Climate sensitivity and stabilization primer

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Climate Sensitivity Uncertainty and the Need for Energy Without CO₂ 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,⁎ Ken Caldeira, Gregory Benford, David R. Criswell, Christopher Green, Howard Herzog, Atul K. Jain, Haroon S. Kheshgi, Klaus S. Lackner, John S. Lewis, H. Douglas Lightfoot, Wallace Manheimer, John C. Mankins, Michael E. Mauel, L. John Perkins, Michael E. Schlesinger, Tyler Volk, Tom M. L. Wigley

28 MARCH 2003 VOL 299 SCIENCE

Energy implications of future stabilization of atmospheric CO₂ content


29 OCTOBER 1998 NATURE VOL 395
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”

What is an acceptable amount of climate change?

What is an acceptable amount of anthropogenic radiative forcing?

Uncertainty in climate sensitivity
“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?

What is an acceptable amount of anthropogenic radiative forcing?

What is an acceptable rate of greenhouse gas and aerosol emissions?

Uncertainty in climate sensitivity

Uncertainty in carbon-cycle, aerosols, etc.
“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?

What is an acceptable amount of anthropogenic radiative forcing?

What is an acceptable rate of greenhouse gas and aerosol emissions?

What is an acceptable system of energy production and consumption?

* Uncertainty in climate sensitivity

* Uncertainty in carbon-cycle, aerosols, etc.

* Uncertainty in engineering, environmental sciences, social systems, etc.
What happens if we do nothing?

![Graph showing historical emissions to year 2000]
What happens if we do nothing?

Historical emissions to year 2000

IS92a “no-policy” to 2100
What happens if we do nothing?

Historical emissions to year 2000

IS92a “no-policy” to 2100

Logistic atmospheric release of remaining fossil-fuel (=5000 GtC in year 2000)
What happens if we do nothing?

**CO₂ emissions**

- Historical emissions to year 2000
- Logistic release of remaining fossil-fuel

**Atmospheric CO₂**

Caldeira and Wickett, submitted
What happens if we do nothing?

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**CO₂ emissions**

- Historical emissions to year 2000
- Logistic release of remaining fossil-fuel

**CO₂ radiative forcing**
“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
What happens if we do nothing?

**CO₂ emissions**

- Historical emissions to year 2000
- Logistic release of remaining fossil-fuel

**CO₂ radiative forcing**
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 $\sim 10$ 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 = $\sim 3.7$ W/m$^2$
  - Temperature change of $1.5^\circ$C to $4.5^\circ$C

- Unrestrained release
  - Radiative forcing = $\sim 10$ W/m$^2$
  - Temperature change of $4^\circ$C to $12^\circ$C
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
    - 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. Opdyke⁶

~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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Reduced calcification of marine plankton in response to increased atmospheric CO₂

~35% reduction planktonic calcification 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).
Consequences of unrestrained atmospheric release of fossil-fuel \( \text{CO}_2 \)

- Unrestrained atmospheric release of fossil-fuel \( \text{CO}_2 \) 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

Caldeira and Wickett, submitted

Greatest change inferred from geologic record of past 300 myr
Change from 1750 to 2000
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
  \[ NP = NP_{\text{max}} \left( \frac{\text{CO}_2}{(\text{CO}_2{-}\text{half} + \text{CO}_2)} \right) \]

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

- Climate sensitivity
  \[ \Delta T = \Delta T_{\text{2x-clim}} \ln_2 \left( \frac{\text{CO}_2}{\text{CO}_2{-}0} \right) \]
Land biosphere in carbon/climate ocean/atmosphere GCM simulations

- IPSL simulation
  - Land biosphere is a CO₂ sink
- Hadley center simulation
  - Land biosphere is a CO₂ source
- LLNL simulations
  - Land biosphere can be a CO₂ source or sink depending on treatment of
    - CO₂-fertilization
    - respiration
    - climate sensitivity
    - etc.
Radiative forcing as a function of temperature change and climate sensitivity

Climate sensitivity (°C/CO$_2$-doubling)

Radiative forcing (W/m$^2$)

Candidate values for “acceptable” amounts of global warming
Atmospheric CO$_2$ as a function of CO$_2$-induced temperature change and climate sensitivity

Candidate values for “acceptable” amounts of global warming
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

Climate sensitivity to a CO$_2$-doubling
Trajectories stabilizing after 2150 at a CO₂-induced climate change of 3°C.
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”
Climate sensitivity uncertainty and avoiding risk of "dangerous interference in the climate system"

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605 ppm would avoid risk, if $\Delta T_{2x} < 4.5°C$
Climate sensitivity uncertainty and avoiding risk of "dangerous interference in the climate system"

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

890 ppm would avoid risk, if $\Delta T_{2x} < 3°C$

605 ppm would avoid risk, if $\Delta T_{2x} < 4.5°C$
Climate sensitivity uncertainty and avoiding risk of “dangerous interference in the climate system”

Let’s pretend we determined that 5°C was “safe”

890 ppm would avoid risk, if ΔT_{2x} < 3°C
605 ppm would avoid risk, if ΔT_{2x} < 4.5°C

There is no risk, if ΔT_{2x} < 1.75°C
Climate sensitivity uncertainty and avoiding risk of “dangerous interference in the climate system”

Let’s pretend we determined that 5°C was “safe”

Climate sensitivity (°C/CO₂-doubling) vs. CO₂ (ppm)

- 890 ppm would avoid risk, if ∆T₂ₓ < 3°C
- 605 ppm would avoid risk, if ∆T₂ₓ < 4.5°C

There is no risk, if ∆T₂ₓ < 1.75°C

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)

- \( C = N \times (\frac{\text{GDP}}{N}) \times (\frac{E}{\text{GDP}}) \times (\frac{C}{E}) \)
  - population, per capita GDP, energy intensity, carbon intensity

- \( C = \text{GDP} \times (\frac{E}{\text{GDP}}) \times (\frac{C}{E}) \)
  - gross product, energy intensity, carbon intensity of primary energy

- \( C = \text{GDP} \times (\frac{C}{\text{GDP}}) \)
  - gross product, carbon intensity of productivity
The Kaya equation (and variants)

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

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

- For climate stabilization, in the long term,
  - $\%\Delta C < 0$

- Thus, for climate stabilization, in the long term,
  - $\%\Delta \text{GDP} + \%\Delta (C/\text{GDP}) < 0$
    - 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.
Trajectories stabilizing after 2150 at a CO$_2$-induced climate change of 3°C

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.
Trajectories stabilizing after 2150 at a CO₂-induced climate change of 3°C

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.
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
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.
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    - 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
How long does it take to burn 5000 GtC?

- $\% \Delta C = \% \Delta \text{GDP} + \% \Delta (E/\text{GDP}) + \% \Delta (C/E)$
How long does it take to burn 5000 GtC?

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

![Graph showing the time taken to burn 5000 GtC for different rates of change.]

0 %: 780 yr
0.5 %: 320 yr
1 %: 220 yr
1.5 %: 170 yr
2 %: 140 yr
3 %: 110 yr
0.5 %: 320 yr
0 %: 780 yr
**CO$_2$ volumes**

- In year 2000, globally, we produced
  - $\sim 25,000$ km$^3$ of gaseous CO$_2$ per year (at STP)
  - $\sim 25$ km$^3$ per year compressed to liquid CO$_2$ density

- By 2100, perhaps
  - $\sim 100,000$ km$^3$ gaseous CO$_2$ per year
  - $\sim 100$ km$^3$ liquid CO$_2$ per year
Unrestrained fossil-fuel burning

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum pCO2 (year = ~2300)</td>
<td>~1940 ppm</td>
<td>adjust for change in land biomass, etc.</td>
</tr>
<tr>
<td>Radiative forcing from CO₂</td>
<td>+10.4 W/m²</td>
<td>+3.71 W/m² per CO₂-doubling (IPCC, 2001)</td>
</tr>
<tr>
<td>Global mean ΔT (4.5 K/CO₂-doubling)</td>
<td>+ 12.5 K (= +23 °F)</td>
<td>does not consider other gases, aerosols, long-term feedbacks,…</td>
</tr>
<tr>
<td></td>
<td>+ 4.2 K (= +7.5 °F)</td>
<td>does not consider other gases, aerosols, long-term feedbacks,…</td>
</tr>
<tr>
<td>Maximum surface ocean pH change</td>
<td>ΔpH &lt; −0.7</td>
<td>Caldeira and Wickett (submitted)</td>
</tr>
<tr>
<td>Range of radiative forcing from short-lived gases in SRES scenarios year 2100</td>
<td>−0.2 W/m² to +1.0 W/m²</td>
<td>Wigley (2002)</td>
</tr>
</tbody>
</table>
What happens if we do nothing?

The short-term carbon cycle

Atmosphere
785 GtC (370 ppm)

Combustion
> 6 GtC/yr

Fossil Fuels
5000 GtC

Land
2200 GtC

Photosynthesis
62 GtC/yr

Respiration
60 GtC/yr

Air-sea exchange
Net ~2 GtC/yr into ocean

Ocean
38,000 GtC