Aspen Global Change Institute
7 July 2003

Climate sensitivity and stabilization primer

Ken Caldeira
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Climate Sensitivity Uncertainty and the Need for Energy Without CO_2 Emission

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28 MARCH 2003 VOL 299 SCIENCE

Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet

Martin I. Hoffert,[1*] Ken Caldeira,[3] Gregory Benford,[4] David R. Criswell,[5] Christopher Green,[6] Howard Herzog,[7] Atul K. Jain,[8] Haroon S. Kheshgi,[9] Klaus S. Lackner,[10] John S. Lewis,[12] H. Douglas Lightfoot,[13] Wallace Manheimer,[14] John C. Mankins,[15] Michael E. Mauel,[11] L. John Perkins,[3] Michael E. Schlesinger,[8] Tyler Volk,[2] Tom M. L. Wigley[16]

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Energy implications of future stabilization of atmospheric CO_2 content

Martin I. Hoffert[*], Ken Caldeira[†], Atul K. Jain[‡], Erik F. Haites[§], L. D. Danny Harvey[‖], Seth D. Potter[*¶], Michael E. Schlesinger[‡], Stephen H. Schneider[#], Robert G. Watts[☆], Tom M. L. Wigley[**] & Donald J. Wuebbles[‡]

NATURE | VOL 395 | 29 OCTOBER 1998

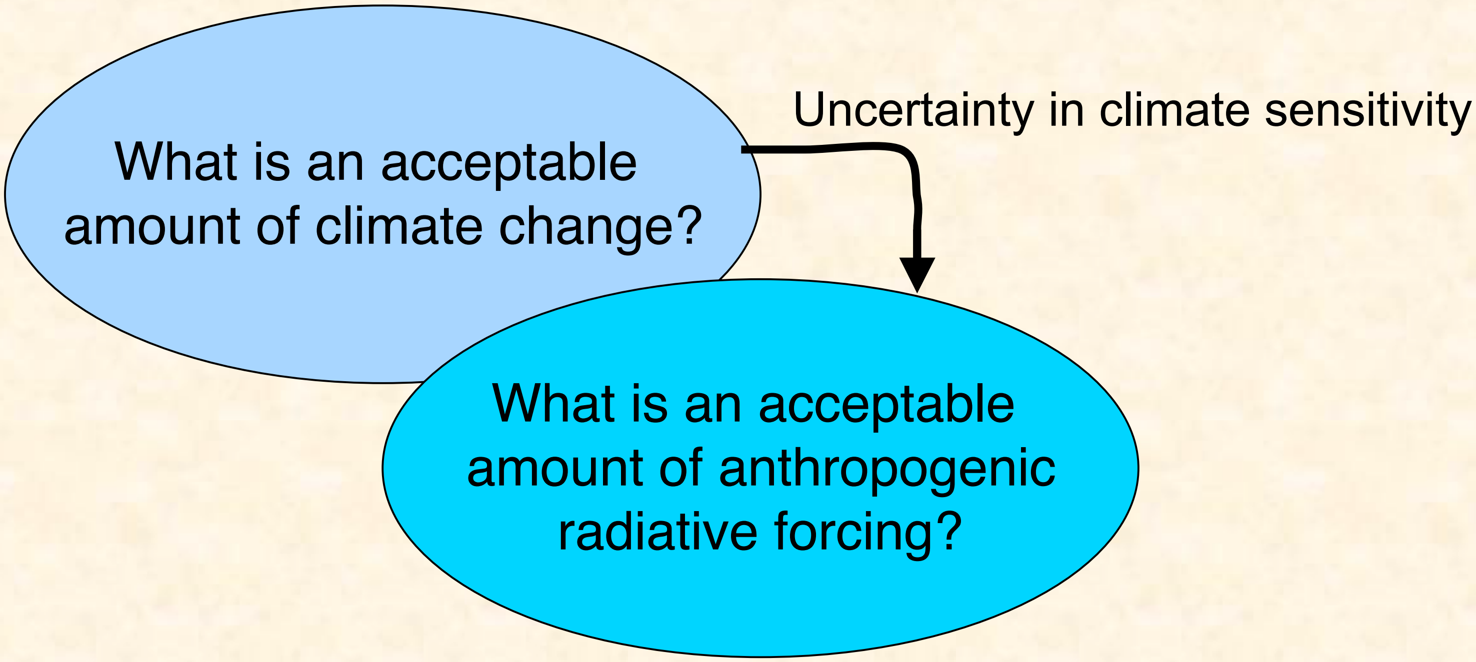
UN Framework Convention on Climate Change

- Signed June 12, 1992
  - by President Bush in Rio de Janeiro, Brazil
- Ratified Oct 15, 1992
  - by the U.S. Senate
- Calls for—
  - “stabilization of greenhouse gases at a level that will prevent dangerous interference with the climate system”
  - “within a time-frame sufficient to allow ecosystems to adapt naturally to climate change”

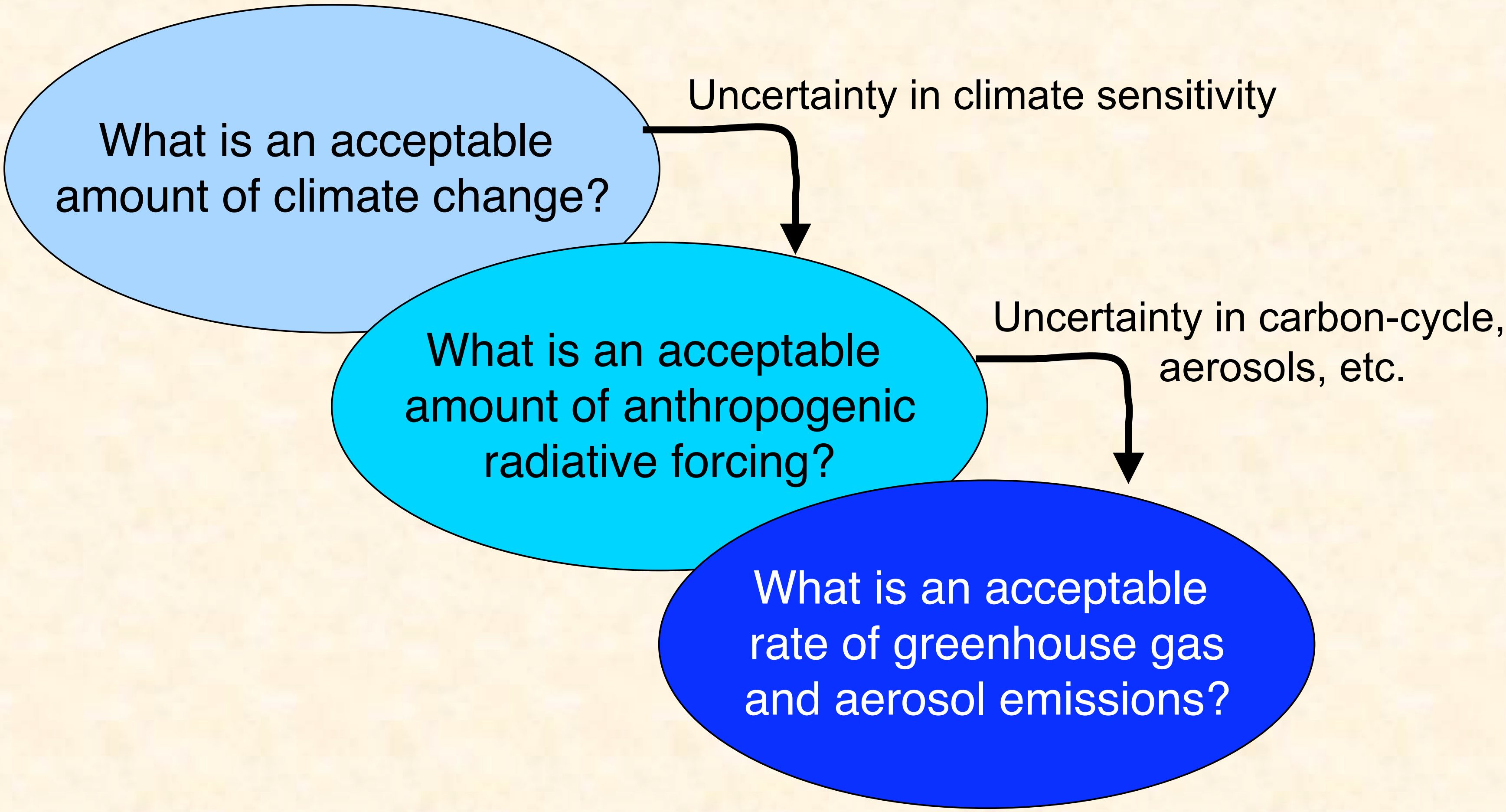
"stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system"

What is an acceptable amount of climate change?

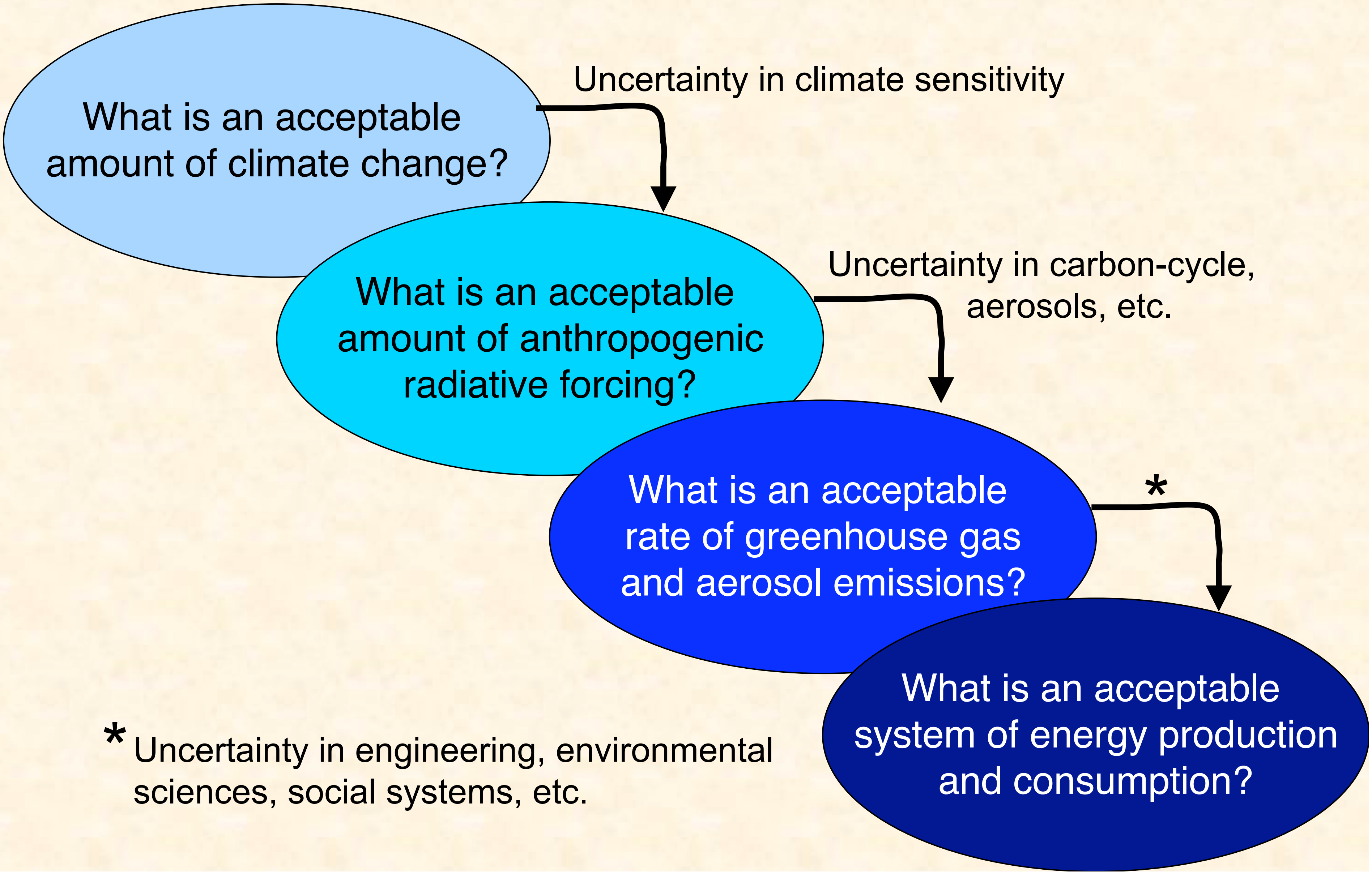
"stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system"



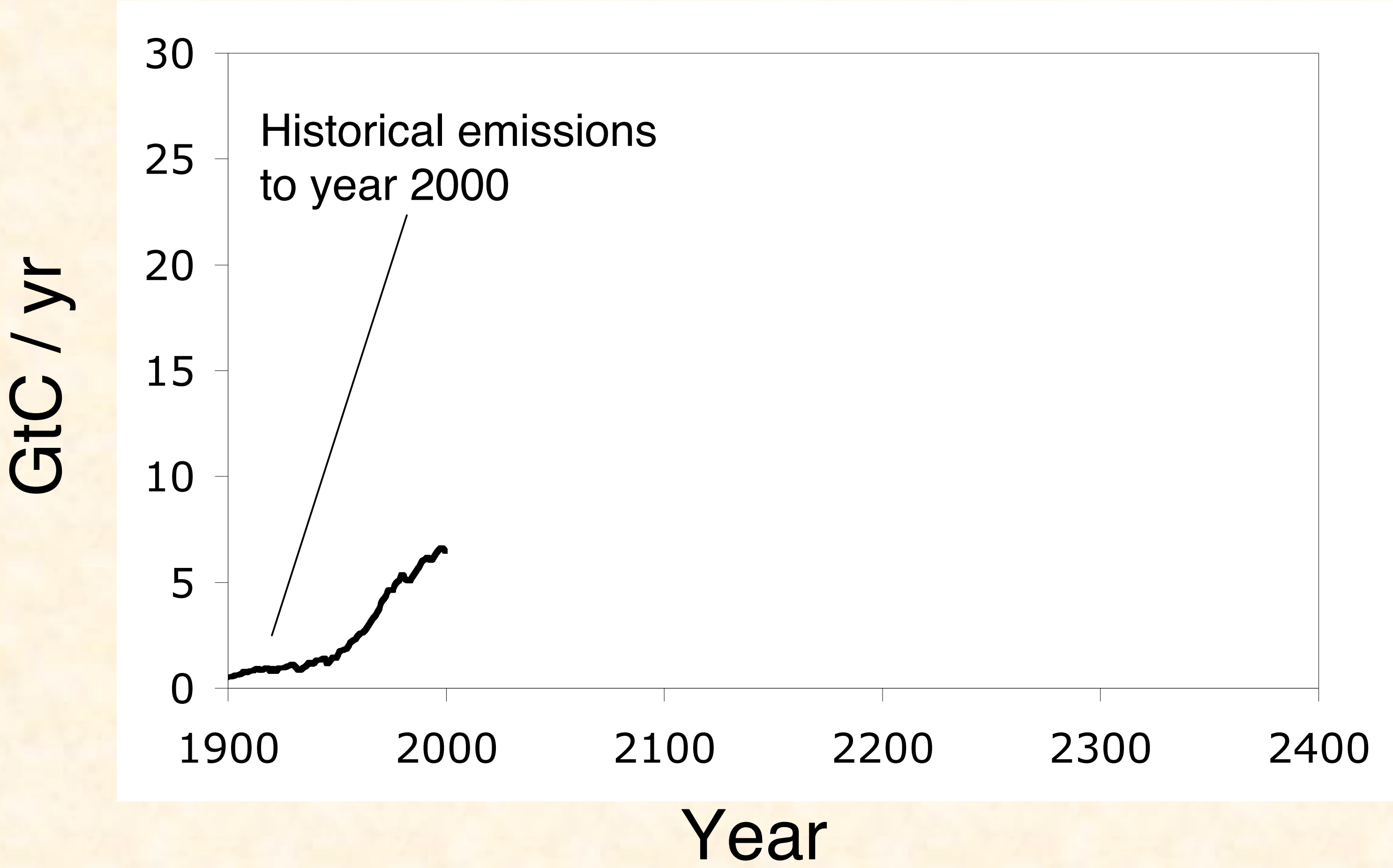
“stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system”



"stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system"



What happens if we do nothing?



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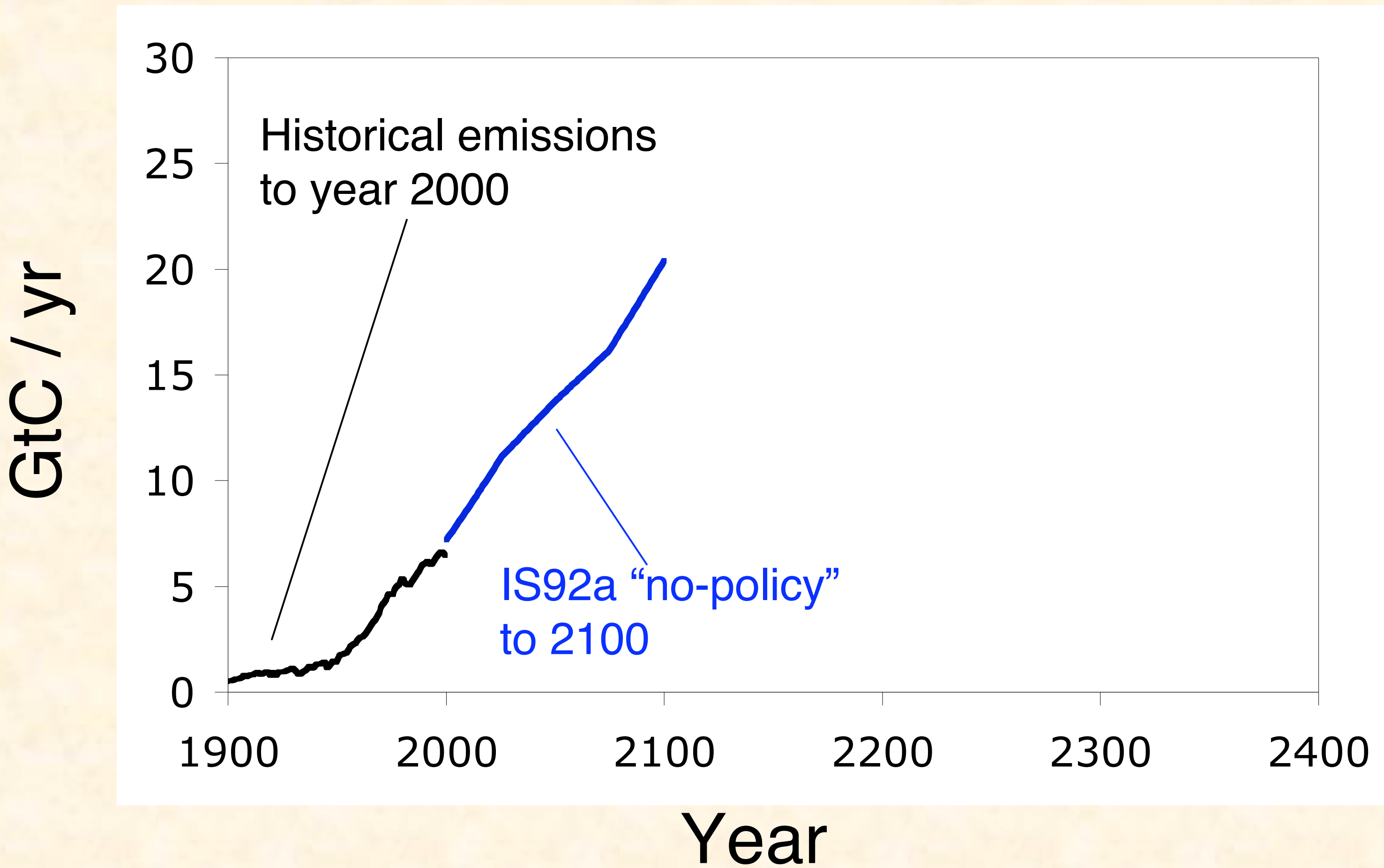

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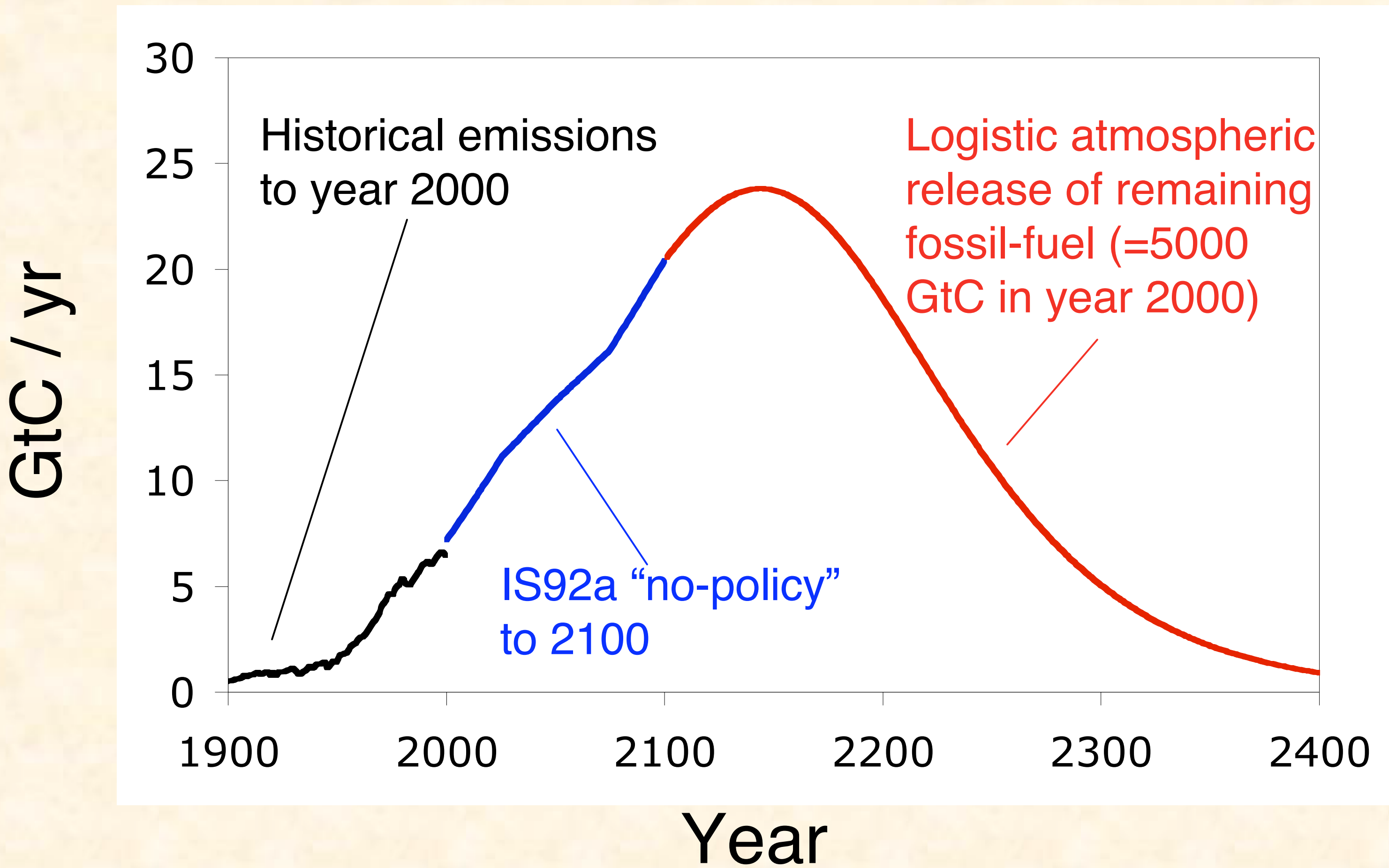

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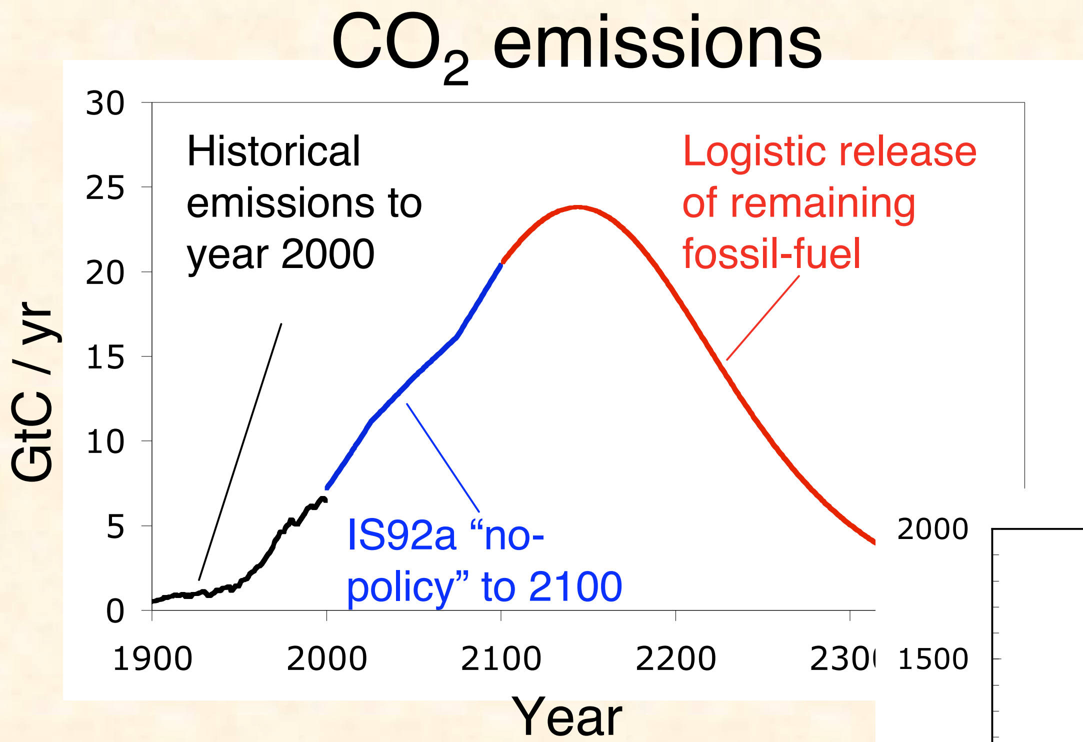

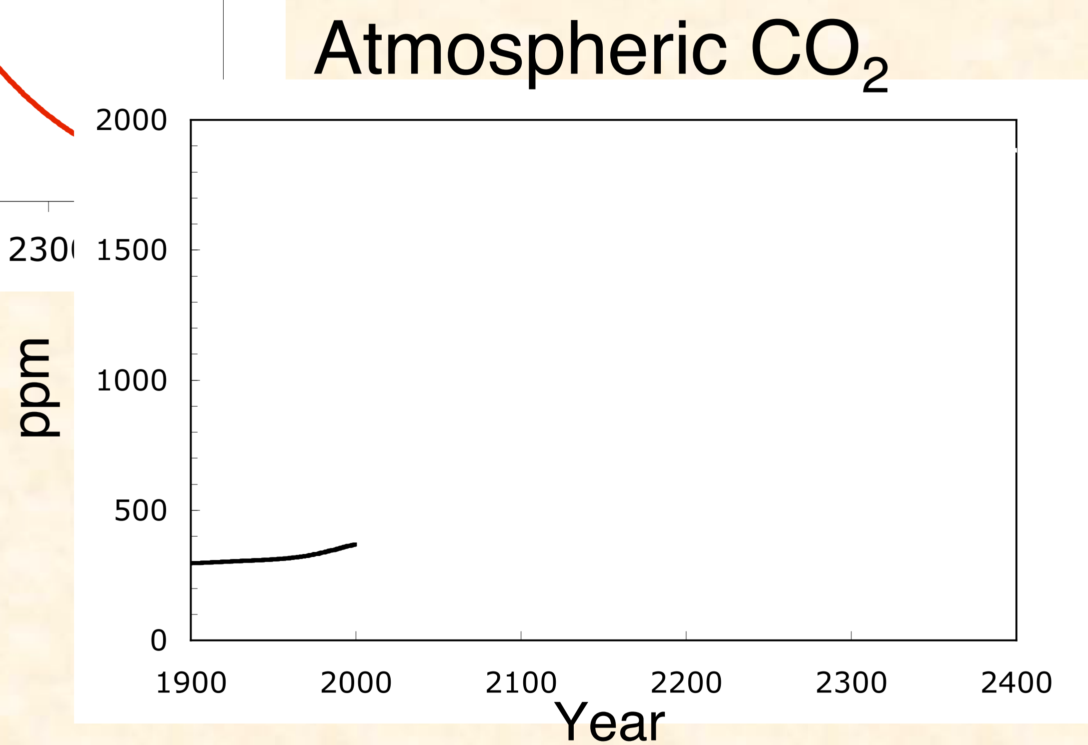

Caldeira and Wickett, submitted

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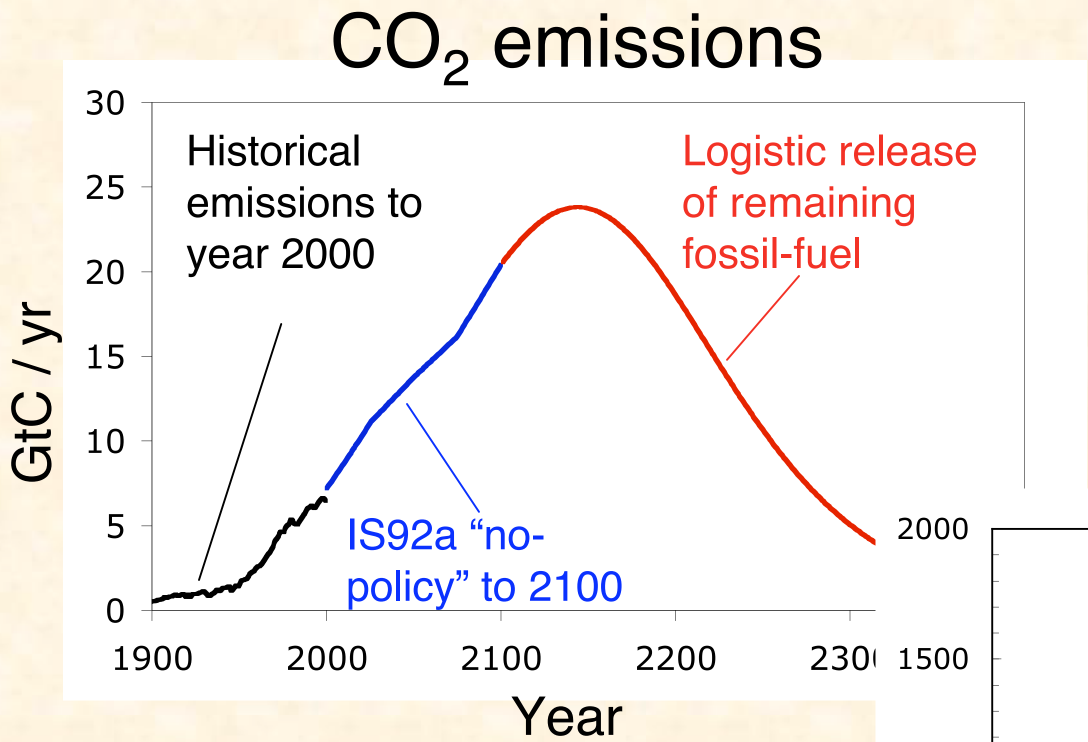

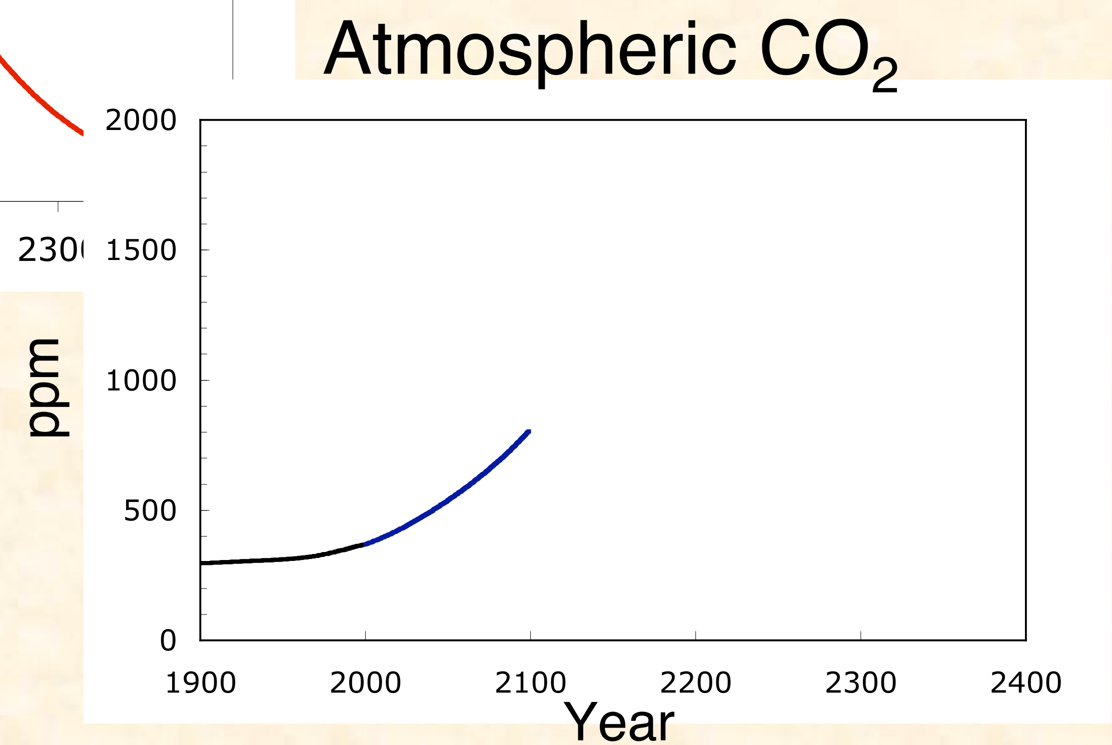

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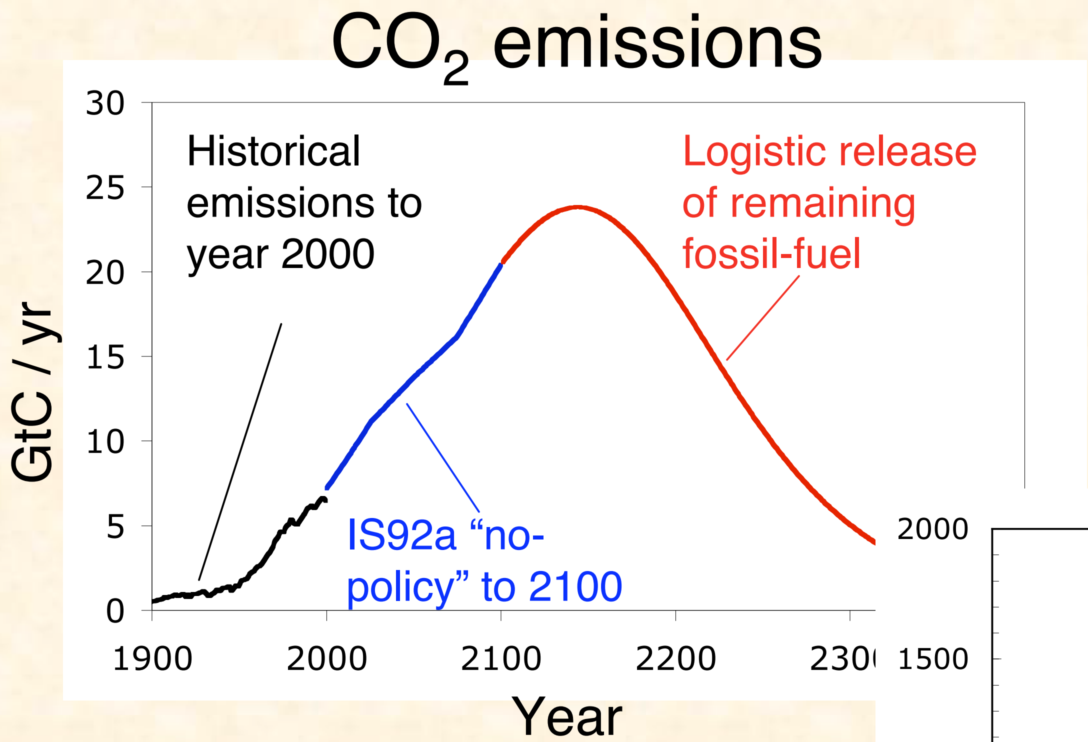

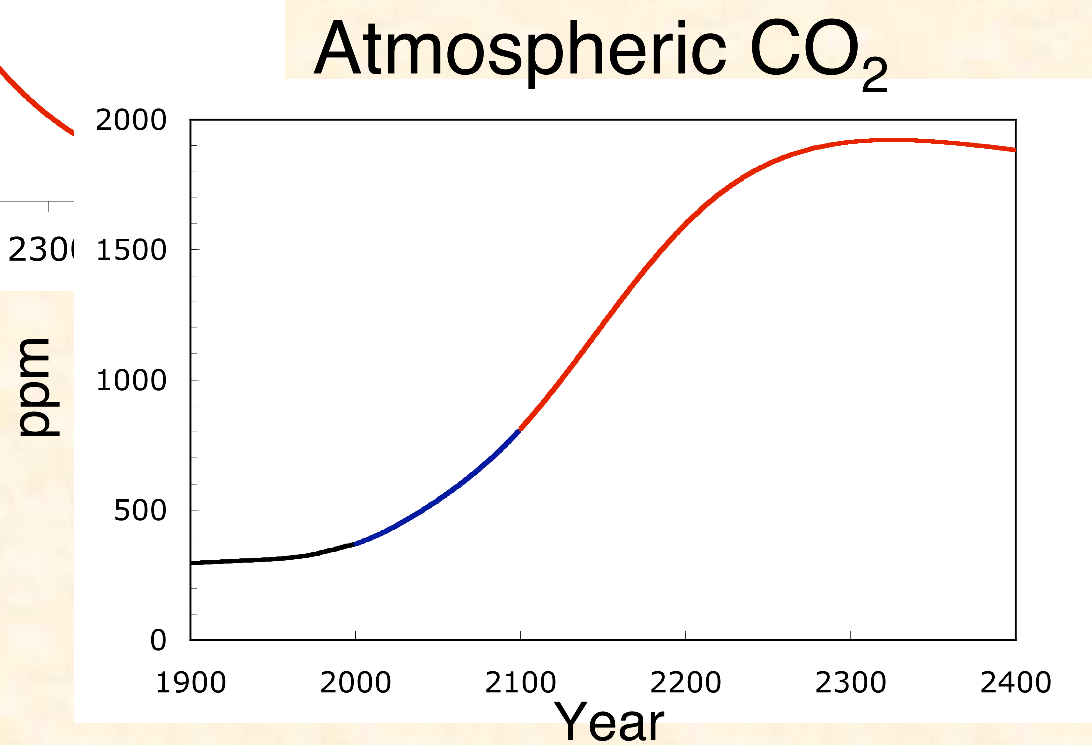

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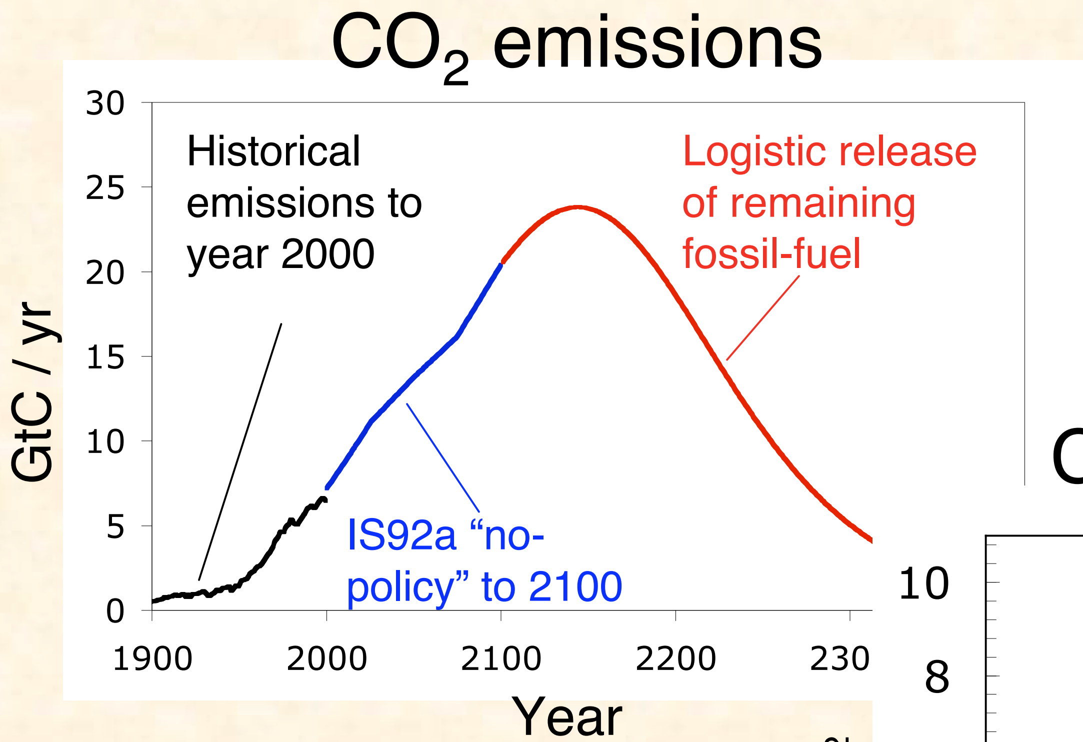

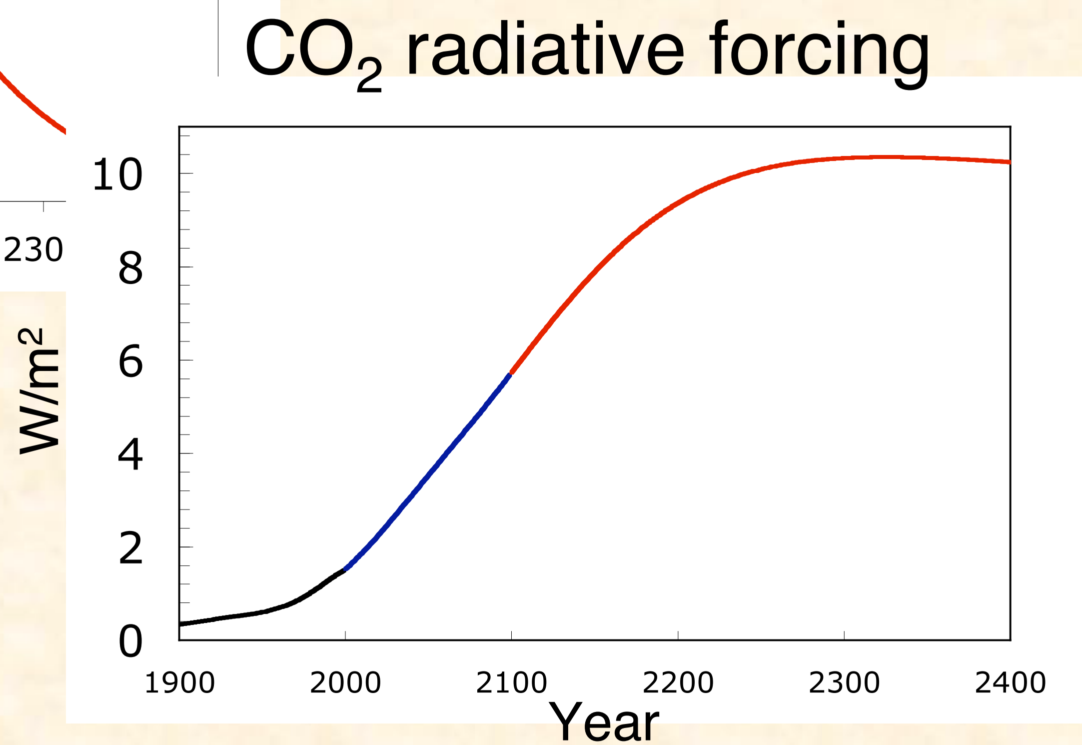

Radiative effect of SRES reactive gas emissions

Relative to 1990 baseline

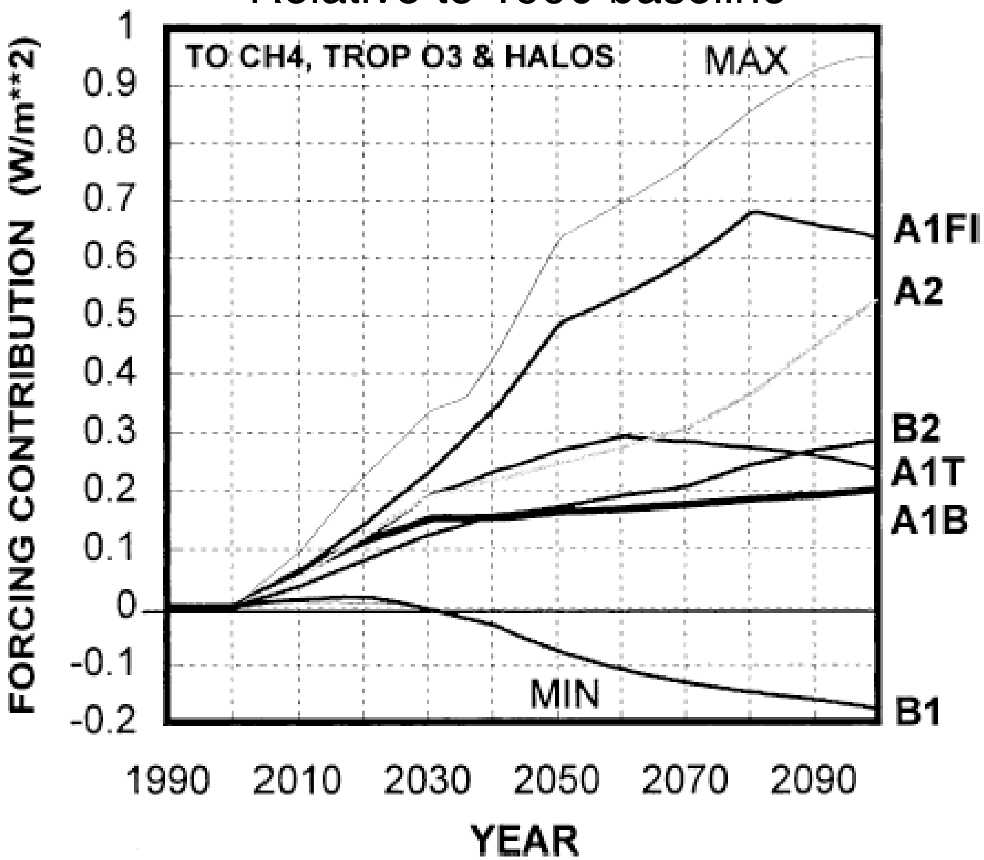

Fig. 4. The effect of reactive gas emissions on total radiative forcing for the 6 SRES illustrative scenarios together with the envelope over all 35 complete scenarios. At different times, different scenarios may be the extremes. The figure shows the sum of effects arising through methane (Fig. 1, bottom), tropospheric ozone (Fig. 2, bottom), and hydrogenated halocarbons (Fig. 3), amplified slightly (approx 5%) by attendant changes in temperature-related feedbacks on the carbon cycle.

"On average, reactive gas forcing accounts for about 5% of total forcing (range, –4% to +12%)."

CO_2 and non-CO_2 greenhouse gases

- Today (decade scale)
  - Radiative forcing by CO_2 is roughly the same order of magnitude as that from non-CO_2 greenhouse gases

- In the long-term (century scale)
  - Radiative forcing by CO_2 is roughly an order of magnitude larger than that from non-CO_2 greenhouse gases

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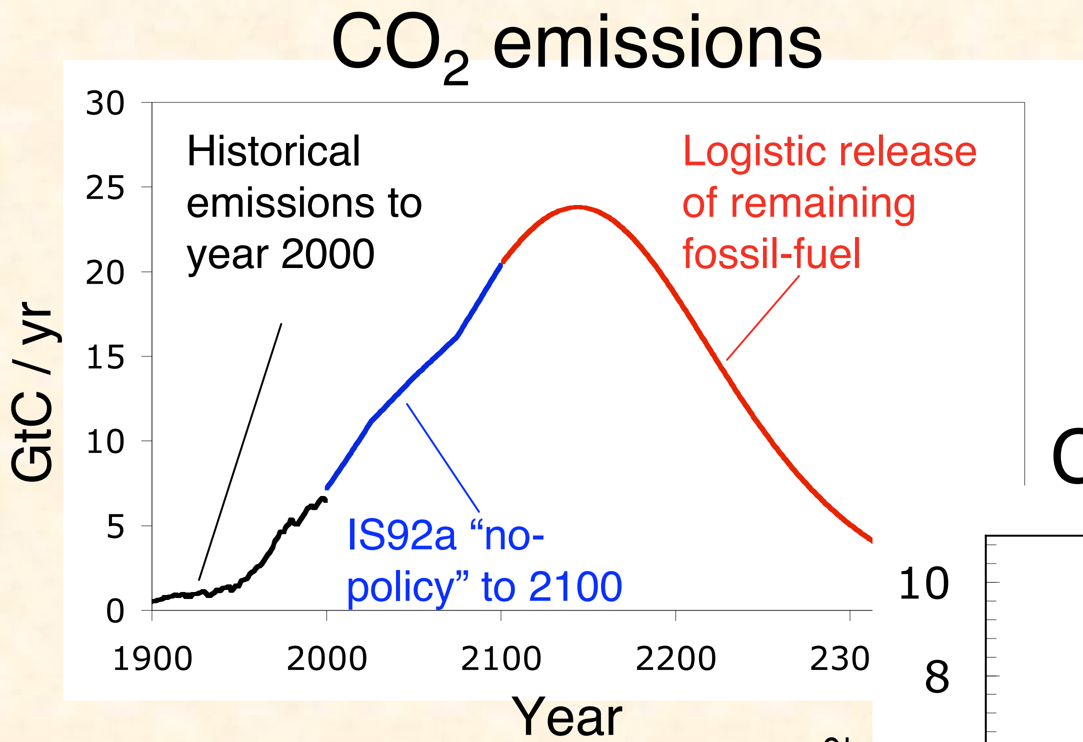

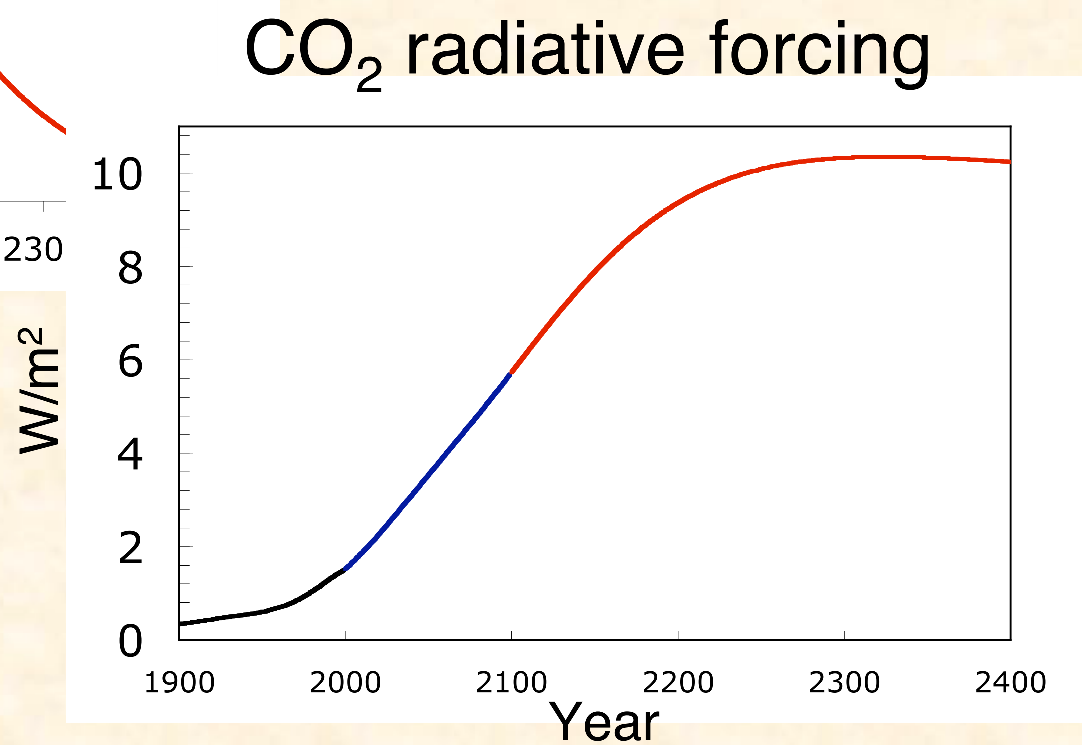

Consequences of unrestrained atmospheric release of fossil-fuel CO_2

- Unrestrained burning and atmospheric release of fossil-fuel carbon may produce a radiative forcing of ~10 W/m^2

Consequences of unrestrained atmospheric release of fossil-fuel CO_2

- Unrestrained burning and atmospheric release of fossil-fuel carbon may produce a radiative forcing of ~10 W/m^2
  - What does that mean in terms of temperature change?

Consequences of unrestrained atmospheric release of fossil-fuel CO_2

- Doubling of CO_2
  - Radiative forcing = ~3.7 W/m^2
  - Temperature change of 1.5°C to 4.5°C
- Unrestrained release
  - Radiative forcing = ~10 W/m^2
  - Temperature change of 4°C to 12°C

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  - Temperature change of 4°C to 12°C

7°F to 22°F

Consequences of unrestrained atmospheric release of fossil-fuel CO_2

- Climate consequences may not be the only important effects of unrestrained atmospheric release of fossil-fuel CO_2

Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs

Joan A. Kleypas,[1*] Robert W. Buddemeier,[2] David Archer,[3] Jean-Pierre Gattuso,[4] Chris Langdon,[5] Bradley N. Opdyke[6]

~35% reduction in coral reef growth by year 2100

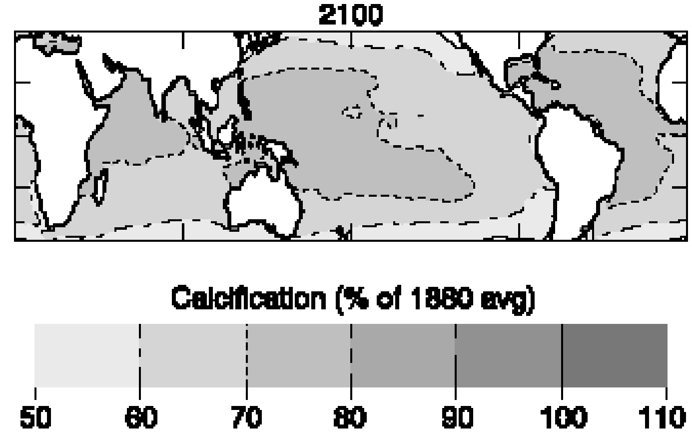

Fig. 2. Projected changes in reef calcification rate based on average calcification response of two species of tropical marine algae and one coral (*12*) and a marine mesocosm (*13*).

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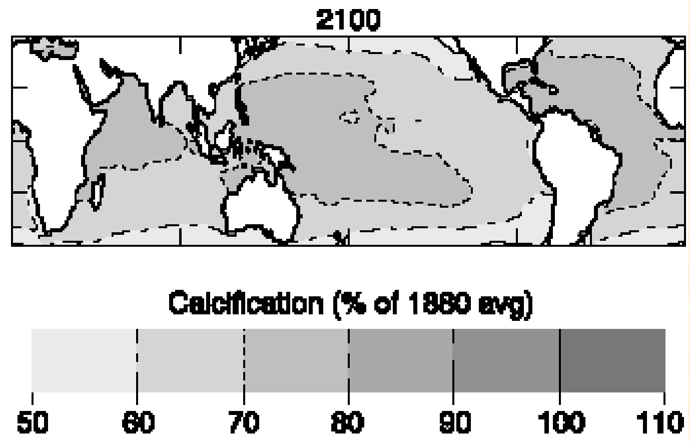

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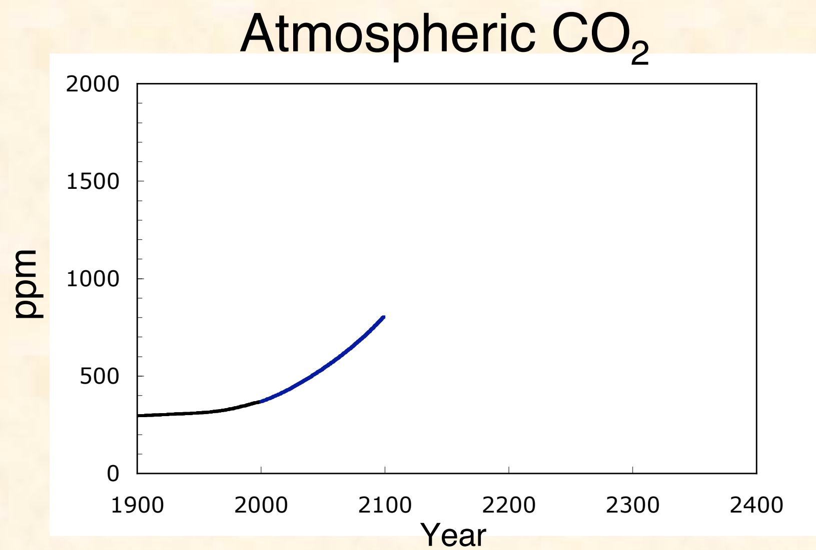

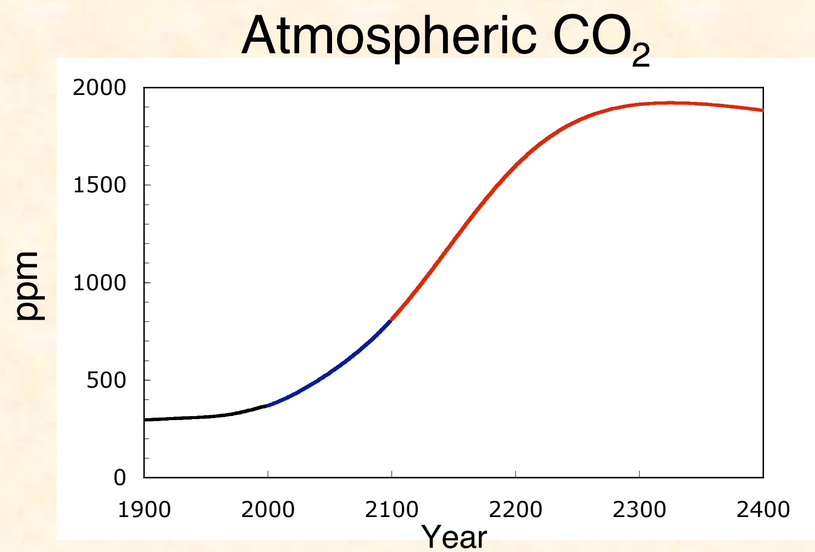

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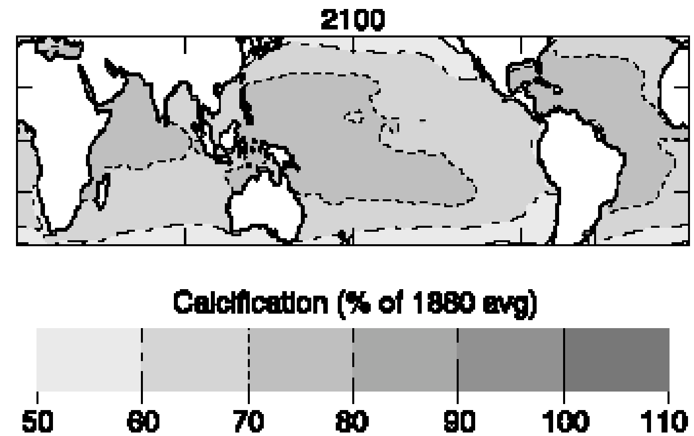

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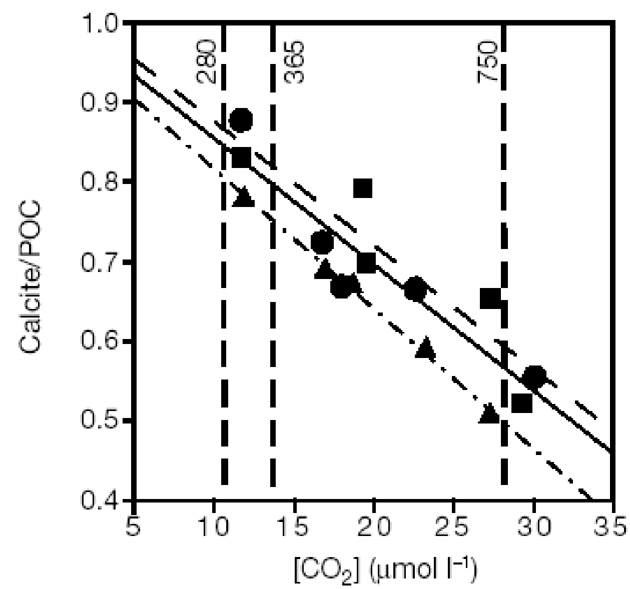
~35% reduction in coral reef growth by year 2100

Reduced calcification of marine plankton in response to increased atmospheric CO_2

Ulf Riebesell *, Ingrid Zondervan*, Björn Rost*, Philippe D. Tortell†, Richard E. Zeebe*‡ & François M. M. Morel†



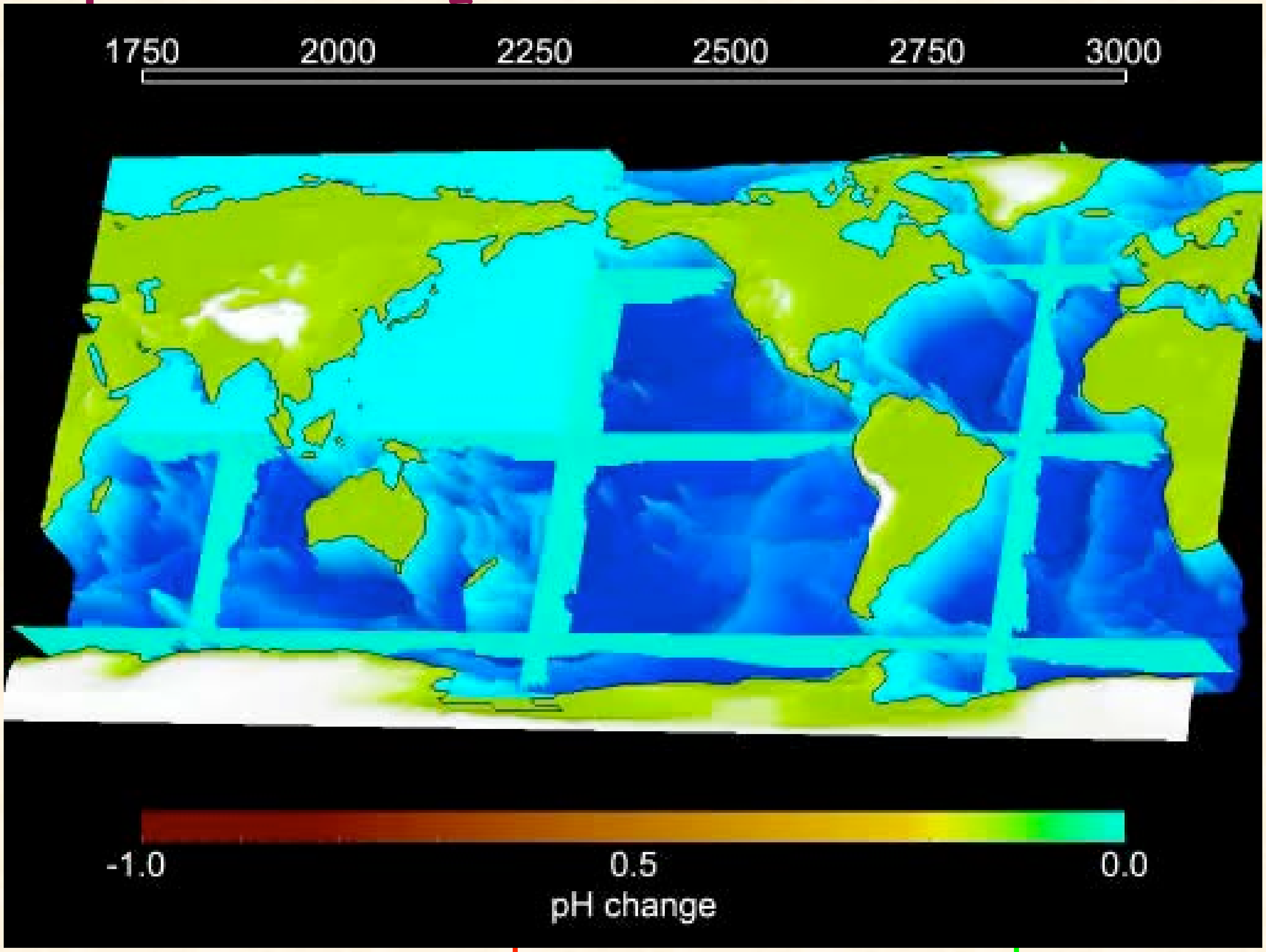
~35% reduction planktonic calcification by year 2100

Consequences of unrestrained atmospheric release of fossil-fuel CO_2

- Unrestrained atmospheric release of fossil-fuel CO_2 may make the ocean more acidic than it has been in the past 300 million years or more

Caldeira and Wickett, submitted

Atmospheric CO_2 release and ocean acidity

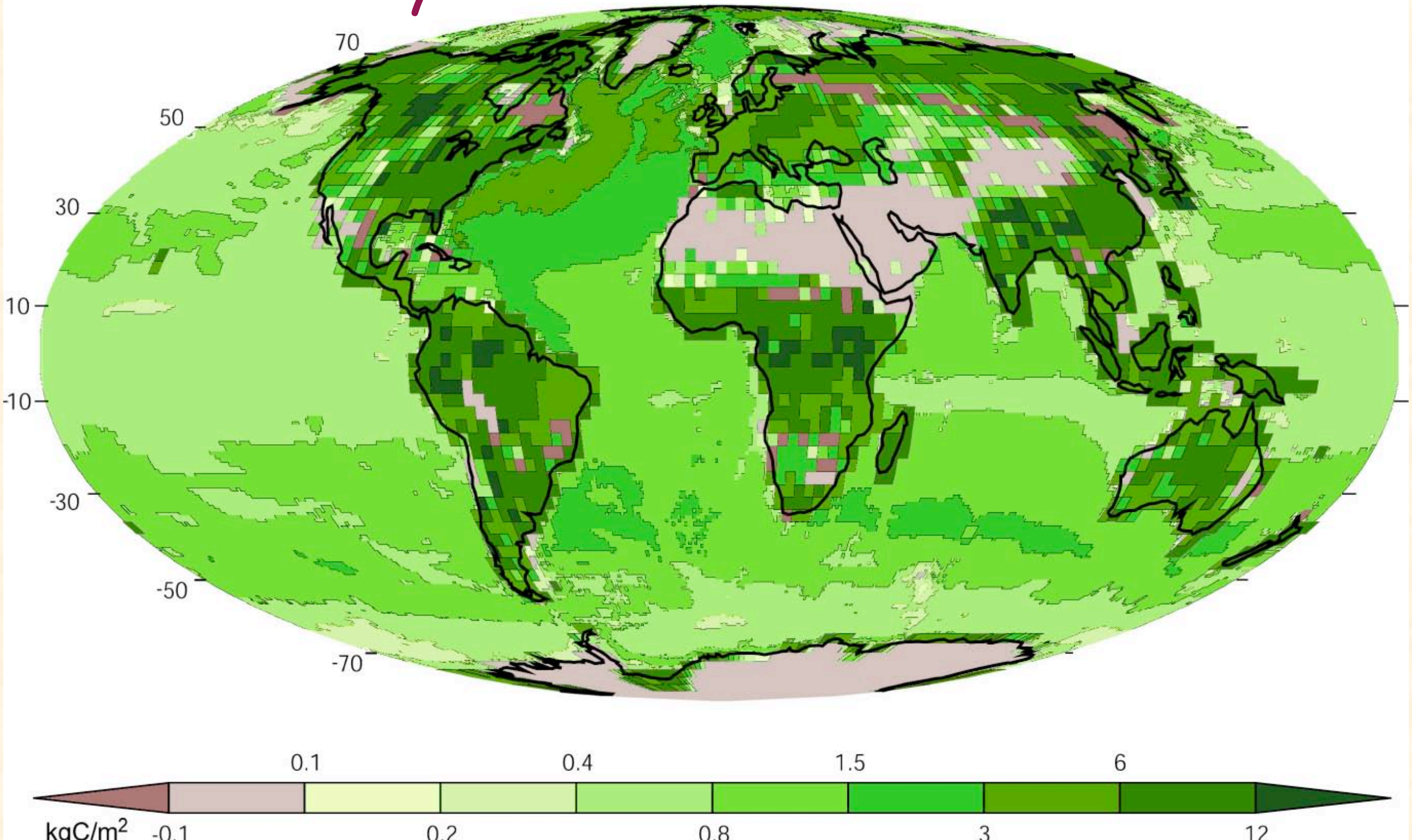


Change from 1750 to 2000

Greatest change inferred from geologic record of past 300 myr

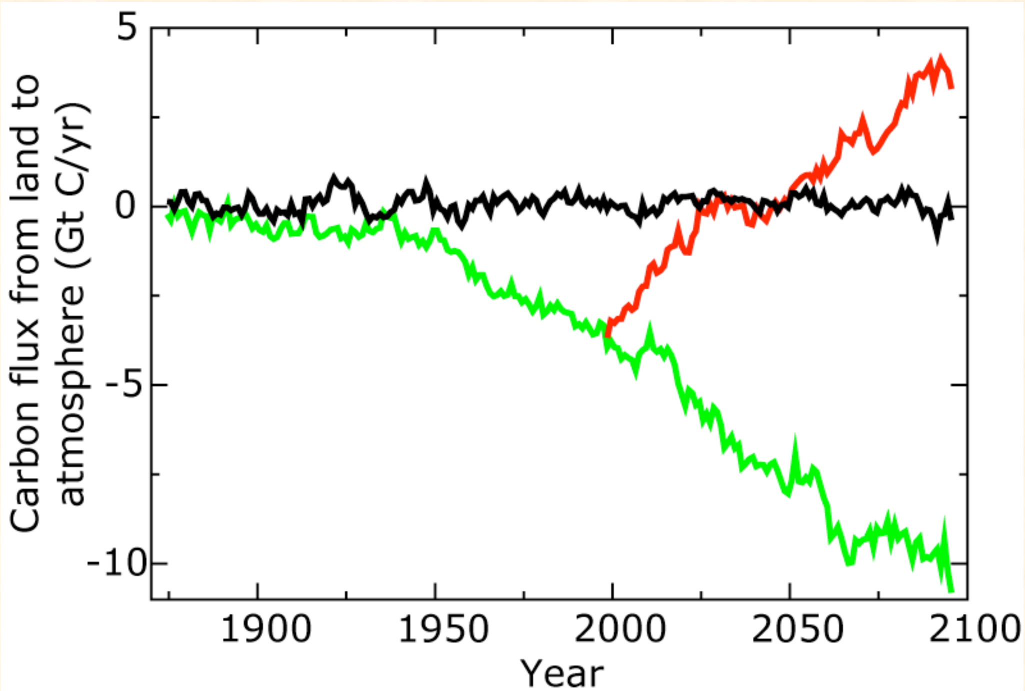
Caldeira and Wickett, submitted

Land and ocean carbon uptake year 1880 to 2100



LLNL 3-D climate/carbon model simulation
with CO_2-fertilization, without nutrient limitation

Carbon flux from land to atmosphere year 1880 to 2100

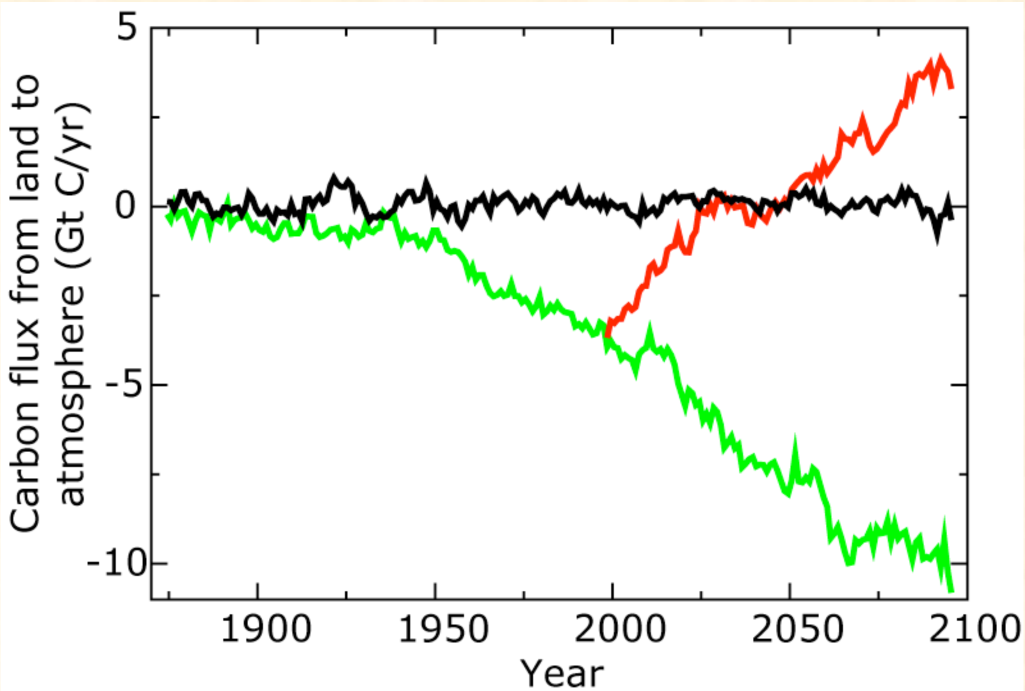


Assuming saturation of CO_2 fertilization in year 2000

Assuming continued CO_2 fertilization

LLNL coupled climate/carbon simulations (Thompson et al., in prep.)

Carbon flux from land to atmosphere year 1880 to 2100



Assuming saturation of CO_2 fertilization in year 2000

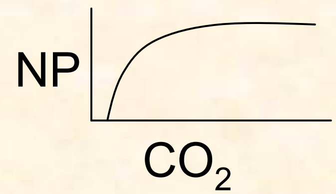
Assuming continued CO_2 fertilization

Whether the land biosphere becomes a CO_2 sink or CO_2 source depends on detailed assumptions regarding CO_2-fertilization, nutrient limitations, sensitivity of respiration to changing climate, and climate sensitivity

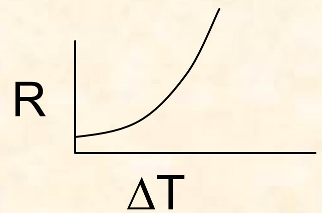
LLNL coupled climate/carbon simulations (Thompson et al., in prep.)

Simplified biosphere fluxes

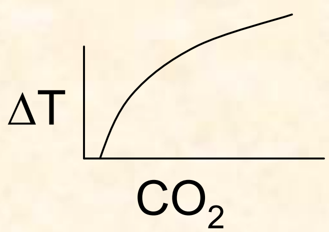
- Net photosynthesis
  - $NP = NP_{max} (CO_2/(CO_{2\text{-half}} + CO_2))$

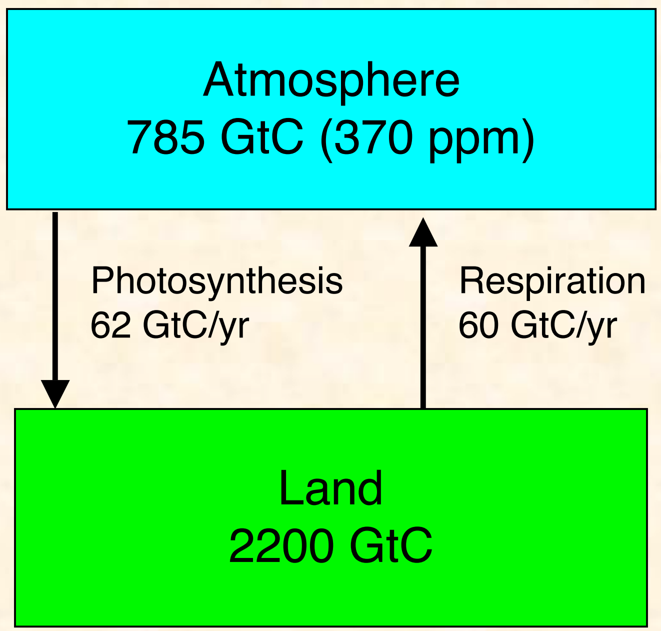


- Respiration
  - $R = R_0\ 2^{(\Delta T/\Delta T_{2x\text{-resp}})}$



- Climate sensitivity
  - $\Delta T = \Delta T_{2x\text{-clim}} Ln_2 (CO_2 / CO_{2\text{-}0})$

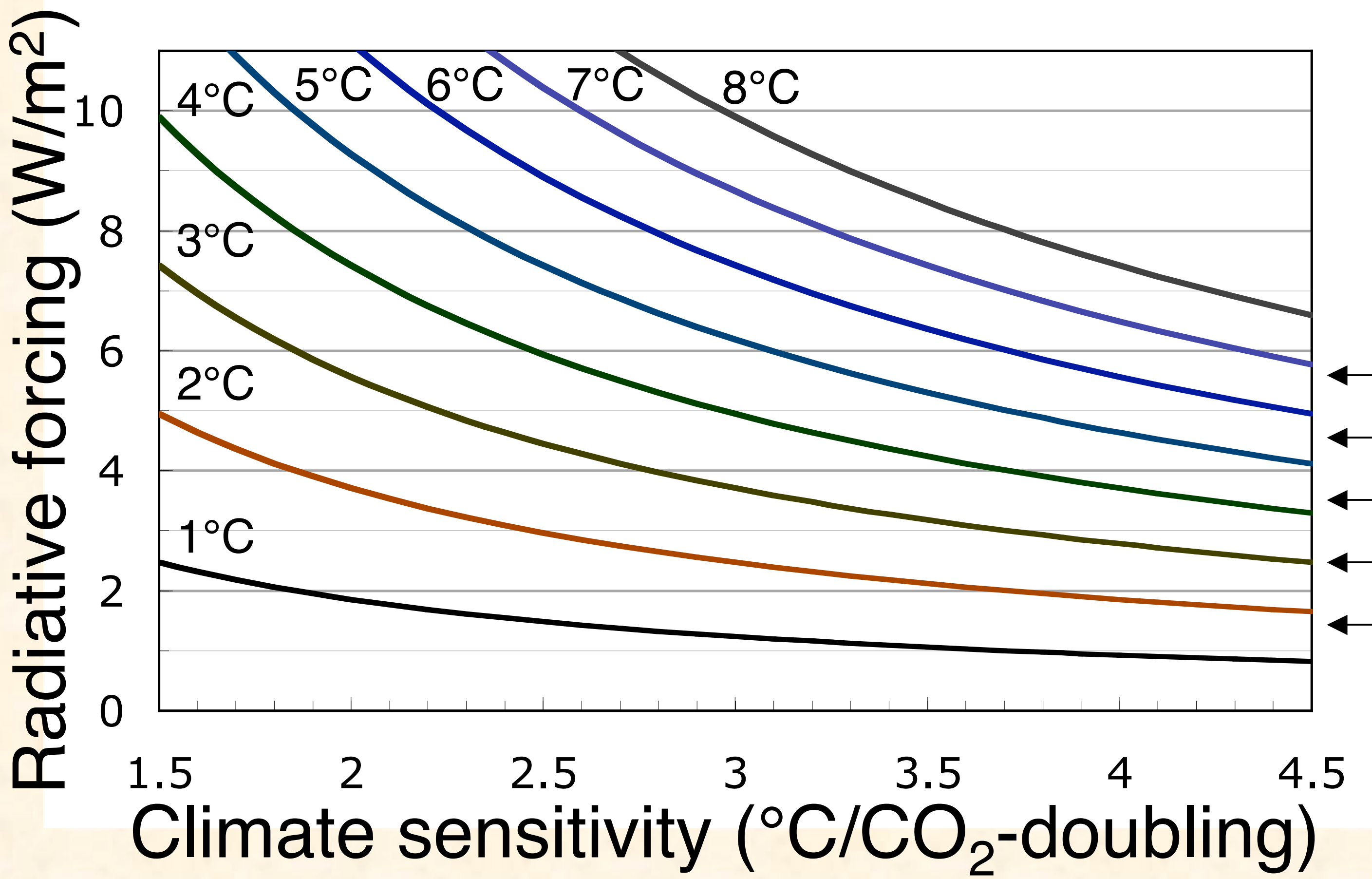




Land biosphere in carbon/climate ocean/atmosphere GCM simulations

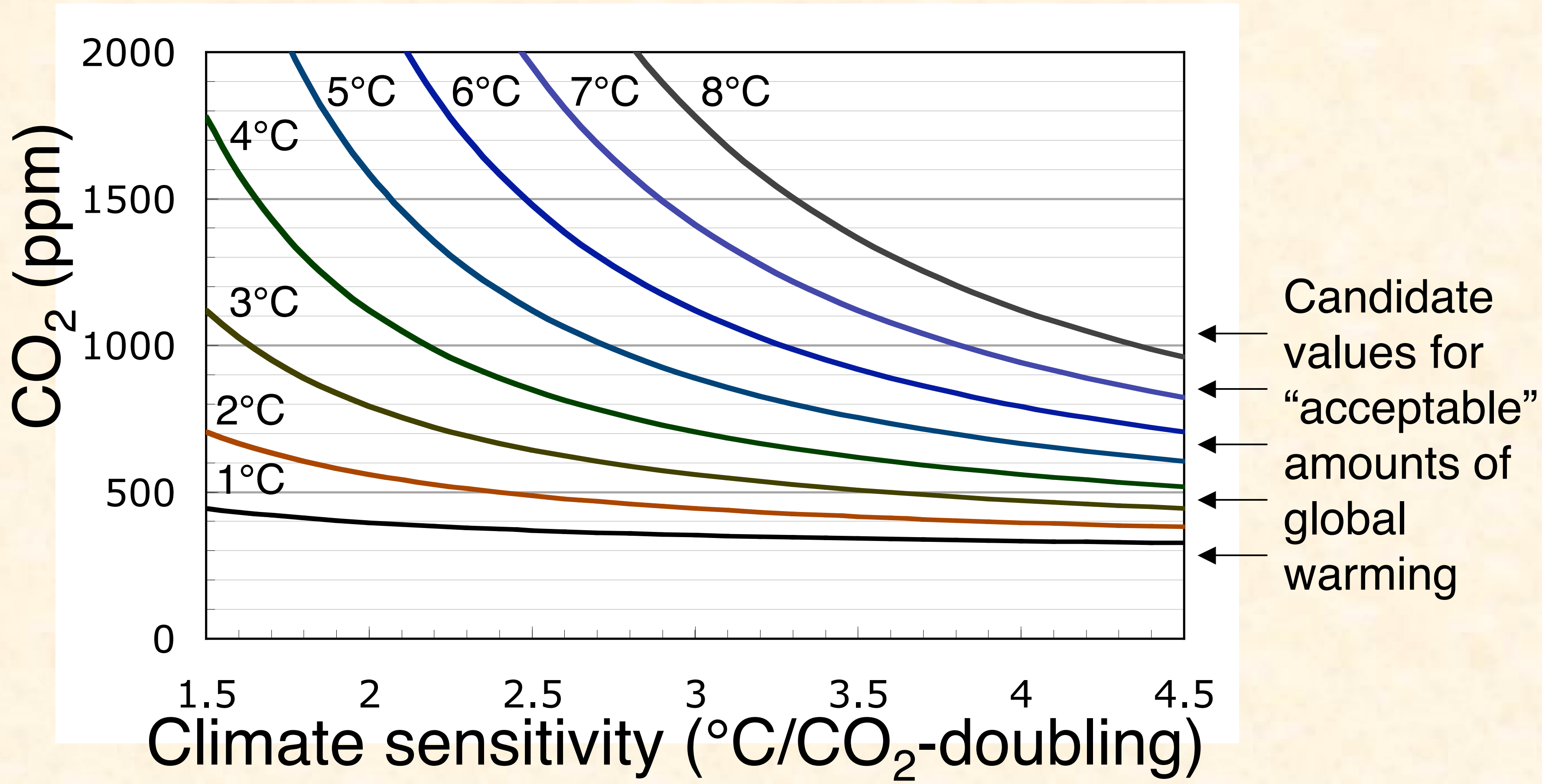
- IPSL simulation
  - Land biosphere is a CO_2 sink
- Hadley center simulation
  - Land biosphere is a CO_2 source
- LLNL simulations
  - Land biosphere can be a CO_2 source or sink depending on treatment of
    - CO_2-fertilization
    - respiration
    - climate sensitivity
    - etc.

Radiative forcing as a function of temperature change and climate sensitivity



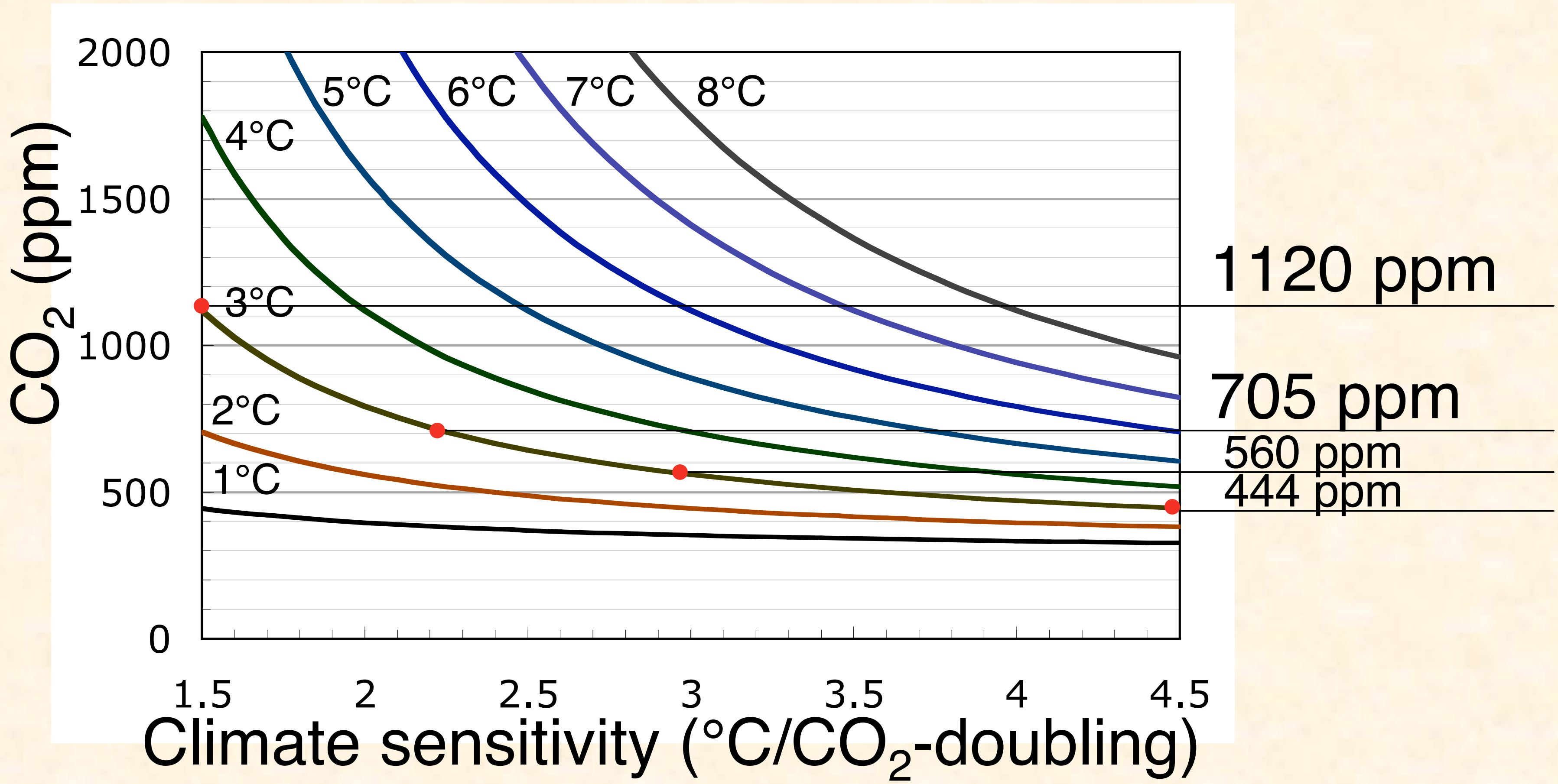
Candidate values for "acceptable" amounts of global warming

Atmospheric CO_2 as a function of CO_2-induced temperature change and climate sensitivity

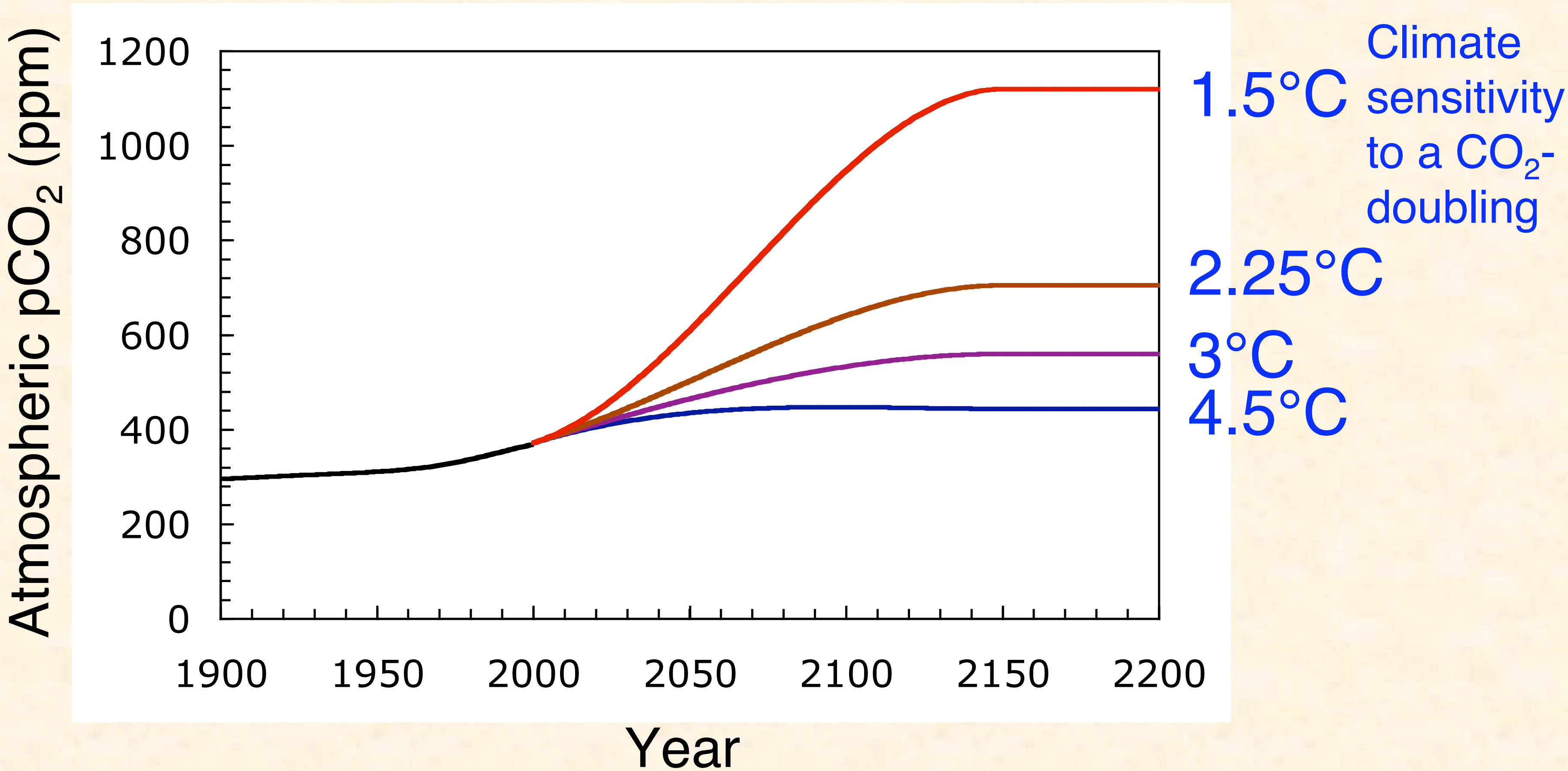


EXAMPLE:

Stabilizing at a CO_2-induced climate change of 3°C



Trajectories stabilizing after 2150 at a CO_2-induced climate change of 3°C



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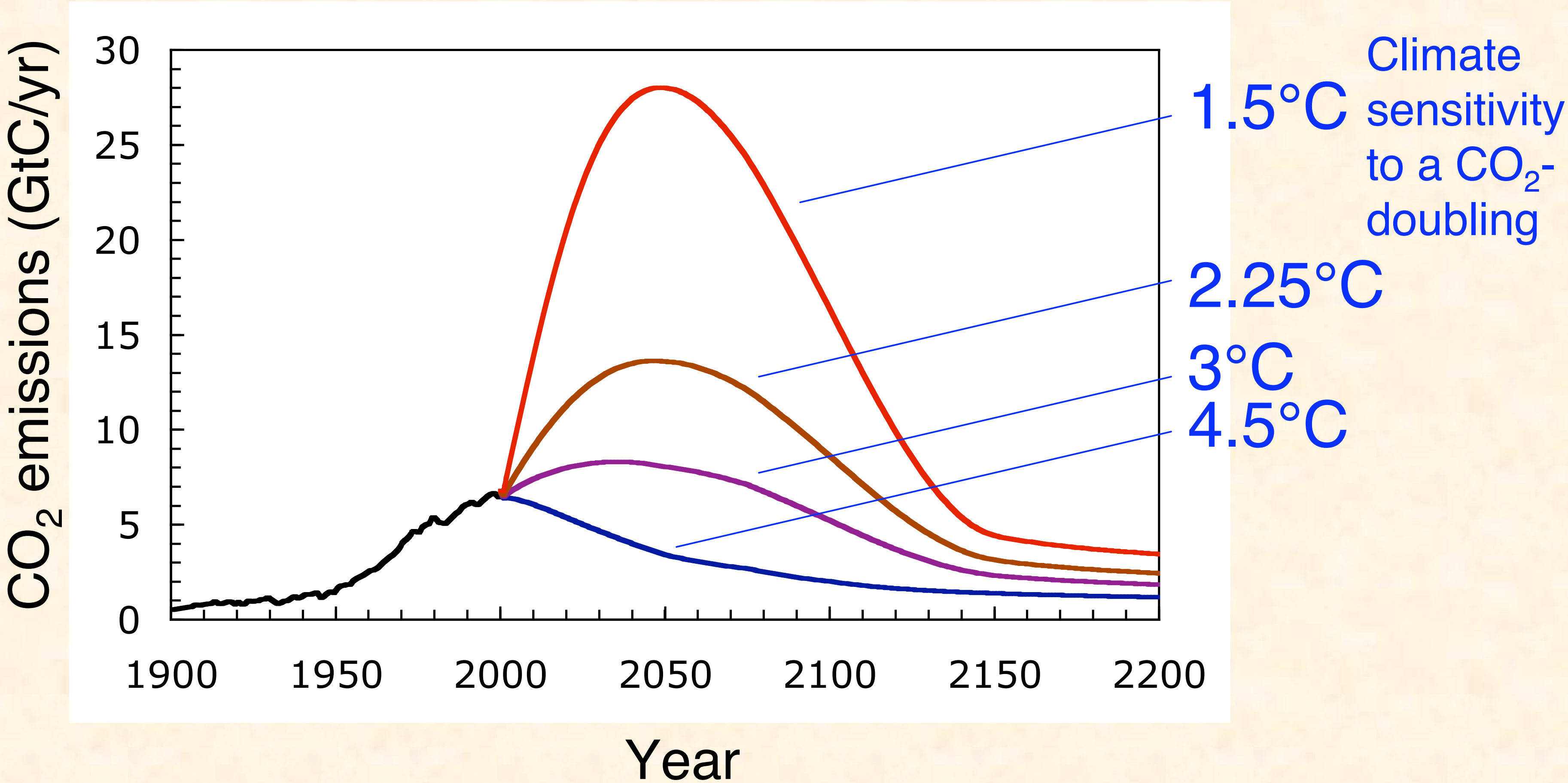
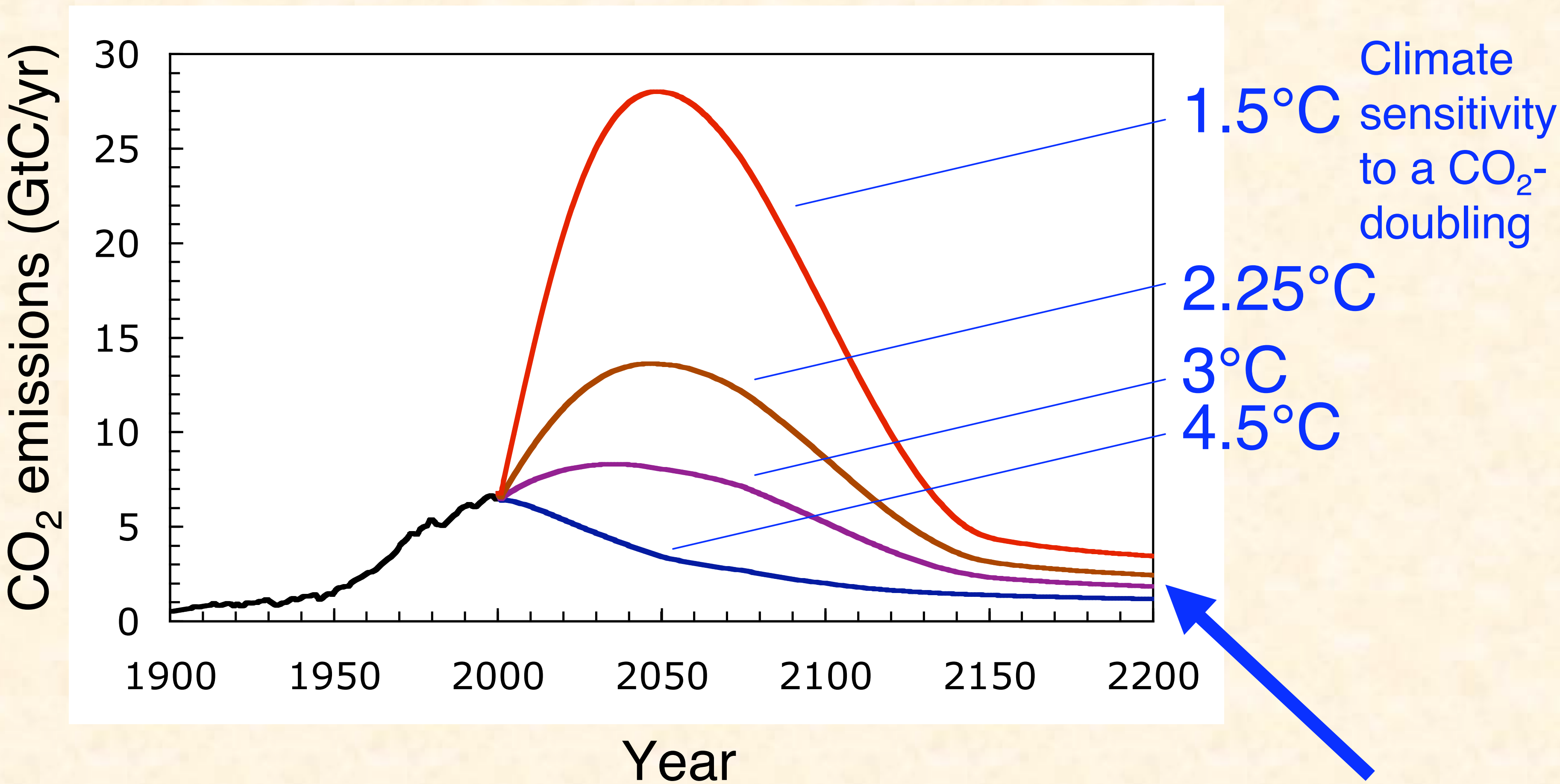
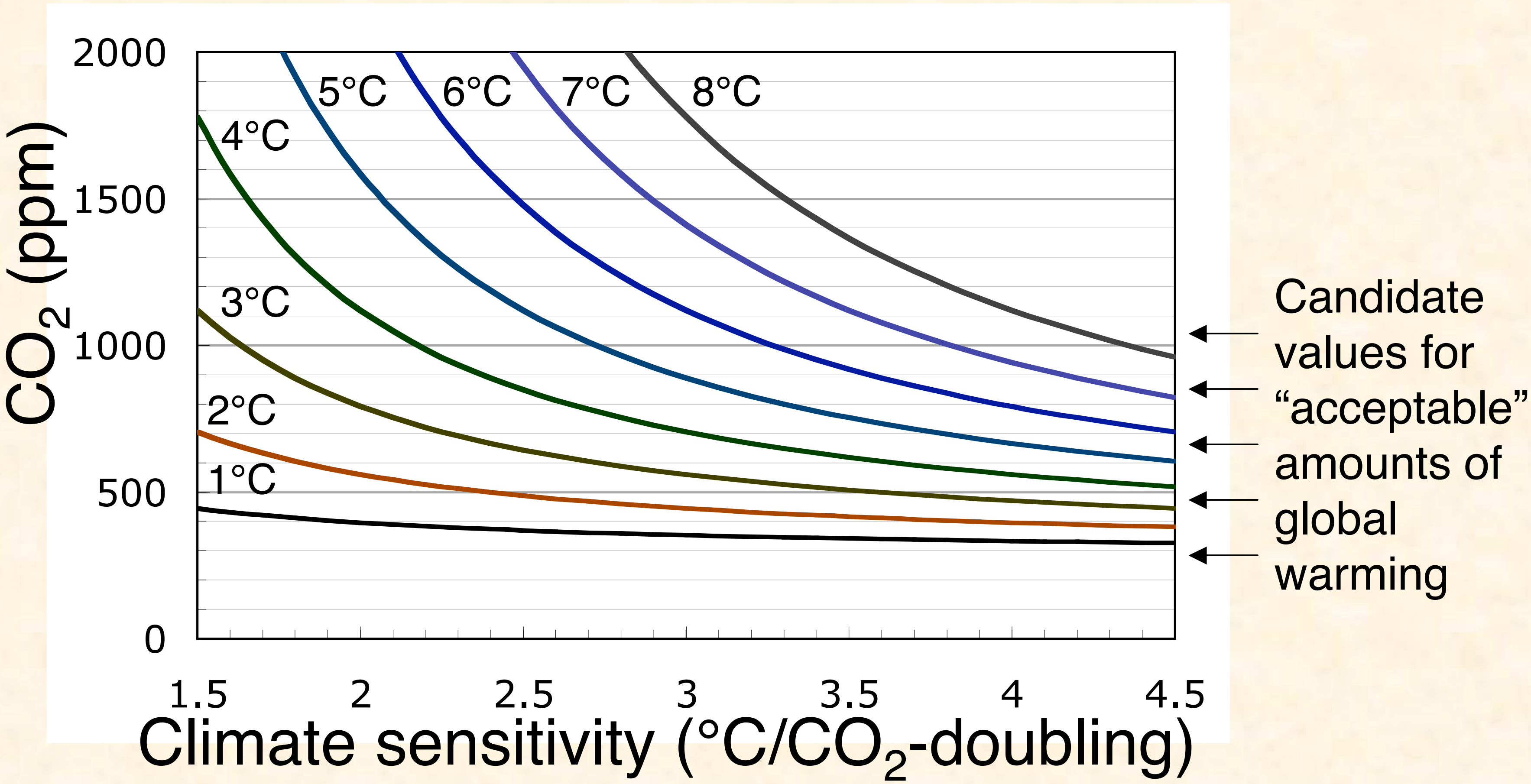


Trajectories stabilizing after 2150 at a CO_2-induced climate change of 3°C



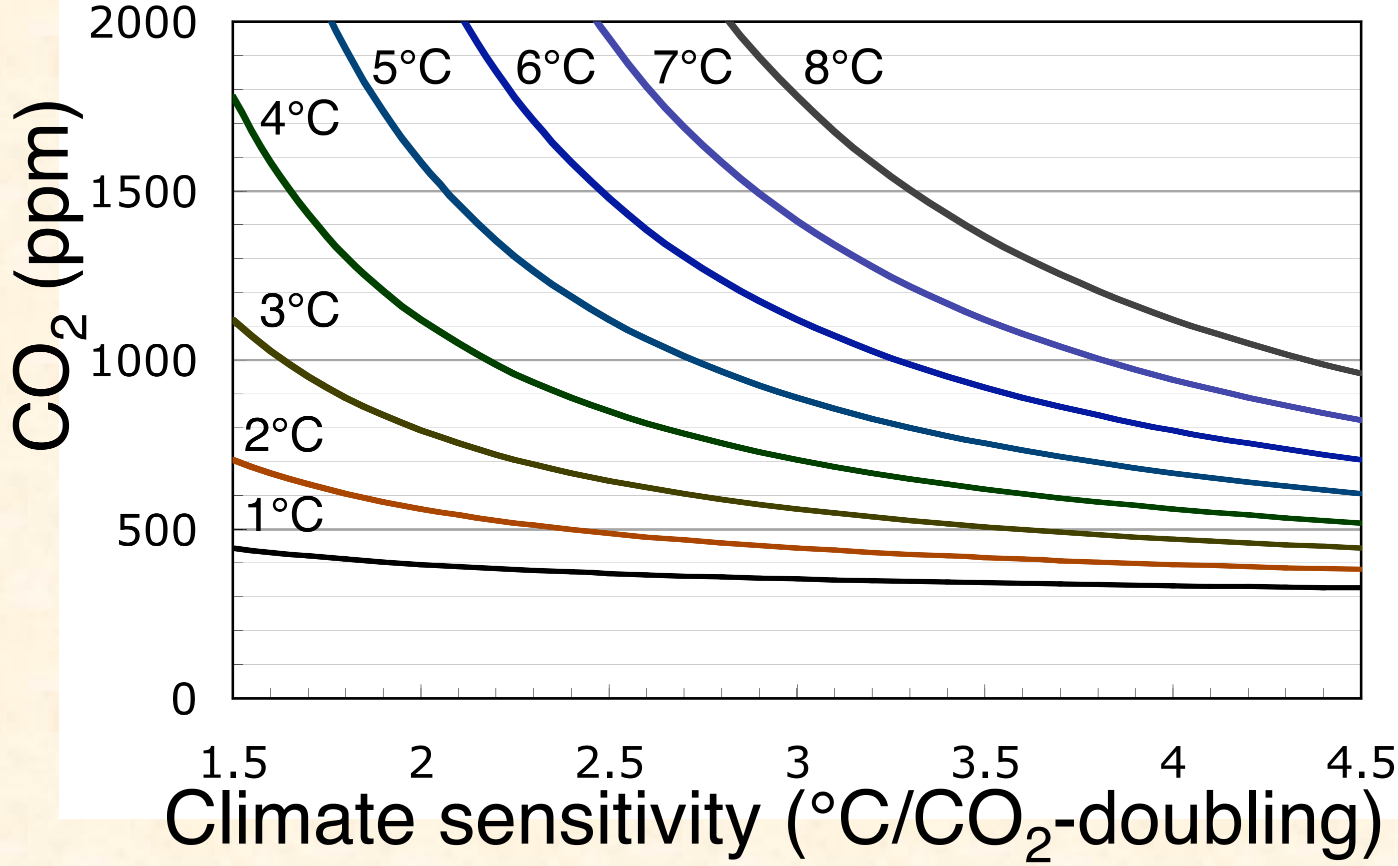
After CO_2 stabilizes, CO_2 emissions roughly balance ocean uptake, less than today's emissions in almost all scenarios

Climate sensitivity uncertainty and avoiding risk of "dangerous interference in the climate system"



Climate sensitivity uncertainty and avoiding risk of "dangerous interference in the climate system"

Let's pretend we determined that 5°C was "safe"



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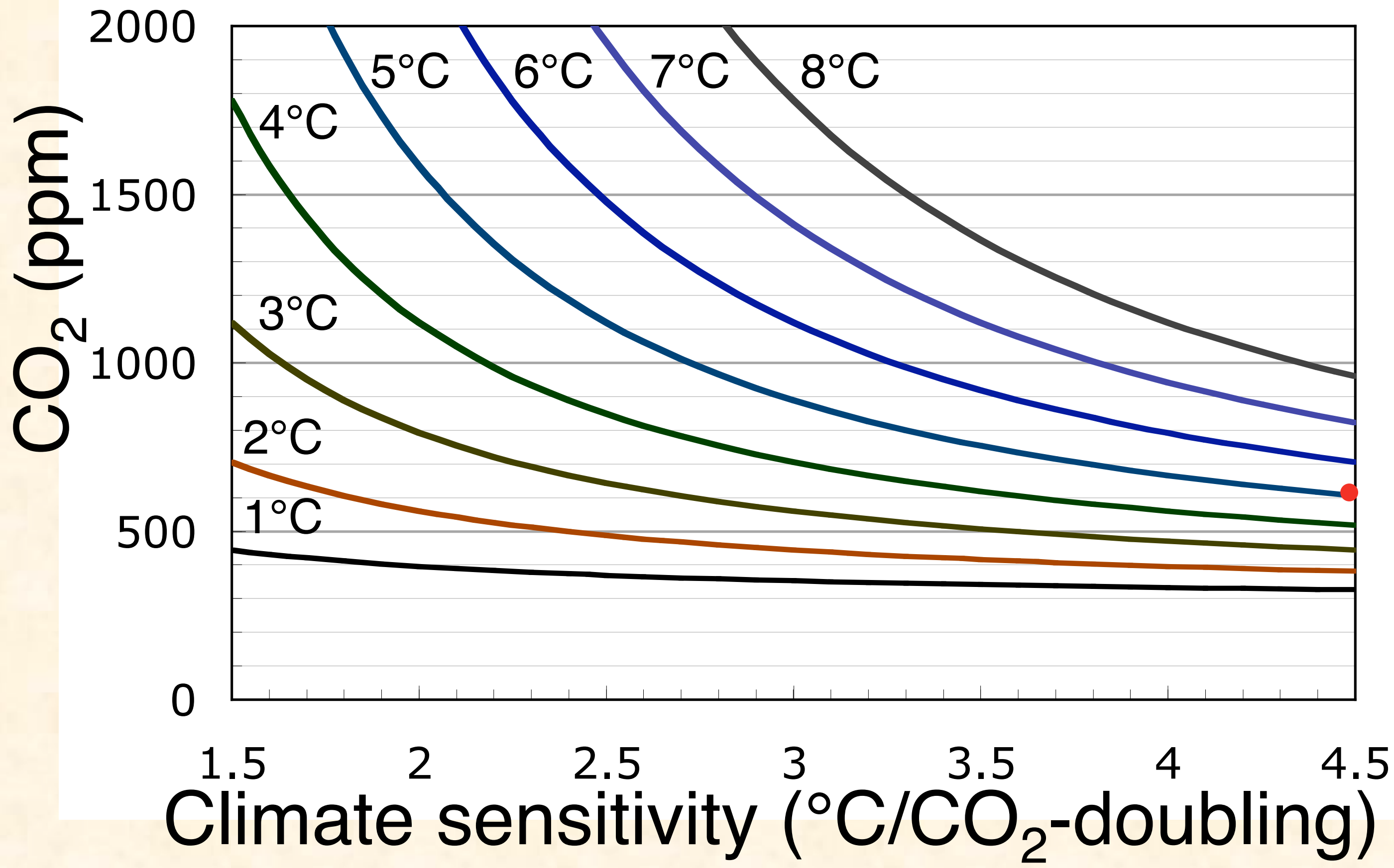

605 ppm would avoid risk, if $\Delta T_{2x} < 4.5$°C

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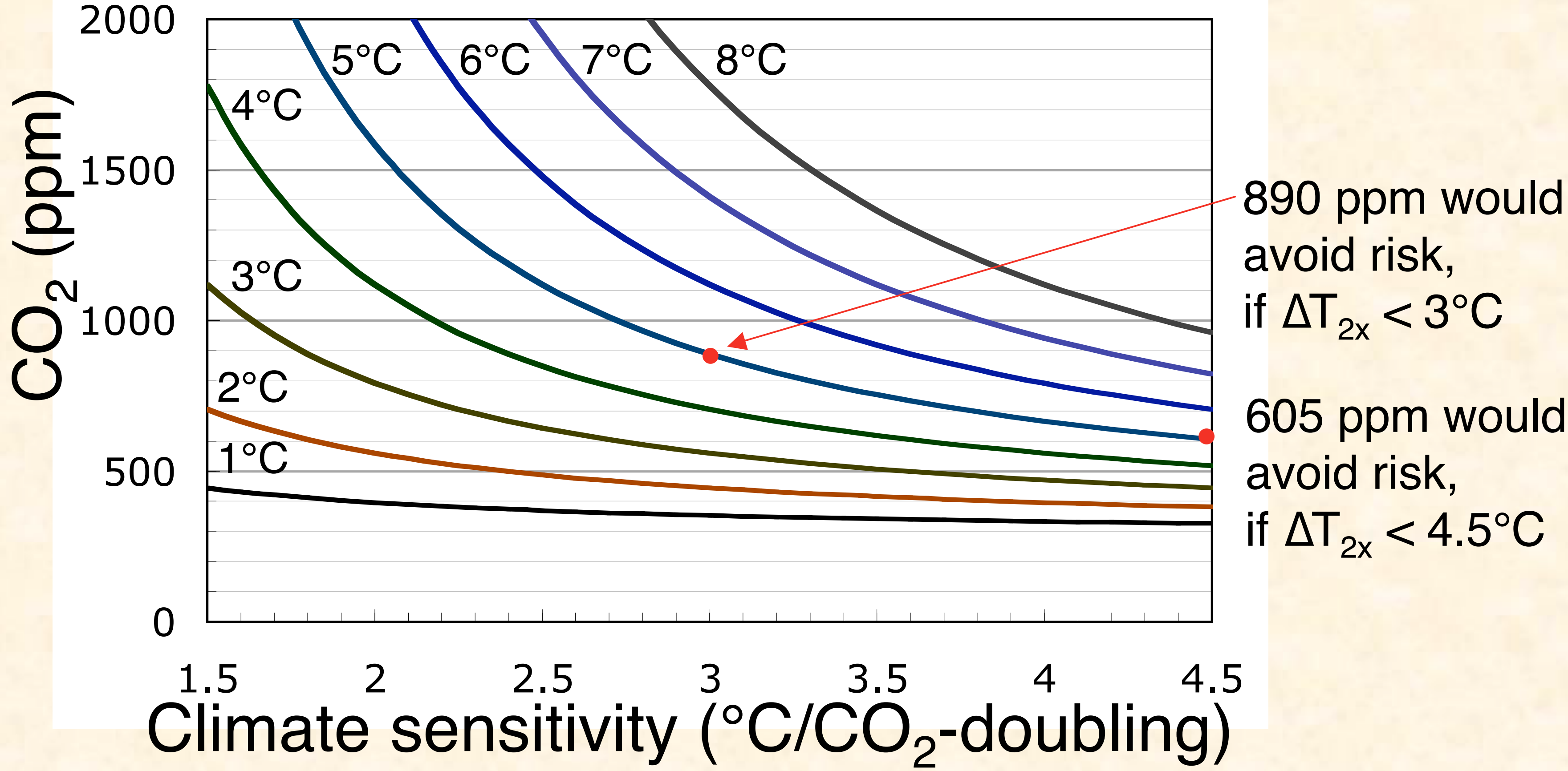

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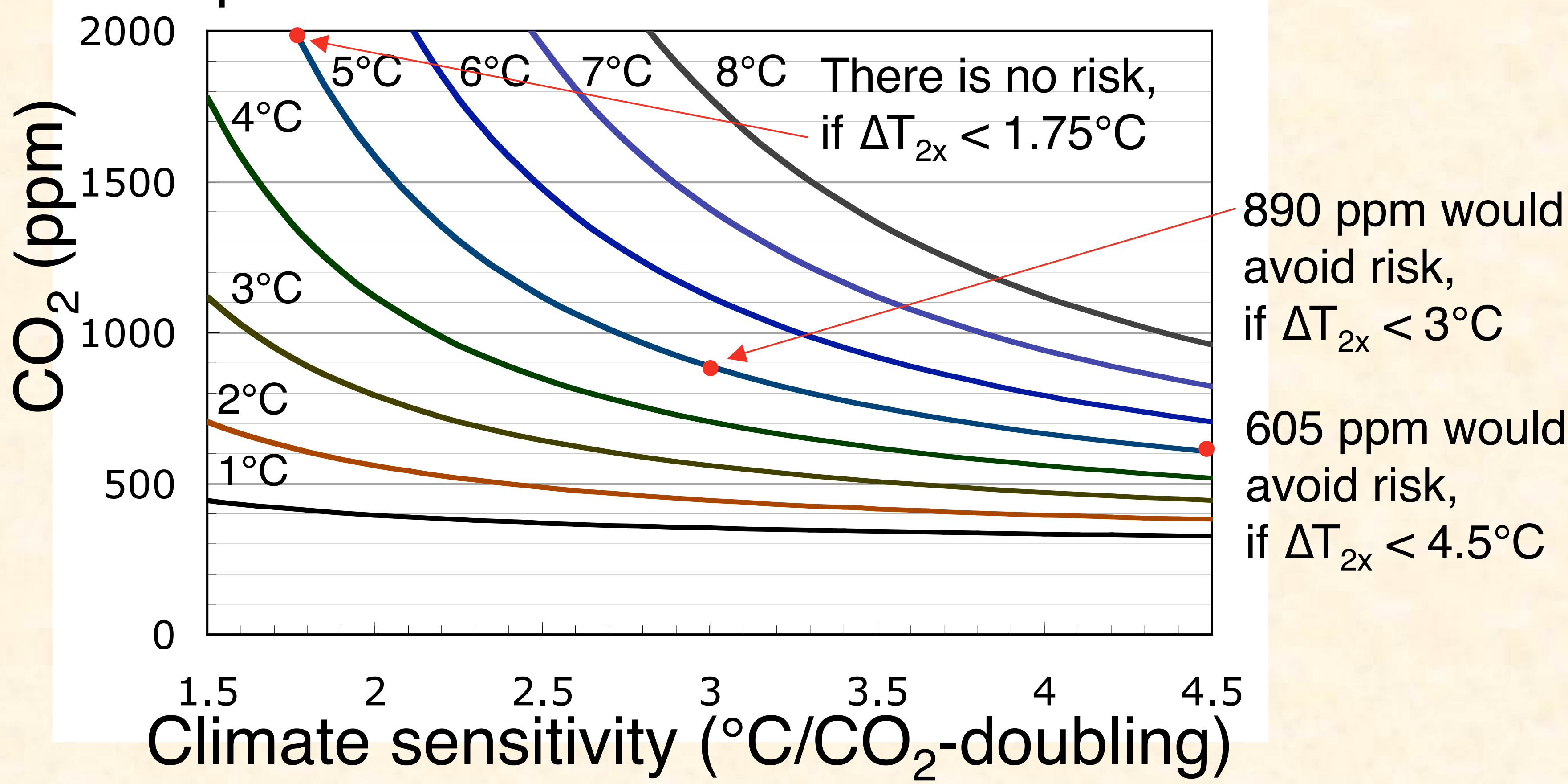

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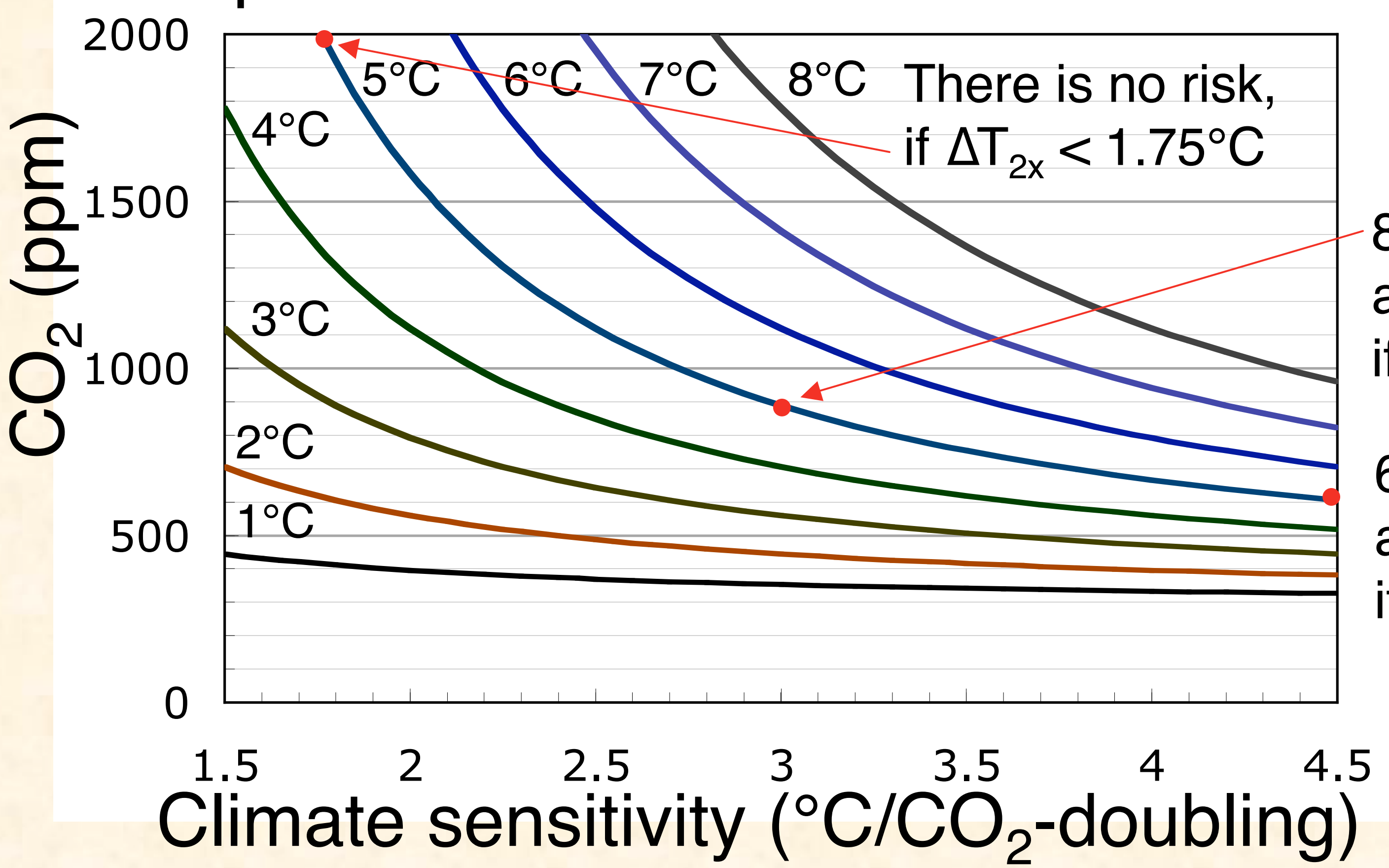


Narrowing uncertainty in climate sensitivity (and climate impacts) can reduce what we need to do to avoid risk of "dangerous interference in the climate system".

The Kaya equation (and variants)

- C = N x (GDP/N) x (E/GDP) x (C/E)
  - population, per capita GDP, energy intensity, carbon intensity

- C = GDP x (E/GDP) x (C/E)
  - gross product, energy intensity, carbon intensity of primary energy

- C = GDP x (C/GDP)
  - gross product, carbon intensity of productivity

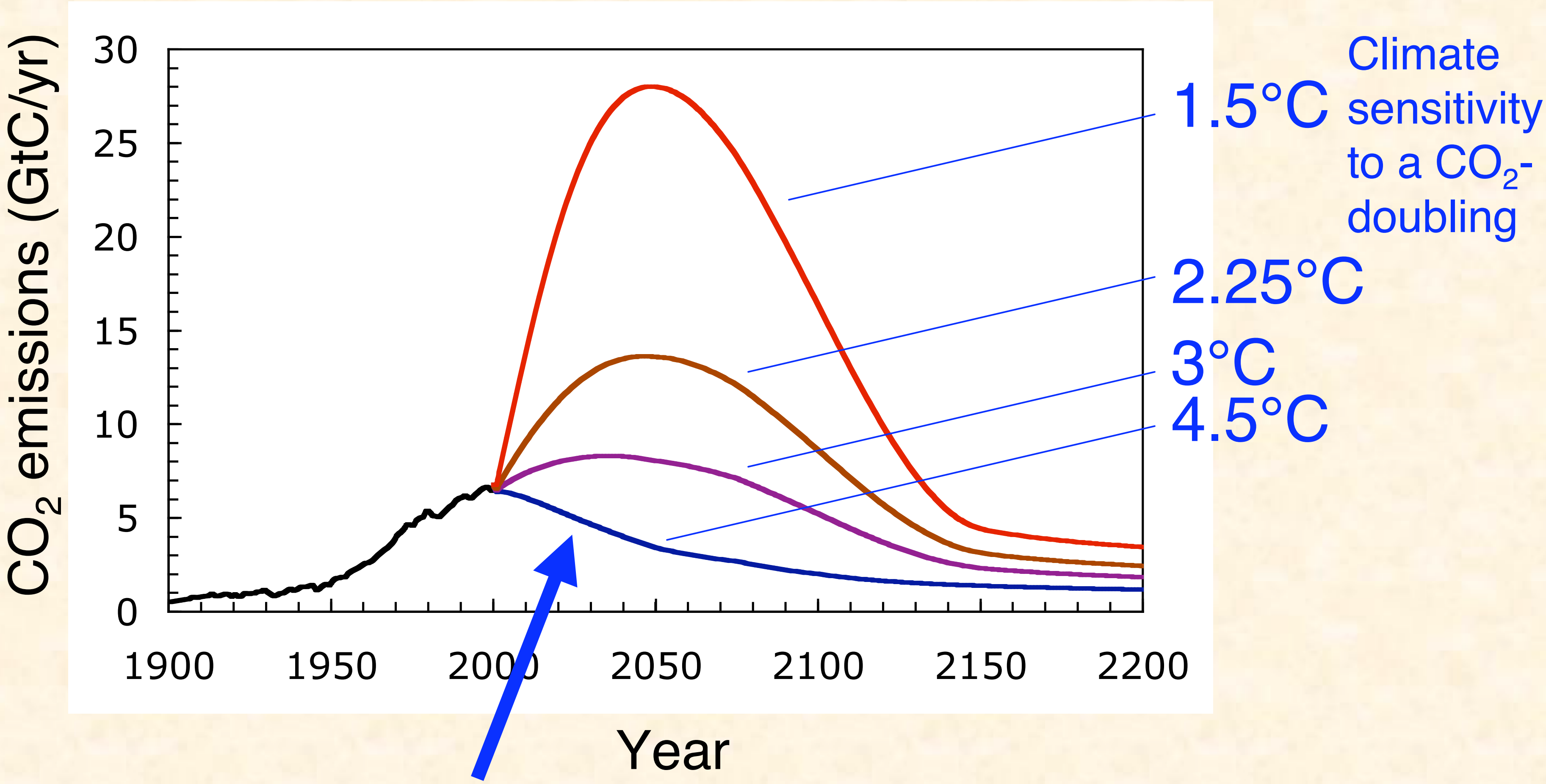
The Kaya equation (and variants)

- $C = GDP \times (C/GDP)$
  - gross product, carbon intensity of economic productivity

- $\%\Delta C = \%\Delta GDP + \%\Delta (C/GDP)$

- For climate stabilization, in the long term,
  - $\%\Delta C < 0$
- Thus, for climate stabilization, in the long term,
  - $\%\Delta GDP + \%\Delta (C/GDP) < 0$
    - The long-term rate of improvement in carbon intensity of economic productivity must exceed the growth rate in GDP

Trajectories stabilizing after 2150 at a CO_2-induced climate change of 3°C



Uncertainty in climate sensitivity and acceptable amounts of climate change greatly affects allowable emissions in the mid-term

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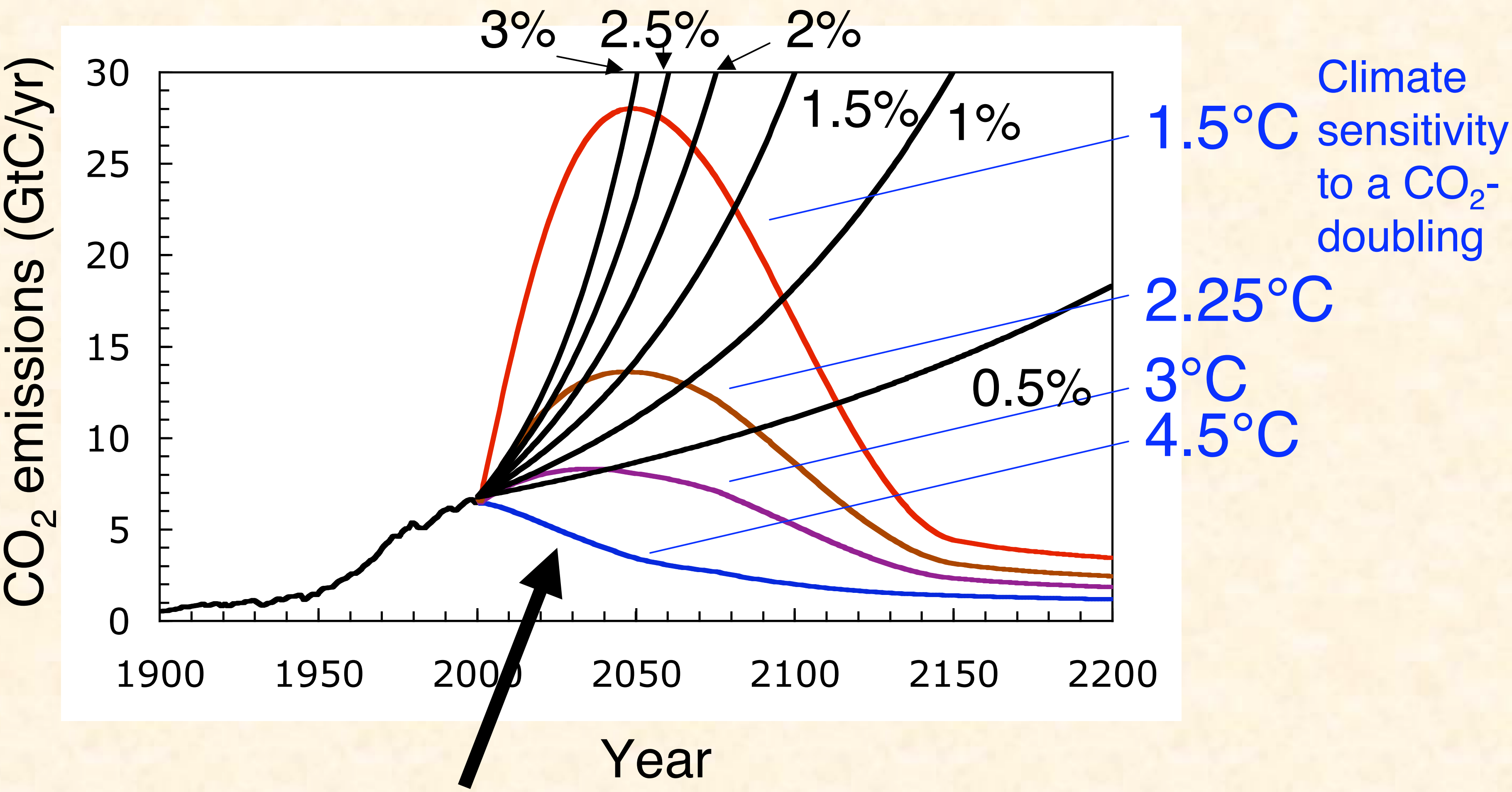

If long-term growth rates in GDP minus improvement in energy intensity is significantly greater than 0 %, we will need vast amounts of carbon-emissions-free energy

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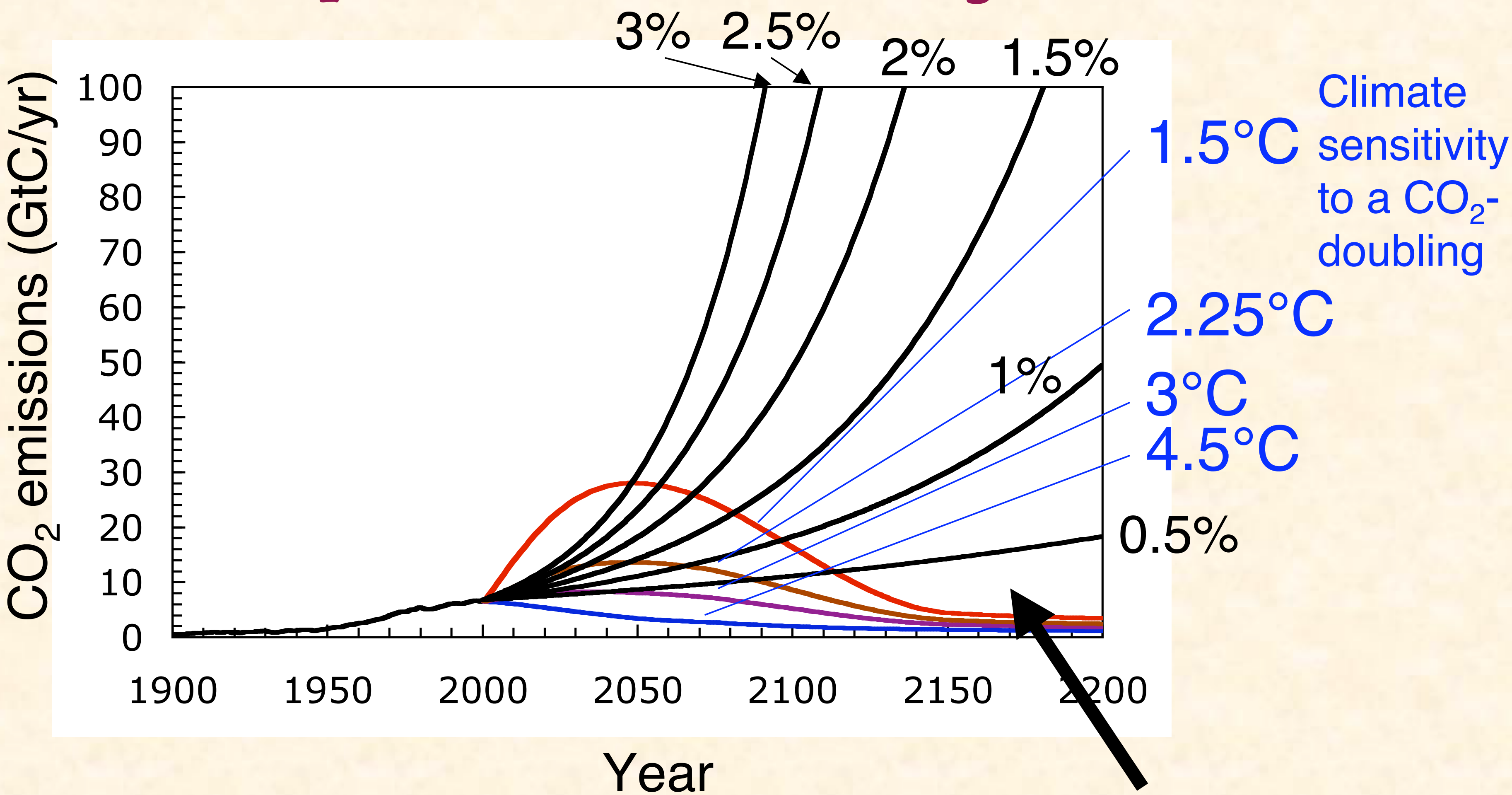

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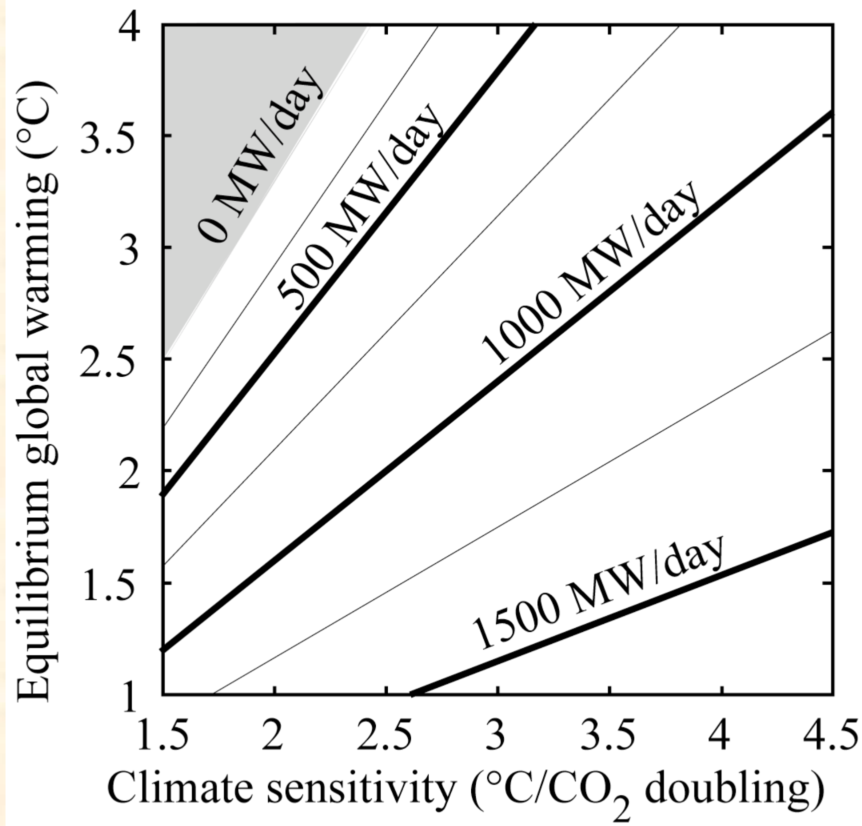
Mean rate of carbon-emissions-free primary power capacity addition over next 50 years

- Assumes
  - IS92a rates of GDP growth, energy intensity improvement, fossil-fuel mix, etc.
  - Stabilization curves used earlier in this talk
    - Doing less now means doing more later
- Rates increase after 2050



Caldeira et al, 2003

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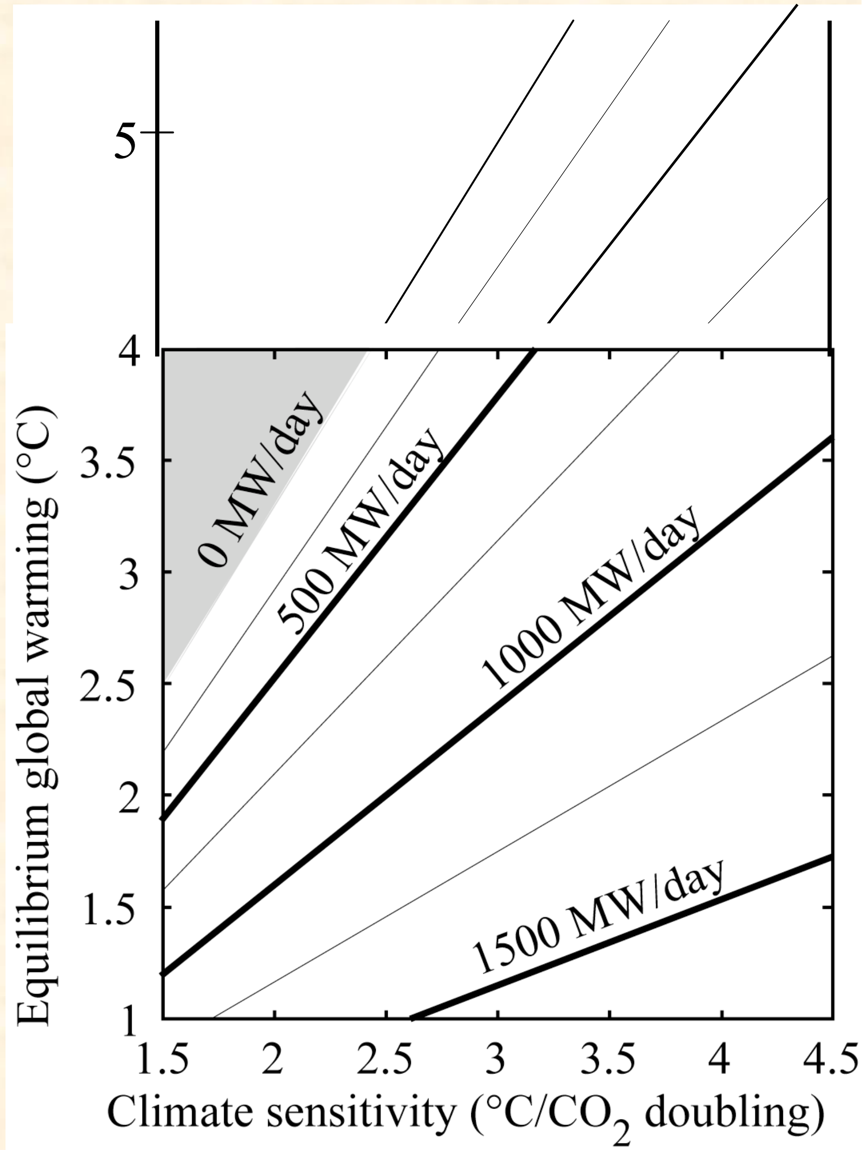
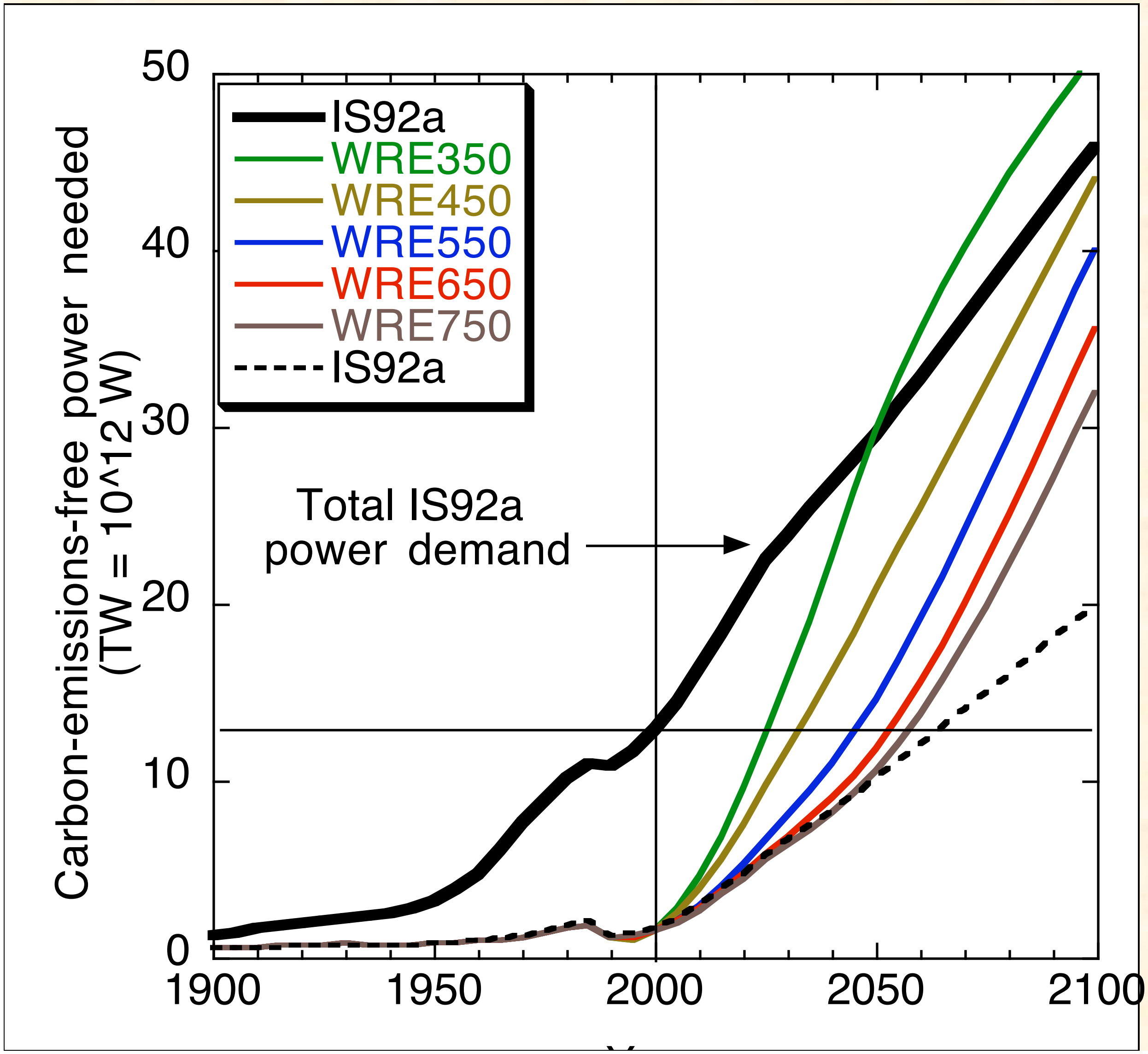
  - IS92a rates of GDP growth, energy intensity improvement, fossil-fuel mix, etc.
  - Stabilization curves used earlier in this talk
    - Doing less now means doing more later
- Rates increase after 2050



Caldeira et al, 2003

Carbon-emissions-free primary power required for CO_2 stabilization



IPCC IS92a "Business as Usual" economic assumptions

calculations from Hoffert et al., 1998

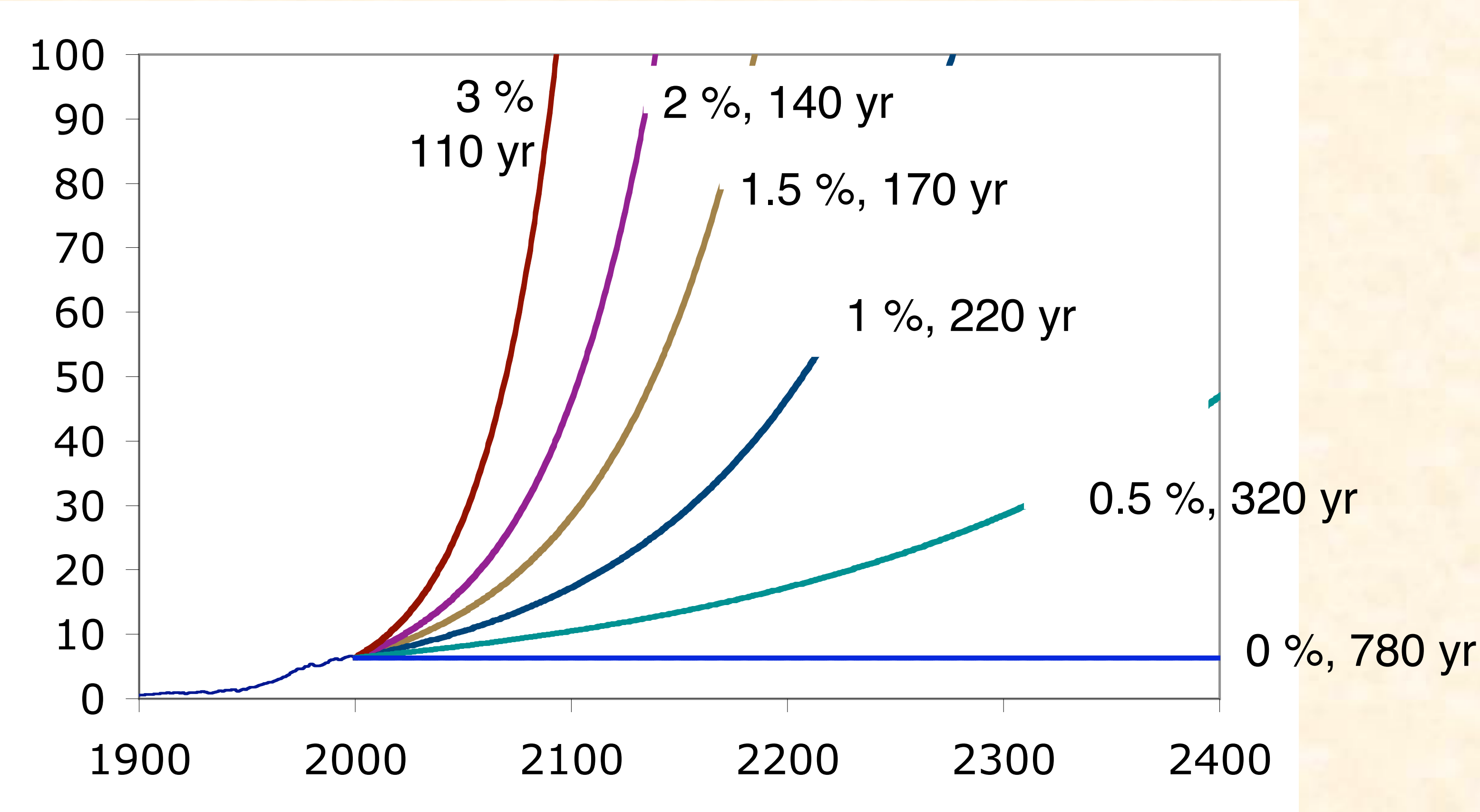
Conclusions

- For most scenarios considered, climate stabilization implies long-term reductions in fossil-fuel emissions below today's values
  - This implies long-term rates of combined improvement in energy-intensity (E/GDP) and carbon-intensity (C/E) that exceed GDP growth rates.
  - Many plausible scenarios require vast amounts of carbon-emissions-free power later this century (10's of TW) combined with aggressive efforts to improve E/GDP
- Narrowing climate impact and climate sensitivity uncertainties can reduce what we need to do to avoid unacceptable risk
  - If climate change is relatively "safe" and climate sensitivity is low, we may not need to do anything to avoid the risk of dangerous climate change, but right now we are risking 12°C (22°F) changes with little understanding of what that means for our planet.
  - Uncertainty in "safe" amounts of climate change and climate sensitivity introduce large uncertainties in the rates at which we need to improve E/GDP and C/E on the decadal time-scale

[redacted]

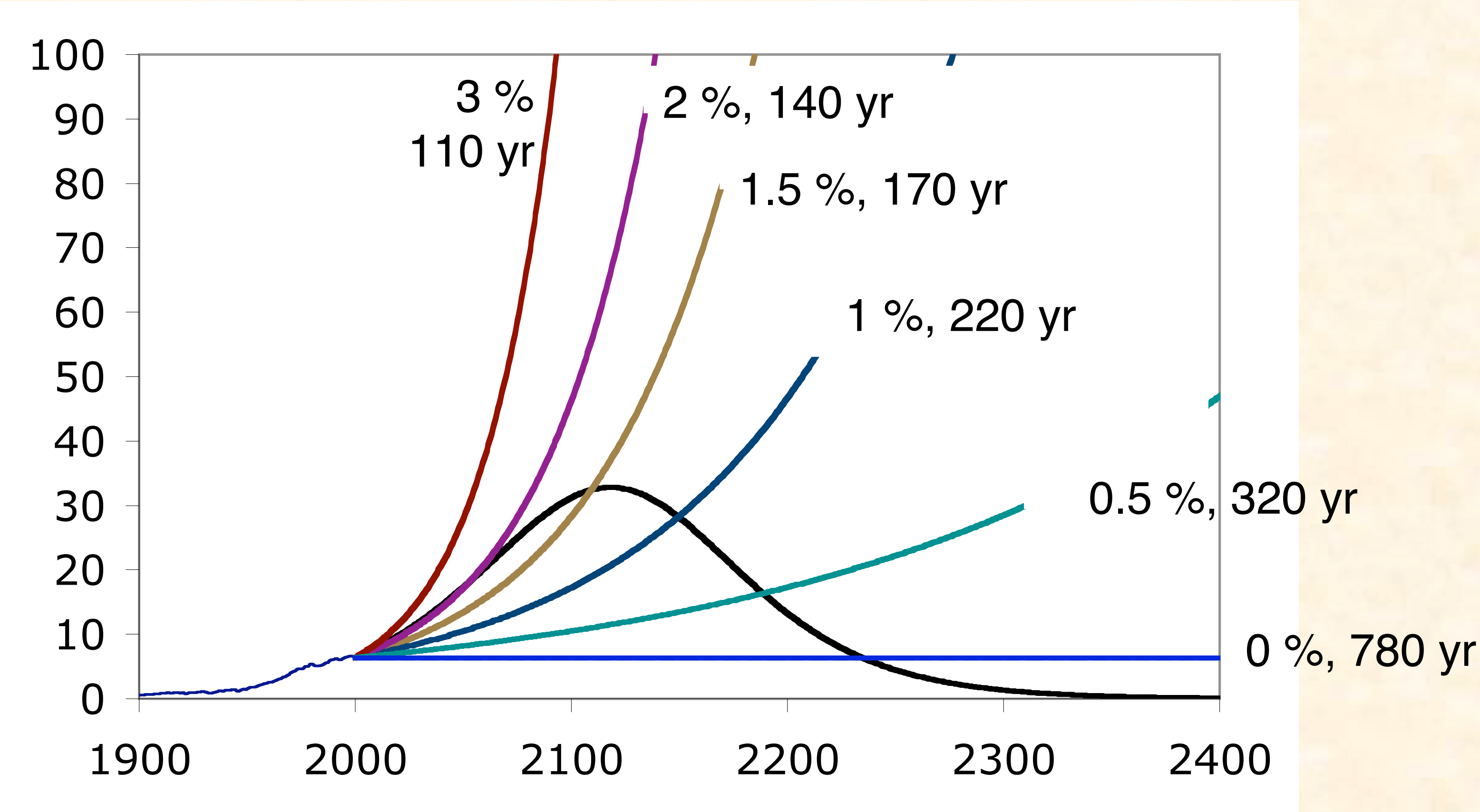
How long does it take to burn 5000 GtC?

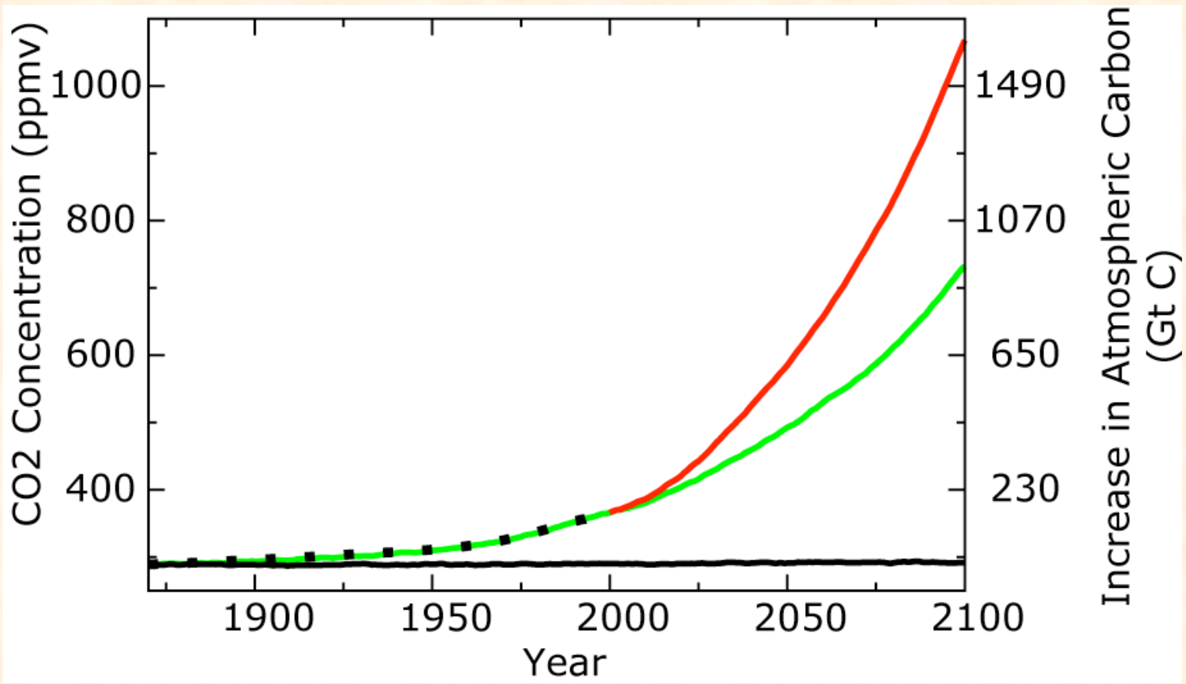
- %ΔC = %ΔGDP + %Δ(E/GDP) + %Δ(C/E)



How long does it take to burn 5000 GtC?

- $\%\Delta C = \%\Delta GDP + \%\Delta(E/GDP) + \%\Delta(C/E)$




CO2 Concentration (ppmv)
1000
800
600
400
1900
1950
2000
2050
2100
Year
1490
1070
650
230
Increase in Atmospheric Carbon
(Gt C)

CO_2 volumes

- In year 2000, globally, we produced
  - ~25,000 km^3 of gaseous CO_2 per year (at STP)
  - ~25 km^3 per year compressed to liquid CO_2 density
- By 2100, perhaps
  - ~100,000 km^3 gaseous CO_2 per year
  - ~100 km^3 liquid CO_2 per year

Unrestrained fossil-fuel burning

Quantity	Value	Notes
Maximum pCO2 (year = ~2300)	~1940 ppm	adjust for change in land biomass, etc.
Radiative forcing from CO_2	+10.4 W/m^2	+3.71 W/m2 per CO2-doubling (IPCC, 2001)
Global mean ΔT (4.5 K/CO_2-doubling)	+ 12.5 K (= +23 °F)	does not consider other gases, aerosols, long-term feedbacks,…
Global mean ΔT (1.5 K/CO_2-doubling)	+ 4.2 K (= +7.5 °F)	does not consider other gases, aerosols, long-term feedbacks,…
Maximum surface ocean pH change	$\Delta pH < -0.7$	Caldeira and Wickett (submitted)
Range of radiative forcing from short-lived gases in SRES scenarios year 2100	–0.2 W/m^2 to +1.0 W/m^2	Wigley (2002)

What happens if we do nothing?

The short-term carbon cycle