The Global Carbon Cycle on Glacial/Interglacial Timescales

The Global Carbon Cycle
Bremen Graduate School Global Change in the Marine Realm (GLOMAR)
September 26–28 2007

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26 Sep 2007
Outline

1. Introduction to the GHG problem

2. Radiative Forcing
   - Radiation
   - Greenhouse Effect

3. Ice core records
   - Ice Core Drilling
   - Overview on Ice Core Records
   - Somethings about Orbital Forcing
   - The Holocene — last 10,000 yr BP
   - Glacial/Interglacial Variation — Termination I and the last 650,000 yr
IPCC: CO₂ & CH₄ data 20,000 yr — the cause

**CO₂**

- Dome C (Monnin et al., 2004)
- Law Dome Ice (Etheridge et al., 1996)
- Law Dome Firn (Etheridge et al., 1996)
- Southpole (Siegenthaler et al., 2004)
- Kohnen Station (Siegenthaler et al, 2004)
- Mauna Loa (Keeling and Whorf)
- NOAA/CMDL Global (Conway, 2004)

**CH₄**

- Eurocore (Blunier et al., 1993)
- GRIP (Blunier et al., 1995)
- D47 (Chappellaz et al., 1997)
- Law Dome (Etheridge et al., 1992)
- Siple (Stauffer et al., 1985)
- Dome C (Flückiger et al., 2002)
- NOAA/CMDL (Dlugokencky, 2004)
IPCC: Radiative forcing — the process

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF values (W m$^{-2}$)</th>
<th>Spatial scale</th>
<th>LOSU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-lived greenhouse gases</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$</td>
<td>1.66 [1.49 to 1.83]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>0.07 [0.02 to 0.12]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>0.07 [0.02 to 0.12]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>0.48 [0.43 to 0.53]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Stratospheric water vapour from CH$_4$</td>
<td>0.34 [0.31 to 0.37]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Surface albedo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land use</td>
<td>-0.2 [-0.4 to 0.0]</td>
<td>Local to continental</td>
<td>Med - Low</td>
</tr>
<tr>
<td>Black carbon on snow</td>
<td>0.1 [0.0 to 0.2]</td>
<td>Local to continental</td>
<td>Med - Low</td>
</tr>
<tr>
<td>Total Aerosol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct effect</td>
<td>-0.5 [-0.9 to -0.1]</td>
<td>Continental to global</td>
<td>Med - Low</td>
</tr>
<tr>
<td>Cloud albedo effect</td>
<td>-0.7 [-1.8 to -0.3]</td>
<td>Continental to global</td>
<td>Low</td>
</tr>
<tr>
<td>Linear contrails</td>
<td>0.01 [0.003 to 0.03]</td>
<td>Continental</td>
<td>Low</td>
</tr>
<tr>
<td>Natural</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar irradiance</td>
<td>0.12 [0.06 to 0.30]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Total net anthropogenic</td>
<td>1.6 [0.6 to 2.4]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IPCC: Global responses — the effect

(a) Global average temperature

(b) Global average sea level

(c) Northern Hemisphere snow cover

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IPCC: Anthropogene versus natural

- Introduction

Peter Köhler (AWI Bremerhaven)

C Cycle on Glacial/Interglacial Times

26/09/2007, Uni HB
From **cause** to **effect**: Understanding the **process**.

From **GHG** to **temperature**: Understanding the radiative forcing.
- From **cause** to **effect**: Understanding the process.
- From **GHG** to **temperature**: Understanding the radiative forcing.
Temperature — Instrumental record

(a) Global average temperature

(b) Global average sea level

(c) Northern Hemisphere snow cover

Year

1850 1900 1950 2000

(c) Northern Hemisphere snow cover

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Introduction

Temperature — 1500 years — The Hockeystick

Reference period: 1961-1990, smoothed with cut-off period of 30 years

Northern Hemisphere Temperature Anomalies (°C)

-1
-0.5
0
0.5

Year

500
1000
1500
2000

B2000
BSHUSV2001
CED2004
JBTI998
MBH1999
MJ2003
MSHDK2005
PS2004
Instrumental

Esper et al. (1.2°C)
Mann and Jones 2003 (0.3°C)
Take-home message:

1) The anthropogenic temperature rise is beyond doubt, but details depend on quality and resolution of data sets and model-based reconstructions.

2) It is caused by changing the radiative budget of the Earth’s atmosphere.
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Planck’s Law

Planck’s Law:

\[ I(\nu, T) = \frac{2\nu^3}{c^2} \frac{1}{e^{\frac{\nu}{kT}} - 1}. \]
Stefan-Bolzmann-Law: $R = \sigma T^4$

Stefan-Bolzmann-Constant: $\sigma = 5.6710^{-8} \text{W/(m}^2 \cdot \text{K}^4)$

Solarconstant: $S = 1367 \text{W/m}^2$.

Albedo: $\alpha = 0.3$

Steady state (without atmosphere):

\[
\text{Incoming} = \text{Outgoing} = S(1-\alpha)\pi r^2 = R4\pi r^2
\]

\[
T_{e,0} = \left(\frac{S(1-\alpha)}{4\sigma}\right)^{1/4}
\]

\[
T_{e,0} = 255K(-18^\circ C)
\]
Black Body Radiation

Stefan-Bolzmann-Law: $R = \sigma T^4$
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Radiative Forcing

Energy Budget of Atmosphere

Reflected Solar Radiation 107 Wm⁻²

Incoming Solar Radiation 342 Wm⁻²

Outgoing Longwave Radiation 235 Wm⁻²

Reflected by Clouds, Aerosol and Atmospheric Gases 77

Emitted by Atmosphere 165

40 Atmospheric Window

Greenhouse Gases

Emitted by Clouds

Absorbed by Atmosphere

Latent Heat 78

168 Absorbed by Surface

24 Thermals

390 Surface Radiation

324 Absorbed by Surface

350

235

24

30

40

107

342

235

77

67

165

30

40
Radiative Forcing

Energy Budget of Atmosphere

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Reflected by Clouds, Aerosol and Atmospheric Gases 77

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Emitted by Atmosphere 165

Emitted by Clouds 30

Latent 78 Heat

78 Evapotranspiration

350 Surface Radiation

324 Back Radiation

324 Absorbed by Surface

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Atmospheric Spectral Transmission

Radiative Forcing

Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.
Transition corresponds to a specific energy $E$ and frequency after

$$\begin{align*}
E &= h \cdot \nu \\
\text{\textit{h}}: \text{Planck's constant}; \text{ } h &\sim 6.6 \times 10^{-34} \text{Js} \\
\text{\textit{\nu}}: \text{frequency [Hz]}
\end{align*}$$
CO₂ — A Molecule

116.3 pm
Additional transitions through the possibility of rotation and vibration.
### Possibilities for Gases to Absorb Energy

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy</th>
<th>Bandwidth</th>
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<tr>
<td><strong>Atoms and Molecules</strong></td>
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<td>Excitation of electrons</td>
<td>eV</td>
<td>VIS to UV</td>
</tr>
<tr>
<td>Finestructure</td>
<td>$10^{-5}$ eV</td>
<td>far IR to sub cm</td>
</tr>
<tr>
<td>Hyperfinestructure</td>
<td>$10^{-6}$ eV</td>
<td>cm</td>
</tr>
</tbody>
</table>

| Molecules only                   |          |                   |
| Vibration                        | $10^{-1}$ eV | IR                |
| Rotation                         | $10^{-3}$ eV | microwave to IR   |
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<tr>
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<td>IR</td>
</tr>
<tr>
<td>Rotation</td>
<td>$10^{-3} eV$</td>
<td>microwave to IR</td>
</tr>
</tbody>
</table>
Radiative Forcing

Atmospheric Spectral Transmission

Radiation Transmitted by the Atmosphere

Dowgoing Solar Radiation
70-75% Transmitted

Upgoing Thermal Radiation
15-30% Transmitted

Spectral Intensity

0.2 1 10 70

Wavelength (μm)

Percent

Total Absorption and Scattering

Water Vapor

Carbon Dioxide

Oxygen and Ozone

Methane

Nitrous Oxide

Rayleigh Scattering

Major Components

0 25 50 75 100

Percent
Radiative Forcing

Atmospheric Spectral Transmission

Solar Irradiance Outside Atmosphere

Direct Solar Irradiance at Sea Level
Airmass = 1.5
Water Vapor = 2.0 cm
Ozone = 0.34 cm
\( \tau \) aerosol 550nm = 0.126
\( \tilde{A} \) exponent = 0.66

MODIS Bands

- O_3
- H_2O
- H_2O & CO_2

Wavelength (nm)

Solar Spectral Irradiance (W/m^2/\mu m^-1)

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Radiative Forcing (RF) is calculated with Radiative Transfer Models and comes up with different equations for every agent.

<table>
<thead>
<tr>
<th>agent</th>
<th>equation</th>
<th>$C_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>$RF = 5.35 \text{ W m}^{-2} \ln(CO_2/CO_{2,0})$</td>
<td>278 ppm</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>$RF = 0.036 \text{ W m}^{-2} \left(\sqrt{CH_4} - \sqrt{CH_{4,0}}\right)$</td>
<td>742 ppb</td>
</tr>
<tr>
<td></td>
<td>$- \left(f[CH_{4,0},N_2O_0] - f[CH_{4,0},N_2O_0]\right)$</td>
<td></td>
</tr>
<tr>
<td>N$_2$O</td>
<td>$RF = 0.12 \text{ W m}^{-2} \left(\sqrt{N_2O} - \sqrt{N_{2O,0}}\right)$</td>
<td>272 ppb</td>
</tr>
<tr>
<td></td>
<td>$- \left(f[CH_{4,0},N_2O] - f[CH_{4,0},N_2O_0]\right)$</td>
<td></td>
</tr>
<tr>
<td>CFC-11</td>
<td>$RF = 0.25 \text{ W m}^{-2} (CFC-11 - CFC-11_0)$</td>
<td>0 ppt</td>
</tr>
<tr>
<td>CFC-12</td>
<td>$RF = 0.32 \text{ W m}^{-2} (CFC-12 - CFC-12_0)$</td>
<td>0 ppt</td>
</tr>
</tbody>
</table>
Radiative forcing (RF): \( RF(CO_2) = 5.35 \text{ W m}^{-2} \cdot \ln\frac{CO_2}{CO_{2,0}} \)

\( CO_{2,0} = 278 \text{ ppmv} \)

Three examples:

<table>
<thead>
<tr>
<th>When</th>
<th>( CO_2 ) ppmv</th>
<th>( \Delta CO_2 ) ppmv</th>
<th>RF W m(^{-2})</th>
<th>All GHG W m(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Today</td>
<td>383</td>
<td>+105</td>
<td>+1.7</td>
<td>2.7</td>
</tr>
<tr>
<td>( 2 \times CO_2 )</td>
<td>556</td>
<td>+278</td>
<td>+3.7</td>
<td>???</td>
</tr>
<tr>
<td>LGM</td>
<td>180</td>
<td>–98</td>
<td>–2.3</td>
<td>–2.8</td>
</tr>
</tbody>
</table>

Radiative forcing of fossil fuel C emission is on the order of the effect from between LGM and preindustrial.
### Radiative Forcing — GHG II

<table>
<thead>
<tr>
<th>Gas</th>
<th>Current Amount</th>
<th>Increase</th>
<th>Preindustrial Greenhouse Forcing</th>
<th>Anthropogenic Greenhouse Forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>383 ppm</td>
<td>105 ppm (38%)</td>
<td>94</td>
<td>146</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>1745 ppb</td>
<td>1045 ppb (150%)</td>
<td>50</td>
<td>1750-2007</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>314 ppb</td>
<td>44 ppb (16%)</td>
<td>1.1</td>
<td>1750-2007</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>268 ppt</td>
<td></td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>CFC-11</td>
<td>533 ppt</td>
<td></td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>CFC-12</td>
<td>84 ppt</td>
<td></td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Other CFCs</td>
<td>102 ppt</td>
<td></td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>HCFC-22</td>
<td>69 ppt</td>
<td></td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>

Radiative forcing (W m$^{-2}$)

- $< 1750$
- $1750-2007$

Peter Köhler (AWI Bremerhaven)
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Radiative Forcing (LGM) is one of several others and of the order of that from ice sheets.
Biggest uncertainty for the anthropogenic RF is the effects from aerosols.
Radiative forcing (RF) after reaching a new steady state:

Stefan-Bolzmann-Law: \( R = \sigma T^4 \)

Stefan-Bolzmann-Constant: \( \sigma = 5.6710^{-8} \text{W/(m}^2 \cdot \text{K}^4) \)

\( T_{e,0} = 255K (-18^\circ C) \)

\[ \Delta R = \left. \frac{\delta R}{\delta T} \right|_{T=T_{e,0}} \cdot \Delta T^{*}_{S,\infty} = RF \]

with \( \frac{\delta R}{\delta T} = 4\sigma T^3 \)

Climate sensitivity without feedbacks \( \lambda^* \)

\[ \lambda^* = \frac{\Delta T^{*}_{S,\infty}}{RF} = \frac{1}{4\sigma T^3_{e,0}} \]

\( \lambda^* = 0.26K/(\text{W/m}^2) \)
Climate sensitivity without feedbacks $\lambda^* = 0.26K/(W/m^2)$

Radiative forcing (RF)
\[
RF(CO_2) = 5.35 \cdot \ln\frac{CO_2}{CO_{2,0}} Wm^{-2} = 5.35 \cdot \ln(2) Wm^{-2} = 3.7 Wm^{-2}
\]

$\Delta T_{S,\infty}^* = \lambda^* \cdot RF = 0.26K/(W/m^2) \times 3.7 Wm^{-2} \sim 1 K$

$\Delta T_{S,\infty}^*$ for $CO_2(t) = 2 \times CO_2(t_0)$ also called $\Delta T_{2\times CO_2}$

With feedbacks (albedo, water vapour content)
\[
\Delta T_{2\times CO_2} = [1.5 - 4.5]K
\]
(measurements, models, global system analysis)

$\lambda = [0.4 - 1.2]K/(W/m^2)$ Climate sensitivity
Climate sensitivity without feedbacks $\lambda^* = 0.26 K/(W/m^2)$

Radiative forcing (RF)

$$RF(CO_2) = 5.35 \cdot \ln \frac{CO_2}{CO_2,0} \text{ Wm}^{-2} = 5.35 \cdot \ln(2) \text{ Wm}^{-2} = 3.7 \text{ Wm}^{-2}$$

$\Delta$Temperature

$$\Delta T^*_S,\infty = \lambda^* \cdot RF = 0.26 K/(W/m^2) \times 3.7 \text{ Wm}^{-2} \sim 1 \text{ K}$$

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Radiative Forcing

From CO$_2$ to W m$^{-2}$ to $\Delta$Temperature, I

Example: CO$_2$ double

Climate sensitivity without feedbacks $\lambda^* = 0.26 K/(W/m^2)$

Radiative forcing (RF)

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$\Delta$Temperature

$$\Delta T_{S,\infty}^* = \lambda^* \cdot RF = 0.26 K/(W/m^2) \times 3.7 \text{ Wm}^{-2} \sim 1 K$$

$\Delta T_{S,\infty}^*$ for $CO_2(t) = 2 \times CO_2(t_0)$ also called $\Delta T_{2 \times CO_2}$

With feedbacks (albedo, water vapour content)

$$\Delta T_{2 \times CO_2} = [1.5 - 4.5] K$$

(measurements, models, global system analysis)

$\lambda = [0.4 - 1.2] K/(W/m^2)$ Climate sensitivity
Radiative Forcing

From $CO_2$ to $W \ m^{-2}$ to $\Delta$Temperature, I

Example: $CO_2$ double

Climate sensitivity without feedbacks $\lambda^* = 0.26 K/(W/m^2)$

Radiative forcing (RF)

$$RF(CO_2) = 5.35 \cdot \ln \frac{CO_2}{CO_2,0} \ W m^{-2} = 5.35 \cdot \ln(2) \ W m^{-2} = 3.7 \ W m^{-2}$$

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(measurements, models, global system analysis)

$$\lambda = [0.4 - 1.2] K/(W/m^2)$$ Climate sensitivity
Radiative Forcing

- From **cause to effect**: Understanding the process.
- From **GHG to temperature**: Understanding the radiative forcing.

**Take-home messages:**

3) The amplitude in the rise in GHG from LGM to preindustrial is of similar size than from preindustrial to present.

4) The full range of observed temperature rise can not be explained solely with the rise in GHG, feedbacks in the climate system contribute a significant amount to it.
Outline

1. Introduction to the GHG problem

2. Radiative Forcing
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     - Overview on Ice Core Records
     - Somethings about Orbital Forcing
     - The Holocene — last 10,000 yr BP
     - Glacial/Interglacial Variation — Termination I and the last 650,000 yr
European Project for Ice Coring in Antarctica

- **Ice Core Drilling**
- **Paleo in the C Cycle**

Peter Köhler (AWI Bremerhaven)

C Cycle on Glacial/Interglacial Times

26/09/2007, Uni HB
European Project for Ice Coring in Antarctica

Backside of Planet Kohnen

- Work shop
- Generator room
- Snow melter with crane
- Sleeping quarters
- Sleeping quarters
- Bathroom & toilet
- Kitchen
- Mess
- Radio room
- Freezer
- Bivac box
- Bivac box
- Bivac box
- Tomato
- Weather port tent

Clean air/snow sector
European Project for Ice Coring in Antarctica
European Project for Ice Coring in Antarctica
European Project for Ice Coring in Antarctica
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Glacial minima (180 ppmv), interglacial maxima (280 ppmv)
CO₂ and Antarctic Temperature

EPICA Dome C
(0-22 kyr BP; 430-650 kyr BP)

Vostok
(0-415 kyr BP)
CO$_2$ on different Time Scales

- **Time [kyr BP]**
  - 700 kyr: glacial/interglacial
  - 10 kyr: Holocene
  - 1 kyr: anthrop.
  - 20 y: seasonal

- **Time [yr AD]**
  - 1750 AD

**CO$_2$ [ppmv]**
- 700 400 100
- 350 300 250 200

**δ$^{13}$C [%oo]**
- -8.5 -8.0 -7.5 -7.0 -6.5 -6.0

**Ice Core Records**
- Vostok
- EPICA DC
- Taylor D.
- Law Dome
- Point Barrow

Peter Köhler (AWI Bremerhaven)

C Cycle on Glacial/Interglacial Times
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Milutin Milankovitch (1941) *Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem*

Variability of the Earth and its Position relative to the Sun

- Eccentricity
- Axial Tilt / Obliquity
- Precession
Eccentricity — $\sim$ 100,000 and 400,000 yr cycles

**ECCENTRICITY**

- **MORE ELLIPTICAL**
- **LESS ELLIPTICAL**

**PERIODICITY:**

100,000 YEARS

Little effect (some %) on total amount of insolation $\varepsilon \in [0.005, 0.607]$
Obliquity — $\sim 40,000$ yr cycles
Caused by Gravity of larger planets (Jupiter)

Changes the difference between seasons, especially in high latitude
Precession — $\sim 20,000$ yr cycles

Precession of the Earth’s Axis

Precession of the Equinoxes

Changes the difference between seasons, especially in high latitude

Peter Köhler (AWI Bremerhaven)
Orbital Insolation at 65° N
From 40-kyr to 100-kyr world

Fig. 5: Comparison of variability in insolation between the Late and Early Pleistocene. (A) Midsummer insolation at 65°N of the last 2 Myr. (B)
Climate Signal in benthic $\delta^{18}$O stack LR04
From 40-kyr to 100-kyr world

A

100 kyr world

MPR

41 kyr world

$\delta^{18}$O (‰)

I II III IV V VI VII

0 200 400 600 Age (kyr BP)

B

C

100 kyr

41 kyr

23 kyr

19 kyr

Spectral density

Frequency (kyr$^{-1}$)

Peter Köhler (AWI Bremerhaven)  
C Cycle on Glacial/Interglacial Times  
26/09/2007, Uni HB  
49 / 55
Power in the 100 kyr band in Insolation is too weak to explain records (100k Problem). Feedbacks (e.g. land ice sheets) are important.
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Ruddiman’s Hypothesis on Early Anthropocene

- Earlier Interglacials had drop in CO$_2$ and CH$_4$ while Holocene has a rise
- Might be caused by Early (8000 yr BP) deforestation
- Direct effect can at maximum explain 25% of the observed offset in CO$_2$
- Feedbacks need to account for rest 75%.
- Problem: Depends on the way Interglacials are compared, typically aligned along insolation minima or maxima
- The jury is still out
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Ice cores, last 20,000 yr

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<th>Today</th>
<th>1750 AD</th>
<th>LGM</th>
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<tbody>
<tr>
<td>(\text{CO}_2) (ppmv)</td>
<td>380</td>
<td>280</td>
<td>180</td>
<td>100 (35%)</td>
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<tr>
<td>(\text{CH}_4) (ppbv)</td>
<td>1750</td>
<td>700</td>
<td>360</td>
<td>340 (49%)</td>
<td>1050 (150%)</td>
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</table>
Experiments with the Carbon Cycle Box Model BICYCLE
Box model of the Isotopic Carbon cYCLE

Box model of the Isotopic Carbon cYCLE

Prognostic variables:
- 1 atmospheric box: CO2, 13C, 14C
- 7 terrestrial boxes: C, 13C, 14C
- 10 oceanic boxes: DIC, 13C, 14C, ALK, PO4, O2

Time-dependent processes:

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1 Temperature

Simulation with the climate model CCSM3
LGM–Preindustrial: light blue: –(2-4)K

Otto-Bliesner et al., 2006
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Sea level rose during Termination I by 125 m; salinity dropped by 3%.
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3 Gas Exchange / Sea Ice

Annual mean sea ice area shrunk by \( \sim 50\% \) (Termination I)
Dynamics coupled to temperature in the high latitude surface boxes

Arctic (present): The Cryosphere Today (www)  Antarctic (LGM) Gersonde et al., 2005
3 Gas Exchange / Sea Ice

Model comparisons came to ambiguous results.

Box models: full sea ice cover in SO reduces CO$_2$.

GCMs: only small changes.

Archer et al., 2003
3 Gas Exchange / Sea Ice

BICYCLE: Sea ice change in N and S
N is sink for CO$_2$; S is source for CO$_2$
S as in box models, but N dominates over S

Archer et al., 2003
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4 NADW Formation

Conveyor belt

Changes in Atlantic THC

Rahmstorf, 2002
4 NADW Formation

Preindustrial circulation: WOCE data
Temporal changes: NADW reduce from 16 Sv to 10 Sv (0 Sv)

Circulation after Ganachaud & Wunsch, 2000
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4 Indirect effects of shutdown of NADW (not in BICYCLE)

Additionally, a NADW shutdown would lead to cooling in Eurasia Temperature anomalies simulated with ECBILT-CLIO

Köhler et al., 2005, Climate Dynamics (after Knutti et al., 2004)
Indirect effects of shutdown of NADW (not in BICYCLE)

Reduction of marine export production (blue) in North Atlantic by 50%

Schmittner, 2005
4 Indirect effects of shutdown of NADW (not in BICYCLE)

Cooling leads to southwards shift of treeline (LPJ-DGVM)
Competing effect of soil respiration and vegetation growth

Köhler et al., 2005, Climate Dynamics
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5 Southern Ocean Ventilation

How to explain $\Delta \delta^{13}C(\text{PRE-LGM}) = +1.2\%$ in deep Southern Ocean?

SO mixing reduced by 2/3 coupled to SO SST = f(EDC $\delta D$)

Different hypotheses on the physical cause behind this process

Hodell et al, 2003

Köhler, et al., 2005, Global Biogeochemical Cycles
**Time-dependent processes:**

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6 Marine Biota / Iron fertilisation

Marine biological productivity might be Fe limited in high nitrate low chlorophyll (HNLC) areas (Martin, 1990)

Ridgwell, 2002
6 Marine Biota / Iron fertilisation

Aeolian dust input to Antarctica LGM export production: + 20% (12 PgC yr\(^{-1}\))

Dust/iron input is reduced before rise in CO\(_2\) starts

Monnin et al., 2001; Röthlisberger et al., 2002
## Time-dependent processes:

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7 Terrestrial carbon storage

Model and data-based estimates range from 300 to 800 PgC
Example from LPJ-DGVM (Preindustrial–LGM)

Köhler et al., 2005, Climate Dynamics
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<td>!/? (off)</td>
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</tr>
<tr>
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8 Carbonate compensation

Dissolution / accumulation of CaCO$_3$ depends on deep ocean [CO$_3^{2-}$ ]

Zeebe and Westbroeck, 2003
8 Carbonate compensation

Anomalies in deep ocean $[\text{CO}_3^{2-}]$ caused by carbon cycle variations relax to initial state with an e-folding time $\tau$ of 1.5 to 6 kyr.

$\tau = 6.0$ kyr:
process-based sediment model
(Archer et al., 1997)

$\tau = 1.5$ kyr:
reconstruction of deep ocean $[\text{CO}_3^{2-}]$
(Marchitto et al., 2005)

after Marchitto et al., 2005
## Time-dependent processes:

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<thead>
<tr>
<th>Which</th>
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| Sum                                        | +75       |
| Sum (without sea ice)                      | +90       |
| Vostok (incl. Holocene rise)               | +103      |
Atmospheric carbon during Termination I

Not only the amplitudes but also the timing of the changes in CO$_2$, $\delta^{13}$C, $^{14}$C seems to be appropriate.

Smith et al., 1999; Monnin et al., 2001; Stuiver et al., 1998; Hughen et al., 2004
Köhler et al., 2005,
Global Biogeochemical Cycles
Termination I

Assumptions on changes in

- Fe fertilization in SO
- Ocean circulation (NADW, SO mixing)
- Climate ($\Delta T$, sealevel, sea ice)
- CaCO$_3$ chemistry
- Terrestrial biosphere

Forcing $\Rightarrow$ Model $\Rightarrow$ Results

Köhler et al., GBC, 2005 doi: 10.1029/2005GB002345
a: Heinrich
b: N-SST
c: NADW
d: EQ-SST
e: NH ΔT
f: deep sea ΔT
g: sea level
h: SO SST
i: Fe fert.
j: CO₂

Köhler and Fischer, 2006, Climate of the Past
Take-Home Messages:

- The anthropogenic temperature rise is beyond doubt, but details depend on quality and resolution of data sets and model-based reconstructions.
- It is caused by changing the radiative budget of the Earth’s atmosphere.
- The amplitude in the rise in GHG from LGM to preindustrial is of similar size than from preindustrial to present.
- The full range of observed temperature rise can not be explained solely with the rise in GHG, feedbacks in the climate system contribute a significant amount to it.
- The variability in CO$_2$ in the Holocene might be partially caused by early anthropogenic activity (Ruddiman’s Hypothesis).
- To understand the glacial/interglacial rise in CO$_2$ at least eight important processes, which were known to have been changed over time, need to be considered (temperature, sea level, sea ice, ocean circulation, marine and terrestrial biota, CaCO$_3$ chemistry).
Further Reading


