Climate Change - Geological Perspective at Stockholms Universitet

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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 ice-house 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.

Processional 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

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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.

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.