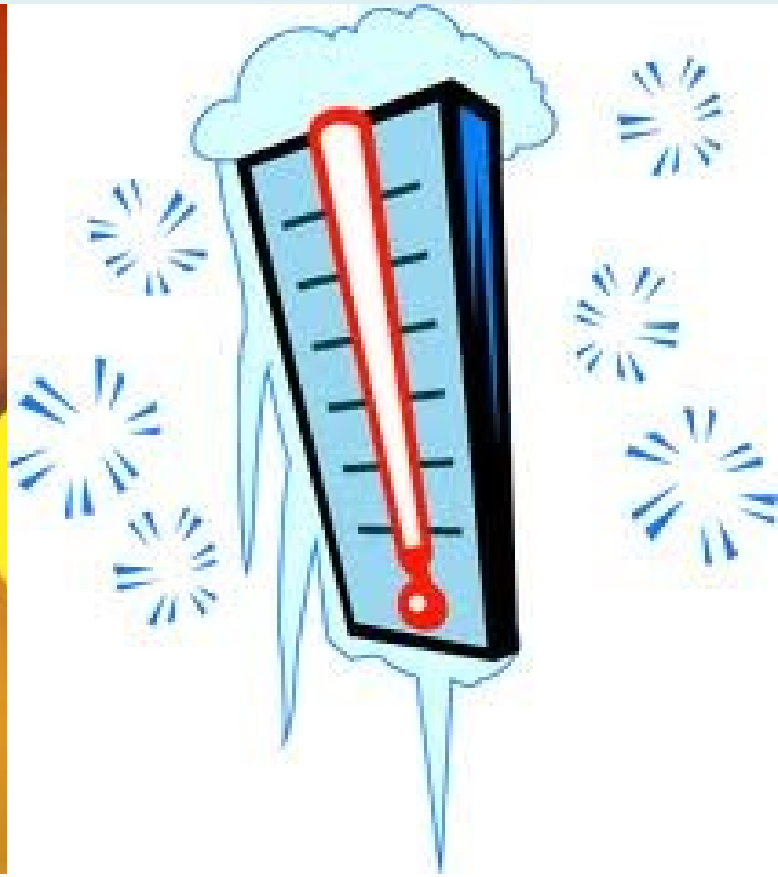
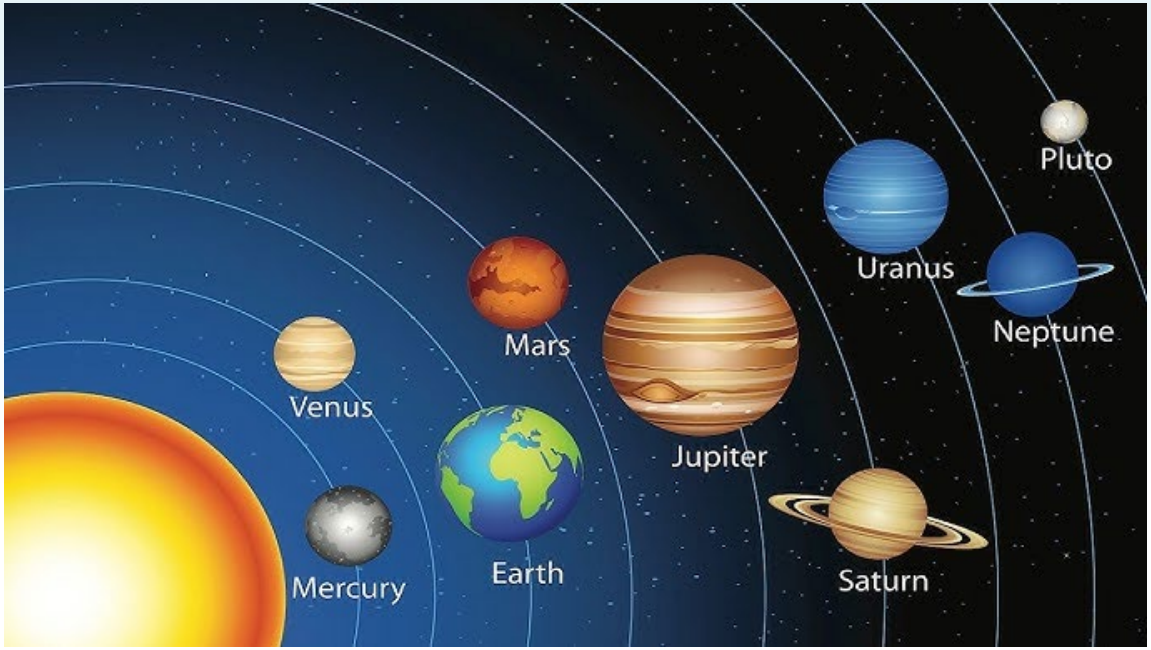


Long-term climate (and CO_2) variations

Source images: Ruddiman, 2007 (Chapter 3)

WHY IS THE EARTH A HABITABLE PLANET?

WHY IS EARTH HABITALE PLANET?
Earth is habitable primarily due to its ideal distance from the Sun, which maintains a suitable average temperature of around 15°C.



WHY THE EARTH HAS REMAINED HABITABLE FOR 4.57 Byrs?
Earth has remained habitable for 4.57 billion years despite the Sun's increasing brightness (+25-30%) because it has shifted between Greenhouse and Icehouse eras, maintaining conditions suitable for life.

This raises doubts about the true importance of the Sun-Earth distance in determining Earth's habitability.

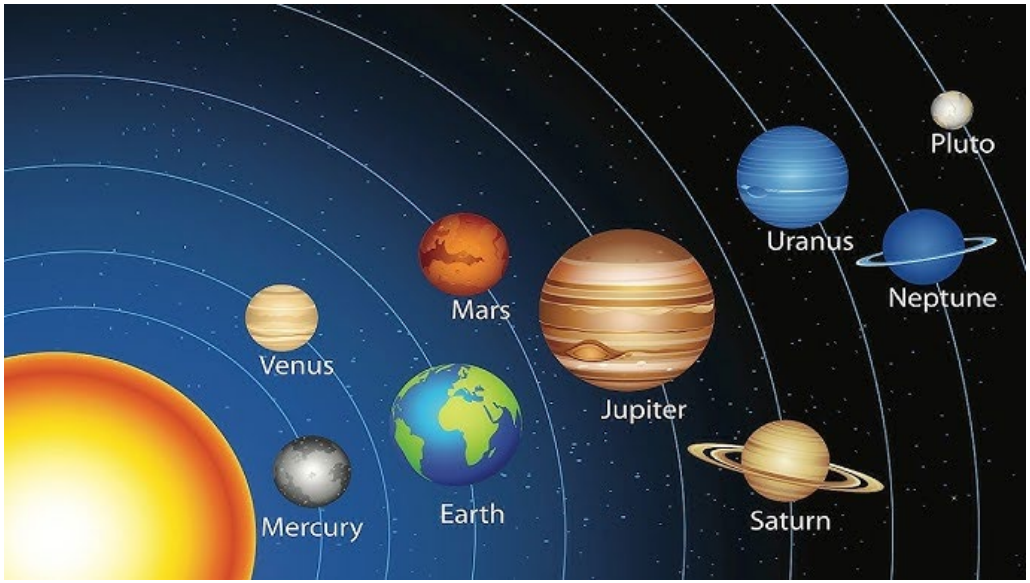
Comparing Venus and Earth

Comparison between Venus and Earth in terms of temperature and distance from the Sun:

- **Venus**:
  - Average distance from the Sun: **108.2 million kilometers**
  - Average surface temperature: **465°C**
- **Earth**:
  - Average distance from the Sun: **149.6 million kilometers**
  - Average surface temperature: **15°C**

$$\frac{Venus - Sun\ distance}{Earth - Sun\ distance} =$$

$$\frac{108.2\ 10^6}{149.6\ 10^6} = 0.72$$



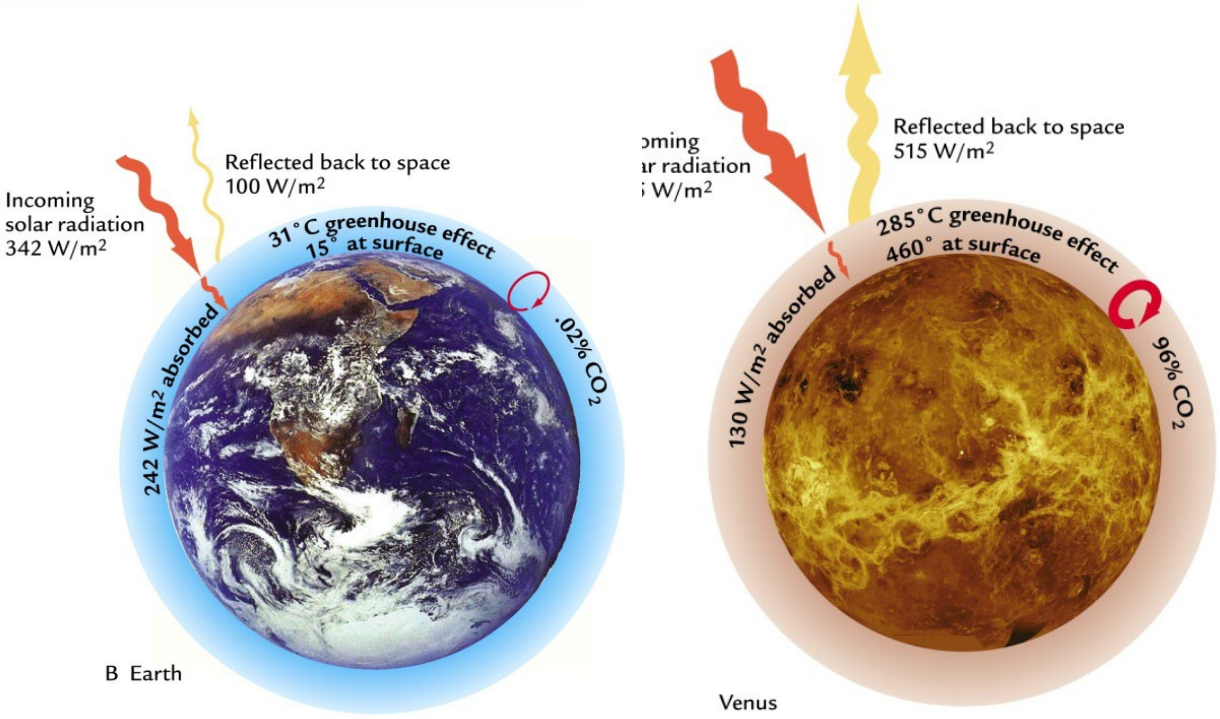
Comparing Venus and Earth

The incoming radiation (or insolation) on the two planets is inversely proportional to the square of the distance, or ($1/d^2$).

$$Incoming\ Solar\ Radiation\ Earth = \frac{1}{{d_T}^2} = \frac{1}{1^2} = 1$$

$$Incoming\ Solar\ Radiation\ Venus = \frac{1}{{d_V}^2} = \frac{1}{(0.72)^2} = \frac{1}{0.518}$$

$$\frac{Incoming\ Solar\ Radiation\ Venus}{Incoming\ Solar\ Radiation\ Earth} = \frac{1}{0.518}/1 = 1.93/1 = 1.93$$



Venus receives 1.93 times more solar radiation than Earth.

Comparing Venus and Earth

Venus receives about 1.93 times more solar radiation than Earth due to its closer distance to the Sun.

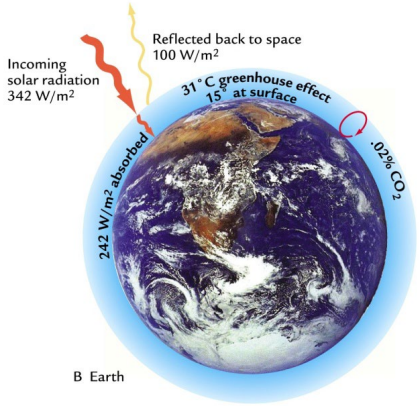
However, Venus has a much higher albedo, reflecting around 74% of incoming solar radiation, while Earth's albedo is about 30%. This means that although Venus gets more radiation, it reflects a larger portion

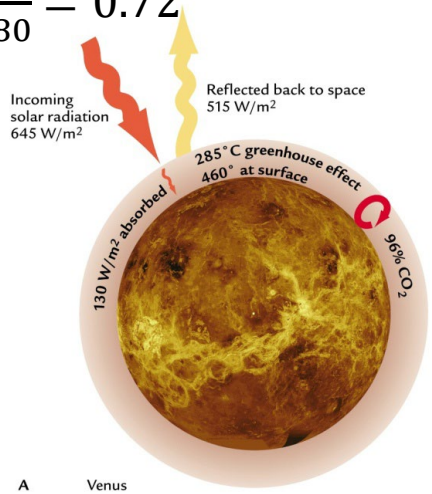
$\text{Albedo}_E = 0.30 \qquad \text{ISR adsorbed} = 0.70$

$\text{Albedo}_V = 0.80 \qquad \text{ISR adsorbed} = 0.20$

$$\frac{Incoming\ Solar\ RadiationV}{Albedo_V} \Big/ \frac{Incoming\ Solar\ radiation_E}{Albedo_E} = \textbf{\textit{Venus NET ISR compared to Earth IRS}}$$

$$\frac{Incoming\ Solar\ RadiationV}{Incoming\ Solar\ Radation_E} * \frac{Albedo_E}{Albedo_V} = 1.93 * \frac{0.30}{0.80} = 0.72$$

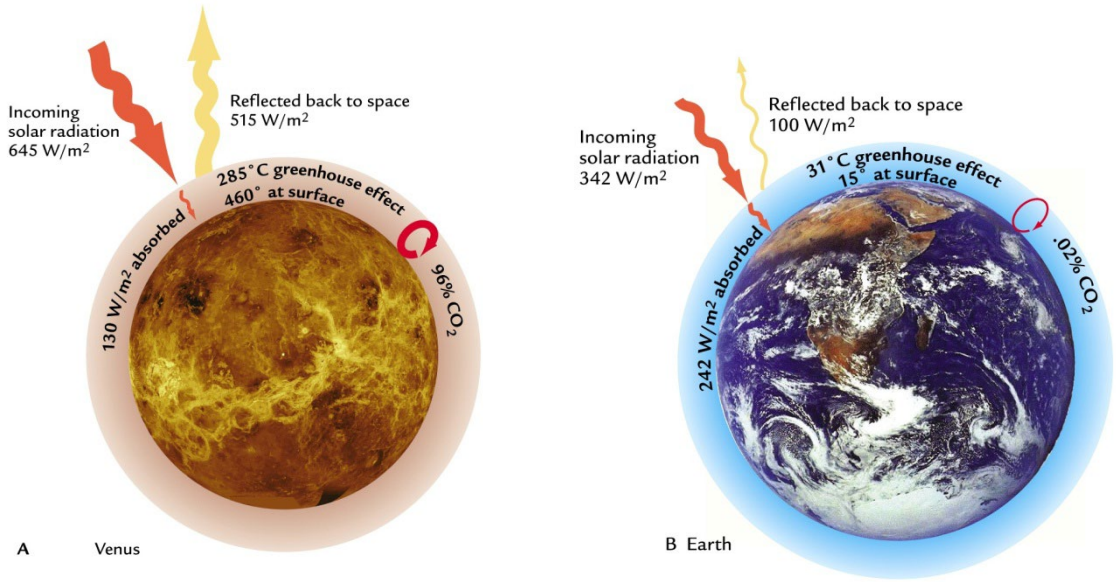




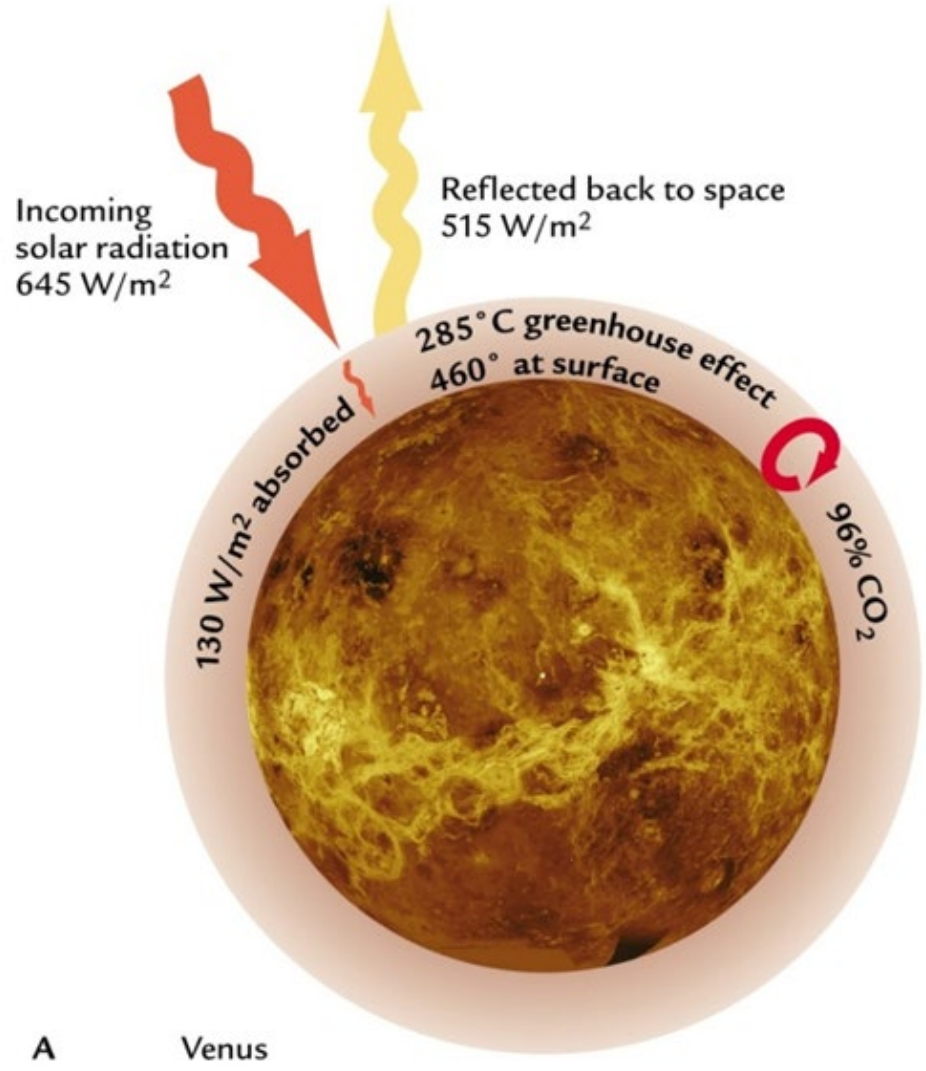
Comparing Venus and Earth

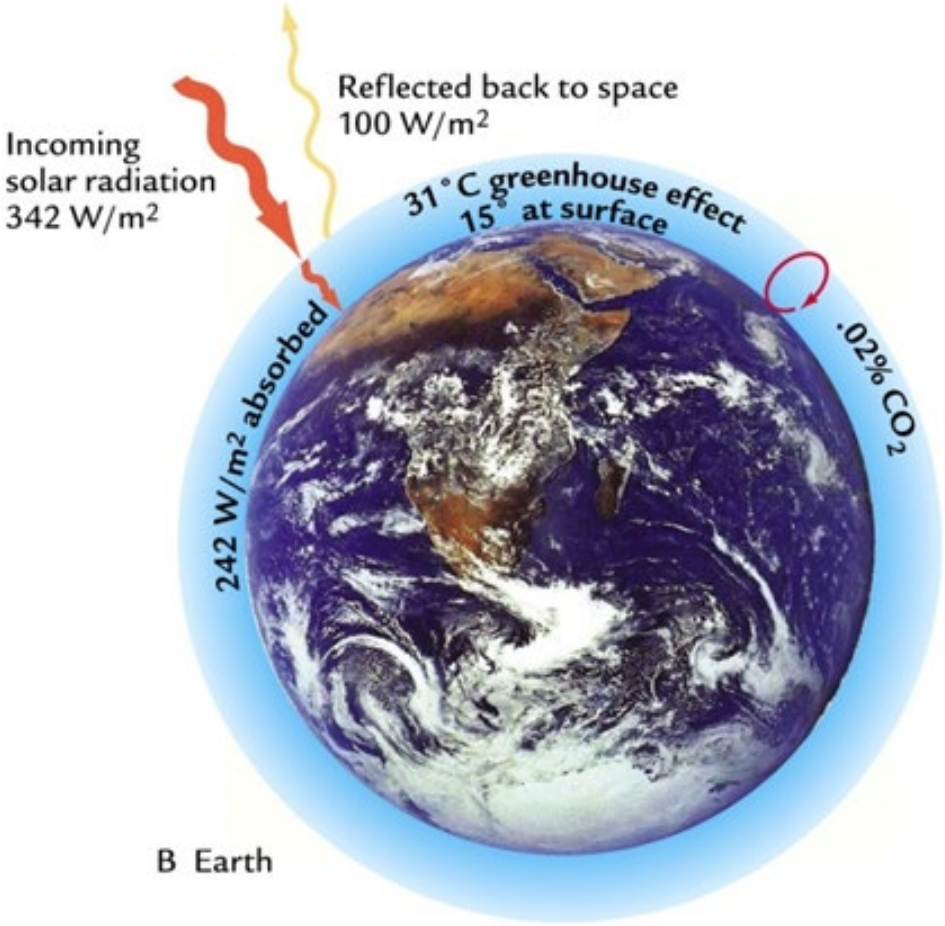
Despite reflecting more solar radiation due to its higher albedo, Venus has a much higher surface temperature because of its **thick atmosphere** rich in carbon dioxide (CO_2).
This creates a **runaway greenhouse effect**, trapping heat very effectively and preventing it from escaping back into space.

As a result, the surface temperature of Venus soars to around **465°C**, making it much hotter than Earth, despite receiving and reflecting more sunlight.



Comparing Venus and Earth

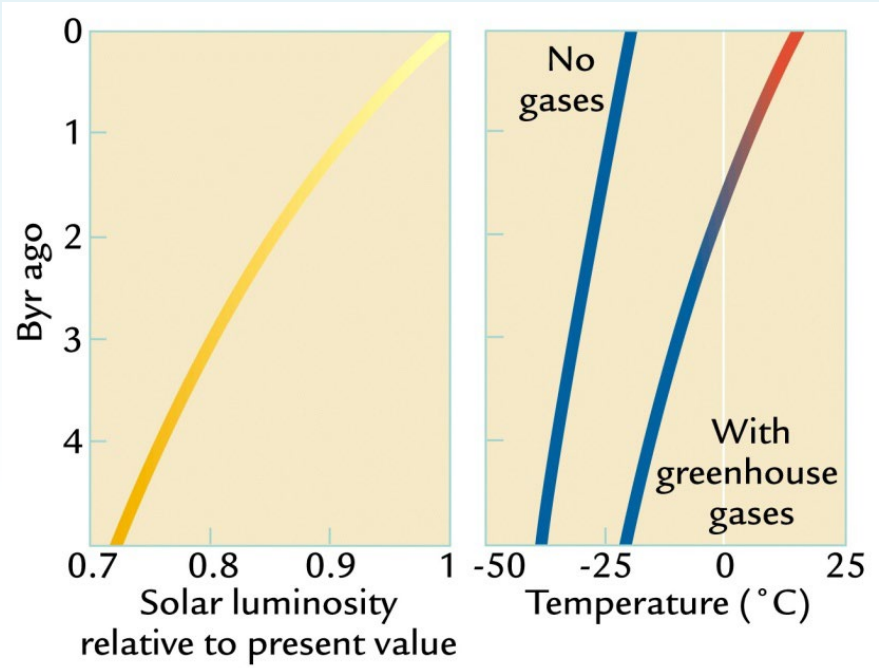




FAINT YOUNG SUN PARADOX

Over 4.57 billion years, solar radiation on Earth has increased by 25-30%, yet the climate has remained hospitable.

The question is: What mechanism has kept Earth in this optimal state?



One –dimensional climate model

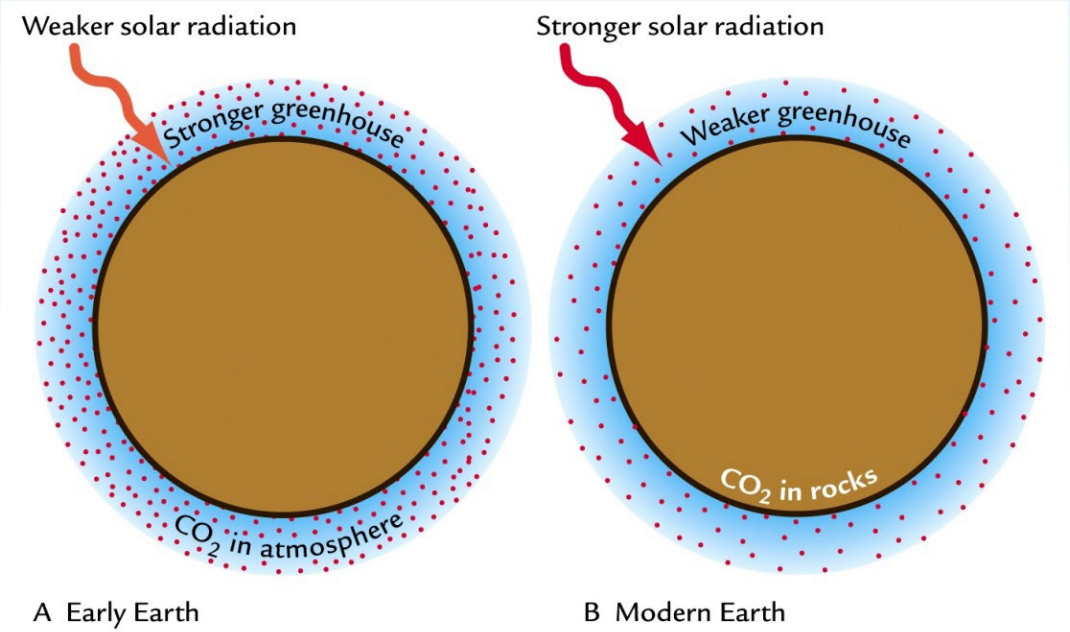
THE EFFECT OF GREENHOUSE GASES

Without greenhouse gases, Earth's temperatures would have likely decreased over time, making it inhospitable and **cold.**

With greenhouse gases, conditions would have been **warmer** and less hostile in the past..

CO_2 CONCENTRATIONS IN THE ATMOSPHERE

In Earth's early history, a mechanism was needed to maintain higher temperatures since the Sun's energy output was 25-30% lower than today.



Reconstructions suggest **increased volcanic activity**, releasing substantial CO2 into the atmosphere. Some scientists propose **that asteroid, comet, and meteorite bombardments** triggered this volcanic activity.

However, volcanic activity alone cannot act as a long-term climate regulator.

The thermostat: Chemical weathering - 1

The faint young Sun resulted in cooler temperatures

↓

Cool temperatures caused less efficient weathering

↓

Decreased weathering slowed the cooling of the Earth

+

Smaller land masses meant less intense weathering

↓

Less weathering allowed CO_2 levels to remain higher (100-1000 times current levels)

↓

Higher CO_2 concentrations increased temperature, compensating for weaker solar radiation

↓

As solar radiation increased, temperatures rose, weathering intensified, and CO_2 levels in the atmosphere decreased.

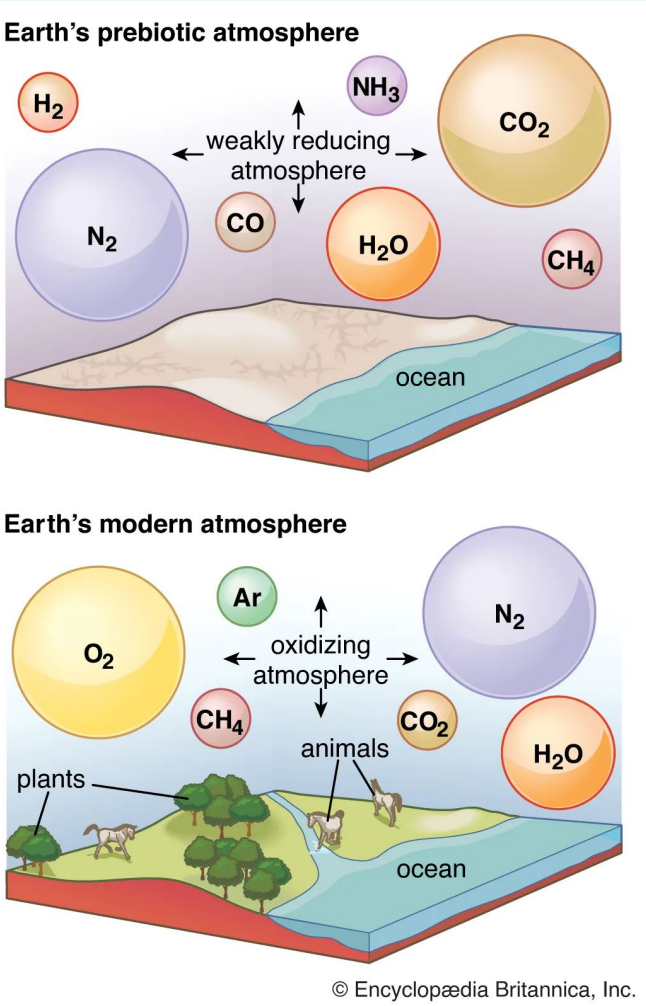
The thermostat: Chemical weathering - 2

THE ROLE OF OTHER GREENHOUSE GASES:
METHANE (CH4) AND AMMONIA (NH3)

Methane (CH_4) and ammonia (NH_3) are both greenhouse gases.

These gases are eliminated from the atmosphere through oxidation processes producing CO_2 and NO.

In the early atmosphere, oxygen was scarce, allowing CH_4 and NH_3 to remain in the atmosphere, contributing to an intensified greenhouse effect and warmer conditions.

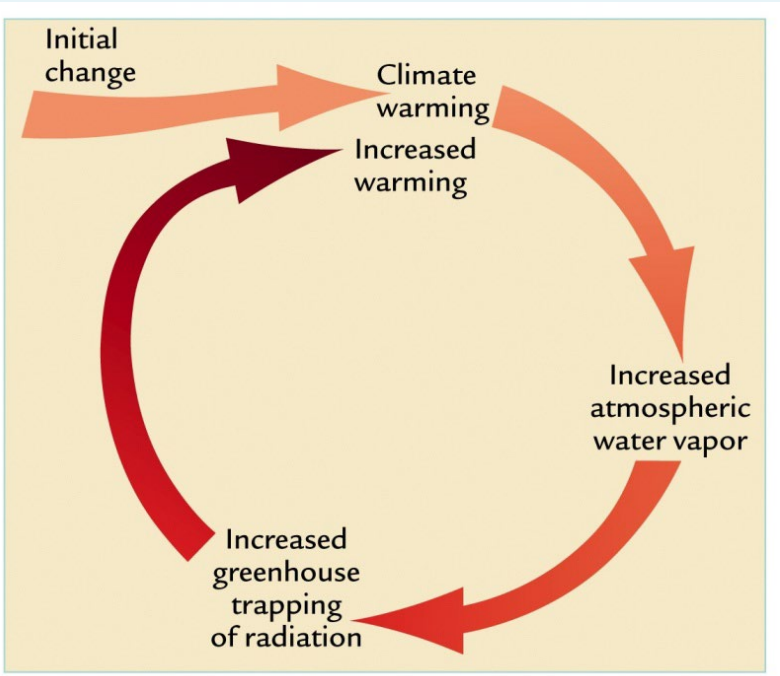


The thermostat: Chemical weathering - 3

Not all greenhouse gases behave the same. The case of water vapor.

While water vapor is the main driver of Earth's greenhouse effect, it lacks the thermoregulatory role of CO_2.

Water vapor functions differently from carbon dioxide.



Water vapor concentrations vary widely, from 0.2% in cold, dry conditions to 3% in hot, humid ones, creating a positive feedback loop.

As temperatures rise, the atmosphere holds more water vapor, which further increases temperatures, continuing the cycle.

Other possible thermoregulating systems?

Does life control the climate?

Gaia Hypothesis:
Gaia (Earth) is self-regulating to "survive." The thermostat involves not only physical processes but also life-related phenomena, much like fur for an animal.

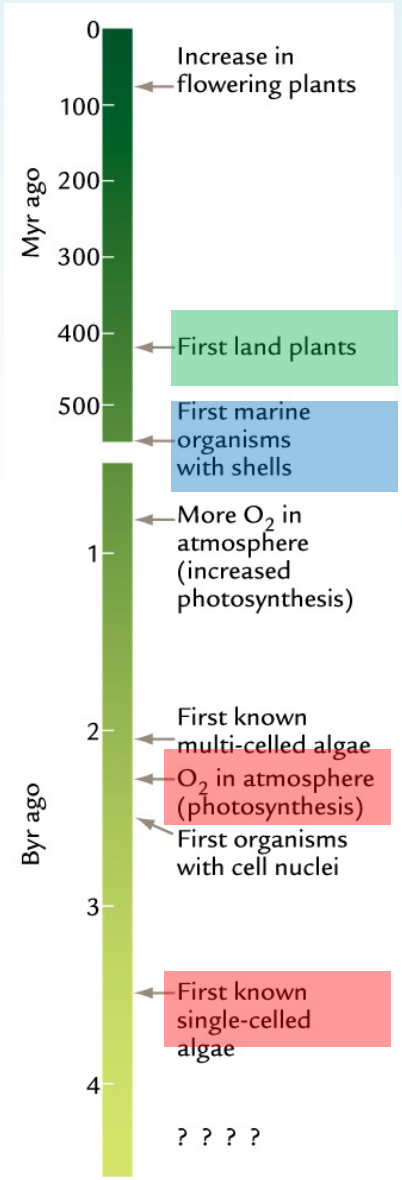
Why can life regulate climate changes?

Carbon is central to the CO_2 cycle. Plants/bacteria, through photosynthesis, produce organic carbon (C_{org}) and oxygen.

Plants transfer CO_2 into soils, enhancing weathering.

Biota help sequester carbon as $CaCO_3$ (in shells).

20% of the exchanges that take place between the various reservoirs take place in the form of $C_{org.}$



ARGUMENTS AGAINST/PRO

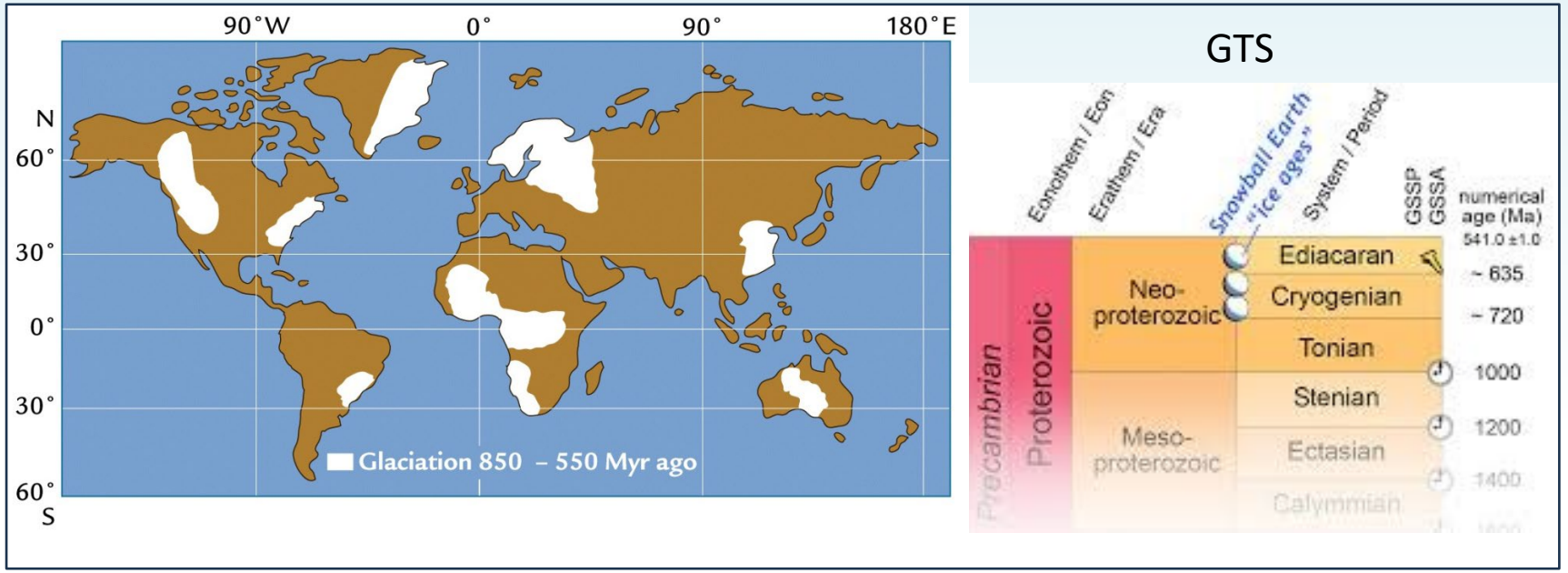
AGAINST

- ✓ The active role played by the biosphere is relatively recent (photosynthesis, carbonate production, CO_2 transport in soils by plants)
- ✓ Life was not as developed / abundant and therefore could not "control" the delicate climatic balances…..

PRO

- ✓ Simple life forms such as bacteria play a fundamental role today, why not in the past?
- ✓ The oxygen content in the atmosphere is linked to photosynthesis.
- ✓ The role of biota in favoring weathering phenomena was less when the planet Earth “needed” to be heated. Increasingly evolved organisms capable of accelerating weathering processes, on the other hand, evolved later when the planet Earth needed "to be cooled".

Snowball Earth:
a malfunction of the terrestrial thermostat?



Between 850 and 550 million years ago (Neoproterozoic), 2-4 glaciations occurred, with glacial deposits found even at low latitudes.

Possible explanations:

- Weaker sun: -6% compared to today.
- Distribution of the continents at low latitudes. Weathering increases significantly, cooling the planet (but see also the polar position hypothesis).