DEPARTMENT OF GEOGRAPHY

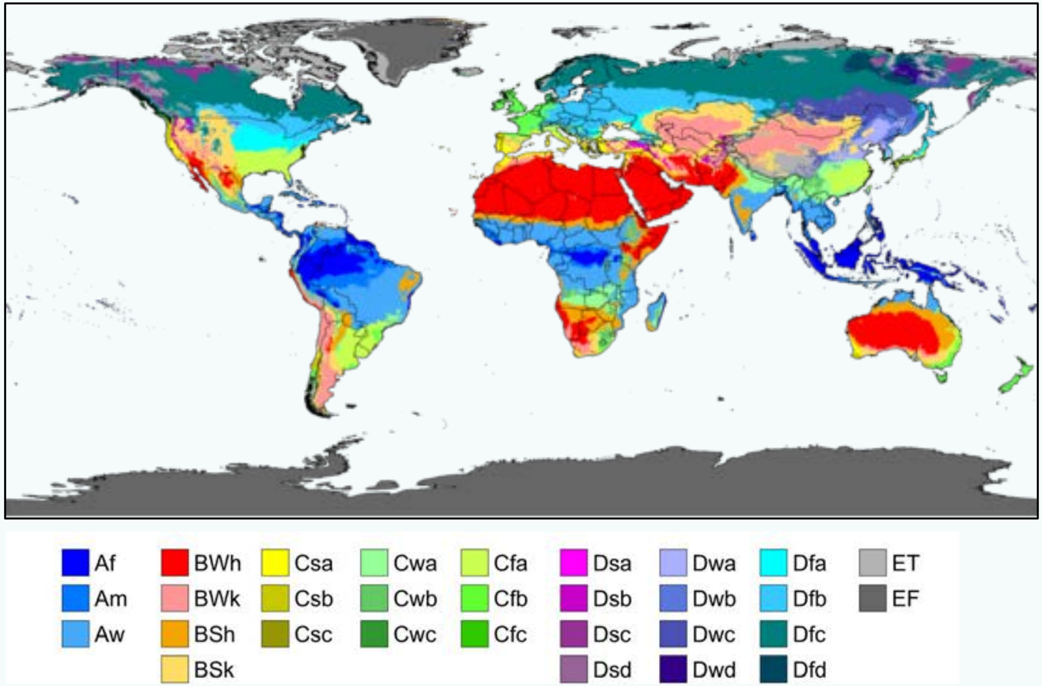
Climate

Earth geog0005

What is climate?

- **Average** or typical conditions of the atmosphere
- The state of climate components
- Averages out weather, but not seasons
- Climate measurements span modern to past climate (paleoclimate)
- Classification can be according to land cover and seasonal precipitation and temperature (Köppen)

Köppen climate classification map (1980-2016)



A = Tropical
B = Dry (arid/semi-arid)
C = Temperate
D = Continental
E = Polar

WHAT CONTROLS CLIMATE?

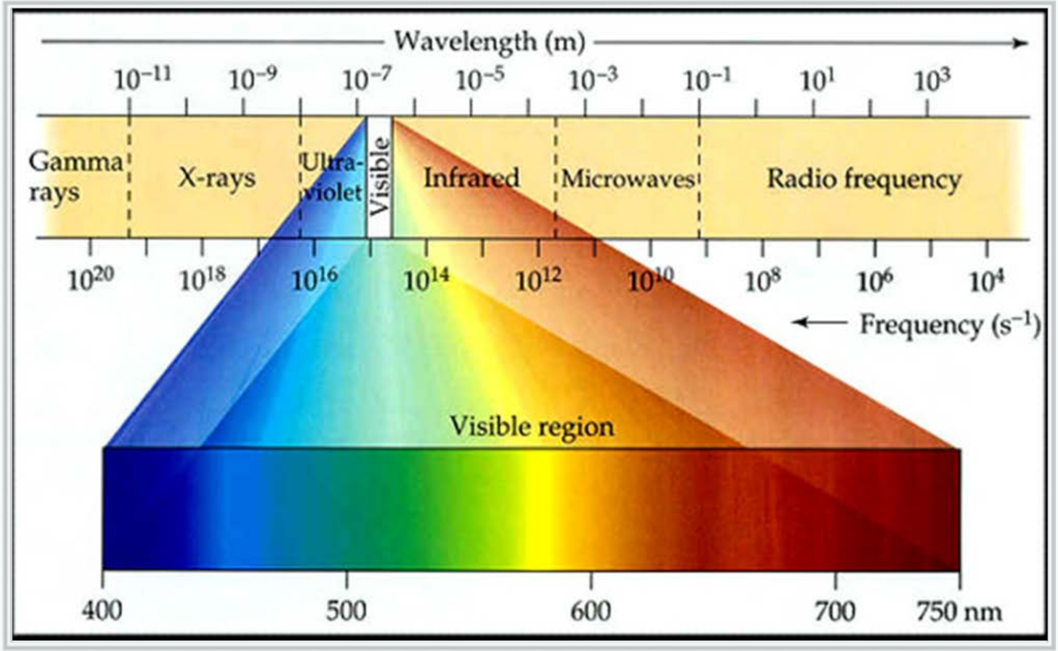
Global Energy Budget

Energy Transfer

- Radiation
- Conduction
- Convection

Radiation

- Transfer of energy as waves or particles through air (emission/transmission)
- Called electromagnetic radiation
- Electromagnetic spectrum: range of frequencies of electromagnetic radiation and their wavelengths (or energies)
- Separated as **Longwave** (low energy) and **Shortwave** (high energy)

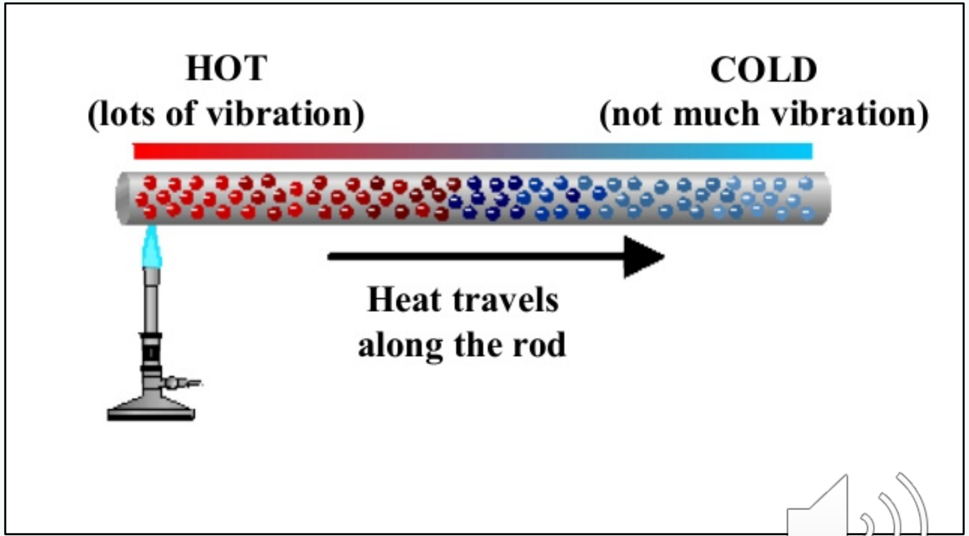


Energy is inversely proportional to wavelength

Conduction

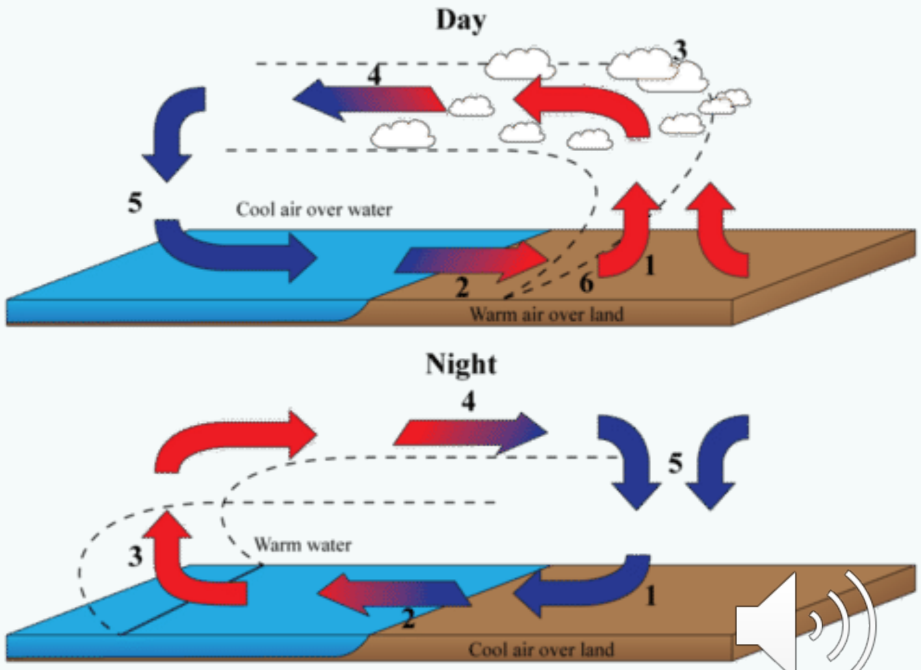
- Heat (energy) transfer from one molecule to next as molecules vibrate

- Rate of transfer of heat depends on temperature difference (gradient)
- Example: heat moving along a metal bar
- Occurs in all fluid phases (gas, liquid, solid)

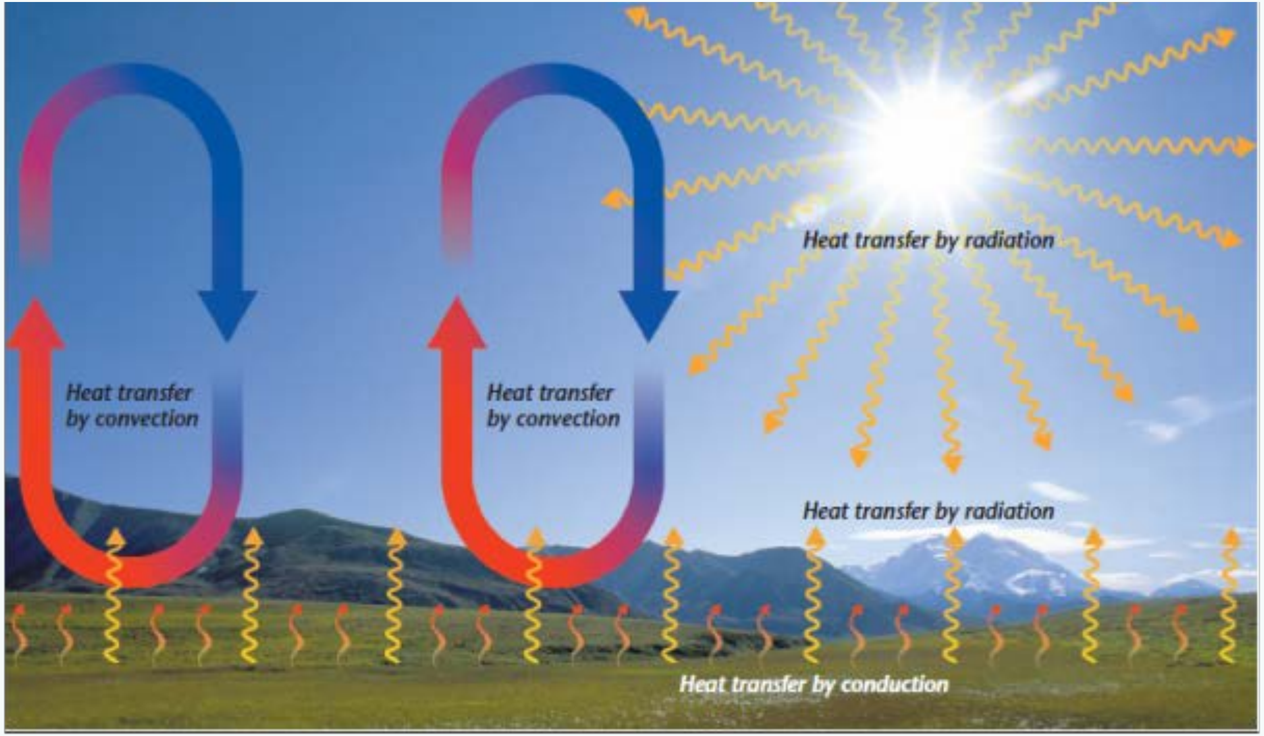


Convection

- Transfer of heat by movement of a fluid (mass transfer)
- Caused by buoyancy forces due to changes in density that arise from changes in temperature
- These present in the atmosphere as turbulence (fluid mixing) or an instability (uneven heating)
- Moist convection leads to thunderstorms



Heat Transfer Processes in the Atmosphere



Steady State

- Earth’s climate system, unperturbed, is in a (quasi-) steady state:

Energy In = Energy Out

(Incoming radiation = Outgoing radiation)

- As space is vacuum, the only form of energy transfer is electromagnetic radiation

Blackbody Radiation

- A perfect blackbody is an object that absorbs all incoming radiation (that is, none is reflected)
- Radiation emitted by a blackbody depends only its temperature
- Planck's law of blackbody radiation defines this relationship:

Planck's Law: $$\boxed{B(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}}$$

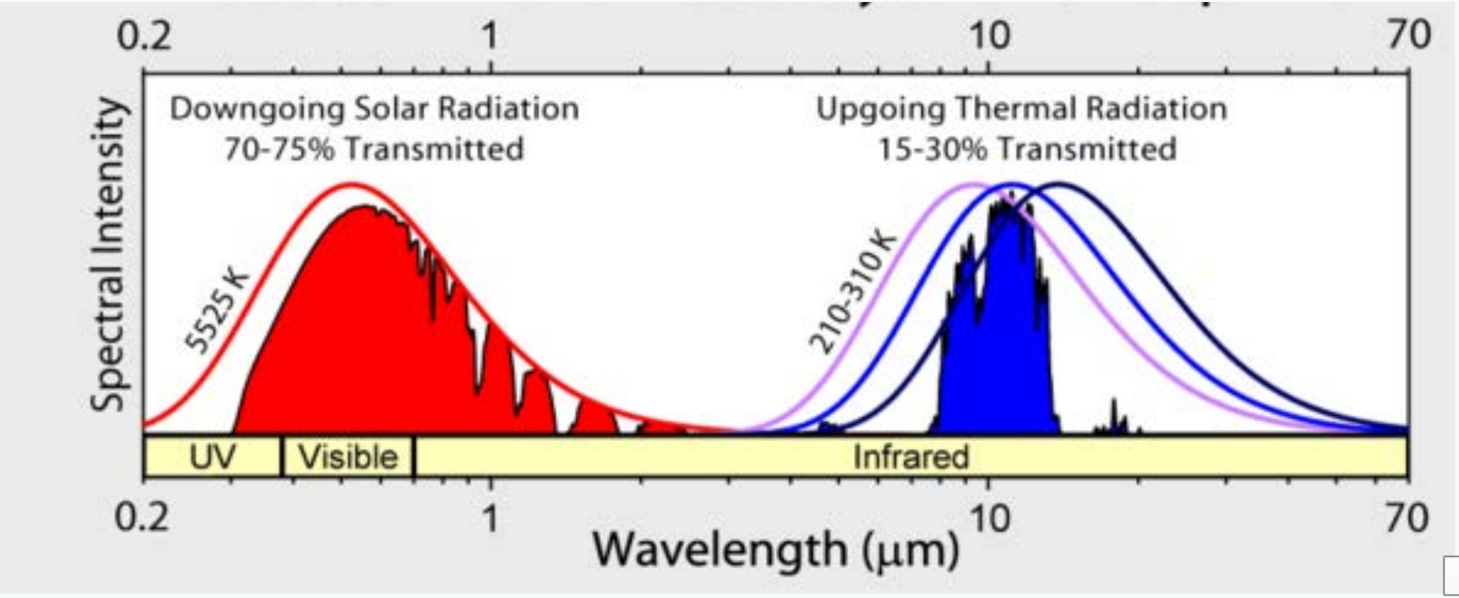
B: spectral radiance
h, c, k: constants
ν: frequency of light
T: absolute temperature

- Tells us how much radiation emitted at a certain wavelength for a body of a certain temperature
- Blackbody is isotropic (radiation emitted at equal intensity in all directions)

Longwave and Shortwave

Radiation from the sun is in the shortwave (UV/visible)

Radiation from the Earth is in the longwave (infrared)



Emission from the sun and Earth hardly overlap

Stefan-Boltzmann Law

- Power radiated from a blackbody in terms of its temperature
- Total energy radiated per unit surface area of a blackbody is proportional to T^4
- This relationship integrated in all directions over a hemisphere and over all frequencies is:

$$I = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} *is the Stefan-Boltzmann Constant*

- I is the black-body irradiance or energy flux density

Test Your Understanding

What kind of heat transfer is taking place above the low-pressure system of a cyclone?

A. Conduction

B. Convection

C. Radiation

D. None of these

The Stefan-Boltzmann constant is 5.67×10^{-8} W m^{-2} K^{-4} and the temperature of the sun is 5778 K. What is the energy radiated from the surface of the sun?

A. 5778 W/m^2

B. 63000 kW

C. 63000 kW/m^2

D. 0.0032 W/m^2

Radiation Modifiers

- Albedo, α, is the ratio of reflected radiation to incident radiation (incoming light striking a surface):

$$0 < \alpha < 1$$

- Transmittance, γ, is the ratio of transmitted radiation (radiation that passes through a fluid) to incident radiation:

$$0 < \gamma < 1$$

- A grey body is a body that emits radiation according to Planck's formula multiplied by fractional emissivity, ε:

$$0 < \varepsilon < 1$$

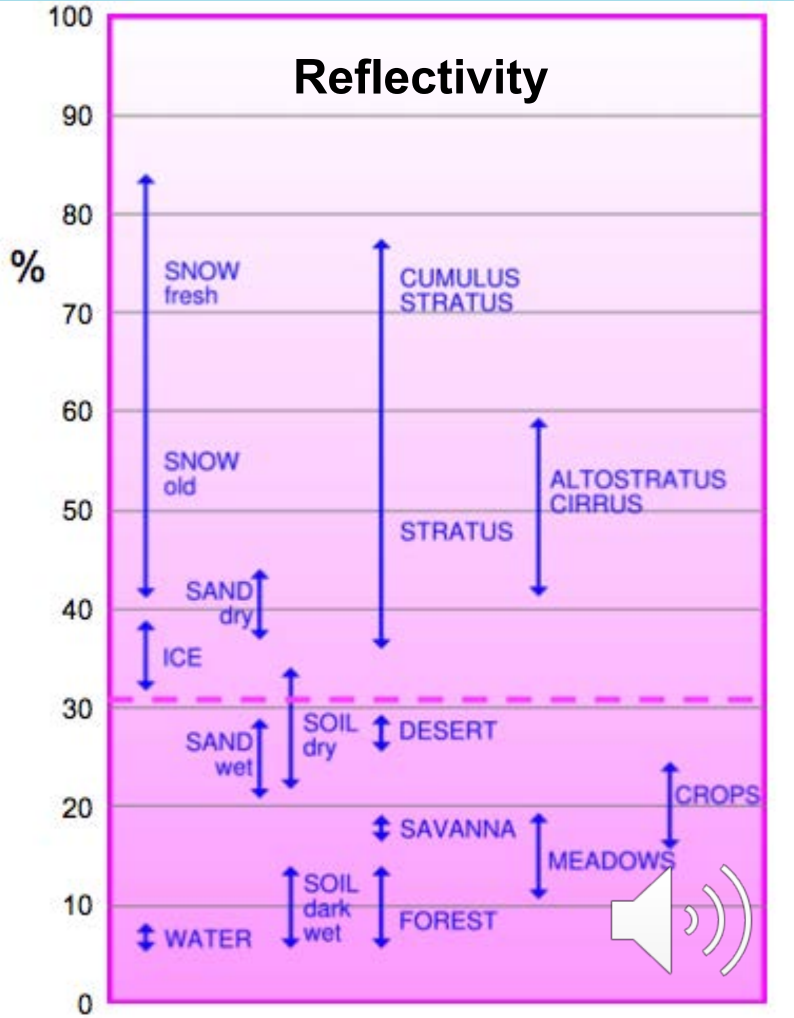
where ε is a measure of efficiency of emitting thermal radiation (0 for shiny object; 1 for blackbody)

Global Albedo

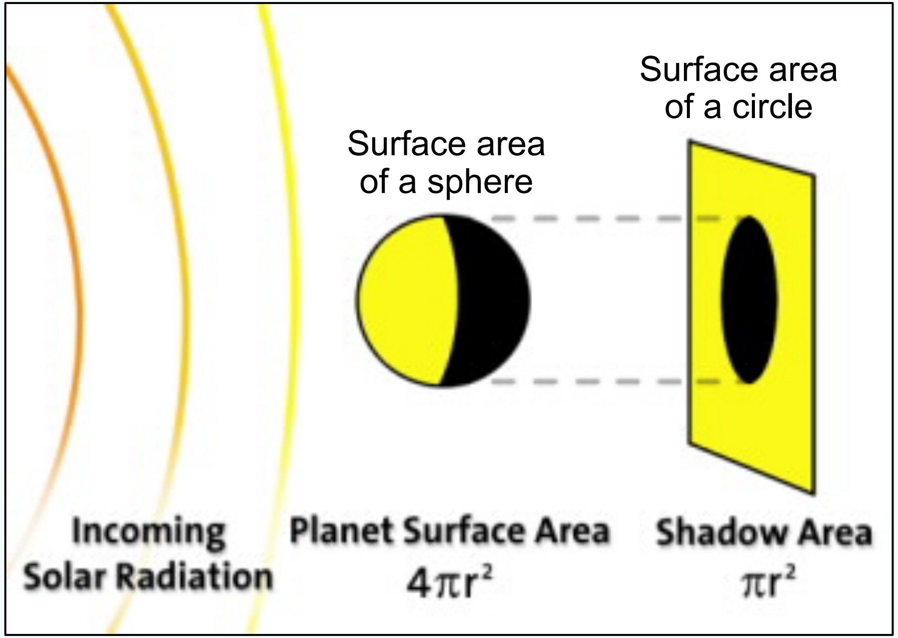
- Earth is not a perfect blackbody
- Clouds, ice, reflective land surfaces like deserts increase α and reduce ε
- Colour varies from white to deep blue (nearly black)

Albedo properties

- Albedo (α) varies as a function of properties of surface (land/cloud).
- The ocean albedo depends on the angle of the solar radiation striking the surface (sun glint)
- The albedo of bare sea ice depends on the density of air bubbles.
- Earth's global average α = 0.3



Global Mean Energy Model (incoming radiation)

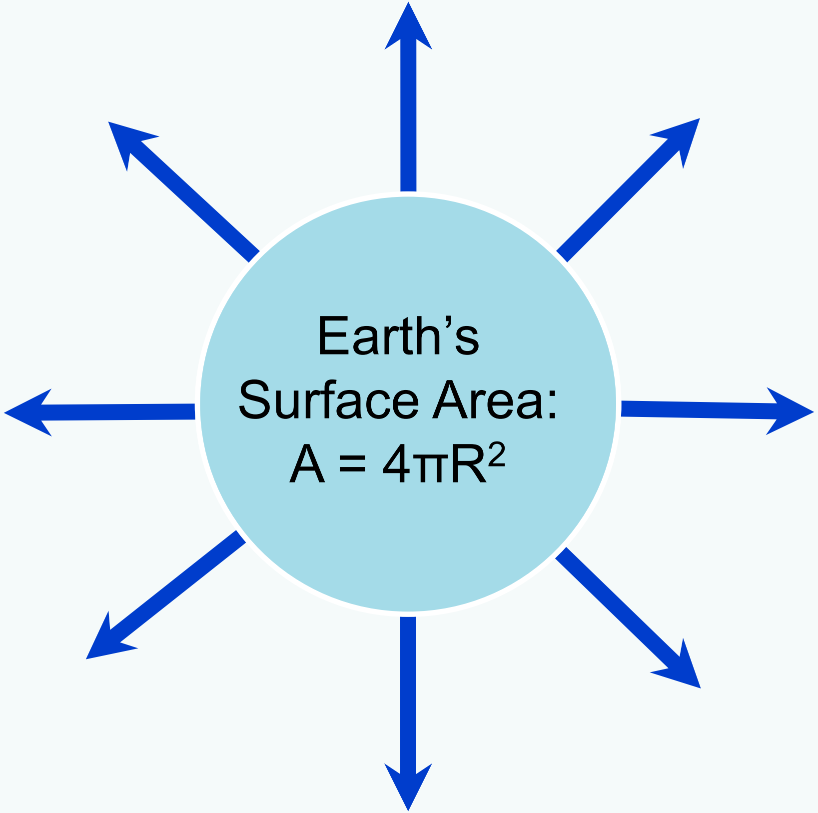


- Energy of incident shortwave solar radiation (solar constant):

$$S_o = 1366\ \mathrm{W/m^2}$$

- Area of the Earth the sun intercepts = πR^2
- Fraction of solar constant received by Earth = $(\pi R^2)/(4\pi R^2) = S_o/4 = 342\ \mathrm{W/m^2}$
- 30% reflected ($\alpha = 0.3$)

Global Mean Energy Model (outgoing radiation)

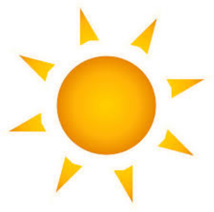


Energy of a blackbody is proportional to its temperature:

$$E_{out} = \sigma T^4$$

(σ=5.67x10^{-8} Wm^{-2}K^{-4})

Global Mean Model (incoming = outgoing)



Steady state: Energy in = Energy out

$$S_o(1-\alpha)\pi R^2 = 4\pi R^2\sigma T^4 \quad \text{...(1)}$$

$$\frac{S_o(1-\alpha)}{4} = \sigma T^4 \quad \text{...(2)}$$

$$T = \frac{\sqrt[4]{S_o(1-\alpha)}}{4\sigma} \quad \text{...(3)}$$

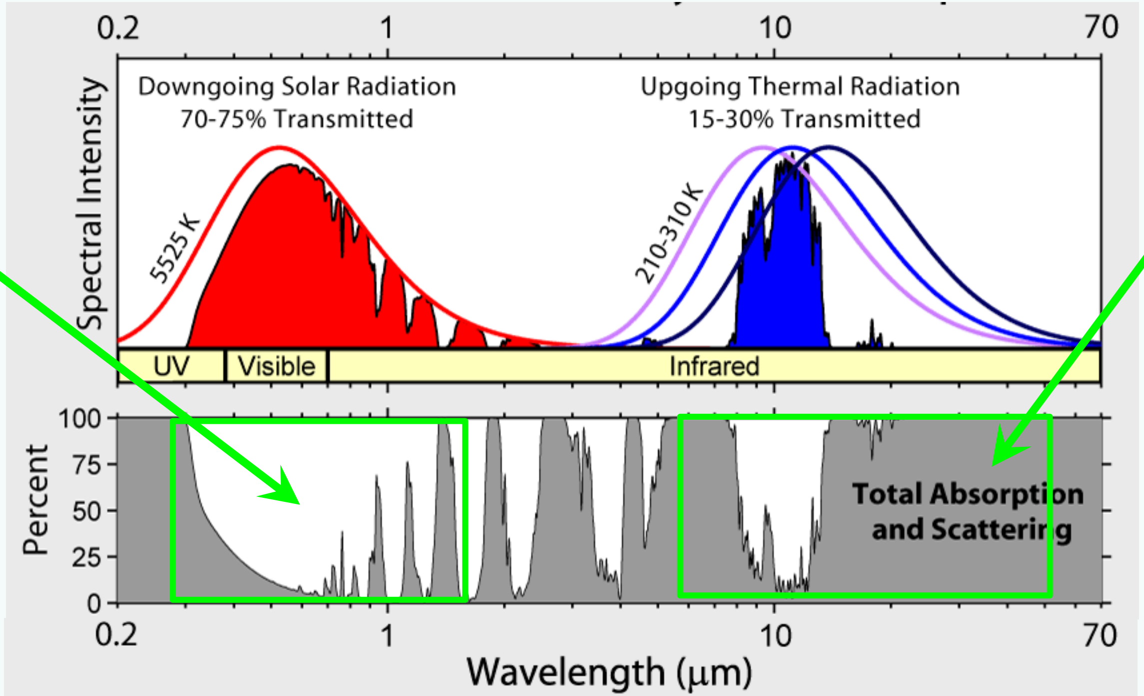
$T_{emission}$ = 255 K = -18^{o}C

Actual temperature is +15^{o}C.

Difference is due to infrared active greenhouse gases

Longwave and Shortwave Radiation

Majority of shortwave penetrates atmosphere

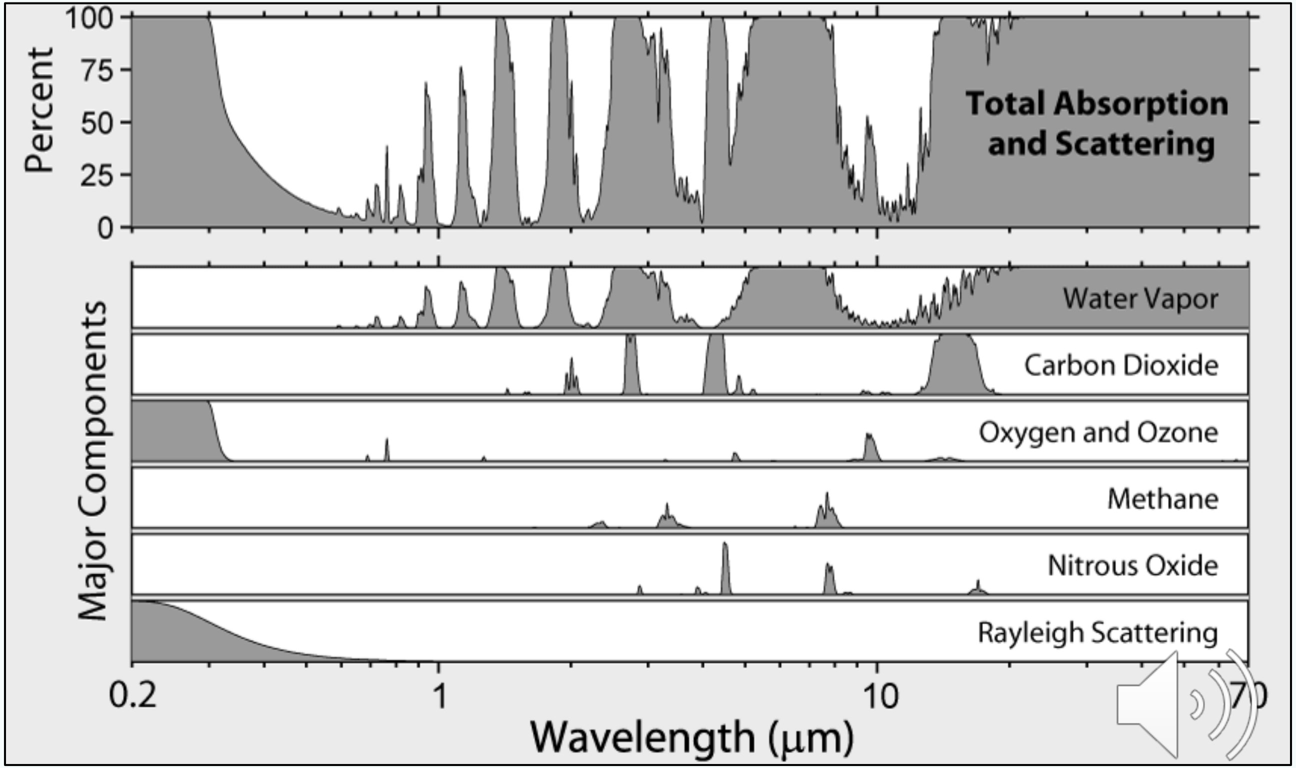


Very little longwave escapes

Absorption of Radiation by Greenhouse Gases

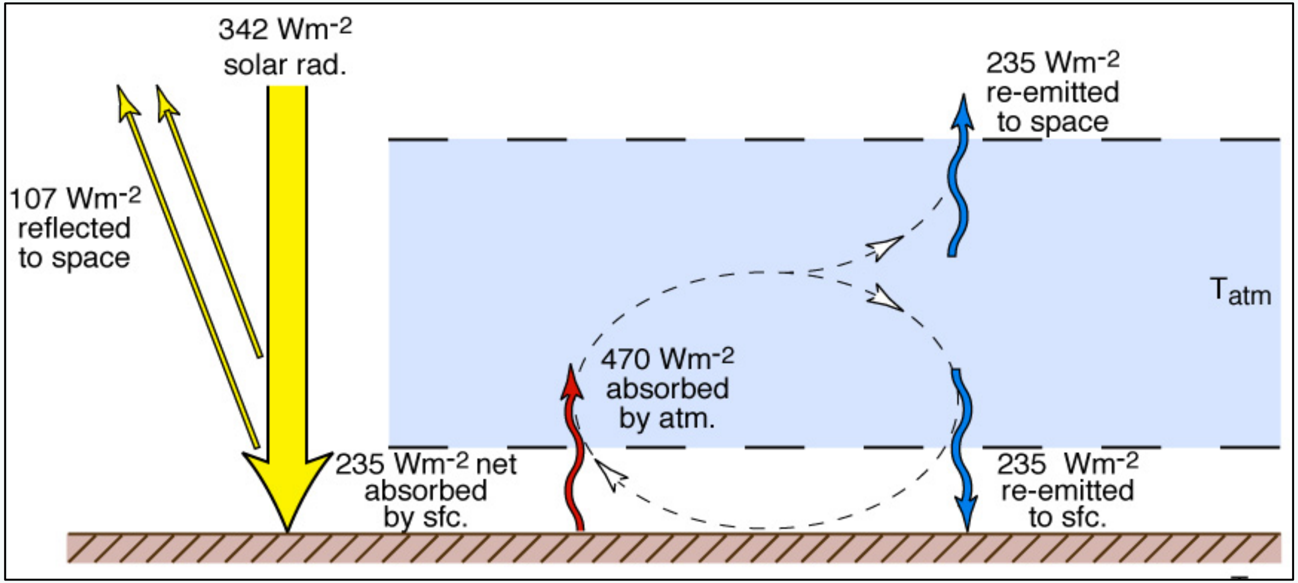
Majority of radiation emitted from surface is absorbed by atmosphere

Dominant GHGs are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)



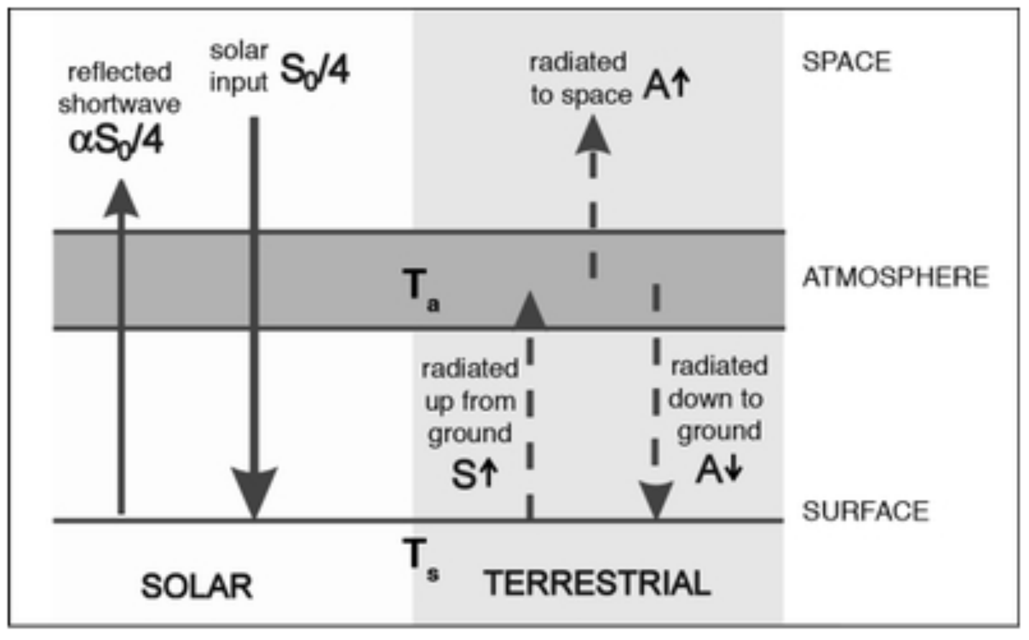
Adding a GHG Layer to the Simple Model

‘Gray’ atmosphere is transparent in the shortwave and includes a layer of infrared absorbing gases that intercept outgoing longwave radiation



sfc. = surface

Greenhouse gas atmosphere temperature



Remember ***$I_o = S_o/4$*** *is the fraction of solar energy received by Earth*

- Surface energy balance:

$$I_{sun}(1\text{-}\alpha) + \sigma T_a^4 = \sigma T_{surf}^4 \; \ldots \; (1)$$

- Atmosphere energy balance:

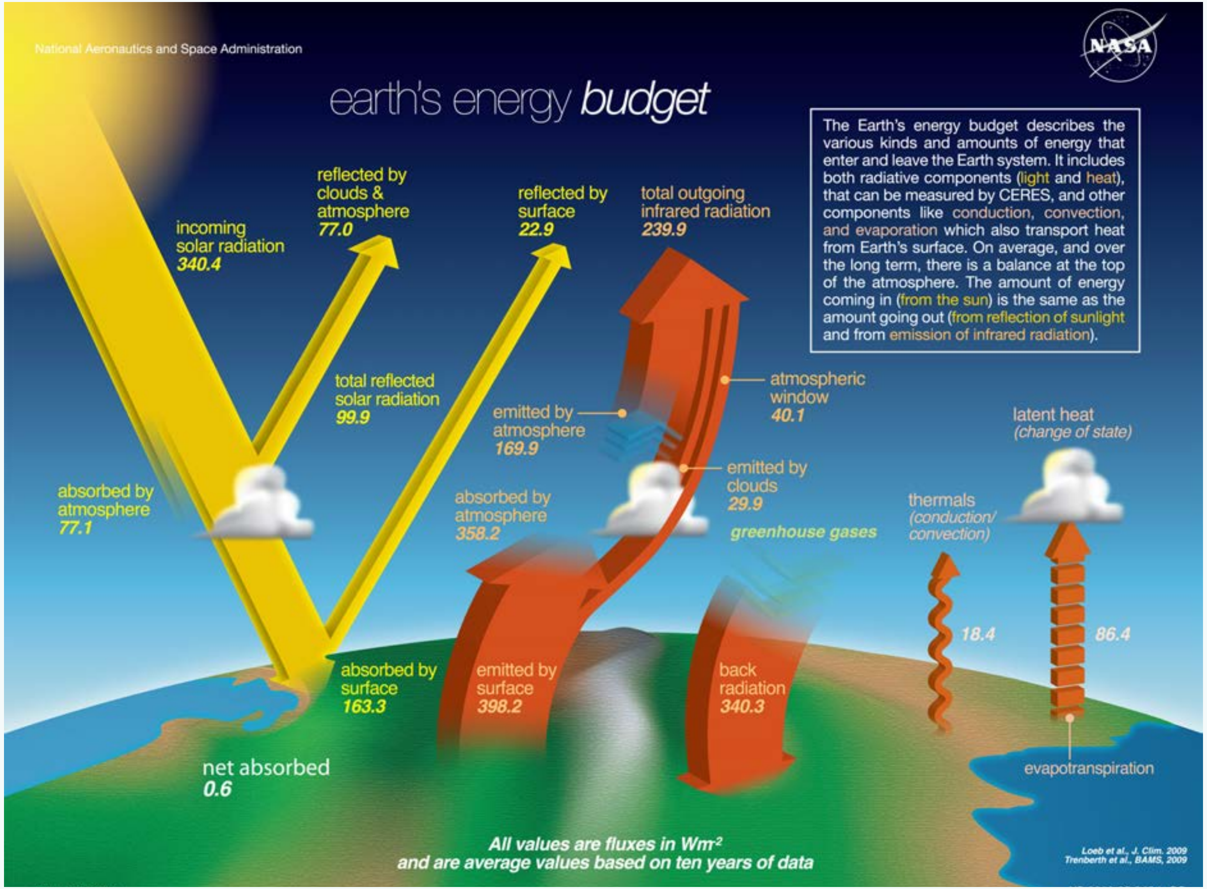
$$\sigma T_{surf}^4 = 2\sigma T_a^4 \; \ldots \; (2)$$

$$T_{surf} = 2^{¼} T_a \; \ldots \; (3)$$

$$T_a = [I_{sun}(1\text{-}\alpha)/\sigma]^{¼} \; \ldots \; (4)$$

- T_a= 255 K = -18^{o}C
- T_{surf} = 303 K = 30^{o}C

Putting it all together: Earth's Energy Balance



Test Your Knowledge

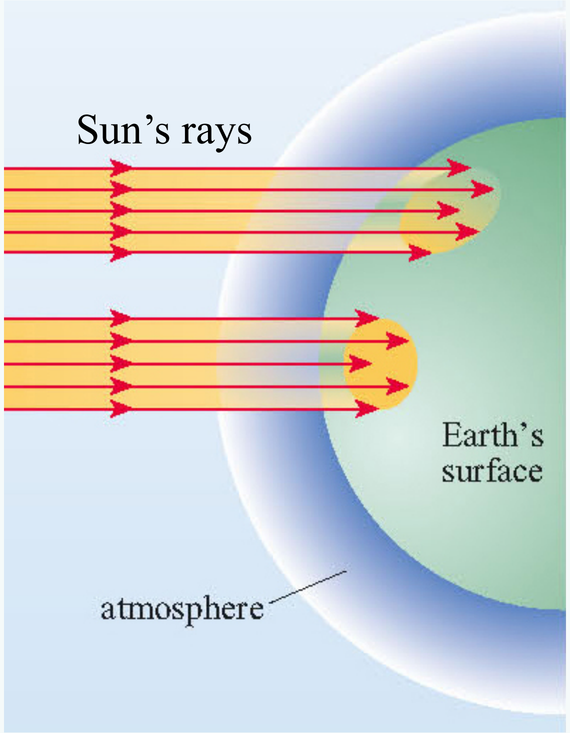
The solar constant for Mars is 586.2 W/m^2 and the albedo is 0.25. What is the blackbody temperature of Mars?

A. -48 degrees C
B. -63 degrees C
C. 19 degrees C
D. The same as Earth's blackbody temperature.

Select form the list the reason why the blackbody temperature of Mars is less than that of Earth

A. Mars is further from the sun than Earth.
B. Mars has a thinner atmosphere than Earth.
C. Mars has more atmospheric dust than Earth.
D. Mars has a lower atmospheric concentration of greenhouse gases than Earth.

Equator gets more sun radiation than the Poles

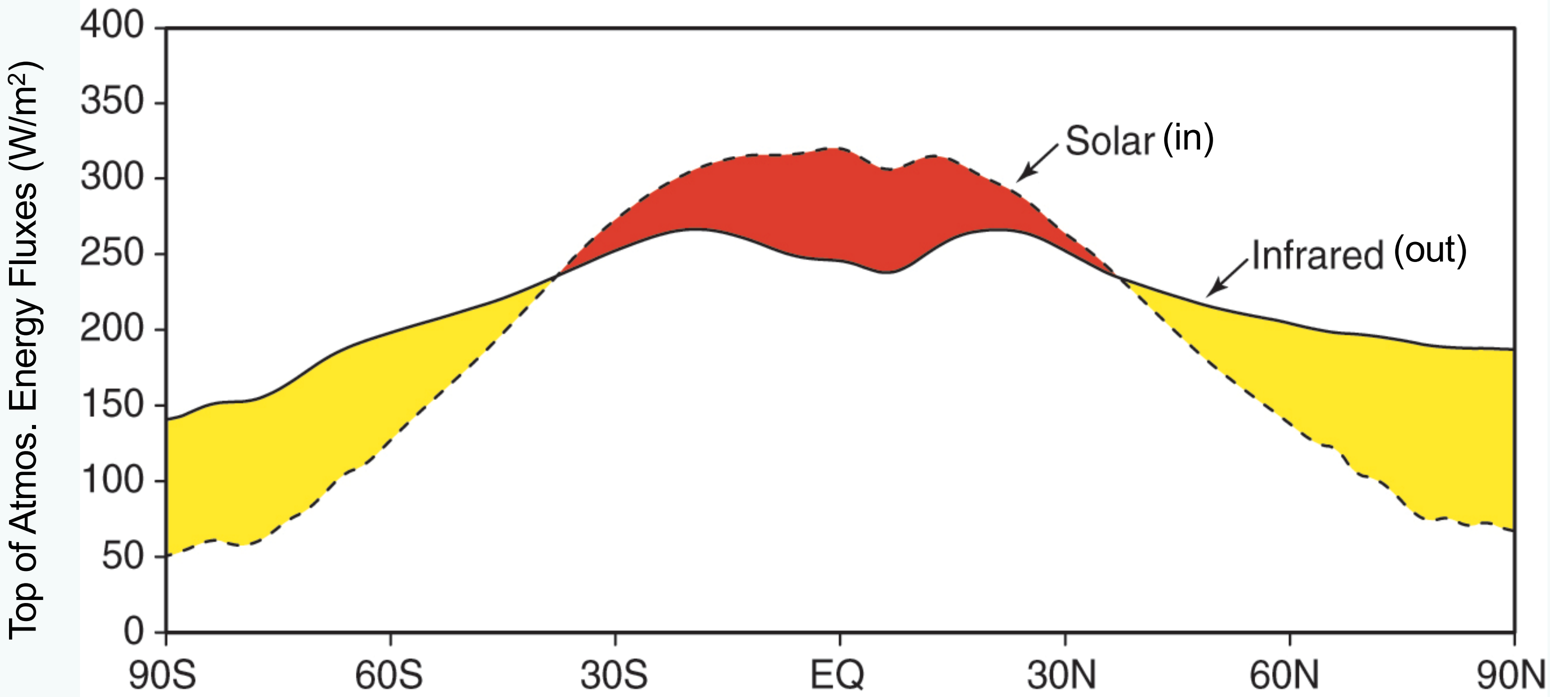


Less

More

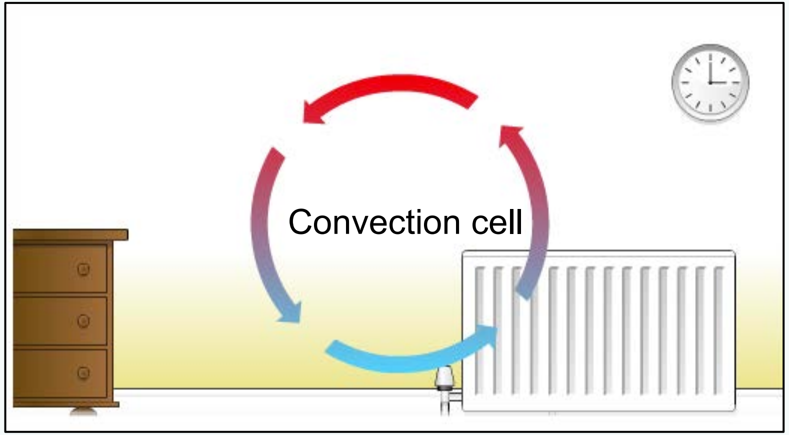
Energy Transfer

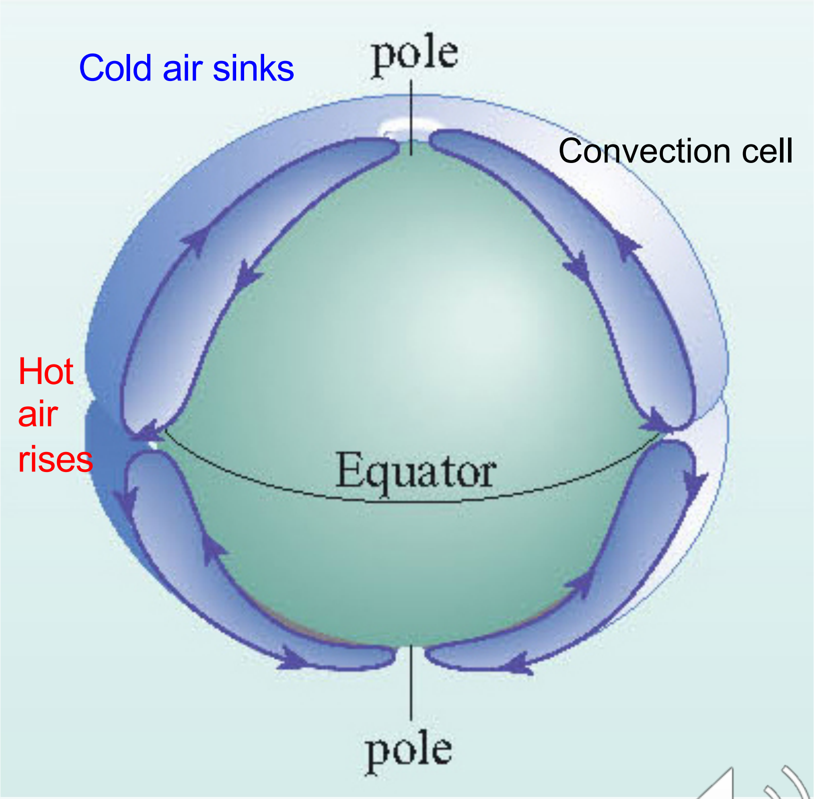
Uneven Heating:
Equator gets more sun radiation than the Poles



Redistribution of Heat

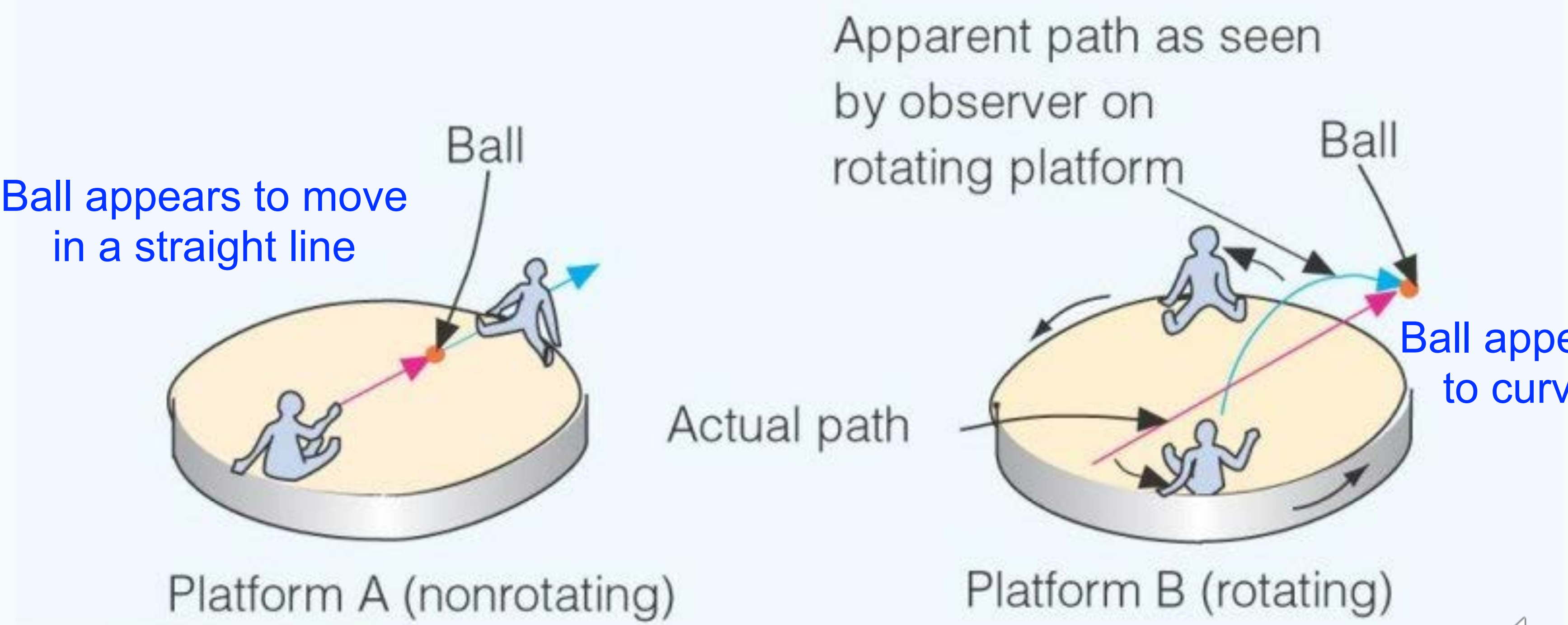
- Convection plays role
- Not as simple as Hadley's 1735 suggestion that convection cell extends from Equator to the Poles





Does not account for the **Coriolis effect**

Reminder of the Coriolis Effect



Ball appears to move in a straight line

Ball appears to curve

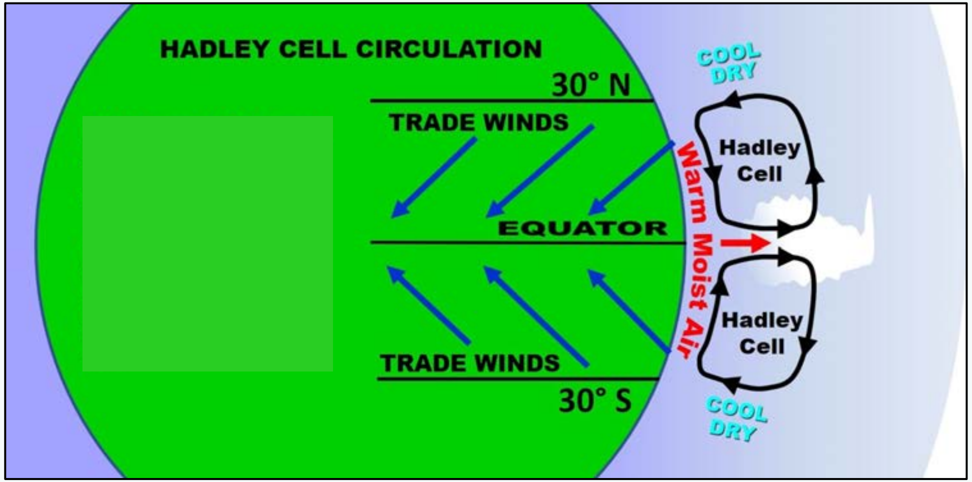
Inertial reference frame

Non-inertial reference frame

Air parcels deflected to the right in northern hemisphere relative to direction of travel

Tropical Hadley Cells

- Sun heats Equator
- Hot air rises
- Air masses move toward Poles
- Air masses diverge from north-south path due to Coriolis effect
- Cool dry air sinks at about 30° latitude (deserts)
- Still named Hadley cell

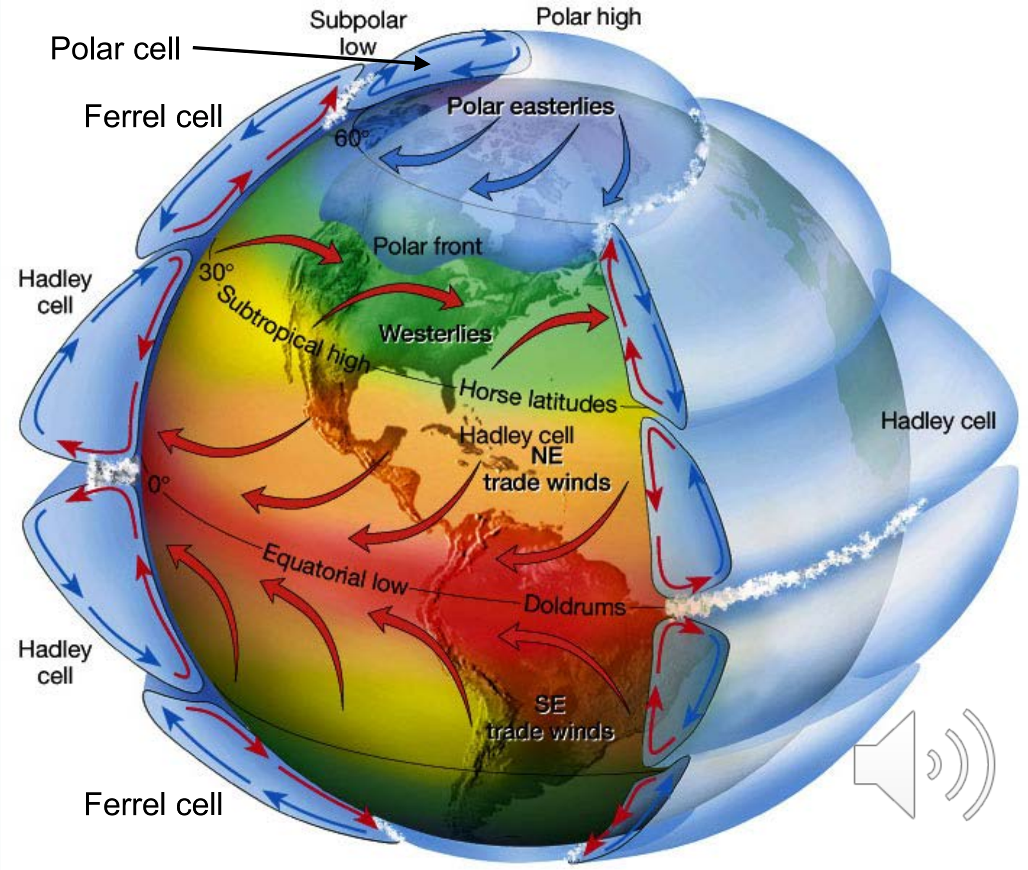


Reminder:
- Air rising (convective uplift) associated with clouds and rain (tropical rainforests)
- Air sinking (subsidence) associated wit ry air (deserts)

Convection cells and Surface Winds

Convection Cells:
- moist, warm air rises forming clouds
- cold, dry air subsides (compresses and warms)

Surface Winds:
- descending branch of cell reaches surface, forms surface winds that diverge due to Coriolis effect
- poleward and equatorward winds meet, air forced upward, maintains convective cells



Annual mean surface temperature

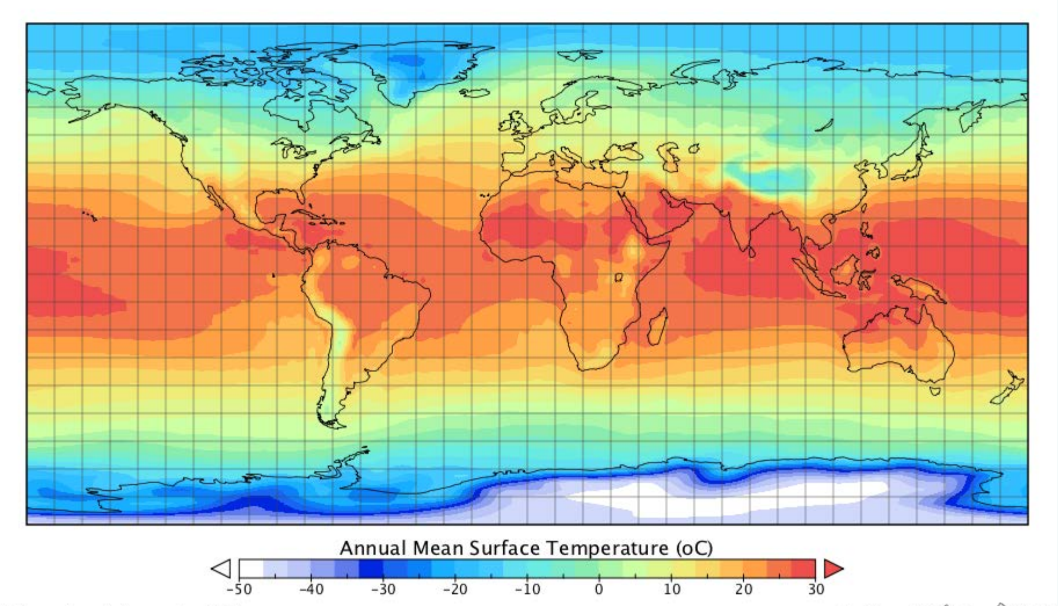
Warmest at the Equator

Coldest at the Poles

Antarctic colder than Arctic (isolated - less land mass to redistribute head)

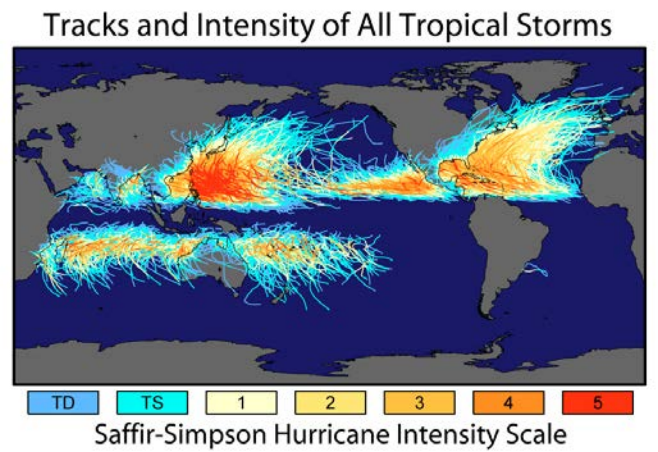
Colder at elevation

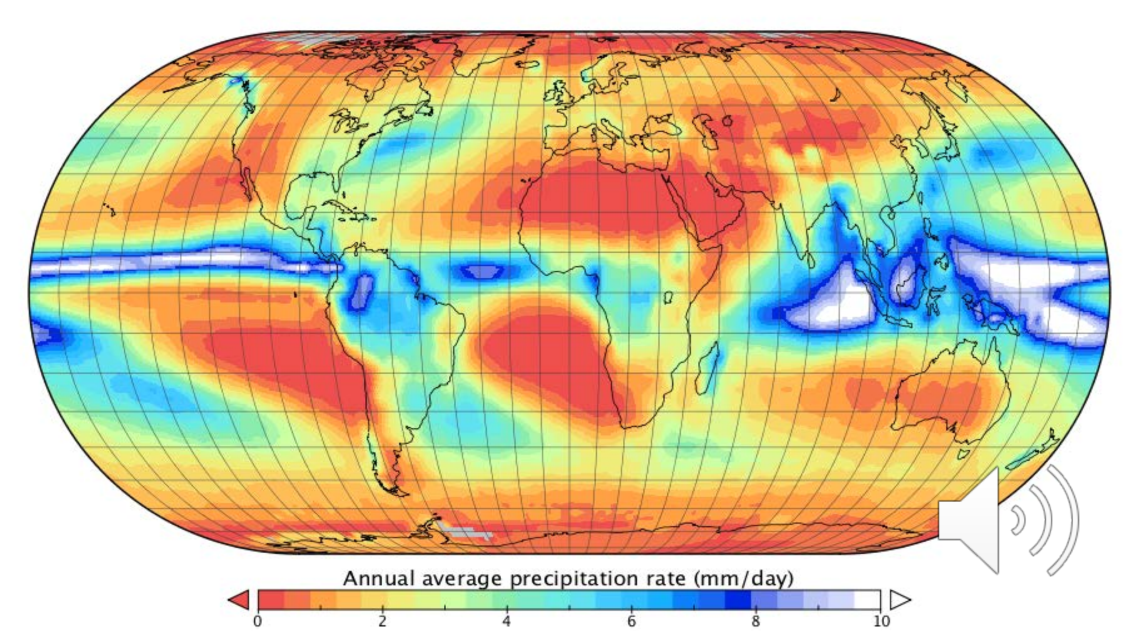
Canada colder than Europe



Annual mean rainfall/precipitation

- Most rain in Intertropical Convergence Zone (ITCZ) (convective uplift)
- Little rain at edge of tropics ~30^{o}N (subsidence)
- More rain over Equatorial oceans (storm tracks)



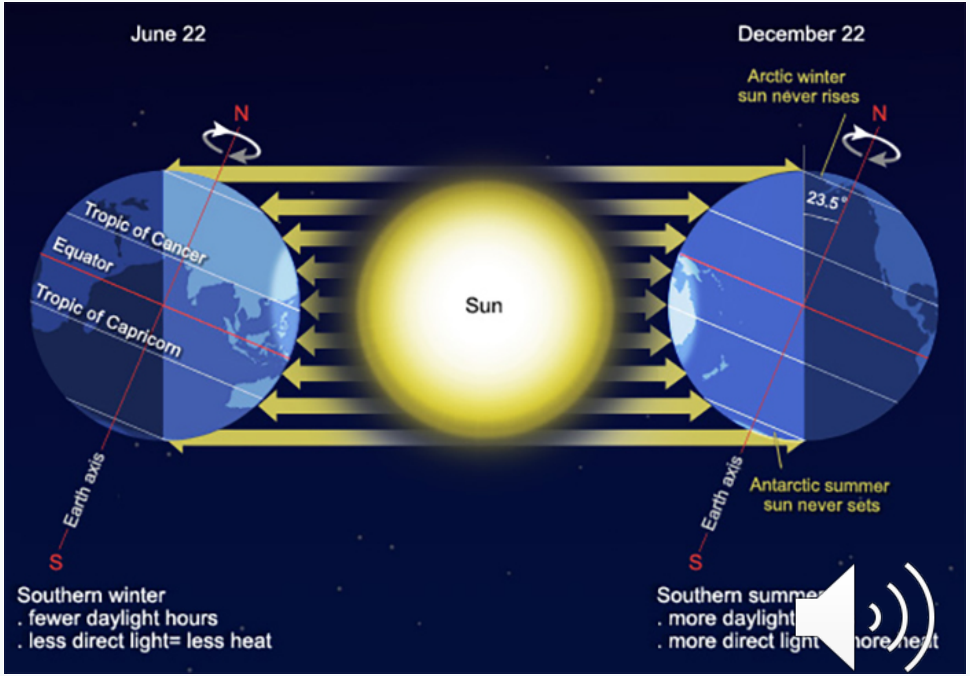


Circulation patterns not always stable

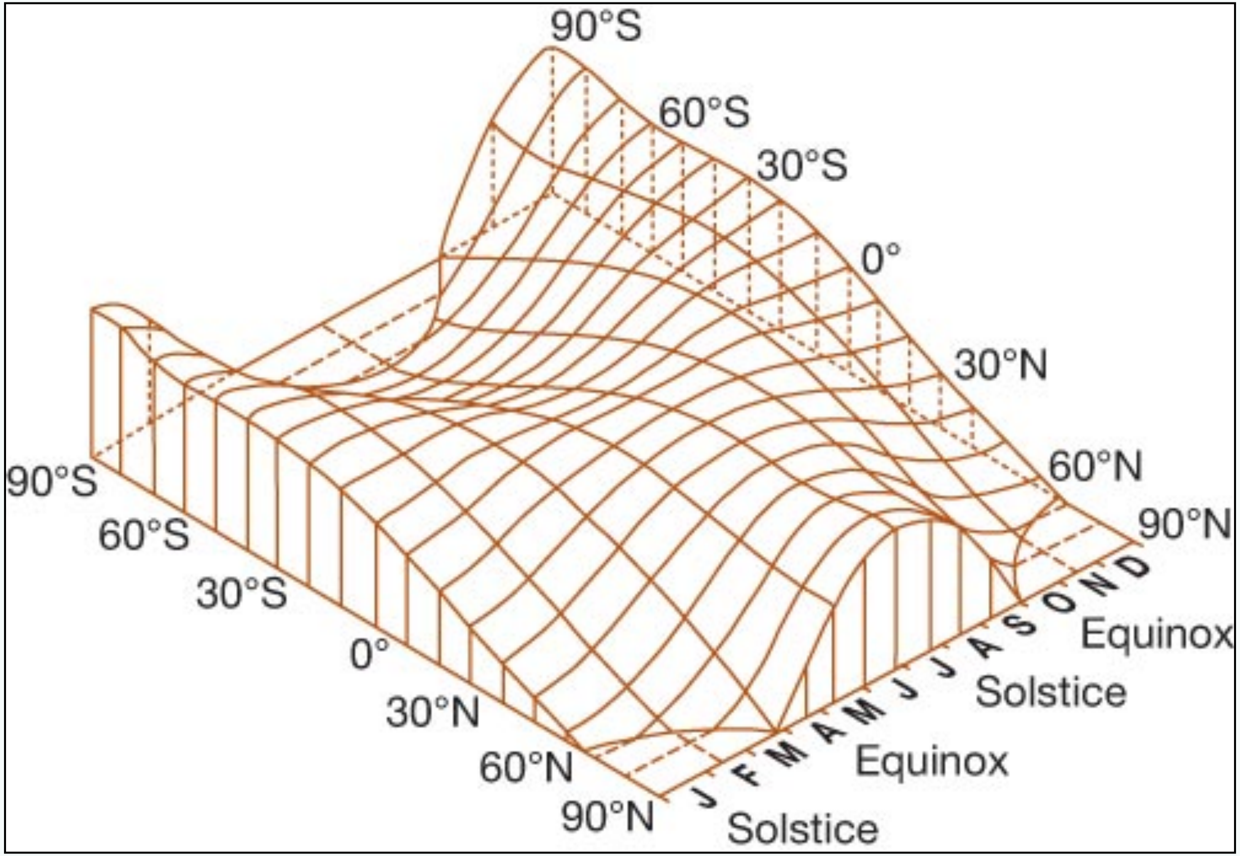
- Seasonal variation
- Interannual variability:
  - North Atlantic Oscillation
  - El Nino-Southern Oscillation
  - Extreme weather
- Longer-timescale variability (not the focus of this module)

Seasons

- Earth is tilted at an angle of 23.5º from its orbital plane
- Different parts of Earth receive the Sun's most direct rays
- When North Pole tilts toward the Sun, it is summer in the Northern Hemisphere.
- When South Pole tilts toward the Sun, it's winter in the Northern Hemisphere.

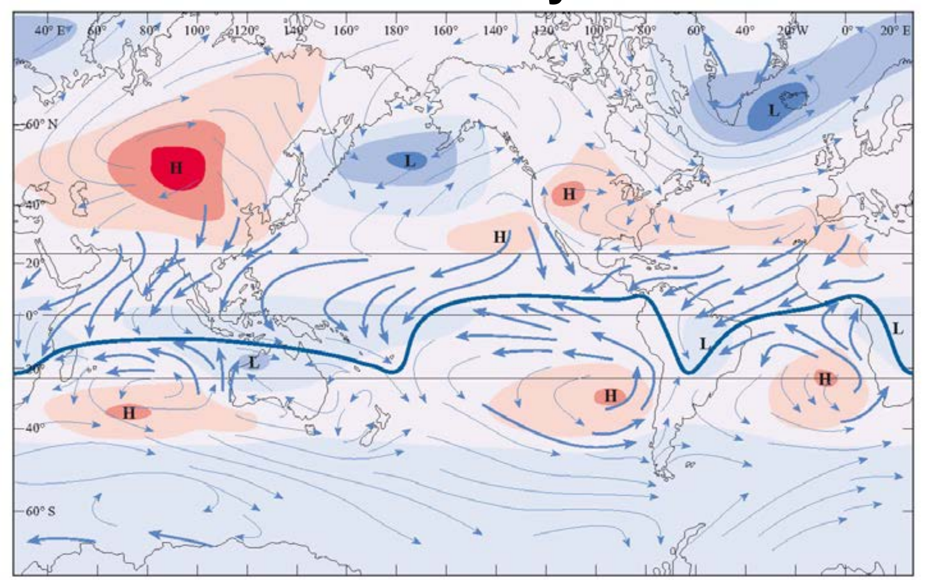


Incoming Solar Radiation Variability in Space and Time

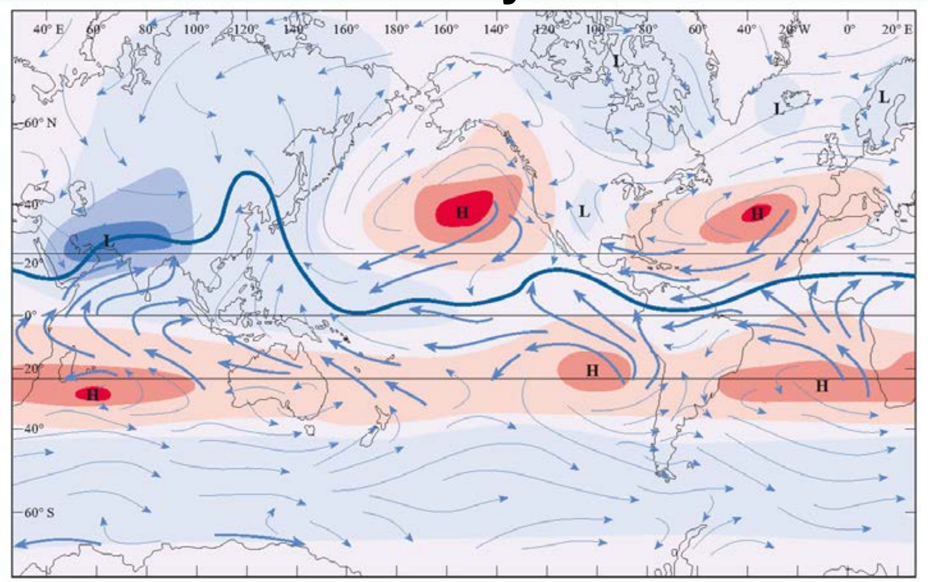


Surface Pressure and Winds

January



July

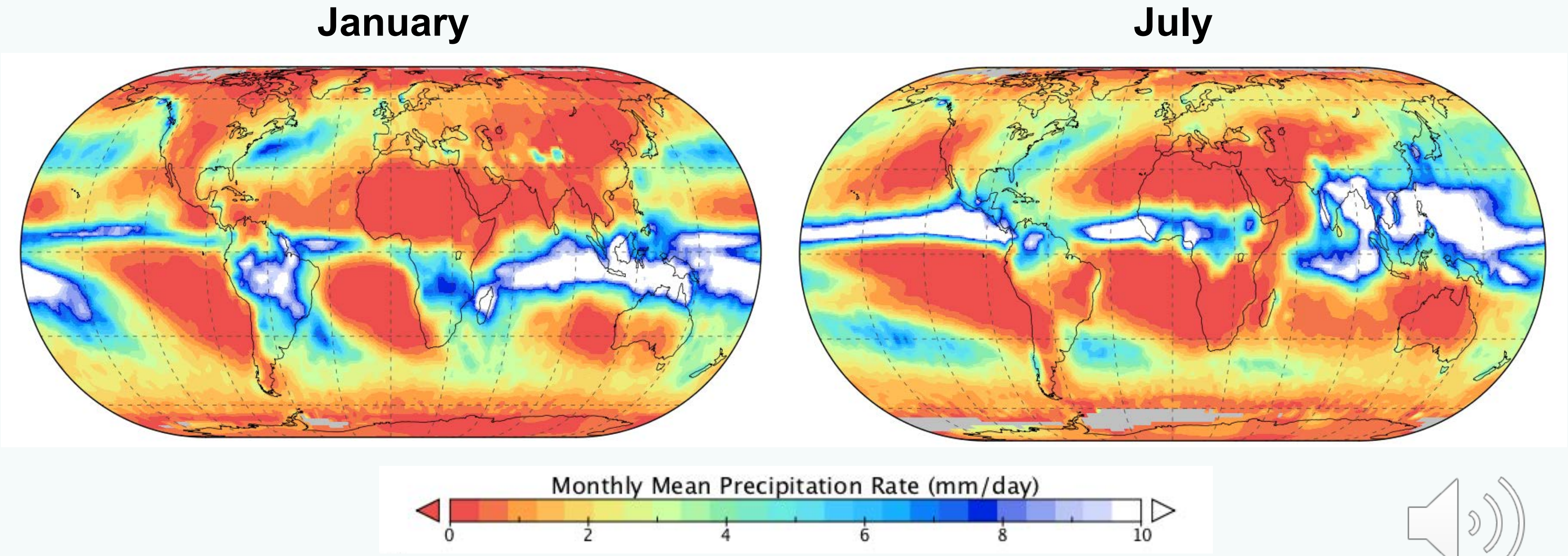


mean position of ITCZ

most frequent wind direction

prevailing wind direction

Seasonality in Precipitation



Summary

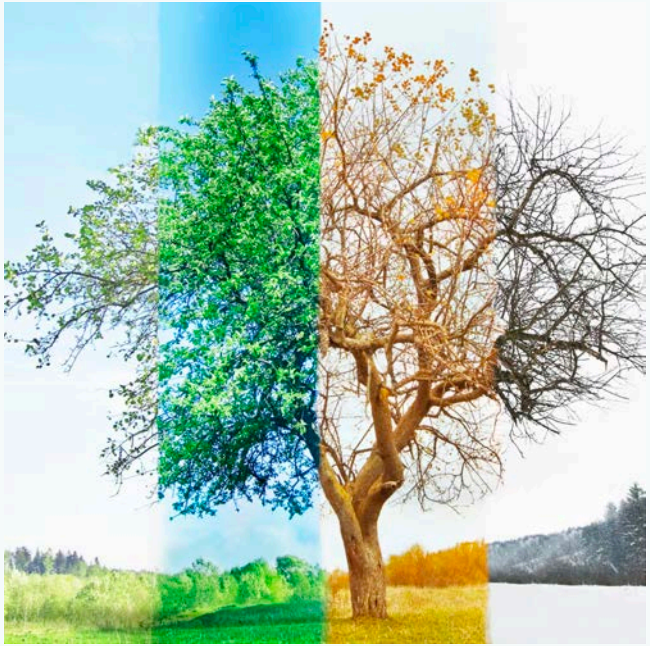
1. Definition of climate
2. Energy transfer: radiation, convection, conduction
3. Simple energy balance model: blackbody radiation, albedo, greenhouse gases
4. Differential heating and redistribution of heat
5. Annual average climate
6. Seasonal average climate

- *Next Lecture: Climate Change*

Task: Seasons

In what month is the Earth farthest from the Sun?

A. January
B. February
C. July
D. August
E. The distance of the Earth from the Sun does not vary.



What causes seasons?

A. Variability in the distance of the Earth from the Sun.
B. The tilt of the axis of the Earth.
C. Sunspots.
D. Distance of a location from the Equator.
E. The greenhouse effect.