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:

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

[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

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:
$E = \sigma T^4$
$E = 342 W.m^{-2}$
$T = (E.\sigma^{-1})^{1/4} = 6°$

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

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 $658 W.m^{-2} \cdot 77\% = 504 W.m^{-2}$. 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

[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} isotope.