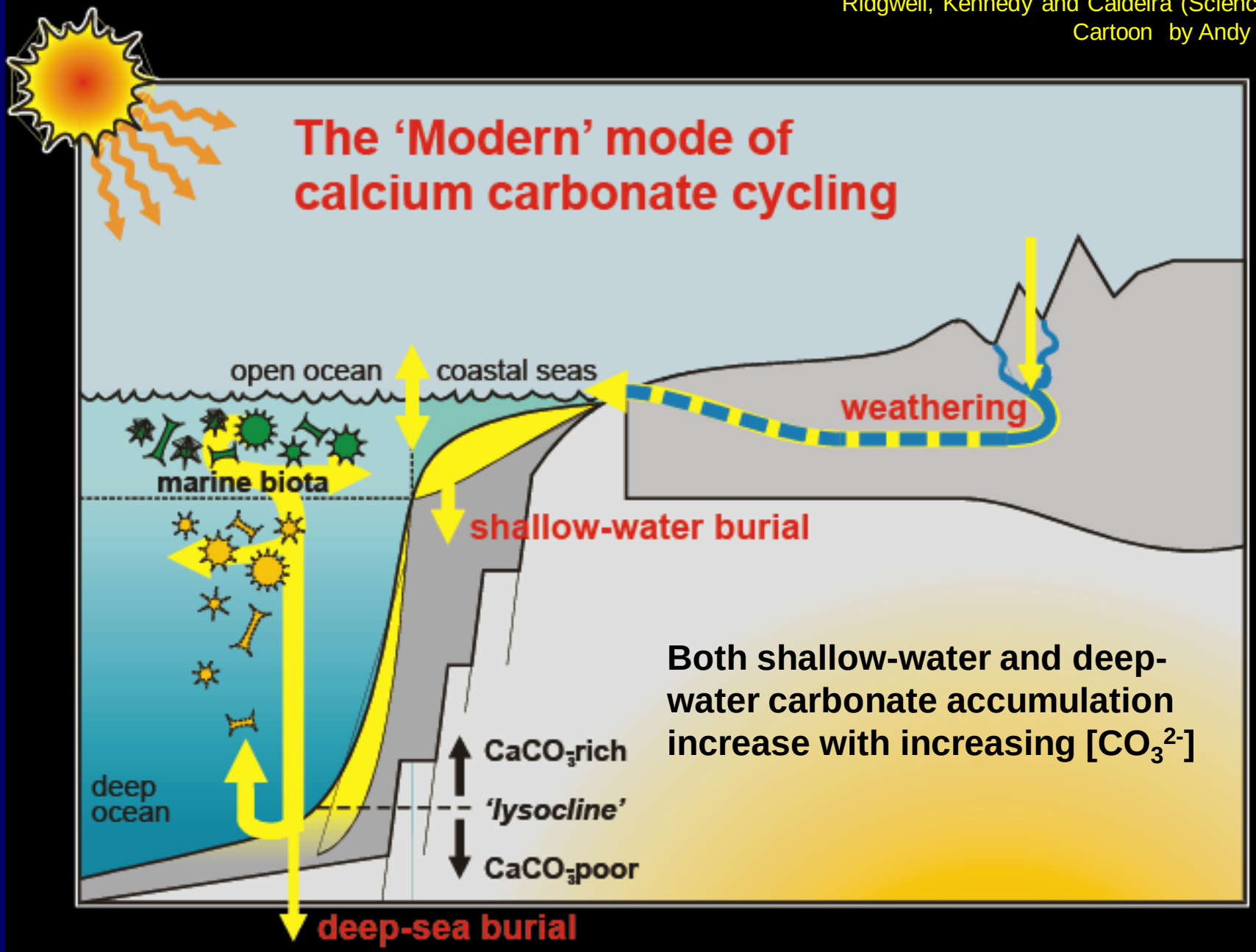
Cao and Caldeira,2008

Latitudinal range of carbonate platforms for past 600 million years



Kiessling, W., Flügel, E. & Golonka, J. 2003 09 12: Patterns of Phanerozoic carbonate platform sedimentation. *Lethaia*, Vol. 36, pp. 195–226. Oslo. ISSN 0024-1164.

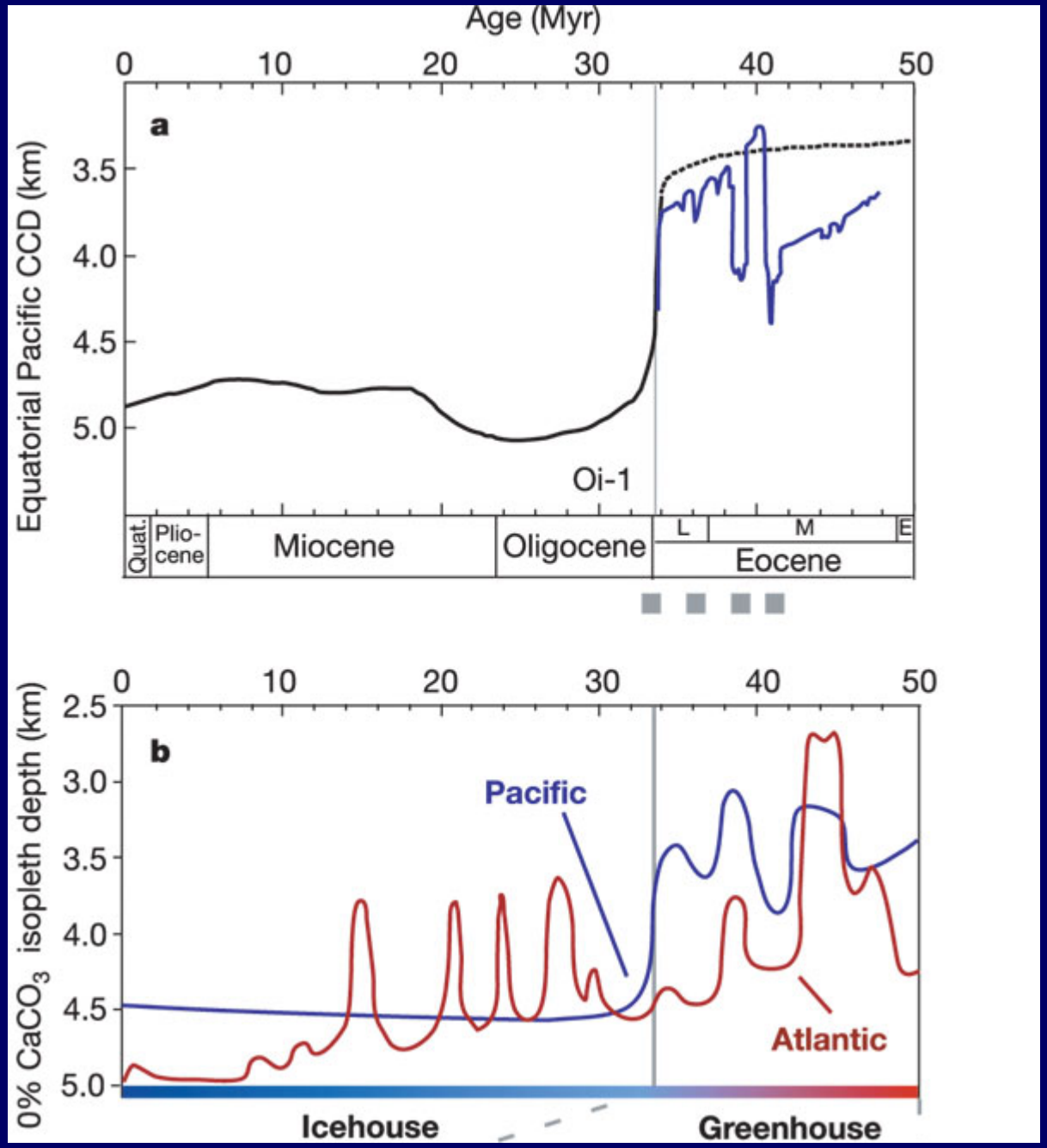
Ridgwell, Kennedy and Caldeira (Science, 2003)
Cartoon by Andy Ridgwell



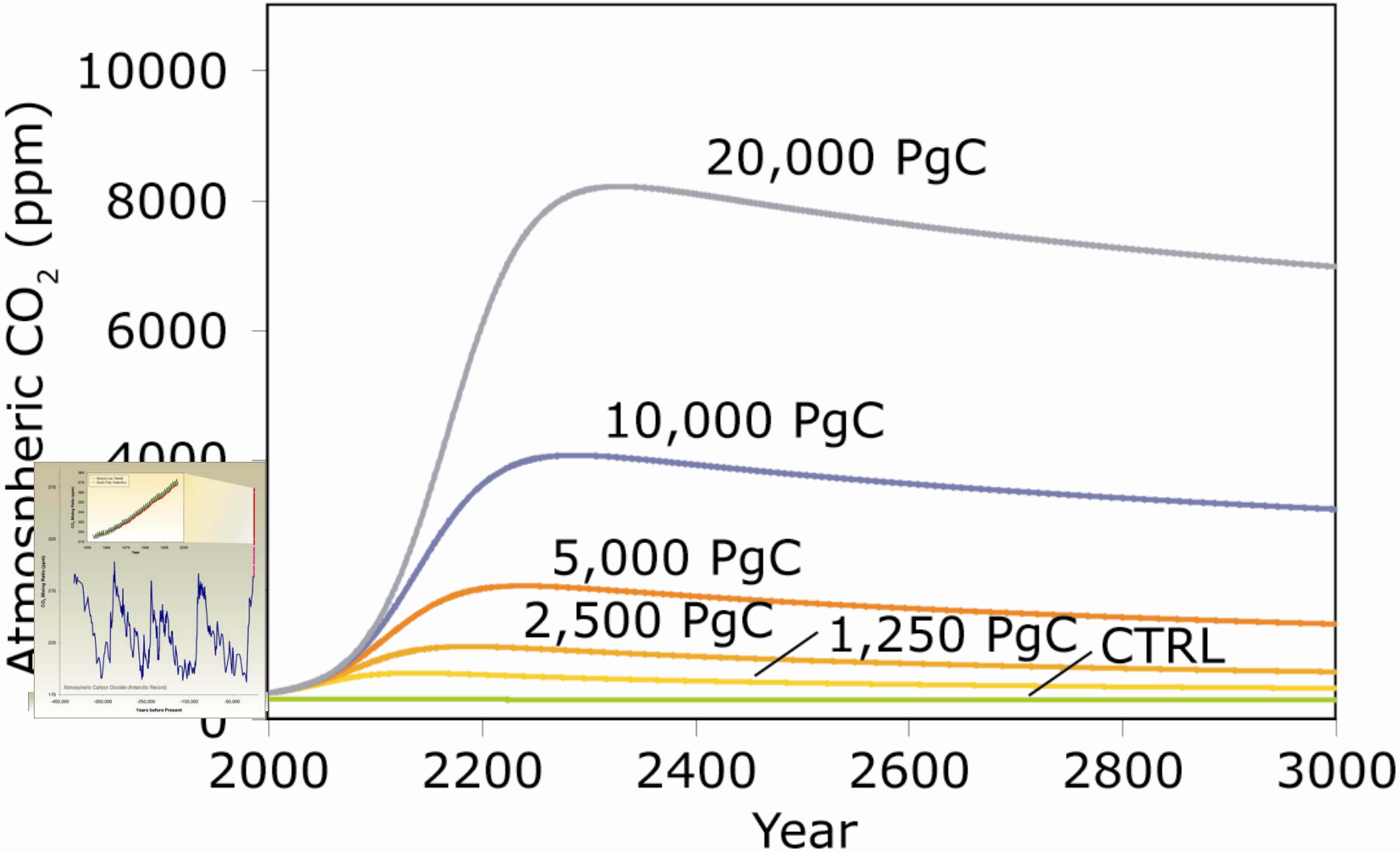
Both shallow-water and deep-water carbonate accumulation increase with increasing $[CO_3^{2-}]$

Even with atmospheric CO_2 stabilization at 450 ppm, the calcite saturation horizon shoals to shallower than 1 km.

There is no evidence that this has happened in at least the past 50 million years



Tripati et al., 2005

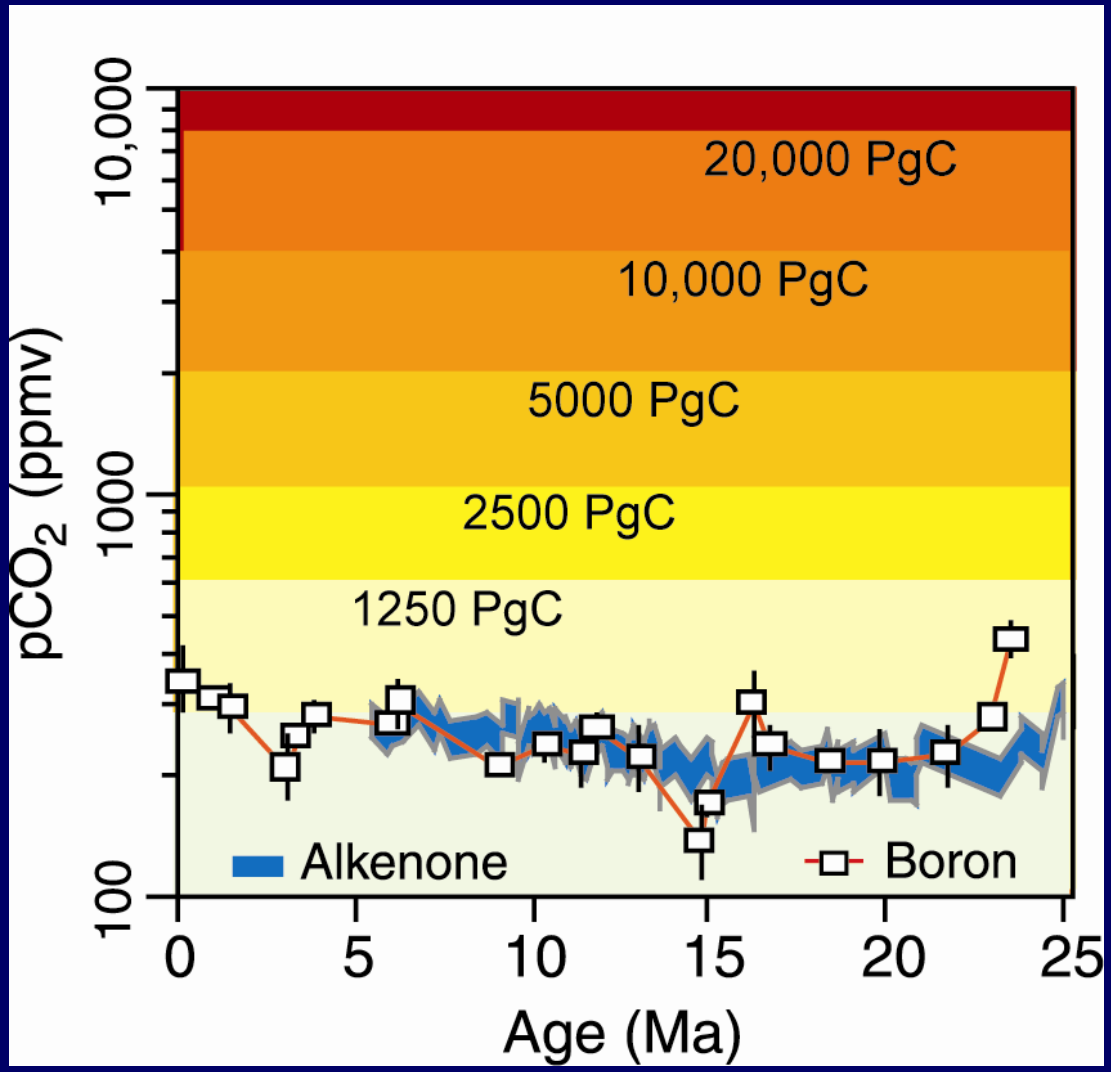


Amounts include total fossil-fuel plus net land biosphere emissions to the atmosphere

Caldeira and Wickett (2005)

Predicted future CO_2 concentration exceed those inferred for past 25 million years

Even if most fossil-fuel carbon is never released to the atmosphere, we will produce geologically unusual conditions



Paleo-CO_2 [lines]
(Pagani et al., 1999;
Pearson and Palmer, 2000)

Year 2300 atmospheric CO_2 predictions for scenarios involving fossil-fuel plus net biomass release over several centuries [colors]
(Caldeira and Wickett, 2005)

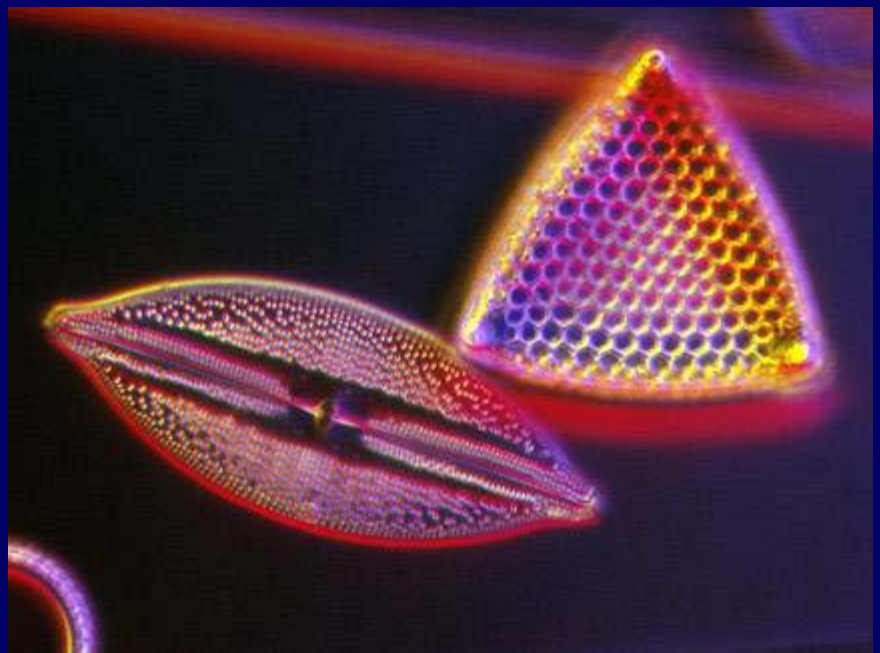
65 Ma
© 2002, PALEOMAP Project

Siliceous plankton bloom in the earliest Tertiary of Marlborough, New Zealand

C. J. Hollis
Institute of Geological and Nuclear Sciences, P.O. Box 30-368, Lower Hutt, New Zealand
K. A. Rodgers
R. J. Parker
Department of Geology, University of Auckland, Private Bag 92019, Auckland, New Zealand

ABSTRACT

In marked contrast to mass extinctions and productivity crises in much of the world's oceans at the Cretaceous-Tertiary boundary, siliceous plankton thrived in earliest Paleocene seas of Marlborough, New Zealand.



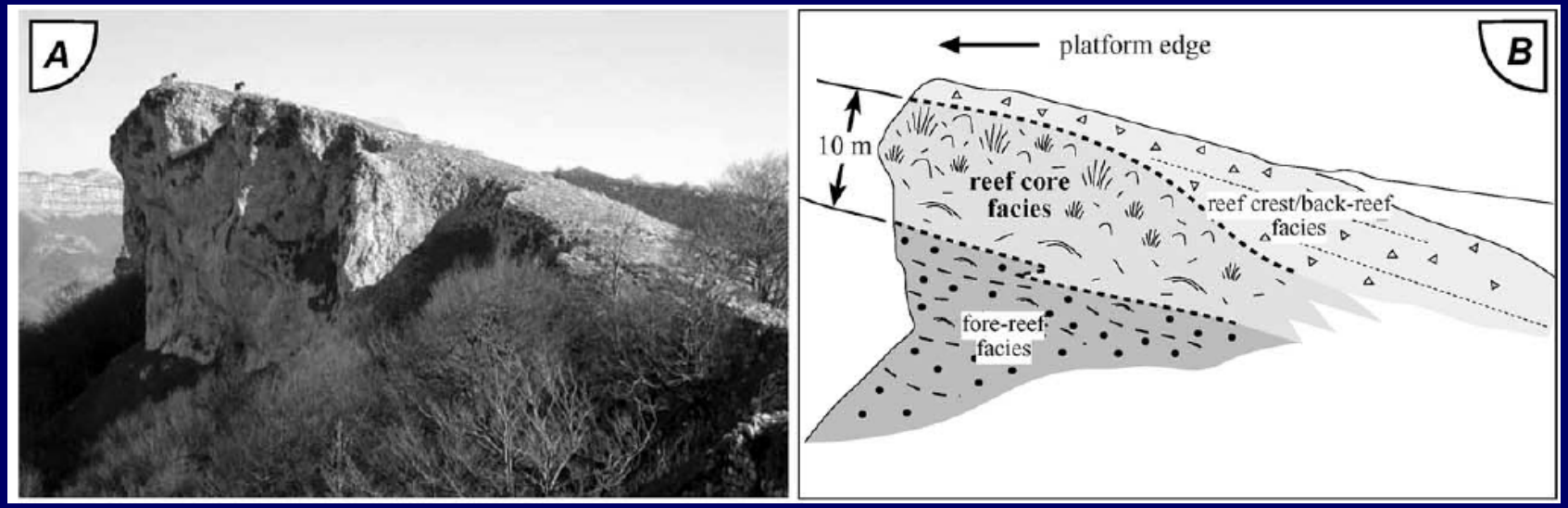
Mel Pollinger

Time scale for recovery after mass extinction

After a comparatively short interval devoid of reefs at the early Danian (<2 Ma) (< 2 million years)

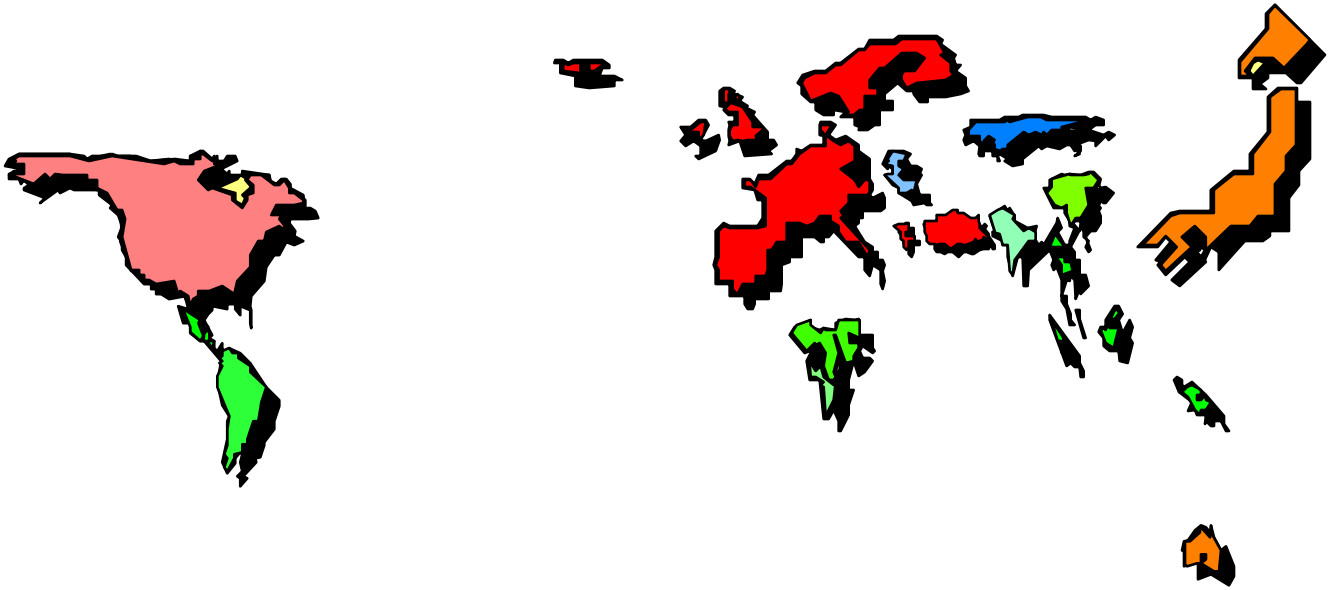
The rate of recovery of photic reefal ecosystems after the Cretaceous–Tertiary crisis is controversial. coral-dominated reef systems came back into existence less than 2 Ma after the K/T boundary,

Juan Ignacio Baceta[a,*], Victoriano Pujalte[a], Gilen Bernaola[b]
Palaeogeography, Palaeoclimatology, Palaeoecology 224 (2005) 117–143



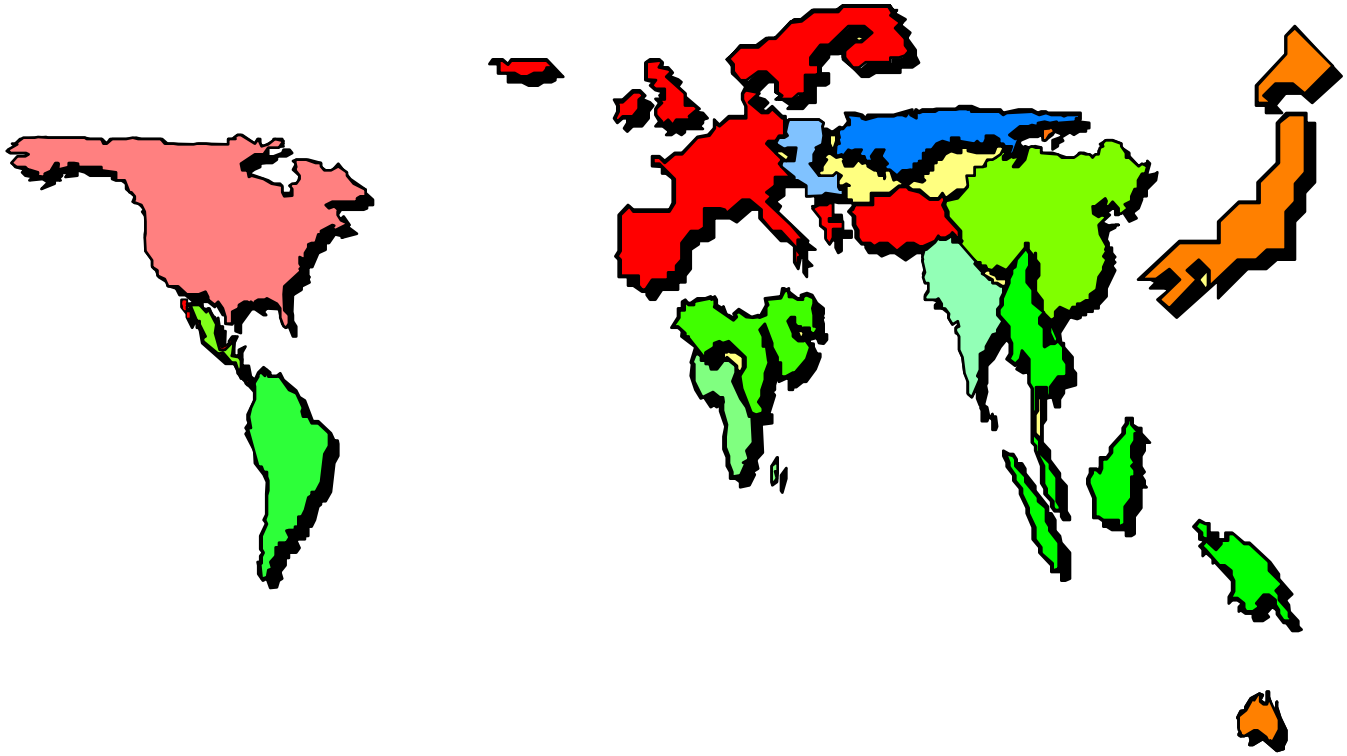
The scale of the solution

GDP in 1990



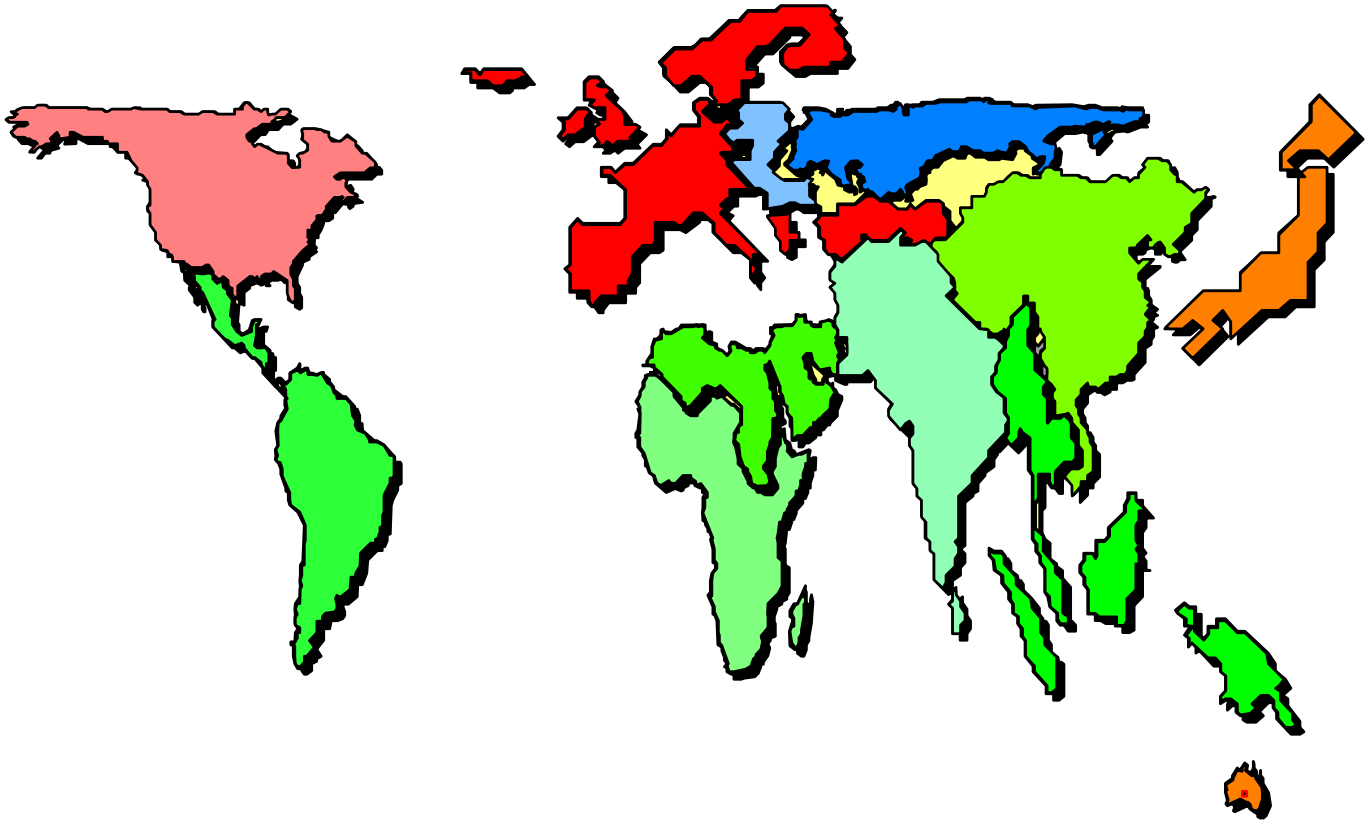
Naki Nakicenovic

GDP in 2050



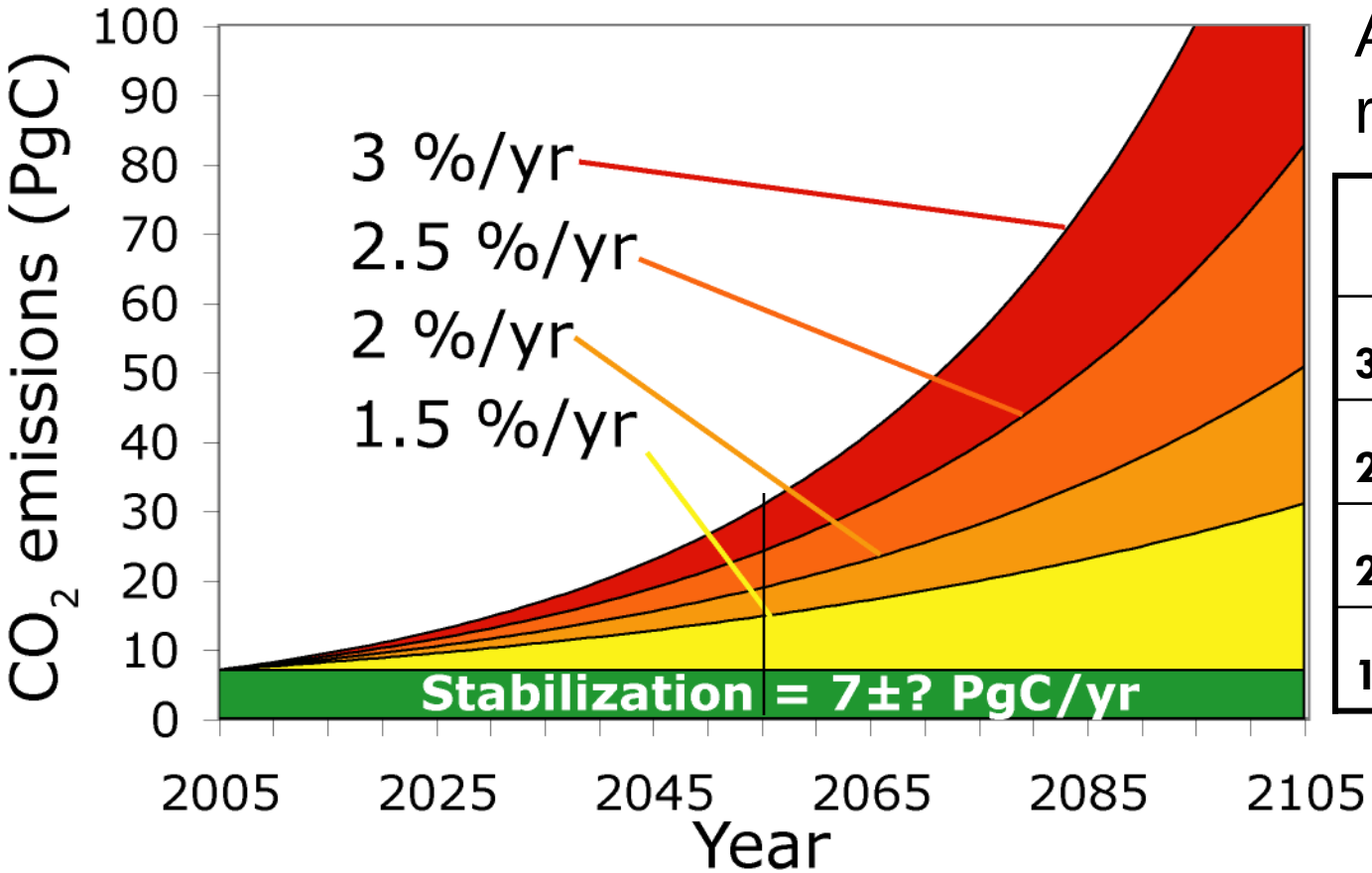
Naki Nakicenovic

GDP in 2100



Naki Nakicenovic

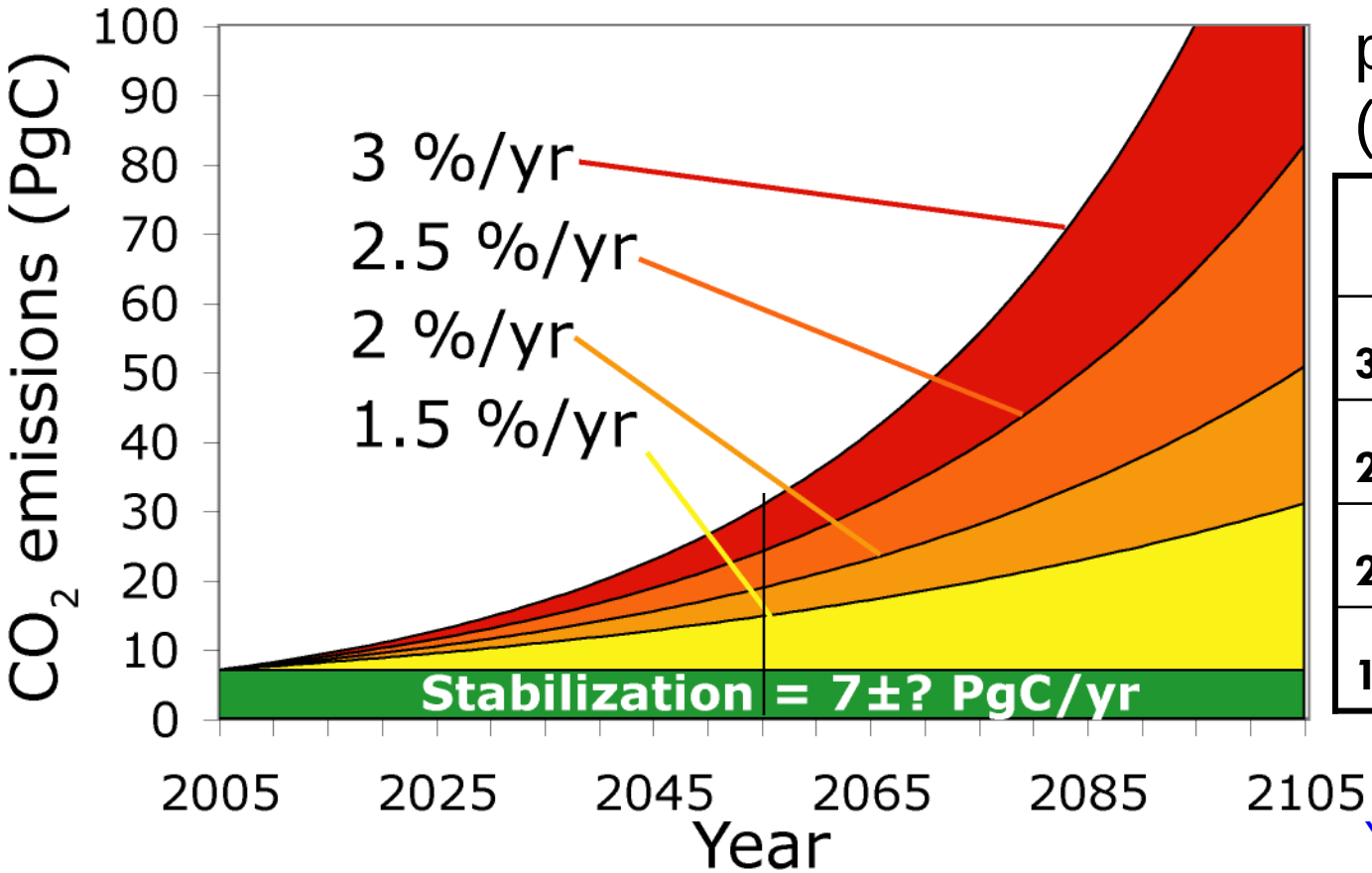
CO_2-stabilization requires a huge abatement effort



Abatement required (PgC/yr)

	Year 2055	Year 2105
3 %	24	128
2.5 %	17	76
2 %	12	44
1.5 %	8	24

CO_2-stabilization requires a huge abatement effort



Carbon-neutral power required (TW/yr)

	Year 2055	Year 2105
3 %	48	256
2.5 %	34	152
2 %	24	88
1.5 %	16	48

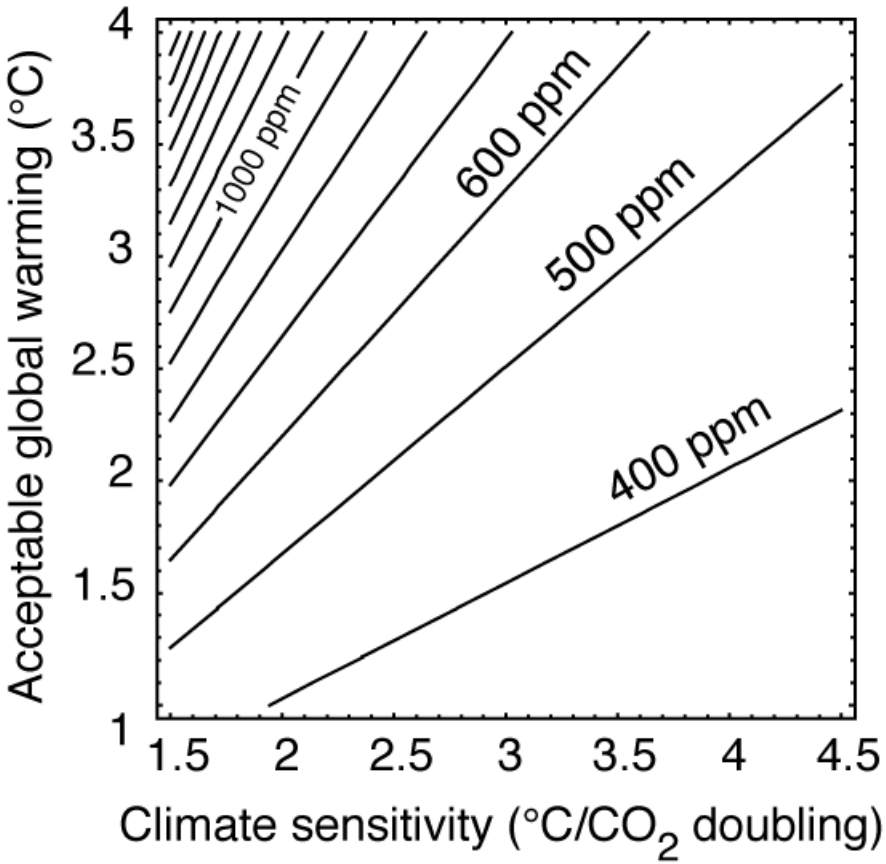
Assuming 2 TW per PgC

Year 2005 power = 13

Carbon-neutral energy needed for 1.5 % to 2 % growth in energy demand:
year 2055 → 16 to 24 TW/yr year 2105 → 48 to 88 TW

Uncertainty in CO_2 stabilization target

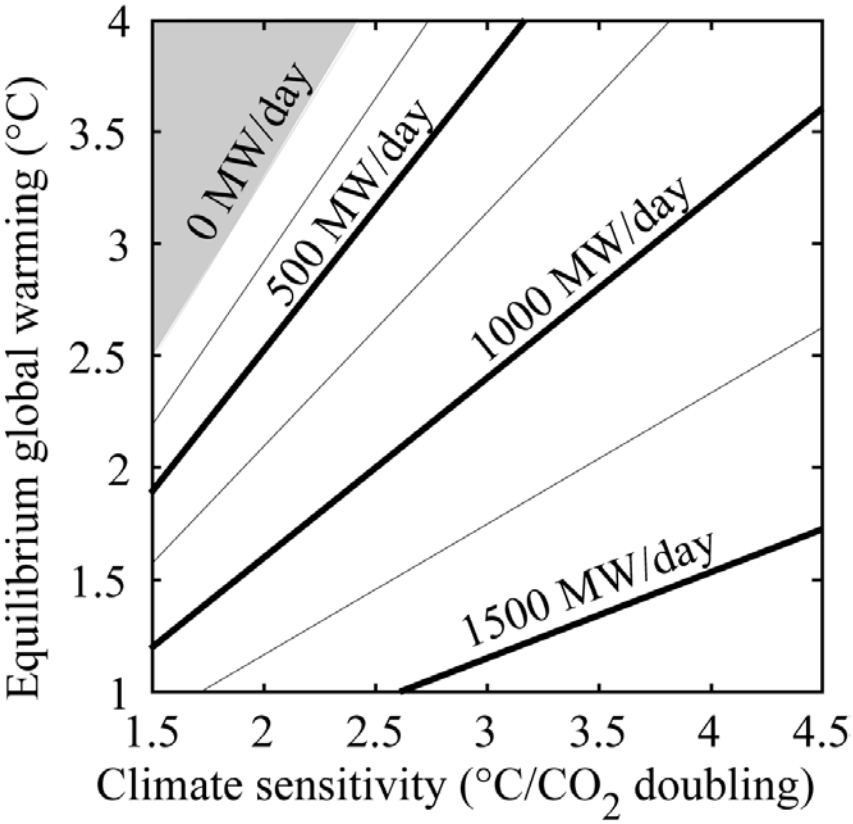
- Uncertainty in CO_2 stabilization target comes from uncertainty in
  - acceptable global warming
  - climate sensitivity to a doubling of atmospheric CO_2 content



Mean rate of carbon-emissions-free primary power capacity addition over next 50 years

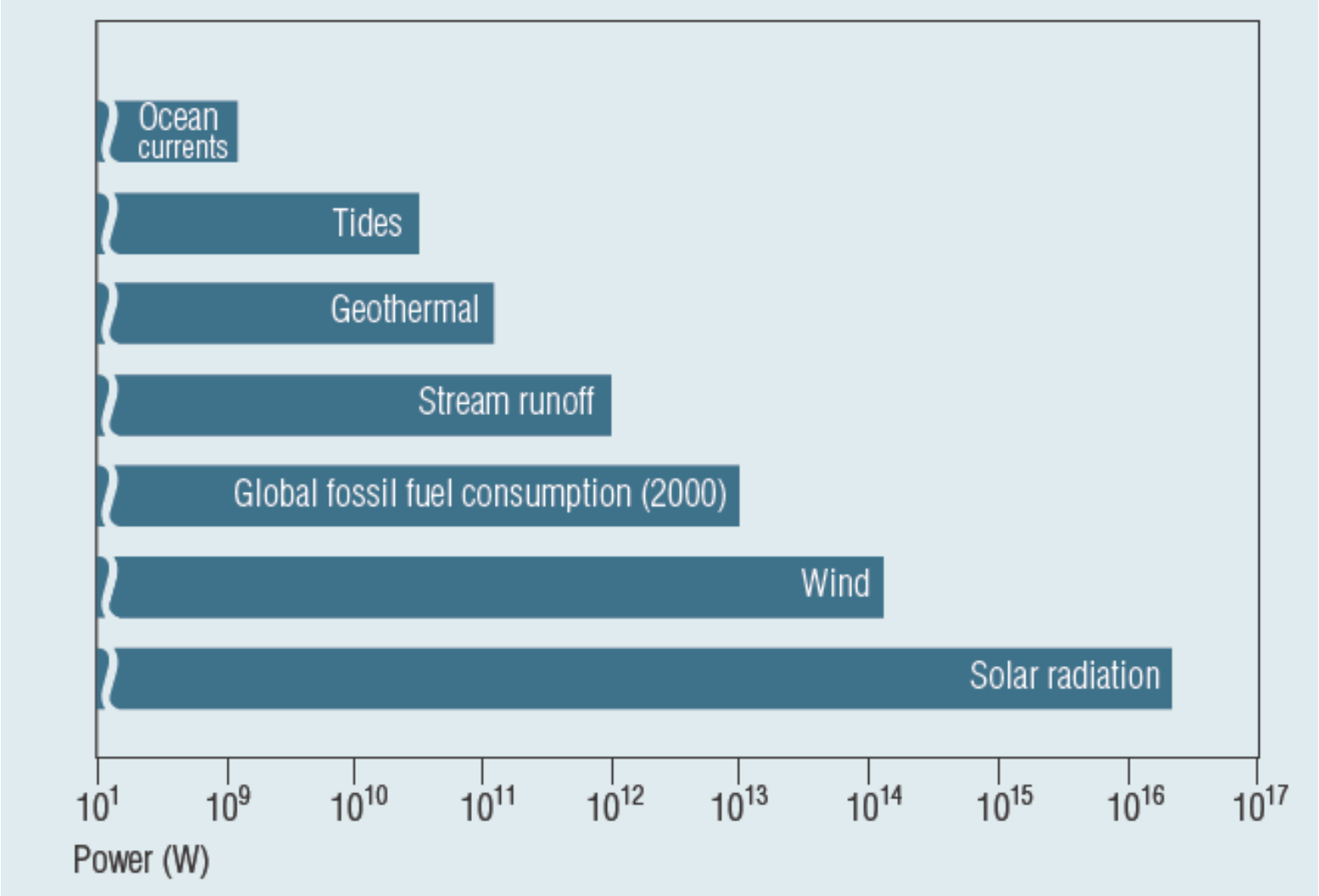
- Assumes
  - IS92a rates of GDP growth, energy intensity improvement, fossil-fuel mix, etc.
  - Stabilization curves from Caldeira et al. 2003

- Rates increase after 2050



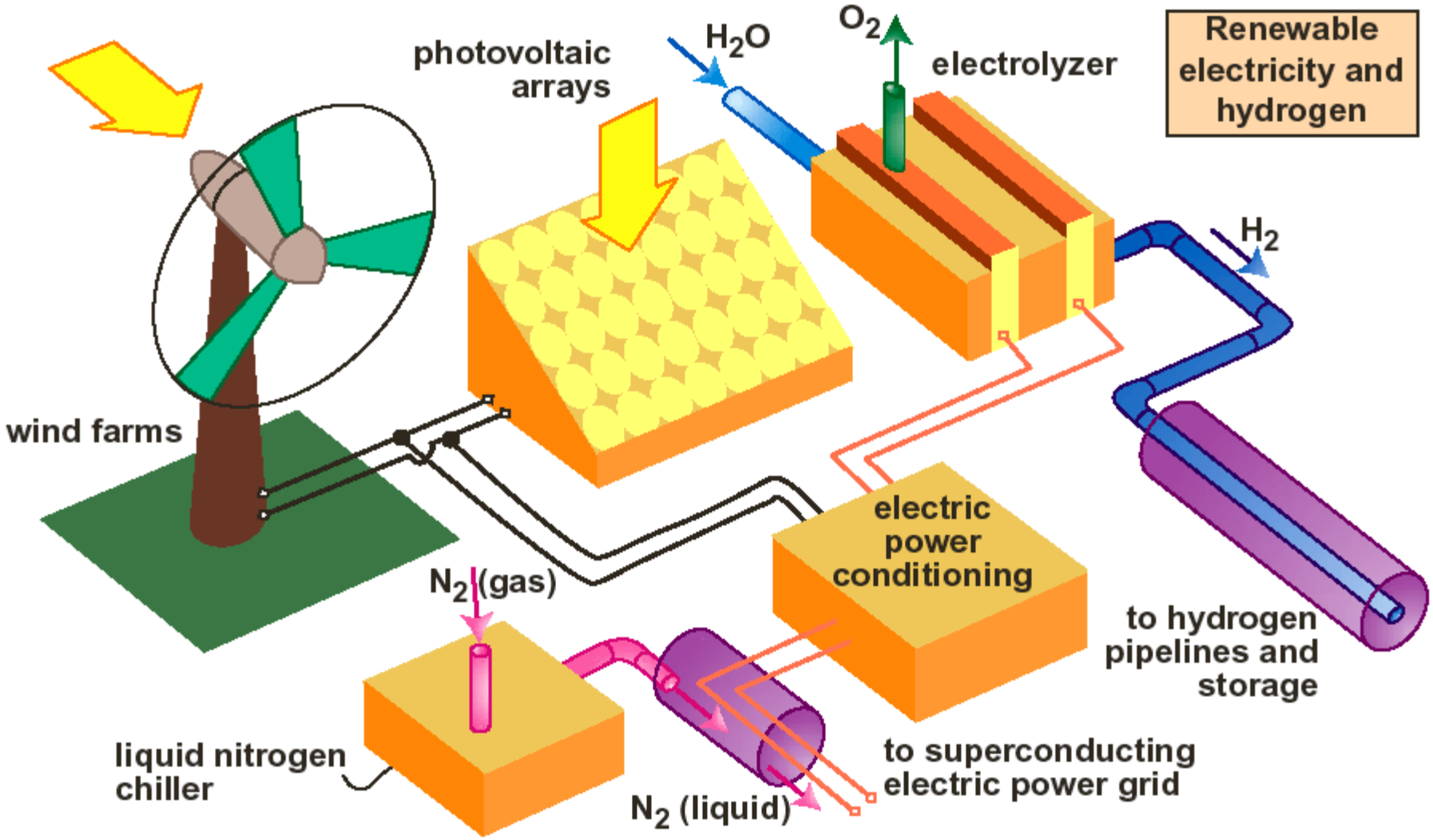
Caldeira, Jain and Hoffert, 2003

Available power



Smil, 2006

Storage and distribution required for wind and solar



Hoffert et al., 2002

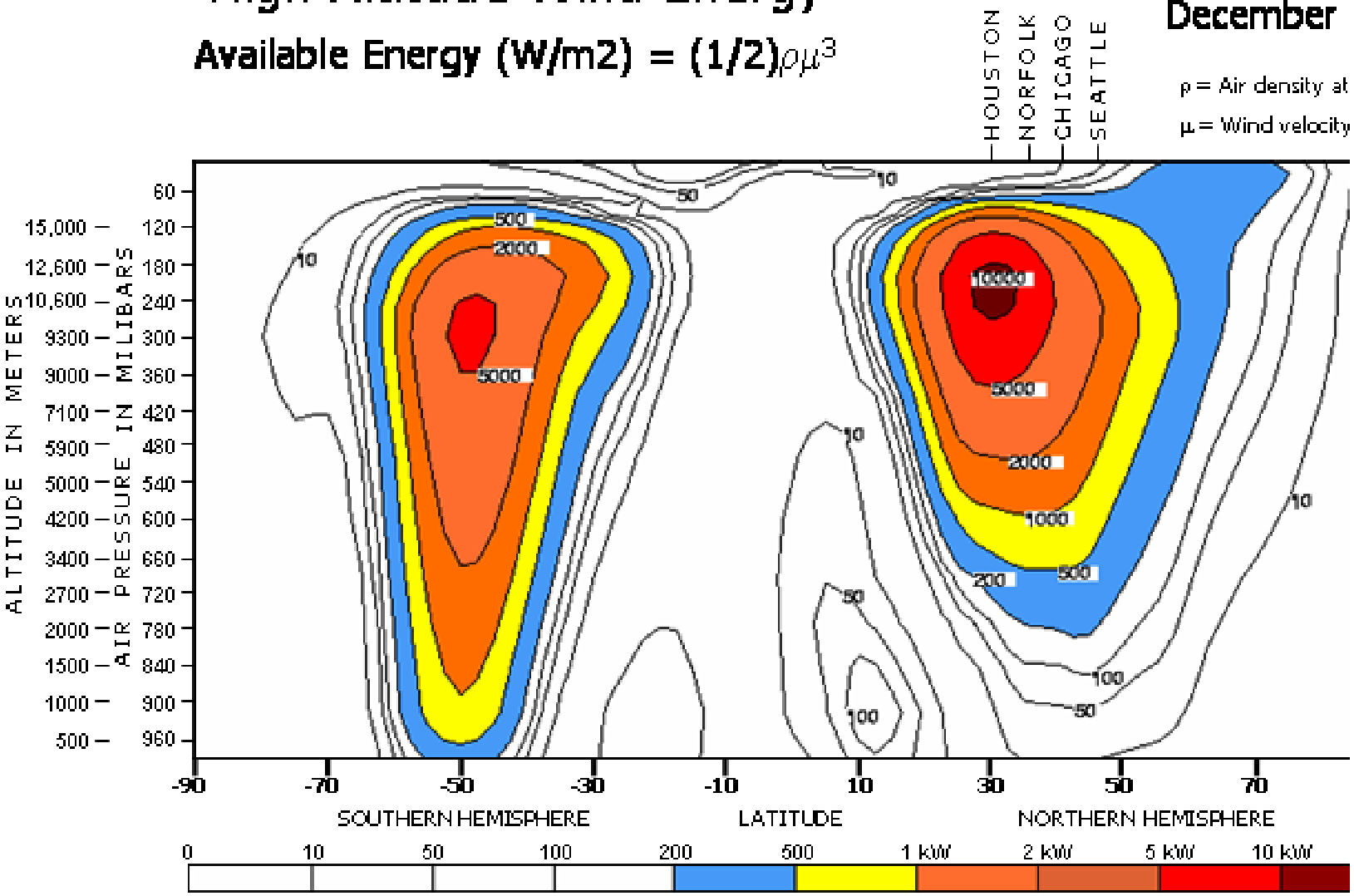
High Altitude Wind Energy

Available Energy (W/m2) = (1/2)$\rho\mu^3$

December

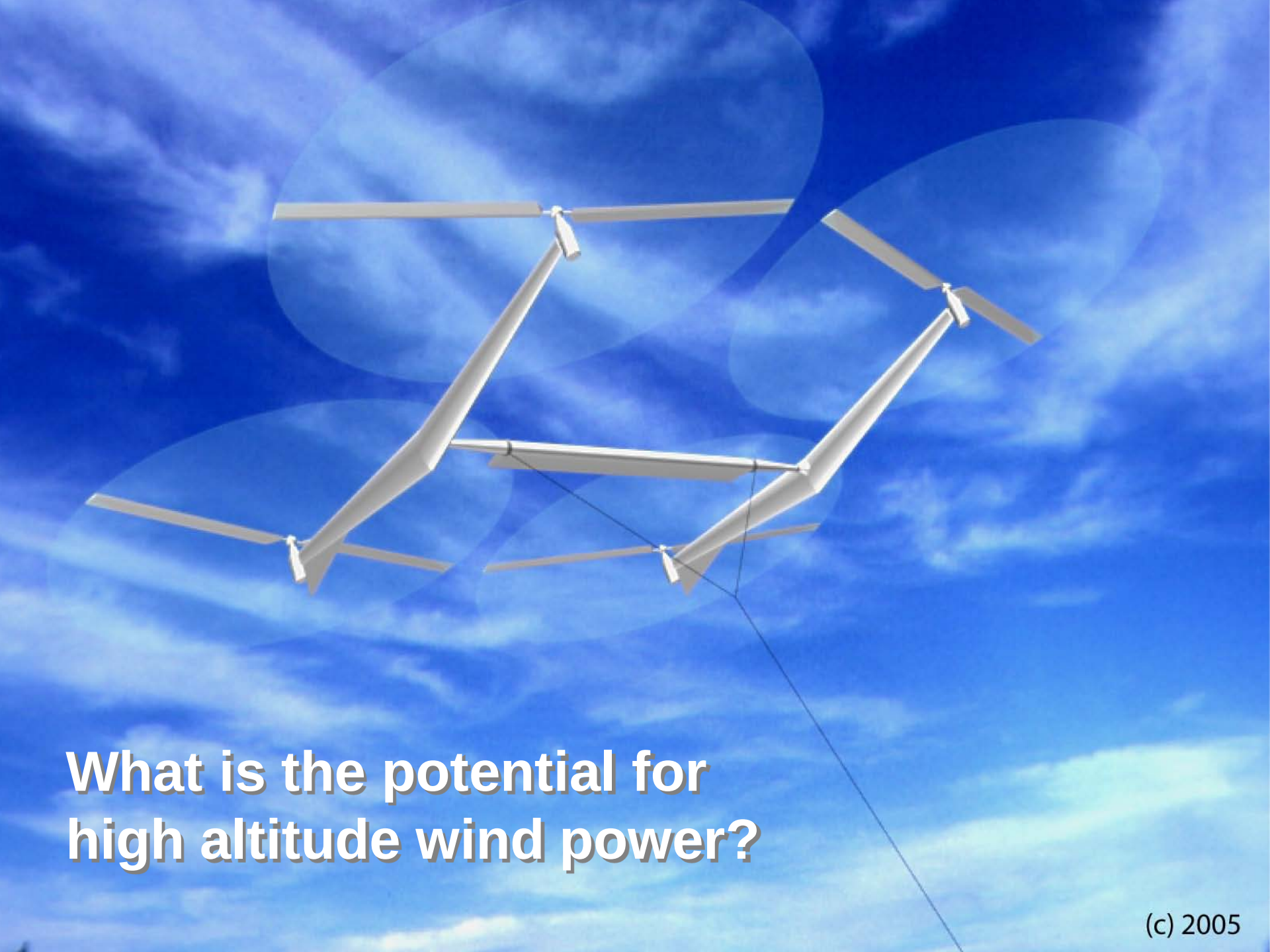
ρ = Air density at

μ = Wind velocity



Calculated by Ken Caldeira (Lawrence Livermore National Laboratory, kenc@llnl.gov), based on ECMWF 1978-1994 seasonal mean wind and temperatures.

Additional scales and city names added by Sky WindPower Corp.


What is the potential for
high altitude wind power?
(c) 2005

Take home points

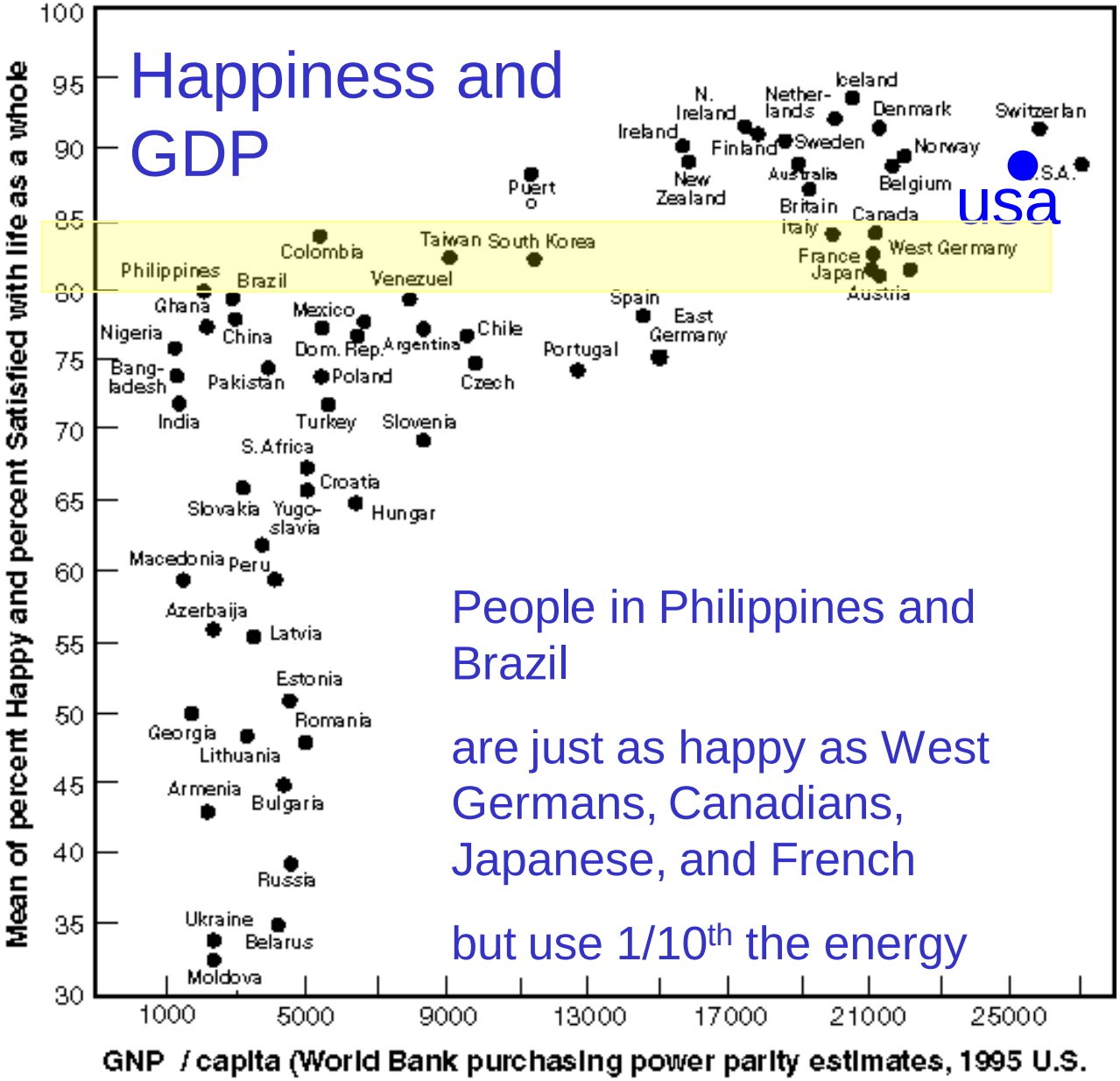
- We need a revolutionary transformation in our global systems of energy production and consumption

- The real challenge is the energy system of the 2nd half of this century, but we are already building the energy infrastructure for the 2nd half of this century

- Global models of the Earth are essential tools for developing sound policy

Reduce consumption

Happiness and GDP



People in Philippines and Brazil

are just as happy as West Germans, Canadians, Japanese, and French

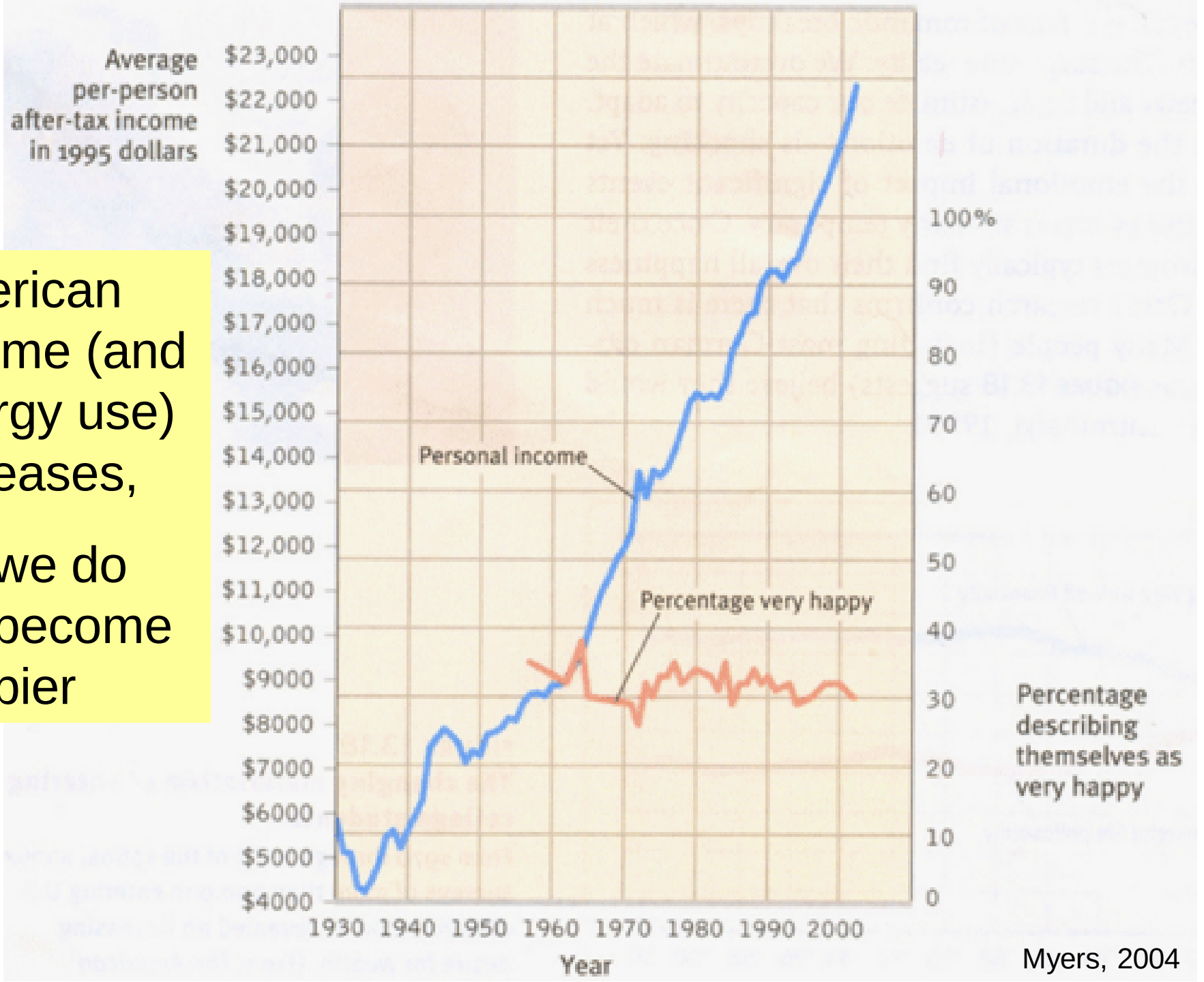
but use 1/10th the energy

Figure 2. Subjective well-being by level of economic development.
Source: World Values Surveys; GNP/capita purchasing power estimates from World Bank, World Development Report, 1997.
R = .70 N = 65 p < .0000

Inglehart and Klingemann 2000.

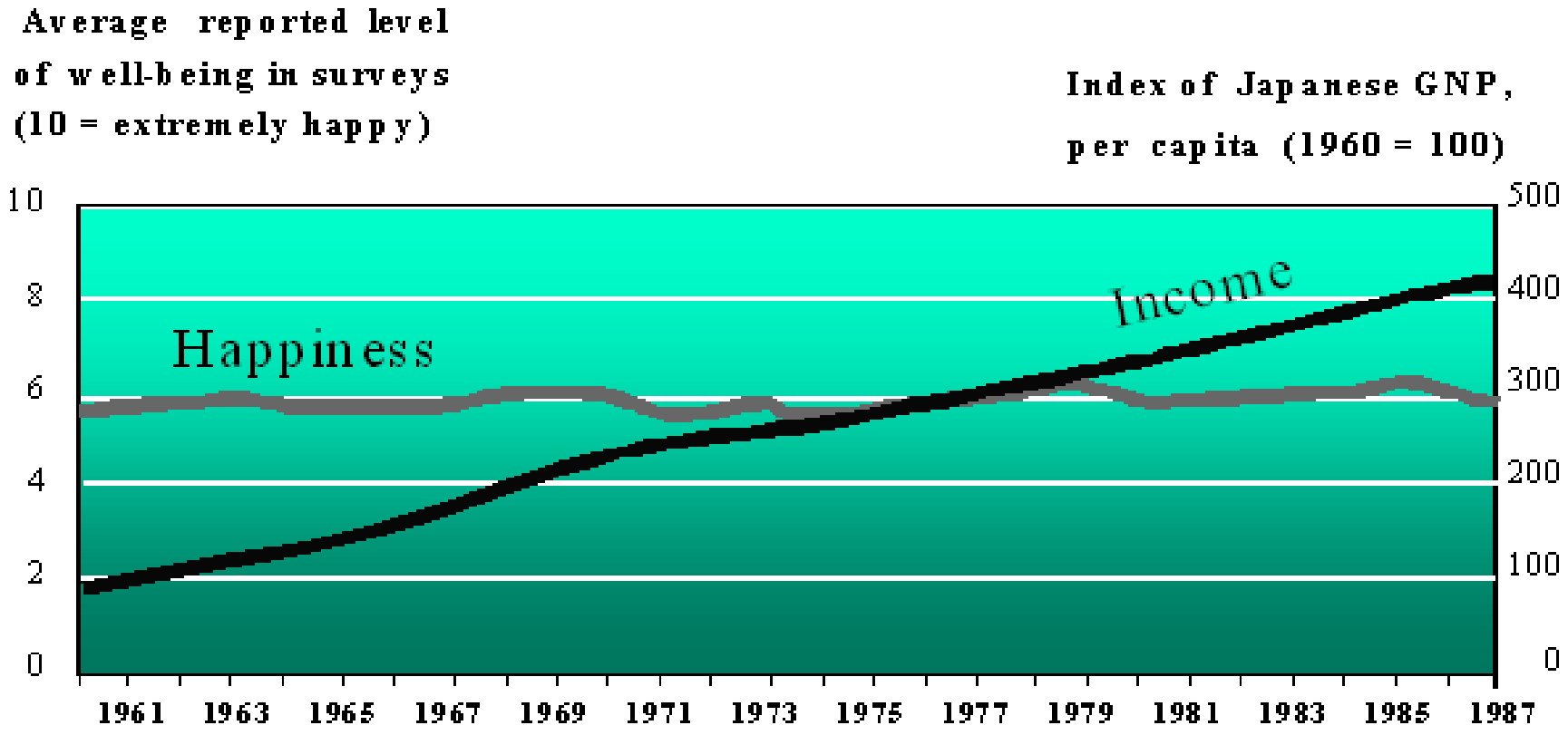
American income (and energy use) increases,

but we do not become happier



Myers, 2004

Japanese income (and energy use) increases, but they do not become happier



Veenhoven, 1993