Milestones in the evolution of the atmosphere with reference to climate change and mass extinctions

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- Climate forcing factors and atmospheric states
- Atmospheric states with time, emergence and the evolution of life
- Long term climate trends
- Episodic mass extinctions
MARS (D 6796 km)
-113°C to 0°C;
thin atmosphere
0.01 Bar at surface;
CO₂ 95.3%;
O₂ 0.13% of O₂ on Earth

VENUS (D 12 100 km)
>450°C
90 Bar at surface;
CO₂ & sulphuric acid

EARTH (D 12,756 km)
mean T +18°C (-50 to +55°C)
(without the greenhouse effect mean T -14°C);
1 bar; N 79%, O₂ 20%
CO₂ ~250-300 ppm
2006: ~381 ppm CO₂

6CO₂ + 6H₂O → C₆H₁₂O₆ + 6O₂
LUNGS OF THE EARTH

- Troposphere: 0-18 km
- Stratosphere: 18-50 km
- Mesosphere: 50-350 km
- Ionosphere: Above 350 km

- Tropopause: 14 km
- Stratosphere Ozone Layer: 90 km

Earth's atmosphere and its analogy to human lungs.
“Paleoclimate data show that the Earth’s climate is remarkably sensitive to global forcing. Positive feedbacks predominate. This allows the entire planet to be whipsawed between climate states. A climate forcing that ‘flips’ the albedo of a sufficient portion of an ice sheet can spark a cataclysm.”
Hansen et al., 2007 (J. Royal Society)
**ORBITAL FORCING**

- **Eccentricity**: Circular, elliptic, parabolic or hyperbolic trajectories.
- **Precession**: Change in the direction of the Earth's axis of rotation relative to the Sun at the time of perihelion and aphelion.
- **Obliquity**: Earth axial tilt relative to the ecliptic plane

The maximum global mean forcing since 1750 due to orbital variations = about 0.25 Watt/m²
(Hansen et al., 2007, Roy. Soc. London)
CLIMATE SENSITIVITY AND AEROSOL EFFECTS

![Graph showing temperature change and atmospheric CO2 by 2100 vs. climate sensitivity.](image)

- **Temperature Change by 2100**: The graph plots temperature change by 2100 against climate sensitivity. Different lines represent various scenarios (A1FI, B2, A2, B1).
- **Atmospheric CO2 by 2100**: The second graph shows atmospheric CO2 levels by 2100 in response to climate sensitivity. Again, different lines correspond to different scenarios.

**Present-Day Aerosol Forcing**:

- **Present-Day Aerosol Forcing w/m²**: The graph on the right illustrates the present-day aerosol forcing, with lines showing the impact on climate sensitivity.
PLANTS
Production of oxygen
- Regulation of carbon dioxide
- Accumulation of methane, pit and coal
- Regulation of ground water level
- Regulation of local temperatures and rainfall
- Extensive fires — tinderbox Earth

ANIMALS
- Absorption of oxygen
- Emission of CO2 and CH4

ANTHROPOGENIC
- Absorption of oxygen
- Emission of CO2
- Extra-emission of CO2
THE GREENHOUSE EFFECT (natural balance)  
(Radiative forcing units Watt/m²)

Earth surface with no greenhouse effect: mean T -18°C  
Earth surface - greenhouse effect: mean T +14°C 

Solar radiation at the top of the atmosphere 342 W/m²

Reflection from the top of the atmosphere 77 W/m²

Atmospheric Absorption 67 W/m²

Reaching the Earth Surface 168 W/m²

Reflection (albedo) from the Earth surface 30 W/m²

155 W/m² Re-emitted toward the Earth surface by greenhouse gases

235 W/m²

IR radiation Emitted from the Earth surface 390 W/m²

Greenhouse Effect/Climate Sensitivity
Doubling of CO₂ ~2 to ~4°C since 1750, i.e.+280 ppm for +3°C  
1 pm CO₂ → 0.0107°C  
100 ppm → ~1.0°C 

H₂O, CO₂, CH₄, N-oxides

1 Watt/m² = 0.75°C
EXTREME ATMOSPHERIC STATES: GREENHOUSE WORLD

LOWER CRETACEOUS
110 – 90 Ma >1000 ppm CO₂; ~7°C warmer than at present

Deep ocean basins (dark blue) and shallow inland seas (light blue) are shown in this view of the Earth 110 million years ago (Cretaceous Period). Note the opening of the central Atlantic Ocean caused by rifting between North America (upper left) and Africa (lower right). Image by Ron Blakey, Northern Arizona University.
EXTREME ATMOSPHERIC STATES: SNOWBALL EARTH
(Cryogenian 850-630 Ma)

Climate Change Fact Sheet
Compiled by Prof. Stefan Rahmstorf
Potsdam Institute for Climate Impact Research
(www.pik-potsdam.de/~stefan)

SEA LEVEL CHANGES BETWEEN EXTREME CLIMATE STATES
SEA LEVEL AMPLITUDE > 200 METRES

GLOBAL MEAN TEMPERATURES (°C)

EARLY STAGE SEA LEVEL RISE?

~4 to 18 metre/1°C

~22 metre/1°C

Last Glacial Maximum 20 kyr

Pliocene ~3 Ma

Eocene ~40 Ma

Today

< 1 metre 2100 IPCC projection

< 1 metre 2100 IPCC projection
EXTRATERRESTRIAL FORCING AND ENDOGENIC RESPONSES
EPISODIC EXTRATERRESTRIAL IMPACT AND ENDOGENIC VOLCANIC FORCING

“Late Cretaceous/Early Tertiary background CO2 levels of 350-500 ppm by volume, with a marked increase to at least 2,300 ppm by volume within 10,000 years of the KTB impact, due to instantaneous transfer of approximately 4,600 GtC to the atmospheric reservoir by a large extraterrestrial bolide impact. A resultant climatic forcing of +12 W/m² would have been sufficient to warm the Earth’s Surface by approximately 7.5 degrees C, in the absence of counter forcing by sulfate aerosols. Beerling et al., 2002, PNAS, 99, 7836-7840

305 GtC EMITTED SINCE 1750

TOTAL ESTIMATED FOSSIL CARBON RESERVES
~ 4000 GtC
Atmospheric states with time, emergence and the evolution of life
Milestones in terrestrial evolution

- Bipedalism: ~5 my – last 1 minute 35 seconds
- Stone tools: ~3 my – last minute
- Fire: ~700,000 yr – last 13 seconds
- Burial: ~100,000 yr – last 2 seconds
- Neolithic: ~12,000 yr – last 0.24 seconds

48% KT extinction (Dinosaurs)

78% PT extinction

ASTEROID/COMET IMPACTS
VOLCANIC ACTIVITY
GLACIATION
RED BEDS
BANDED IRONSTONES
BIOGENIC EVENTS
MASS
THE EARLY ATMOSPHERE

- Low solar luminosity (-70-80%), compensated by super-greenhouse effect (due to high CH₄, H₂O, CO₂, CO, H₂S, polymerized hydrocarbons)
- Evidence of low O₂ from unoxidized pyrite & uraninite in sediments and abundance of ferrous iron – forming banded iron formations.
- Some oxygen available (according to S isotope studies).
- High temperatures of the hydrosphere, due to high geothermal gradients and greenhouse effects.
- CO₂ supplied by volcanic activity, but low sequestration due to high water temperatures (evidenced by scarcity of carbonates pre-2.7 Ga) and limited erosion due to low continent/ocean ratio.
- Anoxic, reducing, sulphur-rich oceans constrained biological evolution of all but the most primitive single-cell prokaryotes lacking in nucleus, including methanogenic bacteria and cyanobacteria (forming stromatolites).
Model of ancient stratified ocean with cyanobacteria colonizing surface mixed layer, above layer of anoxygenic photoautotrophic Fe(II)-oxidizing bacteria, with a hydrothermal source of Fe(II) underneath (Holland, 1973; Morris, 1993). Question mark and double arrow point to thickness of layer of anoxygenic phototrophs supported by Fe(II) input. After Kappler et al., Geology, 2005

\[
6\text{Fe}^{+2} + 0.5\text{O}_2 + \text{CO}_2 + 16\text{H}_2\text{O} \rightarrow [\text{CH}_2\text{O}] + 6\text{Fe(OH)}_3 + 12\text{H}
\]
MILESTONES IN THE EVOLUTION OF LIFE FORMS

- Banded ironstones / possible bacterial deposits Oldest – 3.85 B.Y.
- Ediacara 0.6 B.Y.
- 2.73 B.Y. stromatolites
- 3.42 B.Y. stromatolites
- 3.49 B.Y. stromatolites
- 3.47 B.Y. Apex microfossils
- 2.73 B.Y. stromatolites
- 2.1 Ga
- 1.5 Ga Mitosis
- OXYGEN ENRICHMENT
- 0.54 Ga Multicellular Animals; calcareous shells

- Sulphur-rich oceans
- CO2-rich reducing atmosphere (detrital sulphide, uranitrite, sulphur isotopes)
- Soluble ferrous oxide
- 1.5 Ga Mitosis
- 0.54 Ga Multicellular Animals; calcareous shells
- 2.1 Ga
Stromatolites: past and present

A. 2.63 Ga giant stromatolite, Carawine Dolomite Pilbara, Western Australia.
B. Shark Bay stromatolites.
THE “CAMBRIAN EXPLOSION”

- Trilobite
- Microscopic sponges
- Halkiera: mid-Cambrian
- Molusc-like fossil 555 Ma
- DickinsoniaCostata: Ediacaran
- Opabinia BW

Increase in oxygen was needed to produce the protein collagen, connective tissue required to form complex animals.

Antrim Basalt: Mass extinction 513±12 Ma
Long term climate trends
GREENHOUSE EARTH DESCENT INTO GLACIAL/INTERGLACIAL

OCEAN GAP/SPREADING/ VOLCANISM/CO2 RELEASE

Dense vegetation/ CO2 sequestration

Low atm CO2

ONSET OF LAND PLANTS

PRESENT

Oceans too warm To sequester CO2

Warm

Cold

AGE (Ma)
(variable scale)

Low pH; high CH₄ & H₂S

O₂
CO2 FORCING OF ATMOSPHERIC TEMPERATURES

![Graph showing atmospheric CO2 levels and continental glaciation over time.]

- **A**: Graph of atmospheric CO2 levels (in ppm) over time (Ma), with red line representing GEOCARB III and black line representing proxles.
- **B**: Bar chart of continental glaciation (° paleolatitude) over time, with labels PT, LT, and KT indicating specific time periods.
- **C**: Additional bars indicating the extent of continental glaciation at different time intervals.
CO2 relative to (pre-industrial levels) 230 ppm

CO2 LEVELS THROUGH TIME RELATIVE TO PRE-INDUSTRIAL AGE LEVELS

Advent of land plants – CO2-ABSORPTION
Amphibians / Lizards (cold blooded)
Dinosaurs (warm blooded)

Mammals proliferate

Time (Million years)

Dana L. Royer, 2002
OXYGEN LEVELS AND BIOLOGICAL EVOLUTION

STOMATA (CO₂ capture perforation)

% of O₂ in the atmosphere

Time (million years)

1. Low-O₂ / fast fish
2. Biological diversification
3. Proliferation of arthropods and fish
4. Coal formation / gigantism (reptiles and arthropods)
5. Novel air section organs in dinosaurs / birds
6. Increased mammalian size

EVENTS:
- END-CAMBRIAN EXTINCTIONS
- APPEARANCE OF LAND PLANTS AND ANTHROPODS
- LATE DEVONIAN EXTINCTIONS
- CARBONIFEROUS-PERMIAN GLACIATION (caused in part by plant absorption of CO₂)
- PERMIAN-TRIASSIC EXTINCTION
- TRIASSIC-JURASSIC EXTINCTION
- QUARTERNARY GLACIATION

CHANGES:
- ASTEROID IMPACT
- VOLCANISM
Episodic mass extinctions
### Correlations Between Impacts, Volcanism and Mass Extinctions

<table>
<thead>
<tr>
<th>Time</th>
<th>Impact/Geological Episodes</th>
<th>Extinctions/Radiations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paleocene-Eocene boundary (35 Ma);</td>
<td>Eruption of methane associated with volcanic effects on C-rich sediments.</td>
<td>Extinction of Plesiapidae, Champsosaurus, Appearance of primates.</td>
</tr>
<tr>
<td>Cretaceous-Tertiary boundary (65.5±0.3 Ma)</td>
<td>Chicxulub and Boltysh impacts, affecting C-rich and carbonate-rich sediments; Decan Plateau basalts;</td>
<td>Extinction 47% of Genera, including plankton, marine invertebrates (including reef builders), marine reptiles, dinosaurs.</td>
</tr>
<tr>
<td>Jurassic-Cretaceous boundary (145.5±4 Ma)</td>
<td>Morokweng, Gosses Bluff, Mjoelir impacts, dyke systems, ocean spreading;</td>
<td>Flowering plants become dominant on land.</td>
</tr>
<tr>
<td>End-Permian (251.7±0.4 to 251.1±0.3 Ma)</td>
<td>peak Karoo volcanism;</td>
<td>Extinction of early birds.</td>
</tr>
<tr>
<td>End-Triassic (~201 Ma) Late Triassic (Norian-Rhaetian) (216.5 Ma)</td>
<td>opening of the Atlantic Ocean; Manicouagan [214±1 Ma], Saint Martin [220±32 Ma], Rochechouart [213±8 Ma];</td>
<td>Extinction of 33% of Genera, including marine invertebrates and reptiles.</td>
</tr>
<tr>
<td>Permian-Triassic boundary</td>
<td>Siberian Norilsk plateau basalts; Araguainha impact 252.7±3.5 Ma, affecting C and carbonate-rich sediments;</td>
<td>Extinction of 78% of Genera, including sea floor protozoans, marine invertebrates, reef builders, reptiles.</td>
</tr>
<tr>
<td>End-Devonian (374–359 Ma)</td>
<td>Woodleigh [359±4 Ma], Siljan [361.1 Ma], Alamo [360 Ma] impacts;</td>
<td>Vertebrates invade land</td>
</tr>
<tr>
<td>Late Devonian (Frasnian-Famennian) (383 Ma)</td>
<td></td>
<td>Extinction of 30% of Genera.</td>
</tr>
<tr>
<td>Late Ordovician (443.7±1.5 Ma)</td>
<td>Impact cluster (K-Ar gas retention or shock ages of about 450–500 Myr)</td>
<td>Extinction of 60% of Genera, including trilobites. Cause unknown (supernovae?)</td>
</tr>
<tr>
<td>End-Cambrian (488 Ma)</td>
<td></td>
<td>Earliest fish evolve</td>
</tr>
<tr>
<td>End-lower Cambrian (513±2 Ma)</td>
<td>Kalkarini volcanism, 507±4 Ma;</td>
<td>Extinction of 42% of Genera.</td>
</tr>
<tr>
<td>580 Ma</td>
<td>Acraman impact.</td>
<td>Extinction and radiation of acrystarchs species.</td>
</tr>
</tbody>
</table>

- **Asteroid impact**
- **Volcanism**
- **Methane eruption**

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Schmidt, B. et al., 2008. Asteroid breakup linked to the great Ordovician diversification event. *Nature Geoscience* 1, 49-53
Munta 1

Acraman ejecta layer

Grey et al., 2003
Araguinha impact 252.7±3.8 Ma
CO2 RISE AND REDUCED BURIAL OF ORGANIC MATTER AT THE PERMIAN-TRIASSIC BOUNDARY

RCO$_2$ - ratio of CO2 mass in the atmosphere to that at present (Pleistocene mean 250 ppm).
Fbg - burial rate of organic matter in $10^{18}$ moles/ million years.
End Triassic Extinctions in Continental Tetrapod families and Marine Groups

Volcanism & Impacts

- MAMMALIA
- AMPHIBIA
- REPTILIA

Central Atlantic
200-202 Ma

Manicouagan
214±1 Ma

Reef Organisms

Saint Martin
220±32 Ma

Rochechouart
214±8 Ma

23 km

100 km
Carbon isotopic evidence of mass extinctions across geological boundaries

P. Ward, 2007
METHANE ERUPTION:
Paleocene-Eocene thermal maximum (PETM) 55 Ma

The descent into Quaternary ice ages
Global deep ocean $\delta^{18}O$ values and temperatures with time

Age resolution +/- 0.5 m.y.

Paleocene-Eocene Thermal maximum

Oligocene glaciation

Chicxulub Popigai, Chesapeake Bay Youngest dryas?

HIGH SEA LEVELS

LOW SEA LEVELS

(Hansen et al., 2008)
QUATERNARY CRISIS

~3 Ma Mid-Pliocene Thermal (+20°C to +30°C) and SL (25+/−10 m) rise

~0.7 Ma Discovery of fire by Homo

TER-0, Ters-I, II, III, III

Fire-enhanced peaks?

Australopithacus

Homo Erectus

~0.7 Ma Discovery of fire by Homo

Five Million Years of Climate Change From Sediment Cores
MID-PLIOCOENE ~3 Ma TEMPERATURE ANOMALIES
(R. Chandler, 1997 NASA Goddard Institute of Space Science)
THE MID-PLIOCENE ANALOGY OF CURRENT CLIMATE CHANGE

Images based on Global Gridded Pliocene and Late Quaternary Sea Level,
U.S. Geological Survey Open-File Report 96-000,
Peter N. Schweitzer and Robert S. Thompson.
http://chemistry.beloit.edu/Warming/sealevel/index.html
“The salient feature of terrestrial climate change is its asymmetry. Global Warming events are usually rapid, followed by slower descent into colder climate. Given the slow pace of the weak orbital forcings and the magnitude of glacial-to interglacial climate change, the cause of rapid warming at glacial “terminations” must lie in a climate feedback” (Hansen et al., 2007. Roy. Soc. London)
Estimates of sea levels during Termination-II 135-110 kyr (Siddall et al., 2006) and temperatures from the Vostok ice core (Petit et al., 1999)
Dansgaard-Oeschger warming events

Fig. 1. The climate history of the last great ice age—reconstructed from Greenland ice cores. The figure shows a reconstruction of the temperature of the last 90,000 years based on measurements of oxygen isotopes 18O in the ice. The stable interglacial period of the last 10,000 years is the Holocene; the unstable cold period preceding it is the second half of the last great ice age. Dansgaard-Oeschger events refer to the text for an explanation. They are marked in red and numbered. The vertical lines are spaced at intervals of 3,000 years; the majority of D/O events are located near each line.

Fig. 2. Schematic illustration of three possible circulation modes in the Atlantic during the last ice age. The middle mode is the stable, cold mode prevailing in the ice age, with warm Atlantic water only flowing as far as the mid-latitudes. The situation during a warm Dansgaard-Oeschger event (D/O) with warm Atlantic water flowing right up to the Nordic Seas is shown below. The red contour lines represent the temperature rise in degrees centigrade during each event, as calculated in our model. The globe at the top shows the situation following a total cessation of circulation in the Atlantic, as occurred after Heinrich (H) events.

This graph shows the characteristic temperature evolution of a number of Dansgaard-Oeschger events derived from Greenland ice core data (coloured lines) and a model simulation (black line). An abrupt rise in temperature can clearly be seen at the beginning of each event. It is followed by a plateau phase with a warm temperature and a slight downward trend in the model, due to the gradual weakening of the warm ocean current. In the third phase, the temperature drops relatively quickly back to the cold original level. In the model, this occurs when the current abruptly ceases to flow into the Nordic Seas.
North Atlantic Heinrich events, ice melt and sea level rises (Salzman, 2002)

Fig. 4: Ice cover on the North American continent

Source: Potsdam Institute for Climate Impact Research

% lithics (glacial debris)

Heinrich glacial debris deposits
North Atlantic ocean

Sea Level change (cm/year)

Heinrich glacial debris deposits
Older dryas
Younger dryas

Discharge (km³/year)

0.5
0.4
0.3
0.2
0.1
0
20 18 16 14 12 10 8 6 4 2 0 kyr

20 18 16 14 12 10 8 6 4 2 0 kyr

70 60 50 40 30 20 10 Kyr
ABRUPT CLIMATE CHANGE

For the best-characterized warming, the end of the Younger Dryas cold interval 11,500 years ago, the transition in many ice-core variables was achieved in three steps, each spanning 5 years and in total covering 40 years. However, most of the change occurred in the middle of these steps. The warming as recorded in gas isotopes occurred in decades or less (Alley, 2000, PNAS, 97, 1331-1334).

![Graph showing temperature, accumulation, and sea level changes over time.](image-url)
END-GLACIAL (termination-I) SEA LEVEL RISE

Sea level rise rates:
- +0.35 cm/year
- 2.8 cm/year
- +1.7 cm/year
- 20-40-60-80-100-120 KYR BP
- Sea level (metres) relative to mean 0-7000 yrs

Ice core temperatures (Alley, 2000)

Siddall et al., 2003
ANTHROPOGENIC FORCING
Atmospheric CO₂ levels last 450,000 years

- Last 450,000 years: Vostok ice core record (blue)
- Last 100 years: Contemporary record (red)
- Next 100 years: IS92A scenario (red)
"Sea surface temperatures within 1°C of the warmest interglacial periods over the past million years."

James Hansen (NASA’s chief climate scientist, 2007)
COMBINED TEMPERATURE EFFECTS OF GREENHOUSE EMISSIONS AND THE SOLAR SPOT CYCLE

- 2000-2005 +0.15°C
- ~1980-2000 +0.4°C
- Sunspot cycle (+/-1.5 W/m²)

Total solar irradiance $\text{W/m}^2$

1371
1370
1369
1368
1367
1366


Monthly Land-Ocean temperature anomaly (NASA GISS)

Total solar irradiance

+0.56°C since 1975
CLIMATE TIPPING POINTS

Fig. 4. Temporal development of the energy of tropical storms (Power Dissipation Index – PDI, red) and the average sea-surface temperature in the tropical Atlantic from August to October (blue). For comparison the evolution of the globally averaged near-surface air temperature is shown (dashed grey line). Source: after Emanuel, 2005
Earth System moves to a new state; modern civilization collapses.

Feedbacks push climate change higher; abrupt changes much more likely; massive impacts to humans.

- Loss of Greenland ice sheet = 6.4 metre sea level rise
- Large biodiversity loss; coral reefs disappear

"Committed" Climate Change
The life force

Nanobes
Courtesy: P.J.R. Uwins

1.0 micron