

Climate Change - Geological Perspective at Stockholms Universitet

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Spring 2025

1 Reading assignment: Earth's Climate Chapter 4

1.1 Key terms

Greenhouse era: times when no ice sheets are present

Icehouse era: times 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 \rightarrow warmer climate \rightarrow increased temperature, precipitation, vegetation \rightarrow increased chemical weathering \rightarrow increased CO_2 removal by weathering \rightarrow reduction of initial warming
- initial change \rightarrow colder climate \rightarrow decreased temperature, precipitation, vegetation \rightarrow decreased chemical weathering \rightarrow decreased CO_2 removal by weathering \rightarrow 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 it's 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 with 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 driven 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 double 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 CO₂ 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. They also point out that the very late appearance of shell-bearing oceanic organisms near 540 million years ago means that life had played no obvious role in transferring the products of chemical weathering on land to the seafloor for the preceding 4 Byr.

Supporters claim that critics underestimate the role of primitive life-forms such as algae in the ocean 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 matter in terms of that 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 unit² away from the Sun. Let's calculate it:

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

¹When 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: $1W = 1kg \cdot m^2 \cdot s^{-3}$

²roughly equal to average distance Sun-Earth

Solar constant $S_0 = \frac{Q}{4\pi d^2} = 1362 W.m^{-2}$. 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 $342 W.m^{-2}$.

Now from Stefan-Boltzmann's law, we can calculate the temperature:

$$E = \sigma T^4$$

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

$$T = (E \cdot \sigma^{-1})^{1/4} = 6^\circ$$

Now let's compare with values for Venus:

$$d_{Venus} = 108 \times 10^9 m$$

$$E_{Venus} = 658 W.m^{-2}$$

$$T_{Venus} = -55^\circ$$

Albedo

Black seat: low albedo, white cat: high albedo

Venus has albedo effect of $\alpha = 77\%$

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

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 CO₂'s content in atmosphere increased from 285ppm to 425ppm.

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

2.2 Earth's temperature summary

$$\begin{matrix} 6^\circ & + & -24^\circ & + & 32^\circ \\ \text{Solar radiation} & & \text{Albedo} & & \text{Greenhouse cases} \end{matrix}$$

2.3 Faint Young Sun paradox

We have fossils from 3.5 Byr ago. Earliest fossils are stromatolites³.

Assuming the same percentage of CO₂ 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 CO₂ on geological timescales

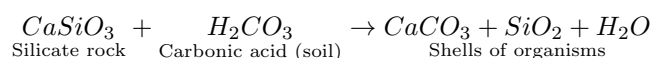
Volcanoes

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

2.5 Earth's thermostat – chemical weathering

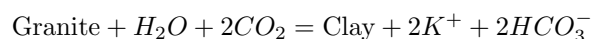
Hydrolysis is the main mechanism for removing CO₂ from the atmosphere. Three key ingredients are minerals that make typical continental rocks, water derived from rain, and CO₂ derived from the atmosphere.

The central equation for chemical weathering is:



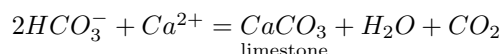
2.6 Chemical weathering of silicate rocks

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



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

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.



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 CO₂ 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 (CaCO₃) or magnesium carbonate (MgCO₃) 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 isotopes⁴ 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 dating. 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

⁴Isotopes 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 unrepeatable 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 tissue (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 information 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 thereby 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 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) 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 silt⁵ 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.

⁵pl: mul

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}N . Radiocarbon dating was invented by Willard Libby.

Varves: annual couplets, sediments in some lakes. They result from seasonal alternations 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: diverse 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 ($\text{SiO}_2 \cdot \text{H}_2\text{O}$).

Radiolaria: sand-sized animals with ornate shells often resembling pre-modern (Prussian) military helmets. Create shells of opaline silica ($\text{SiO}_2 \cdot \text{H}_2\text{O}$).

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 through the 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 running 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 amount 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:
$$\text{residence time} = \frac{\text{reservoir size}}{\text{Flux rate in (or out)}}$$

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:** 10²-0 years back
- **Historical:** 10³-0 years back
- **Tree rings:** 10⁴-0 years back
- **Ice cores:** 10⁶-0 years back
- **Lake sediments:** up to 10⁹ years back
- **Coral reefs:** 10⁶-0 years back
- **Ocean sediments:** up to 10⁹ years back
- **Continental coastal sediments:** up to 10⁹ 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 H₂O molecules that are deposited in ice sheets differs from the average composition of the molecules left in the ocean.
- terrestrial carbon (vegetation) is enriched in one isotope of carbon compared to the average in the ocean