Climate Change - Geological Perspective at Stockholms Universitet

Tomek Garbus

Spring 2025

1 Reading assignment: Earth's Climate Chapter 4

1.1 Key terms

Greenouse era: times when no ice sheets are present

Icehouse era: tmes when ice sheets are present

Faint young Sun paradox: the mystery why the Earth's climate has remained relatively stable throughout most of the planet's history, even though the Sun shone 25% to 30% more faintly 4.55 Byr than today.

Thermostat: thermostat's role is to mitigate extreme temperature by reacting to hot temperature with cooling down the system (e.g. house) and to cold by heating up. We don't know what the Earth's thermostat was through the history, recompensating for the faint young Sun. Candidates include chemical weathering and life.

Silicate materials: examples include quartz and feldspar. Silicate materials typically are made of positively charged cations (Na^{+1}, K^{+1}, Fe^{+2}, Mg^{+2}, Al^{+3} and Ca^{+2}) that are chemically bonded to negatively charged SiO_4 (silicate) structures.

Chemical weathering feedback: chemical weathering creates a negative feedback in the climate. Since chemical weathering is strongly correlated to temperature and precipitation, we can distinguish two causal chains:

- initial change → warmer climate → increased temperature, precipitation, vegetation → increased chemical weathering → increased CO_2 removal by weathering → reduction of initial warming
- initial chage → colder climate → decreased temperature, precipitation, vegetation → decreased chemical weathering → decreased CO_2 removal by weathering → reduction of initial cooling

Gaia hypothesis: in its weakest and commonly accepted form, it states that as life-forms gradually developed in complexity, they played a progressively greater role in chemical weathering and its control of Earth's climate. In its most extreme version, it states that life evolved for the purpose of regulating Earth's climate.

Snowball Earth hypothesis: the hypothesis that Earth was once nearly frozen, around 715 to 640 million years ago. Climate scientists have found evidence that glaciers existed on several continents during that time. Some believe these continents were located in the tropics then, but its hard to locate them back in time.

1.2 Review questions

1.2.1 Why is Venus so much warmer than Earth today?

Its atmosphere has 96% CO_2 (compared to Earth's 0.2%), creating a much stronger greenhouse effect, trapping much more heat.

1.2.2 What factors explain why Earth is habitable today?

Small greenhouse effect adding only 32°C to average temperature in Earth's atmosphere.

1.2.3 Why does the faint young Sun pose a paradox?

Astrophysical models of the Sun's evolution indicate it was 25% to 30% weaker early in Earth's history. Climate model simulations show that the weaker sun would have resulted in a completely frozen Earth for more than half of its early history if the atmosphere had the same composition as it does today.

Primitive life forms date back to at least 3.5 Byr ago, and their presence on Earth is incompatible wit a completely frozen planet at that time.

1.2.4 What evidence suggests that Earth has always had a long term thermostat regulating its climate?

The faint young Sun paradox, the specific evidence being prevalence of water-deposited sedimentary rocks throughout Earth's early history.

1.2.5 Why is volcanic input of CO_2 to Earth's atmosphere not a candidate for its thermostat?

Volcanic processes are diven by the heat sources located deep in the Earth's interior and are well removed from contact with (and reactions to) climate system.

1.2.6 What climate factors affect the removal of CO_2 from the atmosphere by chemical weathering?

Temperature: weathering rates roughly doubl for each 10°C increase in temperature.

Precipitation: increased rainfall boosts the level of groundwater held in soils, and the water combines with CO_2 to form carbonic acid and enhance the weathering process.

Vegetation: plants extract CO_2 from the atmosphere through photosynthesis, and deliver it to soils, where it combines with groundwater to form carbonic acid. It enhances the rate of chemical breakdown of minerals. Presence of vegetation is estimated to increase the rate of chemical weathering by a factor of 2 to 10.

1.2.7 Where did the extra CO_2 from Earth's early atmosphere go?

Sediments and rocks.

1.2.8 What arguments support and oppose the Gaia hypothesis that life is Earth's true thermostat?

Critics say that too many of the active roles played by organisms in the biosphere today are relatively recent developments in Earth's history. The also point out that the very late appearance of shell-bearing oceanic organisms near 540 million years ago means that life had played no obious role in transferring the products of chemical weathering on land to the seafloor for the preceeding 4 Byr.

Supporters claim that critics underestimate the role of primitve life-forms such as algae in the ocan and microbes on land in Earth's earlier history.

Marine organisms that created oxygen through photosynthesis long ago are believed to have enabled the development of oxygen-rich atmosphere 2.4 Byr.

2 Lecture 1: The controls of climate on geological timescales

Time imbalance: Coal takes hundreds of millions of years to accumulate from fossils, but takes decades of burning to release. Accumulation happens on **geological** timescale and release at **antropogenic** timescale.

Average Earth surface temperature is around 15°C.

2.1 Climate factors

Earth absorbs sunlight and radiates heat energy back into space. These 3 factors control the process:

- solar radiation
- albedo effect
- greenhouse effect

Solar radiation

Some prerequisites for calculations:

Stefan-Boltzmann law describes the intensity of the thermal radiation emitted by atter in terms of tat matter's temperature. Formula is $E = \sigma T^4$, where $\sigma = 5.670367 \times 10^{-8} W.m^{-2}.K^{-4}$

Solar radiation constant, in other words, the amount of energy emitted by the Sun is $3.87 \times 10^{26} W$[1].

Solar constant S_0 describes the amount of energy received by a given area one astronomical unit[2] away from the Sun. Let's calculate it:

$d_{Earth} = 149,597,870,700m$

Solar constant $S_0 = \frac{Q}{4\pi d^2} = 1362W.m^{-2}$. Since Earth is not flat, but is a rotating sphere, this number is divided by 4, so the effective energy received from Solar radiation is $342W.m^{-2}$.

Now from Stefan-Boltzmann's law, we can calculate the temperature:
$E = \sigma T^4$
$E = 342W.m^{-2}$
$T = (E.\sigma^{-1})^{1/4} = 6°$

Now let's compare with values for Venus:
$d_{Venus} = 108 \times 10^9 m$
$E_{Venus} = 658W.m^{-2}$
$T_{Venus} = -55°$

Albedo

Black seat: low albedo, white cat: high albedo

Venus has albedo effecto of $\alpha = 77\%$
Earth has albedo effecto of $\alpha = 30\%$

Of course, Earth's albedo is much harder to calculate because the terrain varies a lot, compared to Venus which has a relatively uniform surface.

Venus radiates back to space $658W.m^{-2} \cdot 77\% = 504W.m^{-2}$. Earth radiates back to space $342.m^{-2} \cdot 30\% = 103.m^{-2}$.

Taking into account albedo effect, Venus' surface temperature should be $-46°$ and Earth's $-18°$.

Greenhouse effect

Earth: greenhouse effect increases temperature by 32°.

Let's calculate how much the temperature increased due to greenhouse effect since the preindustrial era, knowing that CO_2's content in atmosphere increased from 285ppm to 425ppm.

$\Delta T = 4.38 \ln \frac{CO_{2\text{present day}}}{CO_{2\text{preindustrial}}} = 4.38 \ln \frac{425\text{ppm}}{285\text{ppm}} = 1.75°$

2.2 Earth's temperature summary

$$\underbrace{6°}_{\text{Solar radiation}} + \underbrace{-24°}_{\text{Albedo}} + \underbrace{32°}_{\text{Greenhouse cases}}$$

2.3 Faint Young Sun paradox

We have fossils from 3.5 Byr ago. Earliest fossils are stromatolites[3].

Assuming the same percentage of CO_2 in the atmosphere, the average temperature on Earth at that time (3.5 Byr ago) should have been around 0° (due to lower solar radiation), meaning no running water, which precludes the possibility of life.

2.4 Source of CO_2 on geological timescales

Volcanoes

[1] When an object's velocity is held constant at one meter per second against a constant opposing force of one newton, the rate at which work is done is one watt: $1W = qkg \cdot m^2 \cdot s^{-3}$

[2] roughly equal to average distance Sun-Earth

[3] Stromatolites are layered sedimentary formations created mainly by photosynthetic microorganisms such as cyanobacteria, sulfate-reducing bacteria and Pseudomonadota (formerly proteobacteria).

2.5 Earth's thermostate – chemical weathering

Hydrolysis is the main mehcanism for removing CO_2 from the atmosphere. Three key ingredients are minerals that make typical continental rocks, water derived from rain, and CO_2 derived from the atmosphere.

The central equation for chemical weathering is:

$$\underset{\text{Silicate rock}}{CaSiO_3} + \underset{\text{Carbonic acid (soil)}}{H_2CO_3} \rightarrow \underset{\text{Shells of organisms}}{CaCO_3 + SiO_2 + H_2O}$$

2.6 Chemical weathering of silicate rocks

First stage of chemical weathering happens under the influence of rain:

$$\text{Granite} + H_2O + 2CO_2 = \text{Clay} + 2K^+ + 2HCO_3^-$$

During the weathering, carbon dioxide switches from being a greenhouse gas to being a sollute.

The bicarbonate ions are then carried by rivers and eventually end up in seas and oceans. In the ocean, bicarbonates find calcium which they react with, and make limestone, which is calcium carbonate.

$$2HCO_3^- + Ca^{2+} = \underset{\text{limestone}}{CaCO_3} + H_2O + CO_2$$

We took 2 molecules of carbon from the atmosphere, and return only one, the other one is deposited in limestone. Thus the precipitation limestone is a sink.

Q: Can chemical weathering of silicate rocks compensate for anthropogenic CO_2 emissions?

A: No, it is way too slow.

3 Geological methods for studying climate

4 major archives of Earth's climatic history:

- sediments
- ice
- corals
- trees

Sedimentary debris deposited by water is the major climate archive on Earth for over 99% of geological time.

3.1 Sediments

Sediment layers:

- lake sediments
- interior sea sediments
- coastal margin sediments
- deep-ocean sediments

Preservation of older sedimentary records is hindered by two factors: tectonic activity and erosion.

Moraines are long curving ridges made up of a jumbled mix of unsorted debris carried by ice, ranging from large boulders to very fine clay.

Loess are sequences depositing silt-sized grains gathered by wind.

3.2 Ocean sediments

Ocean sediments are useful for researching last 150 Myr.

3.3 Ice sheets

Ice recovered from Antarctic ice sheet now dates back to 800000 years, while Greenland's ice sheet just beyond 125000 years. Many small glaciers record only the last 10000 years.

3.4 Other climate archives

Caves contain limestone deposits spanning several hundred thousand years.

Trees contain up to thousands of years of archives in annual layers.

Corals form annual bands of calcium carbonate ($CaCO_3$) or magnesium carbonate ($MgCO_3$) that hold geochemical information about climate. Individual corals may live for time span of up to hundreds of years.

Within the last few thousand years, people have also kept historical archives of climate-related phenomena.

In last 100 to 200 years we also have instrumental records.

3.5 Radiometric dating and correlation

Scientists use **radiometric dating** to measure the decay of radioactive isotopes[4] in rocks. Dates are obtained on hard crystalline igneous rocks that once were molten and then cooled to solid form.

In the second step, dates obtained from the igneous rocks provide constraints on the ages of sedimentary rocks that occur in layers between the igneous rocks and form the main archives of Earth's early climate history.

Radiometric dating is based on the radioactive decay of a **parent isotope** to a **daughter isotope**. Parent is an unstable radioactive isotope of one element and radioactive decay transforms it into the stable isotope of another element (daughter).

The decay occurs at a constant rate which allows to use it as a clock.

Basalt is an igneous rock commonly used for datin. It cools quickly from molten outpourings of lava. The event that starts the clock ticking is the cooling of this material to the point where neither the parent nor the daughter isotope can migrate in or out of the molten mass. At this point, the rock forms a closed system, one in which the only changes occurring are caused by internal radioactive decay.

Factors that complicate radiometric dating:

- Initial abundance of daughter isotope is rarely 0

[4] Isotopes are forms of a chemical element that have the same atomic number but differ in mass.

- System is not fully closed

The age of sediment layers can be obtained from the nearby igneous rocks.

Fossil correlation method relies on the fact that a unique and unrepeated sequence of organisms has appeared and disappeared through Earth's entire history and left fossilized remains

3.6 Radiocarbon

Radiocarbon dating is widely used to date lake sediments and other kinds of carbon-bearing archives. Neutrons that constantly stream into Earth's atmosphere from space convert ^{14}N (nitrogen gas) to ^{14}C (an unstable isotope of carbon). Vegetable and animal life forms on Earth extract this carbon from the atmosphere to build both their hard shells and soft tissue, and a small part of the carbon they extract is the radioactive ^{14}C isotope. The death of plant or animal closes off carbon exchanges with the atmosphere and starts the decay clock. The ^{14}C parent decays to the ^{14}N daughter and escapes to atmosphere as gas. The amount of ^{14}C that has been lost by the time a sample is analyzed can be determined by measuring a different isotope of carbon that is stable.

Half-life of ^{14}C carbon is 5780 years. Radiocarbon dating is most useful over five or six half-lives.

3.7 Counting annual layers

Some climate repositories contain annual layers:

- **mountain glaciers and ice sheets**: alternations between darker layers that contain dust blown from continental source regions during the dry cold windy season, and lighter layers marking the warmer part of the year with little or no dust.
- **varves** are annual couplets in some lakes, in particular deeper parts of lakes containing little or no life-sustaining oxygen. Lack of bottom-dwelling organisms helps preserve the thin annual layers.
- **tree rings** in regions with distinct seasons are alternations between lighter wood issue (cellulose) grown in spring and thin dark layers from autumn and winter
- **coral bands** record seasonal changes in the texture of the calcite ($CaCO_3$) incorporated in corals' skeletons.

3.8 Climatic Resolution

Factors which control the ability to resolve infromation from climatic archives:

- amount of disturbance of the sedimentary record by various processes soon after deposition
- the rate at which the record is buried beneath additional sediments and therebey protected from further disturbance

3.9 Climate proxies

Scientists must first determine the mechanism by which climate signals are recorded by the proxy indicators in order to use them to decipher climate changes.

Two climate proxies most commonly used:

- Biotic proxies, based on canges in composition of plant and animal groups
- Geological-geochemical proxies, measurements of mass movements of materials through the climate system, either as discrete (physical) particles or in dissolved (chemical) form.

Abundance of **pollen** helps reconstruct the climate on land for younger time intervals.

Types of shelled remains of plankton:

- $CaCO_3$: foraminifera
- $CaCO_3$: coccoliths
- SiO_2: diatoms
- SiO_2: radiolaria

Sediments rich in $CaCO_3$ fossils occur in open-ocean waters at depths above 3500-4000 meters. Below that level, corrosive bottom waters dissolve calcite shells. SiO_2-shelled diatoms inhabit deltas and other coastal areas and extract silica from river water flowing off the land.

3.10 Geological and geochemical data

Sediment is eroded from the land and deposited in ocean basins in two forms:

- **physical weathering**, the process by which water, wind and ice physically detach pieces of bedrock and reduce them to smaller fragments. Examples include ice-rafted debris (sand and gravel eroded by ice sheets and delivered by icebergs that melt in ocean), eolian sediments (silts and clays lifted from the continents and blown to ocean by winds).
- **chemical weathering** and subsequent transport of dissolved ions to the oceans in rivers. It occurs mainly in two ways: hydrolysis and dissolution.

3.11 Key terms

Moraines: long curving ridges created by retreating ice sheets.

Loess: sequences of silt[5] deposited by wind as thick layers.

Historical archives: human-made records of climate-related phenomena, available from last few thousand years.

Instrumental records: are available from last 100 to 200 years since the emergence of the first thermometers in the eighteenth century.

Radiometric dating: Radiometric dating is based on the radioactive decay of a parent isotope to a daughter isotope. Time elapsed is measured by comparing the abundance of these two and combining this data with the half-life of parent.

Parent isotope: An unstable radioactive isotope of one element which transforms through radioactive decay to another.

Daughter isotope: The isotope resulting from the process of radioactive decay.

[5] pl: muł

Closed system: A system in which the changes are not driven by external factors but the content of the system itself, fx internal radioactive decay.

Half-life: One half-life is the time needed for half the parent that was present previously to decay to the daughter isotope.

Radiocarbon dating: Cosmic rays generate neutrons as they travel through the atmosphere which can strike ^{14}N atoms and turn them into ^{14}C, also called radiocarbon, which has a half time of 5730 years. Radiocarbon atoms are ingested by animals and plants through the diet. Once they die, they stop exchanging carbon with their surroundings, so the content of radiocarbon in their organisms decreases. Since it decreases at a known rate we can estimate the organisms' age. The daughter isotope of ^{14}C is again nitrogen ^{14}C. Radiocarbon dating was invented by Willard Libby.

Varves: annual couplets, sediments in some lakes. They result from seasonal alternatoins between deposition of light-hued mineral-rich debris and darker sediment rich in organic material.

Tree rings: alternations between thick layers of lighter wood tissue (cellulose) formed by rapid growth in spring, and thin dark layers marking cessation of growth in autumn and winter.

Coral bands: recorded seasonal changes in the texture of the calcite ($CaCO_3$) in corals' skeletons. The lighter parts are laid down during intervals of fast growth and the darker layers when growth slows.

Climate proxies: indicators of past climate, indirect signals of past climate.

Biotic proxies: climate proxies based on changes in composition of plant and animal groups.

Geological-geochemical proxies: measurements of mass movements of materials through the climate system, either as discrete (physical) particles or in dissolved (chemical) forms.

Macrofossils: larger vegetation remains that cannot have been carried far from their points of origin, such as cones, seeds and leaves.

Plankton: diverese collection of organisms that drift in water or air but are unable to actively propel themselves against current or wind.

Planktic foraminifera: globular sand-sized animals that inhabit upper layers of the ocean.

Coccoliths: individual plates or scales of coccolithophores made of calcium carbonate ($CaCO_3$).

Diatoms: hard-shelled plankton, silt-sized plant plankton shaped like pillboxes or needles. Secrete shells of opaline silica ($SiO_2 \cdot H_2O$).

Radiolaria: sand-sized animals with ornate shells often resembling pre-modern (Prussian) military helmets. Create shells of opaline silica ($SiO_2 \cdot H_2O$).

Burial fluxes: measures of the mass of sediment deposited per unit area per unit time. Useful for mapping the changes in the patterns of deposition of ocean sediments spanning the last 170 million years.

Physical weathering: the process by which water, wind and ice physically detach pieces of bedrock and reduce them to smaller fragments.

Ice-rafted debris: a type of sediment created by physical weathering. It results from eroded ice sheets and is delivered by icebergs that melt in ocean waters. It consists of sand and gravel.

Eolian sediments: silts and clays lifted from the continents and blown to the ocean by winds.

Fluvial sediments: refers to the process of creating deposits by carrying sediments by rivers and streams.

Chemical weathering: a second major way of removing sediments from the land (the other one is physical weathering). Chemical weathering happens through changing the chemical composition of the rock. Subsequently, the dissolved ions are transported to the oceans in rivers.

Dissolution: one of two types of chemical weathering, in which carbonate rocks (such as limestone, made of $CaCO_3$) and evaporite rocks (such as rock salt, made of NaCl) are dissolved in water.

Hydrolysis: one of two types of chemical weathering, in which the weathering process adds water to the minerals derived from continental rocks made of silicates, such as basalts and granites.

Benthic foraminifera: sand-sized animals that live on the seafloor and form calcite ($CaCO_3$) shells from Ca^{+2} and CO_3^{-2} ions in deep waters.

Physical climate models: numerical (computer) models used by climate scientists which emphasize the physical operation of the climate system, particularly the circulation of the atmosphere and ocean but also interactions with global vegetation (biology) and with atmospheric trace gases (chemistry).

Geochemical models: models that track the movement of distinctive chemical tracers throughthe climate system.

Control case: simulation of the modern climate. Models must be capable of simulating modern climate reasonably well in order to be trusted for exploring past climates.

Boundary conditions: the features that are altered to test hypotheses of climate change, such as height of mountains, presence of ice sheets, level of CO_2 in the atmosphere.

Climate simulation: the process of runing a climate model during an experiment.

Climate data output: the climatic data produced in a simulation.

Aerosols: airborne particles, such as volcanic ash and dust.

Atmospheric general circulation models (A-GCMs): three dimensional climate models that incorporate many key features of the real world: the spatial distribution of land, water and ice, the elevation of mountains and ice sheets, the mount of vertical distribution of greenhouse gases in the atmosphere, the seasonal variations in solar radiation.

Grid boxes: boundary conditions for A-GCM experiments are specified for hundreds of model grid boxes.

Sensitivity test: An approach to A-GCM experiments, where one boundary condition at a time is altered in relation to the present configuration. When the output of such an experiment is compared to the output from the modern control case, the differences in climate between the two runs isolate and reveal the unique impact caused by the change in that one boundary condition.

Reconstruction: An experiment with climate model where all known boundary conditions are changed at the same time in order to try to simulate the full state of the climate system at some time in the past.

Ocean general circulation models (O-GCMs): are usually simpler than A-GCMs. One reason is that climate researchers know much less about the modern circulation of the oceans, especially critical processes such as the brief but intense episodes when deep water forms at high latitudes.

Geochemical tracers: chemical materials that are tracked by geochemical circulation models.

Reservoirs: environments containing the chemicals, such as the atmosphere, ocean, ice, vegetation and sediments.

Mass balance models: models that trace the movements of chemicals between reservoirs.

Residence time: the average time it takes for a geochemical tracer to pass through a reservoir. For a reservoir at a steady state (equal pace of output and input flux), this time is equal to: residence time $= \frac{\text{reservoir size}}{\text{Flux rate in (or out)}}$

3.12 Review questions

3.12.1 Why does the importance of different climate archives change for different time scales?

Different climate archives vary in precision and availability back in time:

- **Instrumental**: 10^2-0 years back
- **Historical**: 10^3-0 years back
- **Tree rings**: 10^4-0 years back
- **Ice cores**: 10^6-0 years back
- **Lake sediments**: up to 10^9 years back
- **Coral reefs**: 10^6-0 years back
- **Ocean sediments**: up to 10^9 years back
- **Continental coastal sediments**: up to 10^9 years back

3.12.2 Why are ocean sediments and ice cores especially important archives of climate?

Deep ocean is generally undisturbed with relatively continuous deposition. It usually yields climate records of higher quality than records from land, where water, ice and wind repeatedly erode deposits.

Ice cores retrieve climate records extending back thousands of years in small mountain glaciers to as much as hundreds of thousands of years in continent-sized ice sheets.

3.12.3 How does the method of dating climate records vary with the type of archive?

For vegetation and organisms, radiocarbon dating is used. For many kinds of rocks. radiometric dating and correlation. Counting annual layers works for some sediments in water, tree rings, or coral bands. Orbital cycles can be used to date low-latitude monsoons and the growth-decay cycle of high-latitude ice sheets.

3.12.4 How does the resolution from sedimentary archives vary with depositional environment?

In the oceans, four groups of shell-forming animal and plankton are used for reconstructions, two of which made of calcite and two of opaline silica.

In lakes, annual sediment varves are used.

On bedrock, annual ice layers can be analysed.

3.12.5 Which two major groups of organisms are most important to climate reconstructions over the past several million years?

Plankton and pollen (vegetation).

3.12.6 Describe how the products derived from physical and chemical weathering provide different kinds of information about the climate system.

Physically weathered sediments reveal the climate of the source regions, for example grains of quartz and other minerals from ice sheets indicate cold climates.

Chemically weathered sediments record changes in the global volume of ice and in local ocean temperatures.

3.12.7 Describe the two ways the performance of climate models is evaluated.

- control case – simulation of modern climate
- testing climate data output against independent geologic data that played no part in the experimental design

3.12.8 Why aren't models of the atmosphere and ocean allowed to interact continuously?

Air and water responde to climate changes at different rates that impose different computational demands. Ocean models can ignore interactions that occur on a daily cycle because these short-term changes have negligible effects on most ocean circulation. As a result, O-GCMs generally only need to calculate changes over timesteps separated by a month or more. By contrast, daily changes are critical to models of the fast-responding atmosphere.

3.12.9 Describe two features that make the ocean useful in geochemical mass balance models.

- isotopic composition of oxygen in the H_2O molecules that are deposited in ice sheets differs from the average composition of the molecules left in the ocean.
- terrestial carbon (vegetation) is enriched in one isotope of carbon compared to the average in the ocean

4 Lecture 2: Geological methods for studying climate

4.1 Formanifera

Single-celled organisms, members of Rhizarian protists, which are plenty fossilised in the oceans.

4.2 Oxygen isotope analysis

$\delta^{18}\mathrm{O}_{\mathrm{water}}$, the 18-oxygen signature of water describes the presence of the oxygen 18-isotope in a sample of water. The precise definition is:

$$\delta^{18}\mathrm{O}_{\mathrm{water}} = \left[\frac{\frac{^{18}O}{^{16}O}_{\mathrm{sample}}}{\frac{^{18}O}{^{16}O}_{\mathrm{standard}}} - 1 \right] \times 1000‰$$

As per te standard value, we conventionally use:

$\frac{^{18}O}{^{16}O}_{\mathrm{VSMOV}} = 0.002005$

VSMOW stands for Vienna Standard Mean Ocean Water

But it's very rare to have water from the past[6], so we have to compare with other elements like chemicals. $\delta^{18}\mathrm{O}_{\mathrm{calcite}}$

$\delta^{18}\mathrm{O}_{\mathrm{VPDB}} = 0.97\delta^{18}\mathrm{O}_{\mathrm{VSMOW}} - 29.98‰$

$\delta^{18}\mathrm{O}_{\mathrm{VSMOW}} = 1.03091 \times \delta^{18}\mathrm{O}_{\mathrm{VPDB}} + 30.91‰$

VPDB = Vienna Pee Dee Belemnite, a specific fossil used as a standard, because it is very homogenous.

We always compare oxygen isotopes in relation to a standard, not as absolute values.

4.3 Oxygen isotope fractionation

Why is oxygen isotope a proxy?

In lower temperatures formanifera preferably in take the higher oxygen isotope (^{18}O) and in higher, the lighter isotope (^{16}O).

As the shells of formanifera grow, they acquire the oxygen, and the oxygen isotopes they intake depends on the surrounding temperature.

Shackelton and Kenneth (1975): $T = 16.9 - 4.38[\delta^{18}O_{\mathrm{calcite}} - \delta^{18}O_{\mathrm{water}}] + 0.10[\delta^{18}O_{\mathrm{calcite}} - \delta^{18}O_{\mathrm{water}}]^2$

Given $^{18}O_{\mathrm{calcite}}$ from a fossil we could calculate the temperature from the past. But there is one problem, the value for water is not constant on a geological timescale because of glaciers.

Water evaporates around the equator, it is then carried through clouds northwards. Heavier isotope is more likely to fall down as rain, so the further north the less of it is left in the clouds. Eventually the lighter isotope gets trapped in ice (glaciers) and the heavier left in the ocean waters.

Thus bigger values of $\delta^{18}O_{\mathrm{water}}$ is correlated with cooling or icehouse eras (presence of glaciers) or both.

The Earth has been cooling (with some minor interruptions) for the last 55 Myr.

[6]One example is water trapped in bubbles in rocks.

In the last 1 Myr we can see a sawtooth pattern of interglaciar periods and glaciar periods.

$\delta^{18}O$ from marine fossils over the past 500 Myr has been increasing which suggests the climate has been cooling the whole time but we have other proofs that it's not the case. That's example of proxy failing us.

Detrending is a pattern of deleting the high level trend for data if we don't have an explanation for the trend. After detrending data may make more sense even if it's "fake".

4.4 Identifying cold periods in history

- ice-rafted debris
- glacial deposits

Oldest ocean floor on earth is 200 Myr old.

4.5 Carbon isotopes

^{12}C and ^{13}C (don't confuse with the radioactive ^{14}C). It's the same principle as with oxygen isotopes, ^{13}C is heavier.

Hydrothermal (coming from volcanoes) $\delta^{13}C = -6$. Limestones form of $CaCO_3$ or dolomite ($CaMg(CO_3)_2$). Thus limestones will have the same value as volcanoes if nothing else changes it.

Now we add living organisms which preferentially take carbon 12 (^{12}C), thus increasing $\delta^{13}C$ in the water. Extreme events happened around 2000 Myr ago and around 600 Myr ago – very high and very low values of $\delta^{13}C$ (blossom of life and death of life). Both are explained as snowball events.

4.6 Timescales

4000 Myr ago – 500 Myr ago: carbonates, ^{13}C

500 Myr ago – 100 Myr ago: marine fossils, ^{18}O

65 Myr ago – 0 Myr ago: foraminifera

5 Reading assignment 3: Astronomical control of solar radiation

5.1 Key terms

Plane of the ecliptic: the plane in which Earth moves around the Sun.

Tilt: The angle at which Earth is tilted away from the line perpendicular to the plane of its orbit around the sun is 23.5°. The tilt angle changes in cycles of 41000 years.

Solstices: The longest and shortest days of the year: June 21, Dec 21.

Equinoxes: The days in March and September when the lengths of night and day become equal in each hemisphere.

Perihelion: "Close pass", when Earth is 153M km from the Sun. Happens on January 3rd.

Aphelion: "Distant pass", when Earth is 158M km from the Sun. Happens on July 4th.

Wavelength: Length of a cycle.

Period: The wavelength of a cycle, expressed in units.

Frequency: The inverse of the period of a cycle.

Amplitude: A measure of the amount by which cycles vary around their long-term average.

Modulation: Behaviour in which the amplitude of peaks and valleys changes in a repetitive or cyclic way.

Sine waves: Sinusoidals are perfect cycles because they are regular both in period and in amplitude (isn't a sawtooth pattern too?).

Eccentricity: The measure of how elliptic (=not perfectly circular) an ellipse is. It is defined as $\epsilon = \frac{\sqrt{a^2-b^2}}{a}$. Earth's orbit's eccentricity is not constant and has varied through time.

Axial precession: Earth's wobbling motion, caused by changing in the direction of the tilt, at cycle length 25700 years.

Precession of the ellipse: A slow rotation of the entire orbit of the Earth.

Precession of the equinoxes: The movement of equinoxes (and solstices) around Earth's orbit which takes around 23000 years to complete. It results from combined axial precession and precession of the ellipse.

Precessional index: An expression measuring impact of Earth's orbit's eccentricity and the movement of equinoxes around the orbit. It is defined as $\epsilon \sin \omega$, where ϵ is eccentricity and ω is the current angle between the Earth-Sun lines at March 20 equinox and at perihelion. Eccentricity *modulates* the angular motion of the precession of the equinoxes.

Insolation: Radiation arriving at the top of Earth's atmosphere.

Caloric insolation seasons: The summer caloric half-year is defined as the 182 days when the incoming insolation exceeds the amount received during the other 182 days.

Time series analysis: Techniques to extract rhythmic cycles embedded in the records of climate.

Spectral analysis: One of time series analysis. Gradually sliding a series of sine waves (with different phases and cycles) and if one has high correlation with the plot, it is detected as component. Sounds like DFT.

Power spectrum: A type of plot where y-axis represents the amplitude of the cycles, also known as power.

Filtering: A time series analysis technique, also known as band-pass filtering.

Aliasing: A term that refers to false trends generated by under-sampling the true complexity in a signal.

5.2 Review questions

:

5.2.1 Why does Earth have seasons?

Because of the tilt in relation to sun. It is summer when a given part of the world is tilted towards and winter when in opposite direction. Therefore it is summer in Australia when we have winter in Europe.

5.2.2 When is Earth closest to the Sun in its present orbit? How does this "close pass" position affect the amount of radiation received on Earth?

In its present orbit, Earth is closest to the Sun on January 3. It causes the winter radiation in the Northern Hemisphere and summer radiation in Southern Hemisphere to be slightly stronger than they would be in a perfectly circular orbit.

5.2.3 Describe in your own words the concept of modulation of a cycle

Modulation of a cycle are higher level patterns in its amplitude or loudness if we talk about soundwave or intensity.

5.2.4 Earth's tilt is slowly decreasing today. As it does so, are the polar regions receiving more or less solar radiation in summer? In winter?

As the tilt is decreasing, the Arctic and Antarctic cirles move closer to the poles. That is, the area with polar day and polar night becomes slower. Polar regions receive more radiation in the winter and less in the summer.

5.2.5 How is axial precession different from precession of the ellipse?

Axial precession changes the direction of Earth's tilt, precession of the ellipse moves the Earth's orbit.

5.2.6 How does eccentricity combine with precession to control a key aspect of the amount of insolation Earth receives?

Precession affects how much solar radiation the Earth receives on the solstices (the closer the solstice to the perihelion, the more radiation) in a sinewave pattern. Eccentricity modulates this signal. Since there are multiple cycles of eccentricity changes, with multiple lengths, they nearly cancel each other out.

5.2.7 Do insolation changes during summer and winter have the same or opposite timing at any single location on Earth? Why or why not?

They have have exactly opposite timing, they are exactly out of phase. This is because the tilt that brings one pole closer to the Sun, also puts the other pole farther from the Sun. More intense summer insolation maxima and deeper winter insolation minima occur together at any one location.

5.2.8 Do the following changes occur at the same time (same year) in Earth's orbital cycles?

Summer insolation maxima changes at both poles caused by changes in tilt? No, they are out of phase.

Summer insolation maxima in the tropics of both hemispheres by precession? Yes, they are in phase.

6 Reading assignment 3: Insolation Control of Monsoons

Monsoon creation: In summer, strong solar radiation causes a rapid and large warming of the land, but a slower and much less intense warming of the ocean. Rapid heating over the continents causes air to warm, expand and rise, and the upward movement of the air creates an area of low pressure at the surface. The air flowing toward this low-pressure region also warms and rises. The air arriving from nearby ocean carries water vapor that condenses and contributes to monsoonal rainfall.

In winter, when solar radiation is weaker, air over the land cools off rapidly, becomes denser than the air over the still-warm ocean, and sinks from higher levels in the atmosphere. This downward movement creates a region of high pressure over the land, in contrast to the lower pressure over the still-warm oceans. The overall atmospheric flow in winter is a downward-and-outward movement of cold, dry air from the land to the sea.

6.1 Key terms

Orbital monsoon hypothesis: The idea that changes in insolation control the strength of monsoons over orbital time scales proposed by John Kutzbach in early 1980s.

Nonlinear response: In this context, the nonlinear response of the climate system to insolation: the amount of rainfall is highly sensitive to insolation change in one season (summer) but largely insensitive to changes in the other (winter).

Threshold level: A threshold level on insolation, below which the monsoon response will be too weak to leave any evidence in the geologic record.

Sanpropels: Black organic-rich muds, found in Mediterranean sediments.

Anoxic: Lacking the oxygen needed to convert (oxidize) organic carbon to inorganic form.

Clipped response: The truncation of the summer monsoon response at the threshold.

Orbital tuning: A method for dating sedimentary records on land and in the ocean, based on the link between summer insolation forcing and monsoon responses.

6.2 Review questions

6.2.1 In what way is the orbital monsoon hypothesis an extension of processes driving modern monsoons?

Because seasonal monsoon circulations are driven in the modern world by changes in solar radiation, orbital-scale changes in summer and winter insolation should have produced a similar response.

6.2.2 Why does the intensity of 23000-year monsoon peaks vary at intervals of 100000 and 413000 years?

Because of the eccentricity changes happening in cycles of 100000 and 413000 years.

6.2.3 How did the Mediterranean Sea acquire a freshwater lid during times when very little precipitation was falling in that region?

The water was delivered by Nile.

6.2.4 Explain how the opposed July/February timing of past monsoon changes in China and Brazil lends strong support to the orbital monsoon hypothesis.

Cave deposits (stalactites, stalagmites) form as the groundwater drips through water into the caves. They are constructed of calcite ($CaCO_3$). Their layers can be accurately dated by radiometric analysis of small amounts of thorium and uranium. The relative amount of two isotopes of oxygen (^{16}O and ^{18}O) tells us about precipitation. Layers with highly negative $\delta^{18}O$ indicate strong monsoons.

Caves found in Brazil and China show a very similar pattern of monsoon strength over the years, and each is in phase with the midsummer in the respective hemisphere, thus out of phase with each other.

6.2.5 Does peak monsoon strength lag behind summer insolation forcing?

Yes, they lag 2000 years.

6.2.6 What similarities exist between monsoon changes in Pangea 200 million years ago and those in North Africa during the last several hundred thousand years?

Monsoons filled and emptied these Pangaean lakes in response to orbital precessions in the same way that North African lakes have filled and emptied during much more recent times.

6.2.7 How do tectonic uplift and orbital variations combine to affect the long-term intensity of monsoons?

Tectonic uplift creates a slow increase in the amplitude of the orbital-scale cycles. Their combined effect is stronger than a simple linear combination of the two effects.

7 Reading assignment 3: Insolation control of ice sheets

Coral reefs that formed during the last 150000 years confirm that the $\delta^{18}O$ signal is a reasonable proxy for ice sheet size. The ages of the most prominent $\delta^{18}O$ minima correspond to the ages of coral reefs formed during high stands of sea level caused by ice sheet melting, and the amplitudes of the sea level changes estimated from the reefs correspond to the relative changes in ice volume inferred from the $\delta^{18}O$ signal.

7.1 Key terms

Equilibrium line: The boundary between positive and negative ice mass balance (that is between ice sheet growth and ablation), drawn around 10°.

Milankovitch theory: A systematic way of calculating the impact of astronomical changes on insolation received on Earth at diferent latitudes and in different seasons. Formulated by Serbian astronomer Milutin Milankovitch.

Milankovitch proposed that ice growth in the Northern Hemisphere occurs during times when summer insolation is reduced.

3 factors control the summer insolation:

- Earth's tilt
- How far from the Sun is the Earth at summer solstice
- Orbit's eccentricity

Milankovitch noted that the most sensitive latitude for low insolation values is 65°N, at which the ice forms first and melts last.

Climate point: The point where the equilibrium line intercepts the Earth in the higher latitudes. The amount of north-south shift of equilibrium line is proportional to the amount of change in summer insolation. These shifts can cover 10° to 15°.

Phase lag: The persistent delay in ice volume relative to summer insolation. There is also lag in ice volume responses to cycles of orbital tilt and precession. The lag there is roughly $\frac{1}{4}$ of the cycle length.

Elastic response: Immediate sinking response of bedrock depression under the heavy ice load. It represents roughly 30% of the vertical change in bedrock.

Viscous response: The slow response of bedrock sinking over thousands of years. It follows after the elastic response and is caused by the slow flow of rock in a "soft" layer of the upper mantle at a depth between 100 and 350km.

Basal slip: Meltwater at the base of the ice sheet saturates soft sediments and creates a lubricated layer across which ice can slide.

Termination: Abrupt deglaciation.

7.2 Review questions

7.2.1 What is the equilibrium line and why is it important?

The equilibrium line is the boundary between ice sheet growth and ablation. It is important because after crossing it the ablation accelerates. Ice sheet doesn't accelerate towards lower temperatures because at very low temperatures not much snow falls.

7.2.2 Why are northern ice sheets likely to be more responsive to insolation changes than ice in Antarctica?

7.2.3 Why does the size of a growing or melting ice sheet lag well behind changes in insolation?

Both growth and melting is very slow. The rate at which ice grows reaches its maximum when the summer insolation has reached its minimum. The ice sheet then grows and continue to grow even as summer insolation is increasing again. An analogous argument is made about ablation. Even if its rate reaches maximum at peak summer insolation, it takes time for ablation to accumulate.

7.2.4 How does the delay in bedrock response to ice loading or unloading act as a positive feedback on ice volume?

Ice sheet grows → Bedrock sinking delayed for thousands of years (viscous response) → Ice sheet stays at higher, colder elevations → More positive ice mass balance → Ice grows faster

Ice sheet melts → Bedrock rebound delayed for thousands of years (viscous response) → Ice sheet stays at lower, warmer elevations → More negative ice mass balance → Ice melts faster

7.2.5 If the average amplitude of a 41000-year δ^{18}O cycle in the deep North Atlantic prior to 0.9 Myr ago was 1.0‰, and if changes in ice volume account for half of that total, how large was the average changes in deep-water temperature?

7.2.6 How do corals provide an indication of the volume of water tied up in ice sheets on land?

Some coral species grow just below sea levels and have strong structural frameworks that remain intact long after individual coral organisms have died and that preserve records of sea level positions. Old coral reefs can be dated by radiometric decay methods. Their skeletons contain small amounts of ^{234}U that slowly decays to ^{230}Th.

7.2.7 What has been the average rate of uplift of a coral reef formed during the last interglaciation 125000 years ago and now lying 131 meters above sea level?

$U = \frac{Ht-6}{125} = \frac{131-6}{125} = 1m/1000yr$

7.2.8 Which part of the Milankovitch theory has proven accurate? Which parts are insufficient?

It explains the presence of ice volume responses at 41000 and 23000 years and why they lag several thousand years behind he summer insolation forcing. But it fails to explain the dominance of the 41000-year cycle over the 23000-year signal for almost 2 Myr and it does not account for the emergence of large oscillations near 100000 years in the last million years.

7.2.9 If a reef on New Guinea that has been dated to 104000 years formed at 17m below modern sea levels, and if the average uplift rate on that island has been 2m per thousand years, what is the current elevation of that reef?

$2m = \frac{Ht-17}{104}$
$Ht - 17 = 208m$
$Ht = 225m$

8 Lecture 3: Climate variability on a timescale of thousands of years

2 driving forces for climate variability:

- Orbital forcing
- Tectonic forcing

Forcing means something external driving the climate.

Ice age is a long geological interval during which there are glaciations. The current ice age started at the beginning of the Quaternary period.

Multiple glaciations and interglacials happened in current ice age. They occur in cycles driven by the orbital cycles.

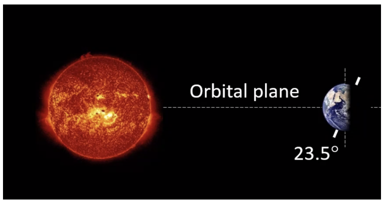


Figure 1: Current axial tilt is 23.5°

Earth's orbit is an ellipse. Sun is in one of its focal points.

Perihelion is when the Earth is the closest to the Sun, currently 153km (but changes depending on orbit's *eccentricity*).

Aphelion is the furthest the Earth can be from the sun, currently 158km.

If axial tilt was 0°, there would be no seasons.

If axial tilt was 90°, there would be extreme seasonality.

Milankovic cycles:

- **axial tilt**: 41000 years cycle between 22.1° and 24.5°
- **eccentricity**: 100000 and 413000 cycles, changes due to gravitational effect of other planets
- **precession** (wobble) of perihelion and aphelion along the orbit

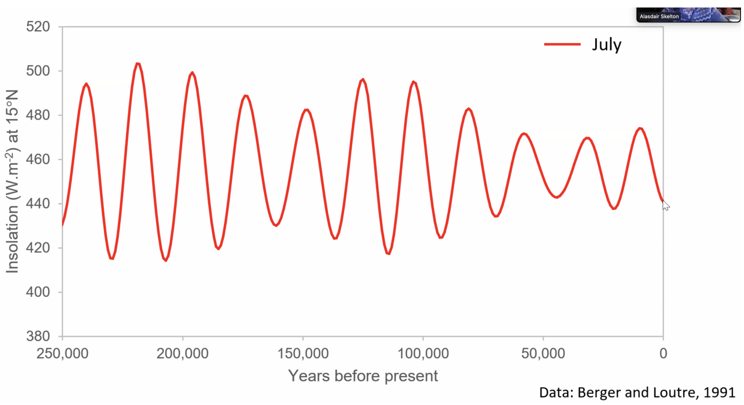


Figure 2: Insolation in July

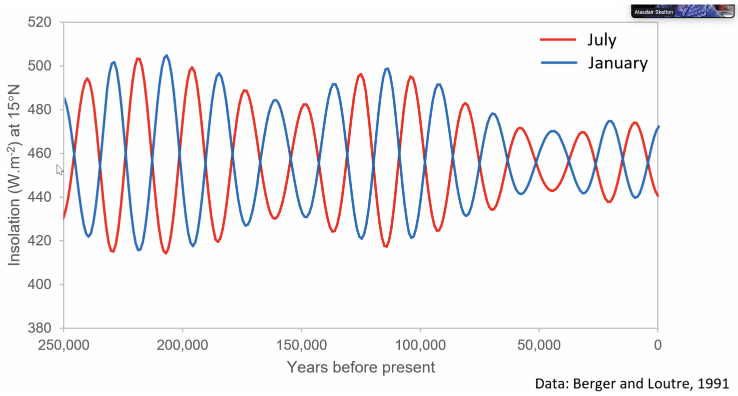


Figure 3: Insolation in July and January

Milankovic cycles drive glaciations, not the other way around.

8.1 Monsoons

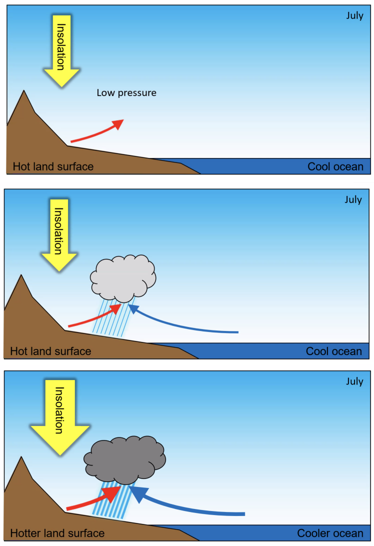
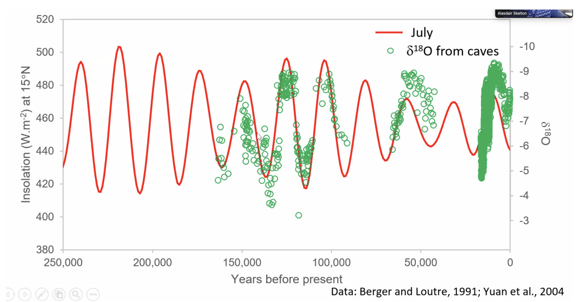
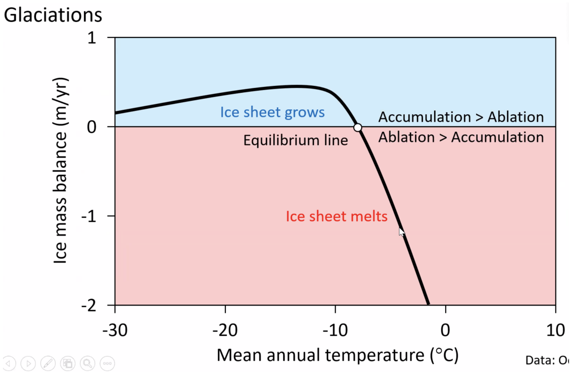
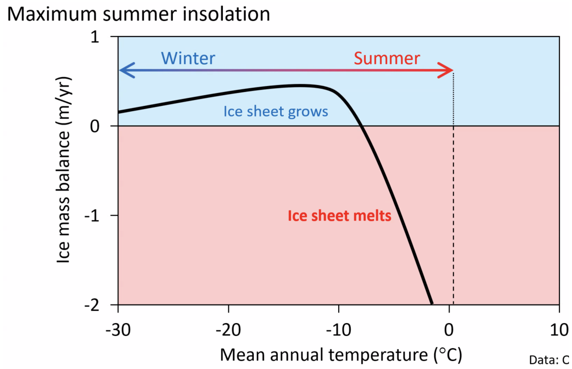


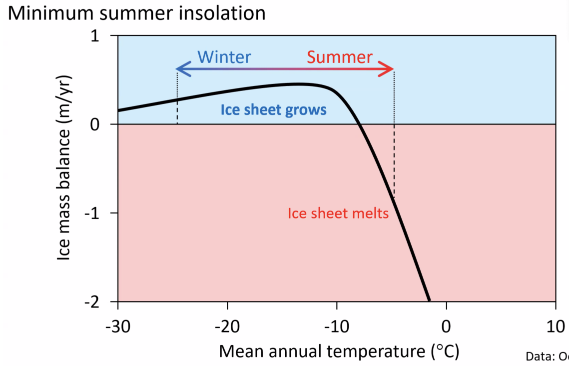
Figure 4: Summer monsoon



8.2 Glaciations







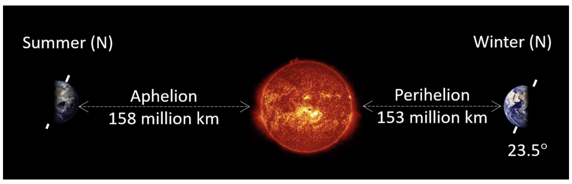
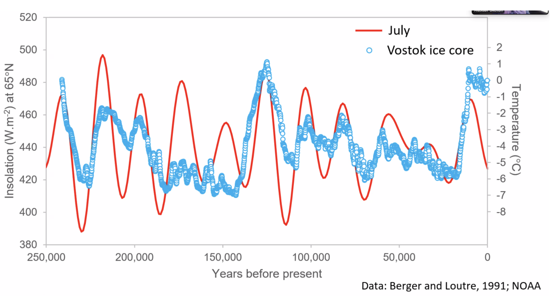


Figure 5: Currently, axial tilt and eccentricity have opposite effects. Tilt is dominating which is why we are currently in interglacial.



9 Reading assignment 4: Plate Tectonics and Long-Term Climate

In 1914 the German meteorologist Alfred Wegener proposed that continents move slowly across Earth's surface. He was almost right: in fact *all* of Earth's surface slowly moves.

The best rocks to use as ancient compasses are basalts, which are rich in highly magnetic iron. Basalts form the floors of ocean basins and are also found on land in actively tectonic regions.

As the molten material cools, its iron-rich components align with Earth's magnetic field like a compass. After lava turns into basaltic rock (when its temperature drops below 1200°, continued cooling to temperatures near 600° allows the "fossilized" magnetic compases to become fixed in position in the rock.

Also locked in the basalts are radioactive materials such as potassium (K) which help date the basalt layers.

The age of the ocean crust steadily increases with distance from the ridges (at divergent margins).

Since 450 Myr ago, major (continent-sized) ice sheets have existed on Earth during three icehouse earas:

- a brief interval centered near 445 Myr ago
- much longer interval from 325 to 240 Myr ago
- current icehouse era of the last 35 Myr

Most CO_2 is expelled to the atmosphere by volcanic activity at two kinds of locations:

- margins of converging plates, where parts of the subducting litosphere melt and form molten magmas that rise to the surface in mountain belt and island arc volcanoes, delivering CO_2 and other gases from Earth's interior
- where hot magma carrying CO_2 erupts directly into ocean water

9.1 Key terms

continental crust: the layer of igneous, metamorphic and sedimentary rocks that forms the geological continents. It is 30-70 kilometers thick, has an average composition like that of granite and is low in density ($2.7\frac{g}{cm^3}$).

ocean crust: uppermost layer of the oceanic portion tectonic plates. Average ocean floor is 4000 meters below sea level. Ocean crust is 5-10km thick, has average composition like that of basalt and is higher in density ($3.2\frac{g}{cm^3}$).

mantle: the layer of Earth that lies below both continental and oceanic rust. It extends halfway towards the Earth's interior (2890km out of 6370km). It is richer in heavy elements like iron (Fe) and magnesium (Mg). It has dencity of $3.6\frac{g}{cm^3}$).

litosphere: rock layer below Earth's surface. It is 100km thick and generally behaves like hard, rigid substance. It enxompasses the crustal layers and the upper part of the underlying mantle.

asthenosphere: the layer below litosphere, lying entirely within the upper section of Earth's mantle at depths of 100 to 350 kilometers. It is partly molten but mostly solid. It behaves like a soft, viscous fluid over long intervals of time, and flows more easily.

tectonic plates: a division of the litosphere. These plates move at rates ranging from ¡1 to 10 cm per year and average about the same rate as growth of a fingernail.

divergent margins: one of 3 types of edges (margins) of tectonic plates, occurring when plates move apart, for example in the middle of Atlantic Ocean. This motion allows new ocean crust to be created. Plates diverging at ocean ridges carry not just the near-surface layer of ocean crust but also a much thicker layer of mantle lying underneath.

convergent margins: another type of edges (margins) of tectonic plates occurring when plates come together.

subduction: a process occuring at convergent margins. The litosphere (ocean crust and upper mantle) plunges deep into Earth's interio and ocean trenches. For example, narrow mountain chains such as the Andes from on the adjacent continnts because of the squeezing (compressing) forces produced when the two plates move together.

continental collision: a less common type of converging plates. It creates massive high-elevation regions such as the Tibetan Plateau.

transform fault margins: the last type of tectonic plates' edges, when plates slide past each other. Sliding of plates at transform faults involves the litosphere, both the upper continental crust and the underlying upper mantle.

magnetic field: the Earth has a magnetic field that determines the alignment of compass needles. Magnetic north is located a few degrees of latitude away from geographic North Pole.

paleomagnestism: the study of prehistoric Earth's magnetic fields recorded in rocks, sediments and archeological materials.

magnetic lineations: stripes of normal and reversed polarity records growing symmetrically out of ocean ridges.

seafloor spreading: the process of divergence of litospheric plates at ocean crust.

polar position hypothesis makes two predictions:

- ice sheets should appear on continents that were located at polar or near-polar latitudes
- no ice should appear at times when continents were located outside of polar regions

In other words, it claims that land presence in polar region is both the sufficient and necessary condition for glacier formation.

However, this hypothesis can be confirmed only one way: indeed polar positioning of land is favorable to formation of glaciers, but it seems not sufficient.

Gondwana: a large southern supercontinent consisting of modern Africa, Arabia, Antarctica, Australia, South America and India. It was located on the opposite side of the globe from North America, but it had begun a long trip that would carry it across the South Pole.

Pangaea: the giant supercontinent, meaning "All Earth"

evaporite: deposits that precipitated out of water in lakes and coatal margin basins with limited connections to the ocean. Evaporite salts form only in arid regions where evaporation far exceeds precipitation. More evaporite salt was deposited during the time of Pangaea than at any time in the last several hundred million years.

red beds: sandy or silty sedimentary rocks stained various shades of red by oxidation of iron minerals. Red-colored soils accumulate today in regions where the contrast in seasonal moisture is strong.

spreading rate hypothesis: a hypothesis proposed in 1983 that the climate changes during the last several hundred million years were driven mainly by changes in the rate of CO_2 input to the atmosphere and ocean by plate tectonic processes.

hot spots: volcanic hotspots are locales where thin plumes of molten material rise from deep within the interior and reach the surface.

uplift weathering hypothesis: a proposition that chemical weathering is an active driver of climate change, rather than just a passive negative feedback that moderates climate. The hypothesis focuses on evidence that exposure of fragmented and unweathered rock is a key factor in the intensity of chemical weathering. It then links this evidence to the fact that freshly fragmented rock is exposed mainly in regions of tectonic uplift.

mass wasting: erosional processes producing rock slides and falls, flows of water-saturated debris, and a host of other processes that dislodge everything from huge slabs of rock to loose boulders, pebbles and soil.

Uplift $\rightarrow$ (steep slopes, mass wasting, mountain glaciers, slope precipitation) $\rightarrow$ increased rock fragmentation $\rightarrow$ increased weathering and CO_2 removal $\rightarrow$ global cooling

9.2 Review questions

9.2.1 Does each litospheric plate correspond to an individual continent or ocean basin?

Most tectonic plates correspond to a combination of a continent and a part of ocean basin.

9.2.2 What kind of physical behaviour in Earth's deeper layers allows the plates to move?

Molten fluids circulating in Earth's liquid iron core create a magnetic field analogous to that of a bar magnet.

9.2.3 Explain how paleomagnetism tells us about past latitudes of continents.

The orientations of magnetic compases frozen in basalt layers deposited on continents in relation to the magnetic poles are used. In molten lavas that cool at high latitudes, the internal magnetic comasses point in a nearly vertical direction because Earth's magnetic field has that orientation at high latitudes. In contrast, lavas that cool near the equator have internal compasses oriented closer to horizontal, nearly parallel to Earth's surface.

9.2.4 Explain how paleomagnetism tells us about rates of spreading of ocean ridges.

Past changes in the magnetic field (inversed polarity) are recorded in fossil magnetic compasses in well-dated basaltic rocks from many regions. These changes are also recorded in magnetic lineations – stripes of normal and reversed polarity recorded in ocean crust – growing symmetrically out of ocean ridges.

9.2.5 Do glaciations *always* occur when continents are located in polar positions?

No, there were greenhouse eras (no glaciations) with continents in polar regions.

9.2.6 What are the major characteristics of the climate of Pangaea?

No ice sheets existed even though its norther and southern limits ay within Arctic and Antarctic circles. This suggests that Pangaea's climate was somewhat warmer than today's climate. This is also supported by fossil evidence of vegetation. Several kinds of palm-like vegetation that would have been killed by hard freezes existed on Pangaea to latitudes as high as 40°. Because the moderating effcts of ocean moisture failed to reach much of Pangaea's interior, the continent was left vulnerable to seasonal extremes of solar heating in summer and cooling during winter.

9.2.7 What is the central concept behind the BLAG (spreading rate) hypothesis?

That changes in the average rate of seafloor spreading over millions of years have controlled the rate of delivery of CO_2 to the atmosphere from the large subsurface rock reservoir of carbon and that the resulting changes in atmospheric CO_2 concentrations have had an impact on Earth's climate.

9.2.8 What role does chemical weathering play in the BLAG hypothesis?

It creates a negative feedback. Warmer climate leads to more precipitation, thus more vegetation, thus higher removal of CO_2 from the atmosphere.

9.2.9 Write a chemical reaction showing how weathering removes CO_2 from the atmosphere.

$$\underset{\text{Silicate rock}}{CaSiO_2} + \underset{\text{Atmosphere}}{CO_2} \rightarrow \underset{\text{Plankton}}{CaCO_3} + \underset{\text{Plankton}}{SiO_2}$$

9.2.10 How soon after deposition does freshly fragmented debris undergo most chemical weathering?

9.2.11 Why is chemical weathering faster in the eastern Andes than in the Amazon lowlands?

The minerals in Amazon lowlands have long been "used up" in the weathering process, while the physical impacts of active uplift in the Andes (steep slopes, earthquakes, mass wasting, heavy precipitation, and glacial erosion) combine to generate a continual supply of fresh, finely ground rock debris for weathering.

9.2.12 How could chemical weathering be both the driver and the thermostat of Earth's climate?

The effects of the uplift weathering processes are probably opposed by the chemical weathering thermostat.

9.2.13 Fast subduction in the modern Pacific Ocean carries down sediments with low amounts of $CaCO_3$ while almost no subduction occurs in the Atlantic Ocean, with its carbonate-rich sediments. What would happen if subduction suddenly began in the Atlantic and replaced an equal amount of subduction in the Pacific?

10 Lecture 4: Climate variability on a timescale of millions of years

10.1 Theory of plate tectonics

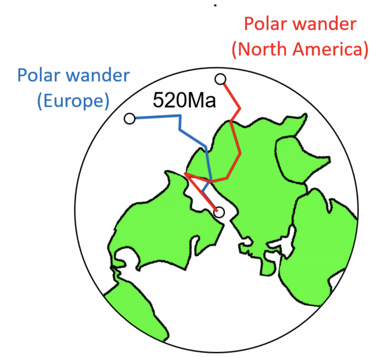
10.1.1 Alfred Wegener's hypothesis of continental drift

Glossopteris: Example of a tree which is found fossilized (leaves) on multiple continents.

Caledonides The mountain chain in Scandinavia was once joined with Caledonides in North-East America and North-West Africa. It was one mountain belt when all continents were together.

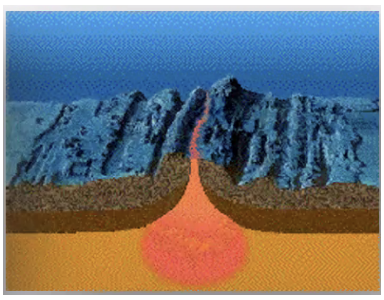
10.2 Patrick Blackett's polar wander

If you look at volcanic rocks, as they solidify, they contain certain magnetic minerals and they line up in magma as they crystallize, and they point towards the North Pole.



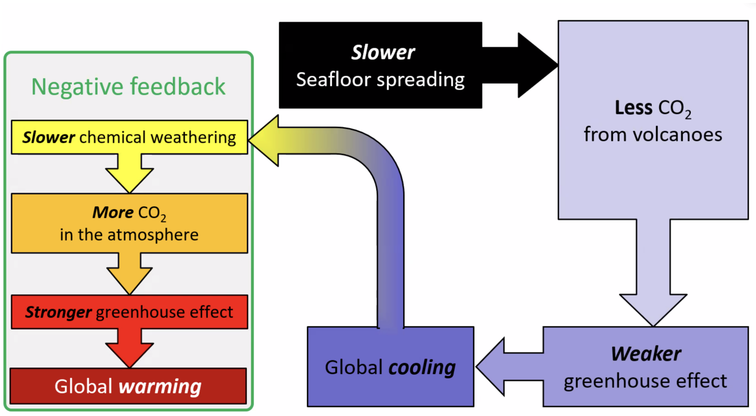
10.3 Ocean spreading

Chicken and egg question: is the floor spreading because of volcanism, or is the lava flowing because of spreading?

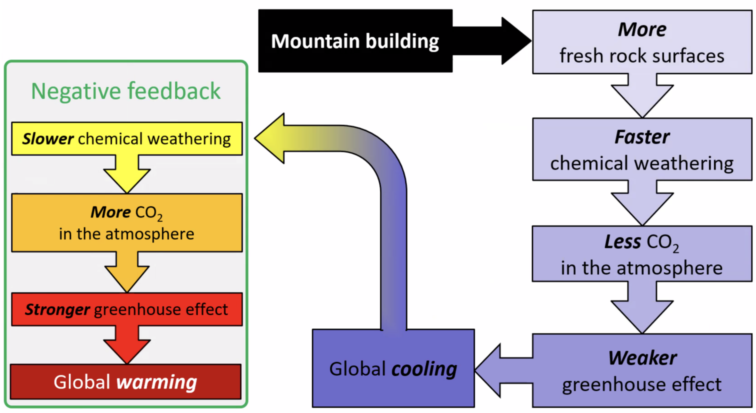


Ocean spreading increases CO_2 in the atmosphere (increased volcanism). Mountain building does the opposite (more rocks for weathering).

10.4 BLAG hypothesis

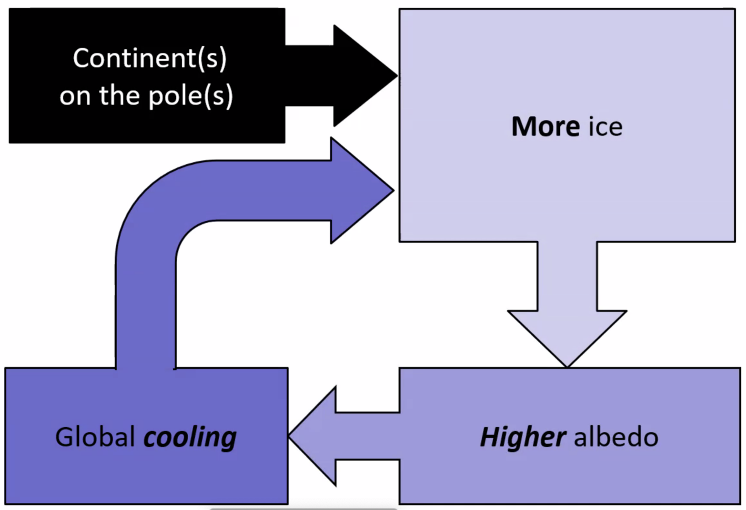


10.5 Uplift weathering hypothesis



10.6 Polar position hypothesis

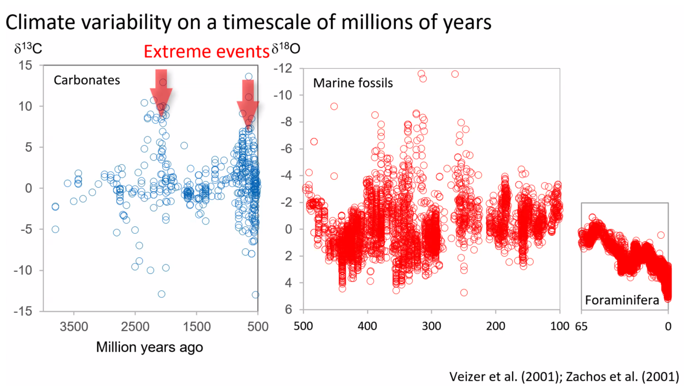
Ice forms easier on land than on sea, which is the basis for polar position hypothesis.



10.7 Plate tectonics and climate

- **BLAG hypothesis**: slower seafloor spreading causes global cooling
- **Mountain building hypothesis**: mountain building causes global cooling
- **Polar position hypothesis**: land in polar positions causes global cooling

A continent (Antarctica) is on the South Pole, seafloor spreading is slow and mountain building is ongoing forming the Himalaya. All these 3 suggest that the climate should be cooling, not warming (when considering plate tectonics in isolation).



11 Reading assignment 5: Snowball Earth by Paul F. Hoffman and Daniel P. Schrag

Between 750 Myr ago and 580 Myr ago 4 drastic climate reversals happened, between icehouse and hothouse.

Neoproterozoic are spans from 1 Byr to 538.8 Myr ago.

Occurrence of glacial debris near sea level in the tropics.

Earth's landmasses were most likely clustered near the equator during the global glaciations that took place around 600 million years ago.

Albedo: ice sheets reflect more of Sun's energy than dark seawater.

Budyko's climate model: *But his climate simulations also revealed that this feedback can run out of control. When ice formed at latitudes lower than around 30 degrees north or south of the equator, the planet's albedo began to rise at a faster rate because direct sunlight was striking a larger surface area of ice per degree of latitude. The feedback became so strong in his simulation that surface temperatures plummeted and the entire planet froze over.*

However, according to his model, the albedo feedback should have gotten out of control and extinguished all life on Earth.

The first of these objections began to fade in the late 1970s with the discovery of remarkable communities of organisms living in places once thought too harsh to harbor life. Seafloor hot springs support microbes that thrive on chemicals rather than sunlight. The kind of volcanic activity that feeds the hot springs would have continued unabated in a snowball earth. Survival prospects seem *even rosier for psychrophilic, or cold-loving, organisms of the kind living today in the intensely cold and dry mountain valleys of East Antarctica. Cyanobacteria and certain kinds of algae occupy habitats such as snow, porous rock and the surfaces of dust particles encased in floating ice.*

In 1992 Joseph L. Kirschvink, a geobiologist at the California Institute of Technology, pointed out that during a global glaciation, an event he termed a snowball earth, shifting tectonic plates would continue to build volcanoes and to supply the atmosphere with carbon dioxide. At the same time, the liquid water needed to erode rocks and bury the carbon would be trapped in ice. With nowhere to go, carbon dioxide would collect to incredibly high levels, high enough, Kirschvink proposed, to heat the planet and end the global freeze.

4 stages of Snowball Earth

- **Snowball Earth Prologue**
  - landmass breakup 770 Myr ago
  - formerly land-locked areas closer to oceanic sources of moisture
  - increased rainfall erodes continental rocks
  - global temperatures fall, carbon-dioxide gets removed from the air
  - the ice sheets reflect sunlight, starting positive feedback
  - planet covered in ice within a millenium
- **Snowball Earth at its coldest**
  - avg global temperatures fall to $-50°$
  - oceans ice over to the depth of one kilometer
  - most microscopic marine organisms die but some live around volcanic hot springs
  - cold dry air, no precipitation
  - due to no precipitation, volcanic carbon dioxide is not removed from the atmosphere
  - the planet warms and sea ice slowly thins
- **Snowball Earth as it thaws**
  - concentrations of carbon dioxide in the atmosphere grow 1000x due to 10 Myr of normal volcanic activity
  - greenhouse warming pushes temperatures to the melting point at the equator
  - the open water absorbs more solar energy and speeds up the warming
- **Hothouse aftermath**
  - seawater evaporates and works with carbon dioxide to create even stronger greenhouse
  - surface temperatures go to more than 50 degree Celsius
  - carbonic acid rain errodes rock debris left in the wake of retreating glaciers
  - swollen rivers wash bicarbonate and other ions into the oceans, where they form carbonate sediment

Animals

- all animals descended from the first eukaryotes, cells with a membrane-bound nucleus
- by the time of the first snowball episode more than 1 Byr later, eukaryotes had not developed beyond unicellular protozoa and filamentous algae
- the extreme climate might have pruned the eukaryote tree
- all 11 animal phyla ever to inhabit the Earth emerged within a narrow window of time in the aftermath of the last snowball event

12 Lecture 5: Snowball Earth

We don't know if it actually happened.

Scientists agree there was a major change in Earth's climate. Disputes concern how major.

12.1 Carbon isotope fractionation

Bacteria take the lighter isotope ^{12}C out of water and preferentially leave out ^{13}C.

"Default" value for δ^{13}C is -6 (when no factors affect it). Values of δ^{13}C equal or below -6 mean there is no life at all.

When organic material intakes ^{12}C, the δ^{13}C in the surrounding water increases.

12.2 Port Askaig Tillite Formation, Islay

...the material of which the mass is composed have in time, deeper than we have hitherto suspected, been transported by the agency of ice. - James Thomson, F.G.S. 1871 on the stratified rocks of Islay

12.3 Sturtian (718-658 Myr) and Marinoan (650-635 Myr)

Similar glaciar rocks as found by Thomson were found everywhere, not only on Islay. This is surprising because what would glaciar rocks do e.g. in Australia?

Howchin (1908): Sturtian Formation in Sturt river, Austrailia

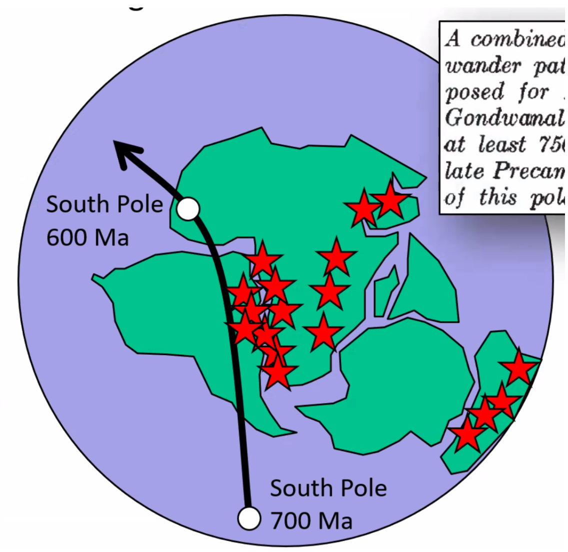
isräfflor - scratches on rocks done by glaciers.

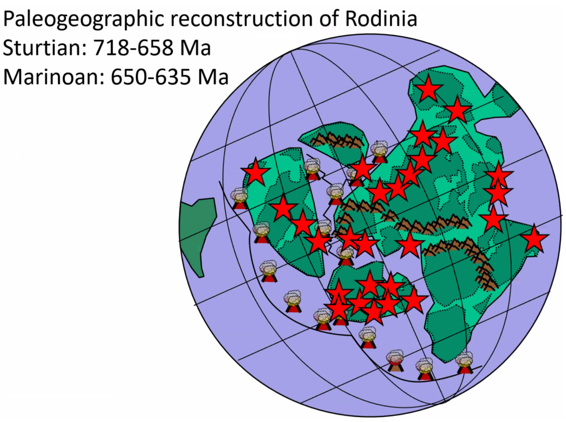
Mawson (1949): Elatina Formation, Australia

Records of severe glaciation in the late Precambrian are fast accumulating. So far as can at present be judged, frequent and widespread refrigerations were a feature of at least middle to late Proterozoic time. Glaciation is evidenced to the Equators itself.

12.4 Paleomagnetic studies of Gondwana during the Neoproterozoic Era

Neoproterozoic[7]





So how do we get the glaciers at the equator?

How about **axial tilt?** It would need to be bigger than 54° for the equator to be cooler than the poles. And it wouldn't explain why it happened twice.

12.5 Ghaub Formation, Namibia

Till[8]

Cap carbonate[9]

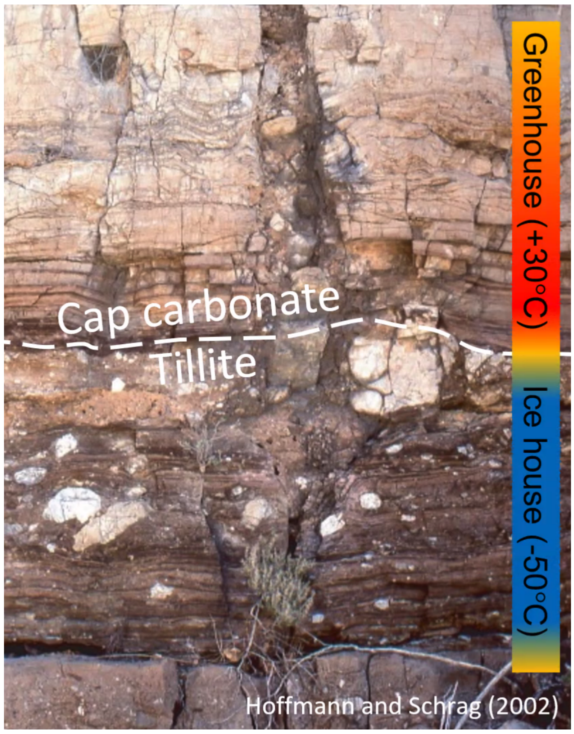
[7] 1 billion to 538.8 million years ago

[8] Till or glacial till is unsorted glacial sediment.

Till is derived from the erosion and entrainment of material by the moving ice of a glacier. It is deposited some distance down-ice to form terminal, lateral, medial and ground moraines.

Till is classified into primary deposits, laid down directly by glaciers, and secondary deposits, reworked by fluvial transport and other processes.

[9] Cap carbonates are layers of distinctively textured carbonate rocks (either limestone or dolomite) that occur at the uppermost layer of sedimentary sequences reflecting major glaciations in the geological record.



12.6 Snowball Earth hypothesis

Kirschvink (1992) first made the hypothesis but Hoffman popularized it.

Continents in the tropics (with no vegetation because it hadn't evolved yet) → Higher albedo (desert with no vegetation has higher albedo than ocean water)

Mountain building in the tropics → Faster weathering

Higher albedo + Faster weathering → Earth becomes **much** cooler → glaciation in the tropics → **even** higher albedo → **even** faster cooling → Snowball Earth

CO_2 from volcanoes → increased GH effect

Ash particles from volcanoes → Lower albedo

Lower albedo + increased GH effect → Earth becomes **much** warmer → Ice melts → **Even** lower albedo → Ice melts **faster** → Extreme GH

12.7 Solar radiation

$T = (E/\delta)^{1/4}$

$E = 342W.m^{-2}$

$\delta = 5.670367 \times 10^{-8}W.m^{-2}.K^{-4}$

$T = 6$°C

Earth's albedo is $\alpha = 30\%$ which equals $103W.m^{-2}$

Then the energy left gives -18°C. GHG contribute $+32$°C

12.8 Solar radiation (716 Myr ago = Onset of Snowball Earth)

Albedo between 50-95%. Volcanic ash on ice sheets decreases the albedo.

$E = 160W.m^{-2}$

$T = -43°$

12.9 Greenhouse effect (658 Myr = End of Snowball Earth)

We're looking for how much CO_2 would be needed in the atmosphere to exit the Snowball Earth. Currently (pre-industrial) at 280 ppm the GHG contribute 32° to global temperature.

$\Delta T = 4.3 \ln(C/C_0)$

For 1000 ppm: $\Delta T = 4.3 \ln(1000/280) = 5.5°$

For 10000 ppm: $\Delta T = 4.3 \ln(10000/280) = 15.4°$

For 100000 ppm: $\Delta T = 4.3 \ln(100000/280) = 25.27°$

$T = -11° + 25.c° = 14.3°$ at 100000 ppm (10% CO_2 in the atmosphere)

12.10 Cap carbonate

$Ca + Mg + CO_2 \rightarrow CaMg(CO_3)_2$

12.11 Iron formations

$Fe + O_2 \rightarrow Fe_2O_3$

13 Reading assignment: The Paleocene-Eocene Thermal Maximum: A Perturbation of Carbon Cycle, Climate, and Biosphere with Implications for the Future

PETM: Paleocene-Eocene Thermal Maximum, ca. 56 Myr ago

Period of carbon release below 20k years, the whole event lasted about 200k years. The global temperature increase was $5 - 8°$.

Kenneth and Stott 1991:

- Ocean Drilling Program 690 off the coast of Antarctica
- Decline in oxygen isotope ratios indicating warming $3 - 4°$ in surface water and 6° in deep water
- Negative shift in $\delta^{13}C$ of benthic and planktic forams
- Rapid onset of the event, around 6k yrs

CIE: Carbon Isotopic Excursion

Dating CIE onset:

- Using radiometric dates of marine ash layers and orbital tunings of marine sediments
- Dated around 56.011-56.293 Ma.
- Orbital timescales suggest total duration of 150-220 ka.

The PETM is defined by a global temperature rise that was initially inferred from a $> 1‰$ negative excursion in in $\delta^{18}O$ of benthic foraminifera, indicating a deep-water temperature increase of 5°C.

A similar warming was inferred from the Mg/Ca ratios.

The absence of warming during PETM at polar latitudes implies lack of ice-albedo feedback loop.

Indicators of massive carbon release at PETM:

- large global negative CIE
- extensive dissolution of deep-ocean carbonates

The negative shift in carbon isotope ($\delta^{13}C$) values shows that the carbon released was depleted in ^{13}C relative to the exogenic reservoir (ocean + atmosphere + biomass) and was likely organic carbon because organisms discriminate against ^{13}C during biosynthesis. The rapid onset (¡20ka) indicates addition of ^{13}C-depleted carbon rather than reduction in organic carbon burial (100ka timescale).

13.1 Summary points

1.The Paleocene-Eocene Thermal Maximum, which took place around 56 Mya and lasted for around 200 ka, stands as the most dramatic geological confirmation of the greenhouse theory – increased CO_2 in the atmosphere warmed Earth's surface.

2. The large release of organic ^{13}C-depleted carbon caused a global carbon isotopic excursion, widespread deep-ocean acidification, and carbonate dissolution.

3. Carbon was removed from the exogenic pool on a timescale of 100 ka, primarily through silicate weathering and eventual precipitation of carbonate in the ocean and/or uptake by the biosphere and subsequent burial as organic carbon.

4. Warming associated with the carbon release implies approximately two doublings of atmospheric pCO_2 unless climate sensitivity was significantly different during the Paleogene.

5. Although there was a major extinction of benthic foraminifera, most groups of organisms did not suffer a mass extinction.

6. Geographic distributions of most kinds of organisms were radically rearranged by $5 - 8°$C of warming, with tropical forms moving poleward in both maritime and terrestial realms.

7. Rapid morphological change occured in both maritime and terrestrial lineages suggesting that organisms adjusted to climate change through evolution as well as dispersal and local extirpation. Where best understood, these evolutionary changes appear to be a response to nutrient and /or food limitation.

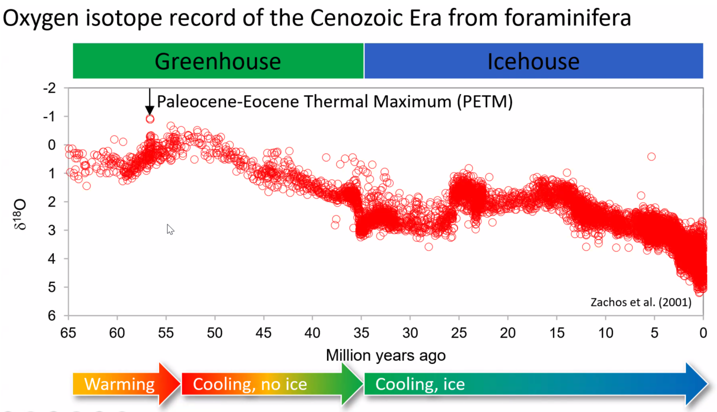
8. Research of the PETM and other intervals of rapid global change has been driven by the idea that they provide geological parallels to future anthropogenic warming, but much remains to be done to gain information that can be acted on.

14 Lecture 6: Paleocene-Eocene Thermal Maximum

Snowball Earth won't happen again because of vegetation it would be very hard to get that albedo effect.

The brown section in sediment blocks from Ocean Drilling Program is pure clay, corresponding to a period without deep marine life.

Cenozoic Era is the last 66 Myr, from the last major extinction to the present day.



If we zoom into the above graph, the spike is very sudden, on a scale of 1 Myr. δ^{18}O changes from 0.5 to -1.

$\Delta T = 4.2[\delta^{18}O_1 - \delta^{18}O_2]$

$\Delta T = 4.2[1.5] = 6.3°$

So what we observe is a temperature change of +6.3°. We're currently experiencing a world 1.5° warmer than it should be.

We see the effect of **extreme warming** in the marine life – there seems to be absence of forams sediments in that period of time. The warming is clearly correlated with a mass extinction.

14.1 Cerrejon mine, Colombia

In this coal mine, researchers have found fossils of a snake *titanoboa cerrejonensis vertebrae*. The snake was *massive*, much bigger than Boa constrictor (3.4m).

14.2 Titanoboa cerrejonensis as a paleothermometer

Modern light green anaconda: 7.3m, living in mean annual temperature of 27°C.

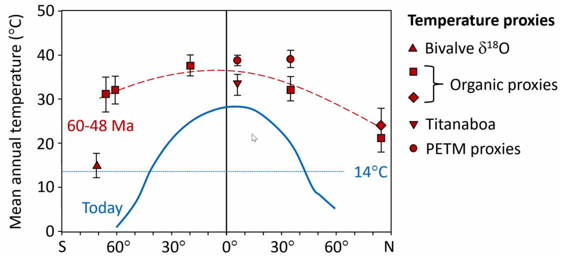
Titanaboa was at least 13m, living in $32 - 33$°C.

(both measured at 5.5°N).

Mean annual temperature at PETM was $39 - 40$°C.

14.3 Mean annual temperature and latitude

In a warmer climate, temperature flattens out. We see it today, we call it Arctic amplification. In the Arctic regions, warming is happening much faster then elsewhere. In Svalbard, there's up to 10 degrees of warming.



14.4 Carbon isotope record: PETM

Carbon isotope value becomes radically more negative at the PETM, mirroring the oxygen data. Whatever was added to the ocean, must have a very negative $\delta 13C$.

Candidates:

- Volcanoes (CO_2; $\delta 13C = -6$)
- Methane from thawing of permafrost (CH_4; $\delta 13C = -22$)
- Methane clathrates – in sediments on a seafloor (CH_4; $\delta 13C = -60$)

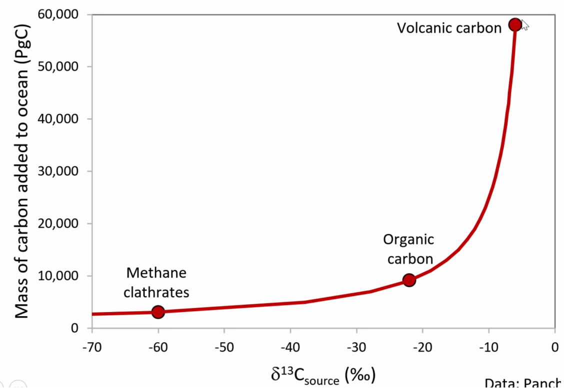
Was it a lot of volcanism, was it a fair amount of thawing permafrost, or was it a little bit of methane clathrates?

$\delta^{13}C_{\text{source}} = [(\delta^{13}C_2 - \delta^{13}C_1) \times (C_{\text{mass in ocean}} + C_{\text{mass added to ocean}}) - (C_{\text{mass in ocean}} \times 1.5)]/C_{\text{mass added to ocean}}$

We know the mass of carbon in the ocean to be 38700 billion tons. We also know that $\delta^{13}C$ dropped from 1.5 to -1.5.

$\delta^{13}C_{\text{source}} = [(-1.5-1.5)\times(38700+C_{\text{mass added to ocean}})-(38700\times 1.5)]/C_{\text{mass added to ocean}}$

Here's how much carbon we would need to add from different sources:



Researchers estimated that between 3000 PgC and 7126 PgC could have accumulated in the ocean. This suggests that the likely source of carbon is not volcanoes, simply not enough carbon is added. It must be one of the other two factors, or the combination (thawing of permafrost or methane clathrates).

14.5 Hypothesis

More CO2 in the atmosphere and oceans because of volcanism → Global warming → Permafrost and/or methane clathrates thaw

→ More CH_4/CO_2 in the atmosphere and oceans → Greenhouse effect strengthens → Global warming

The hypothesis is then that the **volcanism was the trigger** but the thawing of permafrost and/or clathrates was the **feedback loop**.

14.6 Carbonate Compensation Depth (CCD)

CCD describes the depth at which the reaction swaps directions
$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO2 + H_2O$
——————————— (CCD) ———————————
$CaCO_3 + CO2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$

Beyond compensation depth, limestone dissolves.

When we add CO_2, the CCD rises to a higher level, because the bottom reaction is favoured.

Currently, CCD is around 3500-4000 meters.

14.7 Duration of PETM

170000 years

That's how long it takes to recover after a perturbation of the carbon cycle. That's important to know because people are perturbing the carbon cycle today.

14.8 Bighorn Basin, Wyoming

- 5 species found only before PETM
- 22 species found before and after PETM
- 46 immigrant species during PETM
- 5 immigrant species after PETM

We're seeing this today, at 1.5° warming, 2% of species are heading towards extinction.

15 Reading assignment: Chapter 19: Causes of Warming over the last 125 years

15.1 Natural causes of recent warming

Changes over tectonic time scales are clearly irrelevant to the changes of the last 125 years. Average rate of cooling during transitions between greenhouse and icehouse conditions is 0.00001° per century).

Orbital forcing works at the rate of 0.00016° per century or less.

15.1.1 Solar forcing

The amount of radiation arriving from the Sun varies in 11-year cycles changing by a little over 1 W/m^2, equivalent to about 0.1% of the global average.

15.2 CO_2

Bubbles of ancient air trapped in ice and direct measurements of air by the geochemist Charles Keeling begun in 1958 show an accelerating rise in the CO_2 concentration during the last two centuries. By 2010 the CO_2 concentrations had risen to 390 ppm, well above the 180-300ppm range of natural (glacial-interglacial) variations.

On an annual average, cold high-latitude ocean water is a CO_2 sink and warm low-latitude ocean is a CO_2 source. One of the reasons is that CO_2 gas is more easily dissolved in cold water than in warm water.

Greenhouse experiments show that most plants obtain carbon more effectively from CO_2-rich atmosphere and grow faster as a result.

Ice core and instrumental measurements show that atmospheric CO_2 levels have risen by almost 40% in the last 150 years.

15.3 Methane (CH_4)

Since the 1800s, the methane concentration has risen to over 1750 ppb, well above the natural range of 350-700ppb.

Methane comes from sources rich in organic carbon but lacking in oxygen, such as swampy bogs with decaying plants, guts of cattle, animal and human waste, burning of grassy vegetation.

15.4 Increases in Chlorofluorocarbons (CFCs)

These compounds include elements of chlorine (Cl), fluorine (Fl) and bromine (Br).

They have for decades been produced for use in refrigerators and air conditioner coolants, cheical solvents, fire retardants and foam insulation in buildings.

They stay in the atmosphere for around 100 years.

15.5 Ozone

Ozone originates from both natural and human processes such as biomass burning and oil production in refineries.

At high concentrations ozone is toxic to plants and human eyes and lungs.

In the lowermost atmosphere, ozone increased due to human activities, causing periodic smog alerts in many large cities.

15.6 Sulfate aerosols

Large plumes of sulfate aerosols have a cooling effect on the climate by reflecting some of the solar radiation back to space. The second effect is less understood and that is particles of water vapour condensing around aerosole particles and forming clouds.

15.7 Land clearance

Effects:

- Increased albedo at high and middle latitudes

- At tropical and subtropical latitudes, reduced amounts of evapotranspiration[10].
- Consequently, with reduced moisture, land surfaces dry out and bake in the sun.
- On a global average basis, the net effect of land clearance has been a small cooling of the planet.

15.8 Climate feedbacks

Positive feedbacks (evaluated at 2x CO_2)

- Water vapor. According to current estimates it could cause additional 1.1° to 1.5° warming in addition to the 1.1° from radiative forcing.
- Diminishing albedo due to retreat of snow and ice toward the poles. Estimated at about 0.6° additional warming.
- Clouds. Difficult to estimate.

Negative feedbacks:

- Aerosols seeding cloud nuclei.
- CO_2 fertilization effect.

Other effects slowing down climate change:

- Ocean Thermal Intertia. Slows down the oceans' response by decades.
- Anthropogenic aerosols. Offsets the radiative forcing by up to 25%.

15.9 Key terms

chlorofluorocarbons (CFCs): Compounds that include elements of chlorine (Cl), fluorine (Fl) and bromine (Br).

ozone: O_3. It occurs naturally in the stratosphere, with the largest concentrations at altitudes between 15 and 30 km. Incoming UV radiation from the Sun liberates individual O atoms from oxygen (O_2) and produces ozone.

ozone hole: Chlorine reacts with ozone and destroys it, forming chlorine monoxide (ClO). The region over Antarctica in which stratospheric ozone is much less abundant than elsewhere (due to cumulation of CFCs) is called the ozone hole.

brown clouds: Carbon-rich aerosole hazes over Southeast Asia, mostly originating from small cook stoves in which people burn organic matter for fuel, including cow dung.

black carbon: Carbon particles resulting from incomplete combusion, e.g. soot. When they fall down and settle on bright surfaces over snow and sea ice, they absorb solar radiation and reduce the albedo effect.

global dimming: A phenomenon in which the amount of solar radiation reaching the ground slowly decreases due to sulfate aerosols, brown clouds, contrails emitted by jets, and other emissions. Between 1950s and 1980s the solar energy reaching the ground decreased by several percent.

[10]Evapotranspiration = evaportation + transpiration. Transpiration is the process of water movement through a plant and its evaporation from aerial parts, such as leaves, stems and flowers.

2x CO_2 sensitivity: The global average temperature predicted by a climate model (run to equilibrium or near-equilibrium) assuming the doubling of CO_2 in the atmosphere from the preindustrial level of 280ppm.

equivalent CO_2: A unit standardizing different gases' global warming potential in relation to CO_2. For instance, the multiplier for methane is 25.

radiative forcing: Additional radiation hitting the Earth's surface measured in W/m^2, caused by GHGs.

enhanced greenhouse effect: Greenhouse effect contributed since 1850, that is excluding the natural greenhouse effect of $150W/m^2$. Enhanced greenhouse effect is $2.7W/m^2$.

15.10 Review questions

15.10.1 What human activities produce CO_2 and how have they changed in the last 200 years?

Late 1700s and most of the 1800s: clearing of forests for agriculture and charcoal for furnaces in the early part of the Industrial Revolution.

After 1900: extraction of fossil fuels buried beneath Earth's surface: coal at first, then oil and natural gas.

15.10.2 Where does the CO_2 produced by humans go?

- Atmosphere: 55%
- Biosphere: 15-20%
- Shallow ocean: 25-30%

15.10.3 How high in the atmosphere do sulfate aerosols from smokestacks reach?

Within the lower several kilometers.

15.10.4 Why do cholorfluorocarbons (CFCs) reach much higher in the atmosphere than sulfate aerosols?

Because CFCs stay in the atmosphere for around 100 years and SAs are removed by rain after a few days.

15.10.5 What are the strongest positive and negative feedbacks on changes in Earth's temperature?

Positive: water vapour. Negative: aerosols working as cloud nuclei.

15.10.6 In a net sense, do feedbacks increase or decrease the direct radiative effects of greenhouse gases on global temperature?

On a short time scale they moderate this effect.

15.10.7 What factors complicate attempts to estimate Earth's sensitivity to CO_2 by directly comparing the observed twentieth-century warming to the measured rise in greenhouse gases?

Anthropogenic aerosols and ocean's thermal intertia, both of which slow down or moderate the direct warming effect.

15.10.8 Some climate skeptics point out that temperatures were warmer in north polar regions 6000 years ago, and conclude that modern GHG concentrations have not produced warmth that is unusual by natural standards. Evaluate the relevance of this conclusion based on what you have learned from this book.

None of the natural effects (orbital forcing, solar cycles, Milankovic cycles etc.) work with such strong effect on such short time scale as we are observing now.

16 Reading assignment: Chapter 20: Future Climatic Change

16.1 Key terms

CO_2 fertilization effect: Increased vegetation growth caused by addition of CO_2 to the atmosphere.

ocean acidification: The trend in the pH of the ocean to grow more acidic as a result of absorption of CO_2 emitted by humans.

methane clathrate: A partly frozen mix of methane (CH_4) and slushy ice.

16.2 Review questions

16.2.1 What factors will determine how much CO_2 humans add to the atmosphere in the future?

increase in carbon emissions = increase in population × change in emissions per person × changes in efficiency of carbon use

In other words:

population growth × economic growth × technology

16.2.2 Where will all of this excess carbon eventually go?

Subsurface ocean, in decades to centuries. In centuries to millenia, it will dissolve ocean floor and acidify the oceans.

16.2.3 In what way will the future CO_2 warming be like and unlike past CO_2 warmings?

The future warming will be characterized by fast responding parts like atmosphere, land surface and vegetation and slow responding parts like deep ocean and ice sheets. A disequilibrium between them has never been observed before.

16.2.4 In a 3x CO_2 world, where will ice of any kind still be found on Earth?

On Antarctica. Small amounts will probably reform in the Arctic in the winters.

16.2.5 Will future temperature changes be readily apparent to the average person? Why or why not?

Yes because:

- Warming of upper to middle latitudes of around 7°.
- Growing crops at more northern latitudes will be possible.
- Greater stress on water sources in tropics and subtropics where 80% of people live.
- Sea level rise of 50cm.

16.2.6 What are the disadvantages in drastically reducing our industrial emissions of sulfur and carbon?

The sulfates and their cooling properties would disappear but carbon would linger in the atmosphere for ages.

17 Lecture 7: A geological perspective on ongoing global warming

17.1 Atmospheric CO_2 concentration

- measurement data from ice cores (before 1959) and Mauna Loa (after 1959)

17.2 Cumulative anthropogenic emission of carbon

- currently at over 400 PgC
- remaining fuels allow to hit 1000-2000 PgC
- PETM emissions: 3000-7000 PgC
- according to business-as-usual projections, we will enter the PETM levels in 2159 and go beyond them in 2278
- but this is not going to happen, because we'll run out of fossil fuels before that

17.3 Atmospheric CO_2 concentration

- currently at around 350ppm
- remaining fossil fuels allow for 550-750ppm
- 2.13 PgM CO_2 corresponds to 1ppm change
- according to projections, we'll run out of fossil fuels between 2070 and 2120 assuming business-as-usual

17.4 Eocene greenhouse

- sea level was 65 m higher
- temperature was $5 - 15°$ higher
- risk for hyperthermals

- 35 Ma switch from greenhouse to icehouse
- burning out all fossil fuels puts us in the greenhouse conditions

17.5 Comparison of the PETM hyperthermal with ongoing global warming

- based on carbon emission rates, ongoing global warming is calculated to be an order-of-magnitude faster than at the start of the PETM hyperthermal
- carbon accumulation rates in PETM: $0.3 - 1.5$ PgC/yr, currently it is 11 PgC/yr (anthropogenic)

17.6 "Eocene Park"

- if we burn remaining fossil fuels (within 50-100 years), Earth's climate will resemble the Eocene greenhouse frm 56 to 35 Ma
- in the Eocene, sea level was 65m higher and temperature was $10 - 15°$ higher than today
- there were also hyperthermals such as the PETM
- ongoing global warming is an order-of-magnitude faster than global warming at the start of the PETM
- recovery from global warming is likely to take 170000 years

17.7 Summary

- the biggest problem is not the amount of warming, it's the rate of warming
- Earth actually thrives in a warmer climate, provided that the warming happens over very long timescale and ecosystem has time to adapt (e.g. 60 Myr)

18 Reading assignment: The Anthropocene: conceptual and historical perspectives

Will Steffen, Jacques Grinevald, Paul Crutzen and John McNeill

18.1 Abstract

- the case for formally recognizing the Anthropocene as a new epoch
- advent of Industrial Revolution around 1800 is a logical start date for the epoch

18.2 Introduction

- discovery of ozone hole over Antarctica with anthropogenic cause
- in addition to carbon cycle, humans are altering several other element cycles such as nitrogen, phosphorus and sulphur
- humans are also strongly modifying terrestrial water cycle
- driving the 6th major extinction event in Earth's history
- the term Anthropocene suggests that humans have become a **geological** force of their own

18.3 Antecendents of the Anthropocene concept

18.4 History of the human-environment relationship

- *homo erectus* learned how to make stone tools, rudimentary weapons, and control fire
- shift from primarily vegetarian diet to omnivorous
- brain size grew 3fold
- development of spoken language
- written language, accumulation of knowledge
- China started burning coal in 11th century to support its iron industry
- coal started being used as fuel in England around 13th century
- London burned 360000 tonnes of coal annually by 1600s
- but China and England were still exceptions then
- pre-industrial events proposed as beginning of Anthropocene
  - wave of extinctions of the Pleistocene[11] megafauna, to which human hunting pressures played a role
  - Neolithic Revolution in the early phases of the Holocene [12]. Two agriculture-related events: the clearing of forests about 8000 yrs ago and development of irrigated rice cultivation about 5000 yrs ago presumably emitted enough CO_2 to prevent the initiation of the next ice age

18.5 The beginning of the Anthropocene

- the Industrial Revolution had origins in Great Britain in the 1700s
- end of agriculture as the most dominant human activity
- growing energy bottleneck: plants use less than 1 percent of the incoming solar radiation for photosynthesis and animals eating plants obtain only 10% of energy from these plants
- discovery and exploitation of fossil fuels helped bypass that bottleneck
- Haber-Bosch process: energy intensive process synthesizing reactive nitrogen compounds from unreactive nitrogen in the atmosphere, creating fertilizer out of air
- between 1800 and 2000, human population grew from 1B to 6B, energy use grew 40x and economic production 50x

[11] 2.58 Ma to 11700 ago
[12] 11700 ago to now

18.6 The Great Acceleration

- the period from 1945 to 2000+
- population increased 3B to 6B
- economic activity grew 15x
- consumption of petroleum grew 3.5x
- number of motor vehicles rose from 40M to 700M by 1996
- over half of human population now lives in urban areas
- this 6th great extinction will be the 1st caused by a biological species
- atmospheric CO_2 concentration grew by 58ppm

18.7 The anthropocene in the twenty-first century

- the Great Acceleration has become much more democratic and moved to developing countries, such as China, India, Brazil, South Africa, Indonesia
- developing countries have accounted for only about 20% of total emissions since 1751 but contain about 80% of world's population
- for 2004, the emissions of developing countries grew to over 40% total
- **peak oil**
  - maximum rate of the production of oil in any area under consideration, recognizing that it is a finite natural resource
  - availability of oil beyond 2010?
  - increased demand of about 2-3% yr^{-1} has been observed through 2000-2010
- **phosphorus**
  - the world may be close to peak phosphorus
  - phosphorus along with nitrogen is a key element in fertilizers
  - the demand for fertilizer will grow
- in May 2010 scientists built a genome from its chemical constituents and used it to make synthetic life
- they created a bacterial chromosome, which was transferred into a bacterium where it replaced the original DNA, the bacteria cell then began replicating to produce a new set of proteins
- most widely discussed geo-engineering approach is artificially spreading aerosols into the stratosphere
- **planetary boundaries** – approach explicitly based on returning the Earth's system to the Holocene domain
- the set of planetary boundaries defines the safe operating space for humanity with respect to the Earth system

18.8 Societal implications of the Anthropocene concept