Global Warming 56 Million Years Ago: What It Means for Us
Global Temperature and Carbon Dioxide

- Global Temperature (°F)
- CO₂ Concentration (ppm)

20th century average

CO₂ Concentration

NOAA-NCDC
The dashed line on (a) indicates the pre-industrial CO₂ concentration. Simulated by EMICs for the four RCPs up to 2300 (Zickfeld et al., 2013). A 10-year smoothing was applied. Shadings and bars show the range of projections based on the RCP4.5 extension with constant RF (see Section 12.5.1) relative to 1980–1999, AR4 Section 10.7.1). A present-day composition is the pre-industrial CO₂ concentration, or its composition that would occur after stabilizing all radiative constituents at a specified concentration.

Several forms of commitment are often discussed in the literature. The most common is the ‘constant composition commitment’, the warming which is estimated based on this scenario. This can also be interpreted as the warming that would occur after stabilizing all radiative constituents at a constant concentration. The fraction of realized warming rises typically by 10% over the century following the stabilization of forcing. Due to the long time scales in the models, the warming that would have occurred if the forcing had been stabilized at some other level is typically underestimated. Delayed responses can also occur due to processes other than ocean warming, for example, vegetation changes and ice sheet melt that continues long after the stabilization of the forcing has been achieved (Hansen et al., 1985; Knutti et al., 2008; Danabasoglu et al., 2013).

The transient climate response to a doubling of CO₂ (as used to define the radiative forcing, RF) is defined as the equilibrium temperature change (ΔT) of the climate system to a doubling of the pre-industrial carbon dioxide concentration. The transient climate response is typically smaller than the equilibrium climate response (a measure of the climate system’s sensitivity to increased greenhouse gas concentrations) and is longer for higher climate sensitivities. This can also be interpreted as the warming that would have occurred if all radiative forcing were to be stabilized at a constant level (e.g., RCP2.6) prior to stabilization of greenhouse gases. The warming that would have occurred if all radiative forcing were to be stabilized at a constant level after stabilization of greenhouse gases is longer for higher climate sensitivities. A measure of constant composition commitment is the fraction of realized warming at a constant composition, which can be estimated as the ratio of the warming at a constant composition to the warming at the time of stabilization.

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Ice Age past and the next century
65 million year record of CO$_2$

**Atmospheric CO$_2$**

(parts per million – note scale changes)

**Age (Ma)**

**CO$_2$ proxies**
- Red: Phytoplankton
- Blue: Boron
- Green: Stomata
- Yellow: Liverworts
- Black: Nahcolite
- Grey: Paleosols

**IPCC 2013 Fifth Assessment**
Earth temperature, last 65 million years

modified from Hansen & Sato 2011, data from Zachos et al. 2008
Earth temperature, last 65 million years

Modified from Hansen & Sato 2011, data from Zachos et al. 2008
Paleogeography
56 million years ago
The warm climate enigma

Warm poles
Dawn Redwood forest
Axel Heiberg Island, Canada

D. Greenwood photo
The warm climate enigma

Warm winters
palm leaf, Wyoming, USA

Field Museum
Earth temperature, last 65 million years

Paleocene-Eocene Thermal Maximum (PETM)

Global temp (°C > present)

Warm Climate “Enigma”

Millions of years ago

Antarctic Ice Sheets

Arctic Ice Sheets

modified from Hansen & Sato 2011, data from Zachos et al. 2008
Dissolution of deep ocean chalk

http://www.odp.tamu.edu/publications/208_IR/208ir.htm

Zachos et al (2005)
PETM carbon & temperature

δ¹³C from bulk carbonate ODP1266

Temperature from δ¹⁸O N. truempyi ODP1263

Murphy et al. 2010
Paleocene-Eocene Thermal Maximum (PETM)

- Global warming of 7 - 14 °F (4 - 8 °C)
- Dissolution of deep ocean chalk
- Carbon isotope ratio shifts ~5 parts per thousand
- Total duration of about 200,000 years

**CONCLUSION:** release of 4,000-7,000 billion tons of carbon (~present fossil fuel reservoir)
Potential carbon sources

- Methane Hydrates
- Wildfire
- Thermogenic Methane
- Permafrost
Paleocene-Eocene boundary sites

Paleogeography by C.R. Scotese, PALEOMAP Project
The Bighorn Basin
Bighorn Basin Fossil Plant Sites

Millions of Years Before Present

Cumulative # Fossil Plant Sites

Millions of Years Before Present

PETM Recovery
Floral Change during the PETM

Possible extinctions

Local Extirpations

Eocene

PETM-only immigrants

Recovery

PETM

Plant Species Time Ranges

Millions of Years Before Present

Possible extinctions

PETM-only immigrants

Recovery

PETM

Plant Species Time Ranges

Millions of Years Before Present
Possible Extinctions

*Davidia antiqua*
Dogwood family

*Browniea serrata*
Dogwood order
PETM-only, bean family

1.

2.

3.

4.

5.
Possible Extinctions

*Davidia antiqua*
Dogwood family

*Browniea serrata*
Dogwood order
PETM-only, bean family
Post-PETM Immigrants

Climbing fern

Linden family

Alder

Hickory family
Locally extirpated

- Sycamore
- Birch family
- Oak family
- Katsura tree
- Ginkgo
- Dawn redwood
- Sycamore
Floristic Change in Wyoming

1. PETM onset - local/regional EXTIRPATION of temperate deciduous plants (dawn redwood, birch, sycamore, katsura), and immigration of bean family and other dry tropical plants

2. PETM recovery - local/regional EXTIRPATION of bean family et al., return of “natives”, and intercontinental immigration of temperate plants

3. Minor EXTINCTION (~10%)
PETM – abundant insect damage
PETM faunal interchange

Hyracotherium - Perissodactyla

Diacodexis - Artiodactyla

Primates
Horse body size decrease during PETM

(Secord et al. 2012)
Four lessons from the PETM
1. A big release of carbon warmed global climate and dissolved deep marine chalk
2. There were probably self-reinforcing cycles – carbon release increased temperature, which in turn released more carbon.
3. The effects lasted about 200,000 years

Temperature (°C)

Stable Carbon Isotope Ratio

δ¹³C from bulk carbonate ODP1266

Temperature from δ¹⁸O N. truempyi ODP1263

Murphy et al. 2010
4. Rapid global warming changed where plants & animals lived, how they interacted, and drove rapid evolution
Flood basalts ~201 million years old
The Anthropocene
Annual carbon emissions
(from fossil fuels & cement)

Dept. of Energy
CO₂ Analysis Center
Cumulative carbon emission
(from fossil fuels & cement)

Billions of tons

Dept. of Energy
CO$_2$ Analysis Center
Carbon uptake is very slow

Ocean invasion
Land uptake

Ocean invasion

Reaction with CaCO₃

Billions of tons of carbon

Time (Years)

5,000 billion tons of carbon into atmosphere (the whole enchilada)

15-40% remains after 10,000 years

FAQ 6.2, Figure 2 illustrates the decay of a large excess amount of CO₂ (5000 PgC, or about 10 times the cumulative CO₂ emitted so far since the beginning of the industrial Era) emitted into the atmosphere, and how it is redistributed among land and the ocean over time. During the first 200 years, the ocean and land take up similar amounts of carbon. On longer time scales, the ocean uptake dominates mainly because of its larger reservoir size (~38,000 PgC) as compared to land (~4000 PgC) and atmosphere (589 PgC prior to the Industrial Era). Because of ocean chemistry the size of the initial input is important: higher emissions imply that a larger fraction of CO₂ will remain in the atmosphere. After 2000 years, the atmosphere will still contain between 15% and 40% of those initial CO₂ emissions. A further reduction by carbonate sediment dissolution, and reactions with igneous rocks, such as silicate weathering and sediment burial, will take anything from tens to hundreds of thousands of years, or even longer.

FAQ 6.2 (continued)

IPCC 2013 Fifth Assessment Chapter 6 after Archer et al. 2009
Surface Warming (°C)

Year (CE)

Carbon emissions ~7 billion tons/yr
Consumption increase ~2%/yr
Fossil fuel reservoir ~5,000 billion tons

Temperature stays high

Solomon et al. (2009) PNAS
Sea level +10ft – 2200 CE??

IPCC projection for 2100 is 1.5 to 3.5 ft

http://sealevel.climatecentral.org/surgingseas/
Sea level +25ft – 5000 CE???
(whoops! Greenland Ice Cap melted)
Over most of the ocean, gridded data products of carbonate system variables (Key et al., 2004) are used to correct each model for its present-day bias by subtracting the area-weighted averages over the Arctic Ocean (green), the tropical oceans (red) and the Southern Ocean (blue). (b) Maps of the median model's change in surface pH from 1850 to 2100. Panel (a) also includes mean model results from RCP2.6 (dashed lines).

The bias correction reduces the range of model projections by up to a factor of 4, e.g., in panel (a) compare the large range in the Arctic (with bias correction) to the smaller range in the Arctic Ocean (without bias correction). The bias correction reduces the range in the Arctic when atmospheric CO$_2$ is projected to reach 410 ppm, within a decade under the SRES A2 scenario, the volume of ocean with supersaturated calcite and aragonite saturation states is projected to decline from 42% in the preindustrial era to 25% in 2100 (Steinacher et al., 2009). Yet even if atmospheric CO$_2$ does not go above 450 ppm, most of the deep ocean volume is projected to become undersaturated with respect to both aragonite and calcite (Joos et al., 2011).

Although projected changes in pH are generally largest at the surface, the carbonate buffering capacity is lower (Orr, 2011). Then, aragonite undersaturation will become widespread in these regions at atmospheric CO$_2$ levels of 500–600 ppm (Figure 6.28).

Regional ocean carbon cycle models project that some nearshore systems (e.g., China Sea, coastal eutrophication, another anthropogenic perturbation) and model results show that strong seasonal upwelling of carbon-dioxide rich deep waters is projected to decline from 42% in the preindustrial era to 25% in 2100 (Steinacher et al., 2009; Yamamoto et al., 2012). The projected effect of local climate-change by reducing CO$_2$ solubility and thus by effects from increased freshwater input due to sea ice melt, more precipitation, and greater air–sea CO$_2$ fluxes due to less sea ice cover will result in reduced undersaturation of aragonite in the oceans and the spread of undersaturated conditions to more regions (Orr et al., 2005; Orr, 2011).

Future Ocean Oxygen Depletion

Future reduction in CO$_2$ solubility and increased ocean stratification will have implications for nutrient and carbon cycling, ocean productivity and marine habitats. This will be exacerbated by very likely significant increases in ocean energetic warming and decreased nutrient availability due to increased stratification as the ocean warms (Steinacher et al., 2009; Yamamoto et al., 2012). In the Northwestern European Shelf Seas, large spatio-temporal variability is enhanced by local effects from river input and increased ocean stratification with decreased nutrient availability. For example, East China Sea, an eastern boundary upwelling system, observations show that undersaturated conditions will be reached first in winter (Orr et al., 2005; Orr, 2011). Then, aragonite undersaturation will become widespread in these regions at atmospheric CO$_2$ levels of 500–600 ppm (Figure 6.28).

Future projections using ocean carbon cycle models indicate that limiting atmospheric CO$_2$ will reach 450 ppm, within 1–3 decades, which is about 100 ppm below the concentration that would have been attained under the preindustrial CO$_2$ emission rate. Thus, the invasion induced by the invasion of anthropogenic carbon (Orr et al., 2005; Orr, 2011) will not go above 450 ppm, most of the deep ocean volume is projected to become undersaturated with respect to both aragonite and calcite (Joos et al., 2011). Under the SRES A2 scenario, the volume of ocean with supersaturated calcite and aragonite saturation states is projected to decline from 42% in the preindustrial era to 25% in 2100 (Steinacher et al., 2009). Yet even if atmospheric CO$_2$ does not go above 450 ppm, most of the deep ocean volume is projected to become undersaturated with respect to both aragonite and calcite (Joos et al., 2011). Under the SRES A2 scenario, the volume of ocean with supersaturated calcite and aragonite saturation states is projected to decline from 42% in the preindustrial era to 25% in 2100 (Steinacher et al., 2009). Yet even if atmospheric CO$_2$ does not go above 450 ppm, most of the deep ocean volume is projected to become undersaturated with respect to both aragonite and calcite (Joos et al., 2011). Under the SRES A2 scenario, the volume of ocean with supersaturated calcite and aragonite saturation states is projected to decline from 42% in the preindustrial era to 25% in 2100 (Steinacher et al., 2009). Yet even if atmospheric CO$_2$ does not go above 450 ppm, most of the deep ocean volume is projected to become undersaturated with respect to both aragonite and calcite (Joos et al., 2011).
Other Signs we live in the Anthropocene
New Topography

Ami Vitale, National Geographic
Carbon and Other Biogeochemical Cycles

The most important processes causing an indirect link between anthropogenic Nr and climate change include: (1) formation of 

$\text{NO}_x$ and nitrate aerosols. 

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$\text{NO}_x$ and nitrate aerosols. 

Because of the nitrogen cascade, the creation of any molecule of Nr from N

...
EARTH'S LAND MAMMALS BY WEIGHT

- Humans
- Our Pets and Livestock
- Wild Animals

Data from Smil 2002 *The Earth’s Biosphere: Evolution, Dynamics and Change*, and others.


Anthropogenic Biomes of the World (v1)

Urban & dense settlement
- 11 Urban
- 12 Dense settlements

Villages
- 21 Rice
- 22 Irrigated
- 23 Cropped & pastoral
- 24 Pastoral
- 25 Rainfed
- 26 Rainfed mosaic

Croplands
- 31 Residential irrigated
- 32 Residential rainfed mosaic
- 33 Populated irrigated
- 34 Populated rainfed
- 35 Remote

Rangelands
- 41 Residential
- 42 Populated
- 43 Remote

Forested
- 51 Populated forests
- 52 Remote forests

Wildlands
- 61 Wild forests
- 62 Sparse trees
- 63 Barren

*Mosaic: >25% tree cover mixed with >25% pasture and/or cropland

Ellis & Ramankuty, 2008

40% Used Lands, 37% Novel Ecosystems, 23% Wild
## Biotic globalization

<table>
<thead>
<tr>
<th>Country/Region</th>
<th>Native species</th>
<th>Introduced species</th>
<th>Percent introduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Zealand (plants)</td>
<td>1,790</td>
<td>1,570</td>
<td>47</td>
</tr>
<tr>
<td>Hawaii (plants)</td>
<td>956</td>
<td>861</td>
<td>47</td>
</tr>
<tr>
<td>Hawaii (all species)</td>
<td>17,591</td>
<td>4465</td>
<td>20</td>
</tr>
<tr>
<td>Tristan de Cunha (plants)</td>
<td>70</td>
<td>97</td>
<td>58</td>
</tr>
<tr>
<td>Campbell Island (plants)</td>
<td>128</td>
<td>81</td>
<td>39</td>
</tr>
<tr>
<td>South Georgia (plants)</td>
<td>26</td>
<td>54</td>
<td>68</td>
</tr>
<tr>
<td>Southern Africa (FW fish)</td>
<td>176</td>
<td>52</td>
<td>23</td>
</tr>
<tr>
<td>California (FW fish)</td>
<td>83</td>
<td>50</td>
<td>38</td>
</tr>
<tr>
<td>US (plants)</td>
<td>22,000</td>
<td>5,000</td>
<td>19</td>
</tr>
</tbody>
</table>

Zebra mussel, 1988 CE
Photo by M. McCormick

Domestic cat, 8,000 BP

McNeely 2001
How Does the Anthropocene Perspective Help?
The state of the “discussion”

Message: Environmentalists value nature more than people

Message: Business values money more than people
The Anthropocene perspective

• The earth has always changed and we have already changed it. There never was a stable “state of nature.”

• We can discuss the severity, rate and scale of the change we are causing without being apocalyptic. The end is **NOT** near.

• We will always need to manage the planet. To do it well (from a human standpoint) we need to know more about the planet and ourselves.
Current Fossil Hall
Deep Time

- 31,000 sq ft exhibit space
- first total renovation of fossil halls at the Smithsonian since 1913
New Fossil Hall
The past is never dead. It isn’t even past.
William Faulkner
Requiem for a Nun

The past is all we know of the future.
Barbara Kingsolver
The Lacuna
compiled from the literature (100,000-year-and-less time bins) or from lists of extant, recently extinct, and Pleistocene species.

There is no apparent reason to believe that modern extinction rates differ from those of the Pleistocene and Holocene, despite the differences in terms of assessing whether modern means are higher. The Cenozoic data are for the entire million-year bin, then averaging those boundary-crossing counts to compute the empirically determined mean E/MSY for each time bin. Large coloured dots indicate taxa for which very few species (less than 3% for gastropods and bivalves) are known or assessed for each of the groups listed.

For a very few groups, modern assessments are close to adequate. For example, some 49% of bivalves went extinct in the Big Five mass extinctions. Extinctions of species with very low fossilization potential (such as those with very small geographic ranges and bats) were excluded from the counts (under-representation of bats as fossils is a problem prevails for gastropods, exacerbated because most modern molluscan species are marine). For these calculations, 'extinct' and 'extinct in the wild' species that had geographic ranges less than 500 km were excluded from the estimates of standing diversity.

Orange, documented historical extinctions averaged (from regional and global records). Brown triangles represent the 'normal' (non-anthropogenic) range of variance in extinction events. Orange, documented historical extinctions averaged (from regional and global records). Brown triangles represent the 'normal' (non-anthropogenic) range of variance in extinction events. Orange, documented historical extinctions averaged (from regional and global records). Brown triangles represent the 'normal' (non-anthropogenic) range of variance in extinction events.

Given that many clades are undersampled or unevenly sampled, attempts to enhance comparability of modern with fossil data by adjusting for inflation (because species perceived to be in peril are often assessed first). The percentage of species. White icons indicate species 'extinct' and 'extinct in the wild' species that had geographic ranges less than 500 km were excluded from the counts (under-representation of bats as fossils is a problem prevails for gastropods, exacerbated because most modern molluscan species are marine). For these calculations, 'extinct' and 'extinct in the wild' species that had geographic ranges less than 500 km were excluded from the estimates of standing diversity.

Extinction magnitude (percentage of species)
New Fossil Hall
Figure SPM.7 | CMIP5 multi-model simulated time series from 1950 to 2100 for (a) change in global annual mean surface temperature relative to 1986–2005, (b) Northern Hemisphere September sea ice extent (5-year running mean), and (c) global mean ocean surface pH. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as colored vertical bars. The numbers of CMIP5 models used to calculate the multi-model mean is indicated. For sea ice extent (b), the projected mean and uncertainty (minimum-maximum range) of the subset of models that most closely reproduce the climatological mean state and 1979 to 2012 trend of the Arctic sea ice is given (number of models given in brackets). For completeness, the CMIP5 multi-model mean is also indicated with dotted lines. The dashed line represents nearly ice-free conditions (i.e., when sea ice extent is less than 10^6 km^2 for at least five consecutive years). For further technical details see the Technical Summary Supplementary Material {Figures 6.28, 12.5, and 12.28–12.31; Figures TS.15, TS.17, and TS.20}.
When calibrated appropriately, recently improved dynamical ice sheet models can reproduce the observed rapid changes in ice sheet outflow for individual glacier systems (e.g., Pine Island Glacier in Antarctica; medium confidence). However, models of ice sheet response to global warming and particularly ice sheet–ocean interactions are incomplete and the omission of ice sheet models, especially of dynamics, from the model budget of the past means that they have not been as critically evaluated as other contributions {13.3, 13.4}.

GMSL rise for 2081–2100 (relative to 1986–2005) for the Representative Concentration Pathways (RCPs) will likely be in the 5 to 95% ranges derived from Coupled Model Intercomparison Project Phase 5 (CMIP5) climate projections in combination with process-based models of other contributions (medium confidence), that is, 0.26 to 0.55 m (RCP2.6), 0.32 to 0.63 m (RCP4.5), 0.33 to 0.63 m (RCP6.0), 0.45 to 0.82 (RCP8.5) m (see Table TS.1 and Figure TS.15 for RCP forcing). For RCP8.5 the range at 2100 is 0.52 to 0.98 m. Confidence in the projected likely ranges comes from the consistency of process-based models with observations and physical understanding. It is assessed that there is currently insufficient evidence to evaluate the probability of specific levels above the likely range. Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause GMSL to rise substantially above the likely range during the 21st century. There is a lack of consensus on the probability for such a collapse, and the potential additional contribution to GMSL rise cannot be precisely quantified, but there is medium confidence that it would not exceed several tenths of a metre of sea level rise during the 21st century. It is virtually certain that GMSL rise will continue beyond 2100. {13.5.1, 13.5.3}

Many semi-empirical models projections of GMSL rise are higher than process-based model projections, but there is no consensus in the scientific community about their reliability and there is thus low confidence in their projections. {13.5.2, 13.5.3}

TFE.2, Figure 2 combines the paleo, tide gauge and altimeter observations of sea level rise from 1700 with the projected GMSL change to 2100. {13.5, 13.7, 13.8}
Figure 6.3 | Atmospheric concentration of $\text{CO}_2$, oxygen, $^{13}\text{C}/^{12}\text{C}$ stable isotope ratio in $\text{CO}_2$, $\text{CH}_4$ and $\text{N}_2\text{O}$ recorded over the last decades at representative stations (a) $\text{CO}_2$ from Mauna Loa (MLO) Northern Hemisphere and South Pole Southern Hemisphere (SPO) atmospheric stations (Keeling et al., 2005). (b) $\text{O}_2$ from Alert Northern Hemisphere (ALT) and Cape Grim Southern Hemisphere (CGO) stations (http://scrippso2.ucsd.edu/ right axes, expressed relative to a reference standard value). (c) $^{13}\text{C}/^{12}\text{C}$: Mauna Loa, South Pole (Keeling et al., 2005). (d) $\text{CH}_4$ from Mauna Loa and South Pole stations (Dlugokencky et al., 2012). (e) $\text{N}_2\text{O}$ from Mace-Head Northern Hemisphere (MHD) and Cape Grim stations (Prinn et al., 2000).
Long-term Climate Change: Projections, Commitments and Irreversibility

Models show a weaker warming or slight cooling in the North Atlantic as a result of the reduction in deepwater formation. The magnitude of Arctic amplification, for instance, varies among different models, and a subset of models show Arctic warming of 12°C in the RCP8.5 scenario. But the full ensemble shows Arctic warming of only 9°C. Models agree on large-scale patterns of warming at the surface, with an increase in the mean temperature of 2°C by 2100 for high emission scenario RCP8.5, and 1°C for low emission scenario RCP2.6. Note that results are given both relative to 1980–1999 (left scale) and relative to pre-industrial (right scale). Yellow ranges indicate results for the four Representative Concentration Pathway (RCP) scenarios: RCP2.6 (dark blue), RCP4.5 (light blue), RCP6.0 (orange) and RCP8.5 (red); 32, 42, 25 and 39°C change for high and low emission scenarios respectively. Note that results are given both relative to 1980–1999 (left scale) and relative to pre-industrial (right scale). Yellow ranges indicate results for the four Representative Concentration Pathway (RCP) scenarios: RCP2.6 (dark blue), RCP4.5 (light blue), RCP6.0 (orange) and RCP8.5 (red); 32, 42, 25 and 39°C change for high and low emission scenarios respectively. Note that results are given both relative to 1980–1999 (left scale) and relative to pre-industrial (right scale). Yellow ranges indicate results for the four Representative Concentration Pathway (RCP) scenarios: RCP2.6 (dark blue), RCP4.5 (light blue), RCP6.0 (orange) and RCP8.5 (red); 32, 42, 25 and 39°C change for high and low emission scenarios respectively.