Lecture 1

Overview of Climate Science

From Ruddiman's Earth's Climate – Past, Present Future
Chapter 1&2

Climate vs Weather

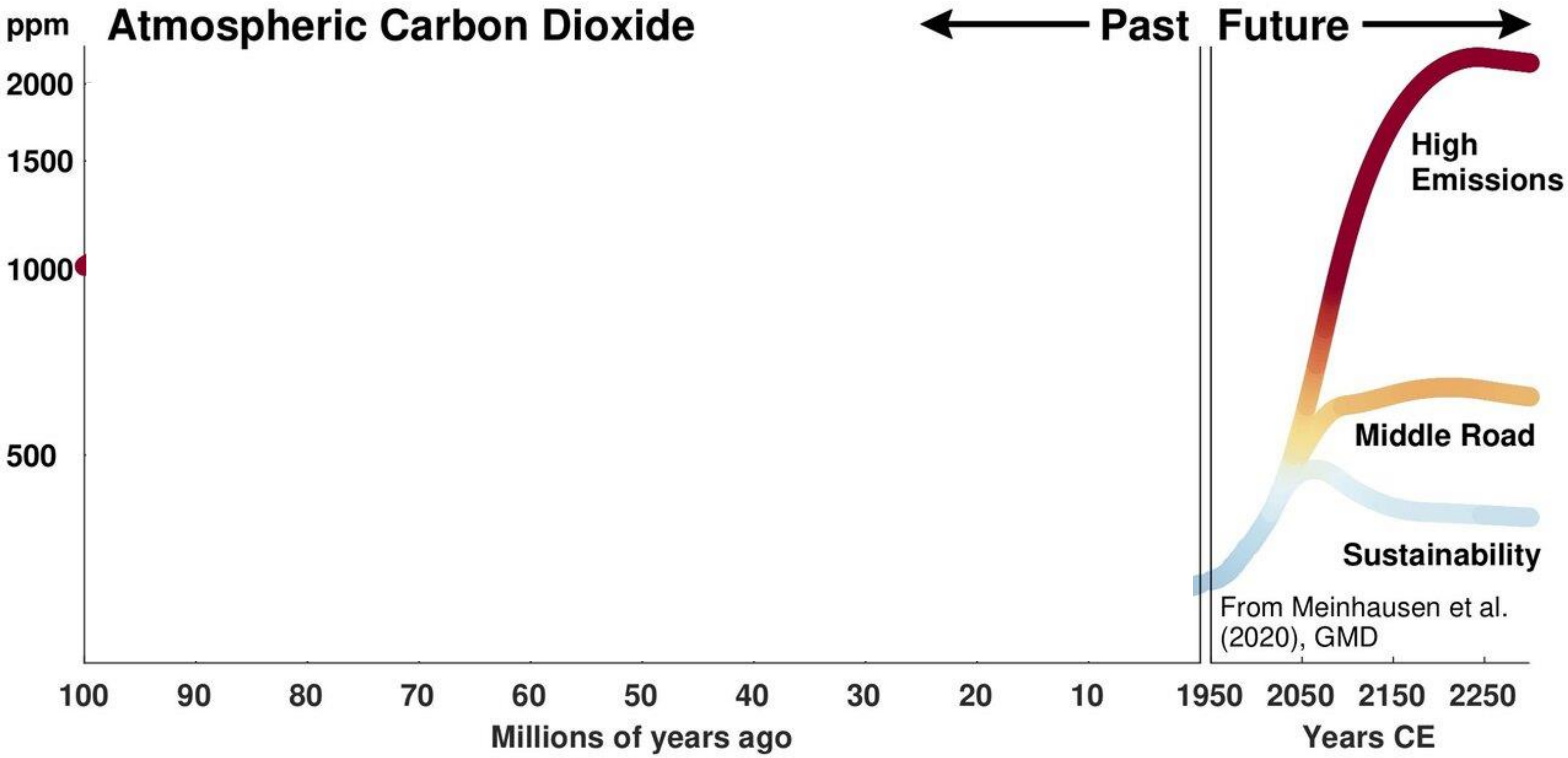
- **Climate** is a broad composite of the average condition of a region, measured by its temperature, amount of rainfall or snowfall, snow and ice cover, wind direction and strength, and other factors.
- Climate change specifically applies to longer- term variations (years and longer),
- in contrast to the shorter fluctuations in **weather** that last hours, days, weeks, or a few months.

Geologic time scales

How old is our dear Earth?

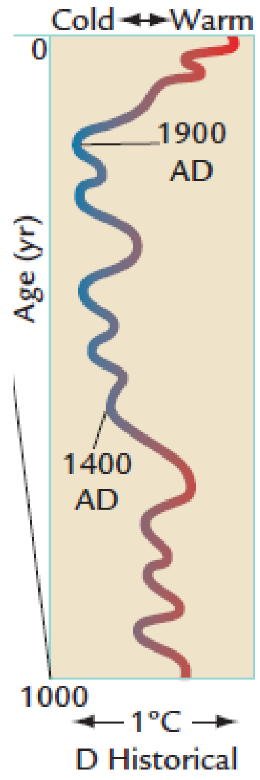
- Earth formed 4.55 billion years (Byr) ago (4,550,000,000 years!).

Future changes in Earth's climate

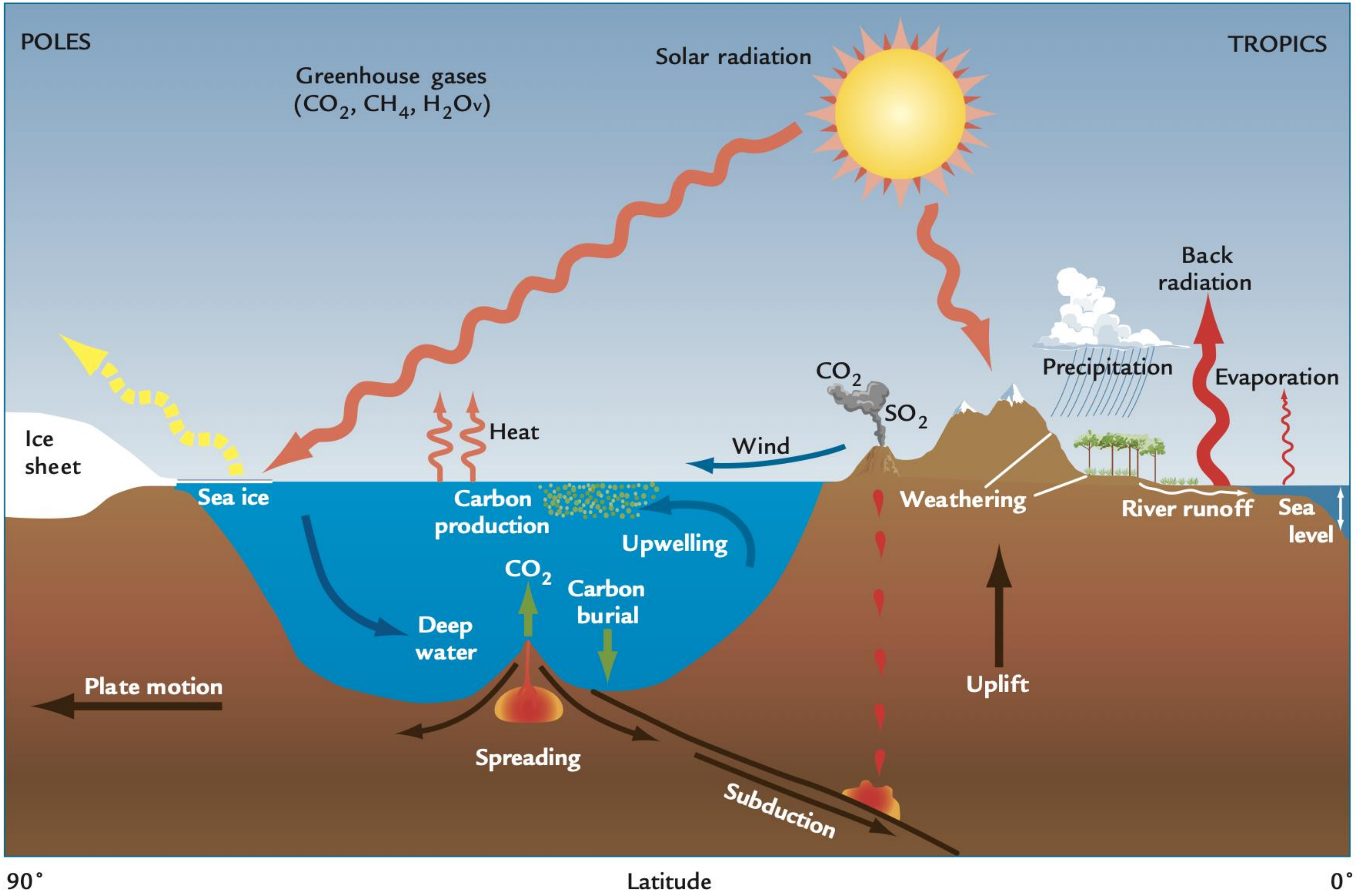


Climate change at various timescales

What are we learning today?



Earth Climate system and interactions of its components



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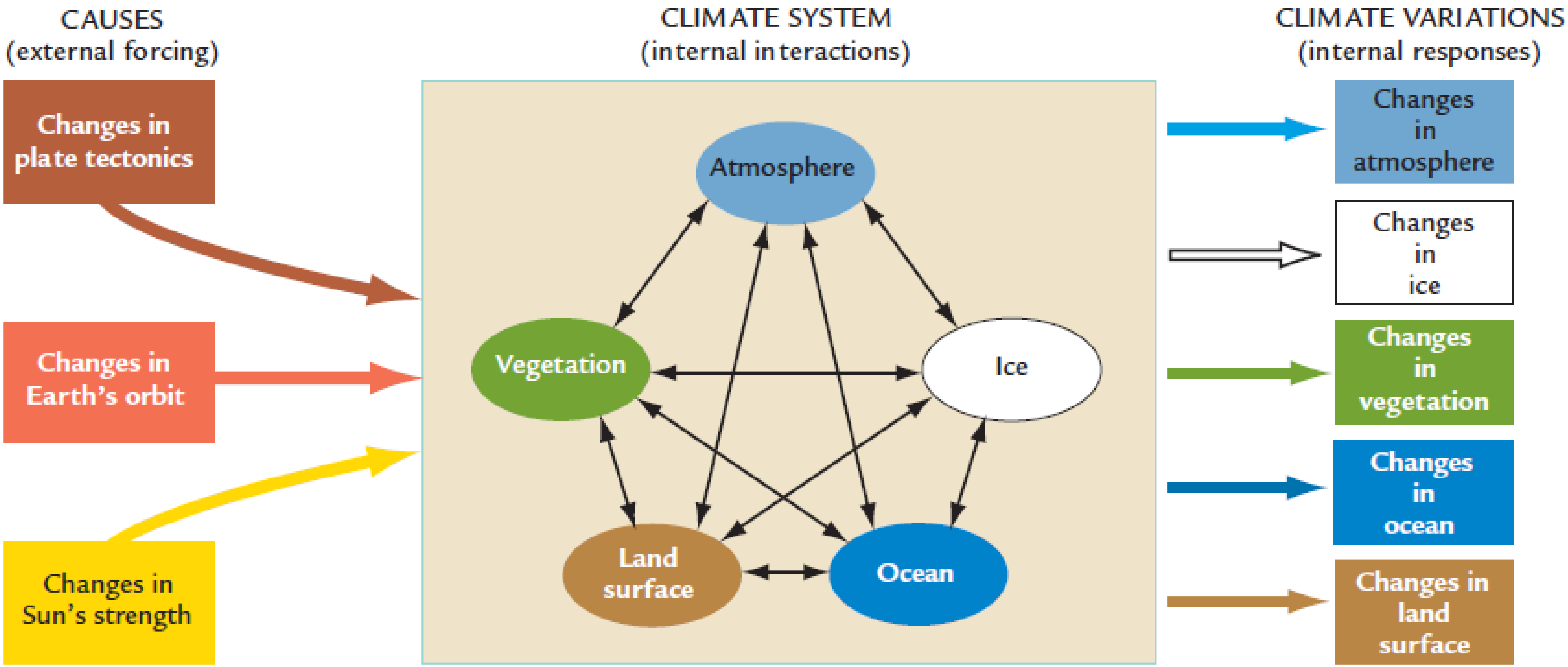


Any other factor external or internal?

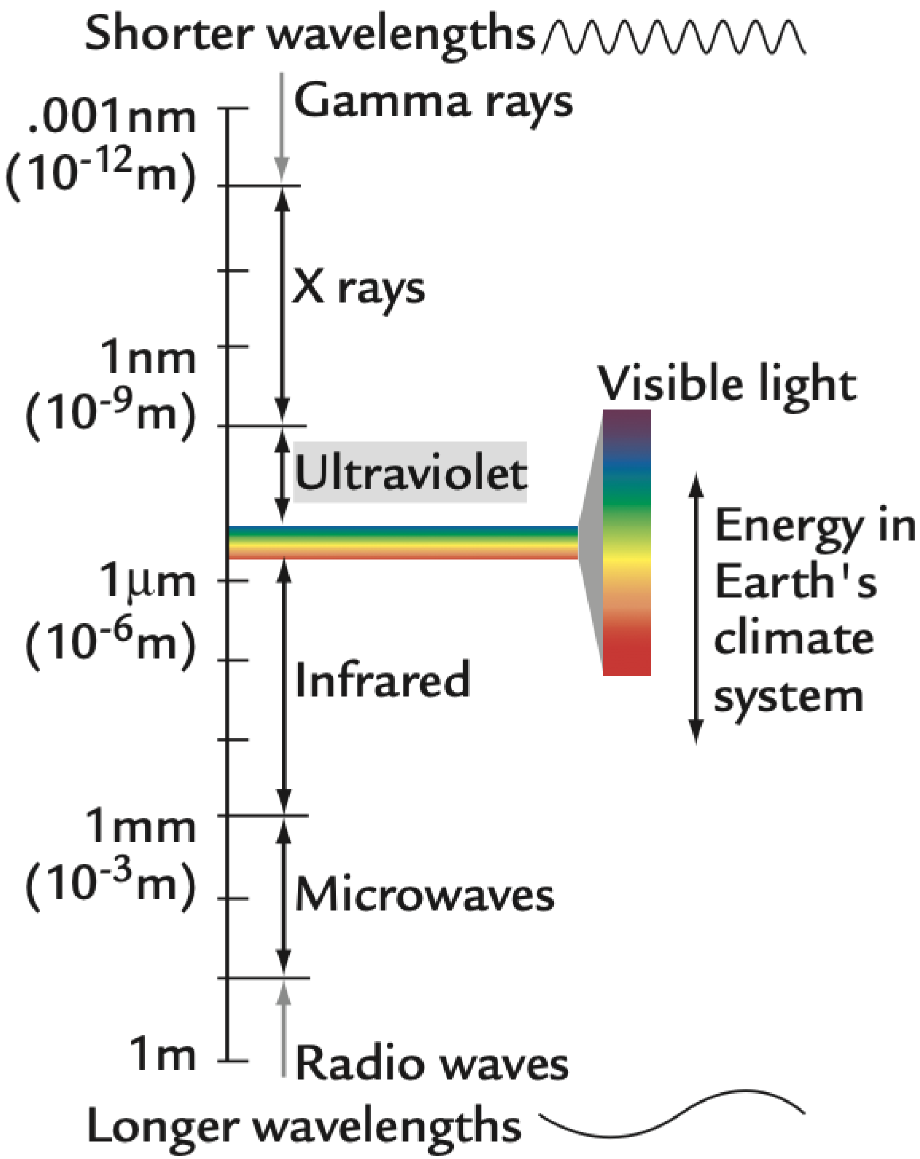
A fourth factor capable of influencing climate, but not in a strict sense part of the natural climate system, is the effect of humans on climate, referred to as **anthropogenic forcing**. This forcing is an unintended by-product of agricultural, industrial, and other human activities, and it occurs through alterations of Earth's land surfaces and through additions of carbon dioxide (CO2) and other **greenhouse gases**, sulfate particles, and soot to the atmosphere.

Response time

Table 1-1 Response Times of Various Climate System Components

Component	Response Time (range)	Example
FAST RESPONSES		
Atmosphere	Hours to weeks	Daily heating and cooling Gradual buildup of heat wave
Land surface	Hours to months	Daily heating of upper ground surface Midwinter freezing and thawing
Ocean surface	Days to months	Afternoon heating of upper few feet Warmest beach temperatures late in summer
Vegetation	Hours to decades/centuries	Sudden leaf kill by frost Slow growth of trees to maturity
Sea ice	Weeks to years	Late-winter maximum extent Historical changes near Iceland
SLOW RESPONSES		
Mountain glaciers	10–100 years	Widespread glacier retreat in 20th century
Deep ocean	100–1,500 years	Time to replace ocean deep water
Ice sheets	100–10,000 years	Advances/ retreats of ice sheet margins Growth/decay of entire ice sheet

The Electromagnetic Spectrum

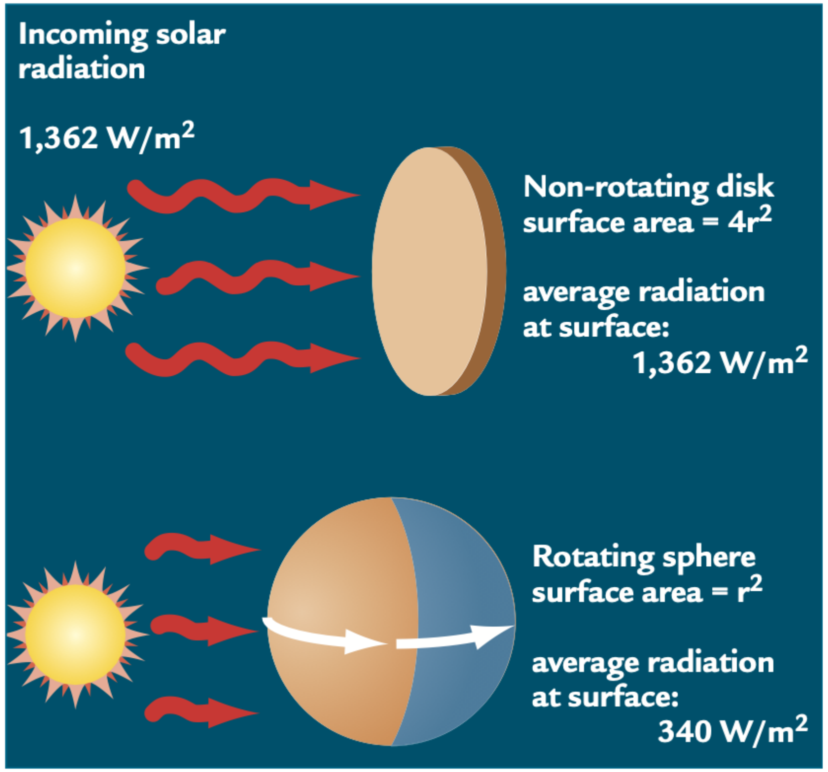


Incoming Solar Radiation

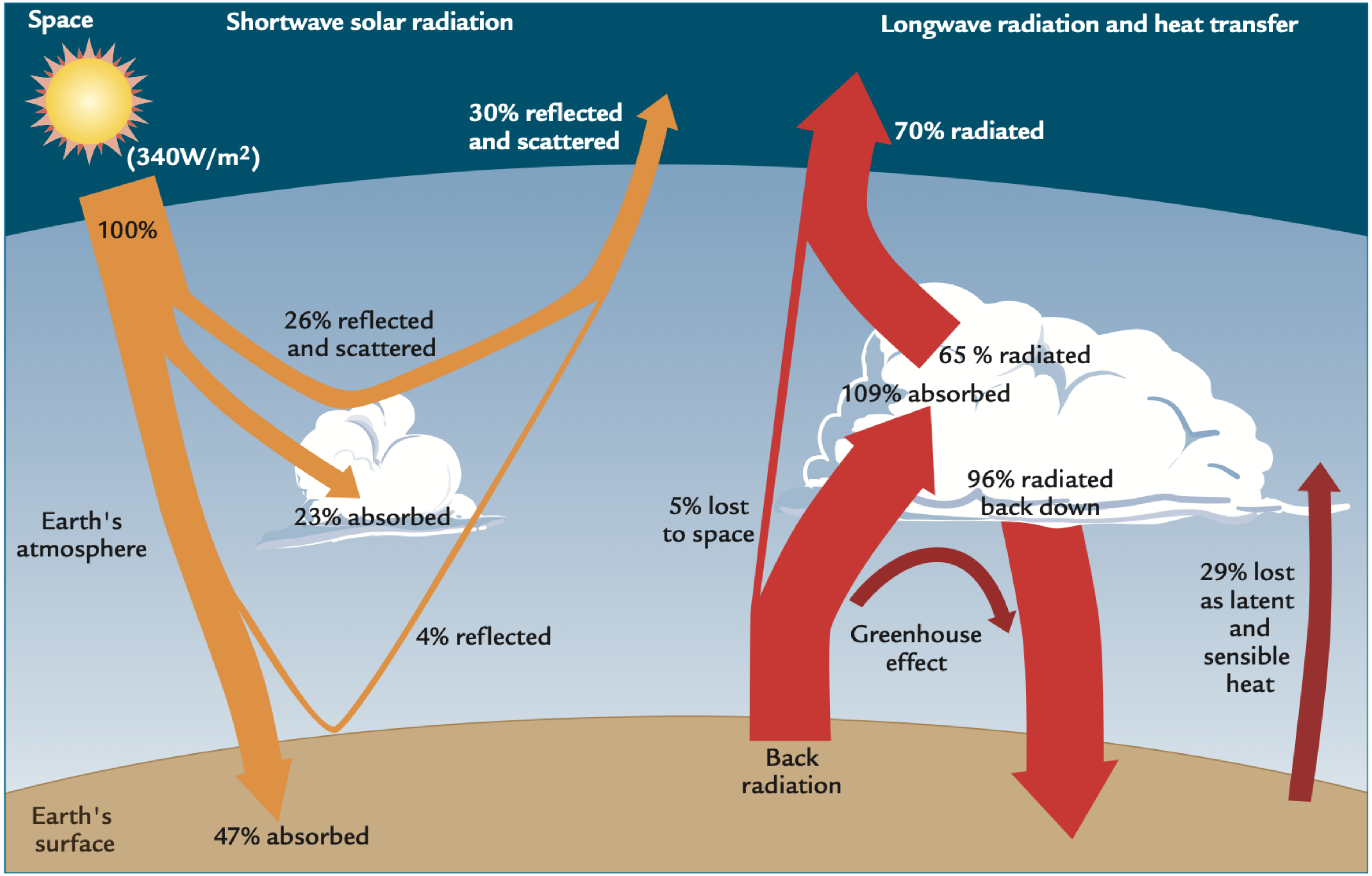
Radiation from the Sun arrives at the top of Earth’s atmosphere with an average energy of 1,362 watts per square meter (W/m^2).
If Earth were a flat, one-sided disk directly facing the Sun, and if it had no atmosphere, 1,362 W/m2 of solar radiation would fall evenly across its entire surface.

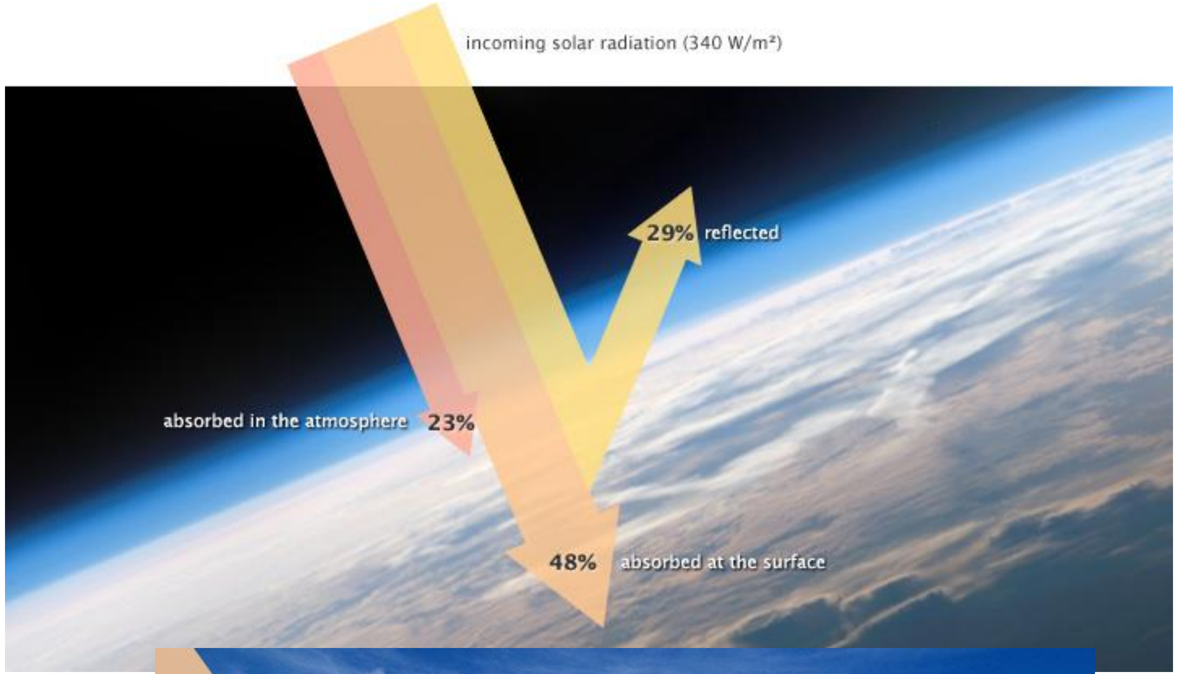
But Earth is a three-dimensional sphere, not a flat disk. A sphere has a surface area of 4πr2 that is 4 * the surface area of a flat one-sided disk (πr2).

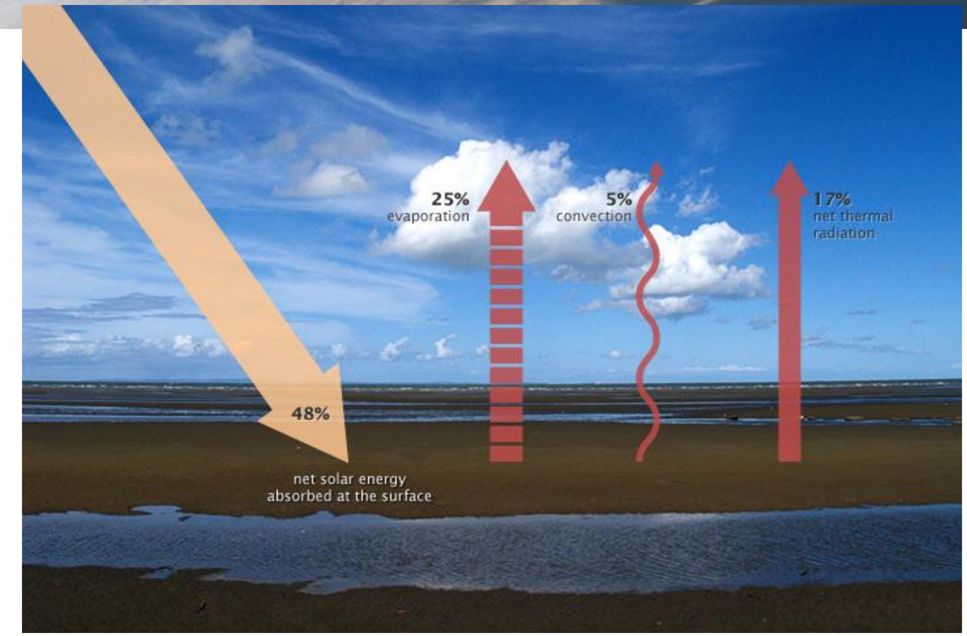
Because the same amount of incoming radiation must be distributed across this larger surface area, the average radiation received per unit of surface area on a sphere is only one-quarter as strong (1,362/4 = 340 W/m2).



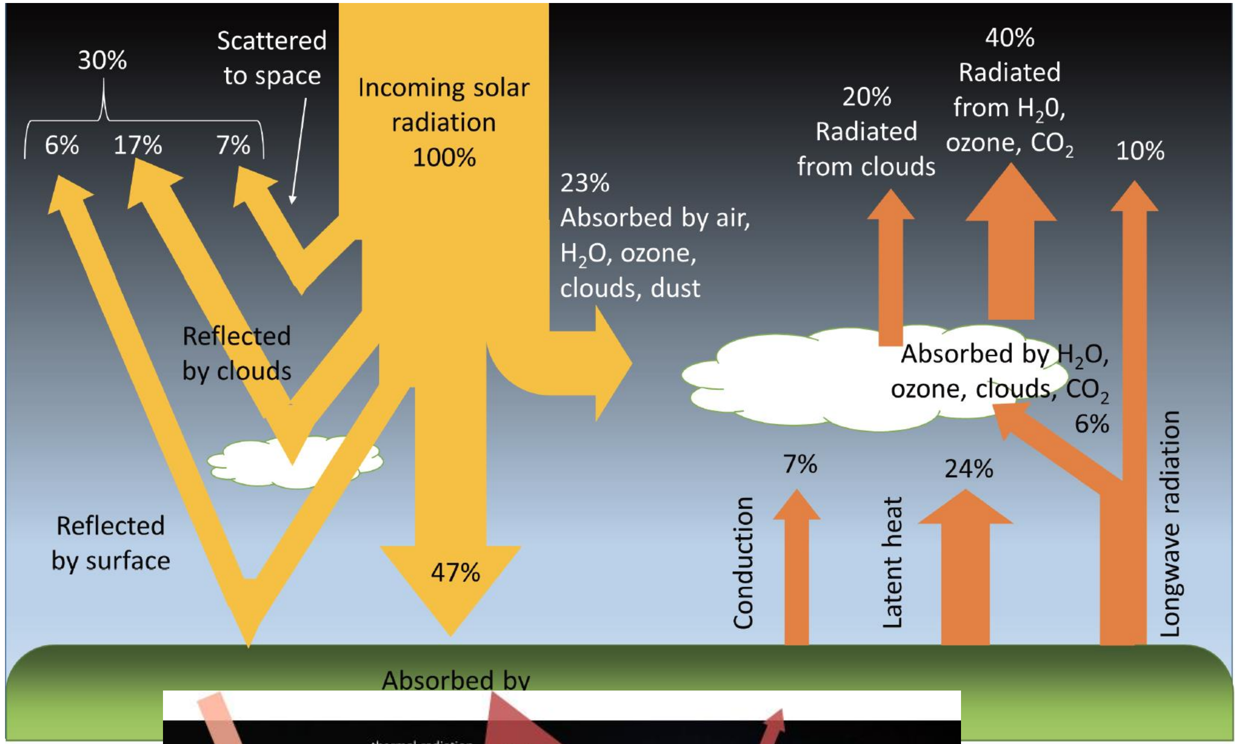
Earth’s radiation budget

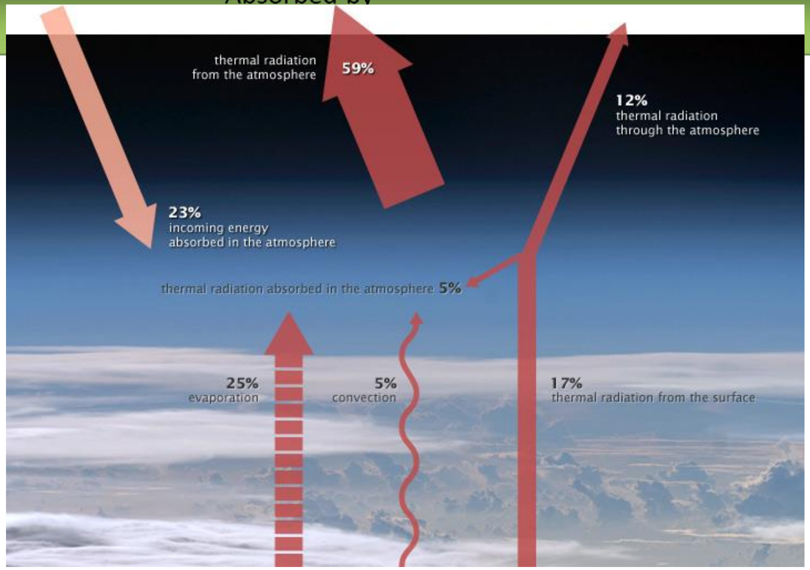






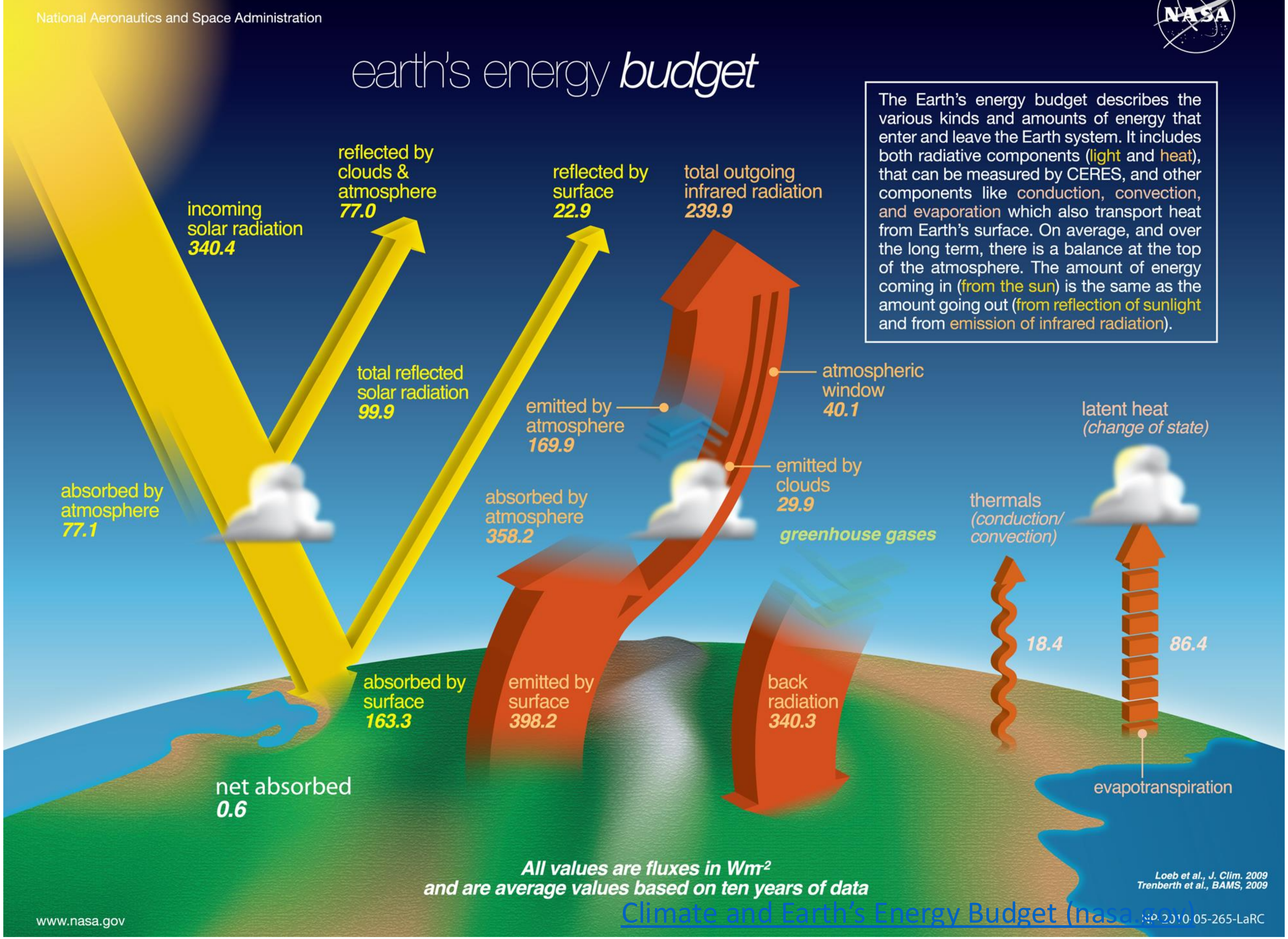
Surface energy budget





Atmospheric energy budget

"measurements made by satellites and space stations in outer space cannot detect the radiation emitted directly from the warmer surface of Earth because of the muffling effect of the blanket of greenhouse gases and clouds. Instead, most of the heat actually radiated back to space is emitted from an average elevation of 5 kilometers, equivalent to the tops of many clouds—still well within the lowest layer of Earth's atmosphere. These cold cloud tops emit radiation at an average value of about 238 W/m2, exactly the level needed to offset the amount of solar radiation retained within Earth's climate system and keep it in balance."



[Climate and Earth's Energy Budget (nasa.gov)]

Unequal heating of Earth's surface

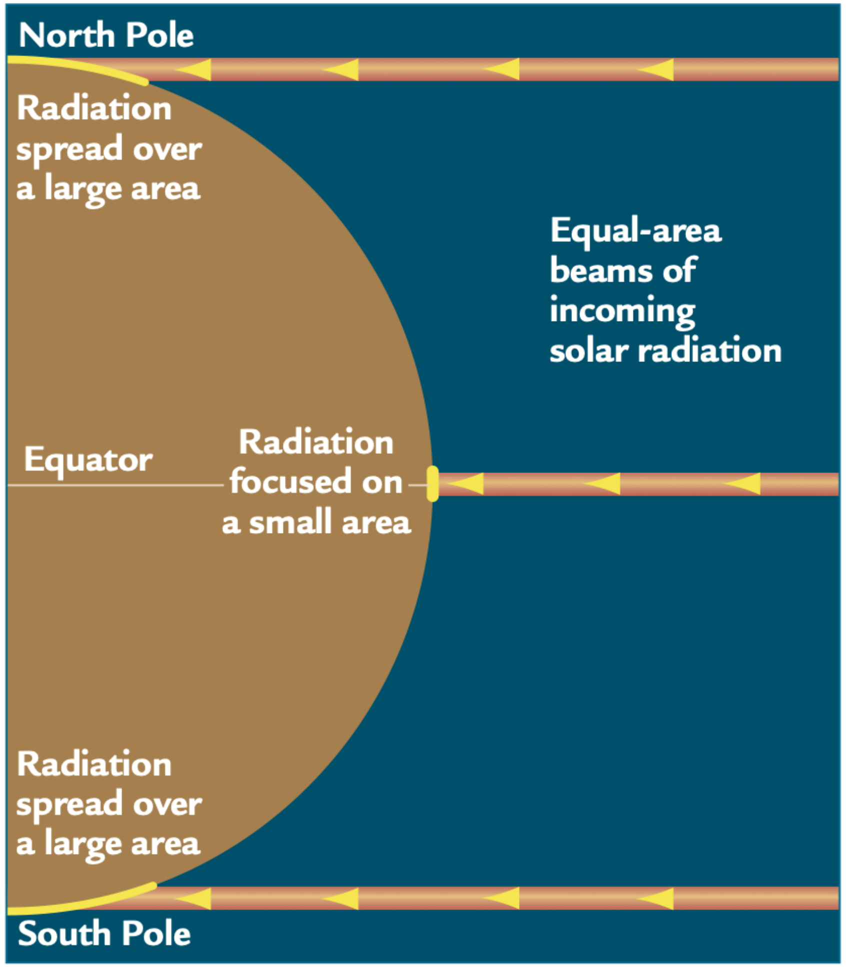


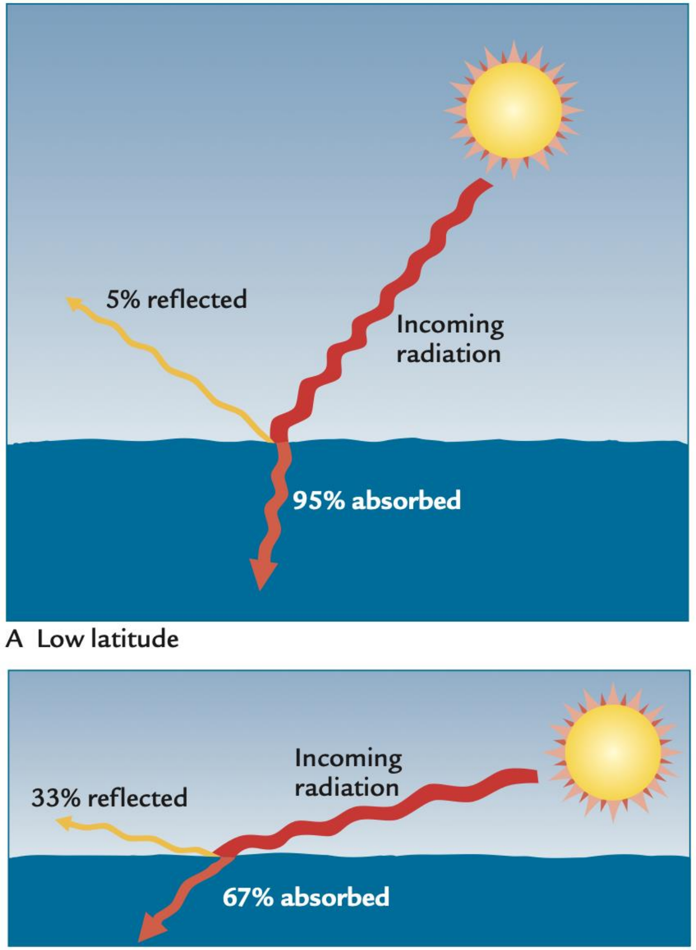
FIGURE 2-4
Unequal radiation on a sphere

Unequal distribution of incoming solar radiation is aggravated by unequal absorption and reflection by Earth’s surface at different latitudes.

A smaller fraction of the incoming radiation is absorbed at higher latitudes than in the tropics mainly because

(1) solar radiation arrives at a less direct angle and

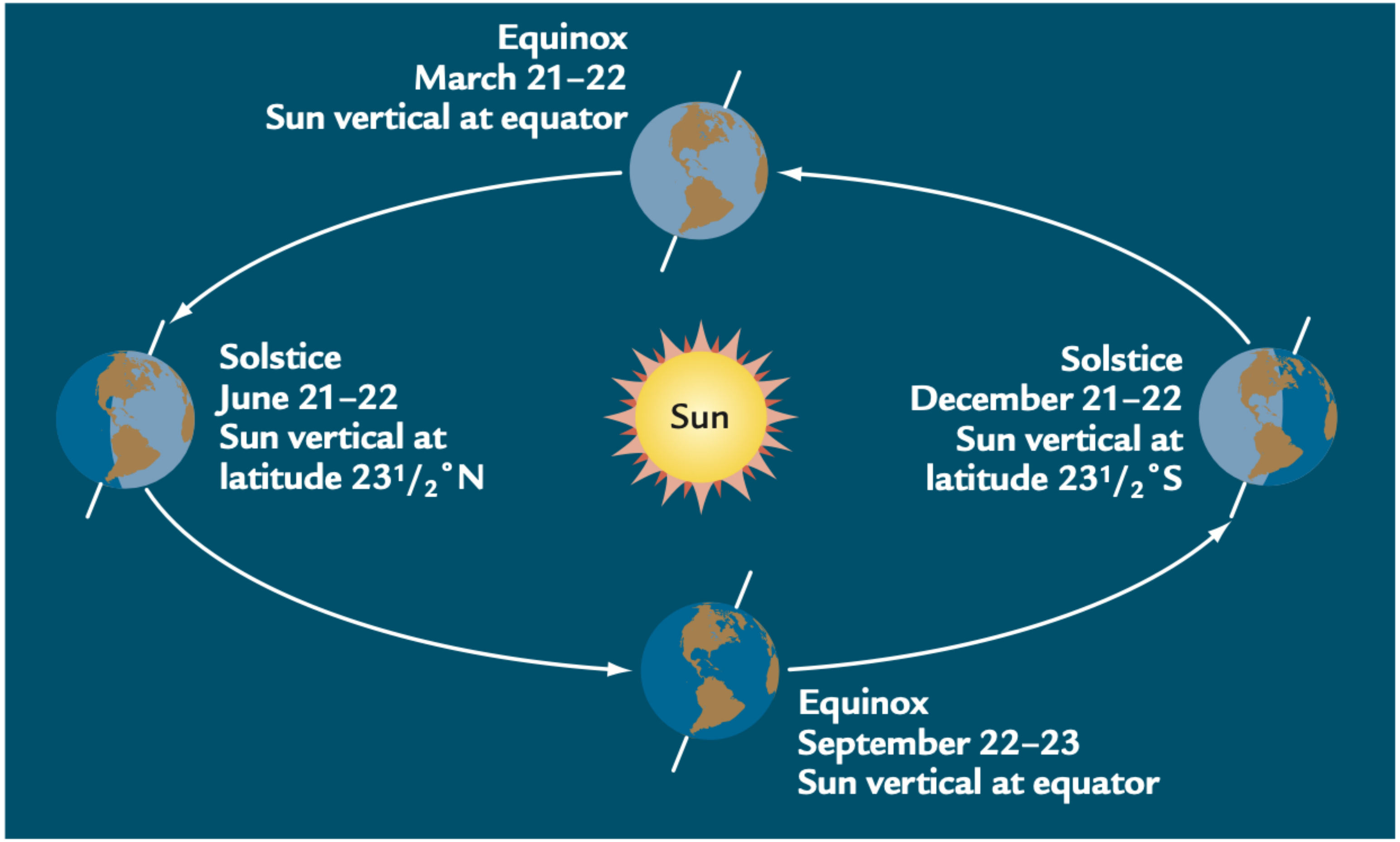
(2) snow and ice surfaces at high latitudes reflect more radiation



A Low latitude

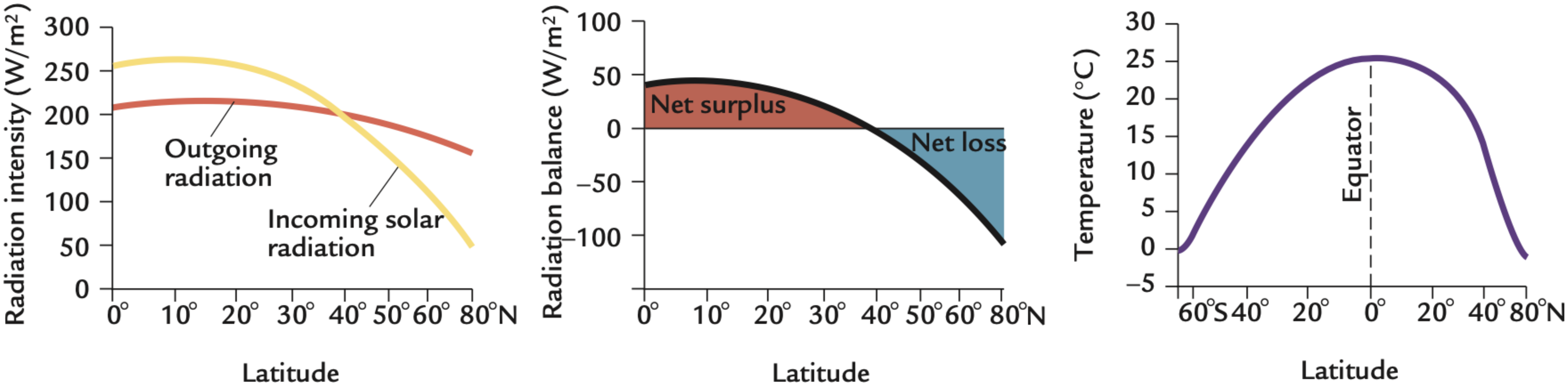
B High latitude

What causes seasons?



A Earth's orbit

Heat transfer in Earth's atmosphere

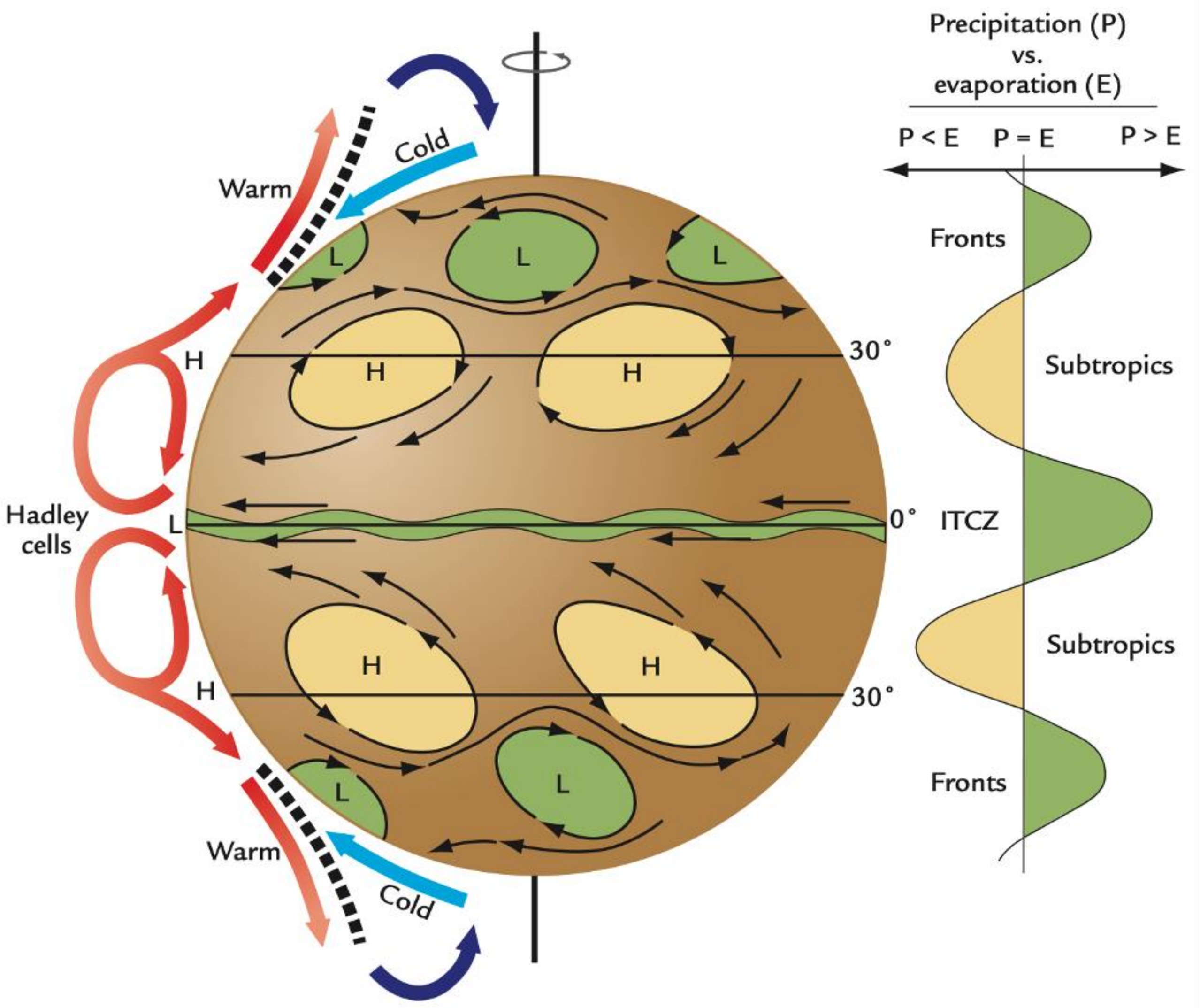


Atmospheric circulation

Heated air rises in the tropics at the intertropical convergence zone (ITCZ) and sinks in the subtropics as part of the large-scale Hadley cell flow, which transports heat away from the equator (left).

Additional poleward heat transfer occurs along moving weather systems (called “fronts”) at middle and higher latitudes, with warm air rising and moving poleward and cold air sinking and moving equatorward.

Rising air in the tropics causes a net excess of precipitation over evaporation, while dry air sinking in the subtropics produces more evaporation than precipitation.
Higher latitudes tend to have small excesses of precipitation over evaporation.

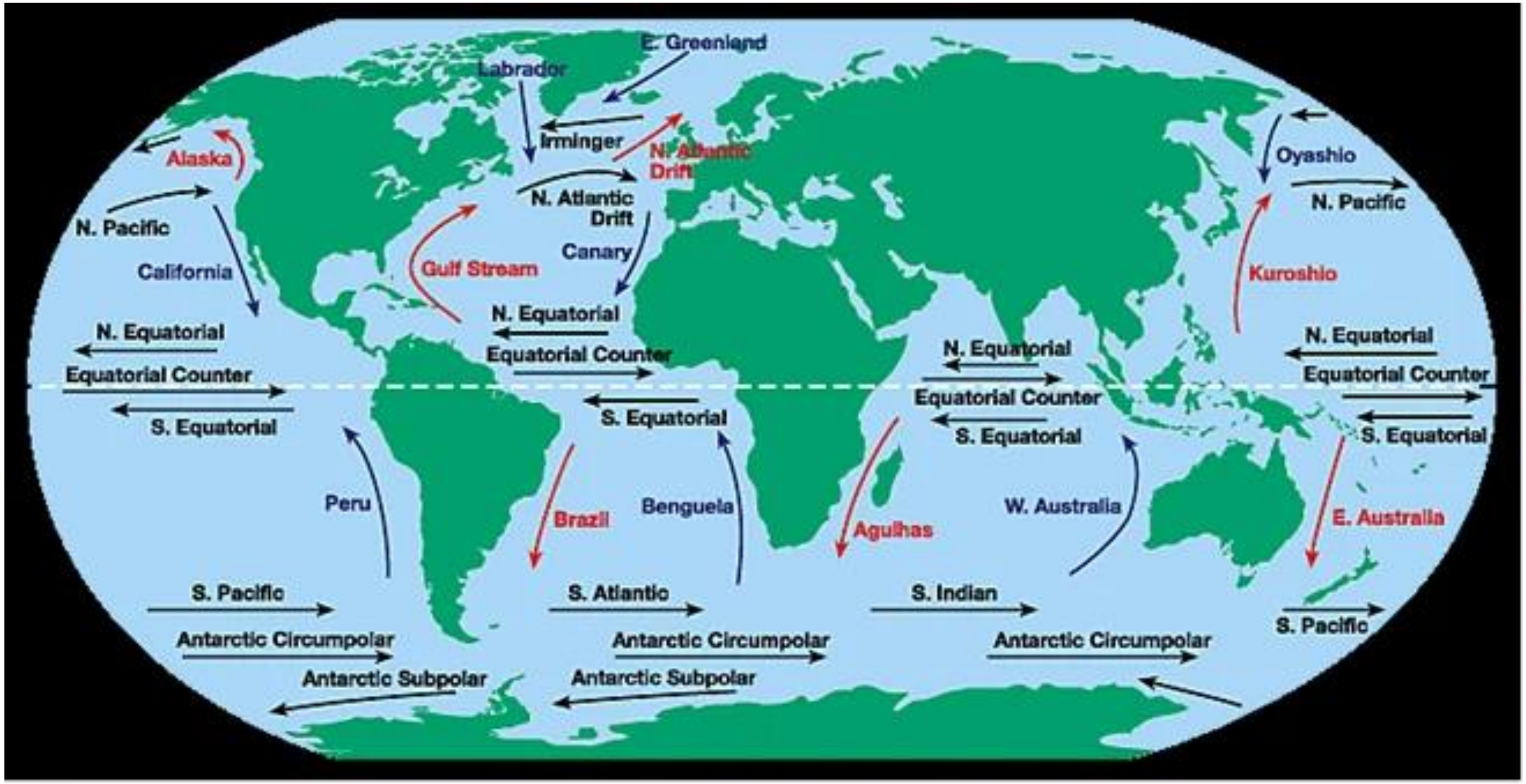


Why are most deserts located around 30 deg?

The sinking air is then warmed by the increasing pressure of the atmosphere at lower elevations (adiabatic process), and it gradually becomes even drier and able to hold still more water vapor.

This Hadley cell flow prevents condensation from occurring in much of the subtropics and makes these latitudes a zone of low average precipitation and high evaporation, in regions such as the Sahara Desert.

Heat transfer in Earth's oceans

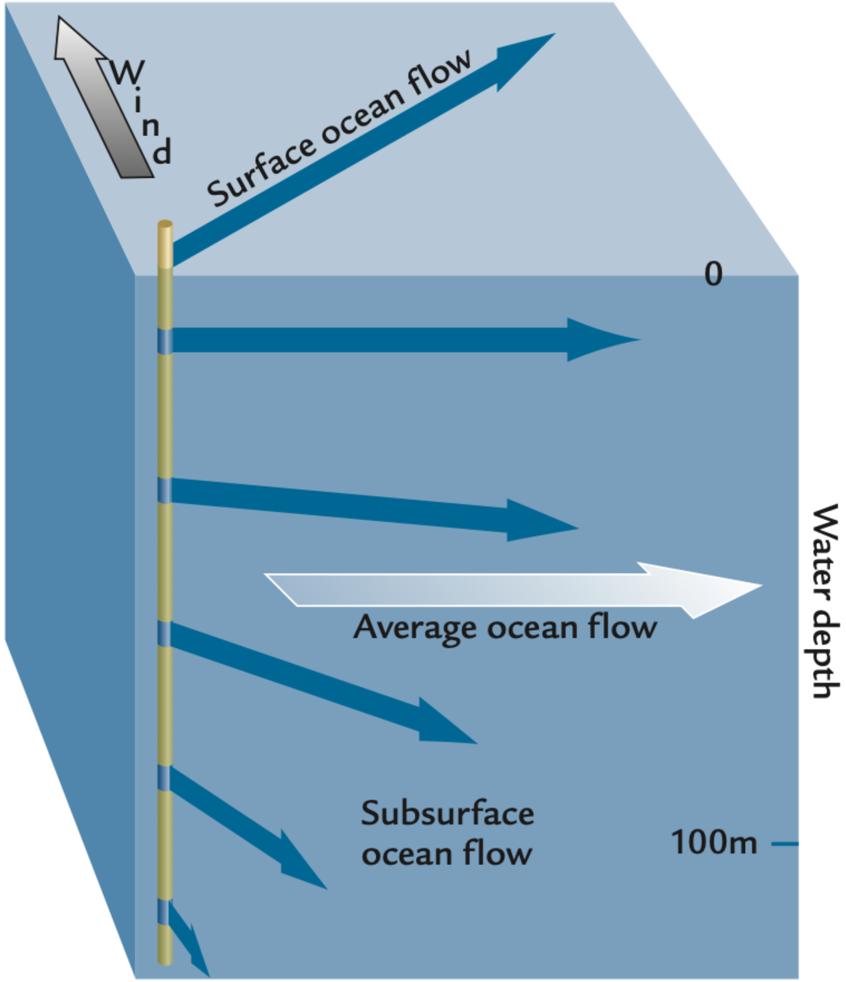


Surface ocean circulation

The surface flow of the oceans is organized into strong wind-driven currents.

These currents encircle large spinning gyres in the subtropical oceans. Currents moving out of the tropics carry heat poleward, while currents moving away from the poles carry cold water equatorward.

Effect of surface winds on the ocean

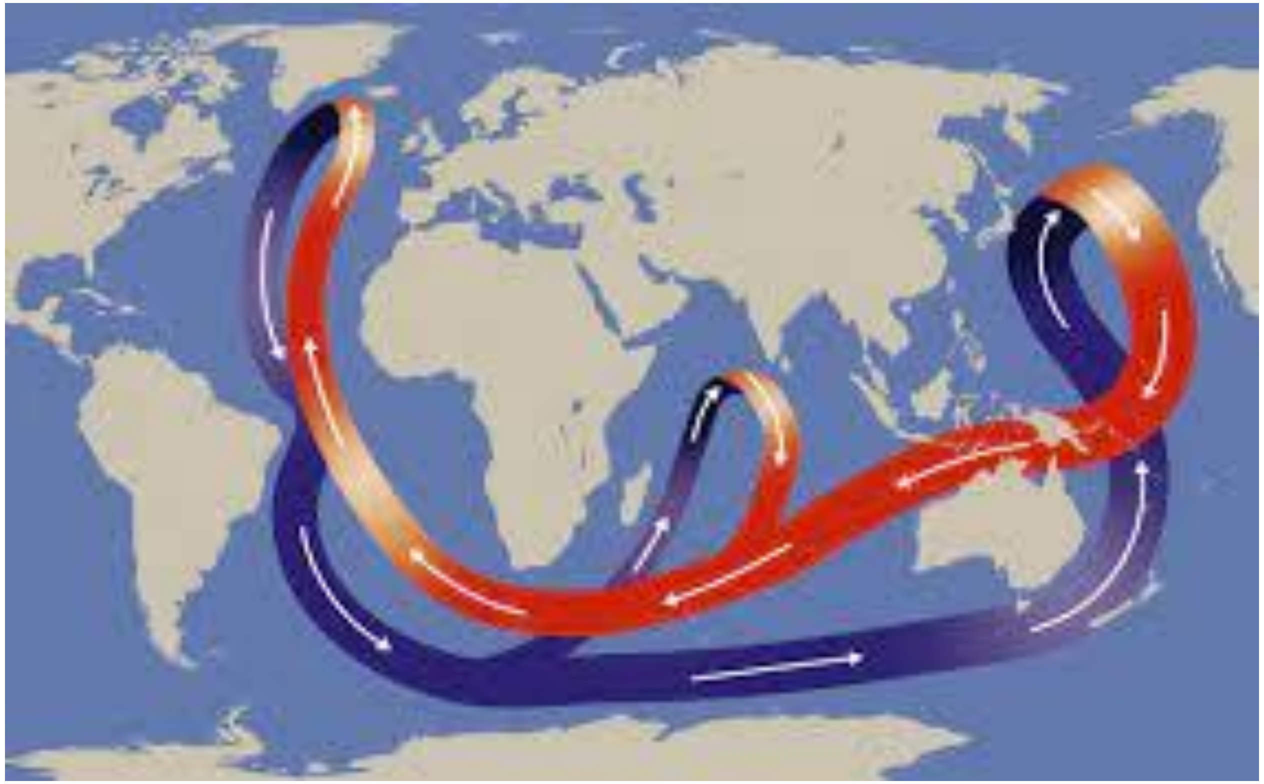


In the Northern Hemisphere, low-level winds drive surface waters to the right of the direction in which the wind is moving.

Subsurface water is turned progressively farther to the right, and the net transport of the upper layer of water is 90 degrees to the right of the direction of the wind.

These spinning **gyres** are mainly the result of an initial push (or drag) of the winds on the ocean surface and of the Coriolis deflection of the moving water

Deep Ocean circulation/ Thermohaline circulation



Why is the water sinking?

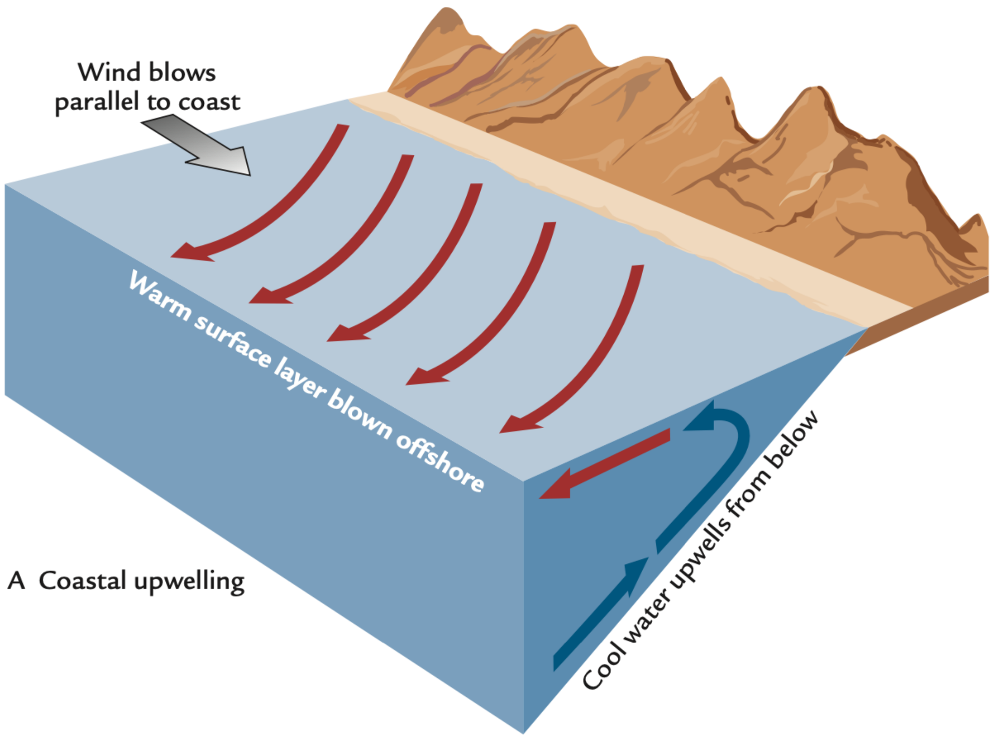
What is the average salinity of seawater ~35psu?

How to increase the density of seawater? Can it occur on low latitudes?

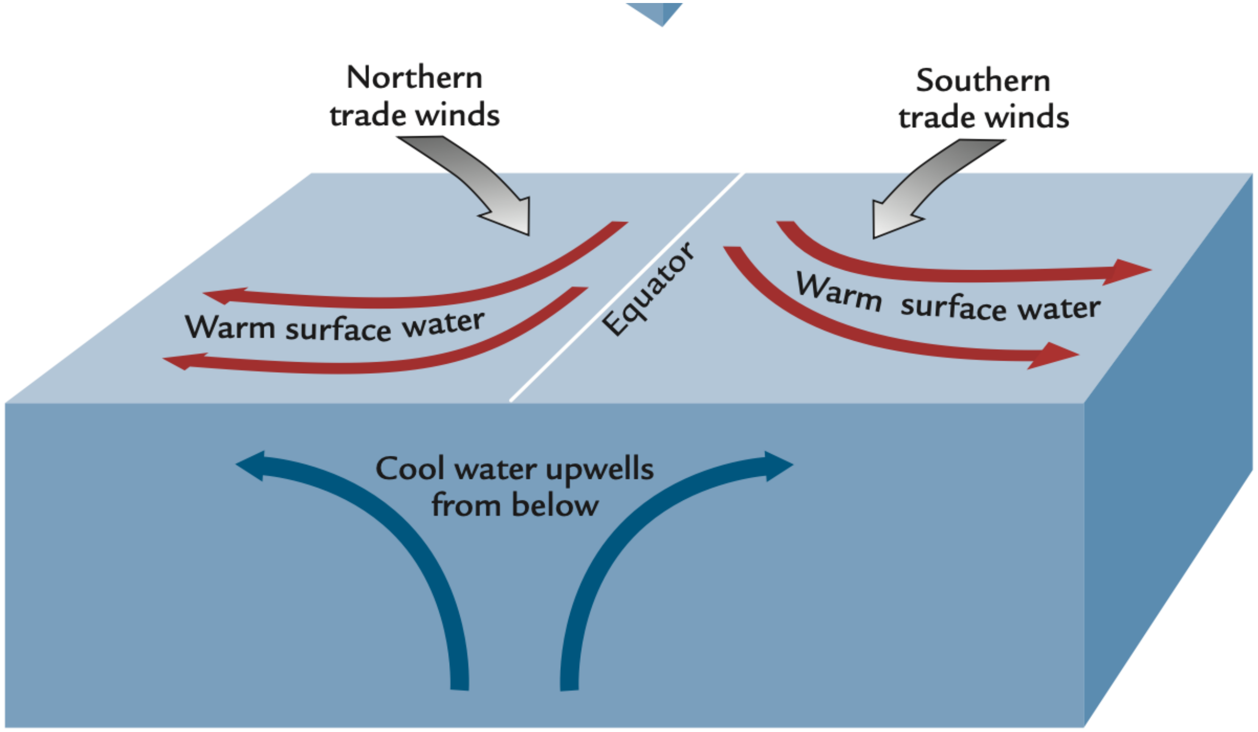
Where does most of the deep ocean water come from?

With all this water sinking into the deep ocean, how does it get back to the surface?

UPWELLING



A Coastal upwelling



B Equatorial upwelling

Both upwelling processes are initiated by surface winds and aided by the Coriolis effect:

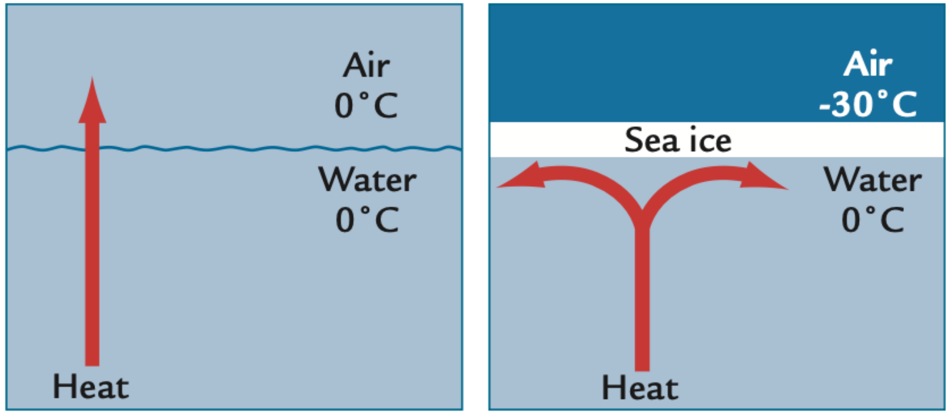
Ice on Earth

- **Sea Ice**

The formation and melting of sea ice are driven mainly by seasonal changes in solar heating.

In the **Southern Ocean**, most of the sea ice melts and forms again every year, over an area comparable in size to the entire Antarctic continent it surrounds. This annual ice cover averages 1 meter in thickness, except where strong winds cause the ice to buckle and pile up in ridges.

In contrast, the landmasses surrounding **the Arctic Ocean** constrain the movement of sea ice and allow it to persist for 4 or 5 years. Older sea ice in the center of the Arctic may reach 4 meters in thickness, while annually formed ice around the margins is about 1 meter thick.



A Without sea ice   B With sea ice

FIGURE 2-28

Effect of sea ice on climate

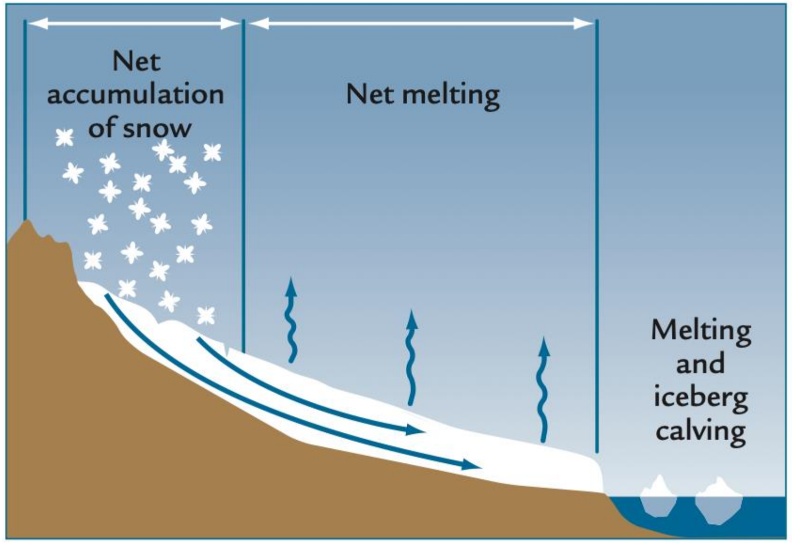
Whereas heat can escape from an unfrozen ocean surface (A), a cover of sea ice (B) stops the release of heat from the ocean to the atmosphere in winter and causes air temperatures to cool by as much as 30°C.

The maximum extent of sea ice is usually reached in the spring, the minimum extent in the autumn – WHY?

Ice on Earth

- **Glacial Ice**

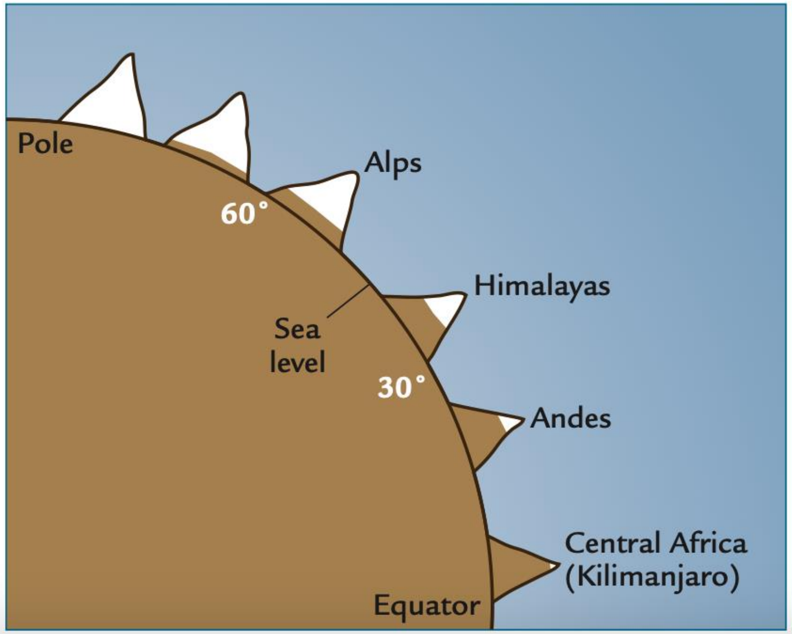
Glacier ice occurs mainly on land, in two forms:
Mountain glaciers and **Continental ice sheets**



Mountain glaciers: Because glaciers can exist only where mean annual temperatures are below freezing, mountain glaciers near the equator are restricted to elevations above 5 kilometers

Continental ice sheets are a much larger form of glacier ice, typically hundreds to thousands of kilometers in horizontal extent and 1 to 4 kilometers in thickness.

The two existing ice sheets, which cover most of Antarctica and Greenland, represent roughly 3% of Earth's total surface area and 11% of its land surface.

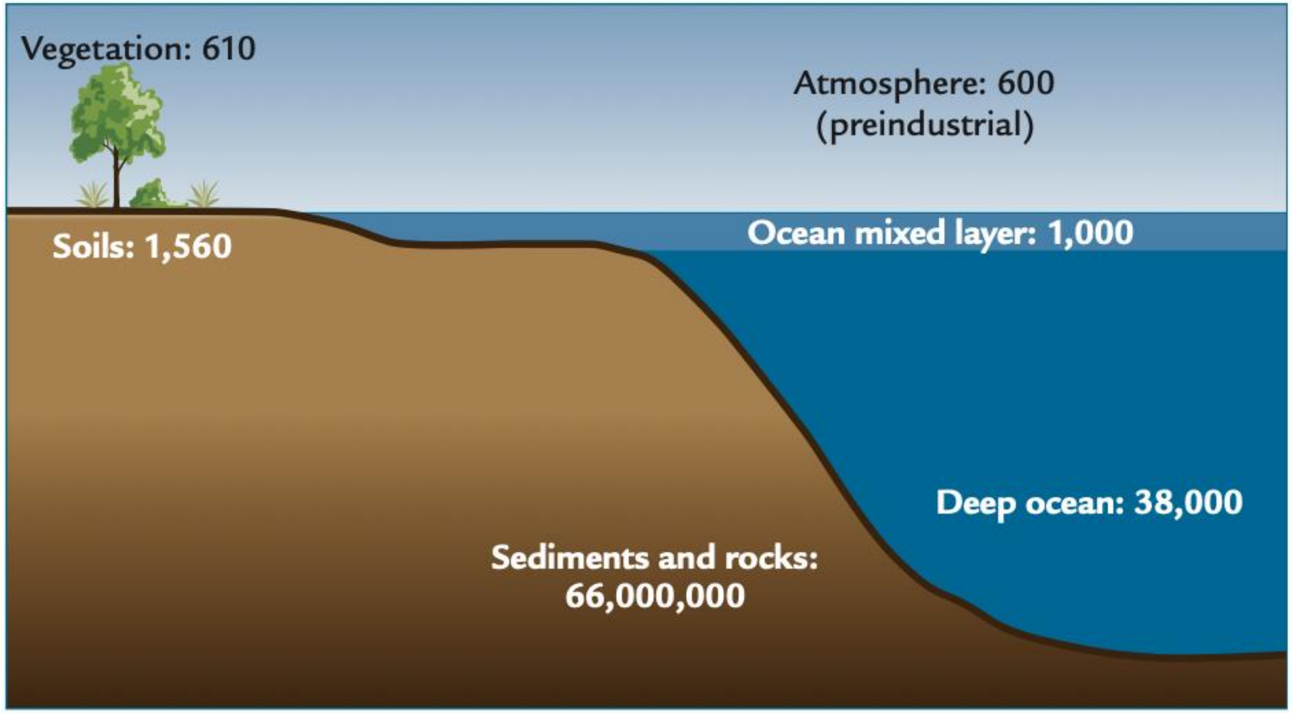


Earth’s Biosphere

Carbon cycle

- Major reservoirs of carbon?

1. atmosphere,
2. the surface ocean,
3. vegetation;
4. soils,
5. deep ocean,
6. and rocks and sediments



A Major carbon reservoirs (gigatons)

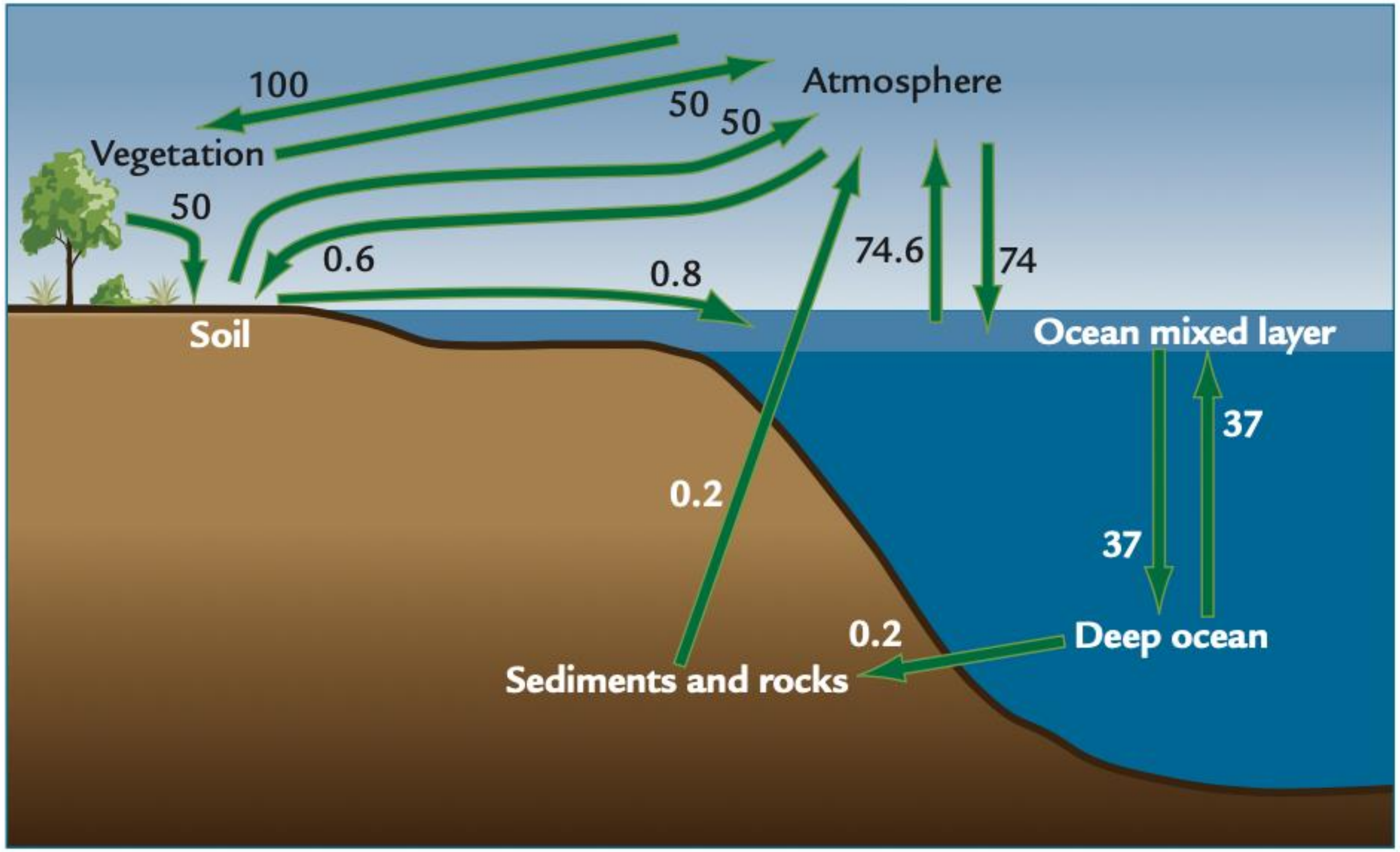
- Which is the largest reservoir of Carbon?

- Amount of carbon in each reservoir is typically quantified in? gigatons (billions of tons, or 1015 grams) of carbon.

Carbon cycle

Carbon takes different chemical forms in these different reservoirs.
In the atmosphere, it is a gas (CO_2).
Carbon in land vegetation is organic, as is most carbon in soils, while that in the ocean is mostly inorganic, occurring as dissolved ions (atoms carrying positive or negative charges).

Larger reservoirs (rocks, the deep ocean) exchange carbon much more slowly than smaller reservoirs (air, vegetation, the surface ocean).



B Carbon exchange rates (gigatons/year)

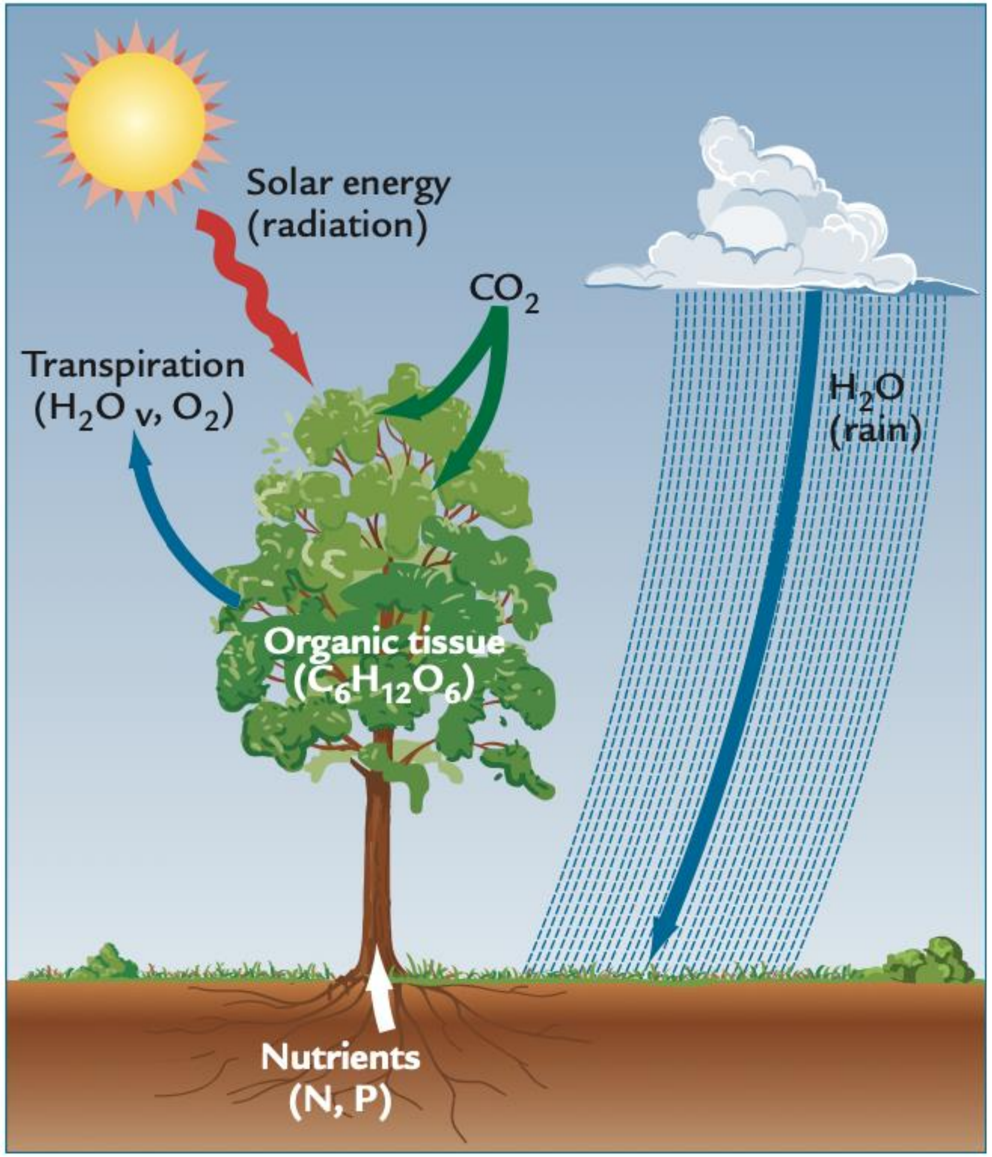


FIGURE 2-33
Photosynthesis on land

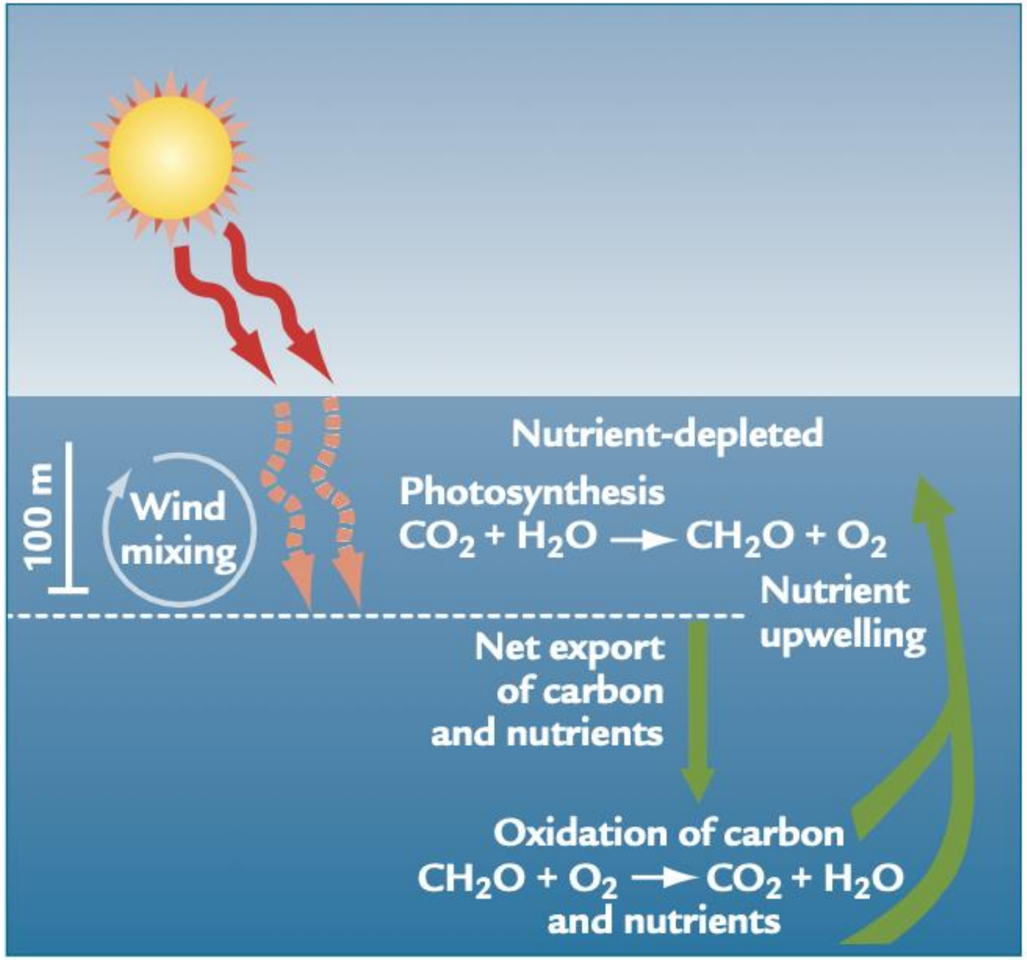


FIGURE 2-35
Photosynthesis in the ocean

What regions of the ocean are most productive? Why?

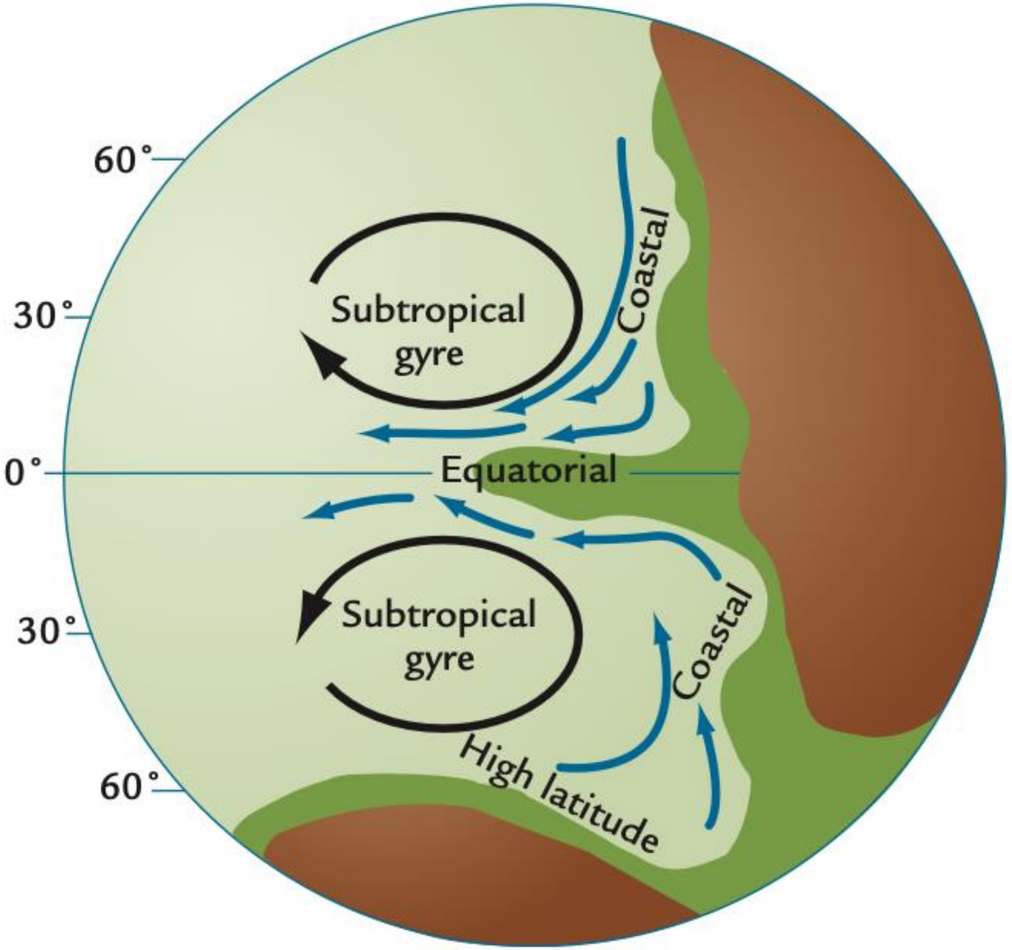


FIGURE 2-36
Ocean productivity

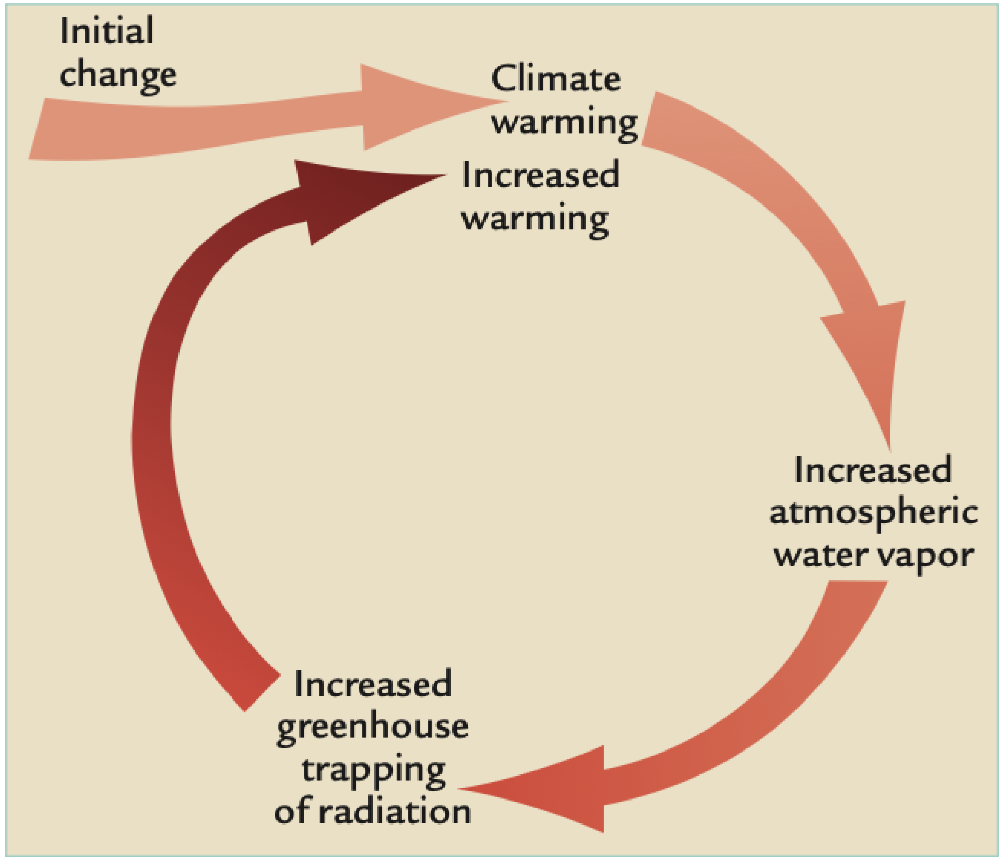
Feedbacks

Assume that some external factor (again, perhaps a change in the strength of radiation from the Sun) causes Earth's climate to change. Those changes will consist of many responses among the various internal components of the climate system at their characteristic (and different) rates. Changes in some of these components will then further perturb climate through the action of feedbacks.

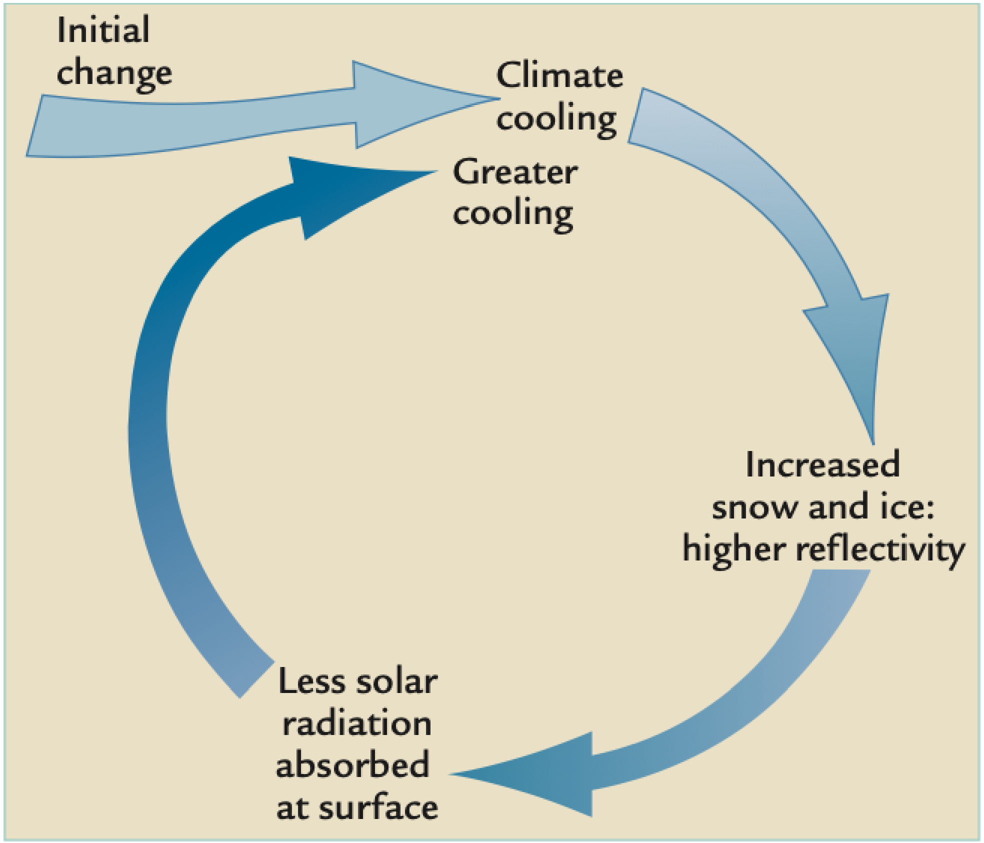
Positive feedbacks produce additional climate change beyond the amount triggered by the initial forcing.

Negative feedbacks work in the opposite sense, by muting climate changes. In response to an initial climate change, some components of Earth's climate system may respond in such a way as to reduce the initial amount of change.

Feedbacks

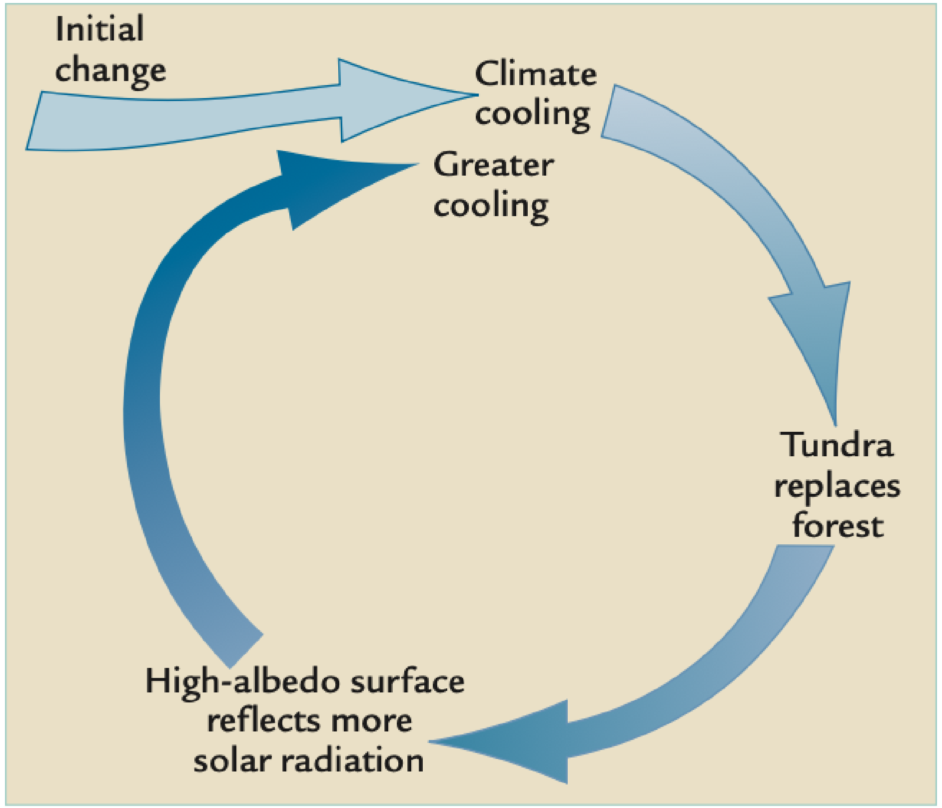


Water vapor feedback When climate warms, the atmosphere is able to hold more water vapor (the major greenhouse gas in the atmosphere), and the increase in water vapor leads to further warming by means of a positive feedback. This feedback works in reverse during cooling.

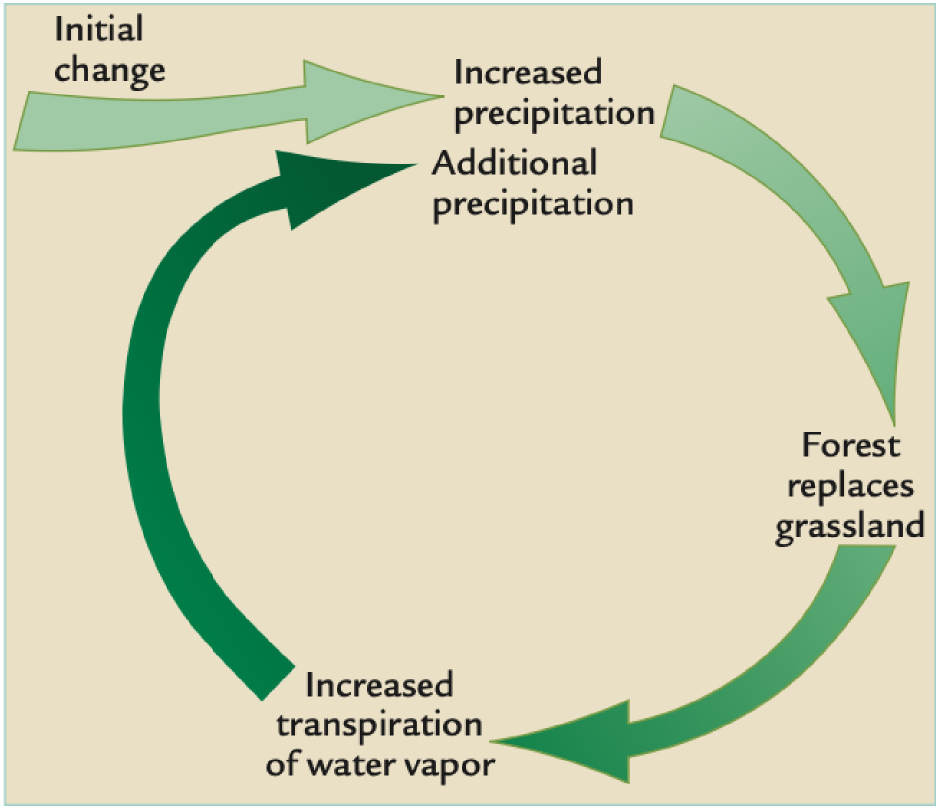


Albedo-temperature feedback When climate cools, the increased extent of reflective snow and ice increases the albedo of Earth's surface in high-latitude regions, causing further cooling by positive feedback. The same feedback process amplifies climate warming.

Feedbacks



A Vegetation-albedo feedback



B Vegetation-precipitation feedback

Vegetation-climate feedbacks When high-latitude climate cools, replacement of spruce forest by tundra raises the reflectivity (albedo) of the land in winter and causes additional cooling as a positive feedback (A). When climate becomes wetter, replacement of grasslands by trees increases the release of water vapor back to the atmosphere and causes increases in local rainfall as a positive feedback (B).