Earth System Processes (ES1201)

Earth's Climate System

(Spring 2025 by Gaurav Shukla)

Books: **1) *The Earth System* by L.R. Kump, J.F. Kasting and R.G. Crane**

2) The Blue Planet: An Introduction to Earth System Science by Skinner and Murck

Earth’s Climate System

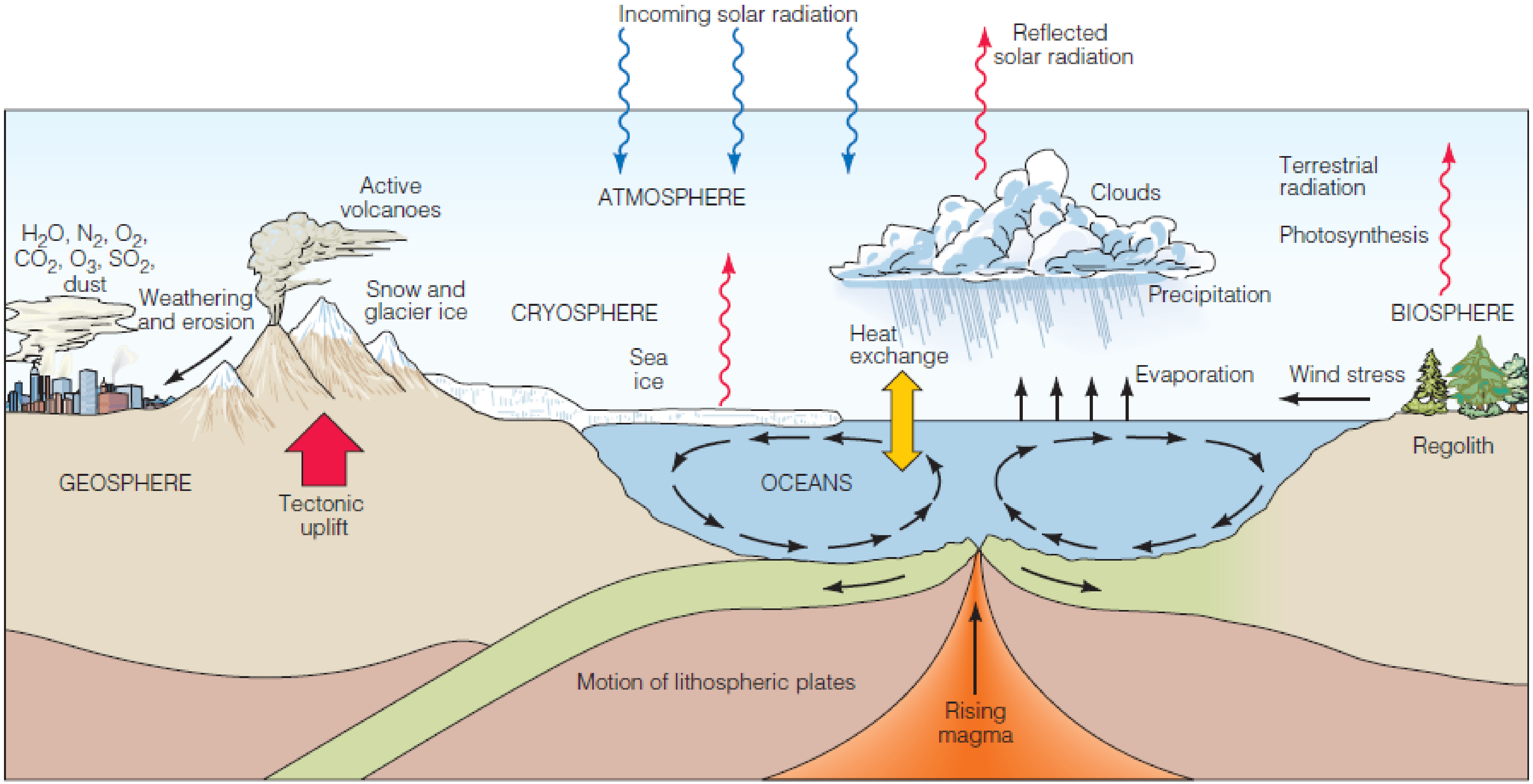
The climate system is defined by the dynamics and interactions of its five major components:

- **Atmosphere**
- **Hydrosphere**
- **Cryosphere**
- **Geosphere**
- **Biosphere**

Earth’s Climate System

FIGURE 13.1 Earth’s climate system

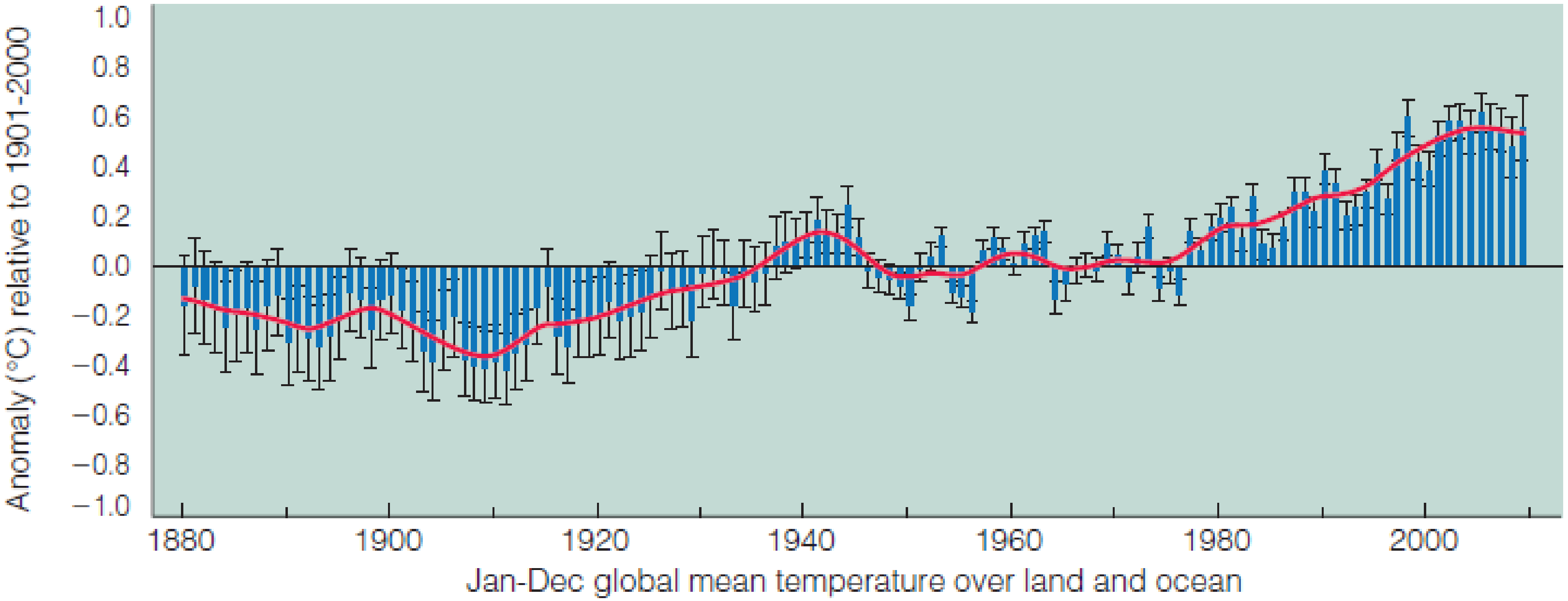
Earth’s climate system has five major interacting components: the geosphere (including land relief); the atmosphere (including the role of gases and particulates); the hydrosphere (especially ocean basins and circulation); the cryosphere (including the reflectivity of the polar ice caps); and the biosphere (including vegetation, soils, and photosynthesis). The anthroposphere—human activities—has become a recent contributor to the climate system.



Earth’s Climate System

Evidence for the Climate Change

FIGURE 13.2. Variations of Earth’s surface temperature
This graph, from the National Climatic Data Centre of NOAA’s National Environmental Satellite, Data, and Information Service, shows global mean surface temperature anomalies from 1880 to 2010. A temperature anomaly is a departure from a long-term average – in this case, the average surface temperature for the 20th century. A positive anomaly indicates that the observed temperature was warmer than the reference temperature, whereas a negative anomaly indicates that the observed temperature was cooler than the reference value.



Earth’s Climate System

Geological Records of Climate Change (Paleoclimate Evidence)

274 Chapter 14 • Pleistocene Glaciations

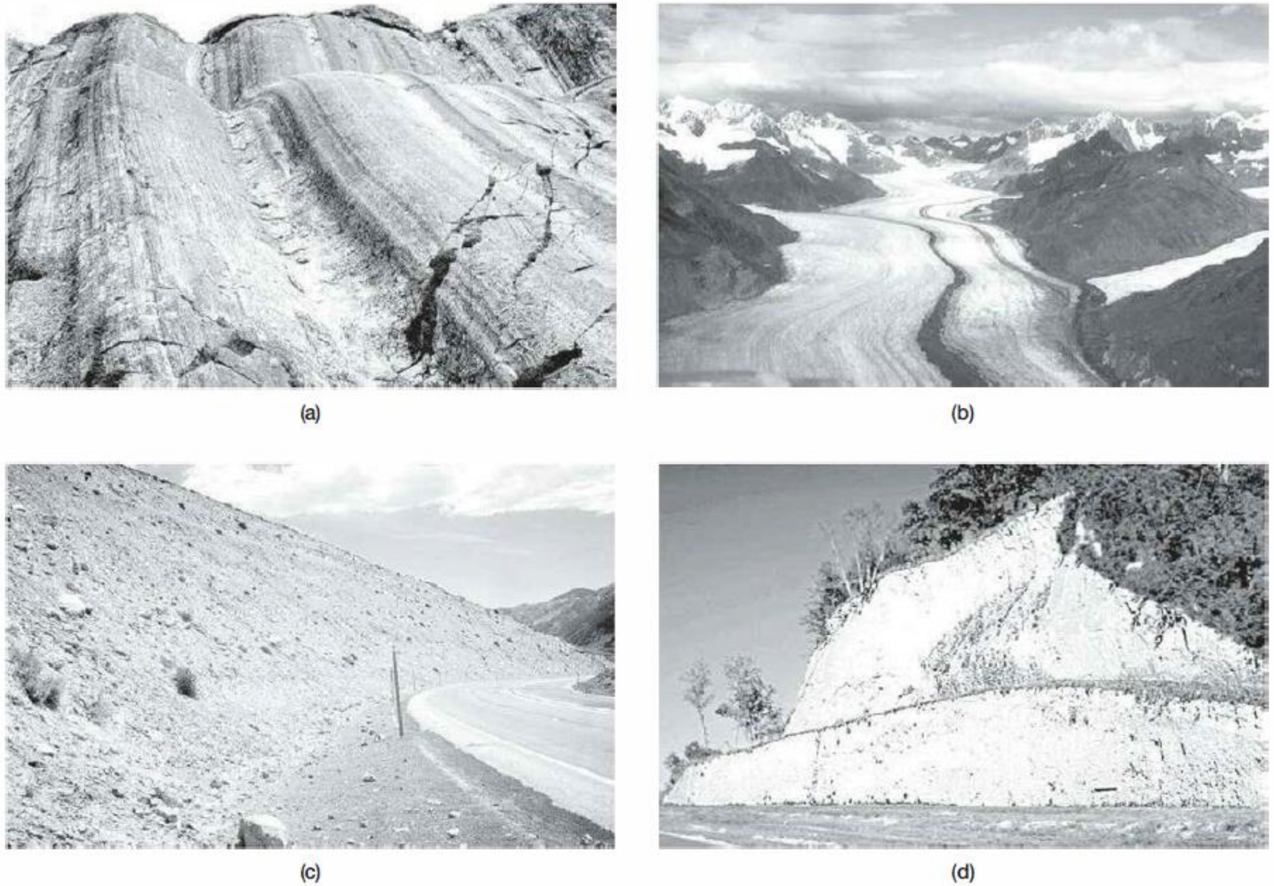


FIGURE 14-2 Various geological features characteristic of glaciation. (a) Glacial striations are formed by the gouging out of bedrock by pebbles frozen onto the base of an advancing glacier. The lineations indicate the direction of glacial movement. (b) Moraines form by the bulldozing action of advancing glaciers. (c) Till is the mix of sediments of various types and sizes resulting from the indiscriminate transportation by glaciers. (d) Loess is fine-grained sediment produced by glacial abrasion and transported to the site of deposition by wind. (*Sources:* (a) Walter H. Hodge/Peter Arnold and (b), (c), (d) TLM Photo.)

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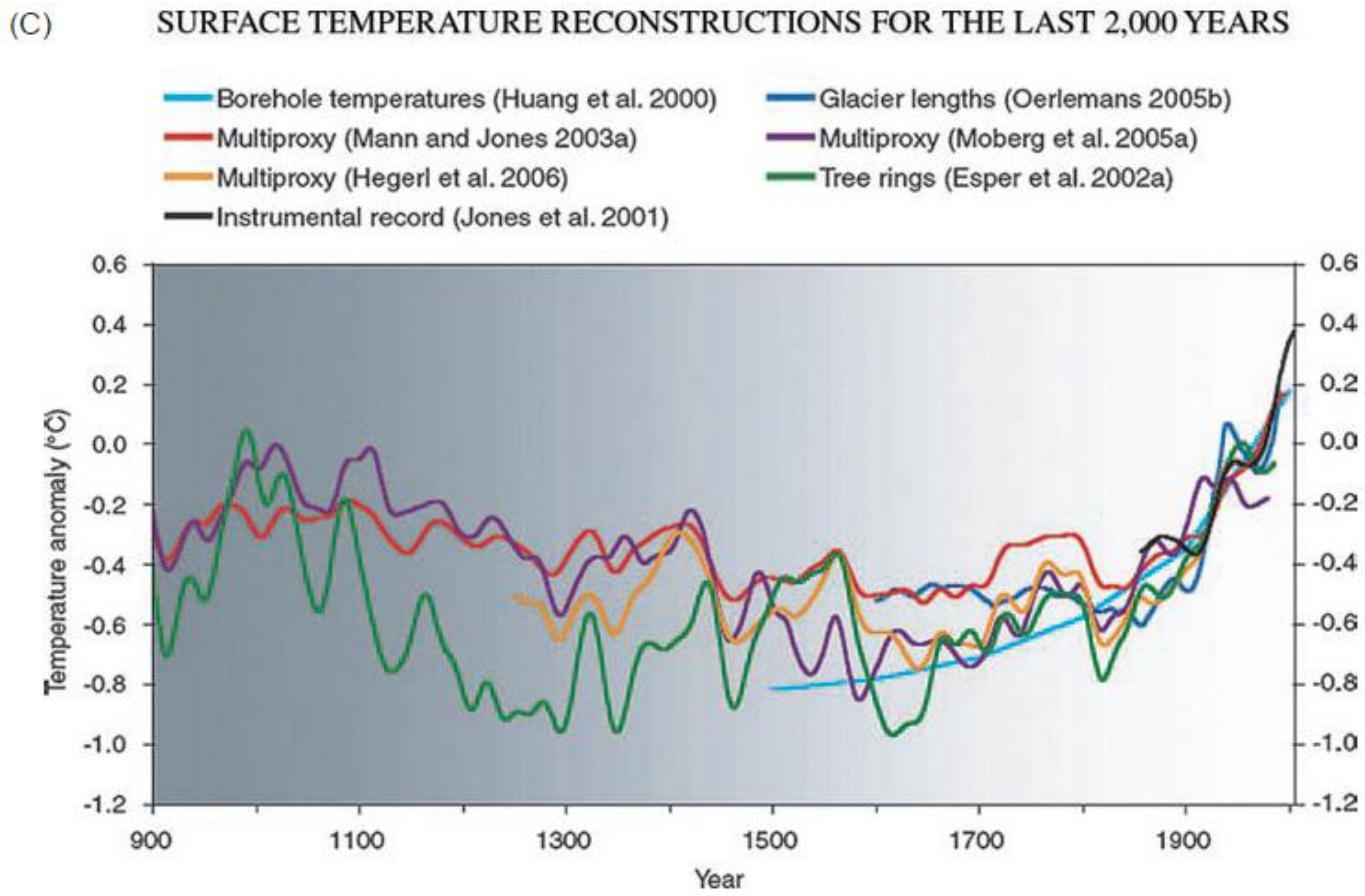
Geological Records of Climate Change



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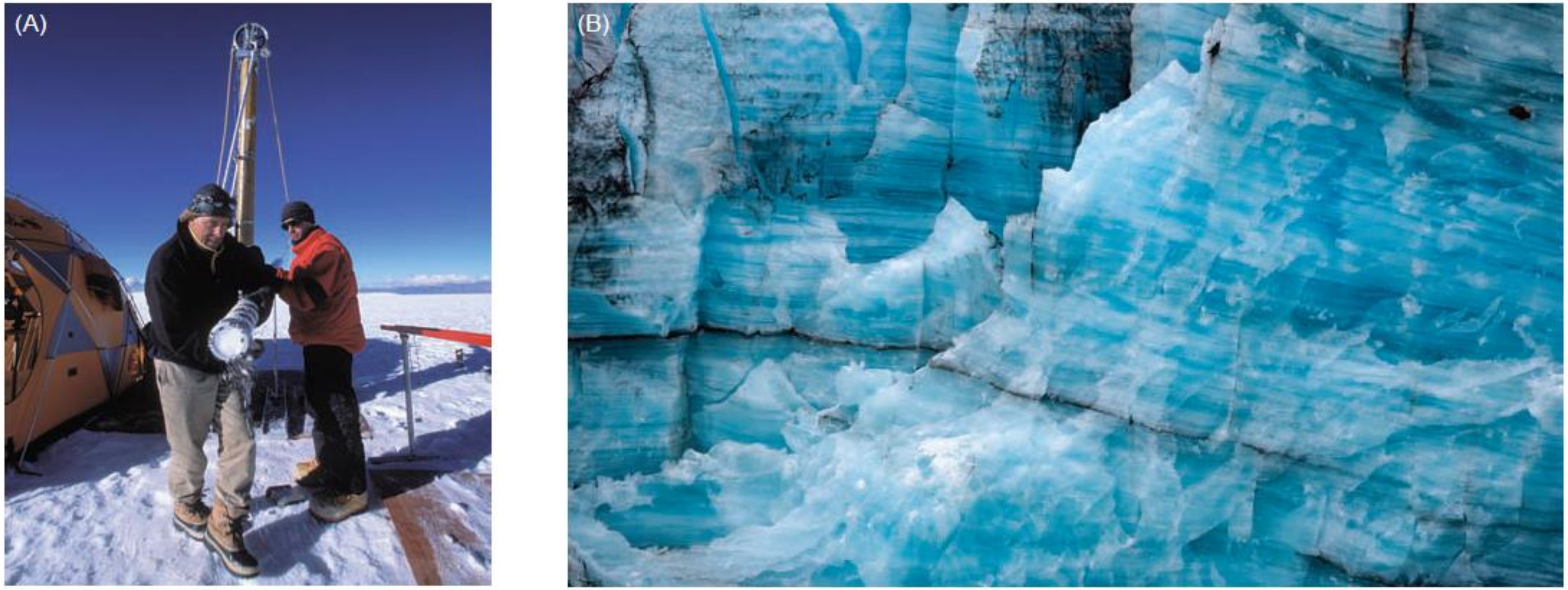
Geological Records of Climate Change

FIGURE 13.6 Reconstructing temperature records from climate proxies
(A) Chemical analysis of ice cores taken from glaciers and ice caps can provide a record of temperature at the time the ice was formed. (B) Glacier ice forms from snow, which is deposited in annual layers, as seen here in glacier ice from Glacier Bay National Park, Alaska. (C) Direct measurements of the temperature in the northern hemisphere from the middle of the nineteenth century onward are shown by the black curve. The other curves are based on indirect reconstructions of temperature from tree rings (green), glacier lengths (dark blue), and ice cores (light blue). The remaining curves (yellow, red, and purple) were reconstructed using a combination of different proxy data sources. All curves show that temperatures during the last few decades of the twentieth century were higher than during any comparable period in the last thousand years.



Earth's Climate System

Isotopic Fractionation

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right) * 1000\ ^{o}/_{oo}$$

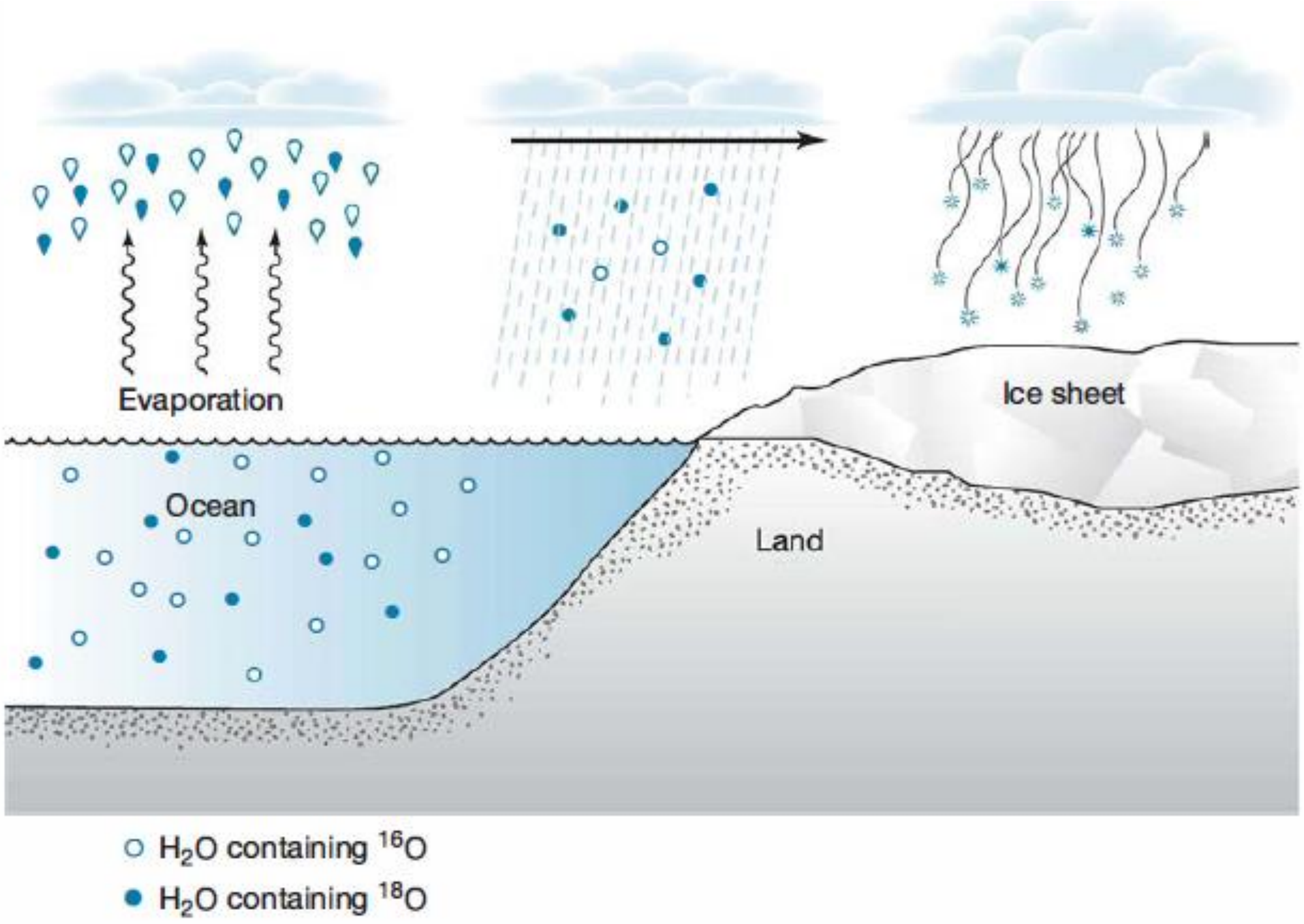


FIGURE 14-3 Changes in the oxygen isotopic composition of seawater during the growth of continental ice sheets.

Earth's Climate System

- **Schematic energy level diagram for <u>hydrogen</u> molecule.**

- **Boltzmann distribution:** The probability that a system will be in the i^{th} energy state at the temperature T is given as

$$p_i \propto exp\left(-\frac{\epsilon_i}{k_B T}\right)$$

- Energy depends on the **effective mass of molecule.** As a result, we find isotopic fractionation.

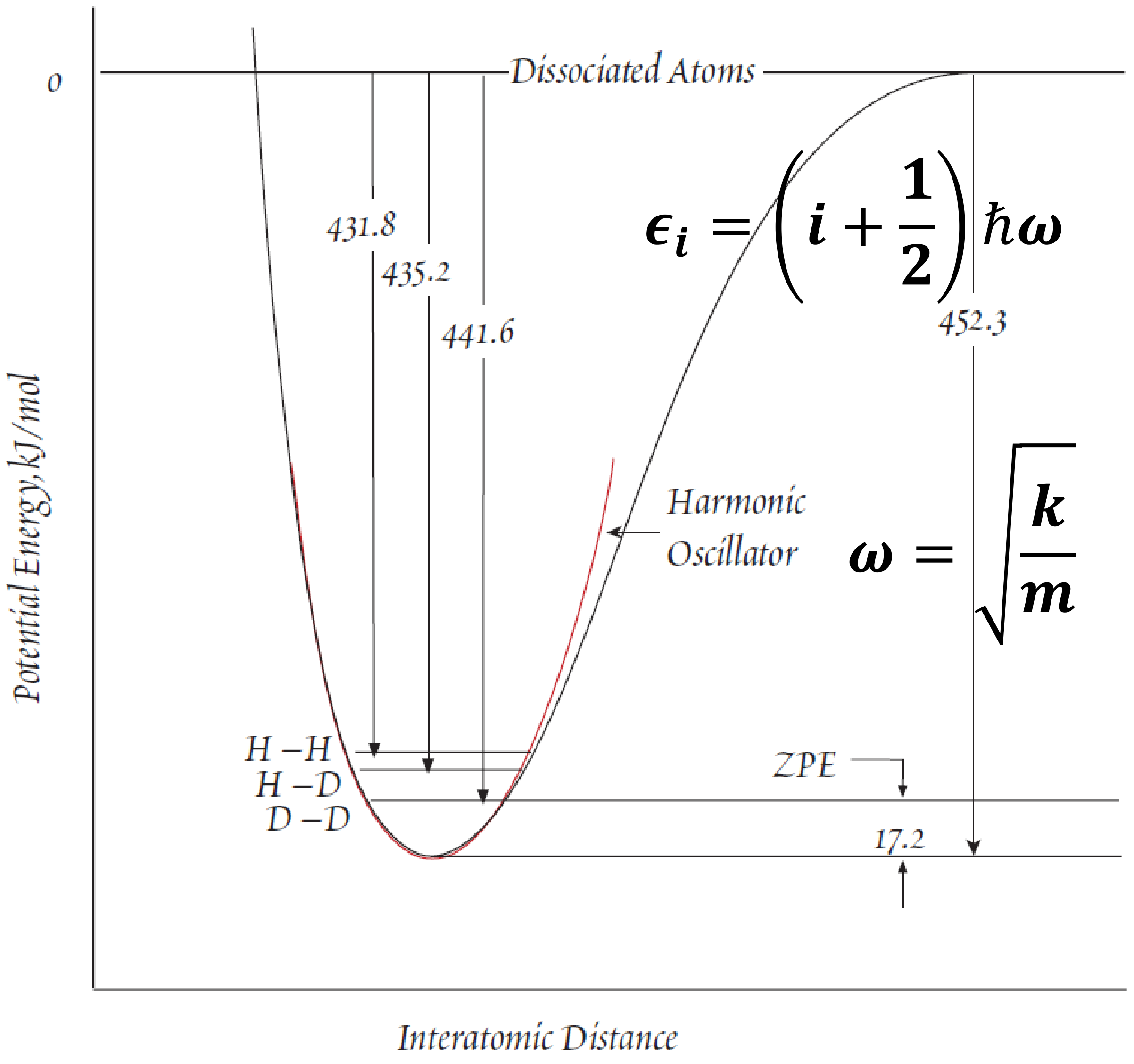


Figure 9.1. Energy-level diagram for the hydrogen molecule. Fundamental vibration frequencies are 4405 cm^{-1} for H_2, 3817 cm^{-1} for HD, and 3119 cm^{-1} for D_2. The zero-point energy of H_2 is greater than that of HD which is greater than that of D_2. Arrows show the energy, in kJ/mol, required to dissociate the 3 species. After O'Niel (1986).

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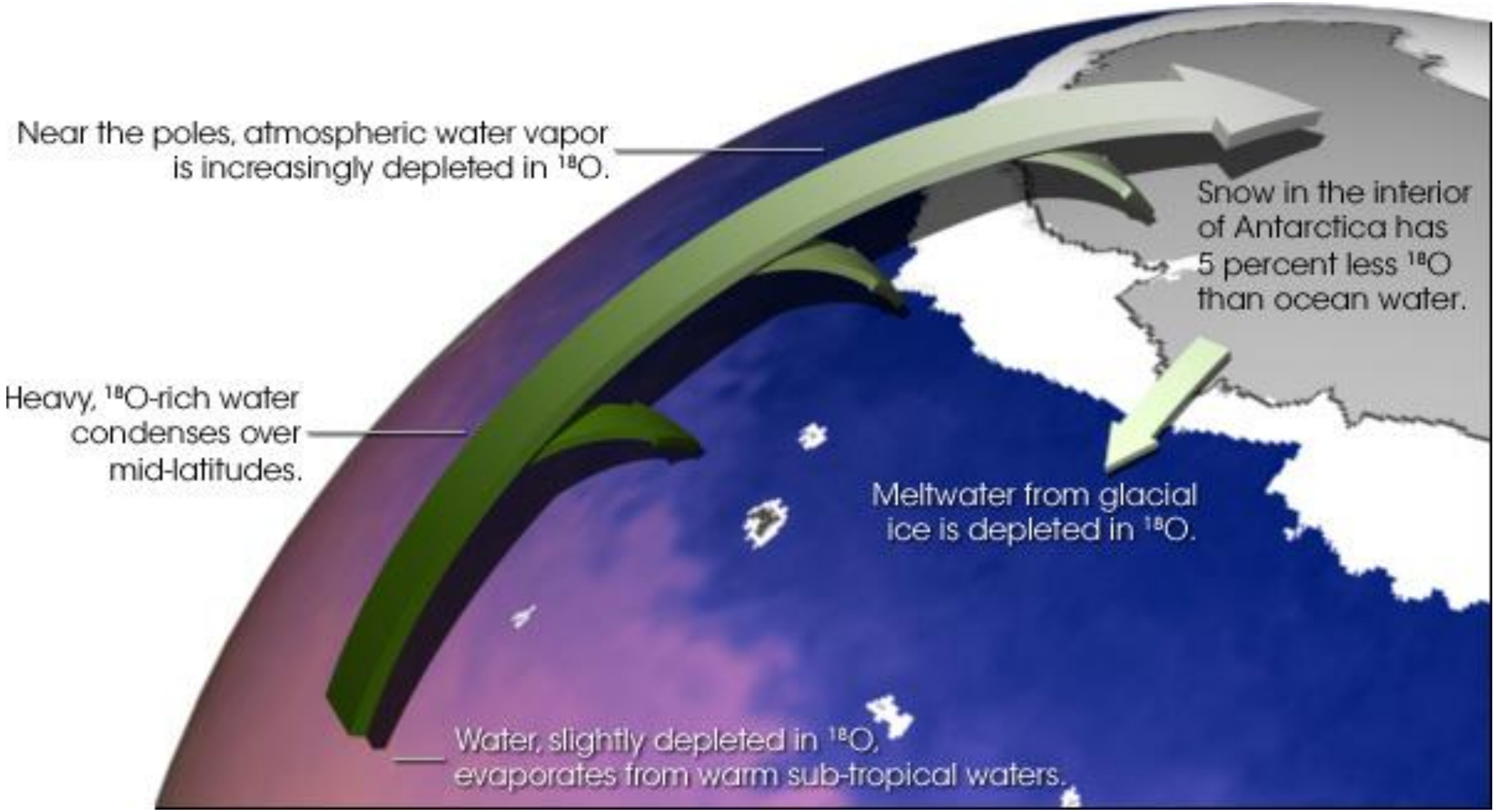
Isotopic Fractionation

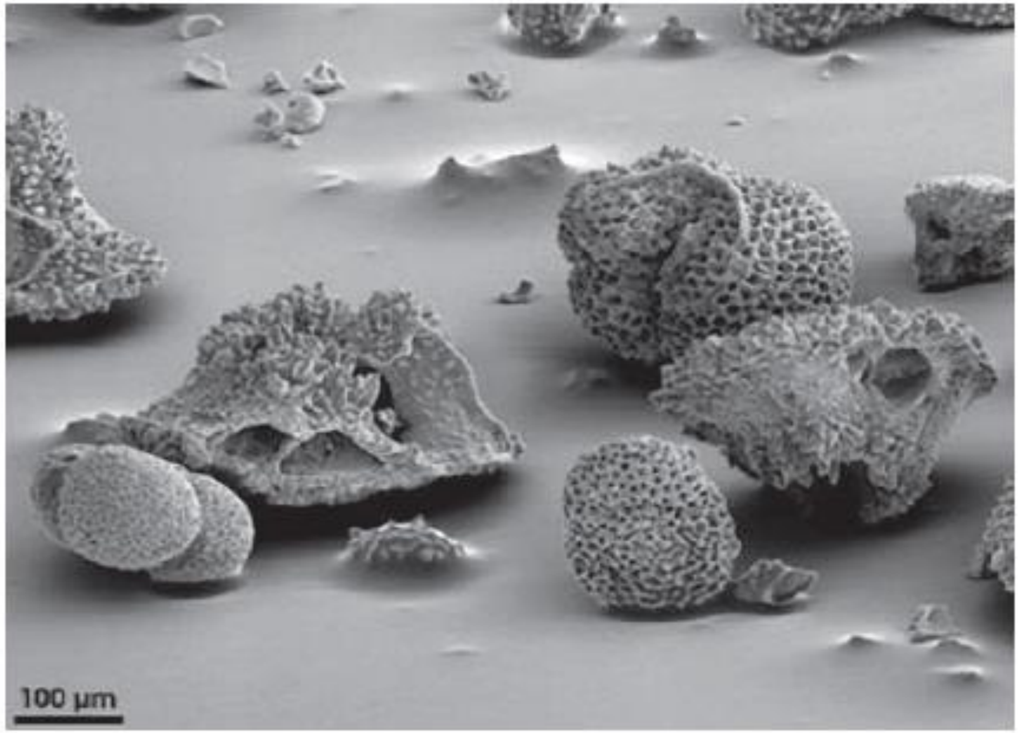


https://earthobservatory.nasa.gov/features/Paleoclimatology_OxygenBalance

Earth’s Climate System

Isotopic Fractionation

FIGURE 13.9 Deep-sea microfossils as climate proxies Seafloor sediment obtained by drilling contains fossils of tiny sea creatures, foraminifera, which once lived in surface waters. These microfossils contain abundant information about the chemistry and temperature of the ocean. Foraminifera have calcium carbonate shells that contain oxygen. The ratio of oxygen-16 (the lighter isotope of oxygen) to oxygen-18 is a measure of the temperature of the seawater in which the microscopic creatures lived.



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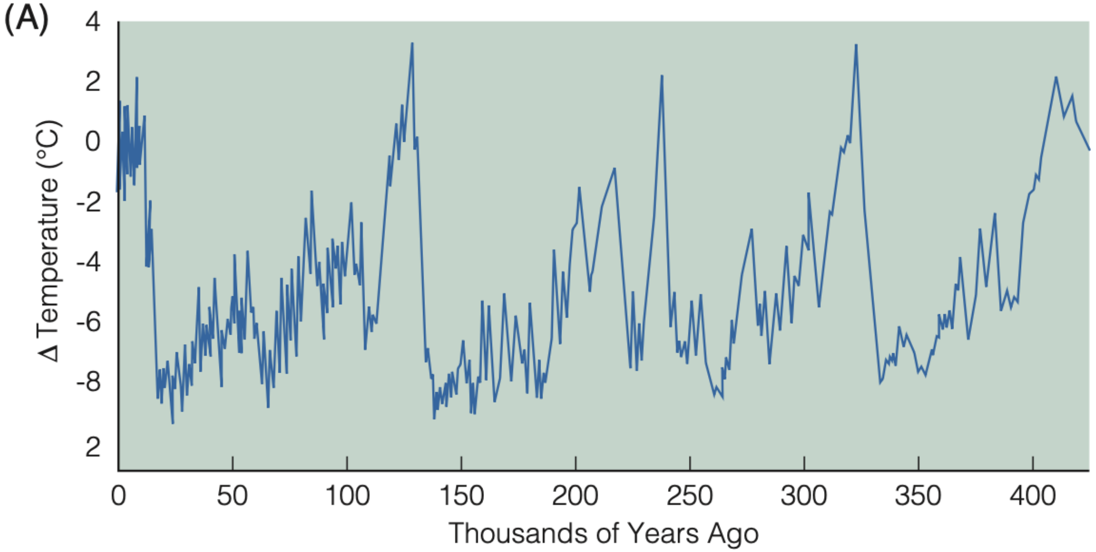
Temperature Reconstruction from Ice-Core Data



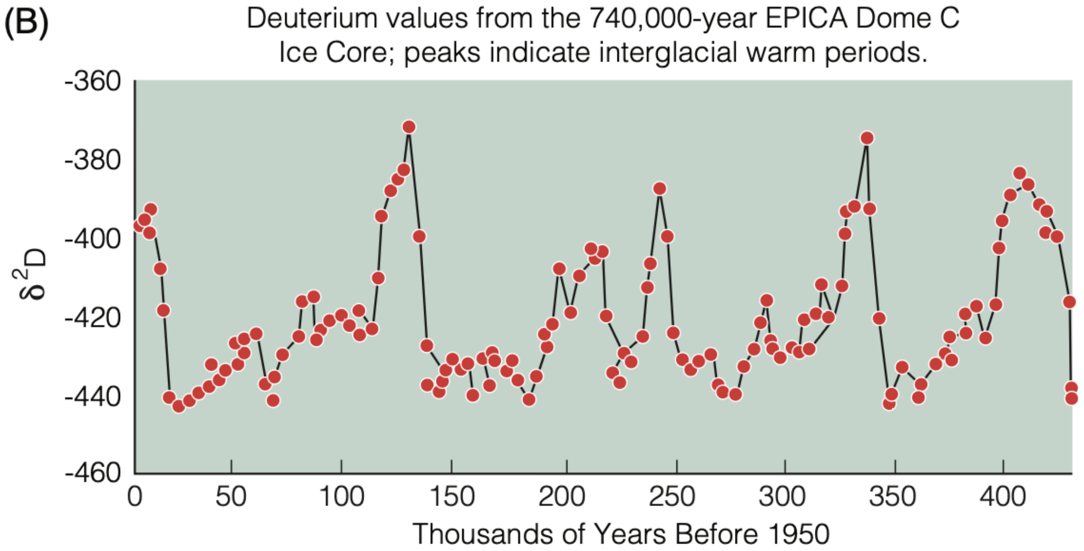


FIGURE C13.1 Temperature reconstruction from ice-core data

(A) Ice-core data from Antarctica shows a reconstruction of temperature, in terms of the difference (Δ) from present-day temperature, going back 420,000 years. This temperature reconstruction is based on analysis of oxygen isotopes from the ice. (B) The temperature reconstruction shown here, also from Antarctica, is based on Deuterium isotopic analyses and extends to 740,000 years before the present.

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Temperature Reconstruction of Geological Past from deep-sea sediment data

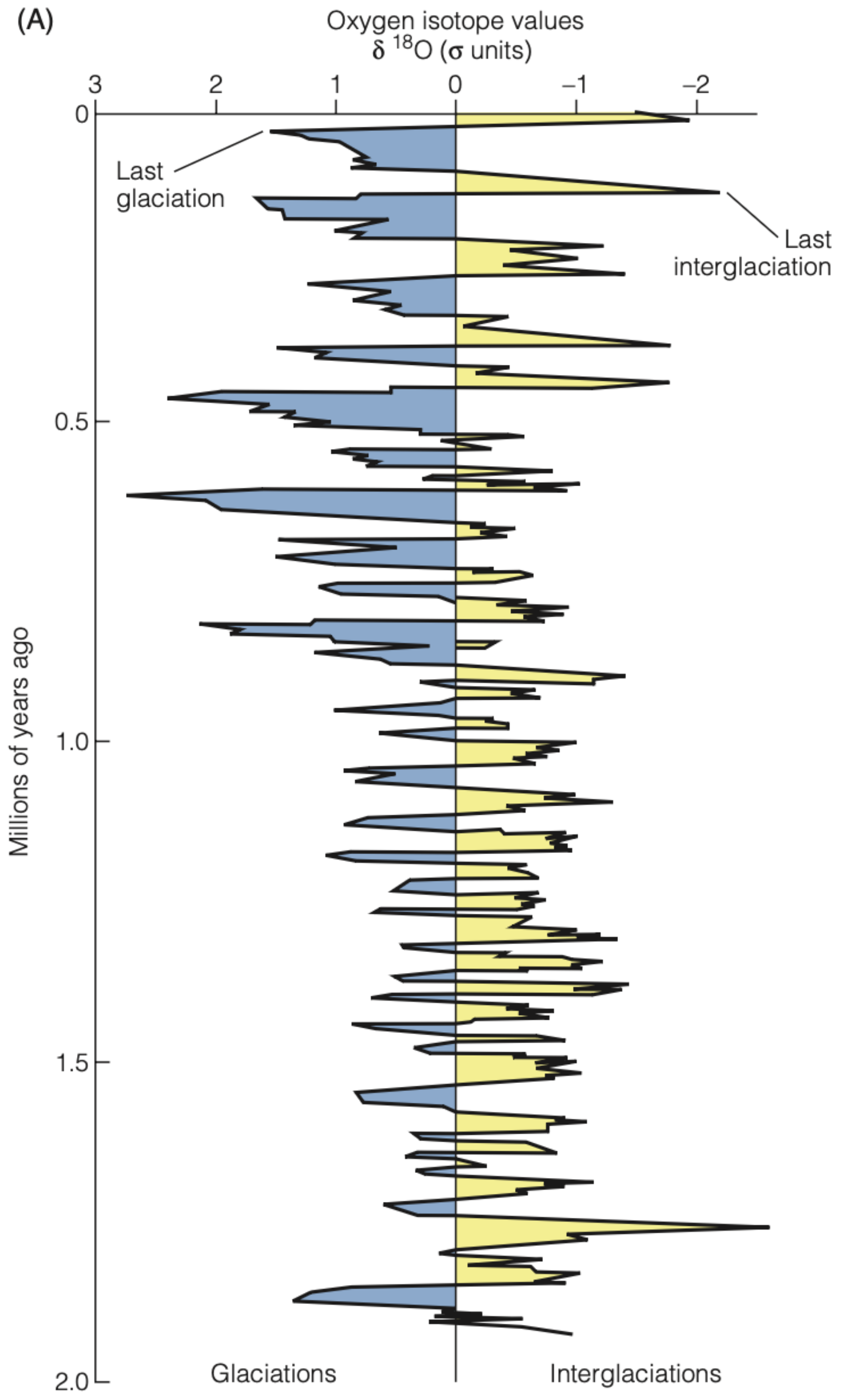

FIGURE C13.2 Temperature reconstruction from deep-sea sediment data
(A) This curve of average oxygen-isotope variations during the last 2 million years is based on analyses of deep-sea sediment cores. The curve illustrates changing global ice volume during successive glacial-interglacial cycles. (B) This record of surface ocean temperatures is based on oxygen-isotope ratios measured in a sediment core from the western Pacific Ocean. Relatively warm surface waters cooled abruptly about 35 million years ago, reflecting a dramatic change that led to the buildup of glaciers in Antarctica. With further cooling, an ice sheet developed over Antarctica, and by 2.5 million years ago, northern hemisphere ice sheets had formed.

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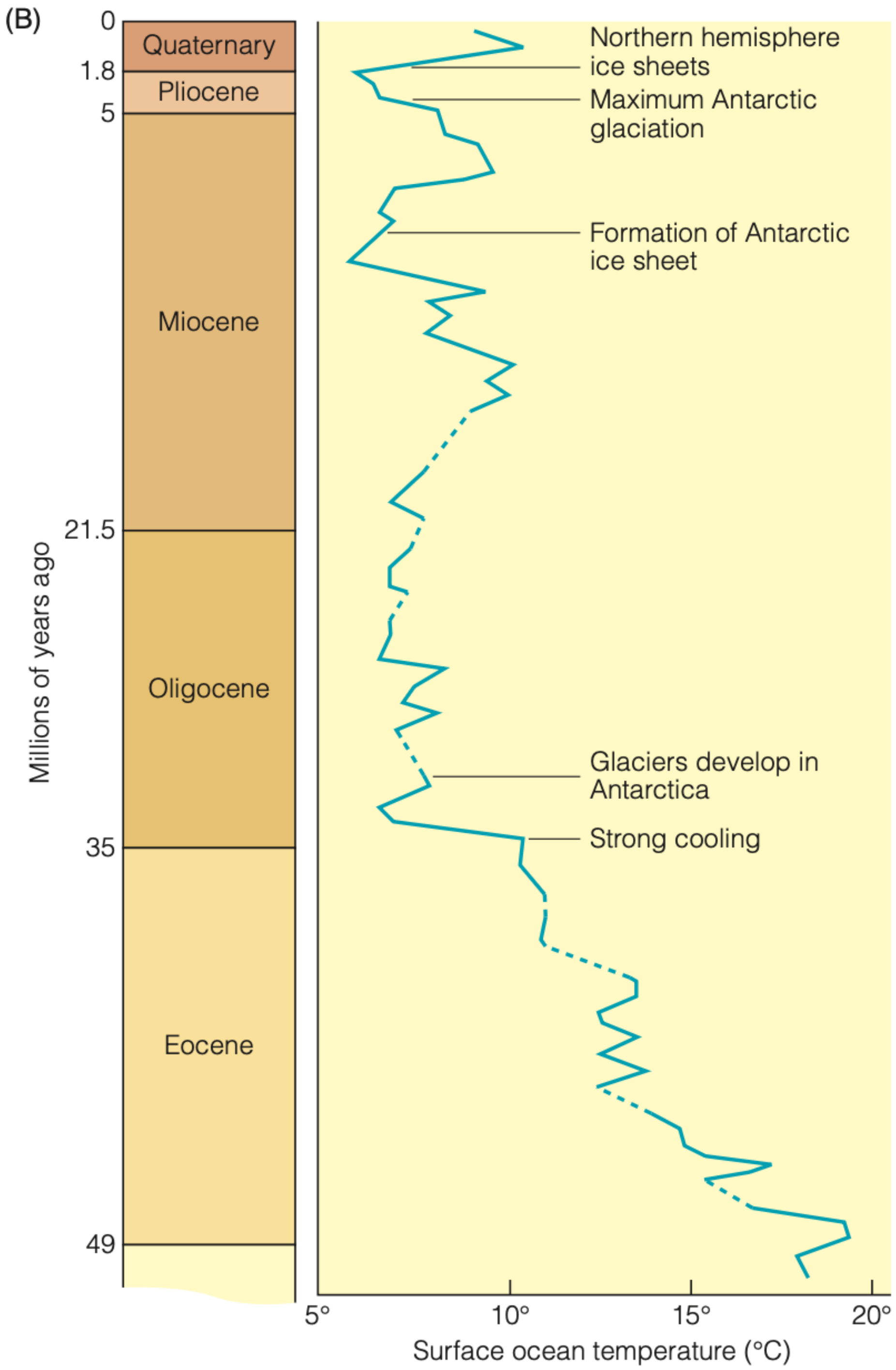
Temperature Reconstruction of Geological Past from deep-sea sediment data

FIGURE C13.2 Temperature reconstruction from deep-sea sediment data
(A) This curve of average oxygen-isotope variations during the last 2 million years is based on analyses of deep-sea sediment cores. The curve illustrates changing global ice volume during successive glacial-interglacial cycles. (B) This record of surface ocean temperatures is based on oxygen-isotope ratios measured in a sediment core from the western Pacific Ocean. Relatively warm surface waters cooled abruptly about 35 million years ago, reflecting a dramatic change that led to the buildup of glaciers in Antarctica. With further cooling, an ice sheet developed over Antarctica, and by 2.5 million years ago, northern hemisphere ice sheets had formed.



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Temperature Reconstruction of Geological Past

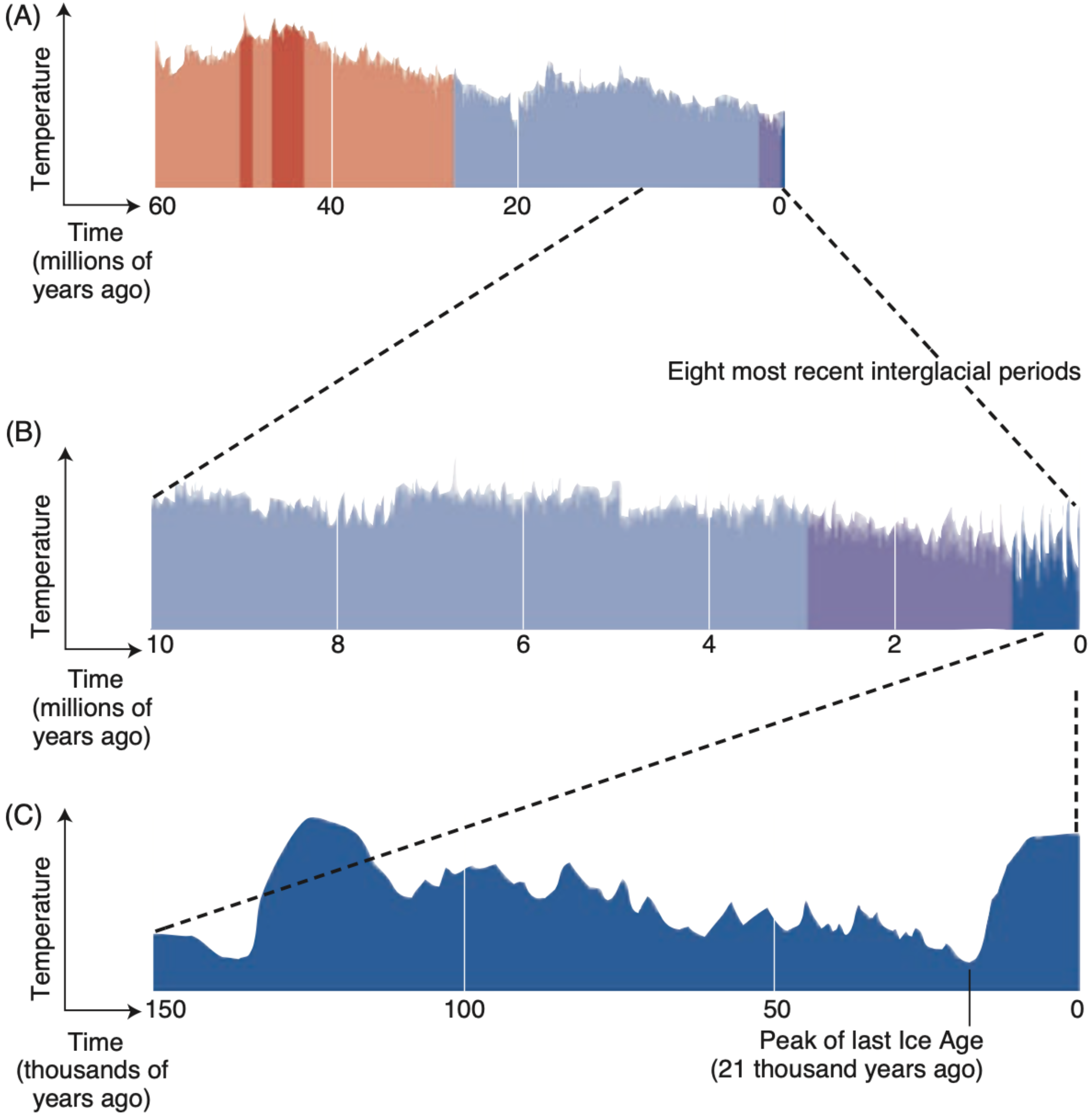

FIGURE 13.11 Past climatic change

These graphs show an estimate of global temperatures, based on deep-ocean sediments, over (A) the last 60 million years ago to present. At the beginning of the Cenozoic Era, Earth's surface was largely free of ice. Sea levels were higher and seawater could circulate freely, (B) As plate motions moved the major landmasses near their present locations, temperatures fell and glaciers appeared at the poles. In the last 800,000 years (the blue band in the temperature graph), the climate has fluctuated eight times between ice ages and warm interglacial periods. (C) At the peak of the last ice age, glaciers blanketed most of North America. Earth is now warmer than it has been at any time in the last 100,000 years, and roughly at the same temperature as it was in the last interglacial period 120,000 years ago.

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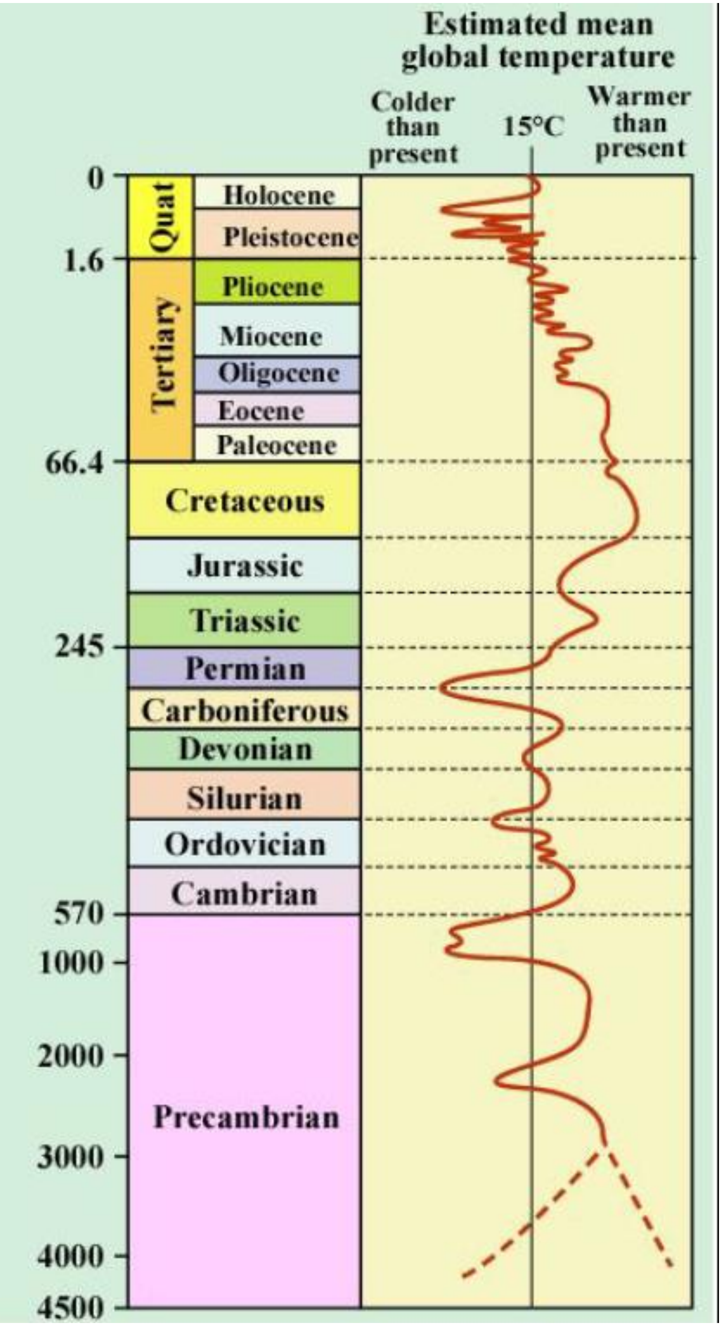
Temperature Reconstruction of Geological Past

- Tertiary and Quaternary have experienced wide fluctuation over a relatively short spans of time with overall cooling towards present.

- The Quaternary is characterized by repeated continental glaciation.

- The cretaceous period was the warmest time (~20℃).



Earth's Climate System

- **Climate system dynamics are driven by both internal and external radiative forcings.**

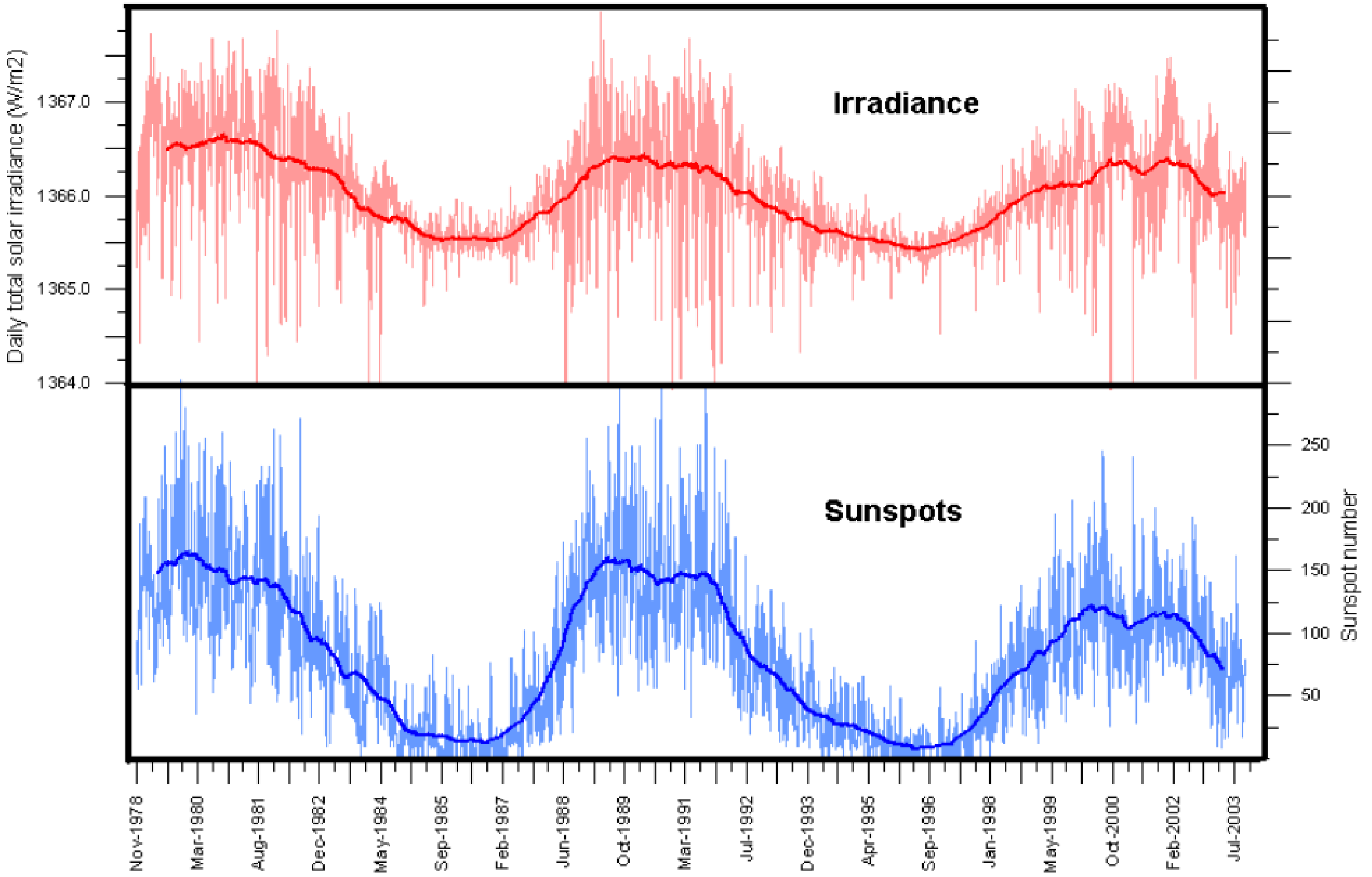
- **Radiative forcing relates to the amount of energy which Earth receives from the Sun, and how much Earth radiates back to the space.**

- **External forcings are those attributable to changes in the amount of energy Earth receives.**

- **Internal forcings are all those factors that determine how much energy is reflected/radiated by Earth.**

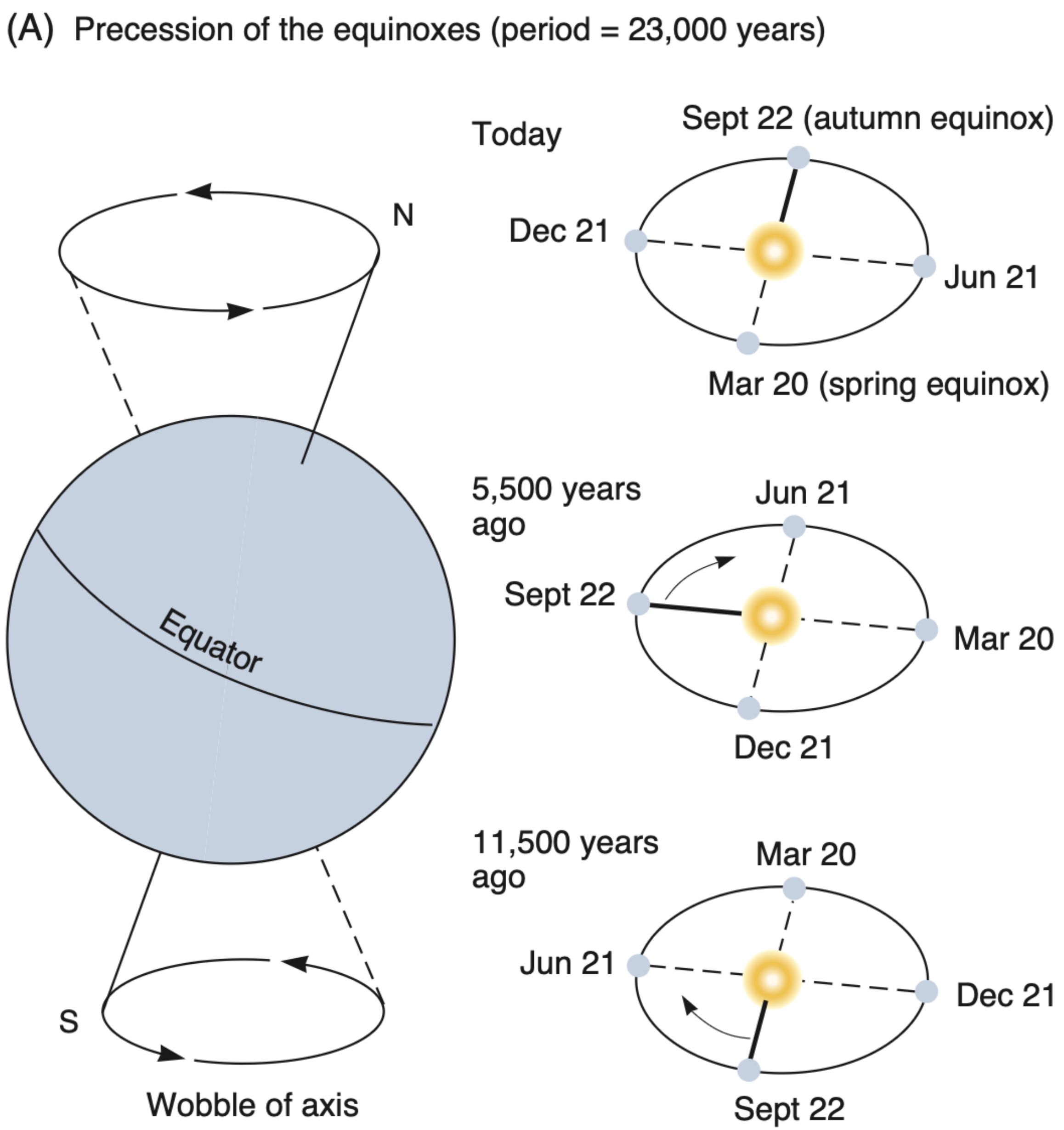
Earth's Climate System

Sunspot Activity and Solar Radiance



Earth's Climate System

Milankovitch Cycles



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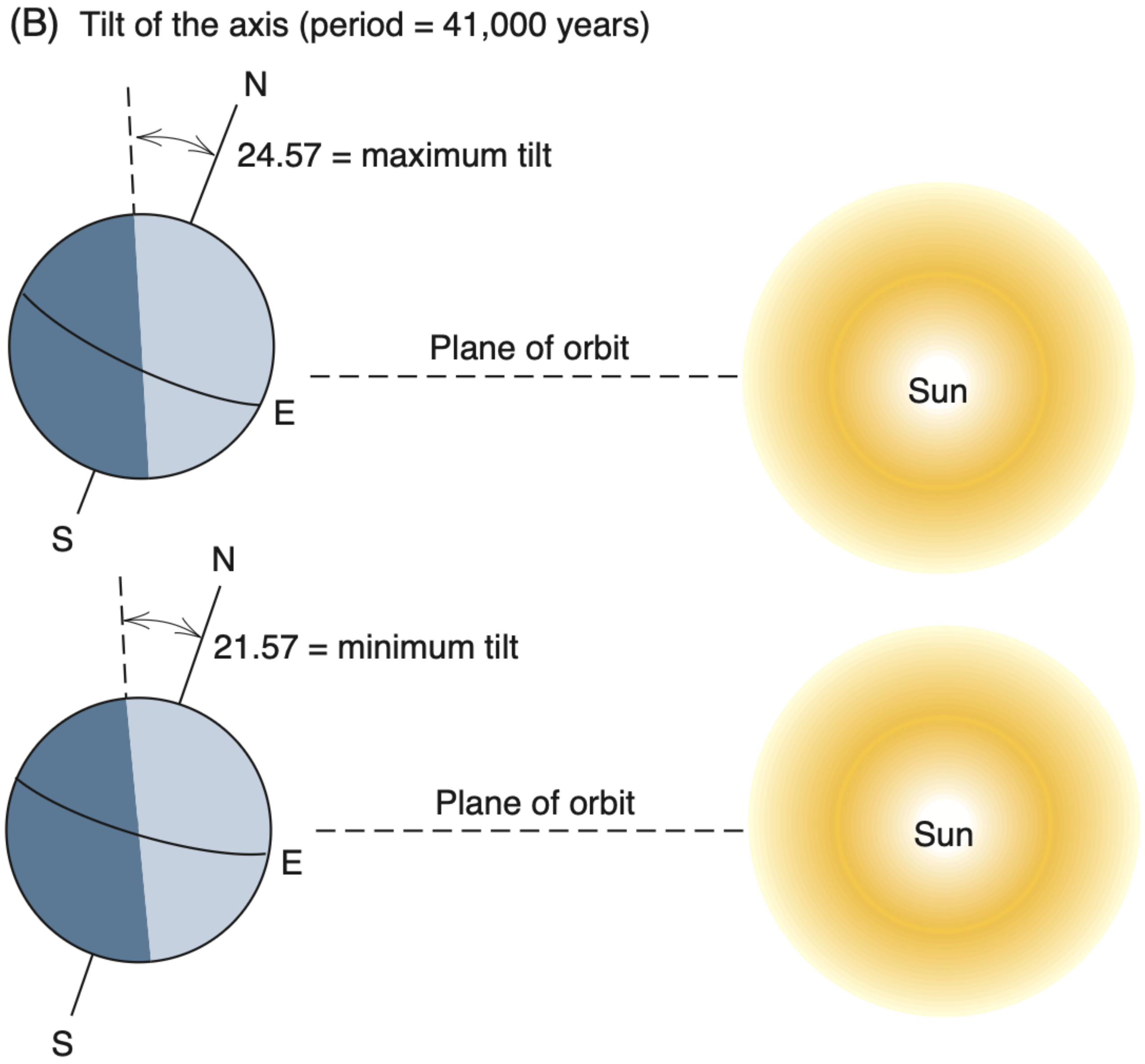
Milankovitch Cycles



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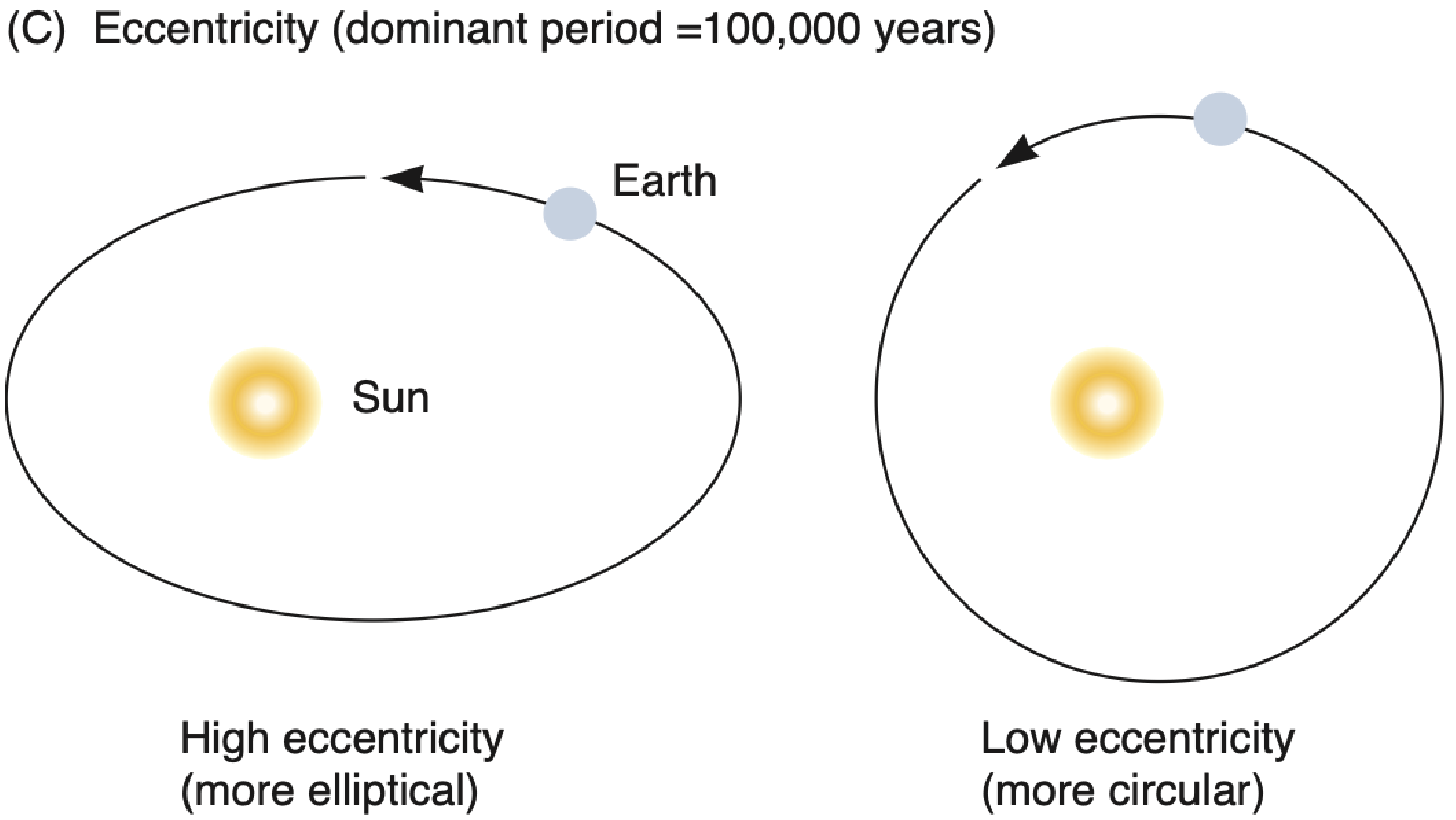
Milankovitch Cycles



Earth’s Climate System

Milankovitch Cycles

FIGURE 13.19 Milankovitch cycles
The geometry of Earth’s orbit and axial tilt influence insolation, which in turn influences climate and glacial cycles. (A) Earth wobbles on its axis like a spinning top, making one revolution every 26,000 years; this is called precession. The axis of Earth’s elliptical orbit also rotates, though more slowly, in the opposite direction. These motions together cause a progressive shift, or precession, of the spring and autumn equinoxes, with each cycle lasting about 23,000 years. (B) The tilt of Earth’s axis, which now is about 23.5°, varies from 21.5° to 24.5°. Each cycle lasts about 41,000 years. Increasing the tilt means a greater difference, for each hemisphere, between the amount of solar radiation received in summer and that received in winter. (C) The shape of Earth’s orbit is an ellipse with the Sun at one focus. Over 100,000 years, the shape of the orbit changes from almost circular (low eccentricity) to more elliptical (high eccentricity). The higher the eccentricity, the greater the seasonal variation in radiation received at any point on Earth’s surface.

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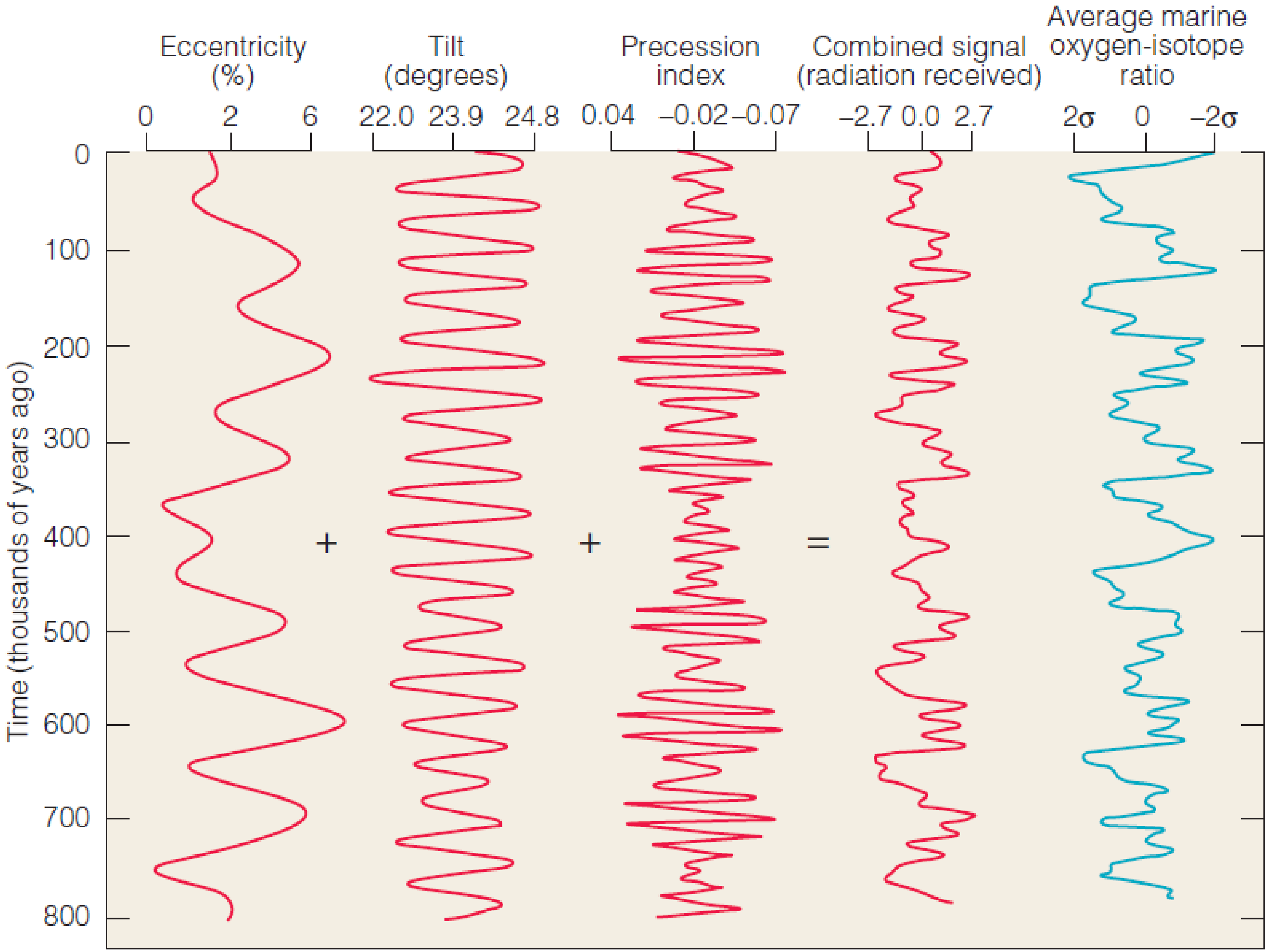
Milankovitch Cycles (Overall Effect)



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Milankovitch Cycles (Overall Effect)

- The slow but predictable changes in precession, obliquity, and eccentricity cause long-term climate variations (about 10%) in the solar radiation at any latitude on the Earth's surface.

- Isotopic analysis suggests that climate fluctuations of glaciation-interglaciation time scale reasonably match the prediction from Milankovitch cycle.

- However, ~10% variation in solar radiation is **too small** to account for the average global temperature change of 4°C to 10°C.

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Milankovitch Cycles (Overall Effect)

- There should be a mechanism where the slight temperature change (due to Milankovitch cycles) must be **amplified** into large temperature change to account for glaciation (to generate and maintain huge continental ice sheets).

- The possible factors:
  1) Change in Greenhouse gases (CGGs) budget
  2) Changes in Albedo (Ice-Albedo positive feedbacks)
  3) Rate of volcanism (Volcanic CO_2)
  4) Shifting Continents (Plate tectonics)

Earth’s Climate System

Change in Greenhouse gases (CGGs) budget

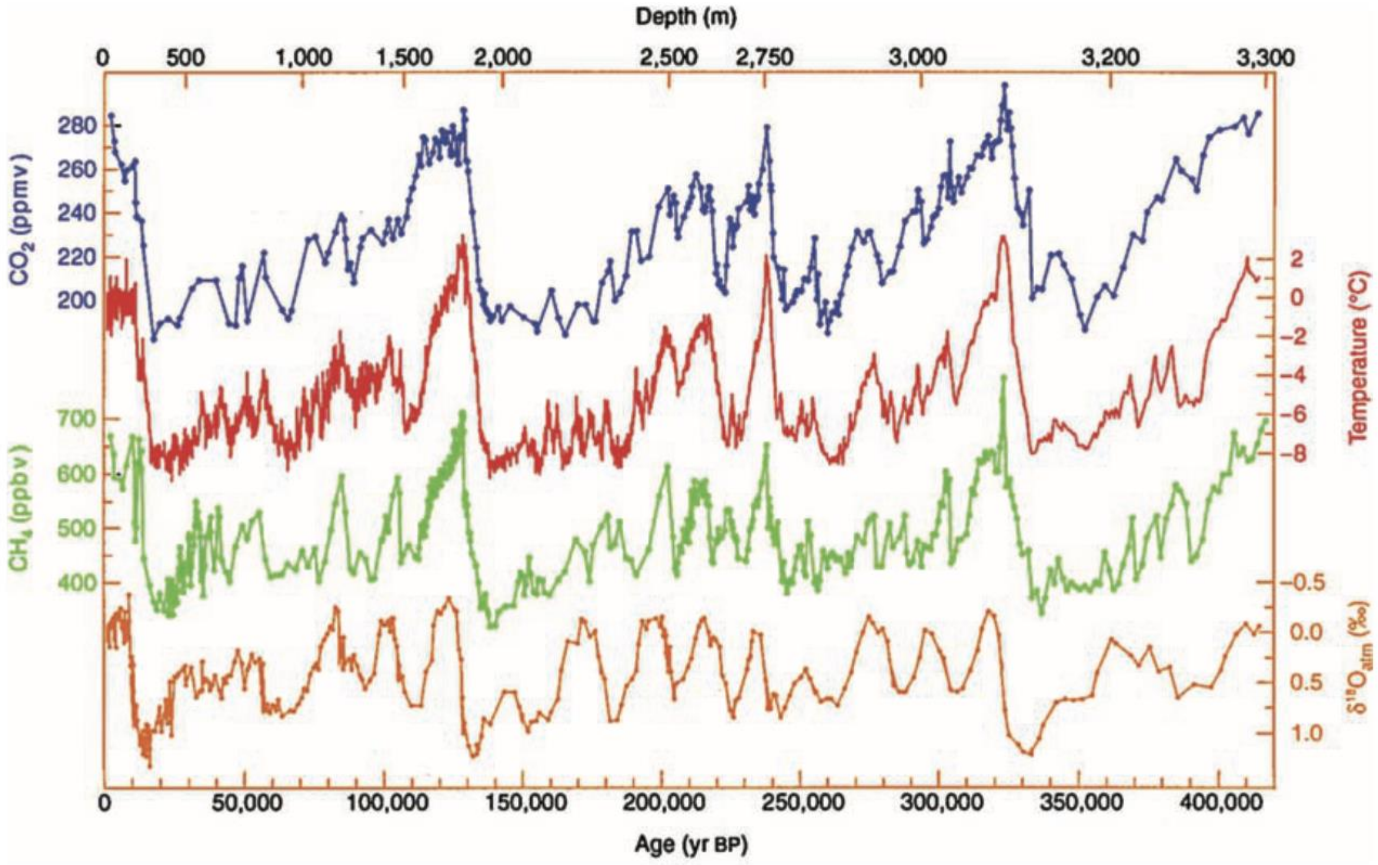

FIGURE 13.21 Atmospheric carbon dioxide and methane over time
These curves show changes in atmospheric carbon dioxide and methane (based on chemical analysis of trapped air samples) compared to changes in temperature (based on oxygen–isotope values from ice) in samples from deep ice cores drilled at Vostok Station, Antarctica. Concentrations of the greenhouse gases were high during the early part of the last interglaciation, just as they are during the present interglaciation, but they were lower during glacial times. The curves are consistent with the hypothesis that the atmospheric concentration of these gases contributed to warm interglacial climates and cold glacial climates. This remarkable record goes back 420,000 years.

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Changes in Albedo (Ice-Albedo positive feedbacks)

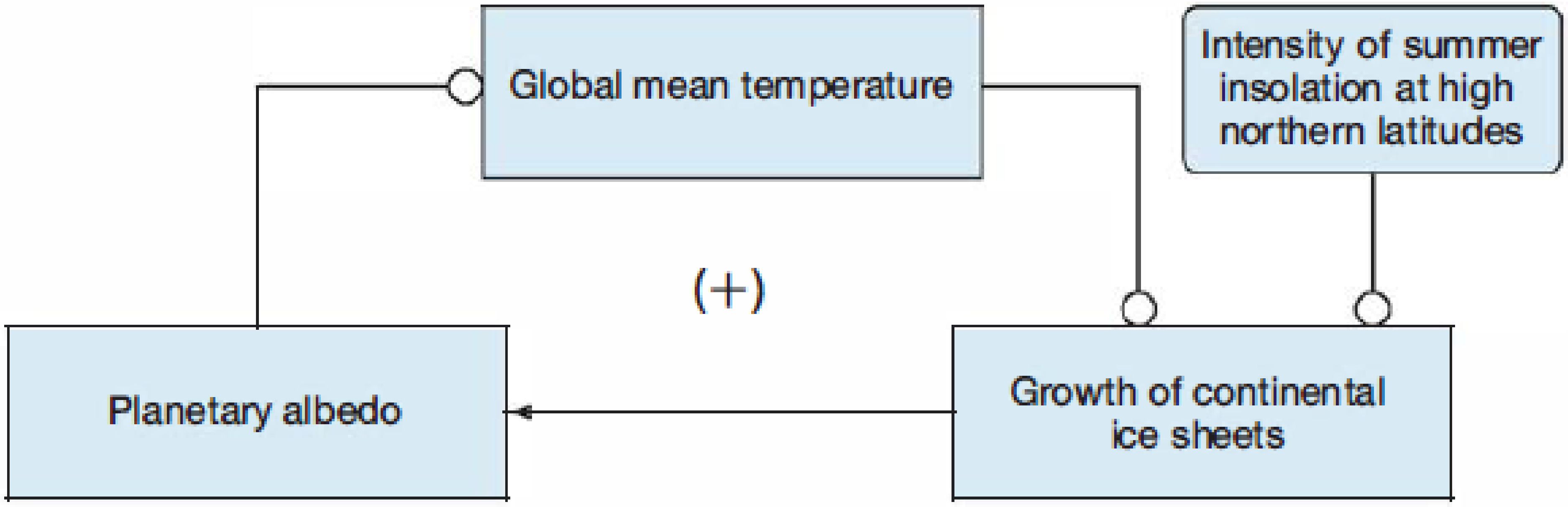
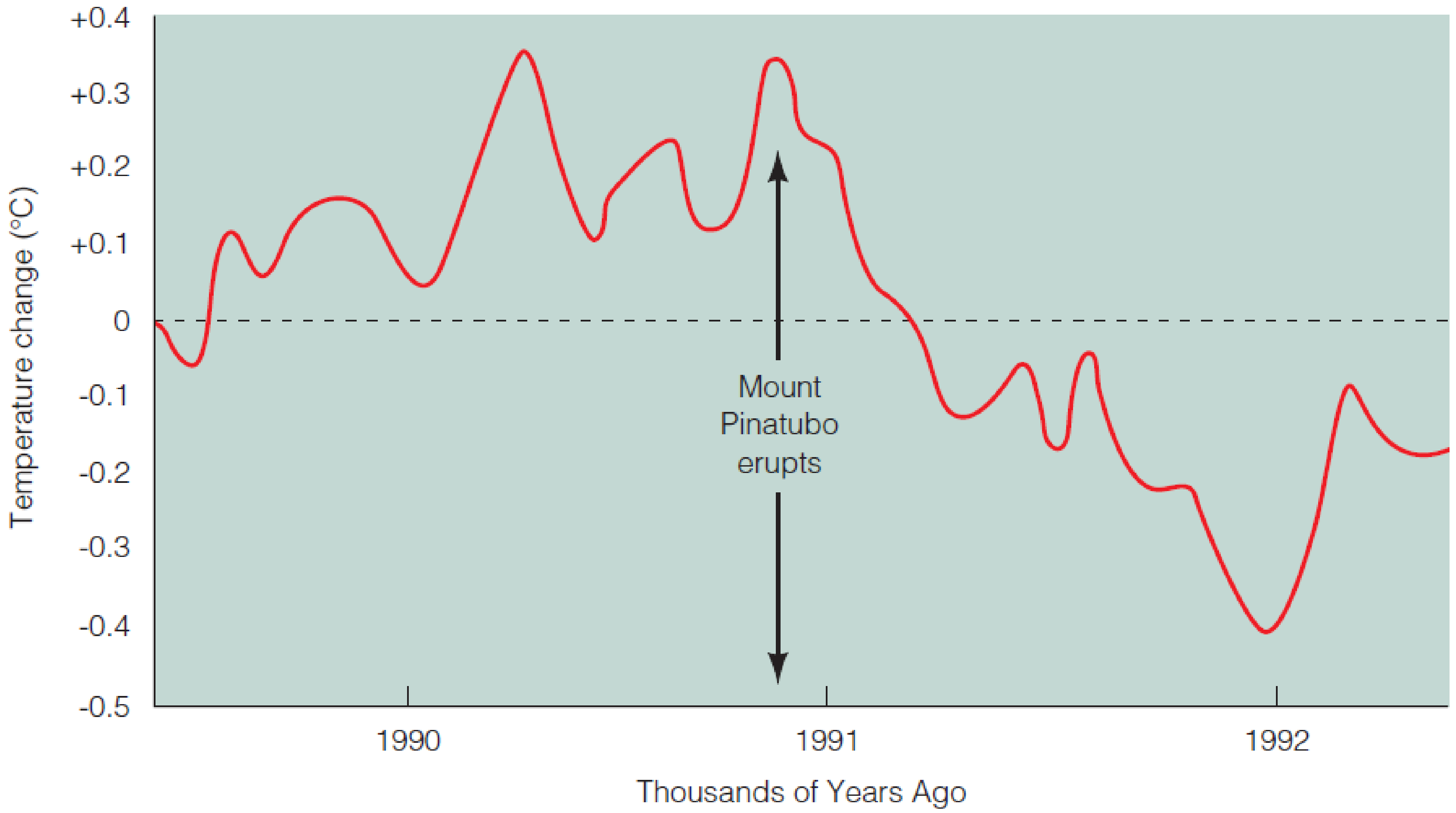


FIGURE 14-9 Feedback diagram showing the effect of changes in glacial growth on global temperature.

Earth's Climate System

Rate of volcanism (Volcanic CO_2)



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Shifting Continents (Plate tectonics)

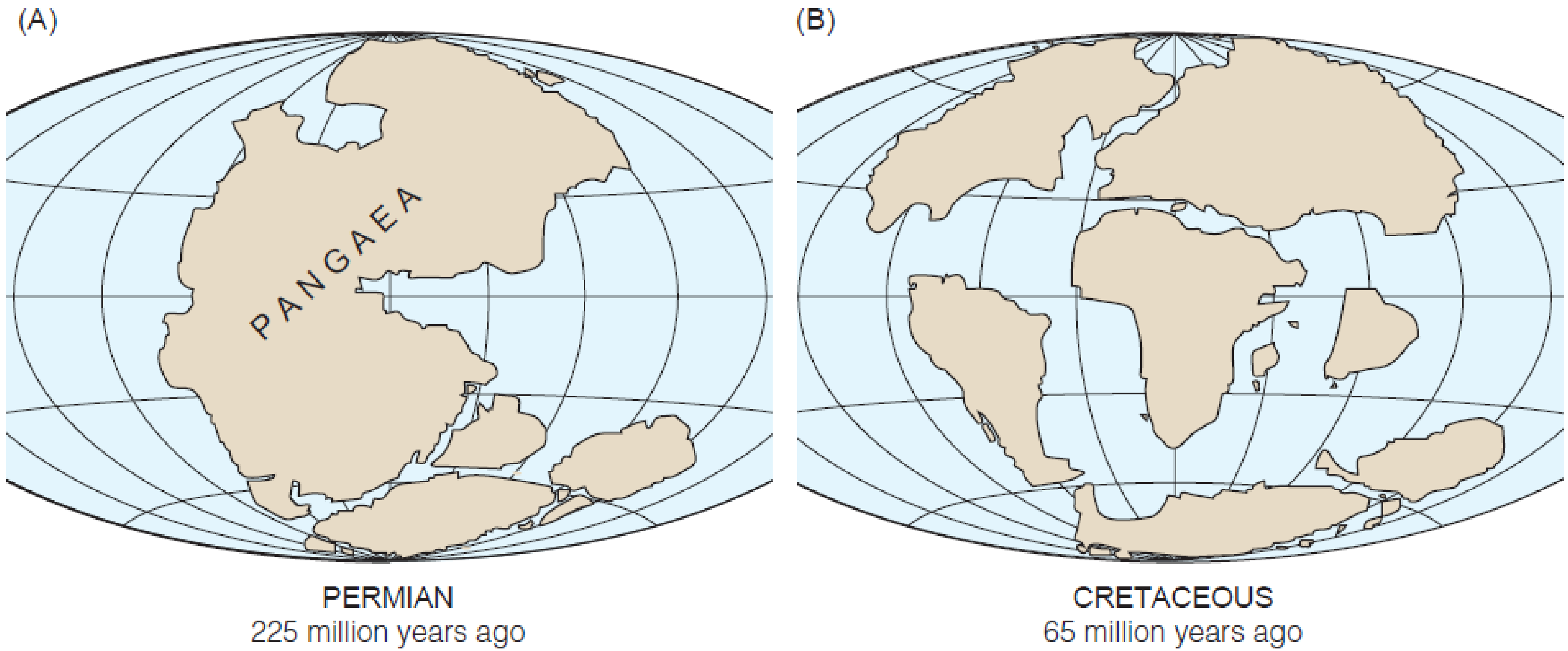

FIGURE 13.23 Pangaea and Panthalassa
(A) Around 225 million years ago the continents were still gathered together in one supercontinent, Pangaea, with vast areas of land located far from the temperature-moderating influence and moisture source of the global ocean, Panthalassa. (B) Early in the Cretaceous Period, however, Pangaea began to split apart, which would have brought much more land in closer contact with the ocean, leading to warmer temperatures, higher precipitation, and lesser extremes in temperature.

Earth's Climate System

Carbon Cycle

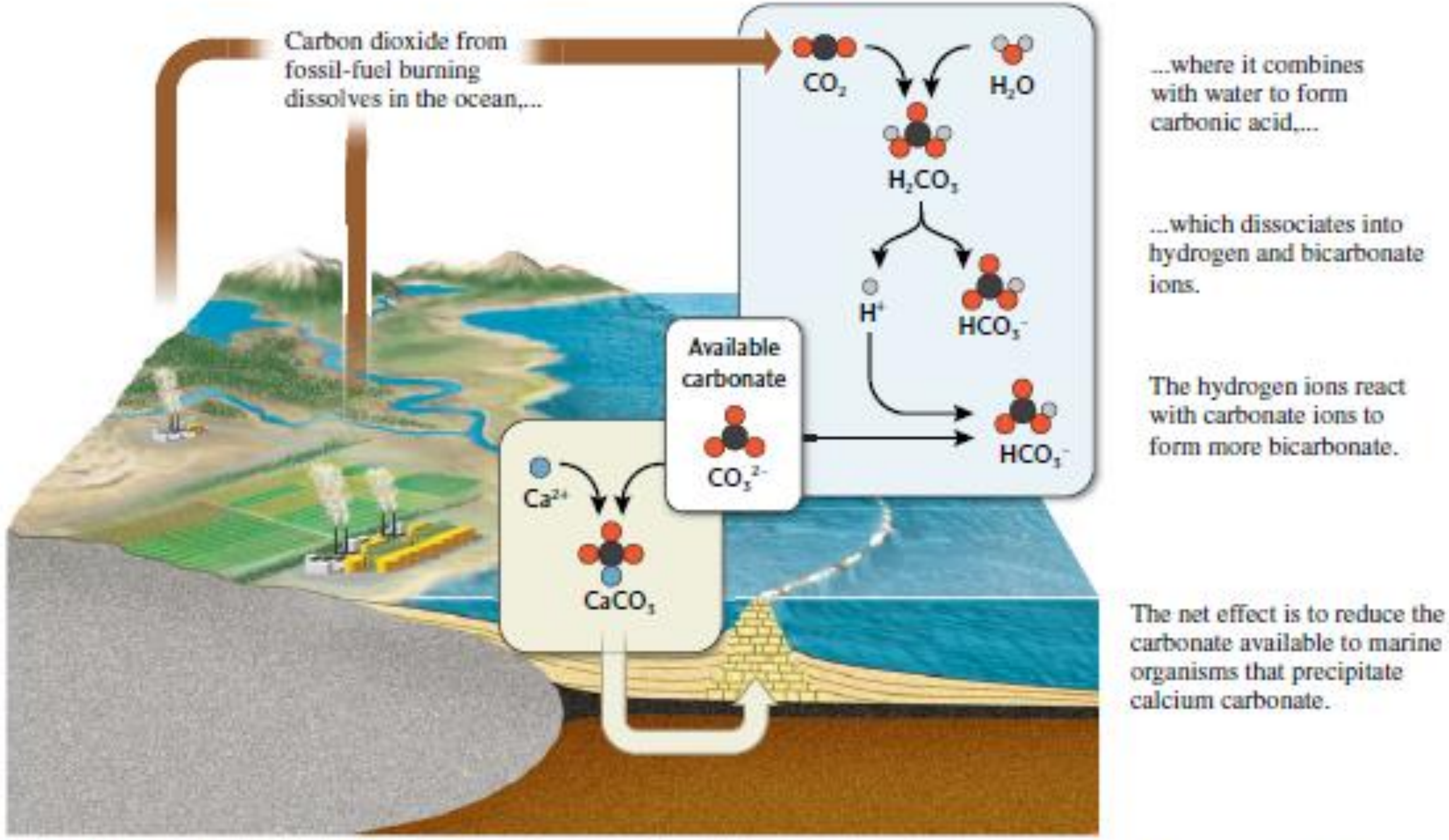

FIGURE 15.15 ▪ Increasing CO_2 concentrations in the atmosphere drive a series of chemical reactions in seawater, causing ocean acidification and reducing the ability of marine organisms to form shells and skeletons of calcium carbonate.

Earth's Climate System

Carbon Cycle

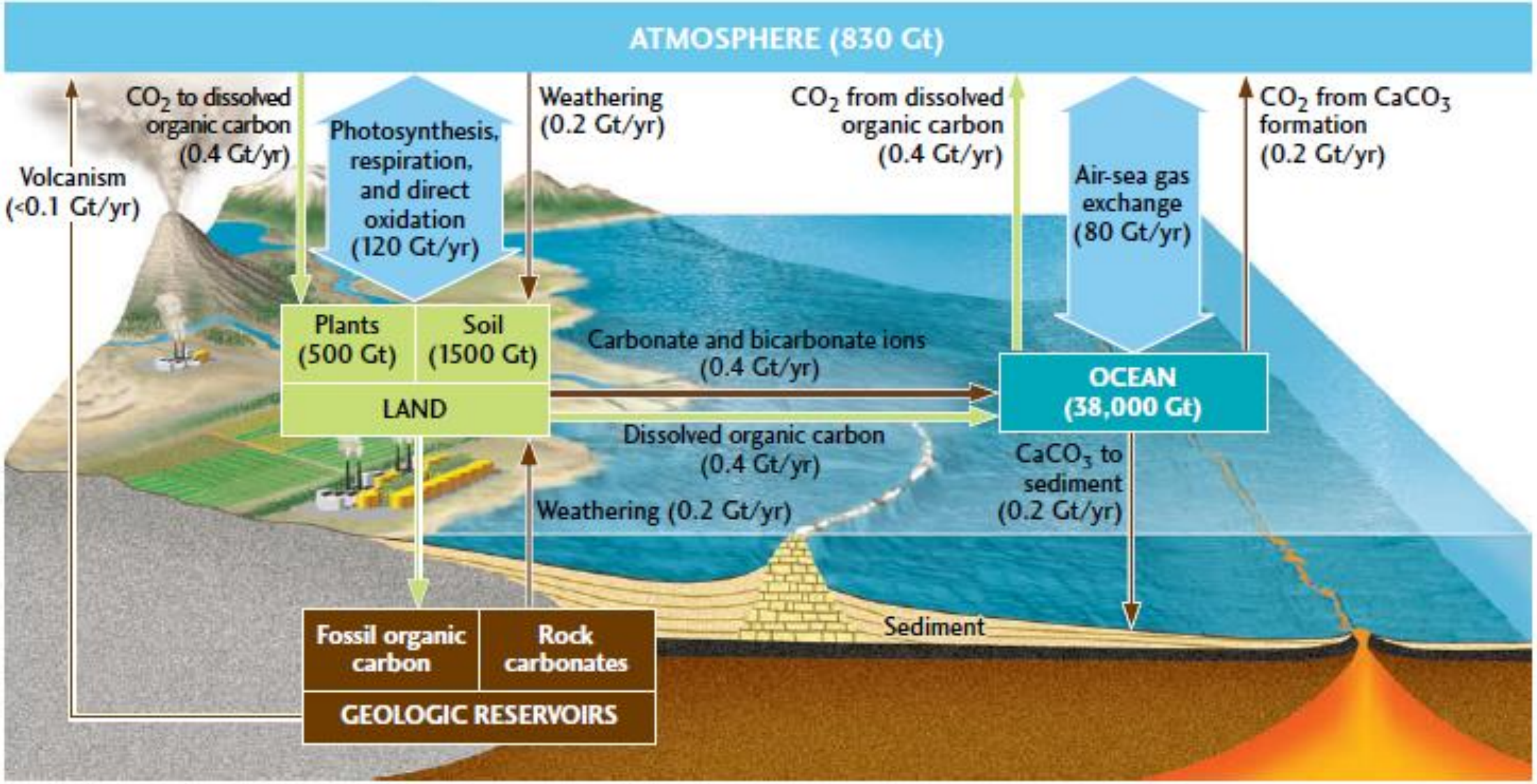

FIGURE 15.18 ■ The carbon cycle describes the fluxes of carbon between the atmosphere and its other principal reservoirs. Amounts of carbon stored in each reservoir are given in gigatons; fluxes are given in gigatons per year. [IPCC, *Climate Change 2001: The Scientific Basis*, updated according to IPCC, *Climate Change 2013: The Physical Science Basis*.]

Earth's Climate System

Feedbacks in Carbon Cycle (Silicate Weathering)

- **Rainwater combines with atmospheric CO_2 to form carbonic acid**

$$H_2O + CO_2 \rightarrow H_2CO_3$$

- **This carbonic acid causes weathering of silicate rocks as follows**

$$CaSiO_3 + H_2CO_3 \rightarrow CaCO_3 + SiO_2 + H_2O$$

Earth's Climate System

Feedbacks in Carbon Cycle (Silicate Weathering)

- **As a result, chemical weathering removes CO_2 from the atmosphere and puts it in carbonate (limestone).**

- **Weathering products carbonates and silica are carried to the ocean by stream and marine organism use them to build their shells and skeletons. When they die, their remains accumulate on the seafloor and eventually buried and stored as sediments.**

- **In the long run, these carbonate minerals get subducted in the mantle (CO_2 sink). You may look at**
  https://en.wikipedia.org/wiki/Carbonate%E2%80%93silicate_cycle

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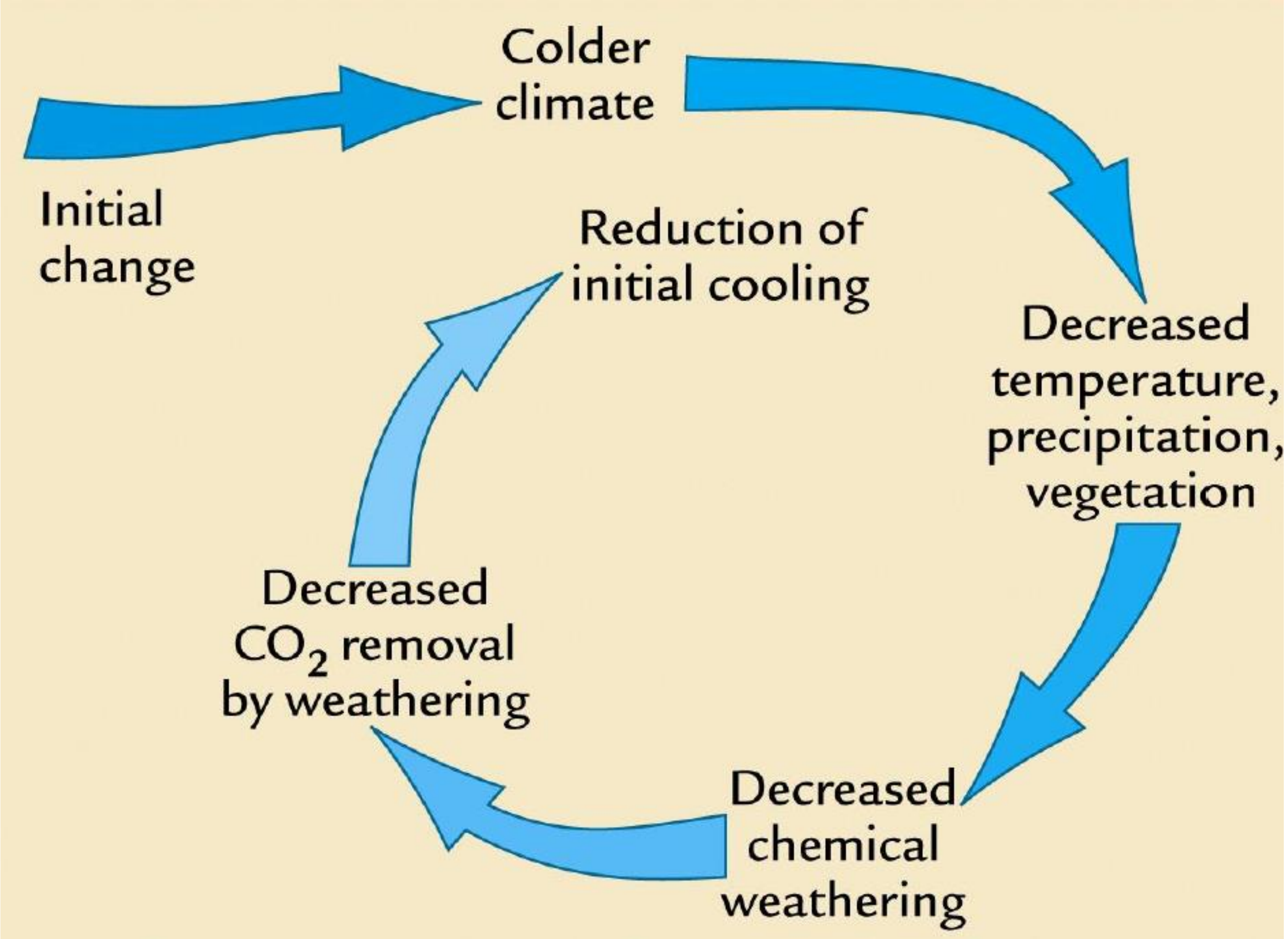
Temperature-Weathering Feedback



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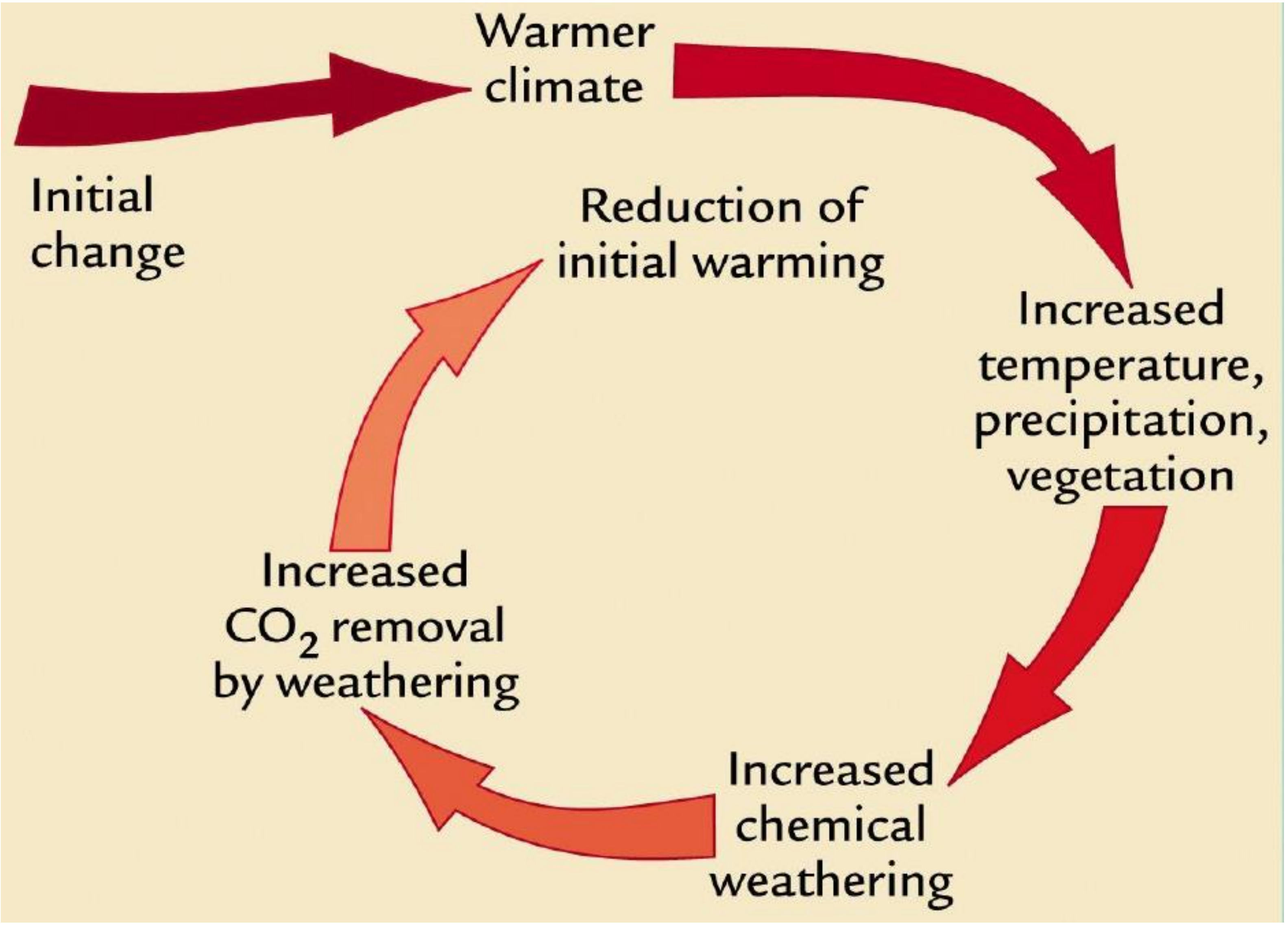
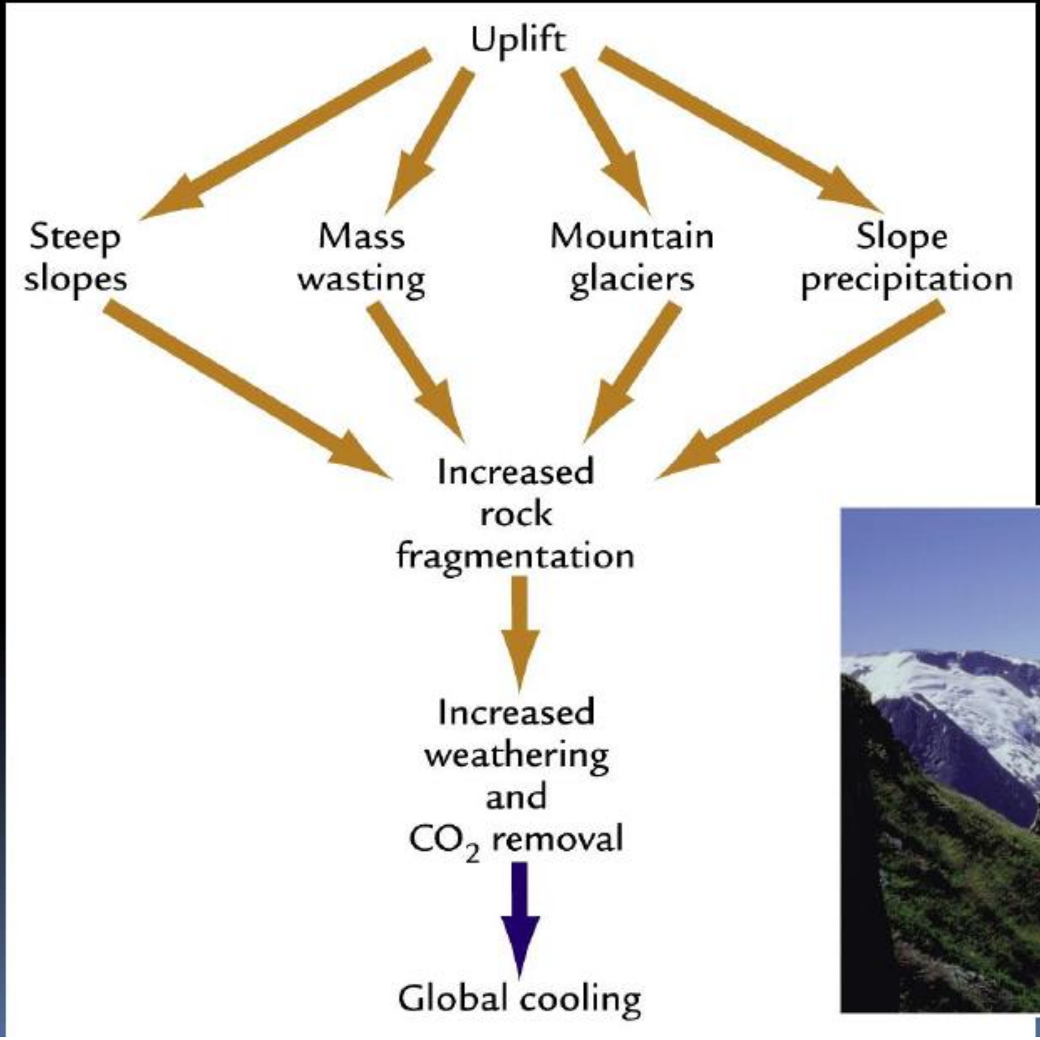
Temperature-Weathering Feedback



Earth’s Climate System

Changes in amount of uplift of continental rock could regulate amount of weathering



The Faint Young Sun Paradox

- The luminosity of the young sun was about 30% less than that of today. So, if we do the energy-balance calculation (we did in the first few lectures), the surface temperature of the Earth, $T_S = -7°\mathrm{C}$, would well below the freezing point resulting in '**snowball Earth**' in the early Earth's history.
- However, mineralogical evidence from zircons suggest that liquid water was present in the Earth as early as ~4.4 b.y. ago (https://en.wikipedia.org/wiki/Origin_of_water_on_Earth).

The possible solution to this problems:

1. Planetary albedo must have been lower:

- The current albedo for the Earth is 0.3
- If the solar luminosity was 30% lower, then to keep surface temperature similar to the one today, the albedo need to be near zero.
- It is highly unlikely to have zero albedo for a planet covered with the liquid water, sea ice in the surface and clouds in the atmosphere.

The Faint Young Sun Paradox

2. Additional Heat source besides Sun: Geothermal Heat from Earth's Interior

- The geothermal heat flux is not sufficient to supply enough energy to keep the Earth's surface temperature constant.

- To balance 30% reduction in solar luminosity, approximately $70\ W/m^2$ addition heating is required.

- Modern geothermal heat flux is only about $0.09\ W/m^2$. Theoretical models of Earth's interior evolution suggests that the geothermal heat flux at 4 b.y. ago was about 3 to 4 times of the present value. Even considering this factor also, the available heat flux would have been just ~0.3-$0.4\ W/m^2$. This heat may have prevented the bottom layer of the oceans from freezing, but they (oceans) would still be covered with several hundred meters of thick ice preventing not allowing light to penetrate. It is not possible to reconcile this scenario with the evidence of ancient photosynthetic life.

The Faint Young Sun Paradox

3. Larger Greenhouse Effect

- The most likely solution to the faint young Sun problems is that Earth's greenhouse effect was larger in the past.

- Sagan and Mullen suggested that ammonia, NH_3, would have been quite abundant in the early atmosphere. NH_3 is reduced (Remember, prior to rise of oxygen, i.e., 2.4 b.y. ago, reduced gases were abundant) and a good absorber of IR, so it might be a strong candidate for early Earth warming.

- However, ammonia would also have been rapidly destroyed by UV radiation, so it may not have been abundant enough to provide the necessary warming.

- Other likely greenhouse gases that could have kept early Earth warm:, CO_2 and, CH_4.

The Faint Young Sun Paradox

A CO_2 rich Early Atmosphere

- CO_2 could have provided the warming for early Earth.
- Small size continents would have reduced the amount of land available for silicate weathering (For carbonate-silicate cycle, please look at: https://en.wikipedia.org/wiki/Carbonate%E2%80%93silicate_cycle) and carbonate storage. Therefore, CO_2 sink would be smaller.
- Impact degassing of late-arriving planetesimals and enhanced volcanic outgassing on the hot and young Earth would have released a lot of CO_2 in the early atmosphere.
- Weathering of the seafloor could have drawn down CO_2 level by converting silicate minerals in carbonates and allowing these minerals to be subducted into the mantle (CO_2 sink).
- The carbonate-silicate cycle acts as a strong negative feedback:
  - If Earth's surface temperature was lower as a result of low solar luminosity→the rate of silicate weathering should have been smaller→rate of CO_2 loss would be lower→ CO_2 emitted from volcanos would have accumulated in the atmosphere →the global temperature would have increased until the global rate of silicate weathering would balance the volcanic outgassing rate.
  - If Earth had ever become entirely ice-covered, silicate weathering would stop completely and volcanic CO_2 would have accumulated in the atmosphere until associated greenhouse effect became large enough to melt the ice. Thus, the Earth system has a natural way of recovering from global glaciation.

The Faint Young Sun Paradox

Effect of CH_4 in the Early Atmosphere

- Along with CO_2, CH_4 could have played a major role in controlling the early Earth temperatures.
- CH_4 could have been relatively abundant prior to 2.4 b.y. ago, when atmospheric O_2 level was quite low.
- Prior to the origin of life, CH_4 could have been produced by impact degassing and serpentinization of rocks on the seafloor (serpentinization is a process in which serpentine minerals are formed from reaction of water with iron- and magnesium-rich basalts. In the process, if CO_2 is present, CH_4 is formed). Estimated CH_4 in the prebiotic atmosphere would be 10-100 ppm.
- After the origin of life, methanogenic bacteria would have generated significantly large amount of CH_4 by converting CO_2 and H_2 from the atmosphere. The estimated amount of CH_4 would be around 1000 ppm or more.
- However, the presence of CH_4 could also have acted as 'anti-greenhouse effect'. The photolysis of CH_4 would produced hydrocarbons which would have enveloped the Earth (organic haze). The organic haze would absorb quite a lot of visible radiation and reflect back the IR radiation in the space.

➡ The abundance of CO_2 and CH_4 seems to be a likely reason for maintaining the early Earth temperature. The greenhouse effect of these gases could have provided the warming to balance the reduced luminosity of young sun.

The Snowball Earth

- The most significant characteristic of Earth's climate on long time scales is that it has been conducive to the presence of life for something close to 4 b.y.
- However, geological records also indicate that the Earth's past climate '**paleoclimate**' have been through long warm periods separated by shorter periods of intense cold.
- In the late Proterozoic, between 0.75 and 0.6 b.y. ago, global glaciation occurred (snowball). Evidence for glaciation during this time interval is found in all seven present-day continents.
- Possible pathways for this snowball episode could be like:
  - Significant fraction of the continental area was situated in the tropics.
  - This allowed enhanced silicate weathering, which allowed CO_2 to sink faster.
  - Increase in the O_2 may have reduced to methane flux from the marine sediments.
  - Significant decrease in the greenhouse effect may have initiated the snowball episode.
  - Once the polar ice sheet gradually crept down the approximately 30°, global glaciation would have happened just within few decades due to strong positive feedback between ice albedo and surface temperatures.
  - Once the surface froze, silicate weathering would have virtually ceased, and volcanic CO_2 would have accumulate in the atmosphere leading to greenhouse warming and ice melt.