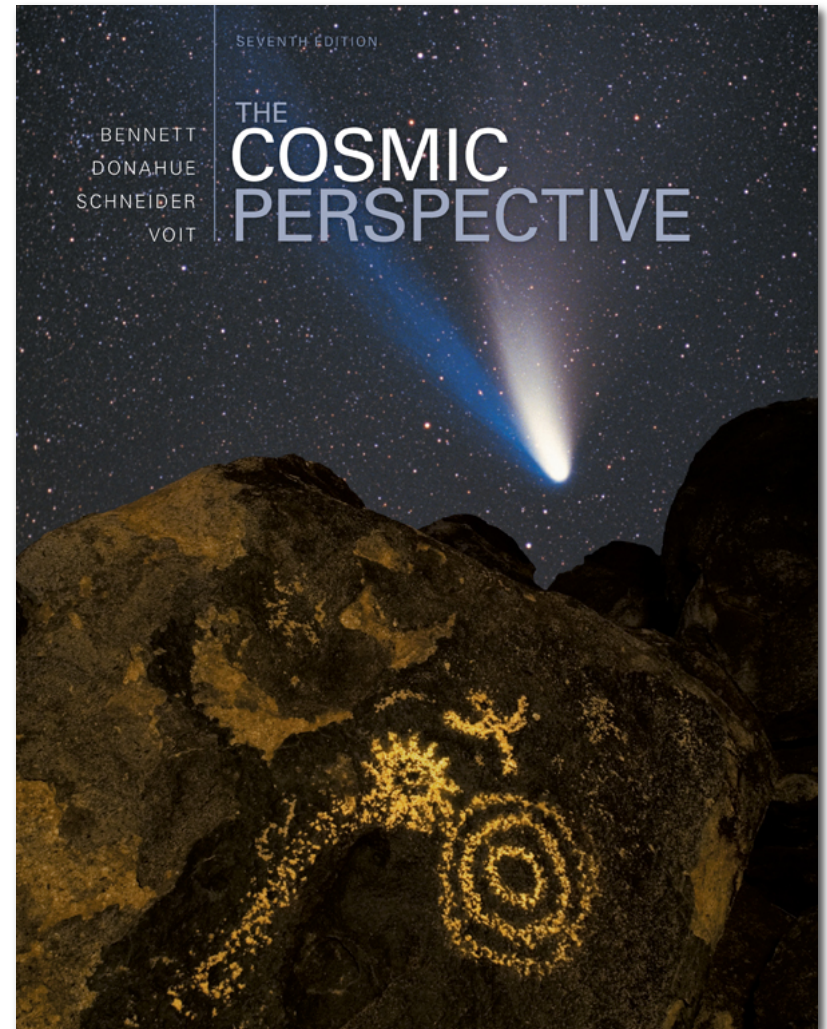


Chapter 10 Lecture

The Cosmic Perspective

Seventh Edition

Planetary Atmospheres: Earth and the Other Terrestrial Worlds



Planetary Atmospheres: Earth and the Other Terrestrial Worlds



10.1 Atmospheric Basics

- Our goals for learning:
 - **What is an atmosphere?**
 - **How does the greenhouse effect warm a planet?**
 - **Why do atmospheric properties vary with altitude?**

What is an atmosphere?



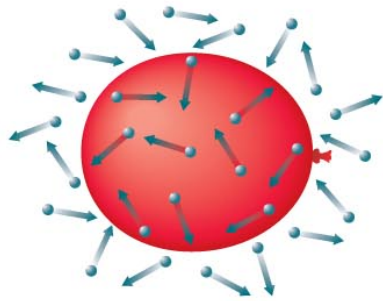
- An atmosphere is a layer of gas that surrounds a world.

Earth's Atmosphere

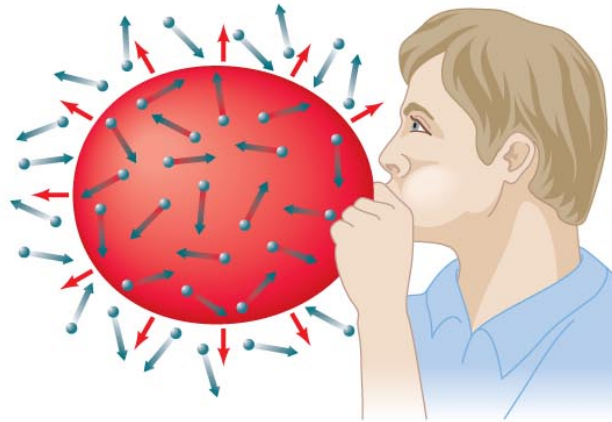


- About 10 kilometers thick
- Consists mostly of molecular nitrogen (N_2) and oxygen (O_2).

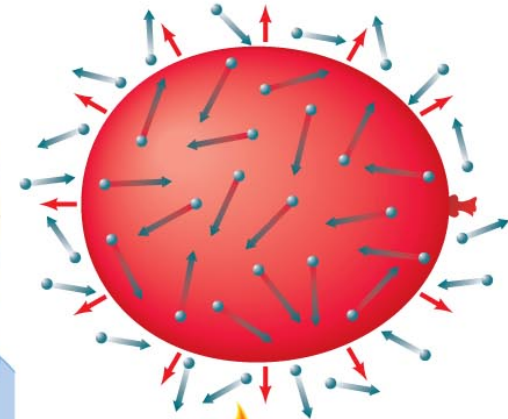
Atmospheric Pressure



a A balloon stays inflated when the inside and outside pressures are balanced.



b Adding air molecules temporarily increases the pressure inside the balloon, so the balloon expands until the pressure balance is restored.



c Heating the balloon increases the speeds of air molecules inside it, thereby increasing the inside pressure. Again, the balloon expands until the pressure balance is restored.

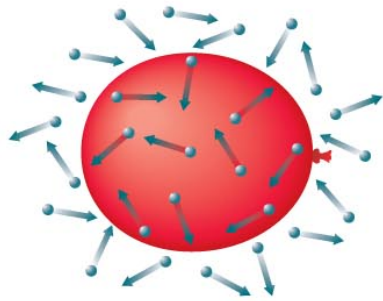
$$P = \frac{F}{A}$$

P = pressure in units of N m^{-2}

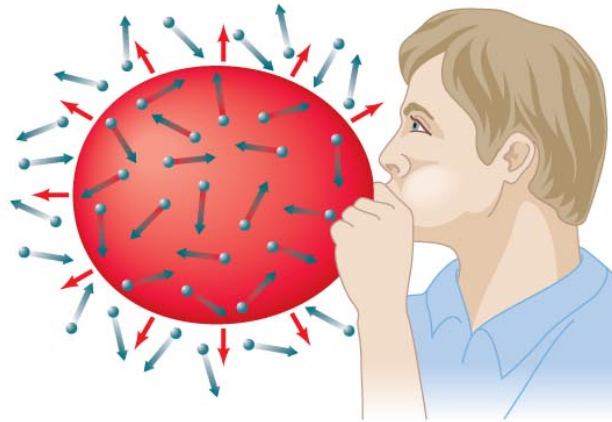
F = Force in units of N

A = area in units of m^2

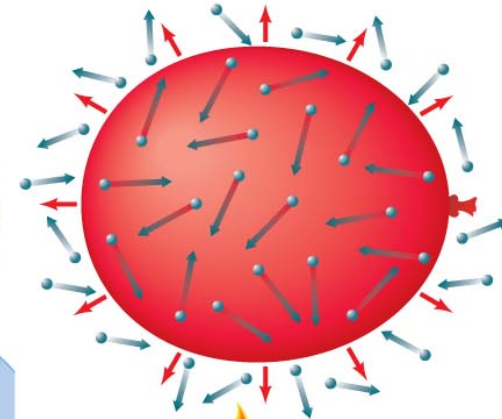
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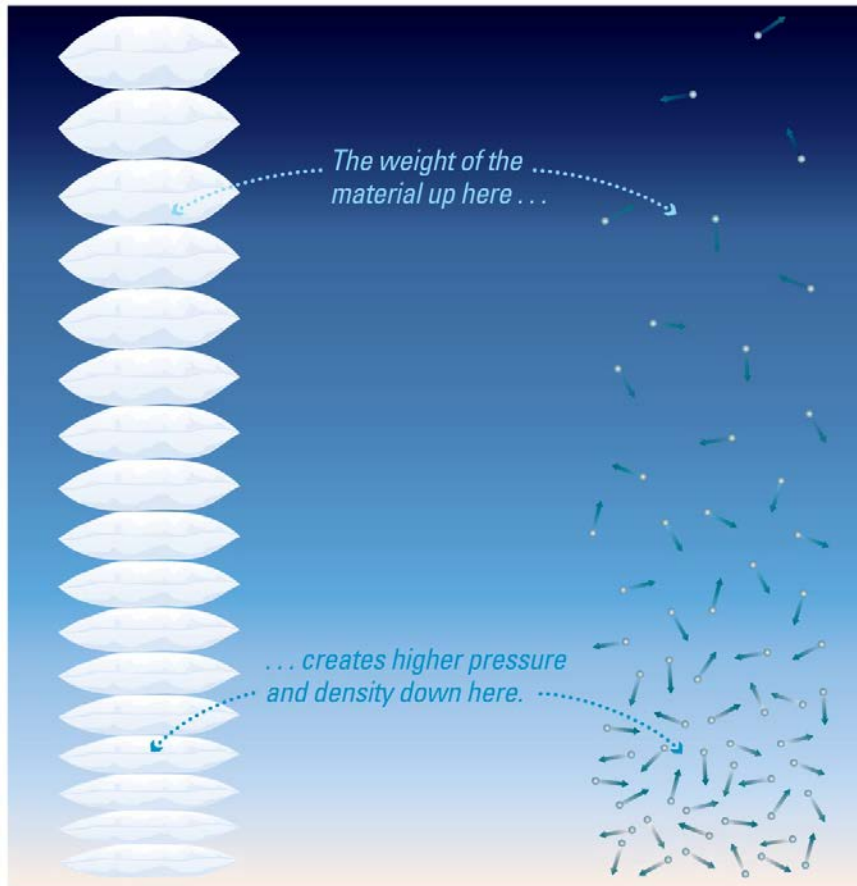


c Heating the balloon increases the speeds of air molecules inside it, thereby increasing the inside pressure. Again, the balloon expands until the pressure balance is restored.

IDEAL GAS LAW

- $P V = N k_B T$
 - k_B is *Boltzmann's Constant*
 - $k_B = R / N_A = 1.38 \times 10^{-23} \text{ J/ K}$
 - N is the total number of molecule

Atmospheric Pressure



- Pressure and density decrease with altitude because the weight of overlying layers is less.

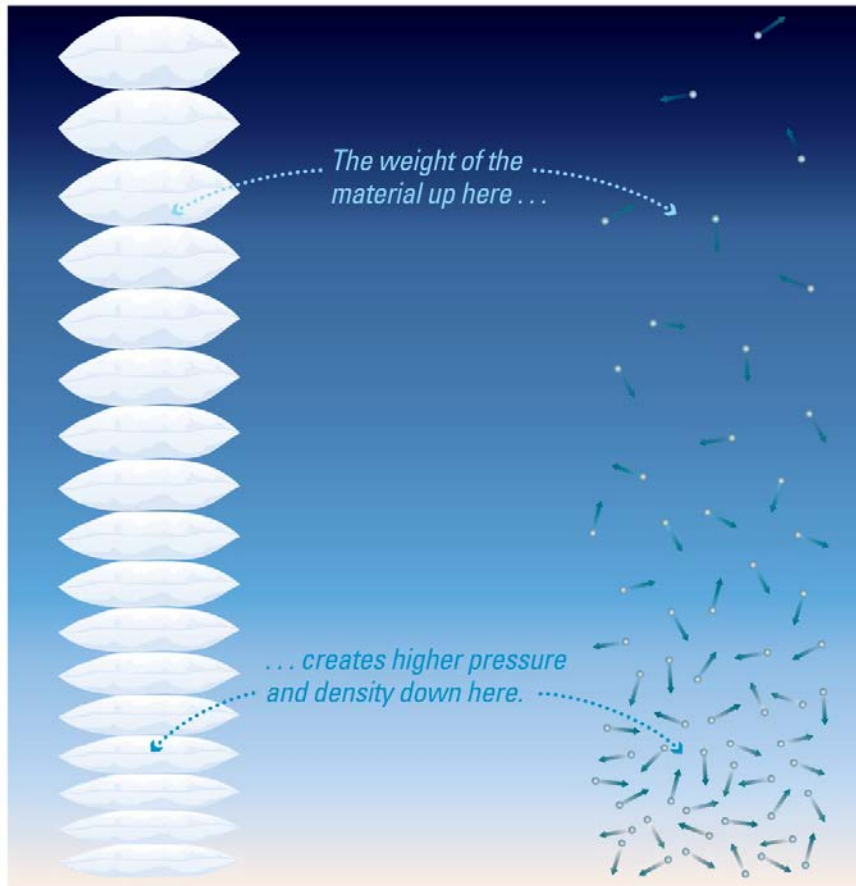
At sea level on Earth, the air weighs down with a pressure of 101,000 Newtons per square meter.

$$1 \text{ atm} = 1.01 \times 10^5 \text{ N m}^{-2}$$

$$1 \text{ bar} = 1.00 \times 10^5 \text{ N m}^{-2} = 0.987 \text{ atm}$$

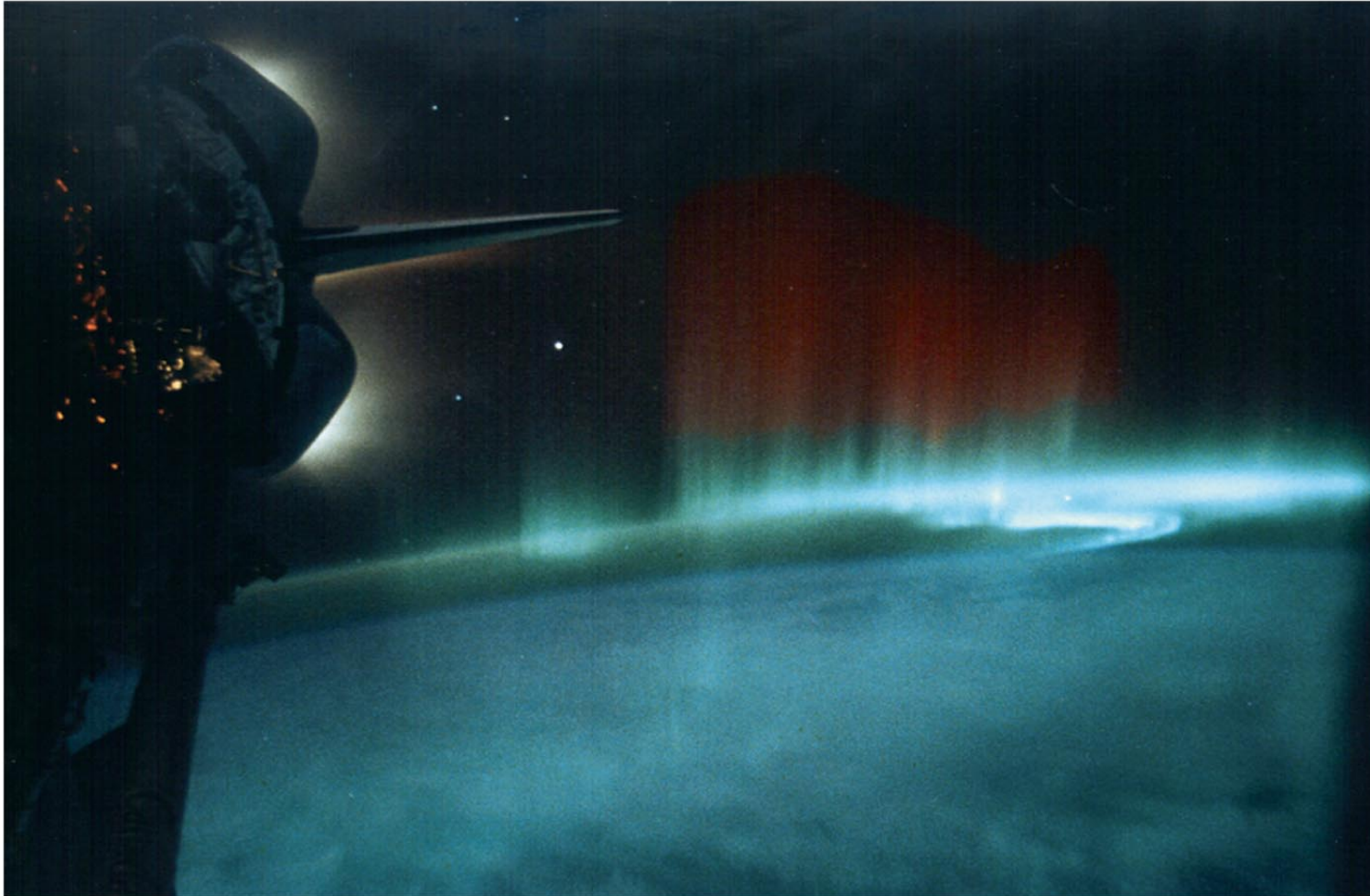
The pressure within Earth's inner core is an astounding 3 million bars.

Where does an atmosphere end?



- There is no clear upper boundary.
- Most of Earth's gas is less than 10 kilometers from surface, but a small fraction extends to more than 100 kilometers.
- Altitudes more than 100 kilometers are considered "space."

Where does an atmosphere end?



- Small amounts of gas are present even above 300 kilometers.

Effects of Atmospheres

- They create pressure that determines whether liquid water can exist on surface.
- They absorb and scatter light.
- They create wind, weather, and climate.
- They interact with the solar wind to create a magnetosphere.
- They can make planetary surfaces warmer through the greenhouse effect.

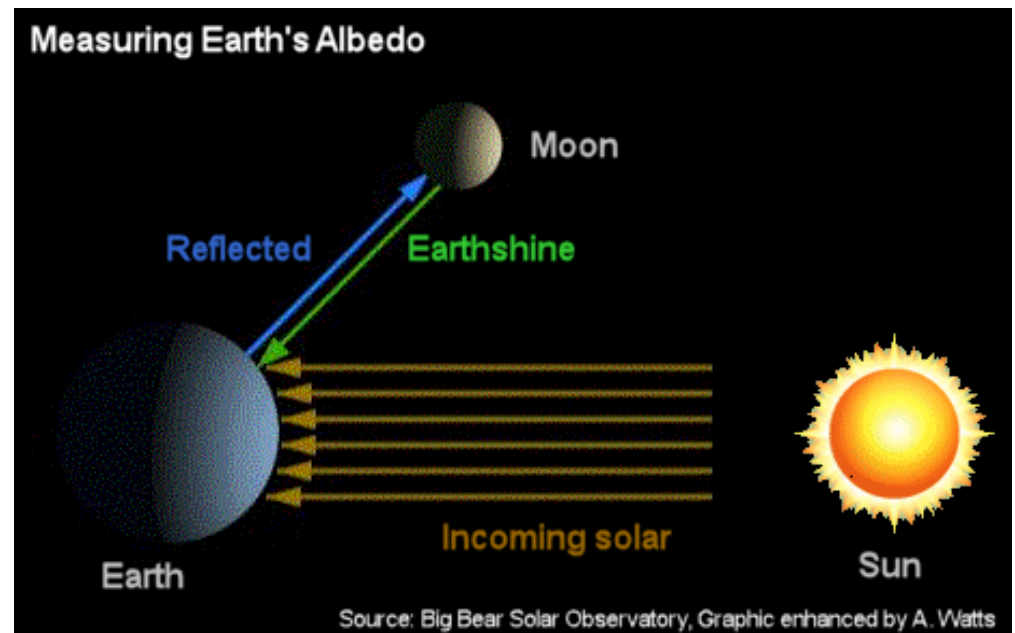
The Earth's Albedo (Reflectivity)

The Earth absorbs radiation from the sun but also reflects a fraction of this radiation.

Albedo (or reflectivity) is the ratio of diffusely reflected to incident electromagnetic radiation.

The Earth's albedo is about 30%.

Planets with low albedo absorb more sunlight, leading to hotter temperatures.



The Earth's climate depends critically on the net energy deposited on Earth which is sensitive to the Earth's albedo.

Greenhouse Effect

Given the energy per second incident on the Earth and the albedo we can calculate the **rate of energy absorbed**.

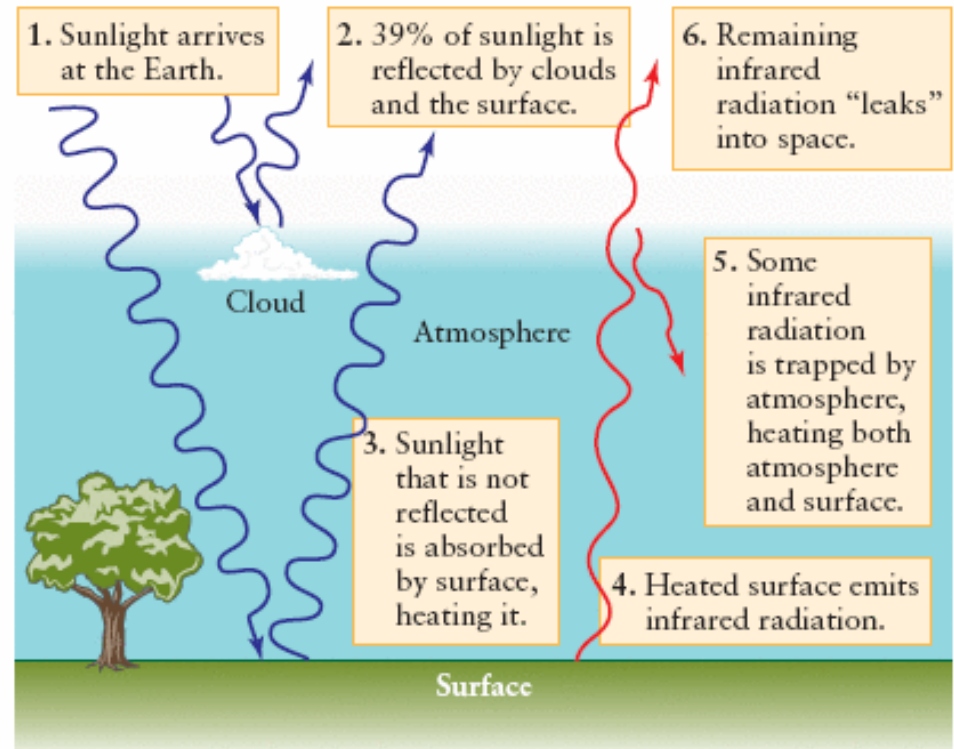
By assuming that the rate absorbed = rate emitted we obtain:

$$T_{\text{surface}} = 254 \text{ K} = -2^{\circ}\text{F}$$

But the average temperature of the Earth's surface is about:

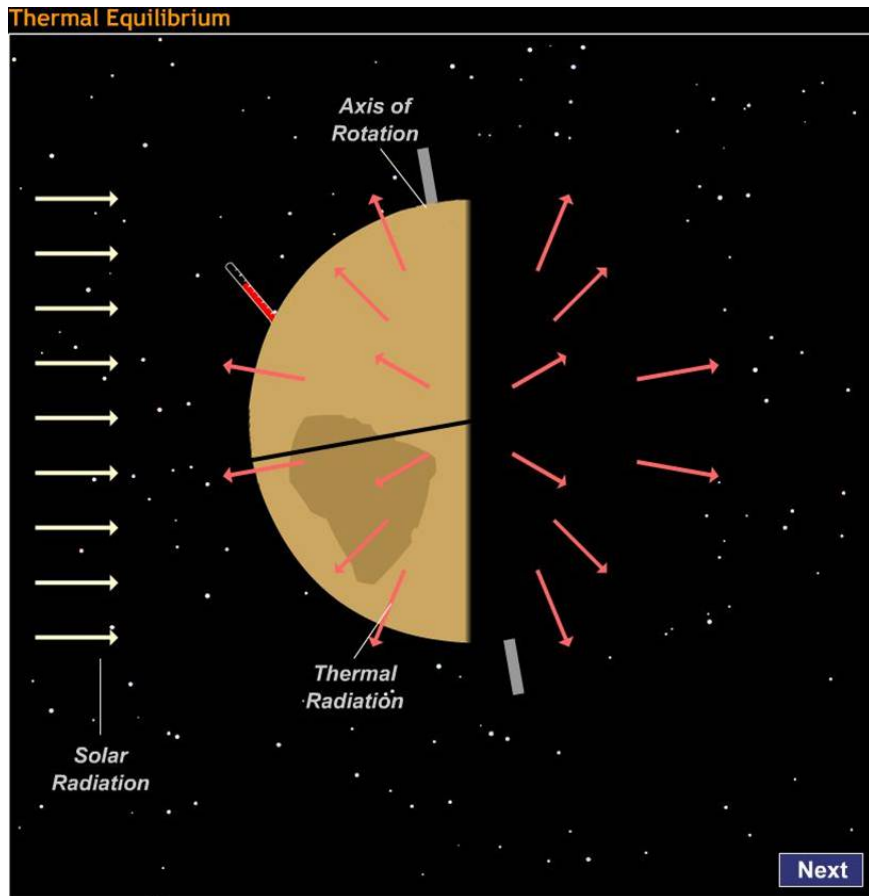
$$T_{\text{surface}} = 287 \text{ K} = 57^{\circ}\text{F}.$$

WHY?



A fraction of the infrared radiation emitted from the Earth's surface is absorbed by atmospheric water vapor and CO_2 , thus raising the Earth's average surface temperature.

Planetary Temperature



Interactive Figure

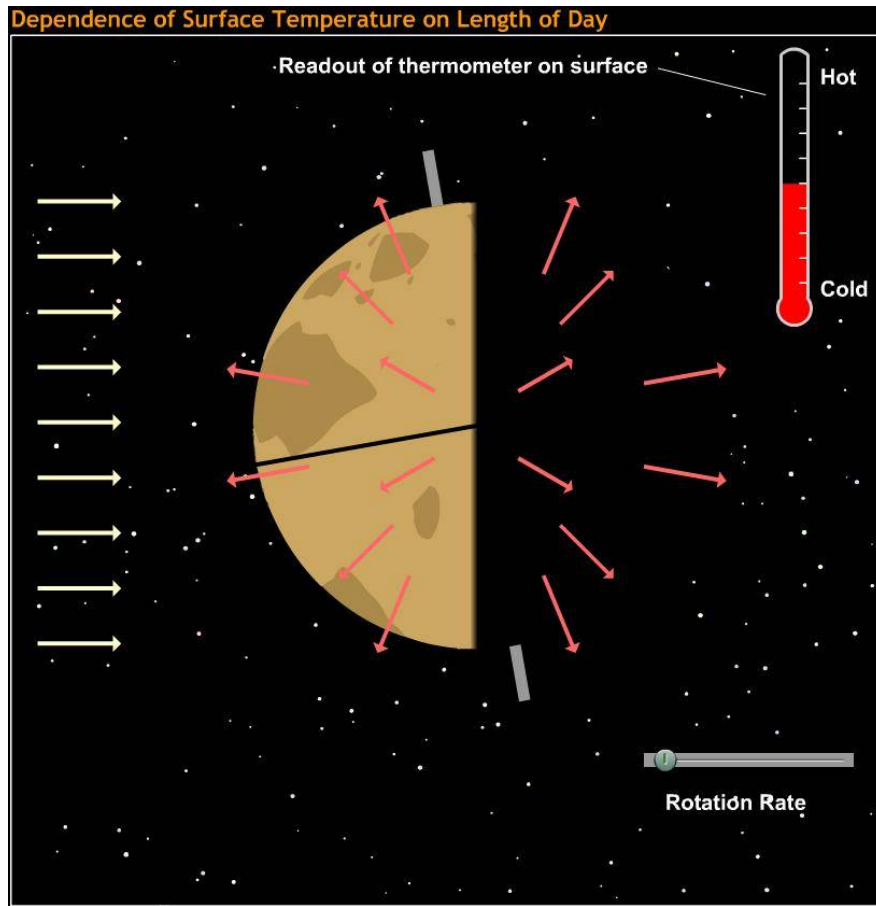
- A planet's surface temperature is determined by the balance between energy from sunlight it absorbs and energy of outgoing thermal radiation.

Temperature and Distance

- A planet's distance from the Sun determines the total amount of incoming sunlight.

$$F = \frac{L_{\text{Solar}}}{4\pi d^2}, \text{ Flux at distance } d \text{ from the sun}$$

Temperature and Rotation



Interactive Figure

- A planet's rotation rate affects the temperature differences between day and night.

"No Greenhouse" Temperatures

TABLE 10.2 The Greenhouse Effect on the Terrestrial Worlds

World	Average Distance from Sun (AU)	Reflectivity	"No Greenhouse" Average Surface Temperature*	Actual Average Surface Temperature	Greenhouse Warming (actual temperature minus "no greenhouse" temperature)
Mercury	0.387	12%	163°C	day: 425°C night: -175°C	—
Venus	0.723	75%	-40°C	470°C	510°C
Earth	1.00	29%	-16°C	15°C	31°C
Moon	1.00	12%	-2°C	day: 125°C night: -175°C	—
Mars	1.524	16%	-56°C	-50°C	6°C

*The "no greenhouse" temperature is calculated by assuming no change to the atmosphere other than lack of greenhouse warming. For example, Venus has a lower "no greenhouse" temperature than Earth even though it is closer to the Sun, because the high reflectivity of its bright clouds means that it absorbs less sunlight than Earth.

- Venus would be 510°C colder without greenhouse effect.
- Earth would be 31°C colder (below freezing on average).

Thought Question

What would happen to Earth's temperature if Earth were more reflective?

- a) It would go up.
- b) It would go down.
- c) It wouldn't change.

Thought Question

What would happen to Earth's temperature if Earth were more reflective?

- a) It would go up.
- b) It would go down.**
- c) It wouldn't change.

Thought Question

If Earth didn't have an atmosphere, what would happen to its temperature?

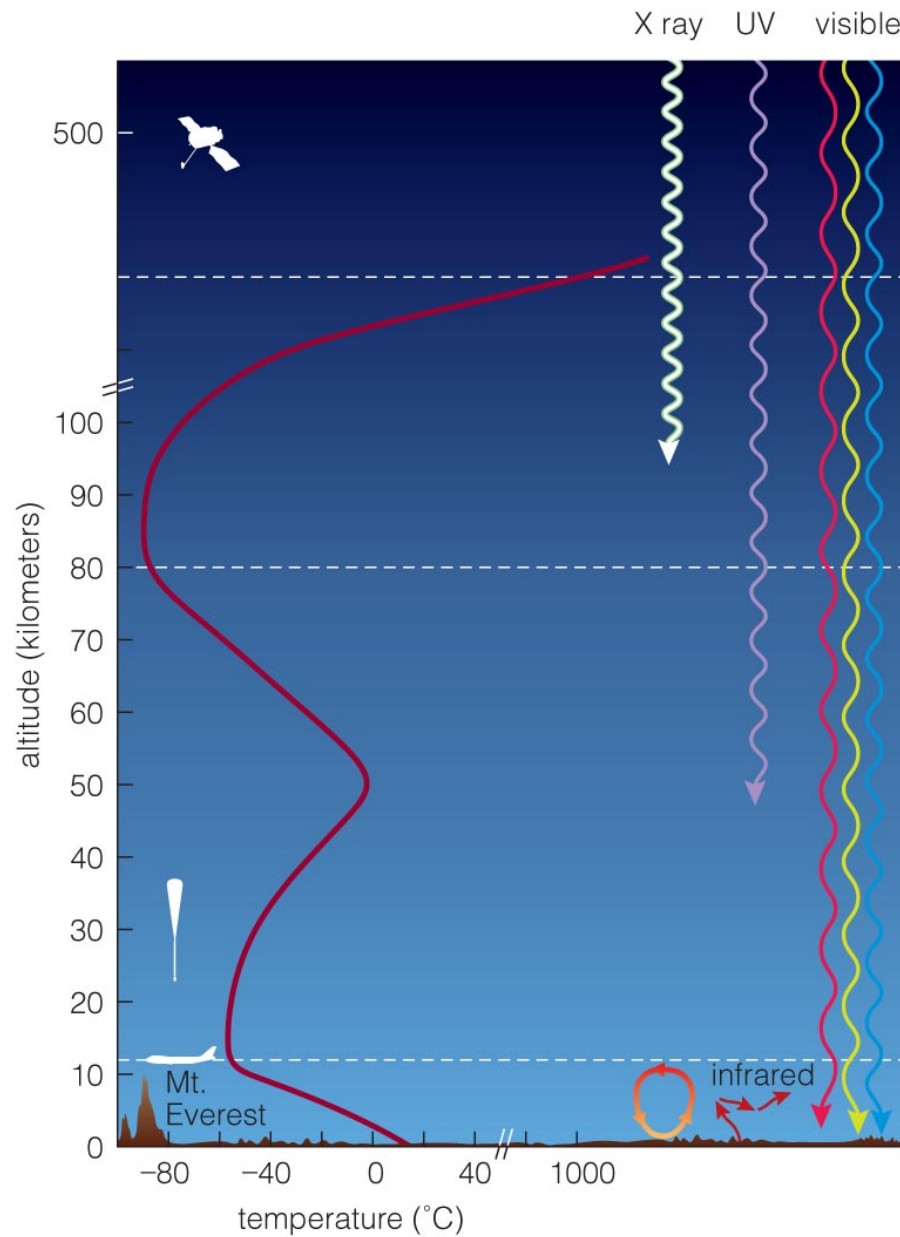
- a) It would go up a little (less than 10°C).
- b) It would go up a lot (more than 10°C).
- c) It would go down a little (less than 10°C).
- d) It would go down a lot (more than 10°C).
- e) It would not change.

Thought Question

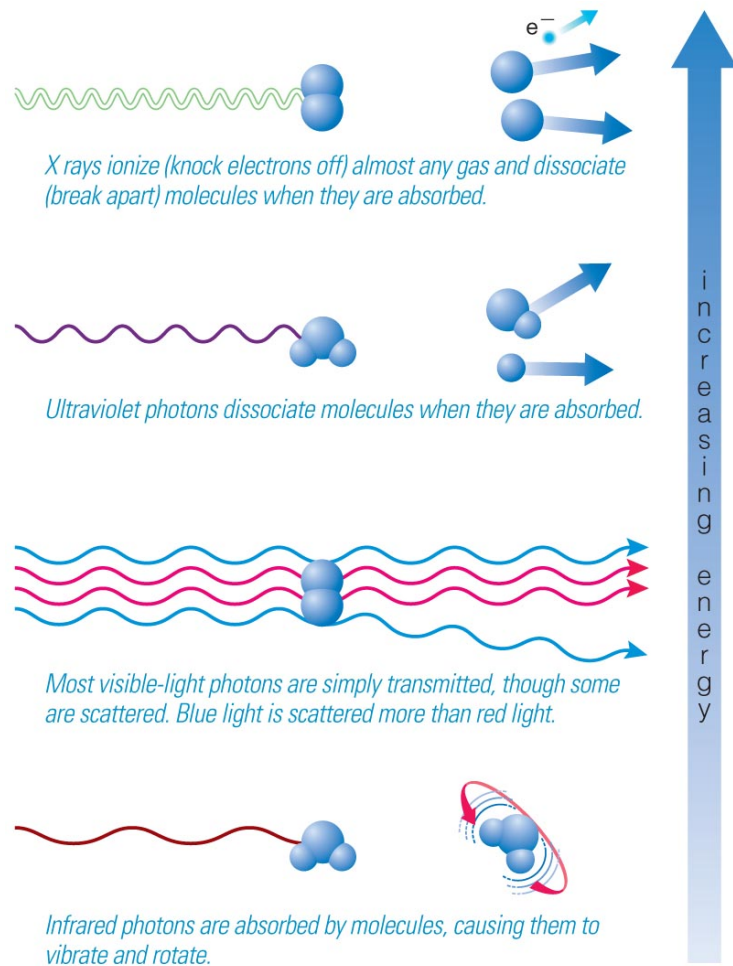
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- e) It would not change.

Why do atmospheric properties vary with altitude?

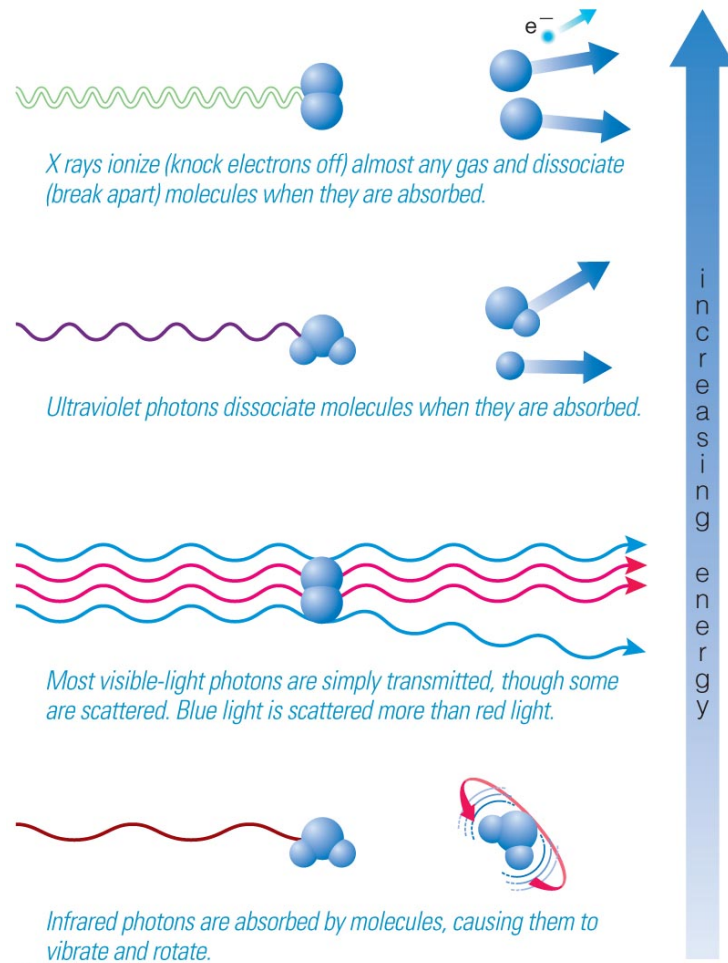


Light's Effects on Atmosphere



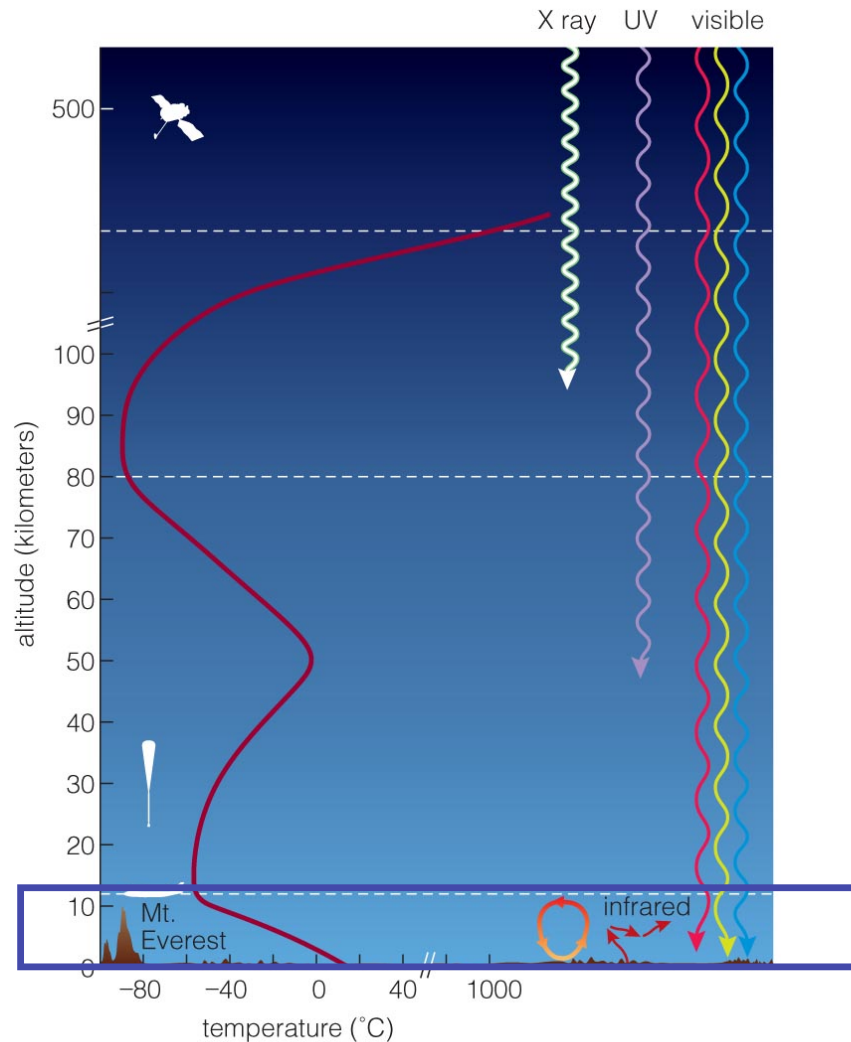
- **Ionization:** removal of an electron
- **Dissociation:** destruction of a molecule
- **Scattering:** change in photon's direction
- **Absorption:** photon's energy is absorbed.

Light's Effects on Atmosphere



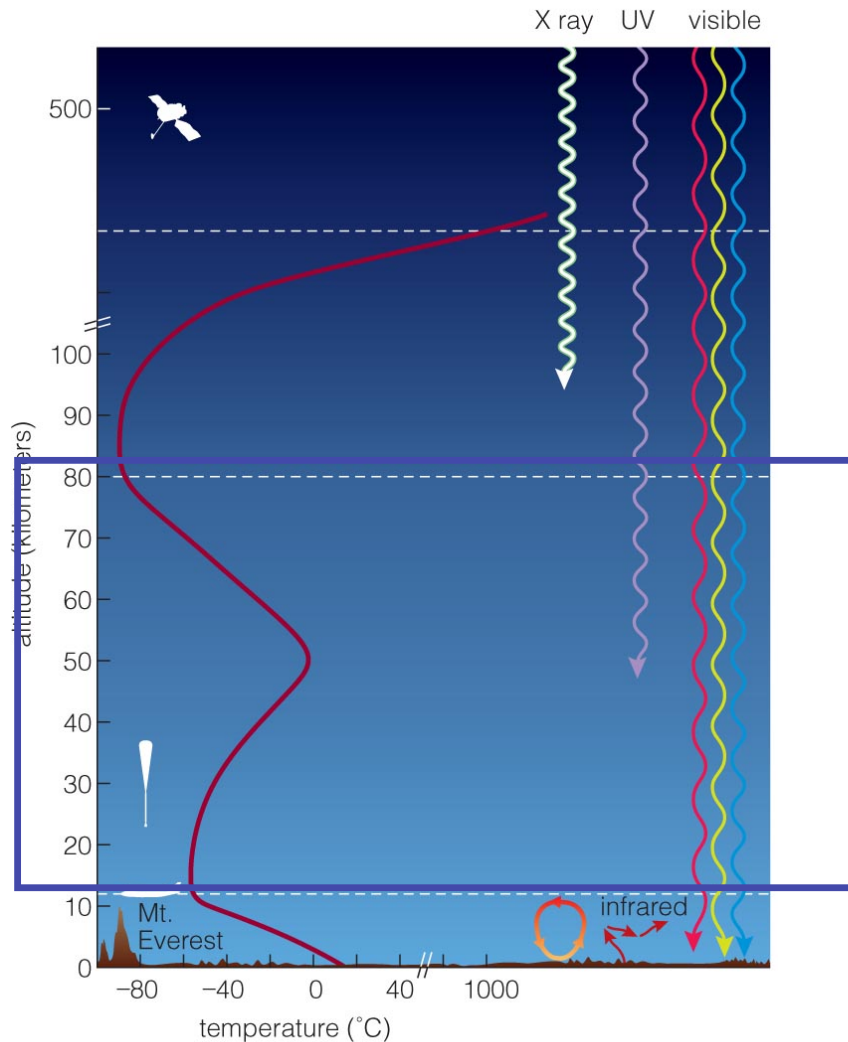
- X rays and UV light can ionize and dissociate molecules.
- Molecules tend to scatter blue light more than red.
- Molecules can absorb infrared light.

Earth's Atmospheric Structure



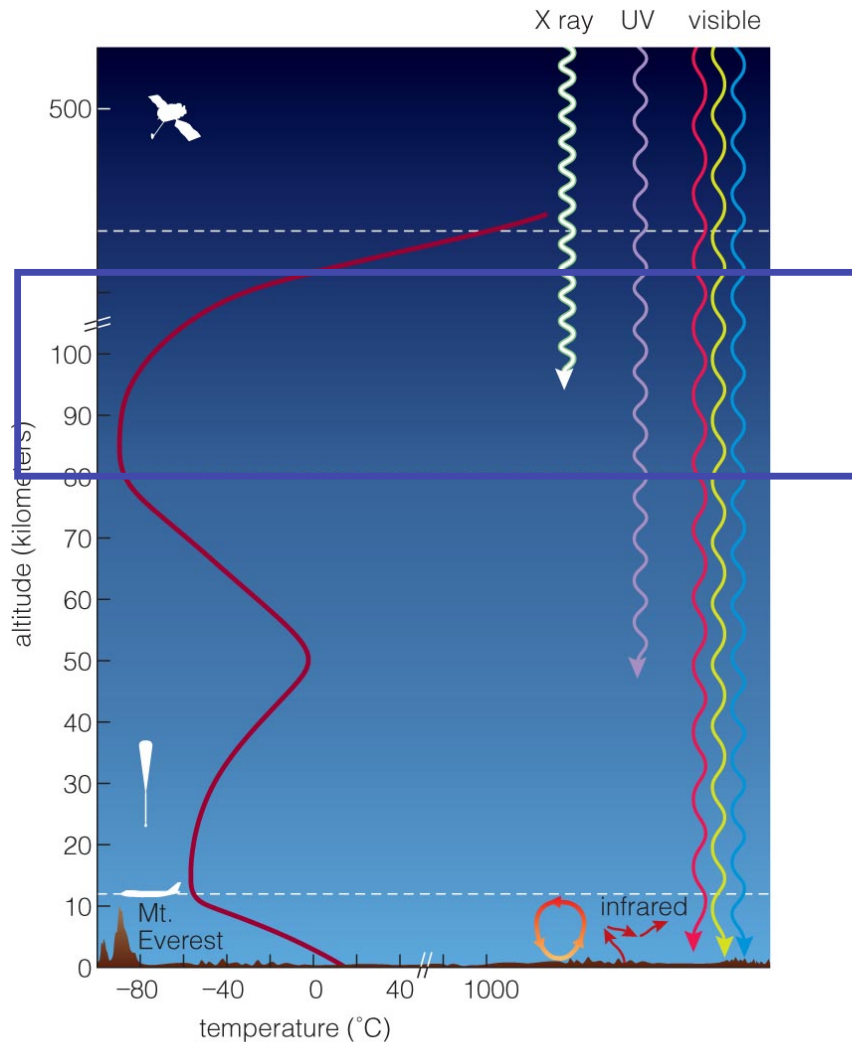
- **Troposphere:** lowest layer of Earth's atmosphere
- Weather occurs in the Troposphere
- Temperature drops with altitude.
- Warmed by infrared light from surface and convection (The lower layers are heated from the surface of the Earth. Heated air rises (less dense) and cools at higher levels in the Troposphere)

Earth's Atmospheric Structure



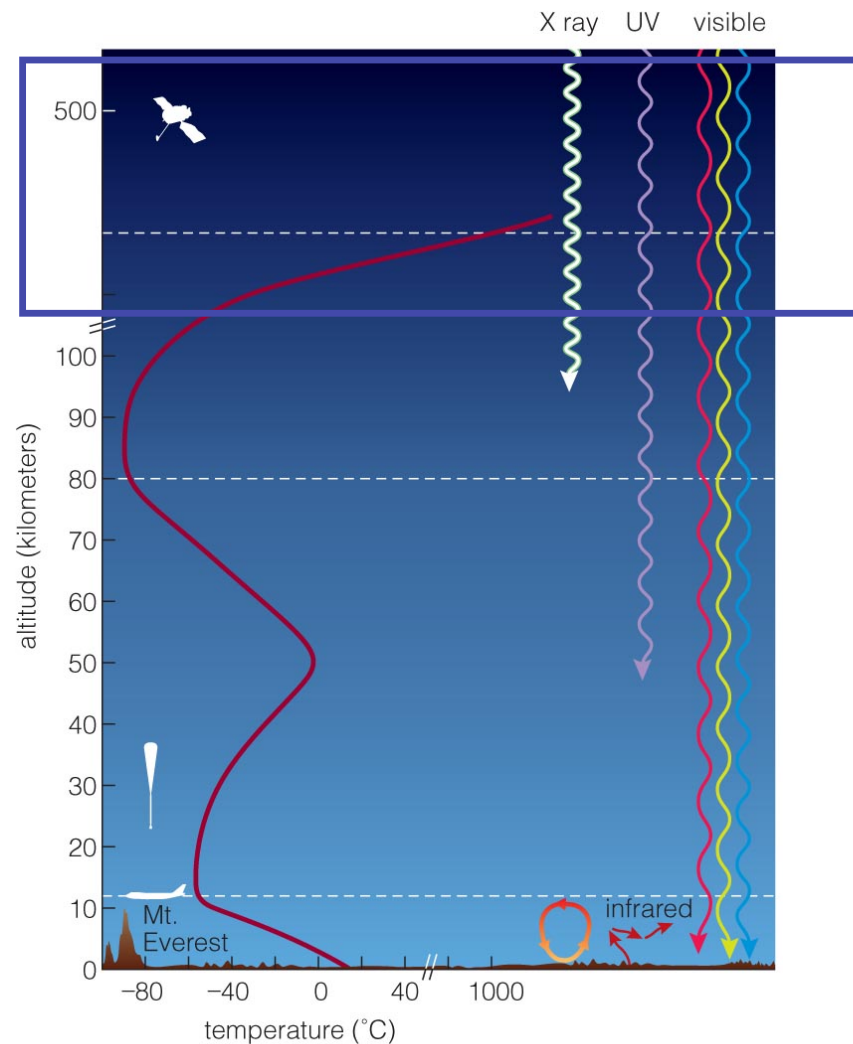
- **Stratosphere:** layer above the troposphere
- The stratosphere contains the ozone layer that protects life from harmful ultraviolet radiation from the sun.
- Ozone (O_3) absorbs UV which results in the temperature of the stratosphere increasing as you go up to about 50 km.
- Airlines fly in the lower levels of the stratosphere.

Earth's Atmospheric Structure



- **Thermosphere:** layer at about 100 kilometers altitude
- The thermosphere contains single atoms of oxygen and nitrogen that can absorb UV light. This results in heating of this layer.
- Note the temperature of the thermosphere can get up to 1000 °C at 300 km.
- Are the ISS and satellites in danger of burning up?
- Charged particles excite atoms in the thermosphere and create the aurora.

Earth's Atmospheric Structure



- **Exosphere:** highest layer in which atmosphere gradually fades into space
- Temperature rises with altitude; atoms can escape into space.
- Warmed by X rays and UV light

Thought Question

Why is the sky blue?

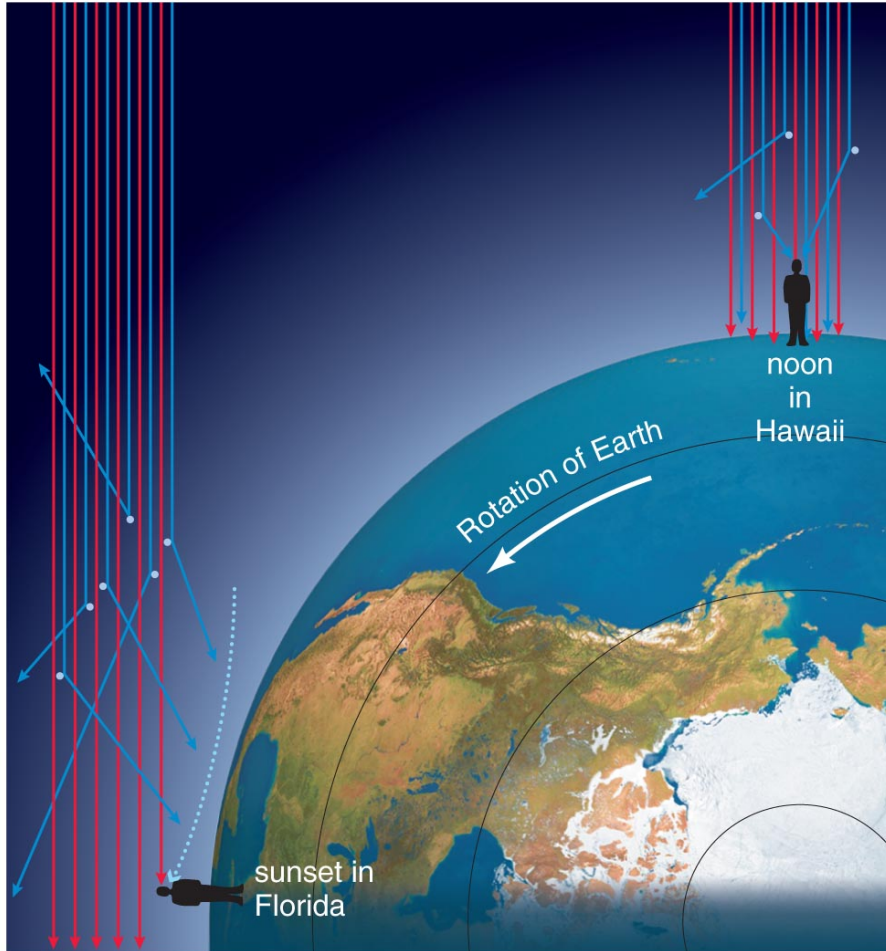
- a) The sky reflects light from the oceans.
- b) Oxygen atoms are blue.
- c) Nitrogen atoms are blue.
- d) Air molecules scatter blue light more than red light.
- e) Air molecules absorb red light.

Thought Question

Why is the sky blue?

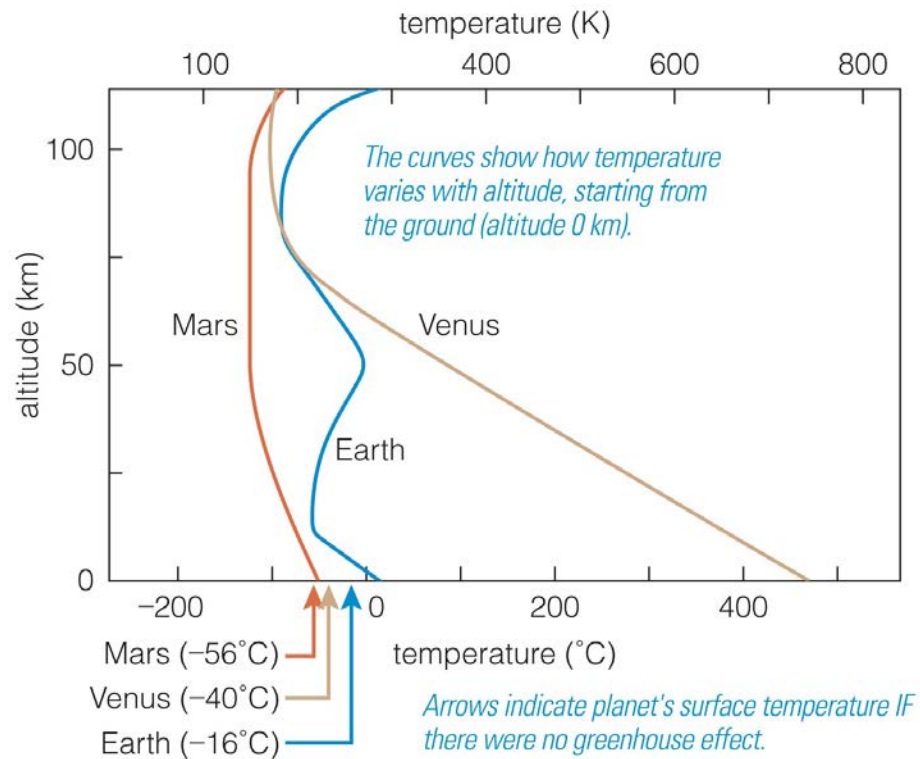
- a) The sky reflects light from the oceans.
- b) Oxygen atoms are blue.
- c) Nitrogen atoms are blue.
- d) Air molecules scatter blue light more than red light.**
- e) Air molecules absorb red light.

Why the Sky Is Blue



- Atmosphere scatters blue light from Sun, making it appear to come from different directions.
- Sunsets are red because red light scatters less.

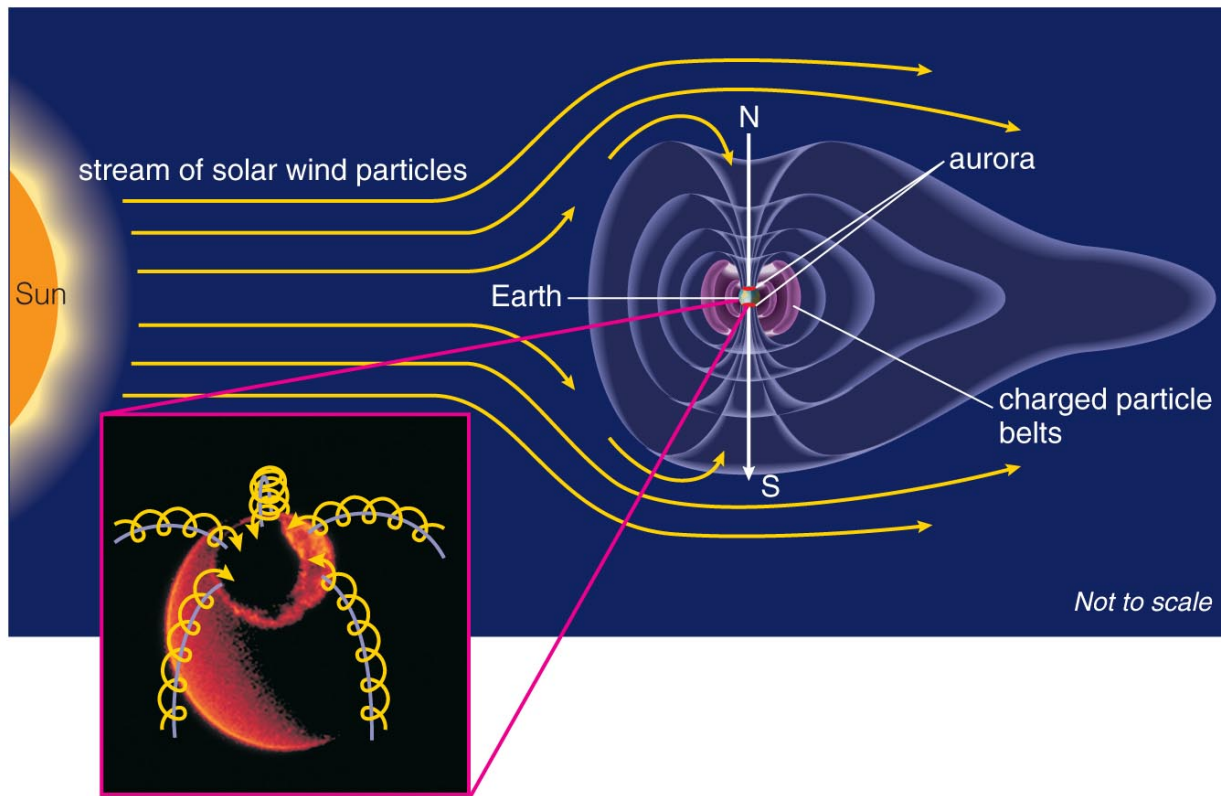
Atmospheres of Other Planets



- Earth is only planet with a stratosphere because of UV-absorbing ozone molecules (O_3).
- Those same molecules protect us from Sun's UV light.

"No greenhouse" temperatures

Earth's Magnetosphere



a This diagram shows how Earth's magnetosphere deflects solar wind particles. Some particles accumulate in charged particle belts encircling our planet. The inset is a photo of a ring of auroras around the North Pole; the bright crescent at its left is part of the day side of Earth.

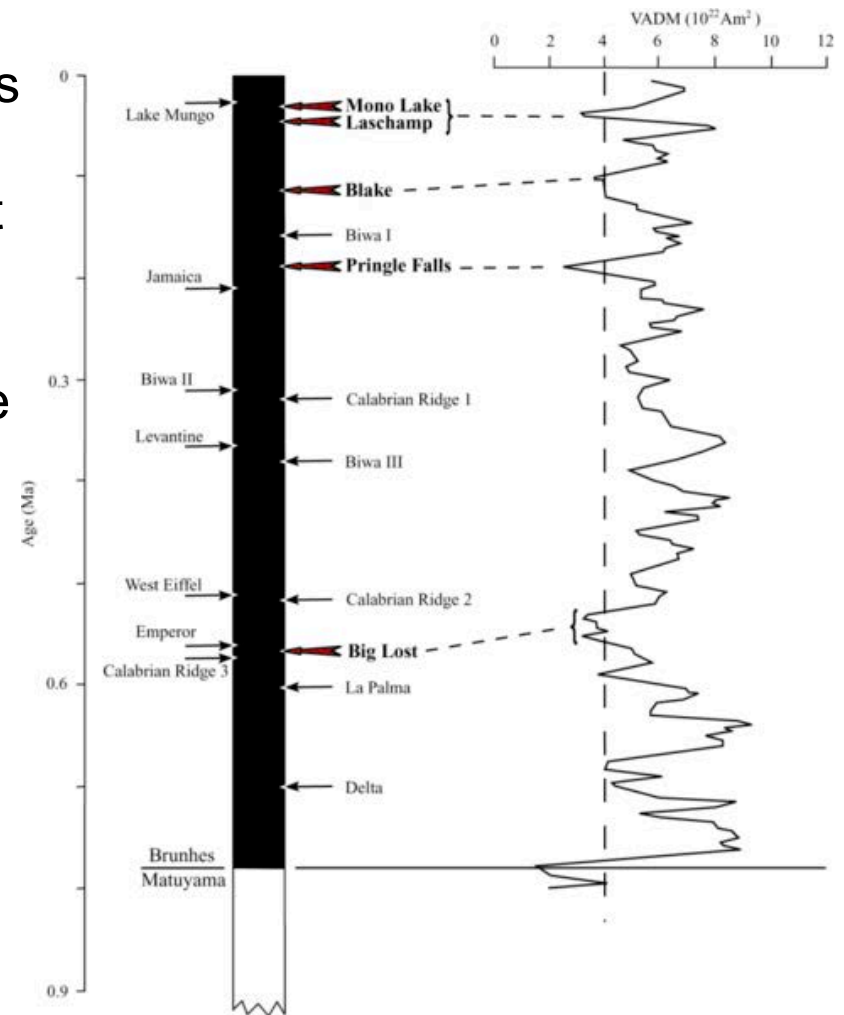
- Magnetic field of Earth's atmosphere protects us from charged particles streaming from Sun (the solar wind).

Earth's Magnetic Field

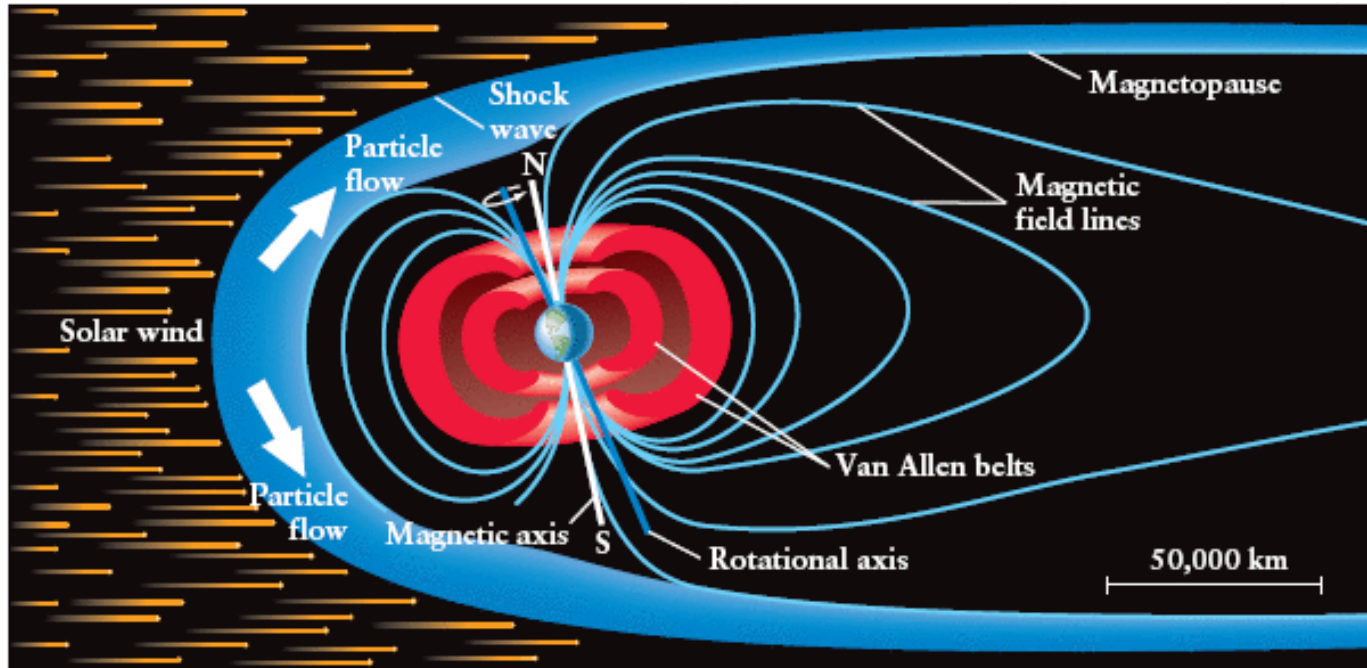
When lava containing a high content of iron cools on the Earth's surface it forms rocks that are magnetized in the direction of the Earth's magnetic field at the time.

By measuring the ages of rocks and the direction of their magnetic field we can infer the direction of the Earth's magnetic field in the past.

The Earth's magnetic field is found to reverse at intervals, ranging from tens of thousands to many millions of years.



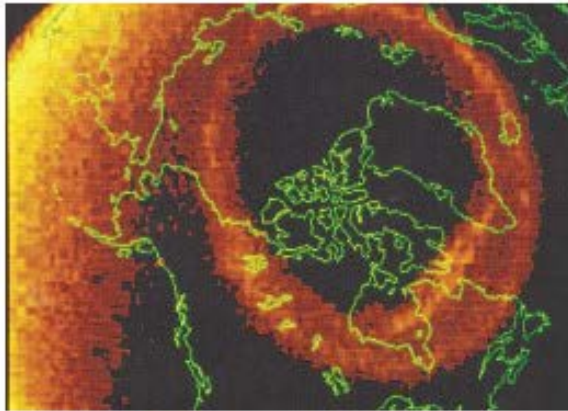
Earth's Magnetic Field



The solar wind is a flow of energetic protons and electrons from the sun. Near the Earth these particles have velocities of about 450 km/s (supersonic).

The magnetic force from the Earth's magnetic field slows these particles down to subsonic speeds (less than the sound speed) and deflects them to flow around the Earth.

Aurora



(a) RIV **U** X G



(b) RI **V** UX G



(c) RI **V** UX G

During solar storms the Van Allen belts become overloaded with charged particles and a few of them leak into the upper atmosphere.

These energetic particles excite atoms in the upper atmosphere. When the electrons in the excited atoms cascade to lower energy levels light is emitted forming the Aurora Borealis in the North and the Aurora Australis in the South.

What have we learned?

- **What is an atmosphere?**
 - A layer of gas that surrounds a world
- **How does the greenhouse effect warm a planet?**
 - Atmospheric molecules allow visible sunlight to warm a planet's surface but absorb infrared photons, trapping the heat.
- **Why do atmospheric properties vary with altitude?**
 - They depend on how atmospheric gases interact with sunlight at different altitudes.

10.2 Weather and Climate

- Our goals for learning:
 - **What creates wind and weather?**
 - **What factors can cause long-term climate change?**
 - **How does a planet gain or lose atmospheric gases?**

What creates wind and weather?



Weather and Climate

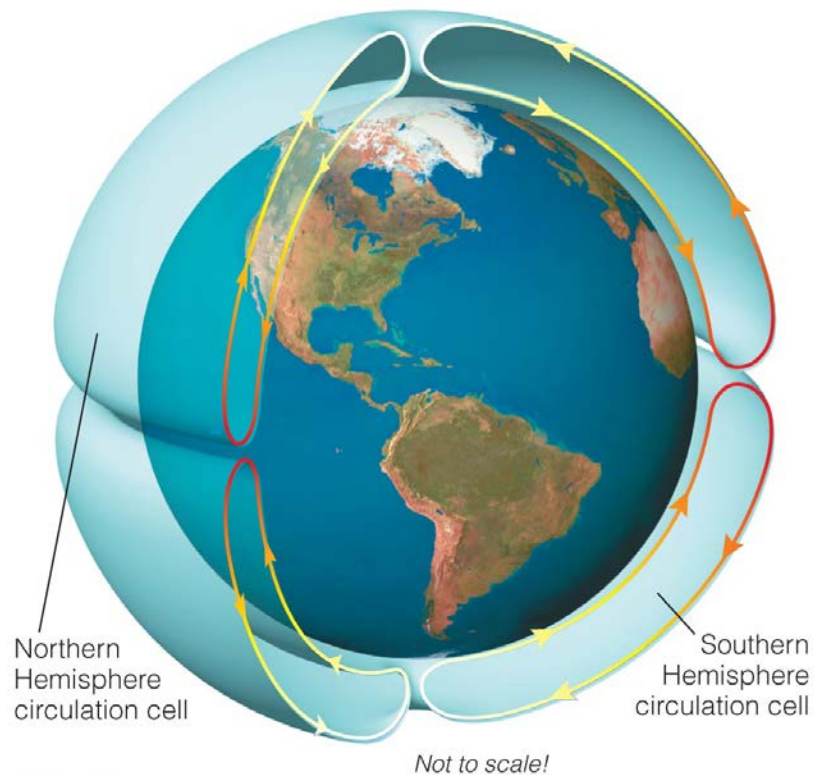
- **Weather** is the state of the atmosphere which is the ever-varying combination of wind, precipitation, temperature, and pressure.
 - Local complexity of weather makes it difficult to predict.
- **Climate** is the long-term average of weather.
 - Long-term stability of climate depends on global conditions and is more predictable.

Global Wind Patterns



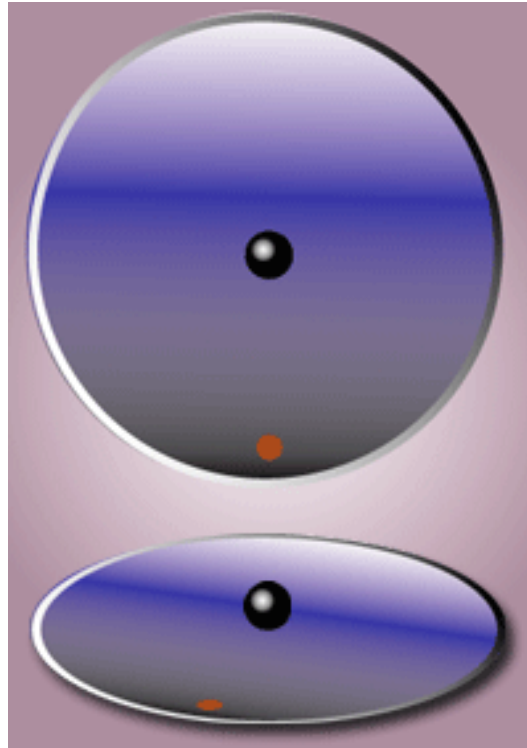
- Global winds blow in distinctive patterns:
 - Equatorial: E to W
 - Mid-latitudes: W to E
 - High latitudes: E to W

Circulation Cells: No Rotation



- Heated air rises at equator.
- Cooler air descends at poles.
- Without rotation, these motions would produce two large circulation cells.

Coriolis Effect



- the **Coriolis effect** is a deflection of moving objects when they are viewed in a rotating reference frame
- <http://video.mit.edu/watch/the-coriolis-effect-4407/>

Coriolis Effect on Earth



a Low-pressure regions ("L") draw in air from surrounding areas, and the Coriolis effect causes this air to circulate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

Interactive Figure 

- Air moving from a pole to the equator is going farther from Earth's axis and begins to lag behind Earth's rotation.
- Air moving from the equator to a pole moves closer to the axis and travels ahead of Earth's rotation.

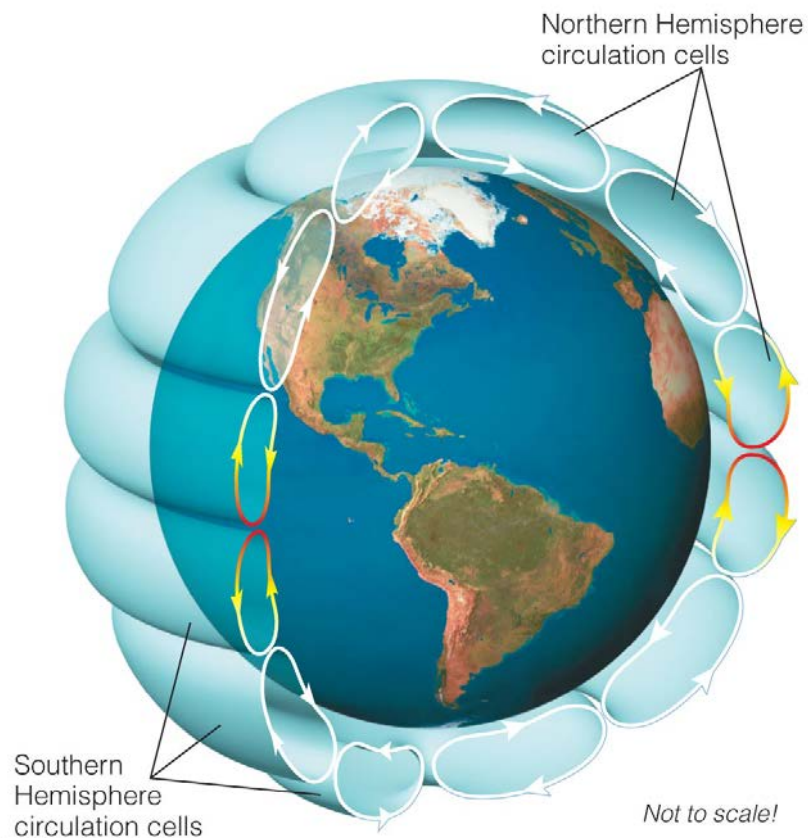
Coriolis Effect on Earth



b This photograph shows the opposite directions of storm circulation in the two hemispheres.

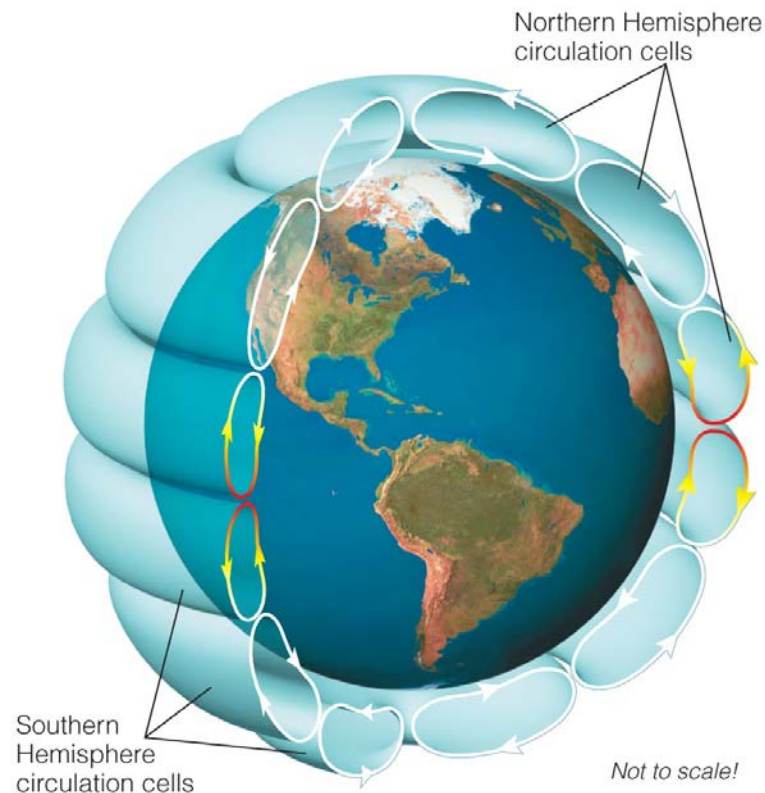
- As air moves towards a low pressure point from different directions it curves due to the Coriolis effect resulting in swirls.
- **Direction of circulation** depends on hemisphere:
 - N: counterclockwise
 - S: clockwise

Circulation Cells with Rotation



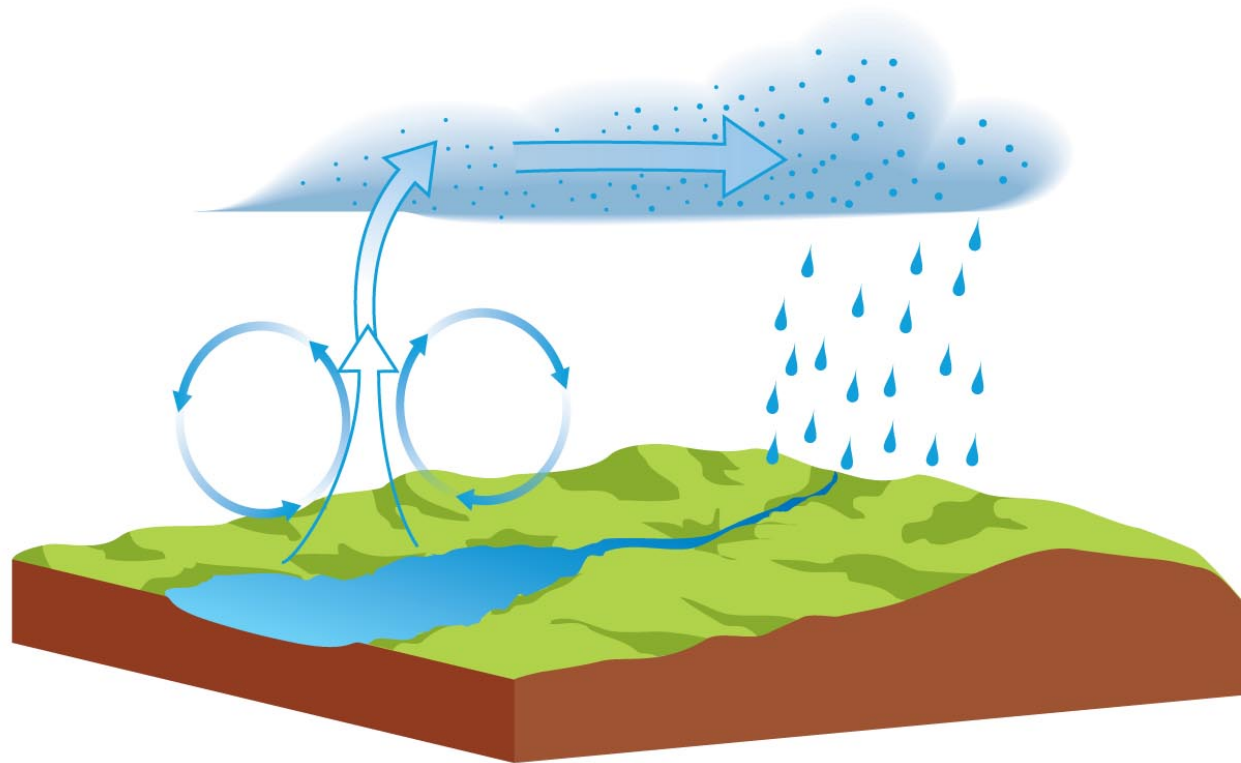
- Coriolis effect deflects north-south winds into east-west winds.
- Deflection breaks each of the two large "no-rotation" cells into three smaller cells.

Prevailing Winds



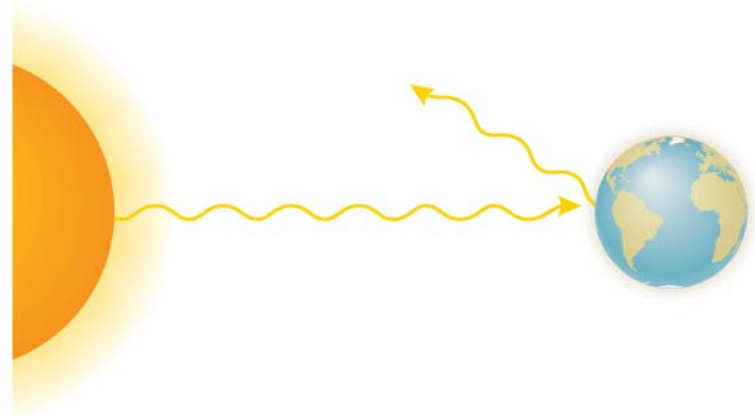
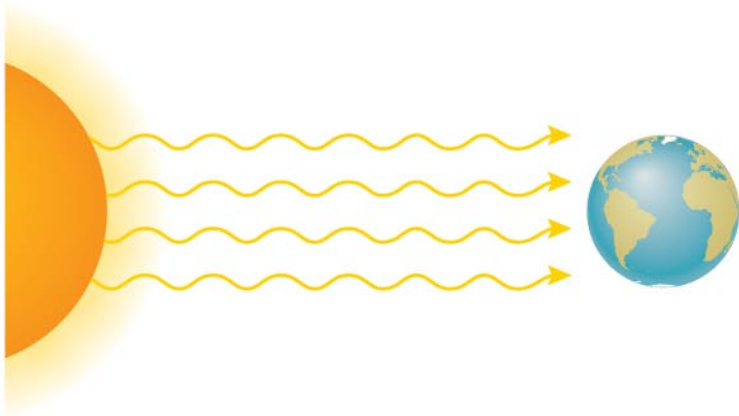
- Prevailing surface winds at mid-latitudes blow from W to E because the Coriolis effect deflects the S to N surface flow of mid-latitude circulation cells.

Clouds and Precipitation

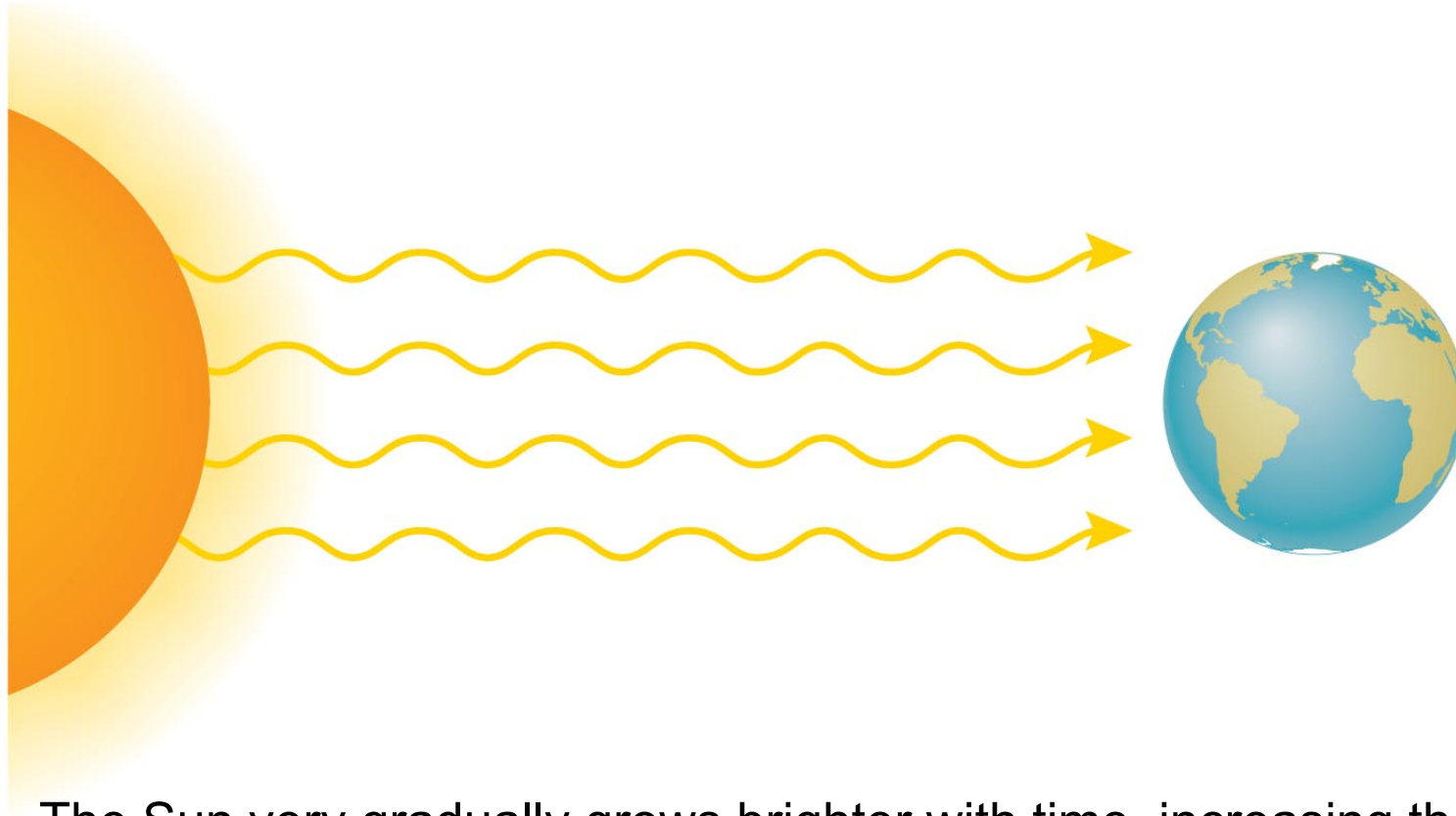


Water from lakes and oceans escapes into the atmosphere through evaporation and is taken by convection currents to higher altitudes near the top of the troposphere. There the water vapor begins to condense and when it becomes too heavy for the upward currents to support it falls back to the surface.

What factors can cause long-term climate change?

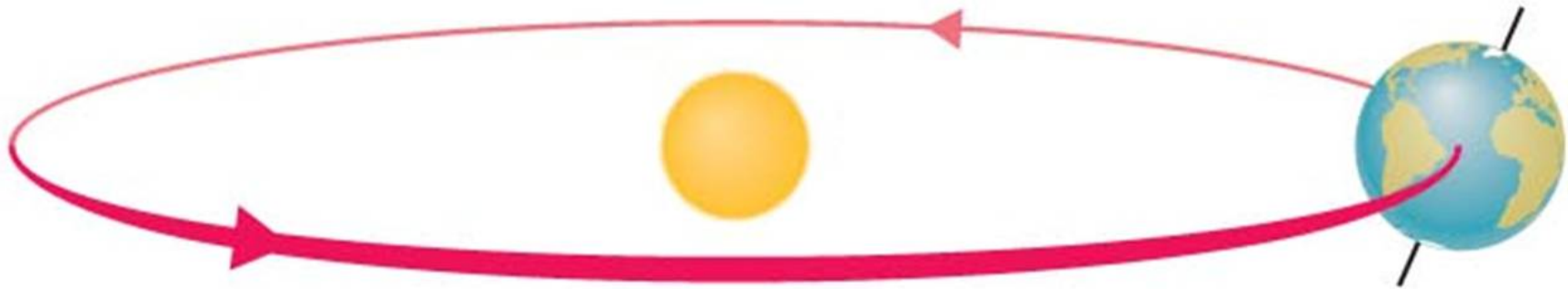


Solar Brightening



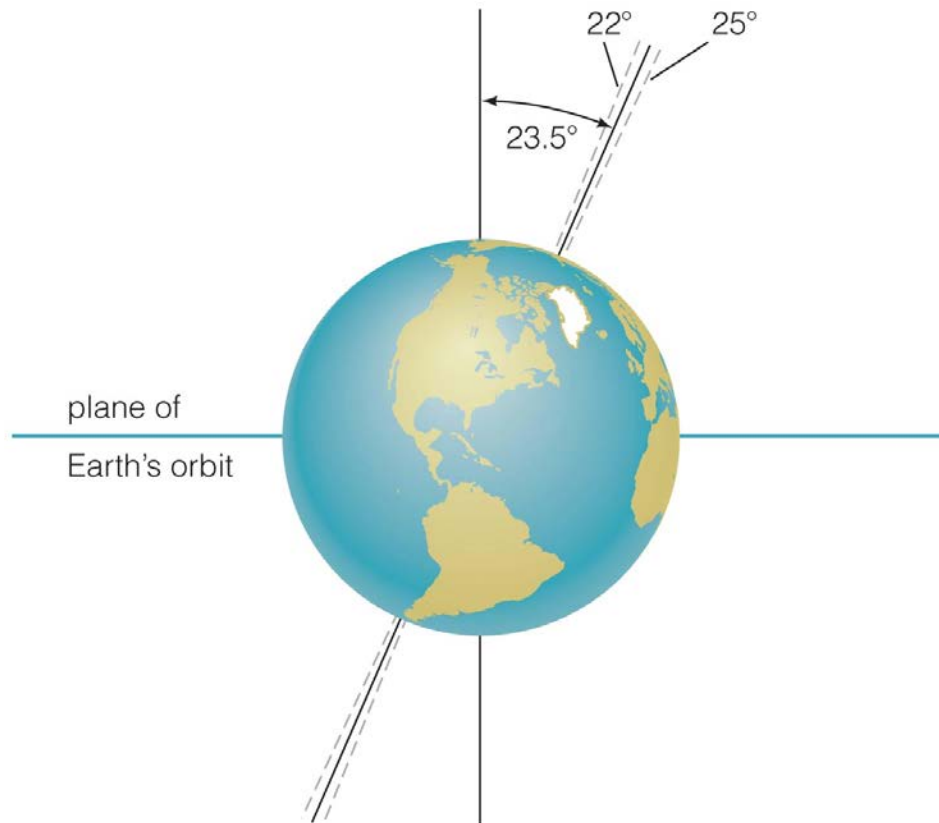
- The Sun very gradually grows brighter with time, increasing the amount of sunlight warming the planets.
- Variations in the Sun's brightness by a few 0.1% can cause significant change in the Earth's temperature. This might explain the very cold European winters between 1450 and 1850.

Changes in Axis Tilt



- Greater tilt creates more extreme seasons, while smaller tilt keeps polar regions colder.
- The tilt of its spin axis varies between 22.1° and 24.5° with a 40,000-year period.

Changes in Axis Tilt



- Small gravitational tugs from other bodies in solar system cause Earth's axis tilt to vary between 22° and 25°.

Gravitational effects that affect our climate

Gravitational effects from the moon and planets cause:

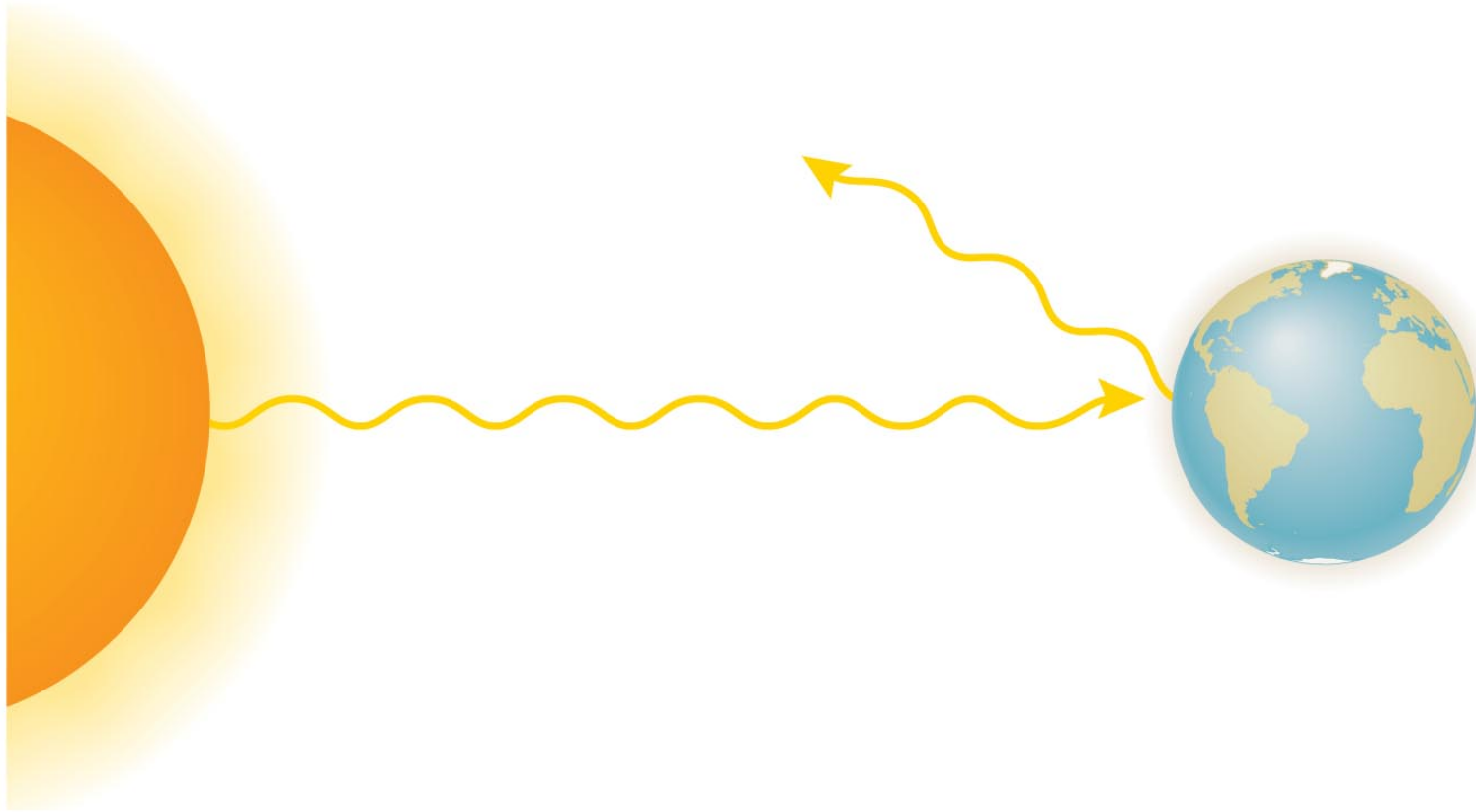
1 the eccentricity of the Earth's orbit to change with a period of $\sim 100,000$ years.

2 the Earth's axis to precess with a period of $\sim 26,000$ years.

3 the tilt of its spin axis varies between 22.1° and 24.5° with a 40,000-year period.

These effects have caused significant periodic changes in the Earth's climate (ice ages).

Changes in Reflectivity



- Higher reflectivity tends to cool a planet, while lower reflectivity leads to warming.

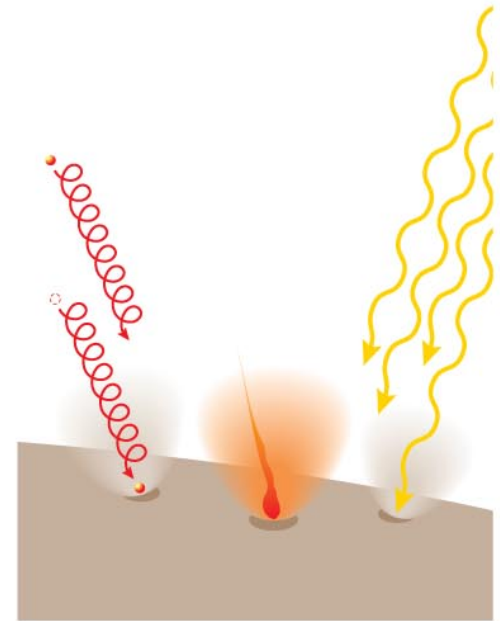
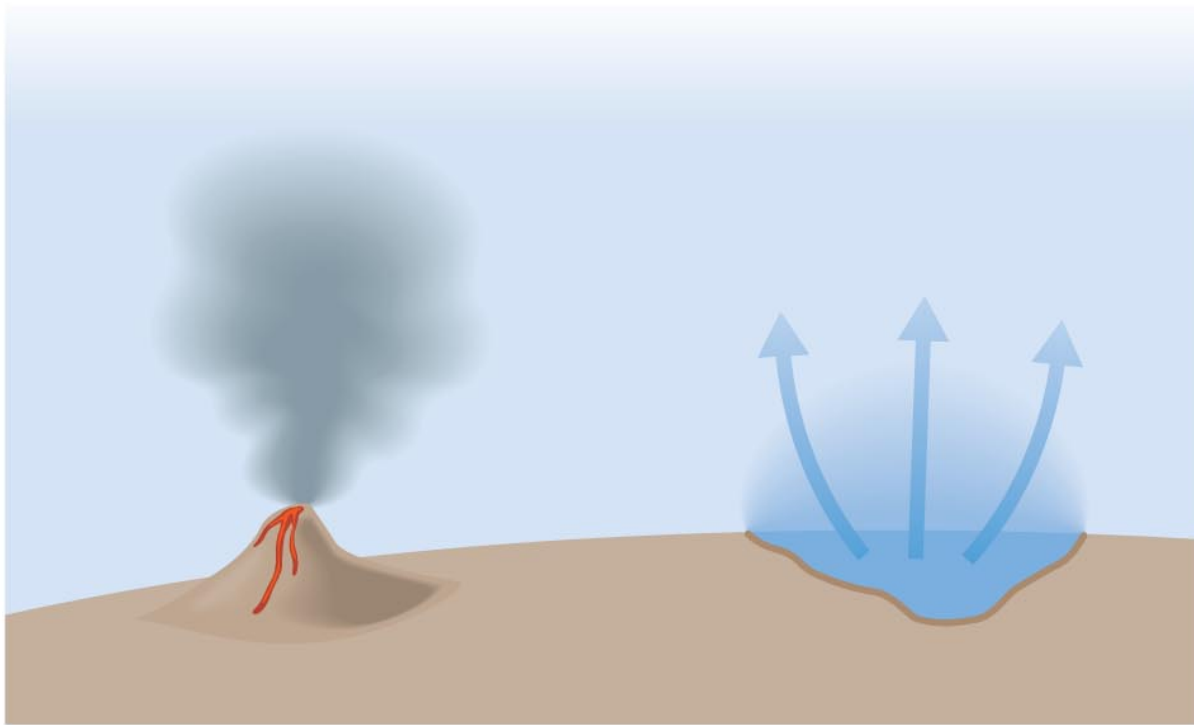
Changes in Greenhouse Gases

- An increase in greenhouse gases leads to warming, while a decrease leads to cooling.
- The major greenhouse gases are :
 - water vapor, causes about 36–70 % of the greenhouse effect
 - carbon dioxide (CO_2), causes 9–26 %
 - methane (CH_4), causes 4–9 %
 - and ozone (O_3), causes 3–7 %.



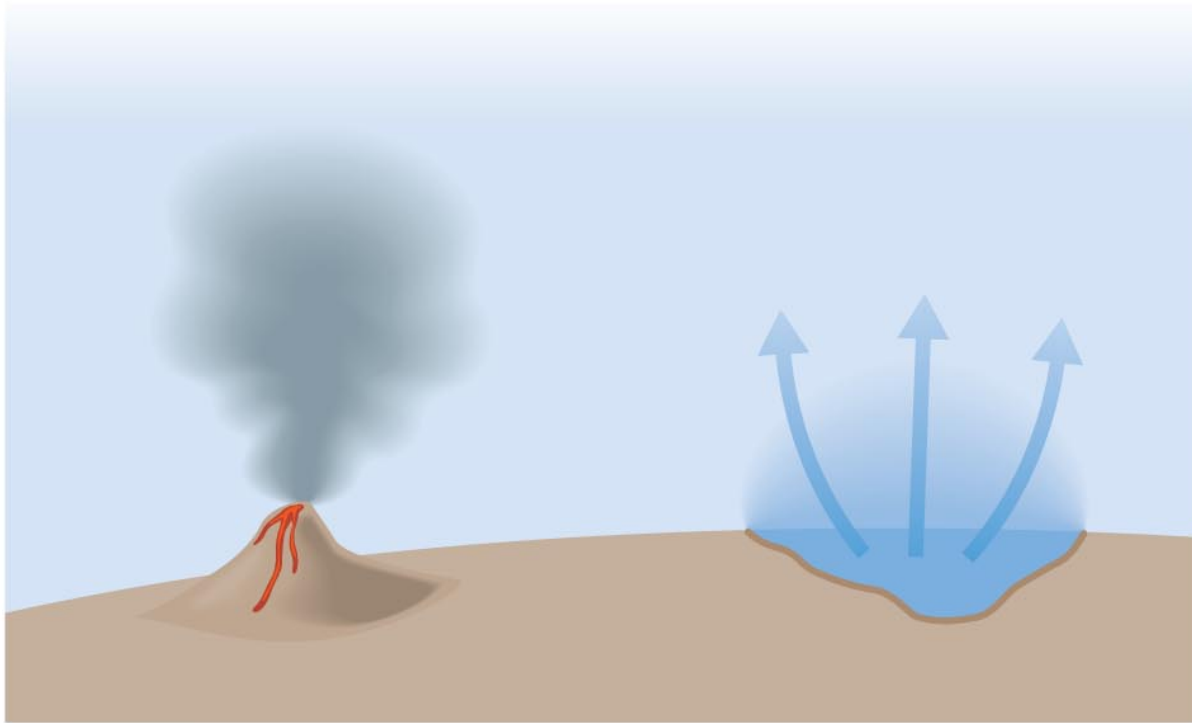
How does a planet gain or lose atmospheric gases?

How Atmospheres Gain Gas



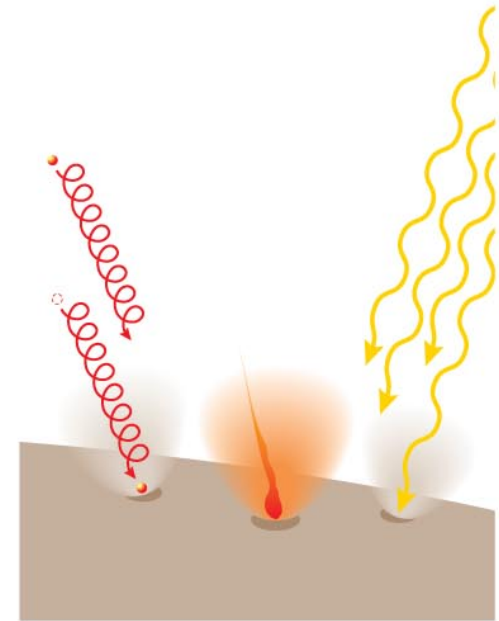
Sources of Gas

How Atmospheres Gain Gas



Outgassing
from
volcanoes

Evaporation of
surface liquid;
sublimation of
surface ice



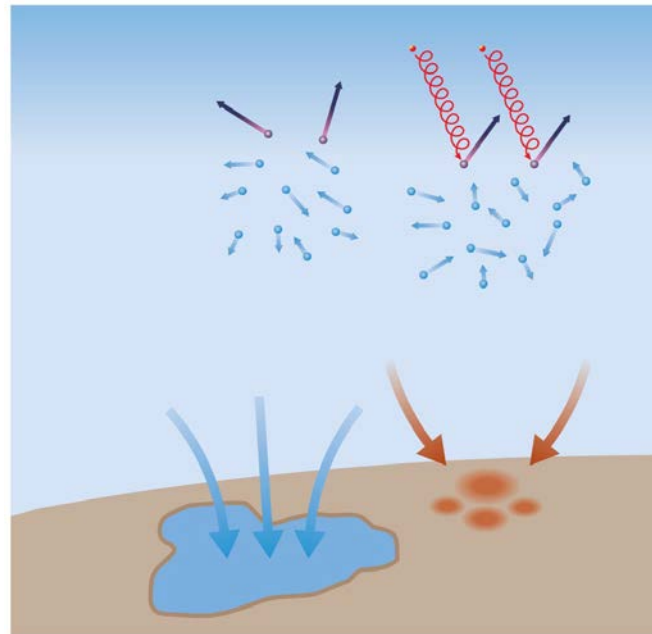
Impacts of
particles and
photons

Losses of Gas

Thermal escape of atoms

Sweeping by solar wind

How Atmospheres Lose Gas

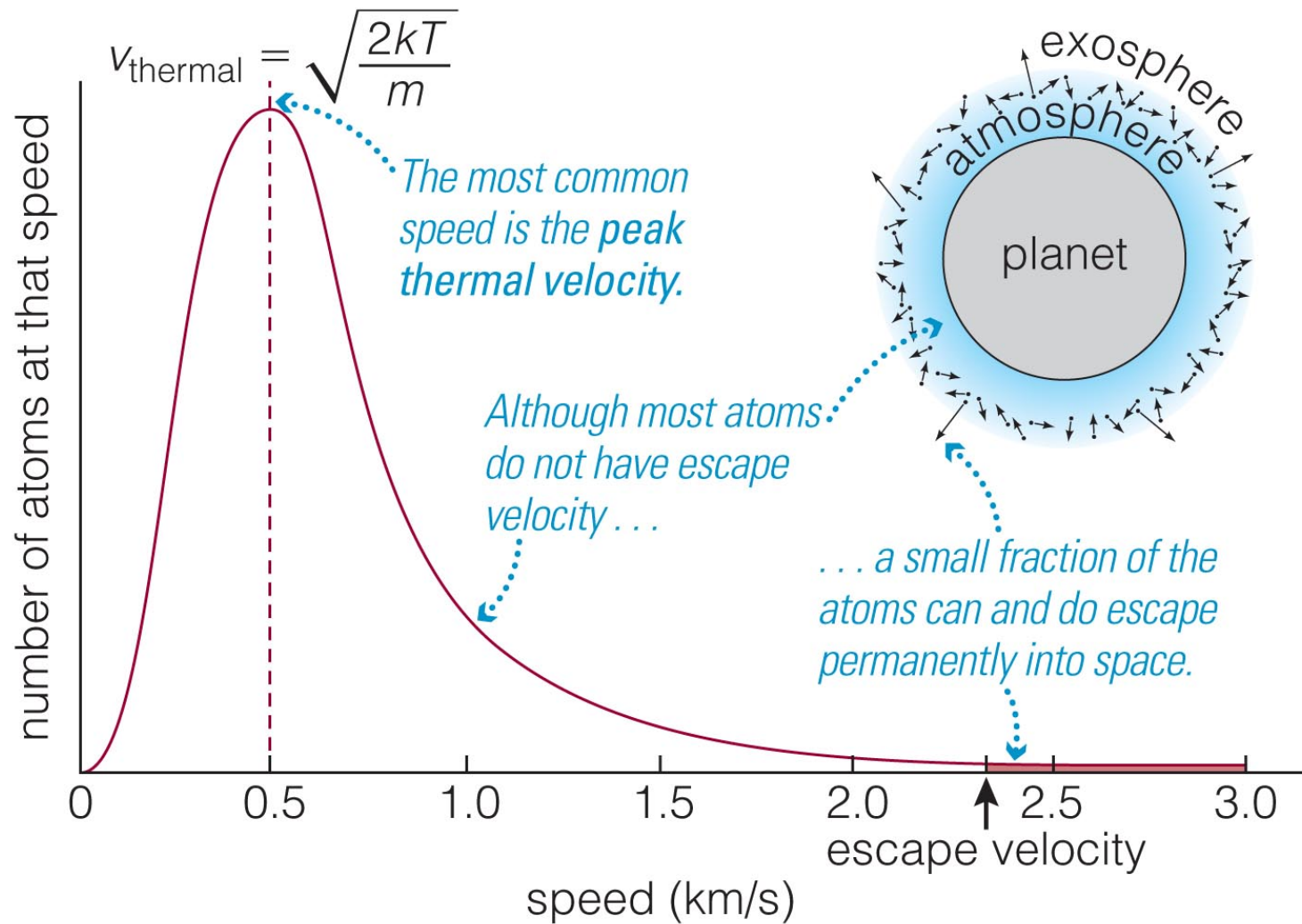


Condensation
onto surface

Chemical
reactions with
surface

Large impacts
blasting gas into
space

Thermal Escape



What have we learned?

- **What creates wind and weather?**
 - Atmospheric heating and the Coriolis effect
- **What factors can cause long-term climate change?**
 - Brightening of the Sun
 - Changes in axis tilt and eccentricity of orbit
 - Precession
 - Volcanism
 - Changes in reflectivity
 - Changes in greenhouse gases

What have we learned?

- **How does a planet gain or lose atmospheric gases?**
 - Gains: outgassing, evaporation/sublimation, and impacts by particles and photons
 - Losses: condensation, chemical reactions, blasting by large impacts, sweeping by solar winds, and thermal escape

10.3 Atmospheres of Moon and Mercury

- Our goals for learning:
 - **Do the Moon and Mercury have any atmosphere?**

Do the Moon and Mercury have any atmosphere?

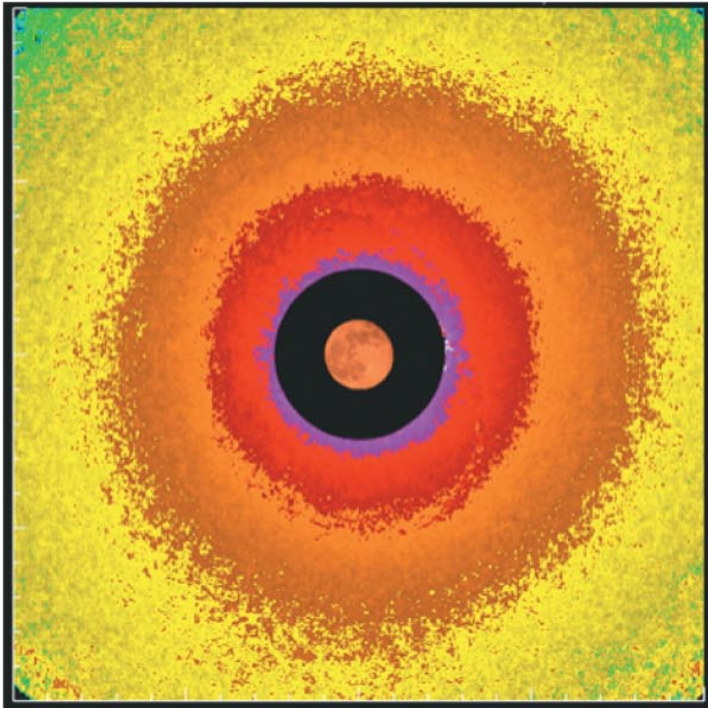


Moon

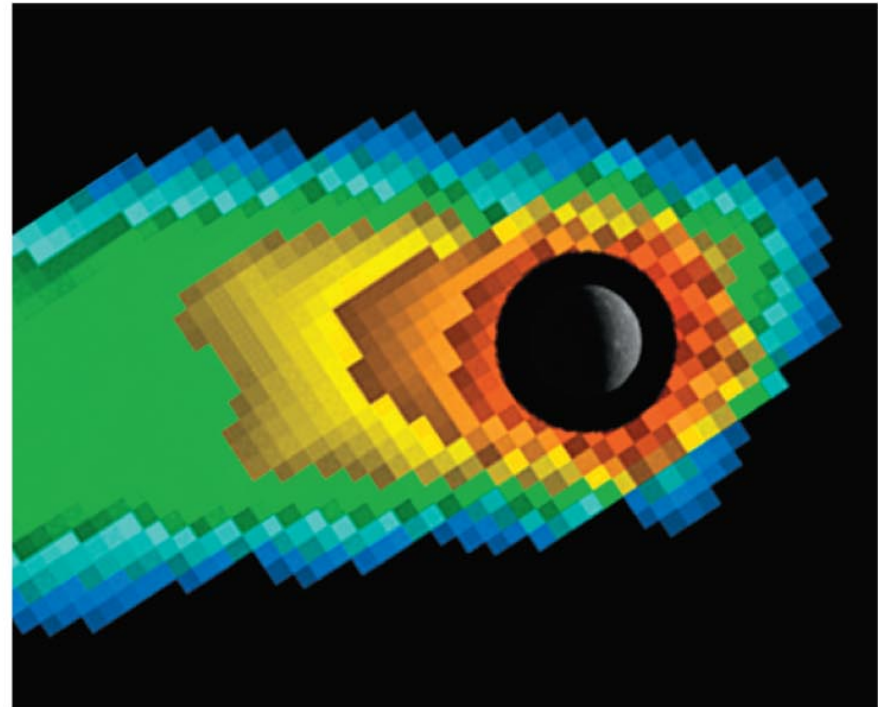


Mercury

Exospheres of the Moon and Mercury



a The Moon's exosphere, which extends high above the surface.

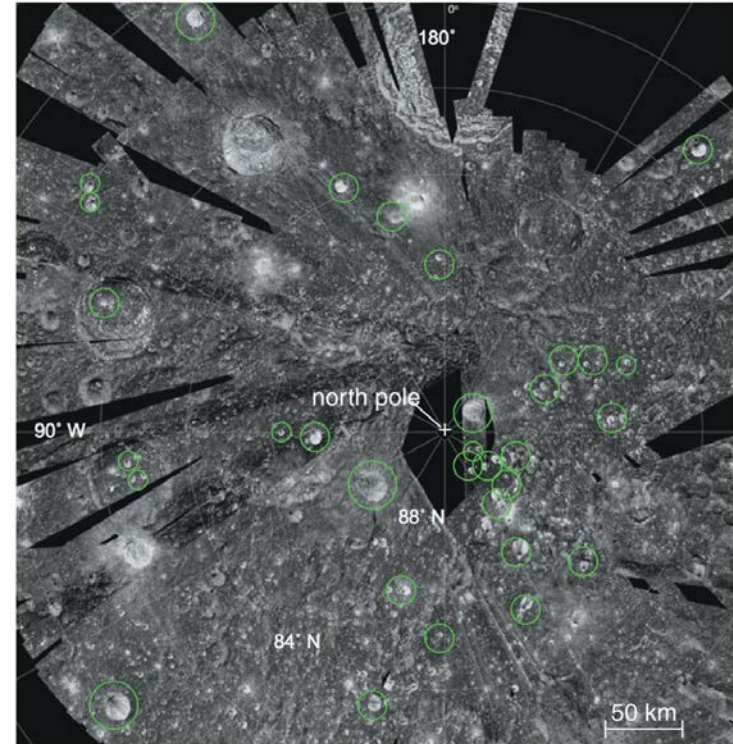


b Mercury's exosphere, much of which is escaping in this image.

- Sensitive measurements show that the Moon and Mercury have extremely thin atmospheres.
- Gas comes from impacts that eject surface atoms.

Ice in Polar Craters

- Deep craters near the lunar poles show evidence of water ice.
- Possible on Mercury as well.



Green circles indicate craters with ice.

What have we learned?

- **Do the Moon and Mercury have any atmosphere?**
 - The Moon and Mercury have very thin atmospheres made up of particles ejected from surface.

10.4 The Atmospheric History of Mars

- Our goals for learning:
 - **What is Mars like today?**
 - **Why did Mars change?**

What is Mars like today?

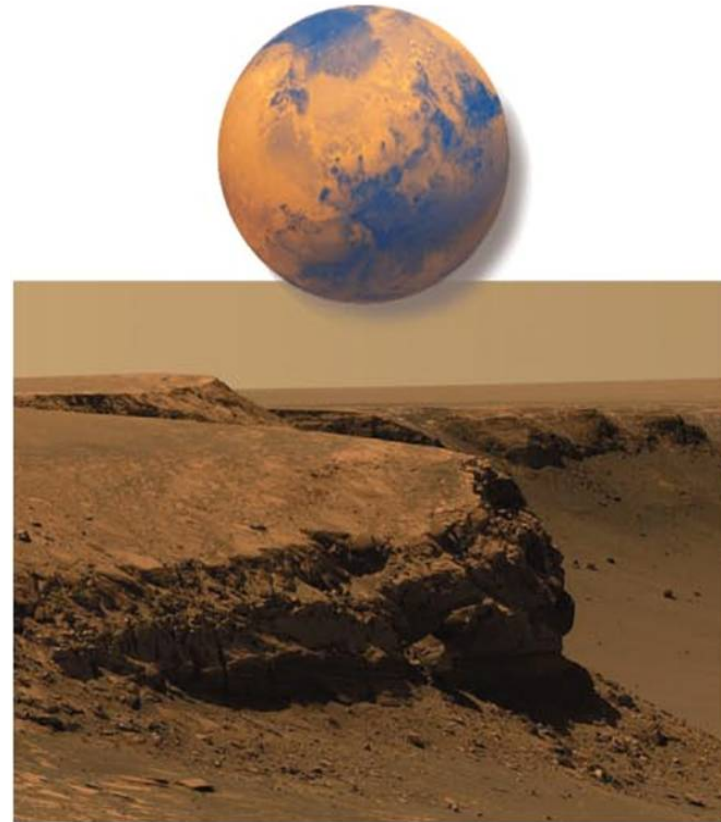
Thin Atmosphere and very cold

Low Pressure, less than 1% of Earth's pressure at the surface

No liquid phase of H₂O due to low pressure

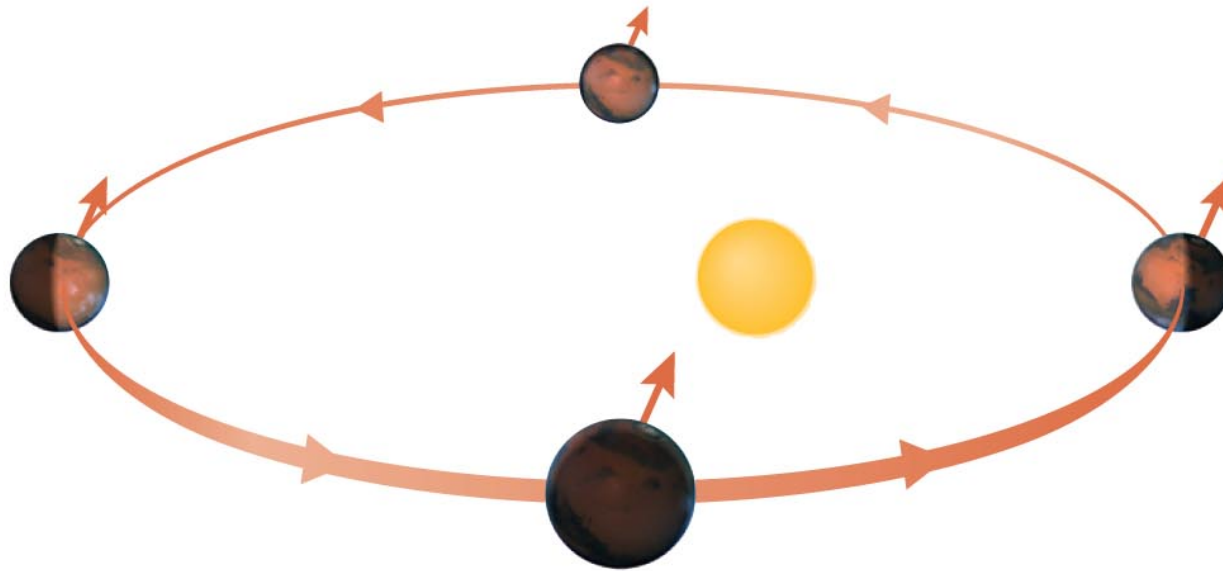
Atmosphere mostly composed of CO₂ (but weak greenhouse effect because of low density)

Lack of oxygen means there is also no ozone in the atmosphere to protect from UV



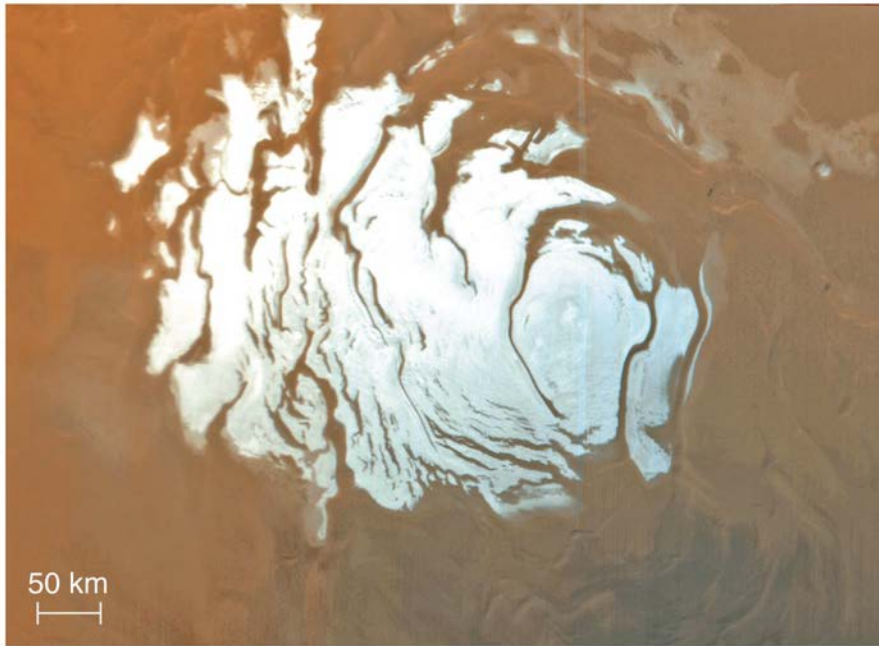
Seasons on Mars

Seasons on Mars



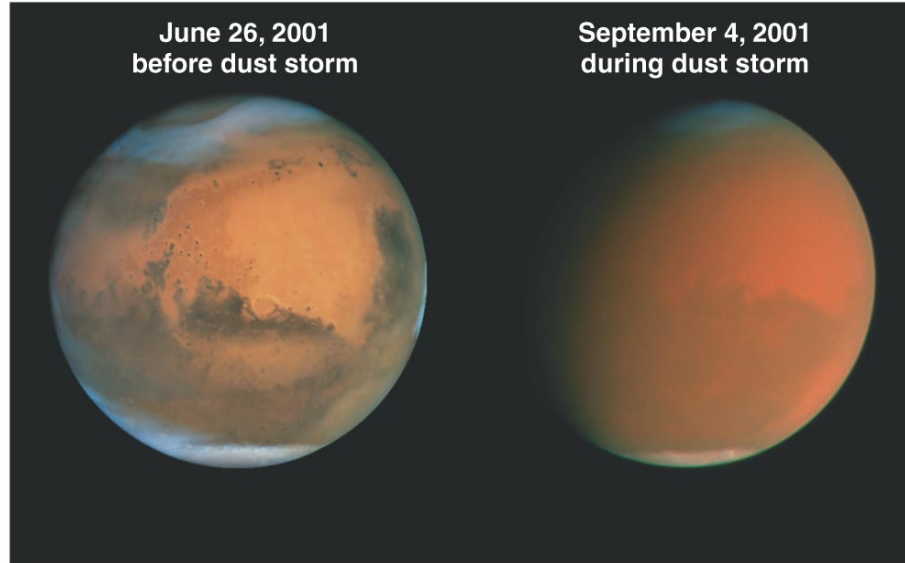
- The large eccentricity of Mars's orbit makes seasons more extreme in the southern hemisphere.
- Notice that during the winter in the south pole Mars is much further away from the sun making winters colder and longer in the south pole.

Polar Ice Caps of Mars



- Residual ice of the south polar cap remaining during summer is primarily water ice.
- Carbon dioxide ice of polar cap sublimates as summer approaches and condenses at opposite pole.

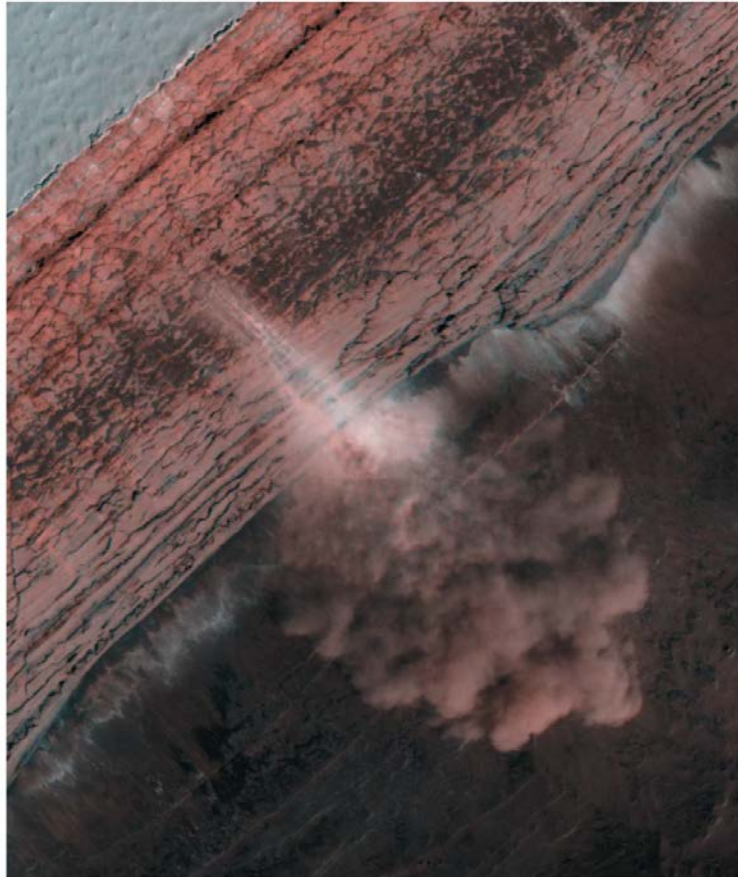
Dust Storms on Mars



Interactive Figure 

- Seasonal winds can drive dust storms on Mars.
- Dust in the atmosphere absorbs blue light, sometimes making the sky look brownish-pink.

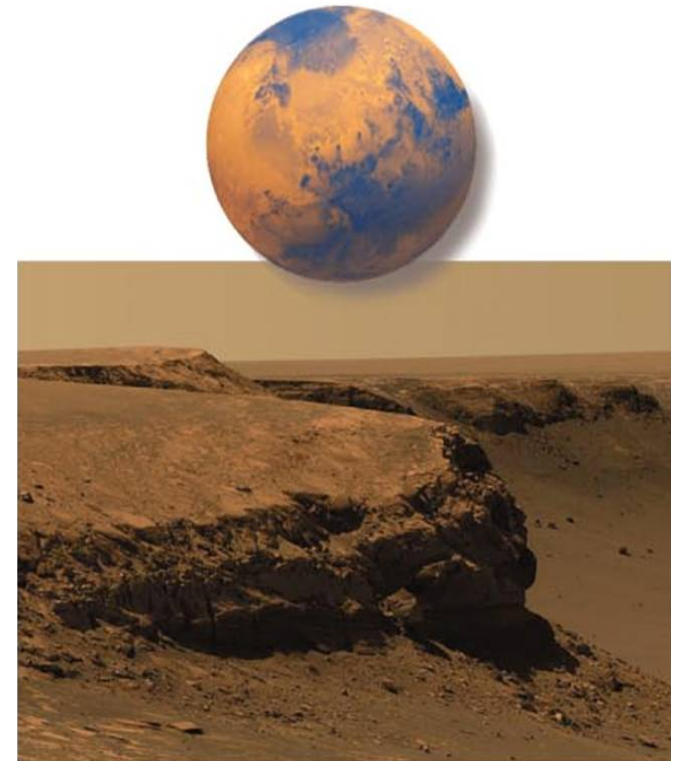
Changing Axis Tilt



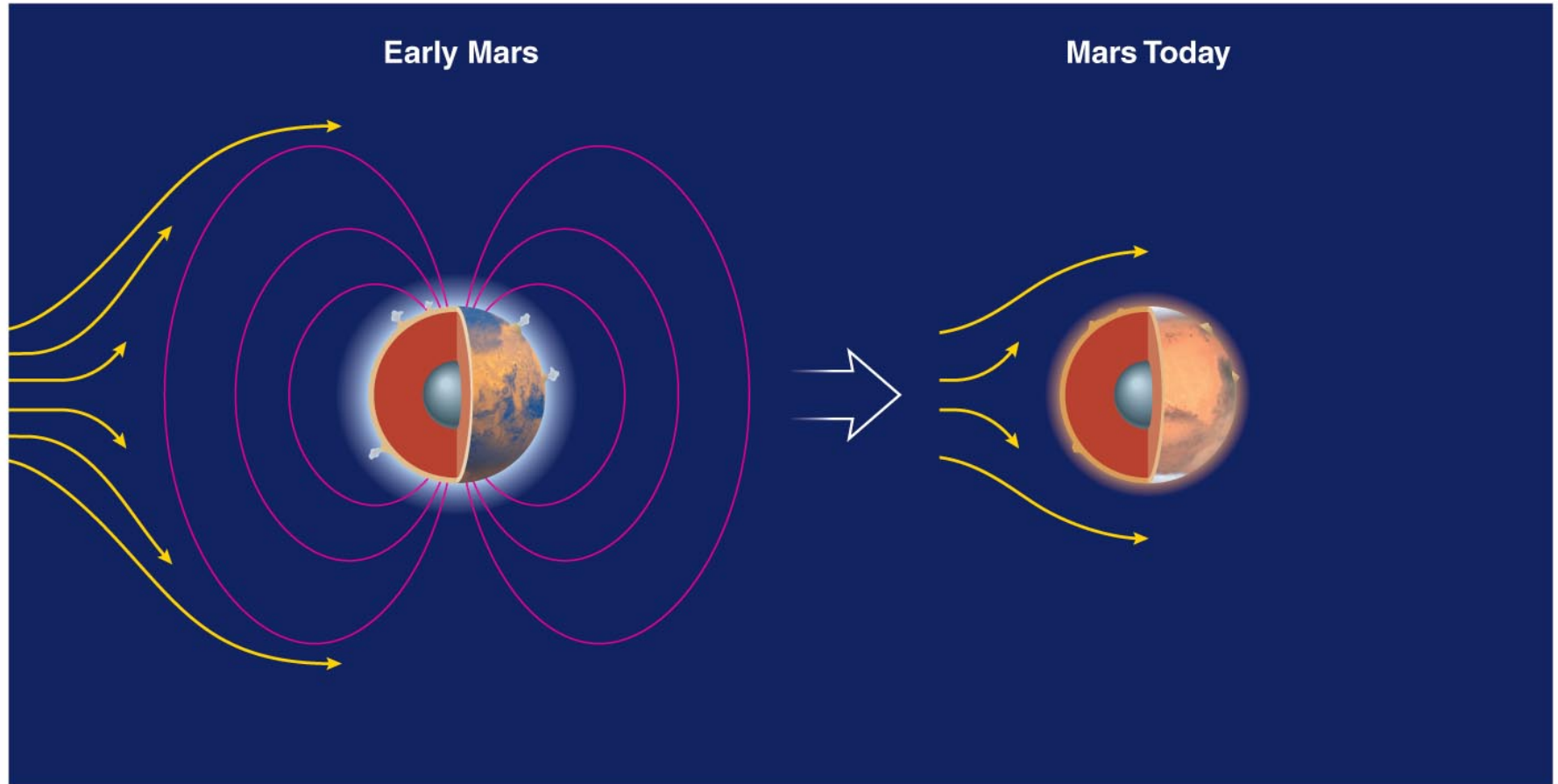
- Calculations suggest Mars's axis tilt ranges from 0° to 60° .
- Such extreme variations can cause climate changes.
- Alternating layers of ice and dust in polar regions reflect these climate changes.

Why did Mars change?

- Mars has not had widespread surface water for 3 billion years.
- Greenhouse effect probably kept the surface warmer before that.
- Somehow Mars lost most of its atmosphere.



Climate Change on Mars



- Magnetic field may have preserved early Martian atmosphere.
- Solar wind may have stripped atmosphere after field decreased because of interior cooling.

What have we learned?

- **What is Mars like today?**
 - Mars is cold, dry, and frozen.
 - Strong seasonal changes cause CO₂ to move from pole to pole, leading to dust storms.
- **Why did Mars change?**
 - Its atmosphere must have once been much thicker for its greenhouse effect to allow liquid water on the surface.
 - Somehow Mars lost most of its atmosphere, perhaps because of its declining magnetic field.

10.5 The Atmospheric History of Venus

- Our goals for learning:
 - **What is Venus like today?**
 - **How did Venus get so hot?**

What is Venus like today?

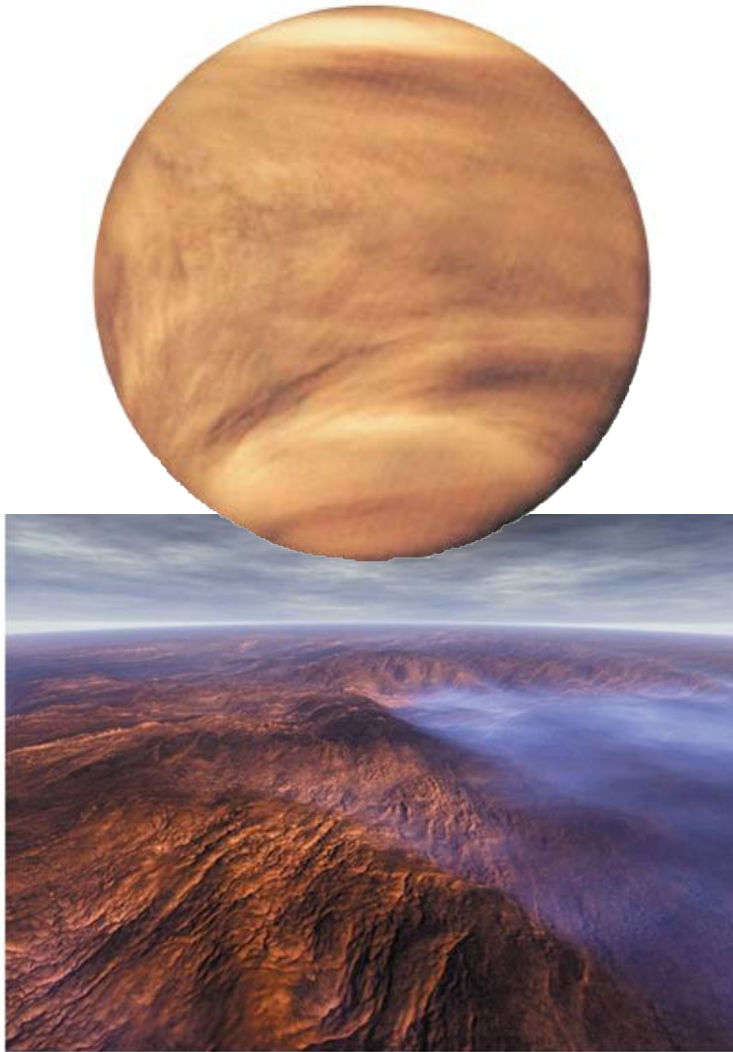


Atmosphere of Venus



- Venus has a very thick CO_2 atmosphere with a surface pressure 90 times that of Earth.
- Thick CO_2 atmosphere produces an extremely strong greenhouse effect.
- Earth escapes this fate because most of its carbon and water is in rocks and oceans.
- Slow rotation produces a very weak Coriolis effect and little weather.

Atmosphere of Venus



- Reflective clouds contain droplets of sulphuric acid H_2SO_4 .
- The upper atmosphere has fast winds that remain unexplained.

How did Venus get so hot?



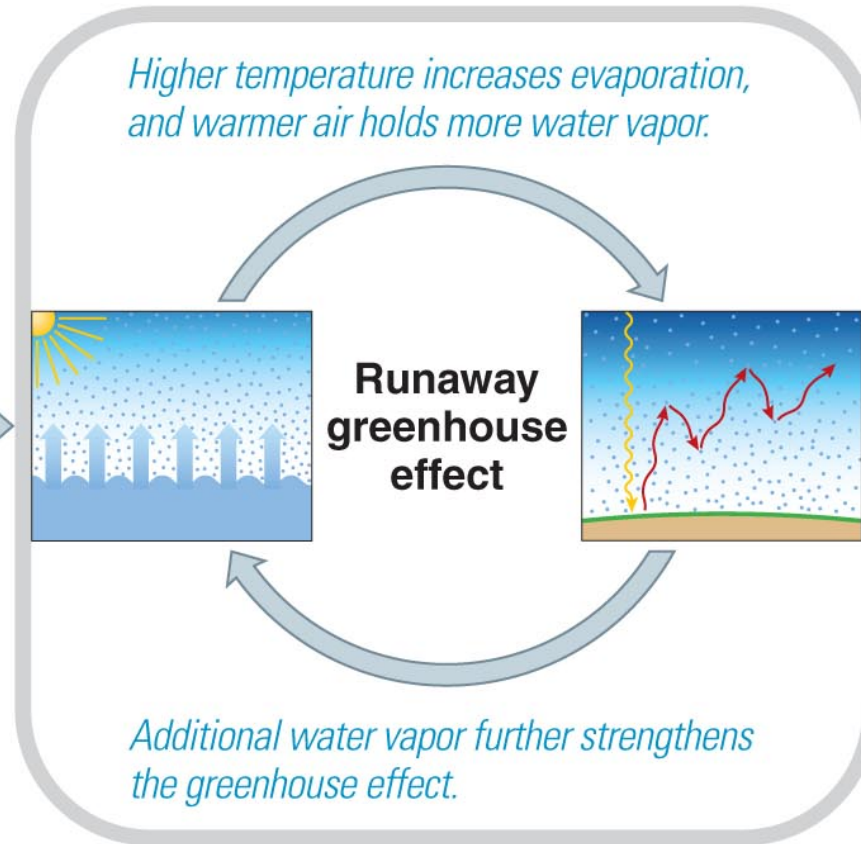
Runaway Greenhouse Effect

If Earth moved to Venus's orbit

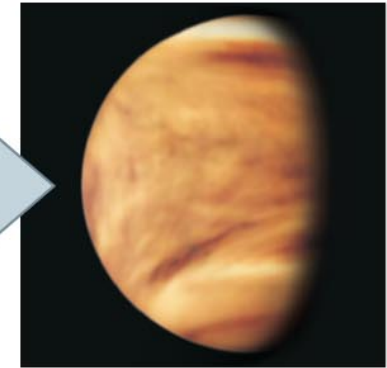
More intense sunlight...



...would raise surface temperature by about 30°C.



Result: Oceans evaporate and carbonate rocks decompose, releasing CO₂...



...making Earth hotter than Venus.

- A runaway greenhouse effect would account for why Venus has so little water.

Thought Question

What is the main reason why Venus is hotter than Earth?

- a) Venus is closer to the Sun than Earth.
- b) Venus is more reflective than Earth.
- c) Venus is less reflective than Earth.
- d) Greenhouse effect is much stronger on Venus than on Earth.
- e) Human activity has led to declining temperatures on Earth.

Thought Question

What is the main reason why Venus is hotter than Earth?

- a) Venus is closer to the Sun than Earth.
- b) Venus is more reflective than Earth.
- c) Venus is less reflective than Earth.
- d) **Greenhouse effect is much stronger on Venus than on Earth.**
- e) Human activity has led to declining temperatures on Earth.

What have we learned?

- **What is Venus like today?**
 - Venus has an extremely thick CO₂ atmosphere.
 - Slow rotation means little weather.
- **How did Venus get so hot?**
 - Runaway greenhouse effect made Venus too hot for liquid oceans.
 - All carbon dioxide remains in atmosphere, leading to an extreme greenhouse effect.

10.6 Earth's Unique Atmosphere

- Our goals for learning:
 - **How did Earth's atmosphere end up so different?**
 - **Why does Earth's climate stay relatively stable?**
 - **How is human activity changing our planet?**

How did Earth's atmosphere end up so different?

Earth



Four Important Questions

- Why did Earth retain most of its outgassed water?
- Why does Earth have so little atmospheric carbon dioxide, unlike Venus?
- Why does Earth's atmosphere consist mostly of nitrogen and oxygen?
- Why does Earth have an ultraviolet-absorbing stratosphere?

Earth's Water and CO₂

Earth



- Earth's temperature remained cool enough for liquid oceans to form.
- Oceans dissolve atmospheric CO₂, enabling carbon to be trapped in rocks.

Nitrogen and Oxygen

Earth



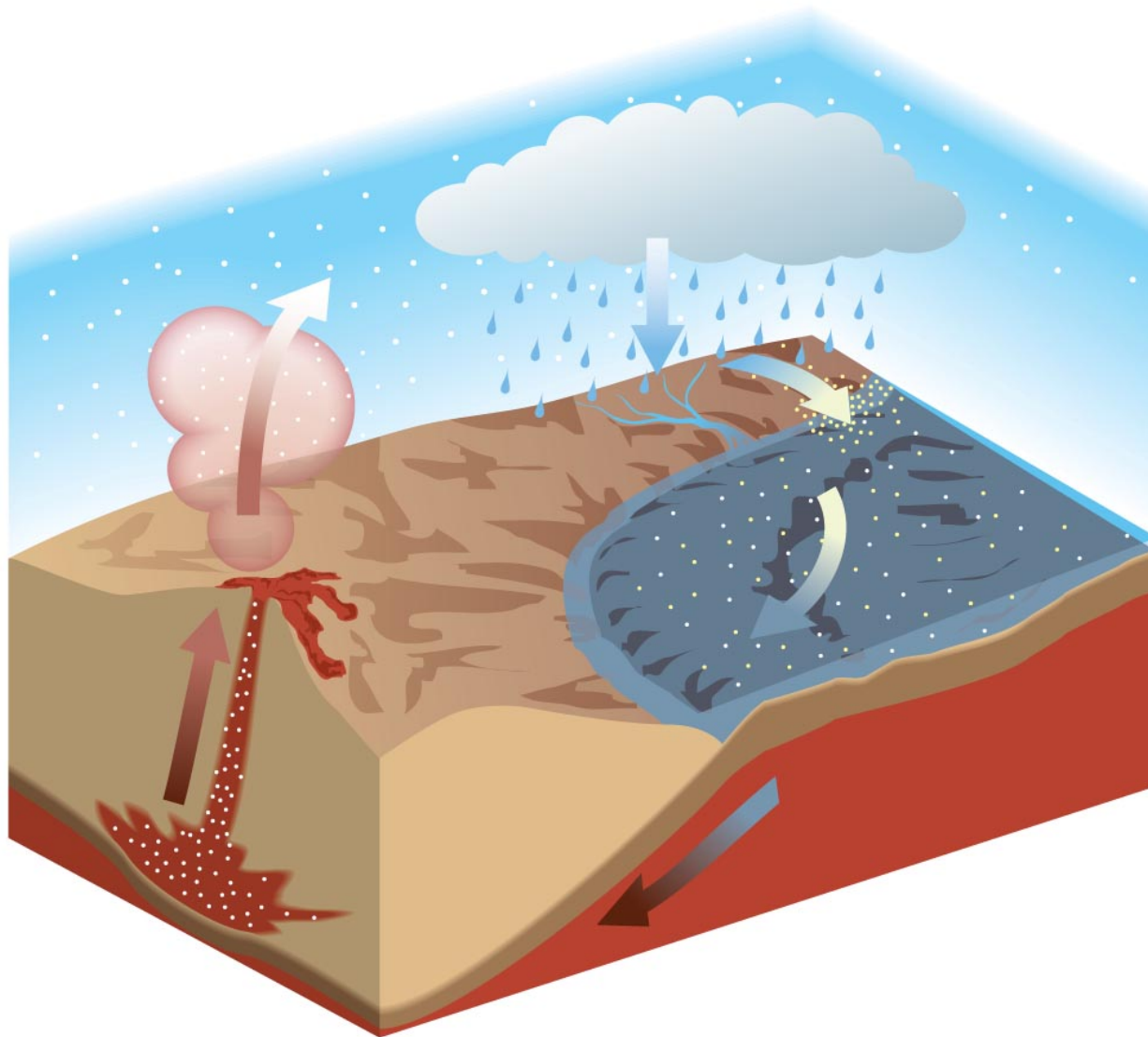
- Most of Earth's carbon and oxygen is in rocks, leaving a mostly nitrogen atmosphere.
- Plants release some oxygen from CO_2 into atmosphere.

Ozone and the Stratosphere

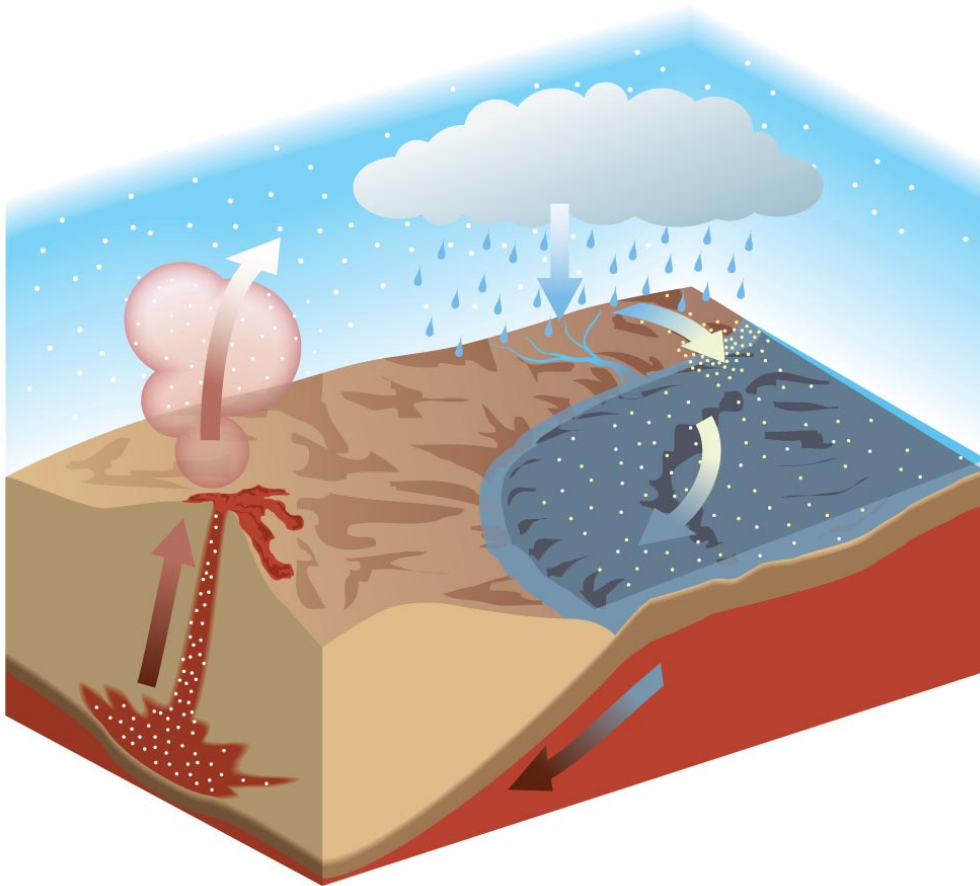


- Ultraviolet light can break up O_2 molecules, allowing ozone (O_3) to form.
- Without plants to release O_2 , there would be no ozone in stratosphere to absorb ultraviolet light.

Why does Earth's climate stay relatively stable?

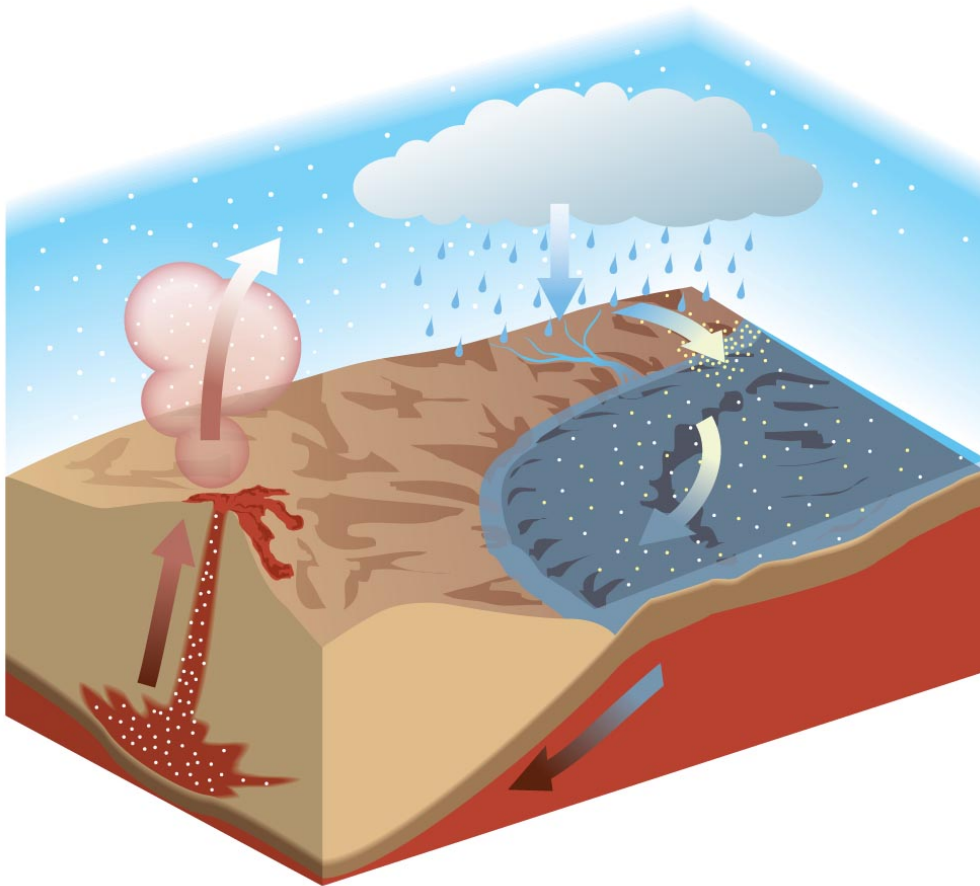


Carbon Dioxide Cycle



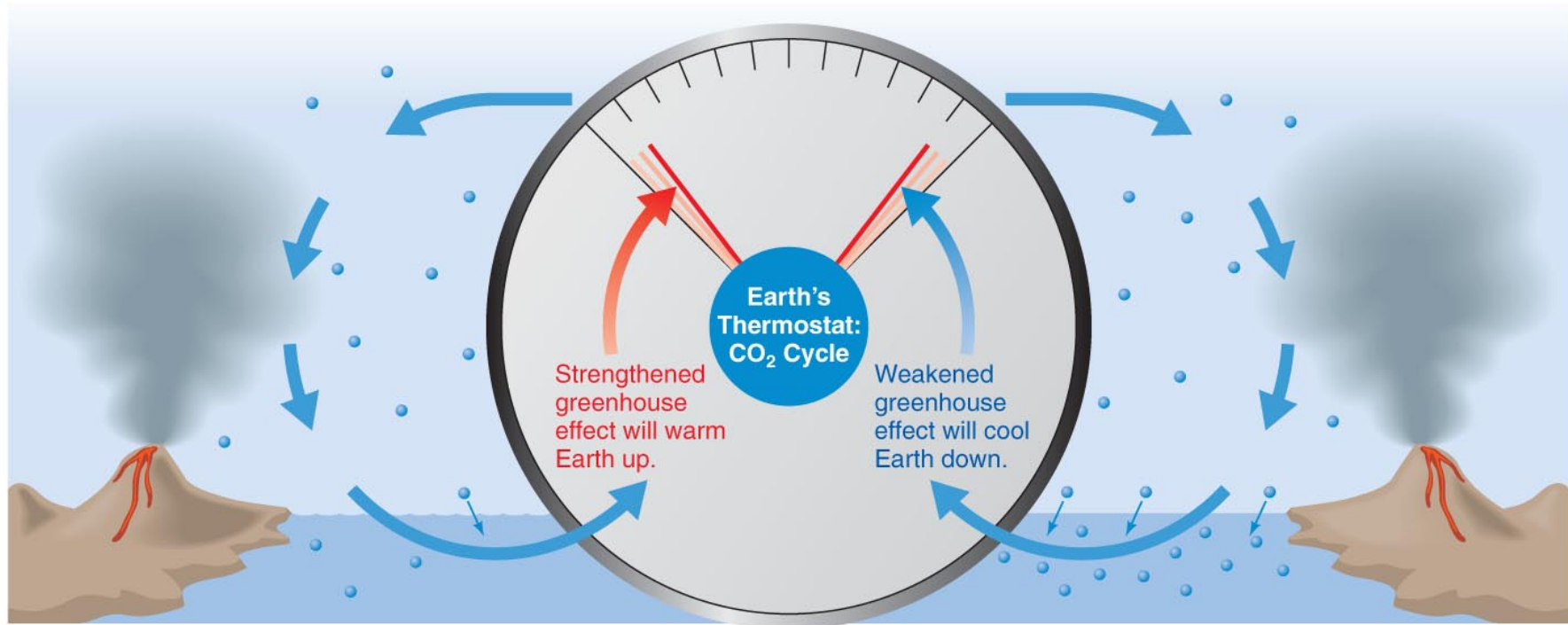
1. Atmospheric CO₂ dissolves in rainwater.
2. Rain erodes minerals that flow into ocean.
3. Minerals combine with carbon to make rocks on ocean floor.

Carbon Dioxide Cycle



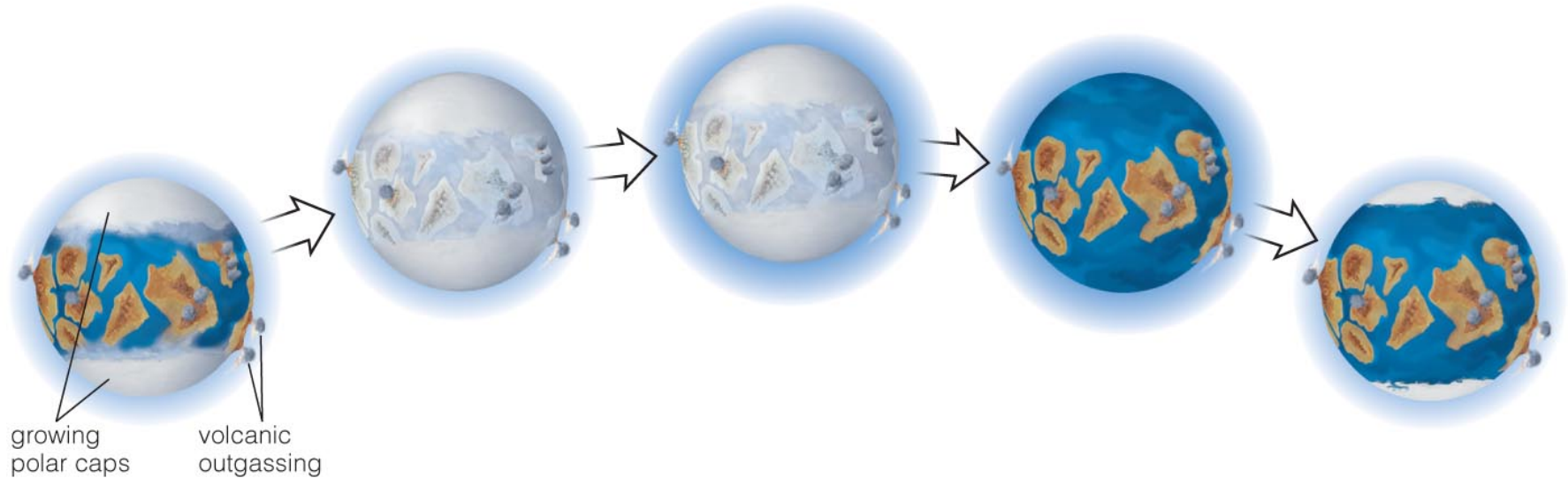
4. Subduction carries carbonate rock down into mantle.
5. Rock melts in mantle and CO_2 is outgassed back into atmosphere through volcanoes.

Earth's Thermostat



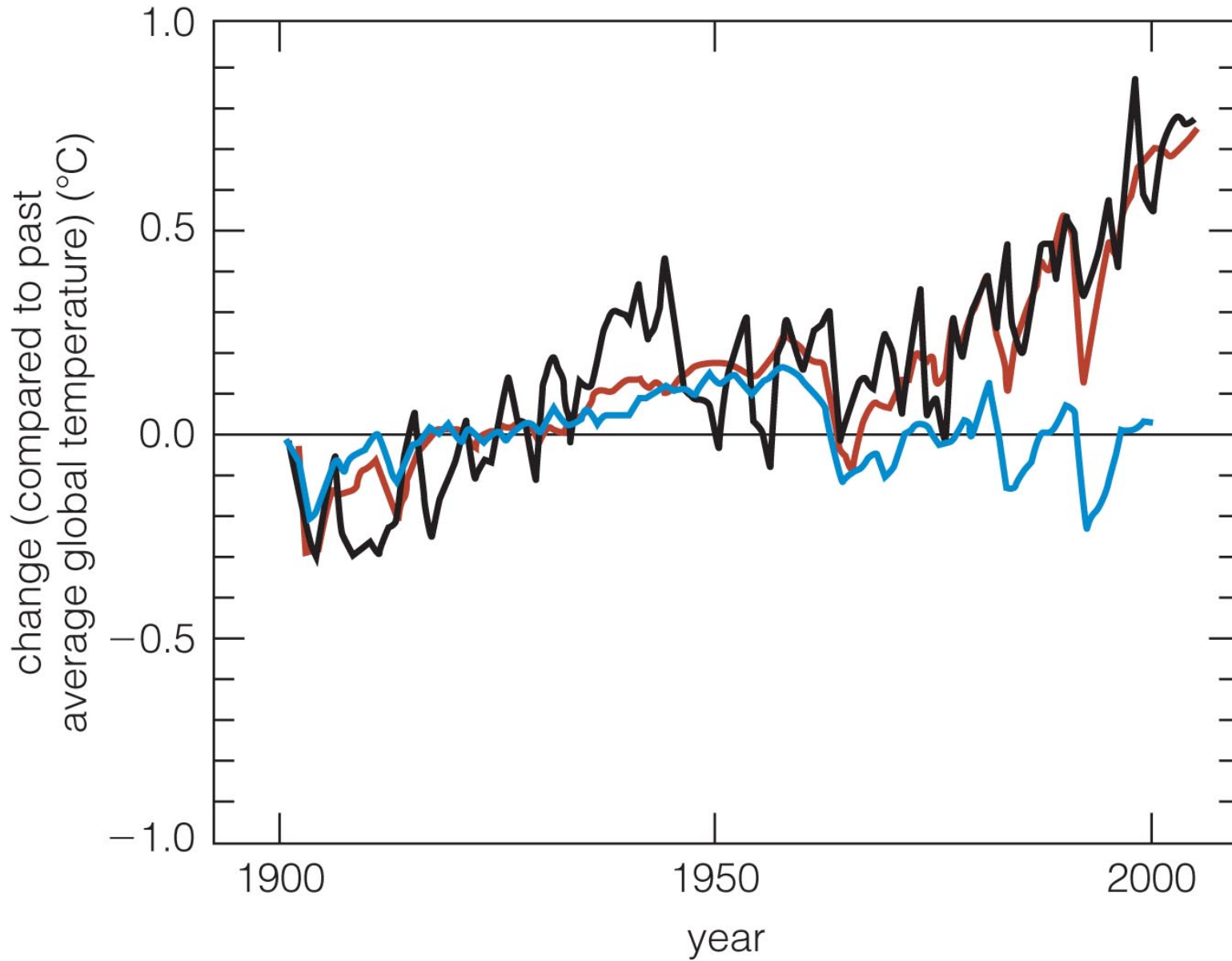
- Cooling allows CO₂ to build up in atmosphere.
- Heating causes rain to reduce CO₂ in atmosphere.

Long-Term Climate Change



- Changes in Earth's axis tilt might lead to *ice ages*.
- Widespread ice tends to lower global temperatures by increasing Earth's reflectivity.
- CO₂ from outgassing will build up if oceans are frozen, ultimately raising global temperatures again.

How is human activity changing our planet?

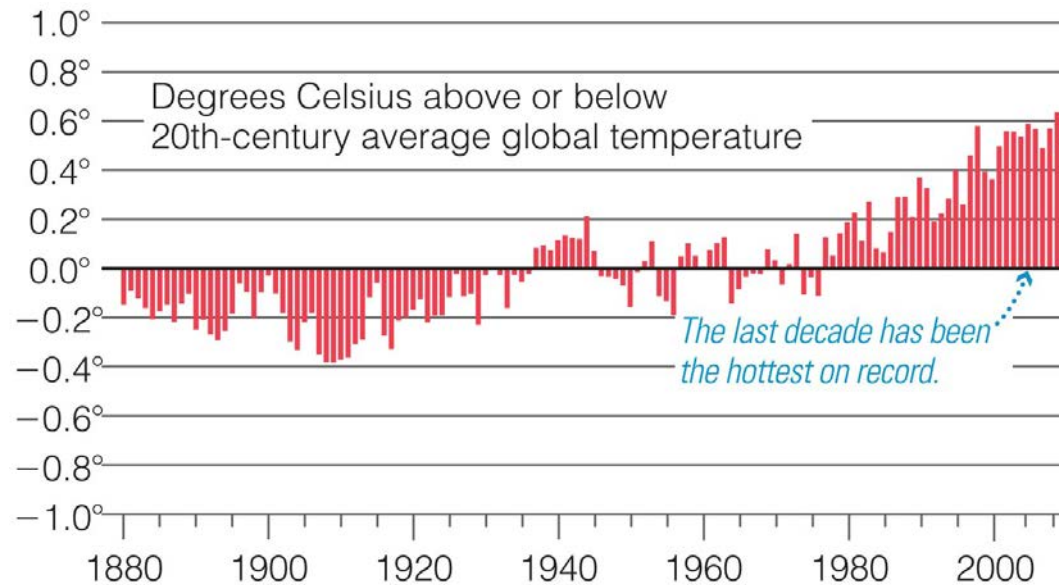


Dangers of Human Activity

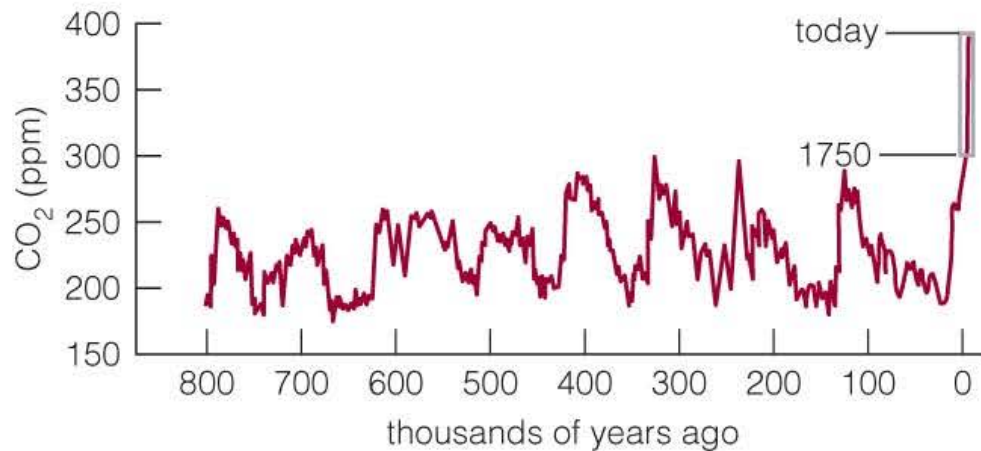
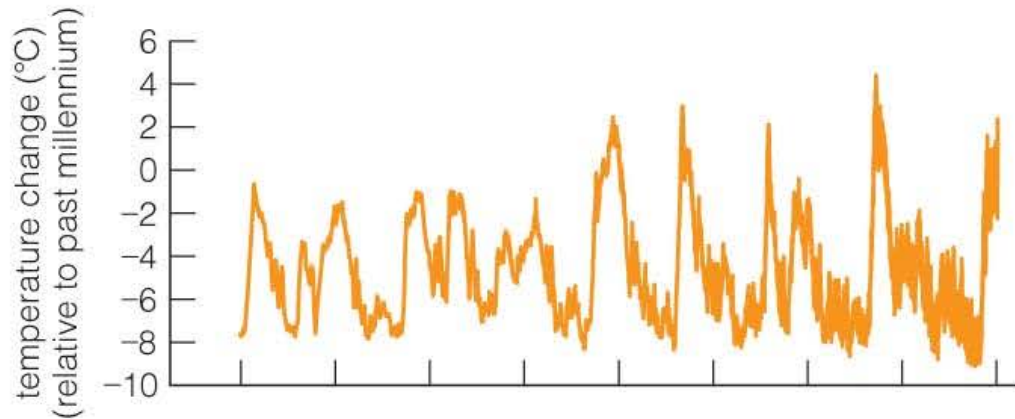
- Human-made Chlorofluorocarbons (CFCs) in the atmosphere destroy ozone, reducing protection from ultraviolet radiation.
- Human activity is driving many species to extinction.
- Human use of fossil fuels produces greenhouse gases that can cause global warming.

Global Warming

- Earth's average temperature has increased by 0.5°C in past 50 years.
- The concentration of CO_2 is rising rapidly.
- An unchecked rise in greenhouse gases will eventually lead to global warming.

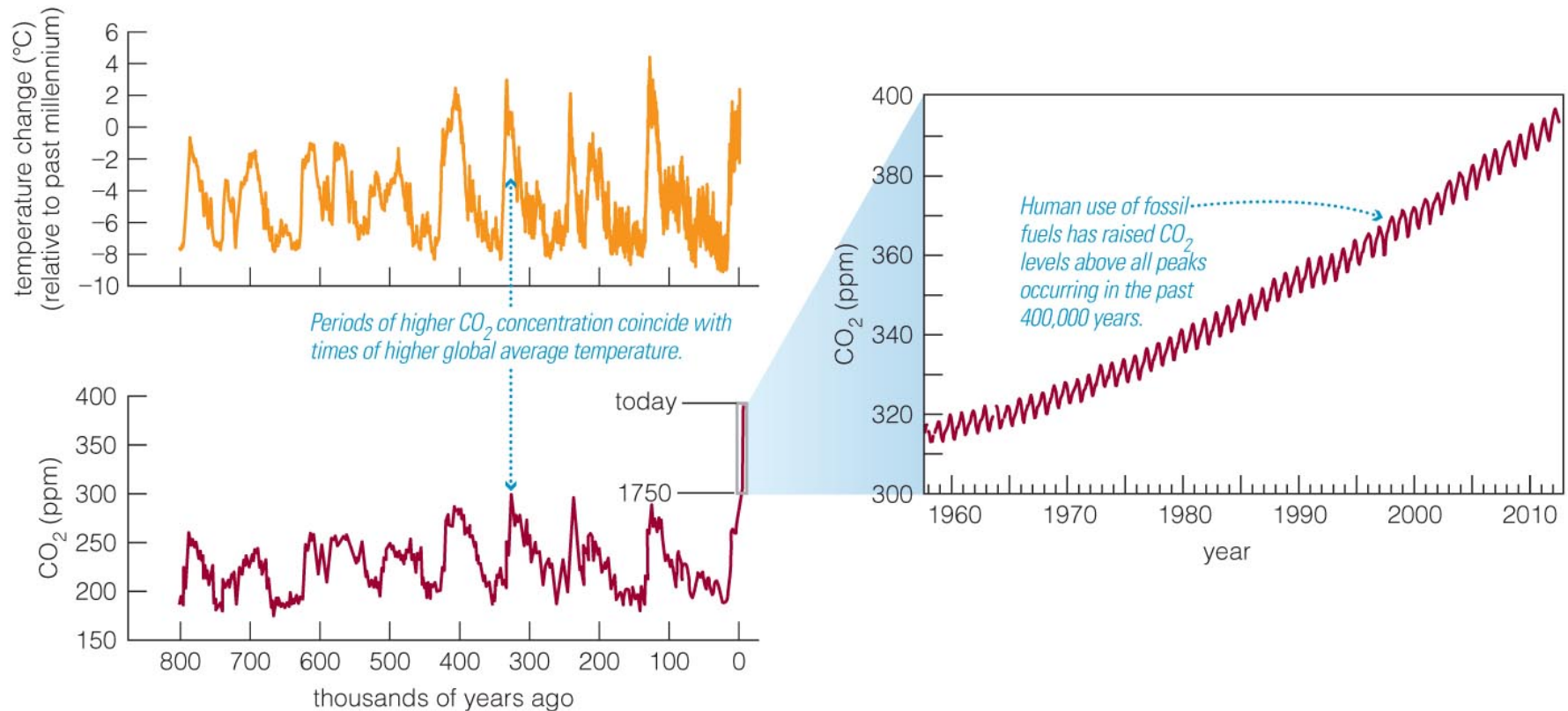


CO₂ Concentration



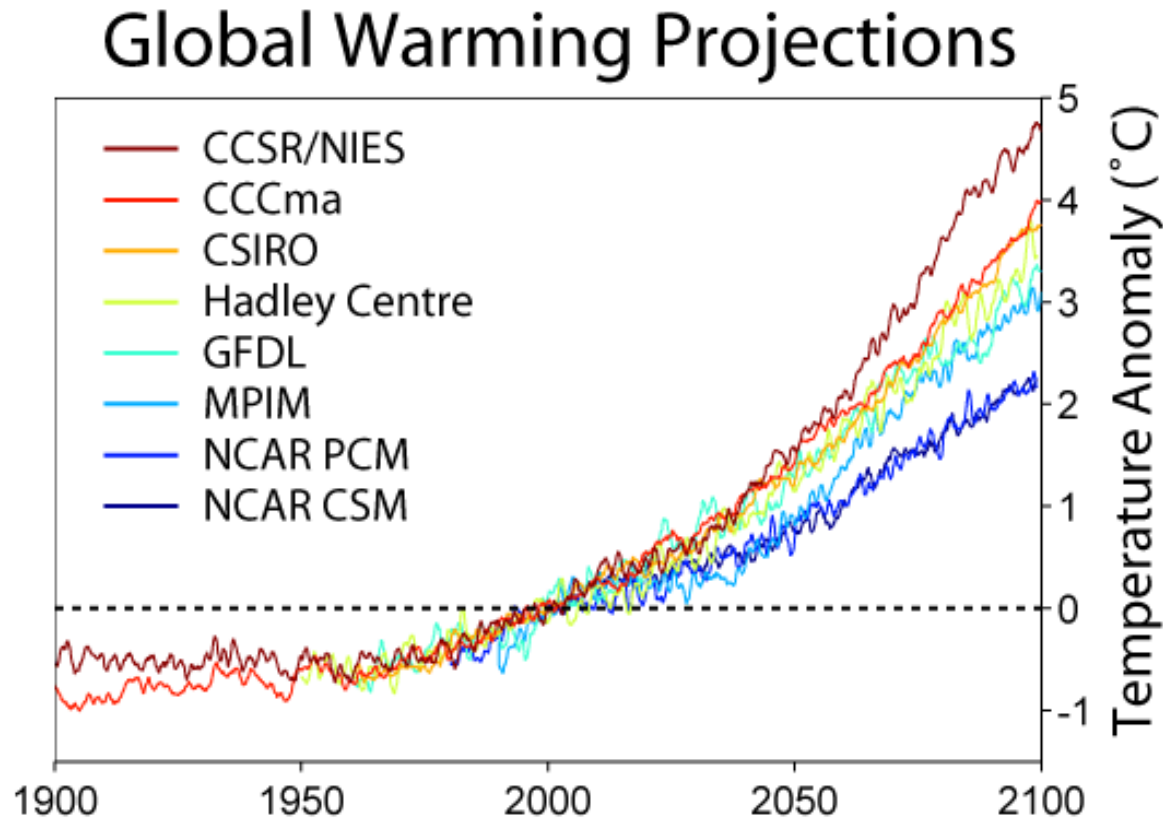
- Global temperatures have tracked CO₂ concentration for last 500,000 years.
- Current CO₂ concentration is the highest it's been in at least 500,000 years.

CO₂ Concentration



- Most of the CO₂ increase has happened in last 50 years!

Modeling of Climate Change



- Complex models of global warming suggest that recent temperature increase is consistent with human production of greenhouse gases.

Consequences of Global Warming

- Storms more numerous and intense
- Rising ocean levels; melting glaciers
- Uncertain effects on food production, availability of fresh water
- Potential for social unrest

What have we learned?

- **How did Earth's atmosphere end up so different?**
 - Temperatures are just right for oceans of water.
 - Oceans keep most CO₂ out of atmosphere.
 - Nitrogen remains in the atmosphere.
 - Life releases some oxygen into atmosphere.
- **Why does Earth's climate stay relatively stable?**
 - Carbon dioxide cycle acts as a thermostat.

What have we learned?

- **How is human activity changing our planet?**
 - Destruction of ozone
 - High rate of extinction
 - Global warming from the production of greenhouse gases