What is climate?

•**Climate vs Weather**: Weather describes short-term atmospheric conditions, while climate refers to the long-term average of weather patterns over decades to millennia.

Climate components:

•Temperature
•Precipitation
•Wind patterns
•Solar radiation

WEATHER, CLIMATE & E PALEOCLIMATE

WEATHER
It refers to the complex of short-term fluctuations (hours, days, or weeks) that occur in a region.

CLIMATE
It refers to the complex of conditions that occur in a region over long periods (years or more).

This complex can be "described" through measurements of:
TEMPERATURE PRECIPITATION (RAIN OR SNOW)
COVERAGE (SNOW OR ICE)
WIND DIRECTION AND STRENGTH
SOLAR RADIATION

...PALEOCLIMATE

Refers to climatic conditions that occurred in the geological past.

Definition of Paleoclimatology

•**<u>Definition of Paleoclimatology</u>**: Paleoclimatology is the study of Earth's past climates, using proxies from climate archive (e.g., sediments, ice cores, corals, tree rings, instrumental records) to reconstruct climate conditions.

•**Ice cores**: Preserve atmospheric gas bubbles and isotopic composition, revealing temperature and greenhouse gas concentrations over hundreds of thousands of years.

•**Tree rings**: Reflect annual climate conditions, such as rainfall and temperature, through ring width and density.

•**Sediments and fossils**: Marine sediments capture historical ocean temperatures and biological activity.

•**Instrumental records**

PALEOCLIMATOLOGY

Paleoclimatology is the study of climate changes that occurred in the geological past.

⇩

This discipline utilizes a wide variety of proxies to gather information from rocks, sediments, ice, trees, corals, microfossils, etc., the so-called geological archives.

⇩

These data are then used to reconstruct Earth's past climate. Climate models are also starting to play an increasingly important role in paleoclimate reconstructions.

Why study paleoclimatology?

•**Context for modern climate change**: It provides a long-term perspective, helping us to understand how climate systems have responded to different forcings in the past.

•**Predicting future changes**: Insights into natural climate variability and extreme climate events can improve future climate models.

Climate Change:

- **Natural climate variability**: Over millions of years, Earth has experienced major shifts, including ice ages, warm interglacial periods, and abrupt events like volcanic eruptions.

- **Anthropogenic (human-caused) climate change**: Since the industrial revolution, human activities such as burning fossil fuels have led to increased greenhouse gas emissions, causing rapid warming.

Key historical climate changes:

- **Glacial-Interglacial Cycles**: Driven by Earth's orbital variations (Milankovitch cycles), these cycles shift the planet between ice ages and warmer interglacial periods.
- **Holocene Warm Period (8,000–5,000 years ago)**: A relatively warm phase within the current interglacial period, influencing early human civilizations.

The Climate System

The Earth's climate system is a complex interaction between five major components:

1. **Atmosphere**: The layer of gases surrounding Earth, primarily composed of nitrogen and oxygen, along with trace gases like carbon dioxide and methane that drive the greenhouse effect.

2. **Hydrosphere**: Includes all water on the planet—oceans, rivers, lakes, and groundwater. Oceans store vast amounts of heat and play a crucial role in regulating global temperatures.

3. **Cryosphere**: All frozen water, including glaciers, polar ice caps, and sea ice. The cryosphere reflects solar radiation (albedo effect) and influences sea level.

4. **Lithosphere**: The Earth's solid outer layer, consisting of the crust and upper mantle. Volcanic eruptions from the lithosphere can inject aerosols into the atmosphere, affecting global climate.

5. **Biosphere**: Encompasses all living organisms, from plants to animals. Vegetation impacts carbon storage and affects regional climates through processes like evapotranspiration.

How do these components interact?

The **carbon cycle** involves the exchange of carbon among the atmosphere, oceans, lithosphere and biosphere, influencing the greenhouse effect and temperature.

Feedback loops:

Positive feedback (e.g., melting ice reducing albedo, leading to further warming)

Negative feedback (e.g., increased plant growth absorbing more CO_2) regulate the climate.

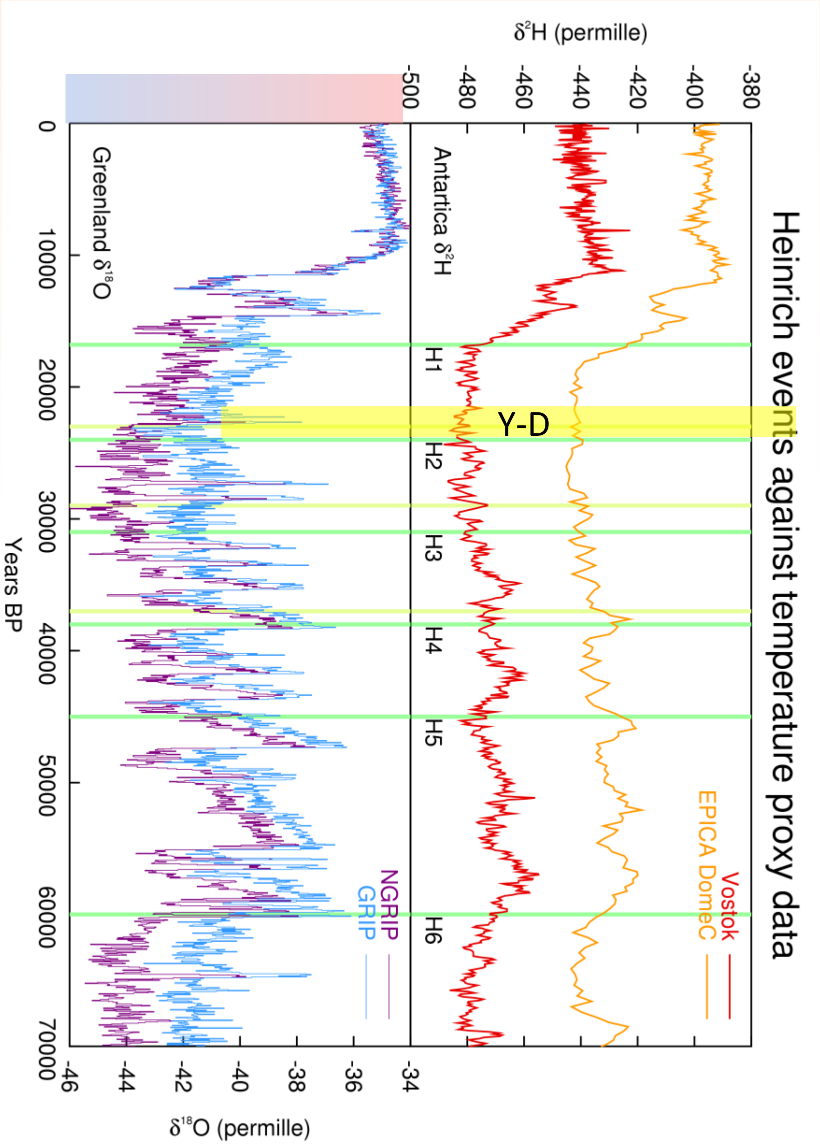
Climate Variability Examples

Climate Variability

Climate changes naturally, sometimes dramatically, at different time scales.

Long-term "Geological" timescales:
Glacial regimes (e.g., Quaternary Period).
Global warming regimes (e.g., Cretaceous Period).

Short-term "Geological" timescales:
Younger Dryas (cooling between 12.8-11.5 kyr).
Heinrich Events (warming phase before the D-O events during the last glacial period).
Dansgaard-Oeschger (D-O) events (warming followed by cooling during the last glacial period).



A WORLD WITHOUT ICE CAPS: THE CRETACEOUS

EVIDENCE

Fossils of large reptiles and tropical plants have been found in regions that today would be inhospitable. Reconstruction shows that during this time, lush forests extended into regions now covered by ice, like the Arctic.

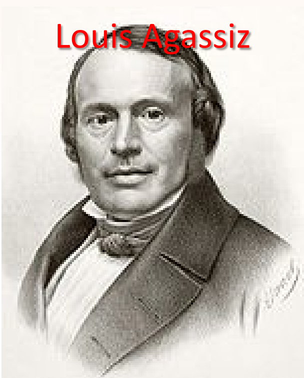
Left: Champsosaurus (a close relative of crocodiles) found in the rocks of Axel Heiberg Island, Canadian Arctic Ocean, at over 70°N. This discovery aligns with isotopic data indicating that between 80-90 million years ago, the average temperature at the Arctic Circle was above 14°C.

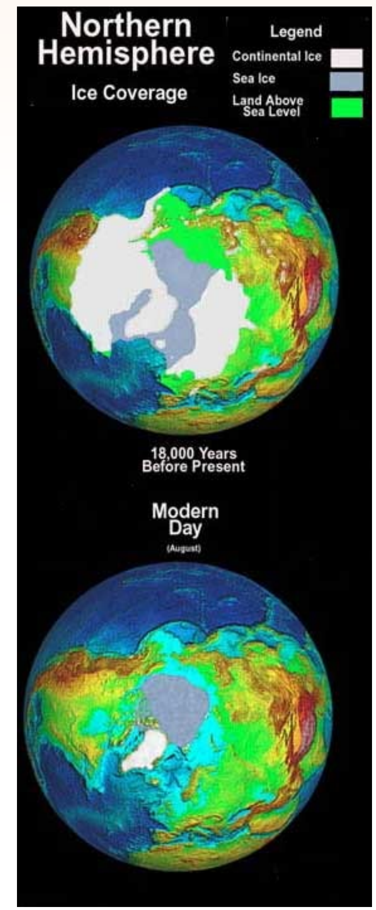
Right: reconstruction of the landscape that characterized both hemispheres (even at high latitudes), with lush forests extending into areas currently covered by ice.

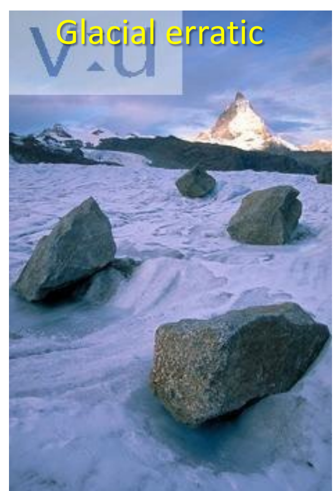
The Great Ice Age

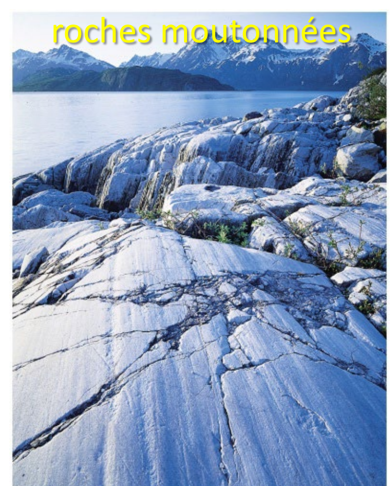
In the 1800s, the Swiss naturalist Louis Agassiz proposed the idea that Earth had experienced a major glaciation in recent times, with Alpine glaciers extending into the plains.

Fossil evidence soon confirmed this hypothesis. We now know there were many glaciations, and during the last glacial maximum, the global temperature was 5-8°C lower than today.

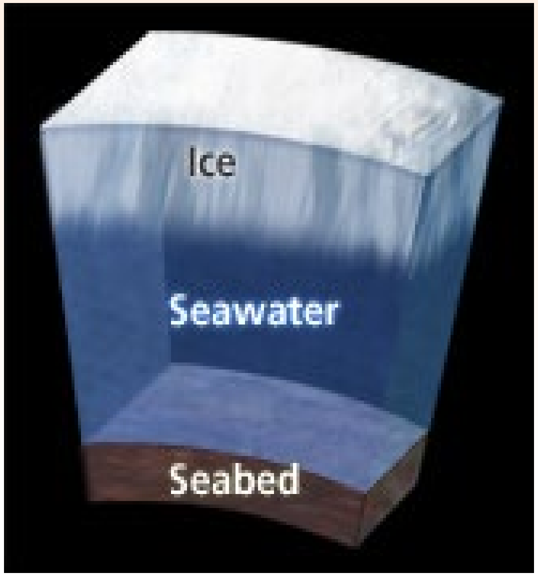


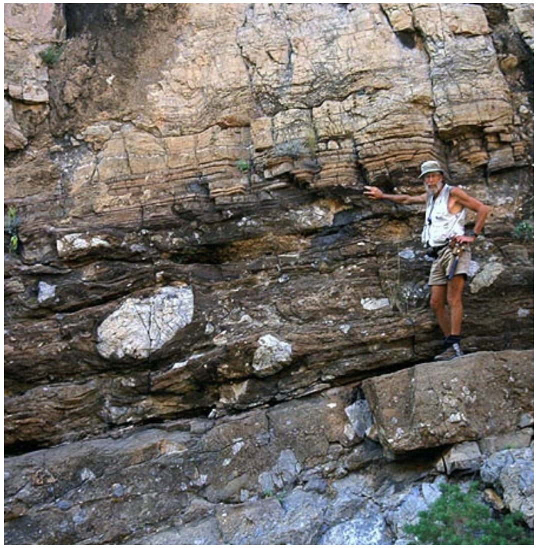






Snowball Earth (Neoproterozoic Era)

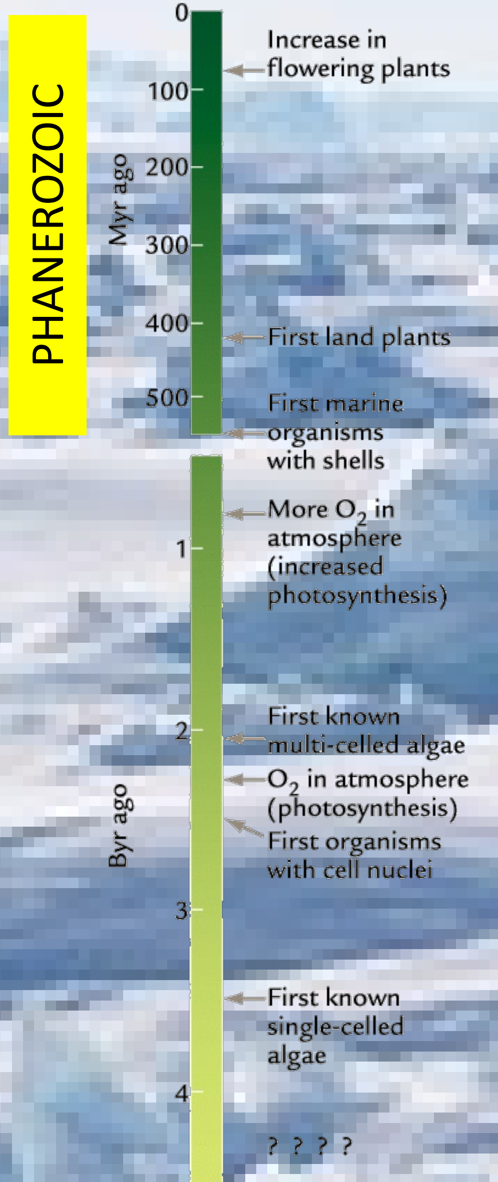


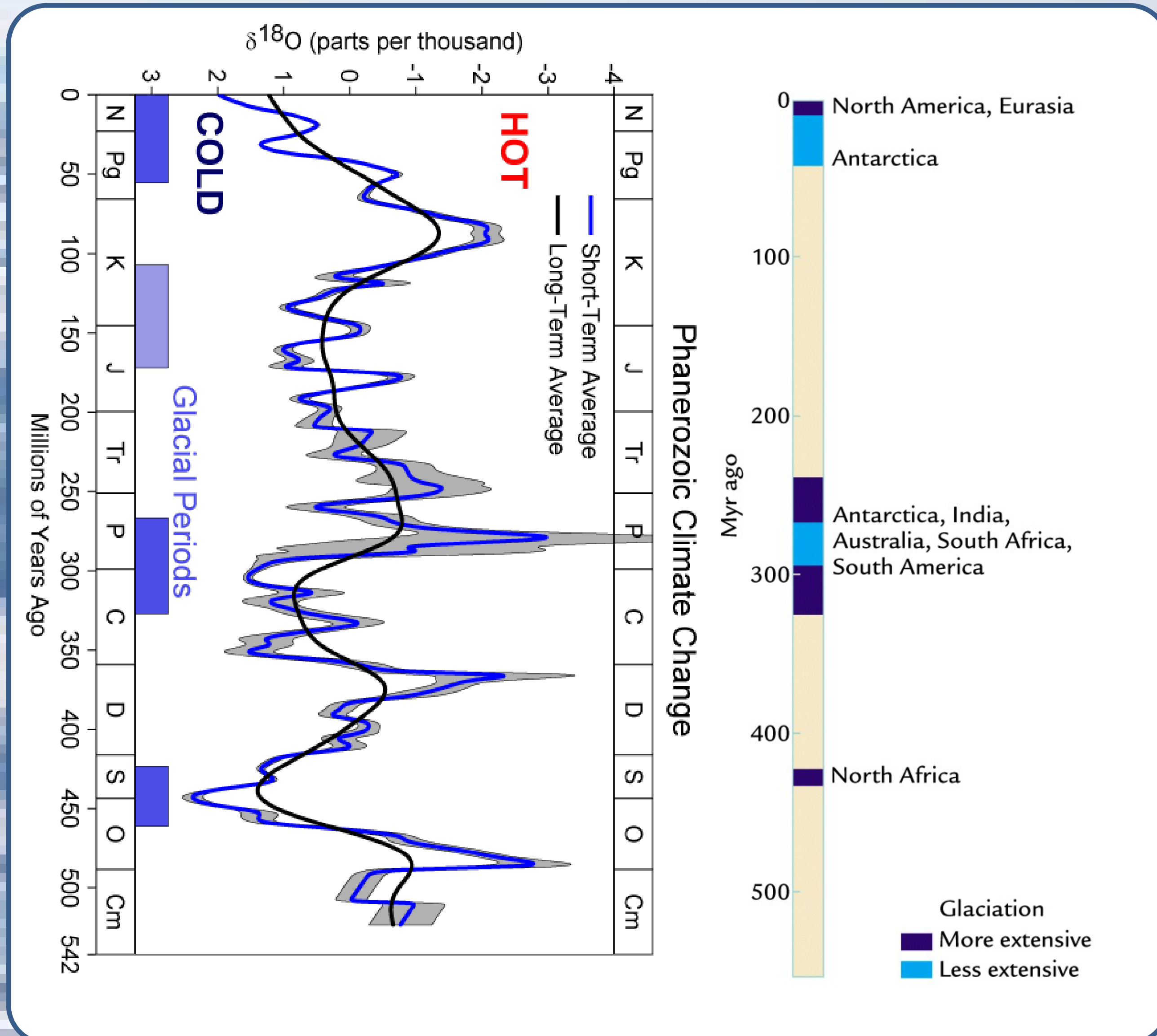


•Around 600 million years ago, Earth underwent a dramatic climate instability, with oceans freezing from the equator to the poles. Heat from the ocean floor prevented deeper freezing.

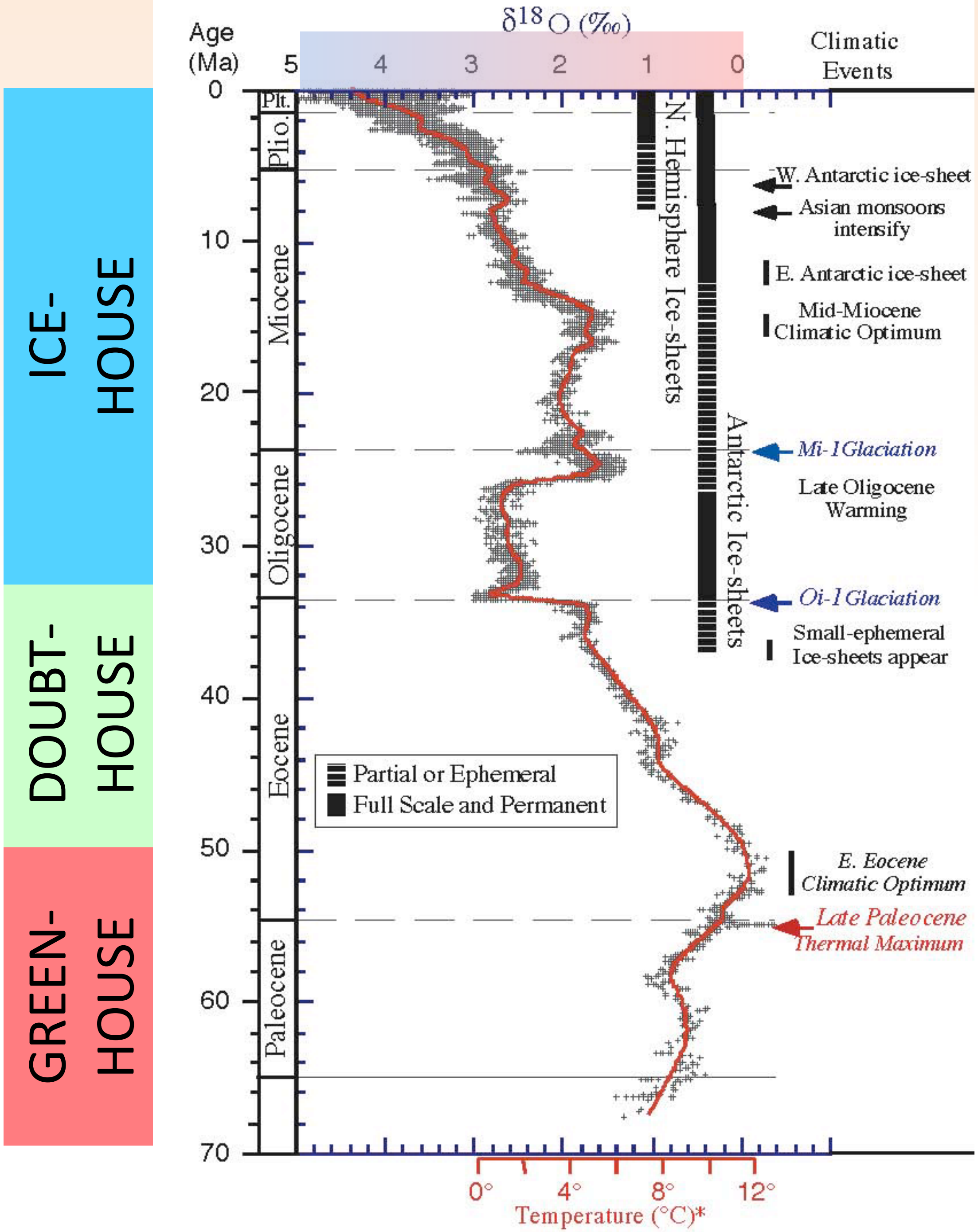
•The main evidence of this "Snowball Earth" comes from glacial-marine deposits found in regions near the equator during this period.

PHANEROZOIC (542-0 MA)

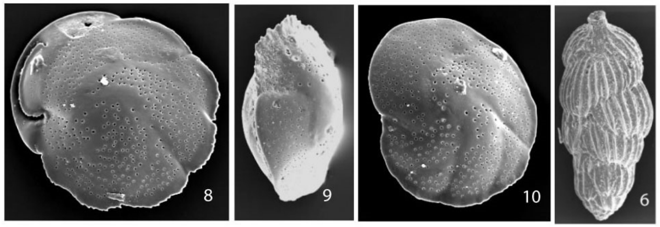




Ocean temperature over the last 70 million years:



Data collected from ocean sediments show changes in ocean



Benthic foraminifera: marine heterotrophic eukaryotic protozoa

THE STAGES OF THE CENOZOIC"

The "GREENHOUSE" World of the Cretaceous and lower Paleogene

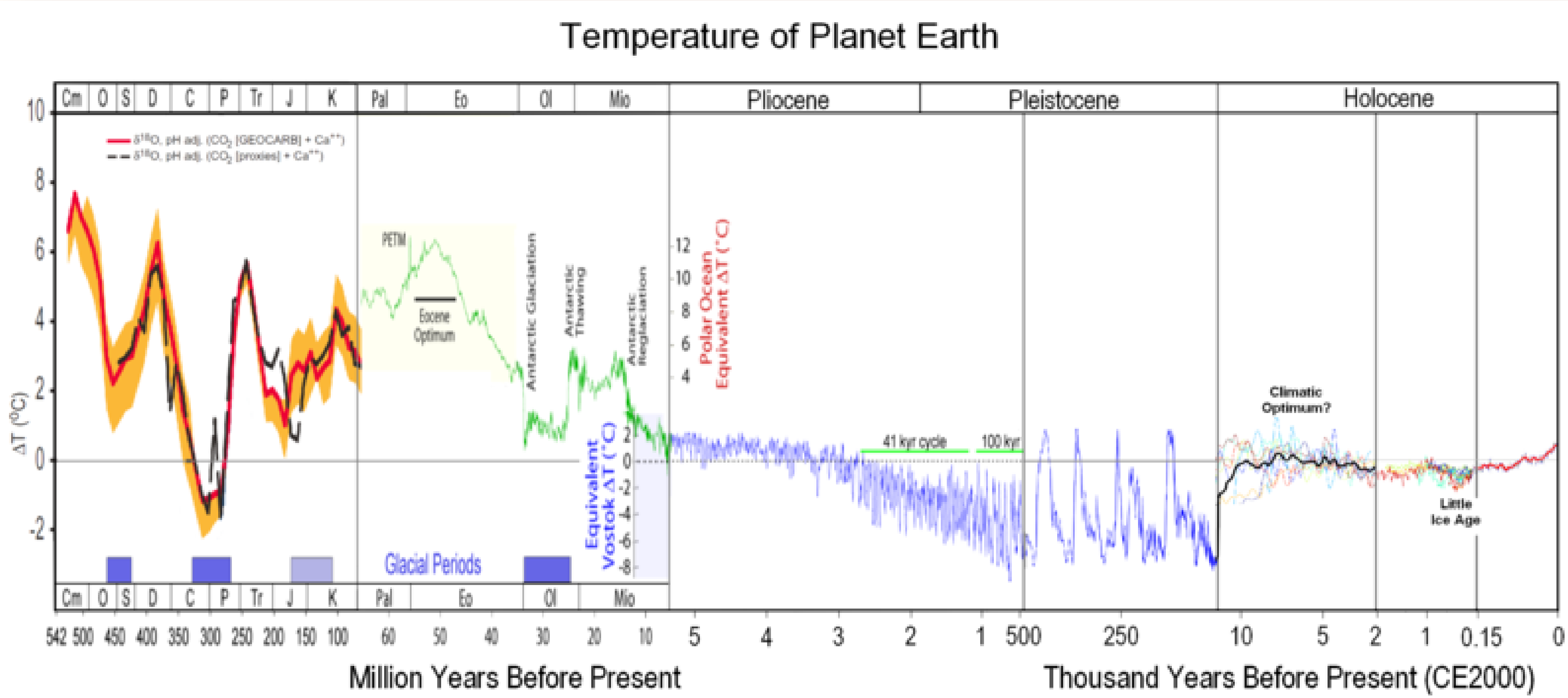
The Paleocene/Eocene Thermal Maximum (ca. 56 Ma) and the Evolution of Modern Mammals

The Early Eocene Climatic Optimum (EECO) and Whales

DOUBTHOUSE and the Beginning of the ICEHOUSE World (Upper Eocene-Early Oligocene)

The ICEHOUSE World of the Last 34 Million Year

PALEOCLIMATIC CURVE OF THE PHANEROZOIC



CLIMATE SCIENCE

Source images: Ruddiman, 2007

LIFE ON EARTH

Life exists on Earth because the CLIMATE allows it, both on a planetary scale and a regional scale.

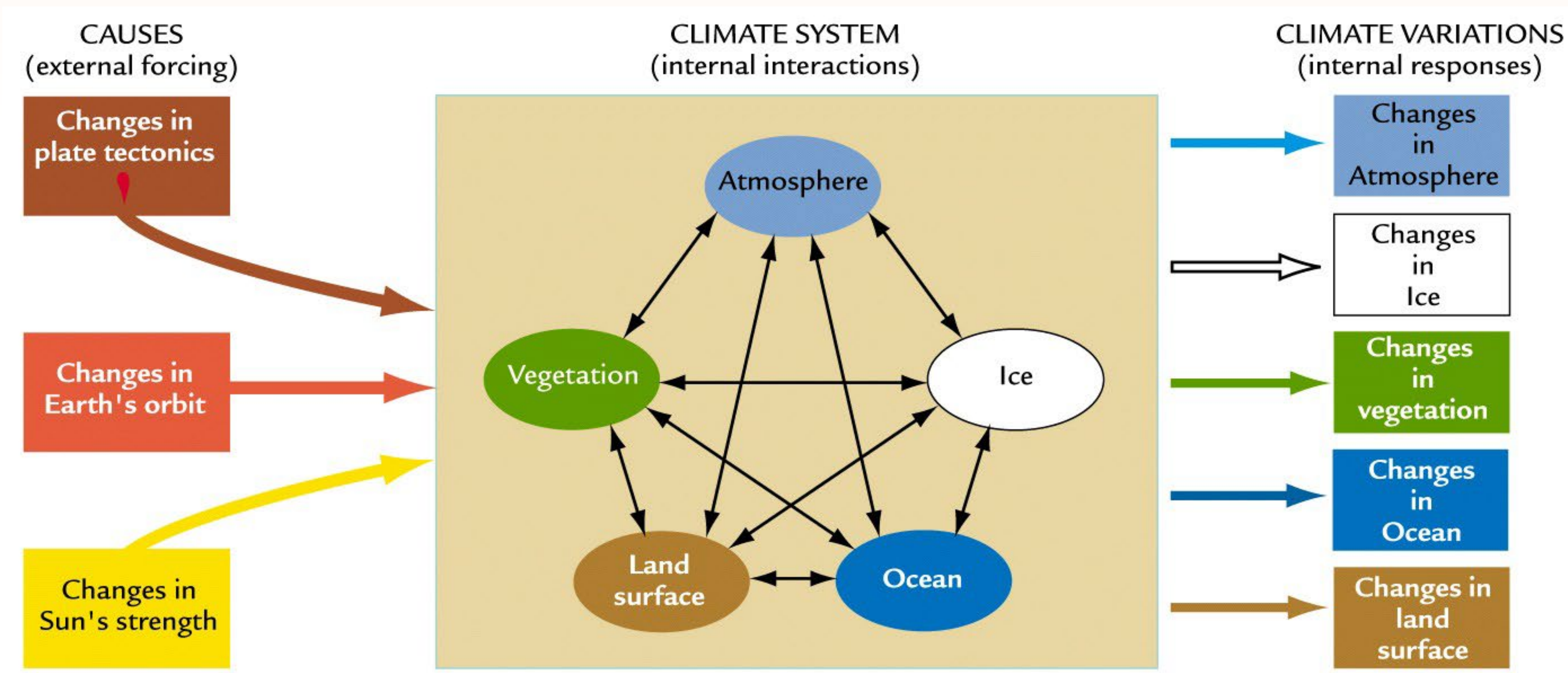
The average temperature on our planet is 15°C, and most of the planet ranges between 0 and 30°C.

The CLIMATE can be seen as a SYSTEM composed of the following elements:

- **Atmosphere**
- **Land masses (Lithosphere)**
- **Oceans (Hydrosphere)**
- **Ice (Cryosphere)**
- **Biosphere**

CLIMATE SYSTEM

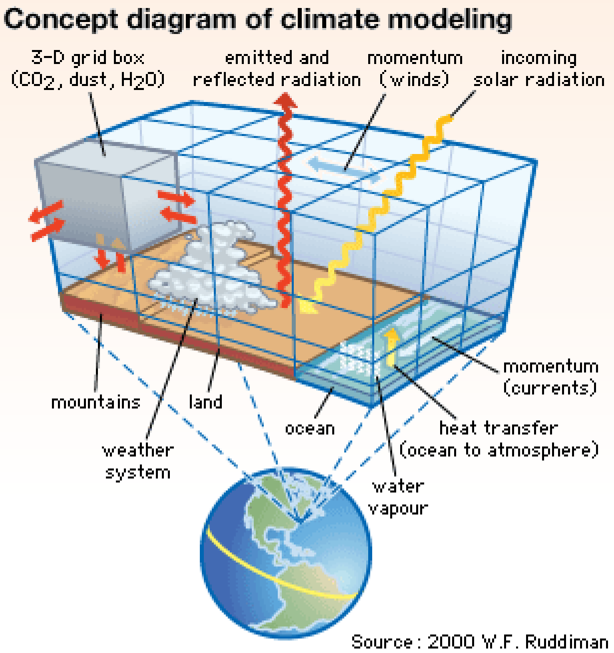
EXTERNAL FORCING → CLIMATE SYSTEM → CLIMATE CHANGES



CLIMATE MODELS & PALEOCLIMATOLOGY

Climate models use quantitative methods to simulate the interactions between the components of the climate system (atmosphere, ice, oceans, vegetation, and land surface.

Models are systems of differential equations based on the basic laws of physics and chemistry. To run a paleoclimate model, the planet is divided into a three-dimensional grid, the equations are applied, and the results are observed.



BUT HOW CAN WE VERIFY THE RESULTS OF THESE PREDICTIONS? ...NO TEST TUBE...

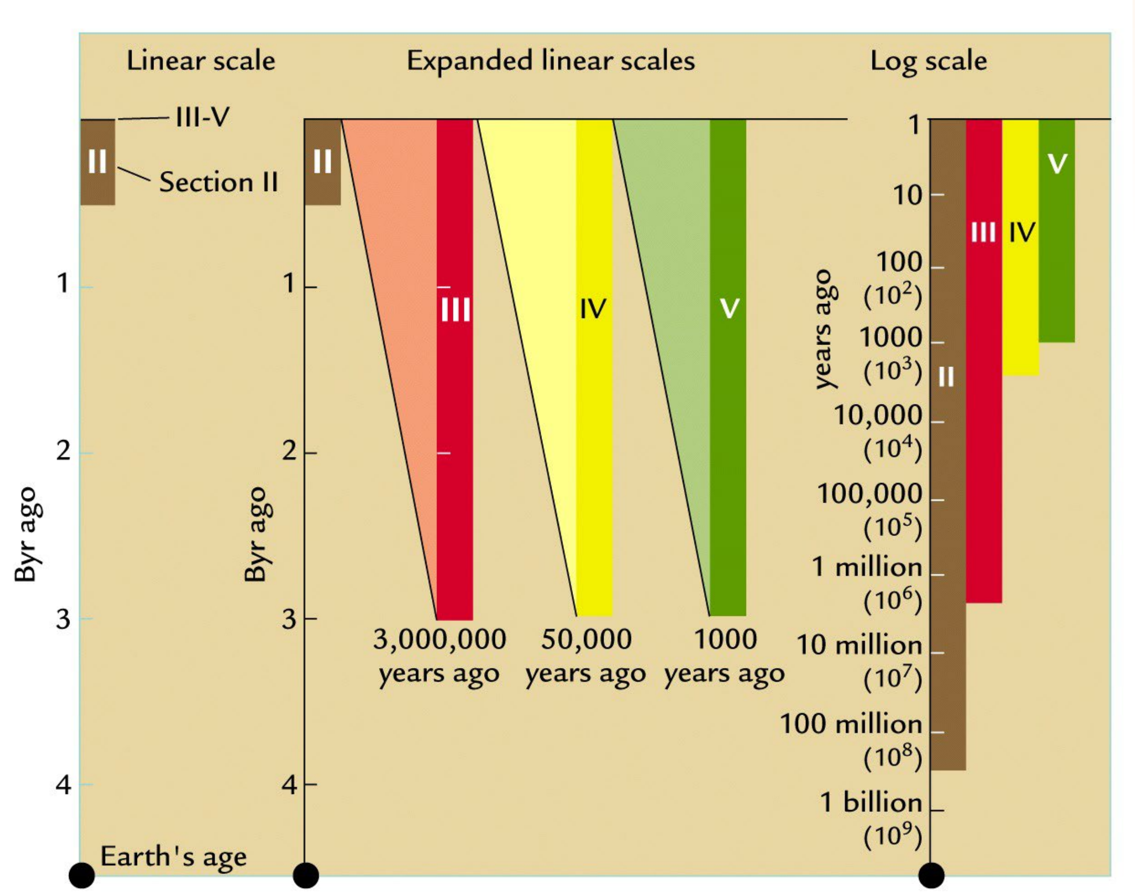
The geological record provides an exceptional natural laboratory where these models can be verified.

THE PAST CAN BE THE KEY TO UNDERSTANDING THE FUTURE

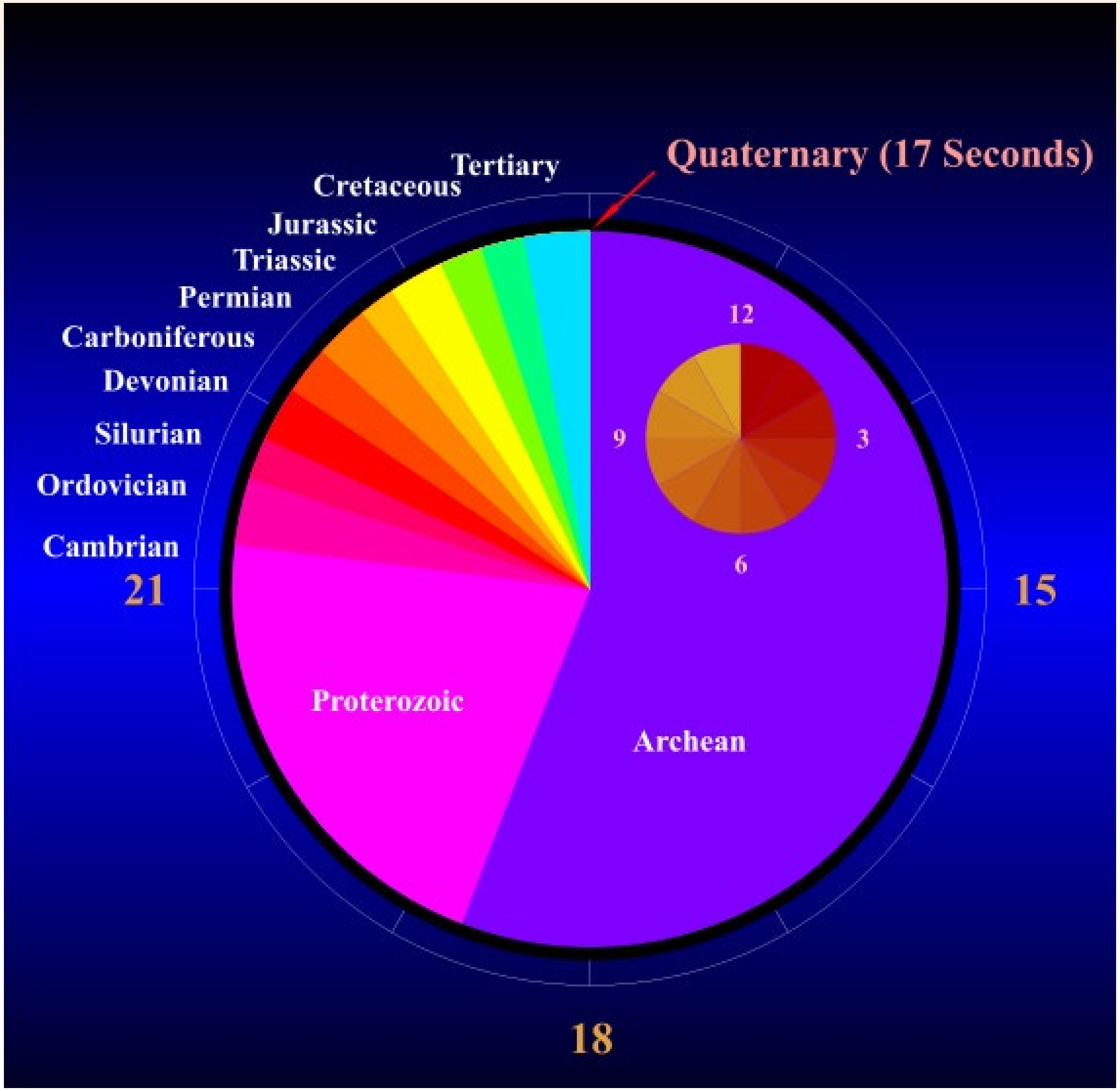
DEEP TIME

Human life generally unfolds on the scale of decades. The phases of our lives, such as childhood and adolescence, last a few years. The goals we set for ourselves and our needs are achievable within the span of days, weeks, months, or at most years.

The history of the Earth goes far beyond human perception.
The Earth formed approximately 4.55 billion years ago. The earliest part of Earth's history is completely unknown or, at best, known in a very fragmentary way.
The main reason for this gap is the rarity of sediments that can help us reconstruct and/or understand the oldest time intervals.

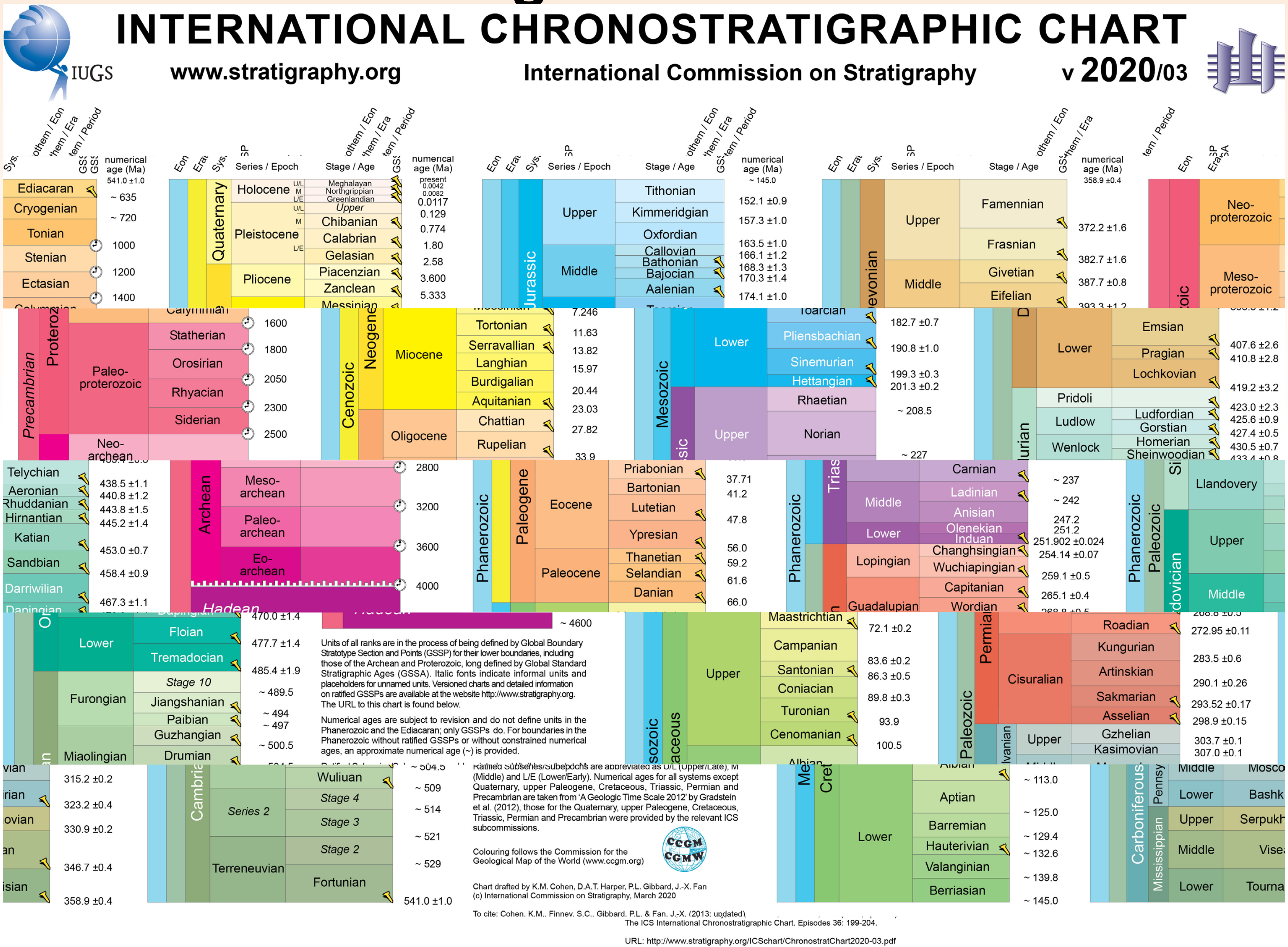


DEEP TIME – THE IMMENSITY OF TIME



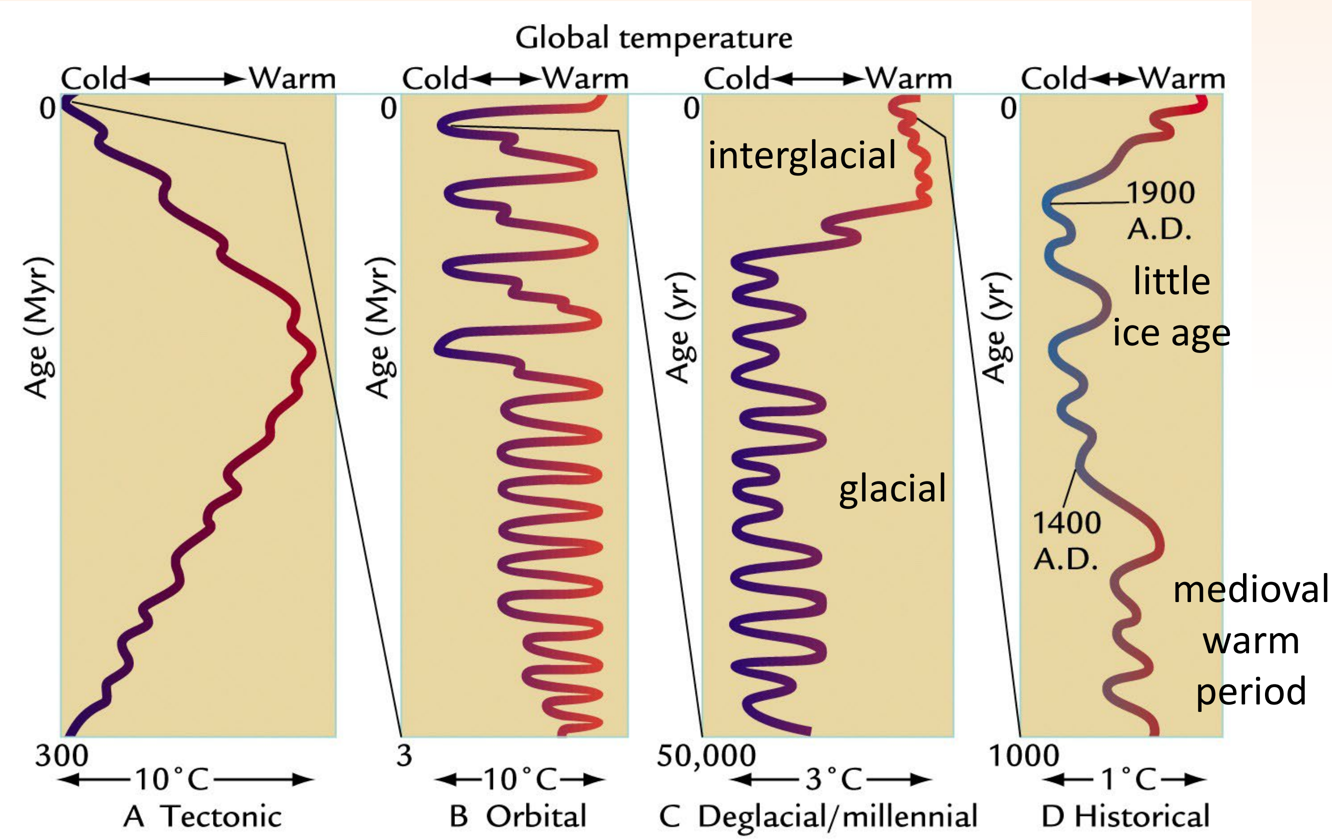
The notion of time that relentlessly flows may have always existed, but the ability to precisely date rocks has revealed how the "History of the Earth" involves timeframes that are completely beyond our daily perception.

Geological time scale



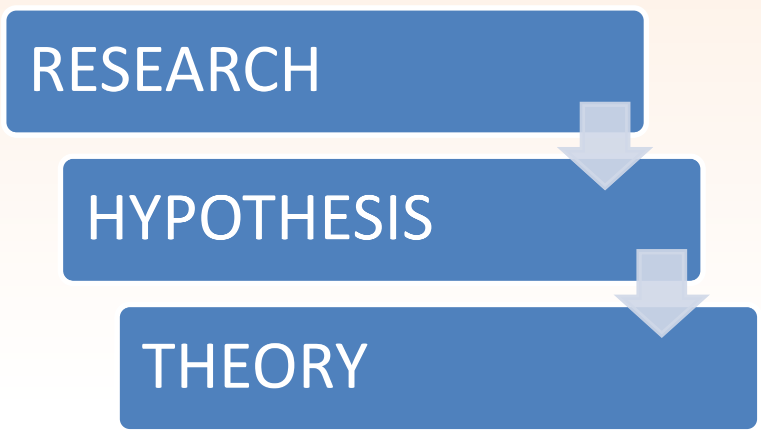
TIME SCALES OF CLIMATE CHANGES

Most paleoclimate studies focus on less than 10% of Earth's entire history, particularly on the more recent part.



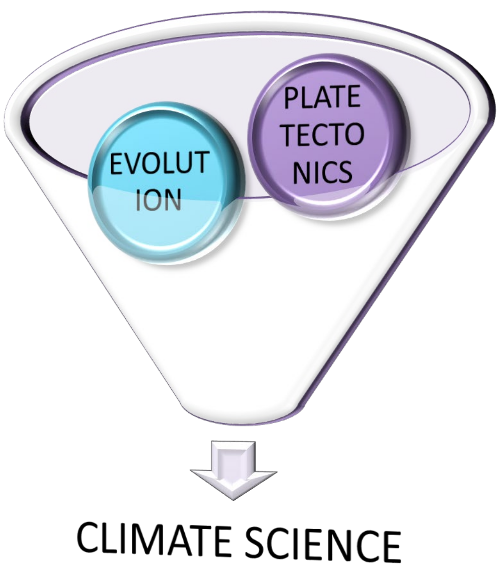
As we move from older time intervals to more recent periods, the degree of resolution increases. It is possible to identify climate changes on different scales (long-term, short-term) nested within the geological record.

METHODOLOGY AND REVOLUTION

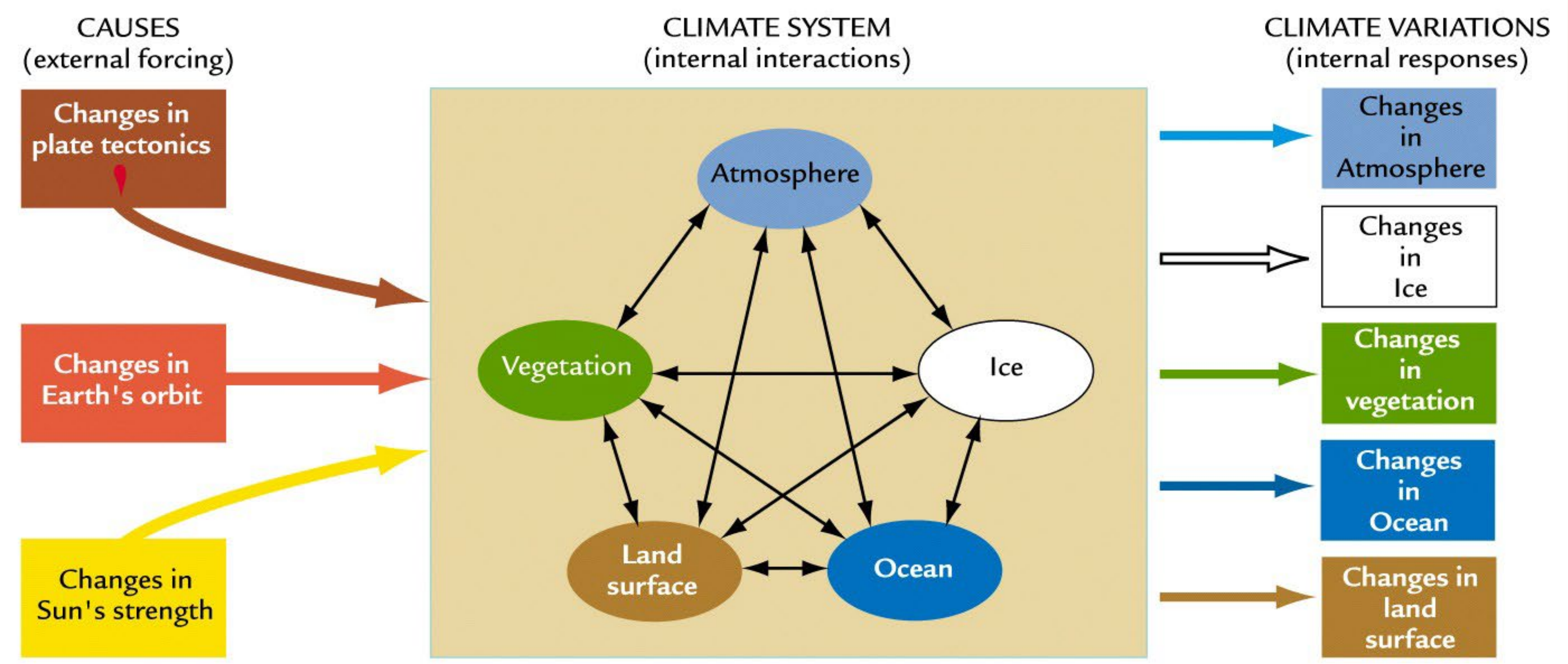


SCIENTIFIC METHODS

The Theories That Revolutionized Paleoclimatology

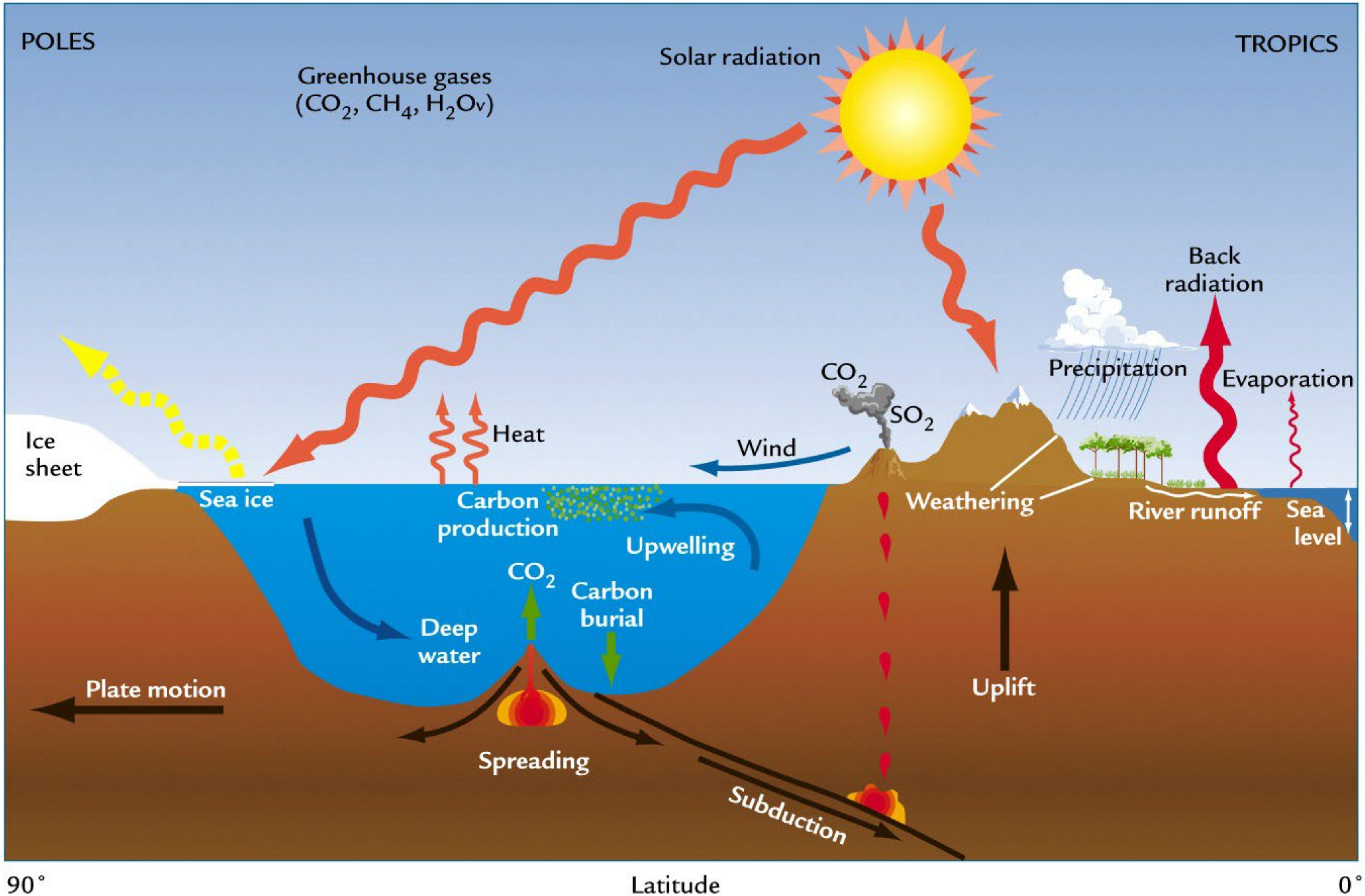


THE SIMPLIFIED CLIMATE SYSTEM



A limited number of factors "force" climate change (EXTERNAL FORCING). These factors cause interactions between the internal components of the climate system (air, water, ice, land, vegetation). The result of these interactions is measurable and is called the CLIMATE RESPONSE.

THE COMPLEX CLIMATE SYSTEM



Processes
rainfall, evaporation, winds

CLIMATE FORCING (EXTERNAL)

TECTONIC PROCESSES

They are generated by Earth's internal heat and influence its surface by altering the geography (Plate Tectonics). These processes operate very slowly, on the scale of millions of years. Examples: slow movement of continents, orogeny, the opening and closing of oceans.

EARTH-ORBITAL CHANGES

These are variations in Earth's orbit around the Sun. These changes alter the amount of solar radiation (season, latitude) over hundreds of thousands of years. Examples: Eccentricity, Obliquity, Precession.

CHANGES IN SOLAR OUTPUT

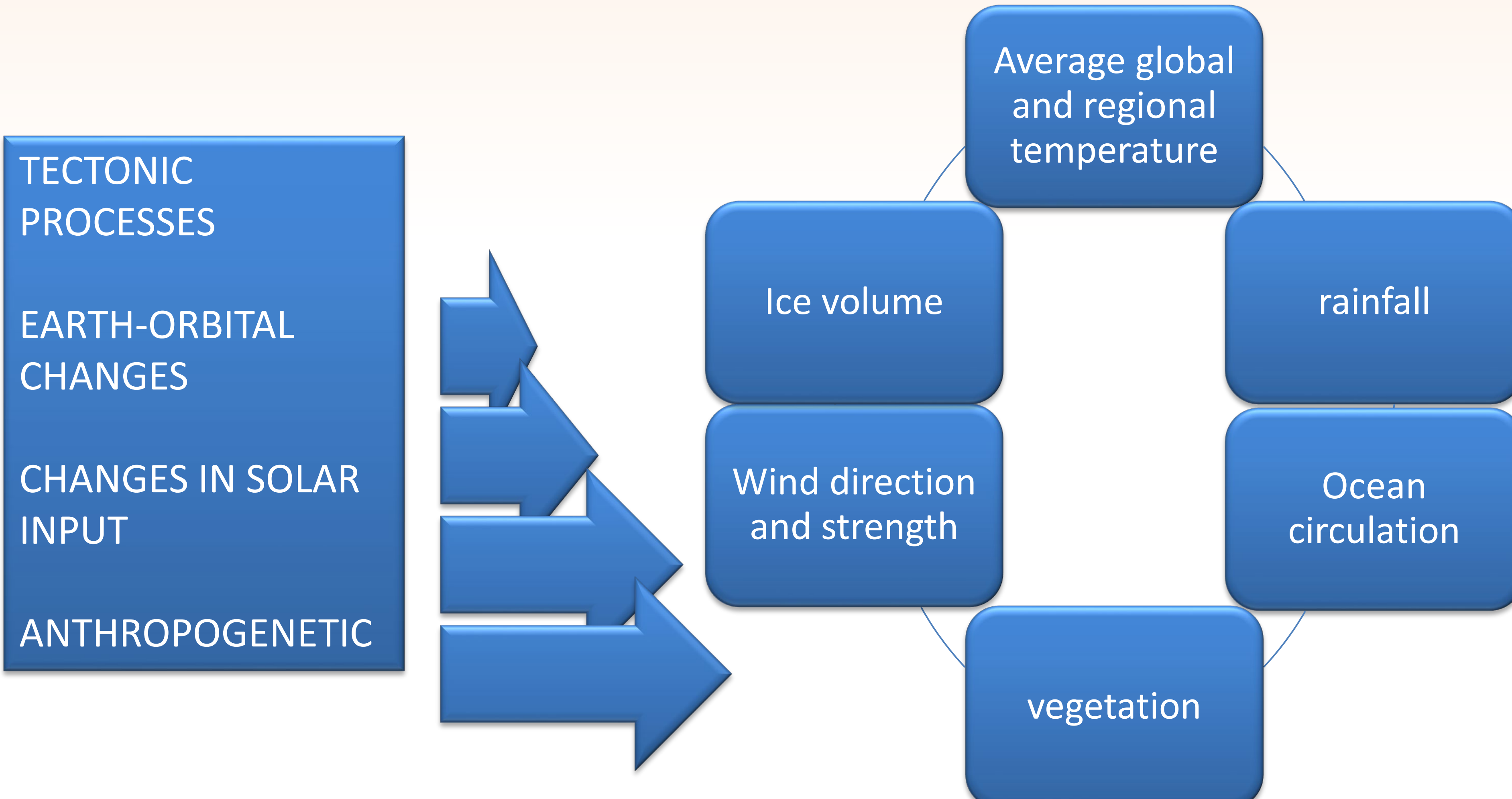
They influence solar radiation. Examples: Solar output has increased over the last 4.55 billion years. Short-term variations (decades and longer).

ANTHROPOGENIC

The release of greenhouse gases (e.g., CO2) through human activities (agriculture, industry, **etc.).**

CLIMATE SYSTEM RESPONSES

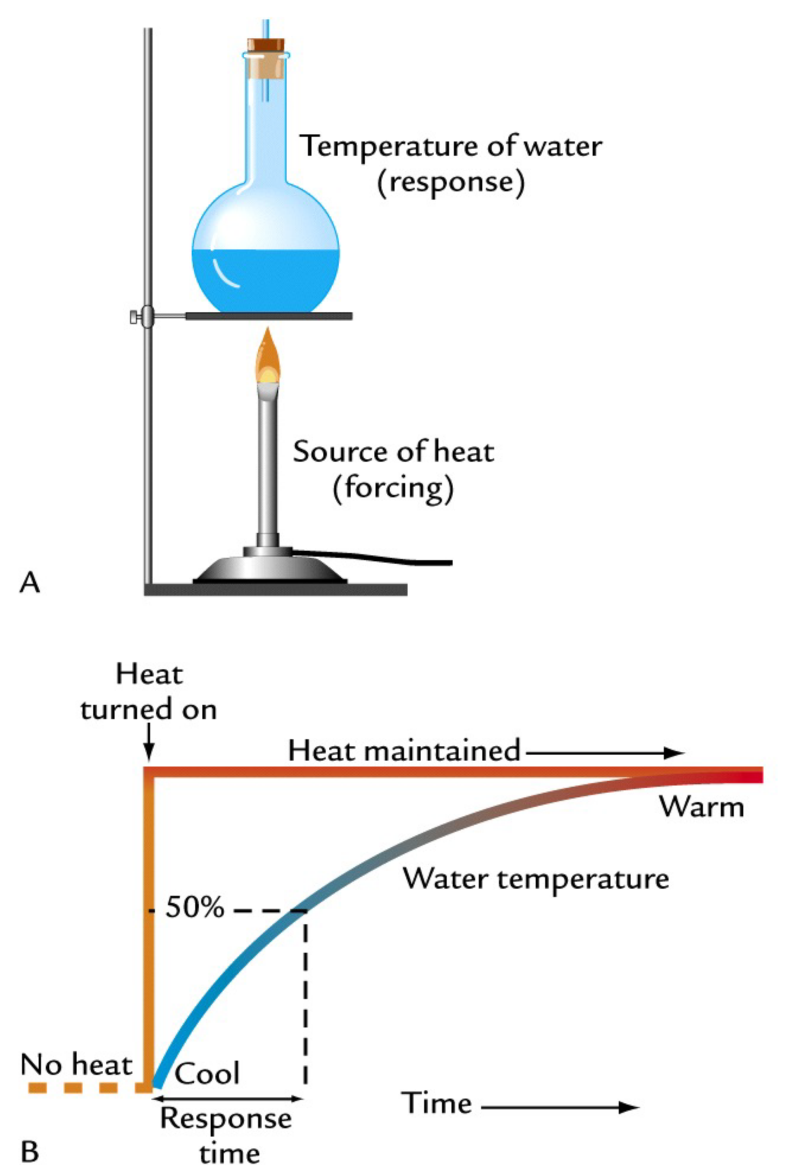
EXTERNAL FORCING | **RESPONSE TIME** | **CLIMATE CHANGE**



RESPONSE TIME

Water temperature clkimate response
Bunsen : External forcing

The rate at which the temperature (T°C) increases is greater the further away it is from the equilibrium temperature (asymptotic trend).



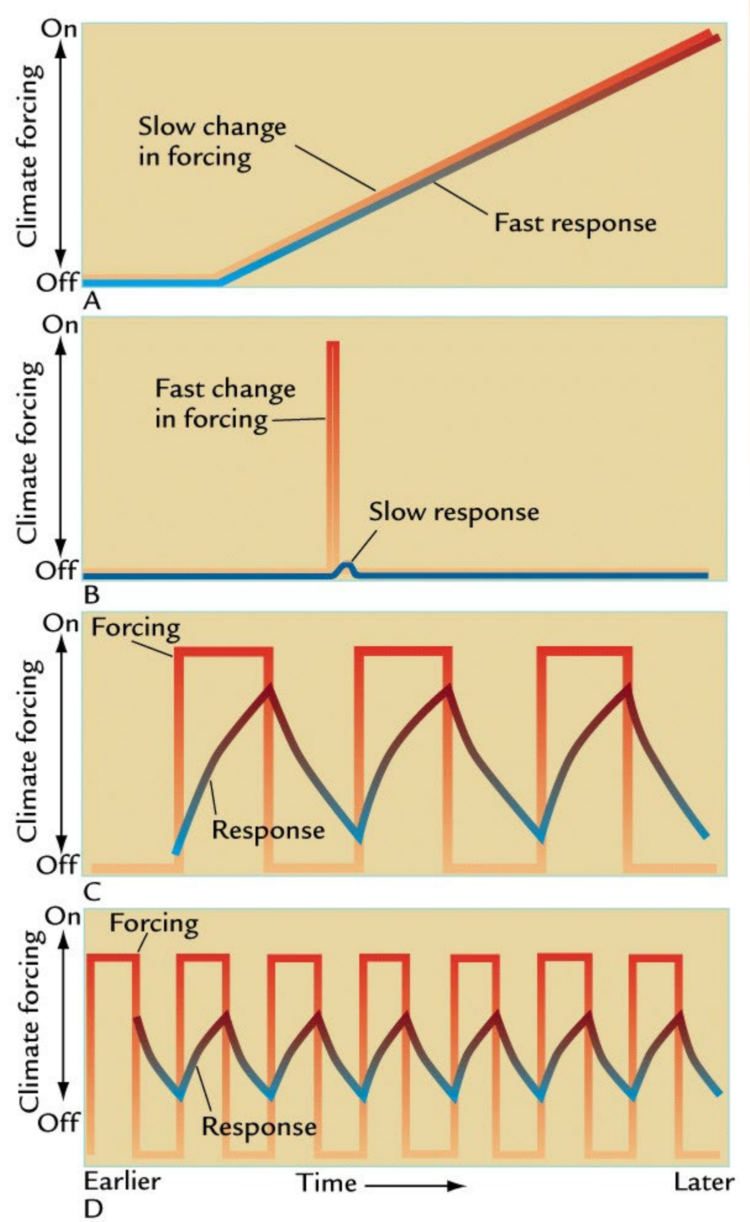
<u>Response time </u>(in this case):
The time required for the water to reach a temperature equal to the average between the initial temperature (T°$C_{initial}$) and the equilibrium temperature (T°C_{final}).

TIME SCALES OF FORCING vs RESPONSE

The forcing is **very slow** compared to the system's response time. The system moves in step with the forcing. Example: slow movement of tectonic plates (Km/Myr).T

The forcing is **very fast** compared to the system's response time. The system shows no response or a minimal response. Example: Solar eclipse, volcanic eruptions (Pinatubo -0.5°C).

The forcing has a speed similar to the system's response time. ON-OFF way.
Slow ON-OFF switch: Temperature (T°C) changes significantly. Fast ON-OFF switch: Temperature (T°C) changes minimally.

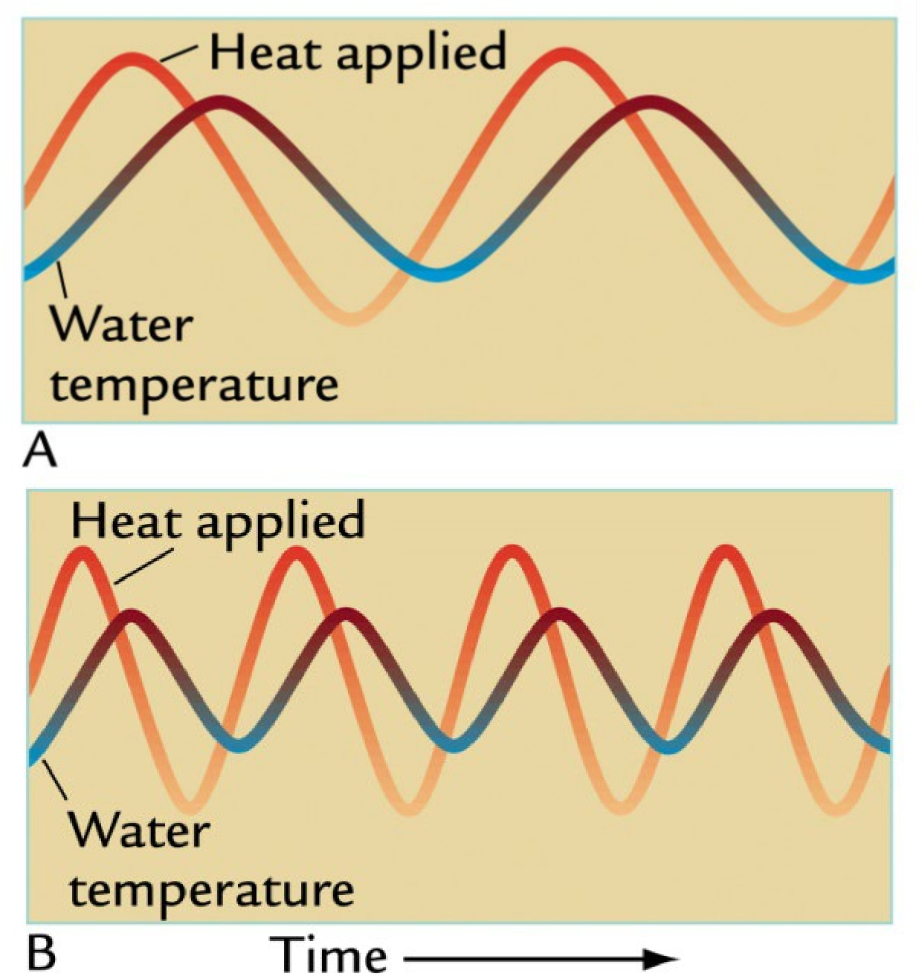


TIME SCALES OF FORCING vs RESPONSE

In nature, there are no true ON-OFF processes; rather, external forcing can follow a cyclical pattern. The forcing is cyclical between two equal equilibrium temperatures (Tequilibrium).

If the cycle has a low frequency (long), the temperature (T°C) changes a lot, with a large Δ MAX-MIN.

If the cycle has a high frequency (short), the temperature (T°C) changes little, with a small Δ MAX-MIN.

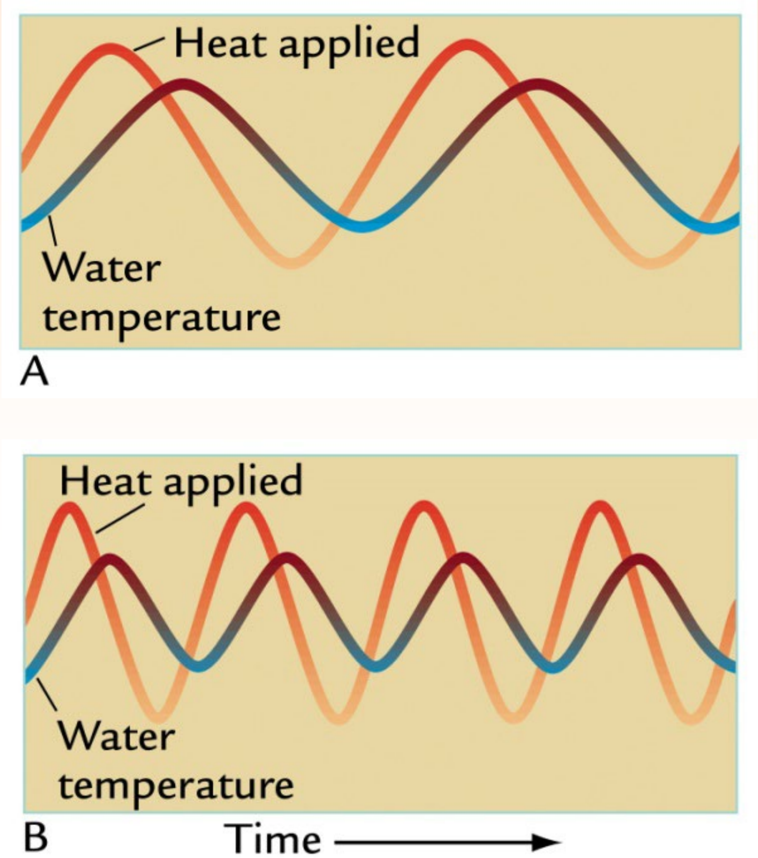


ESEMPI DI FORCING CICLICI

Northern Hemisphere
The sun is strongest during the summer solstice (June).MAX temperatures are reached in July (land) and August (ocean).

The sun is "weakest" during the winter solstice (December).MIN temperatures are reached in January/February.

During the day, MAX temperatures are not reached when the sun is at its strongest (noon), but in the afternoon.



The relationship between cyclical forcing and climate response simulates well the case of solar radiation changes that occur due to changes in orbital parameters, because the forcing (Δ solar radiation) and the climate system's response (Δ ice volume) operate on the same timescales (around 10,000 years).

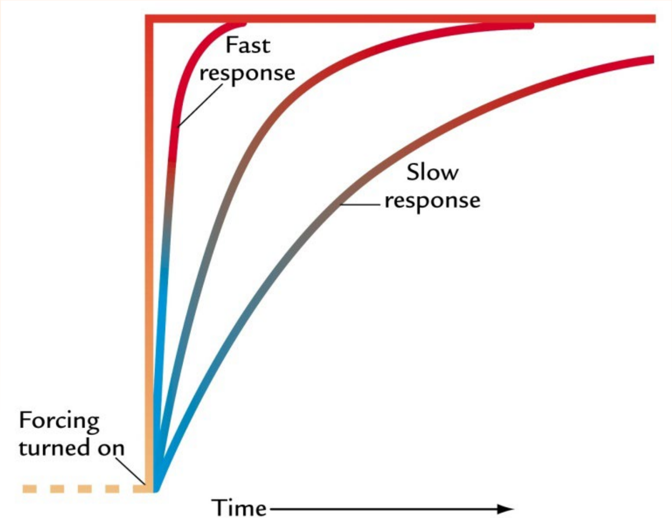
FORCING AND DIFFERENT RESPONSE TIME

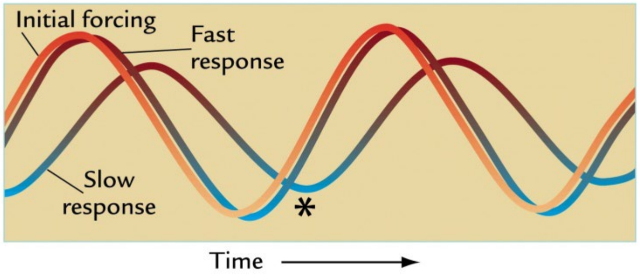
The forcing is strong and abrupt,for example > solar radiation.

Each component of the climate system (air, water, ice, land, and vegetation) responds to the forcing with its own response time.

Cyclical forcing (smooth cycles of orbital parameters):The components with a fast response time keep pace with the forcing.

The components with a slow response time show a delay and do not reach MAX and MIN in synchrony (ice sheets).



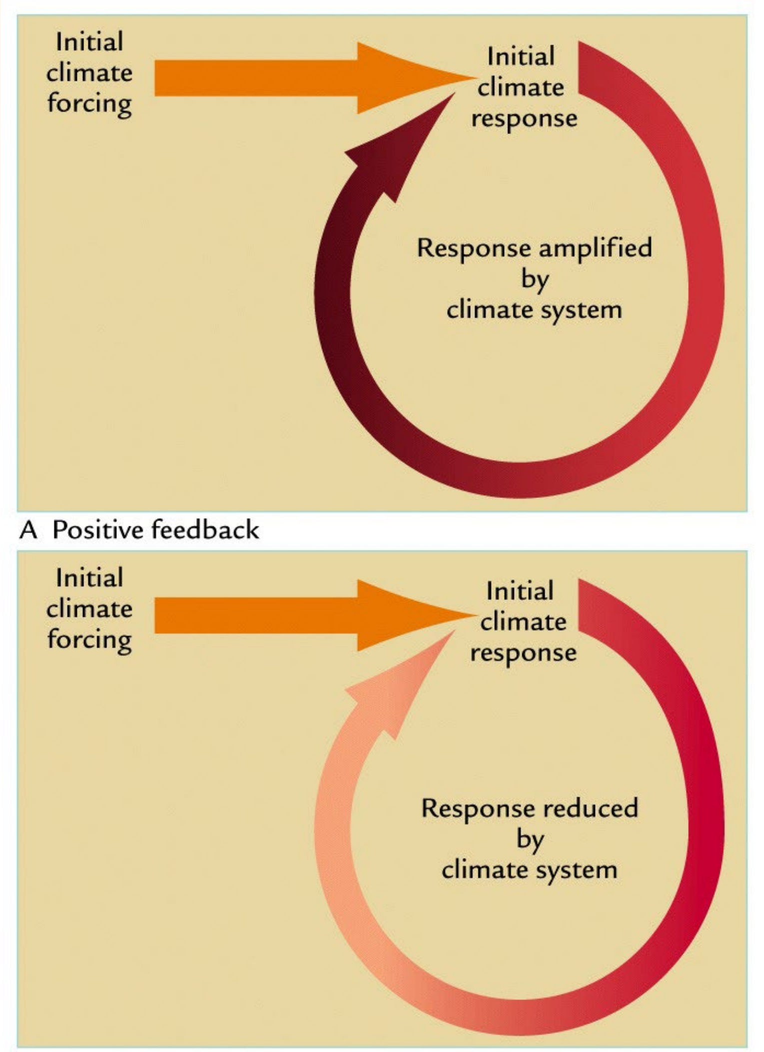


FEEDBACKS IN THE CLIMATE SYSTEM

FEEDBACK = process that alters ongoing climate changes

Amplifying them **POSITIVE FEEDBACK**
< solar insolation
>ice sheets
>albedo
< temperature
>ice sheets

Reducing them **NEGATIVE FEEDBACK**
>solar insolation
< ice sheets
< albedo
>Temperature
< ice sheets



A Positive feedback
B Negative feedback