Chapter 10: 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?**

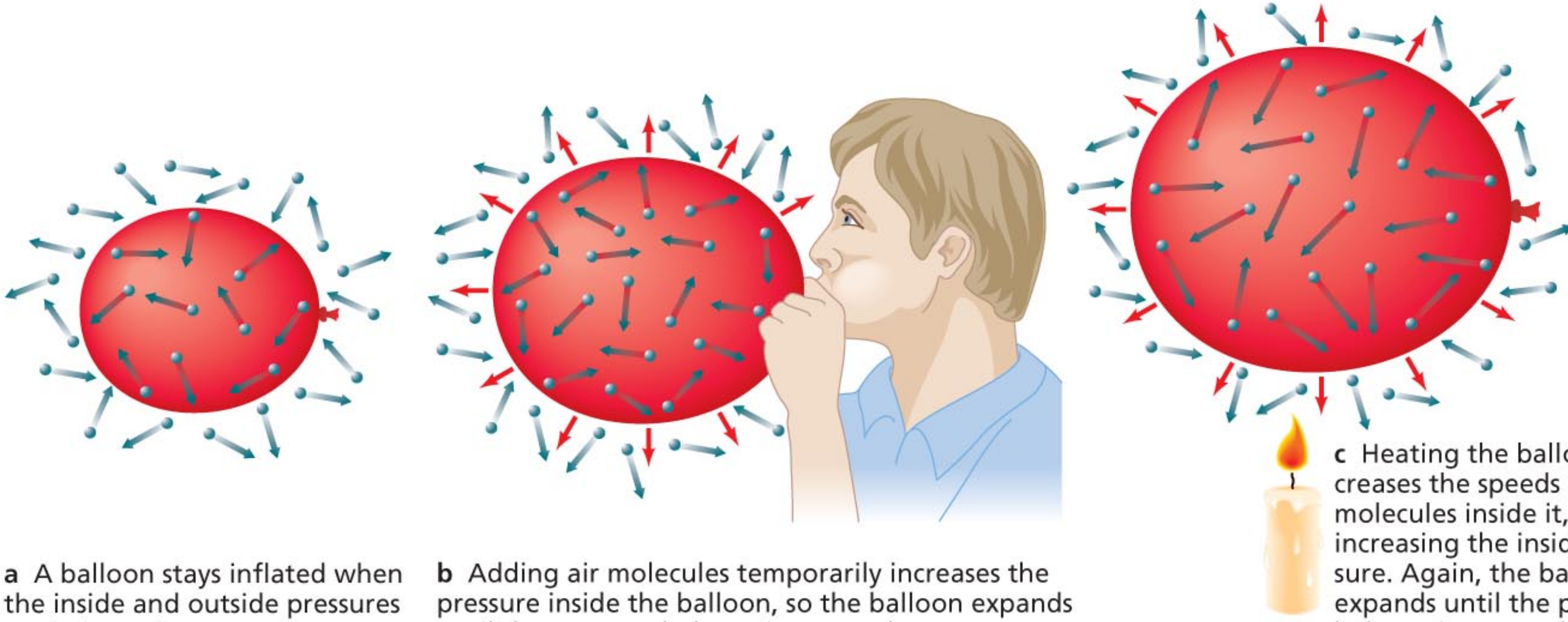
What is an atmosphere?

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

Earth's Atmosphere

- About 10 miles (50,000 feet) thick, but up to 300 miles with gas traces. At ~25 miles (125,000 feet or 40 kilometers) we are virtually at the edge of space.
- Consists mostly of molecular nitrogen (N_2) and oxygen (O_2).

Atmospheric Pressure



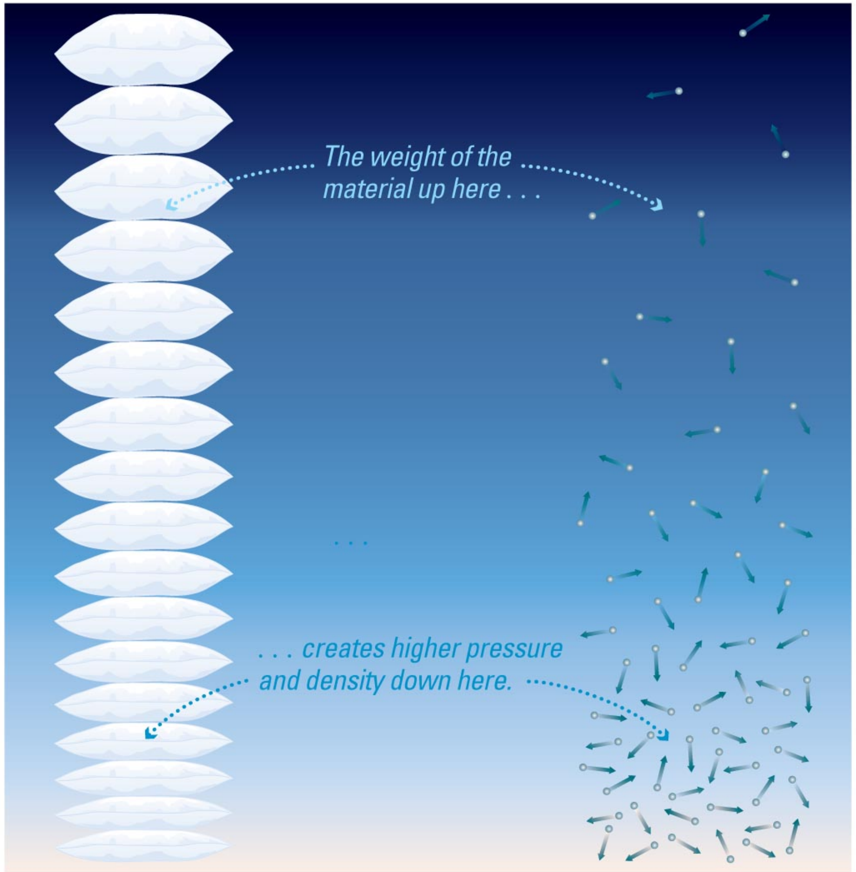
a A balloon stays inflated when the inside and outside pressures are balanced.

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

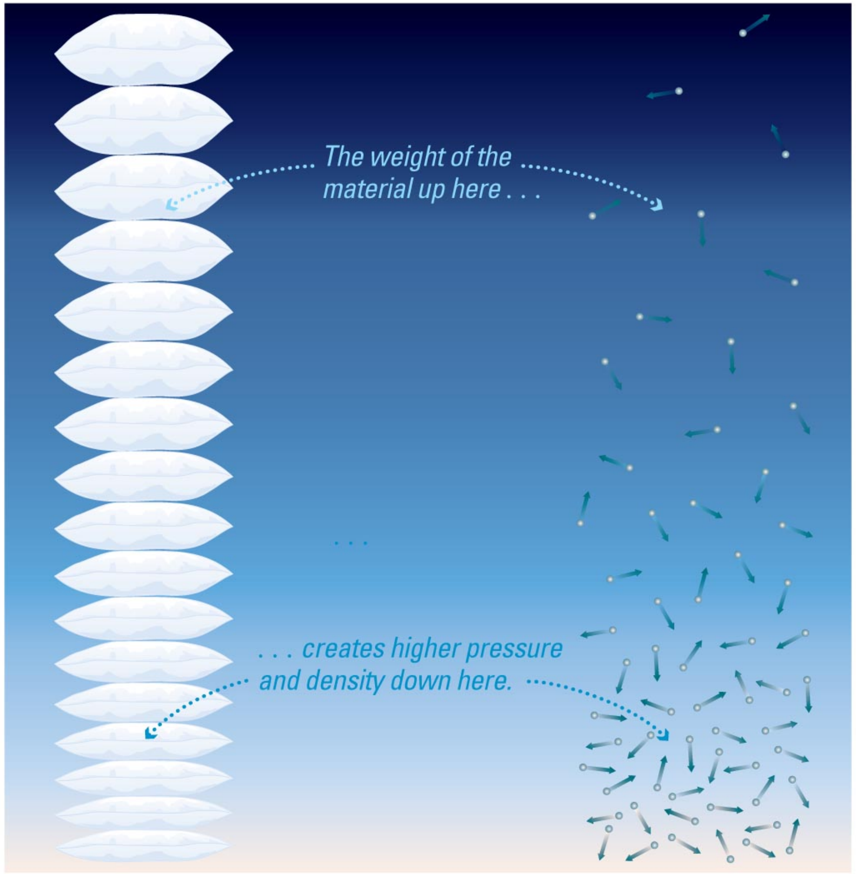
c Heating the balloon increases the speeds of air molecules inside it, thereby increasing the inside pressure. Again, the balloon expands until the pressure balance is restored.

Atmospheric Pressure

- Pressure and density decrease with altitude because the weight of overlying layers is less.
- Earth's pressure at sea level is:
  - 1.03 kg per sq. meter
  - 14.7 lb per sq. inch
  - 1 bar



Where does an atmosphere end?



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

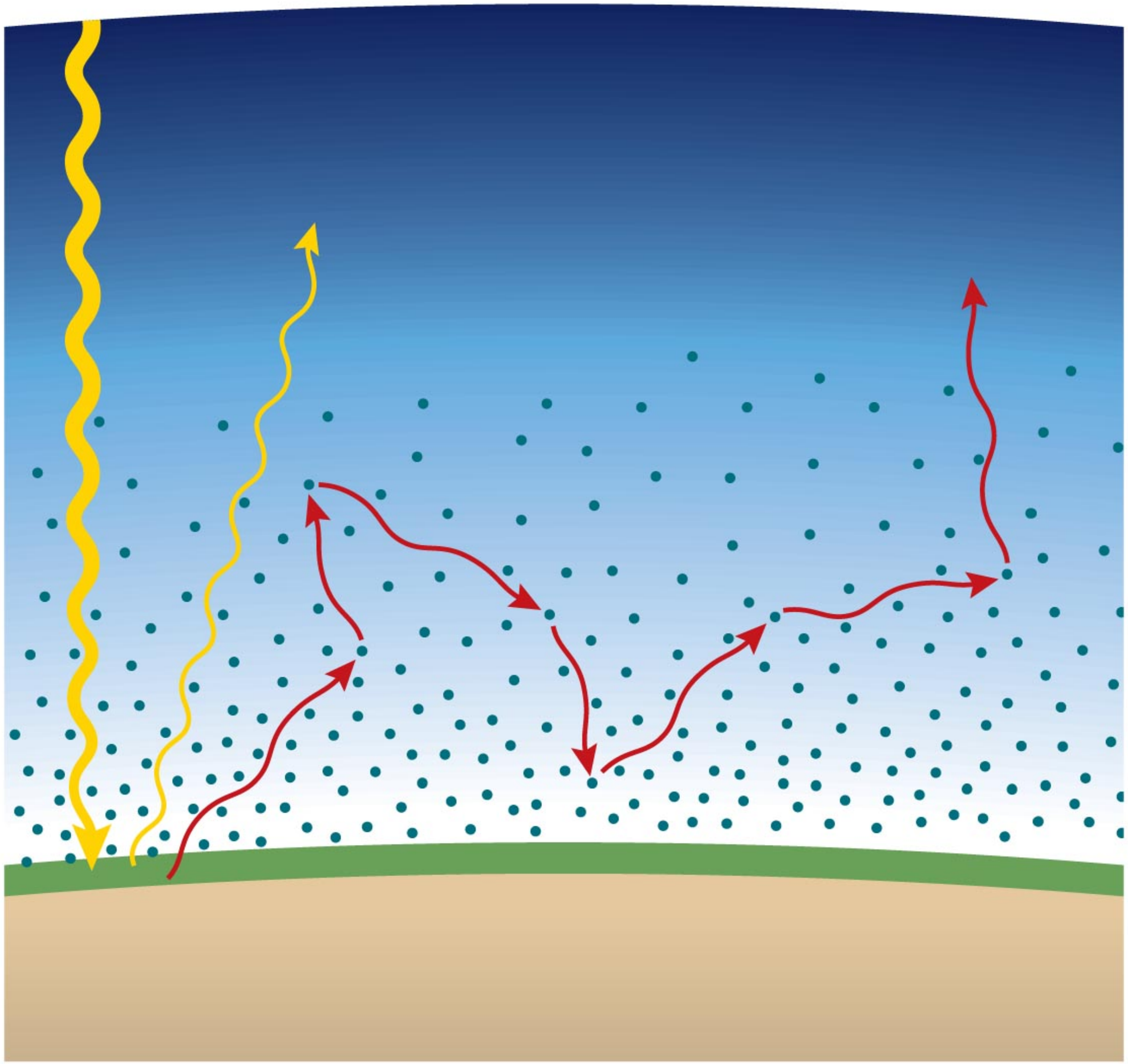
Where does an atmosphere end?

- Small amounts of gas are present even above 200 miles.

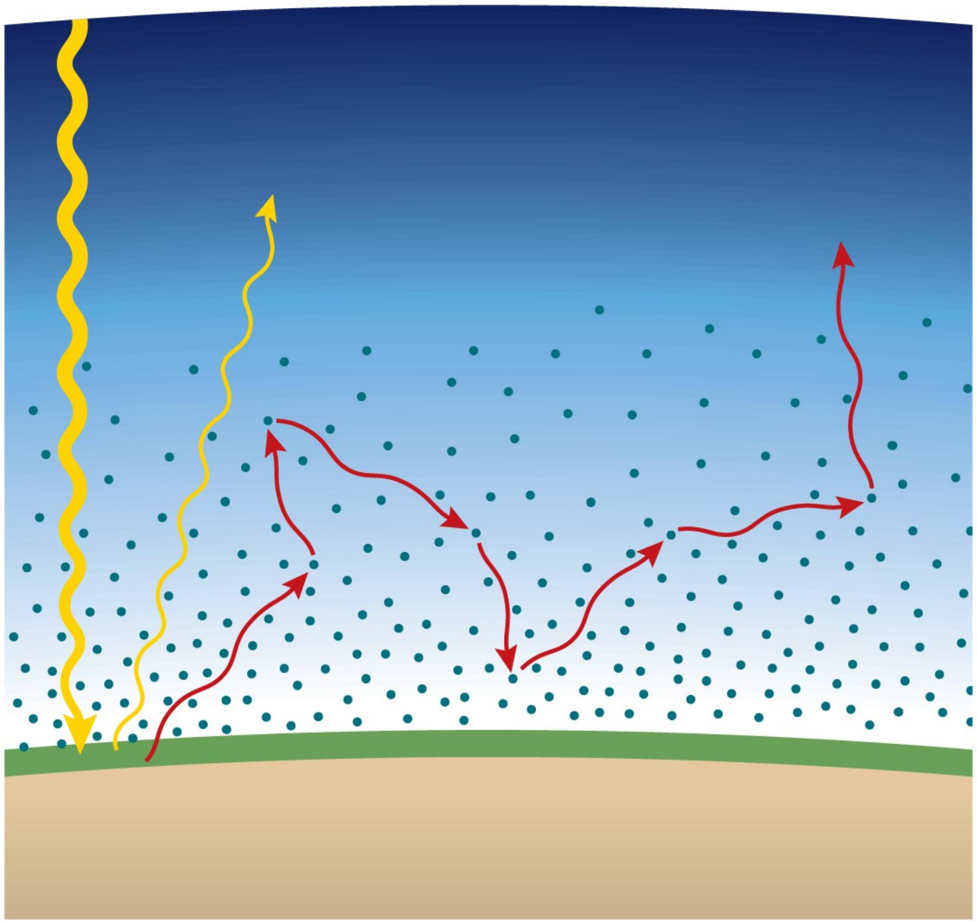
Effects of Atmospheres

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

How does the greenhouse effect warm a planet?



Greenhouse Effect

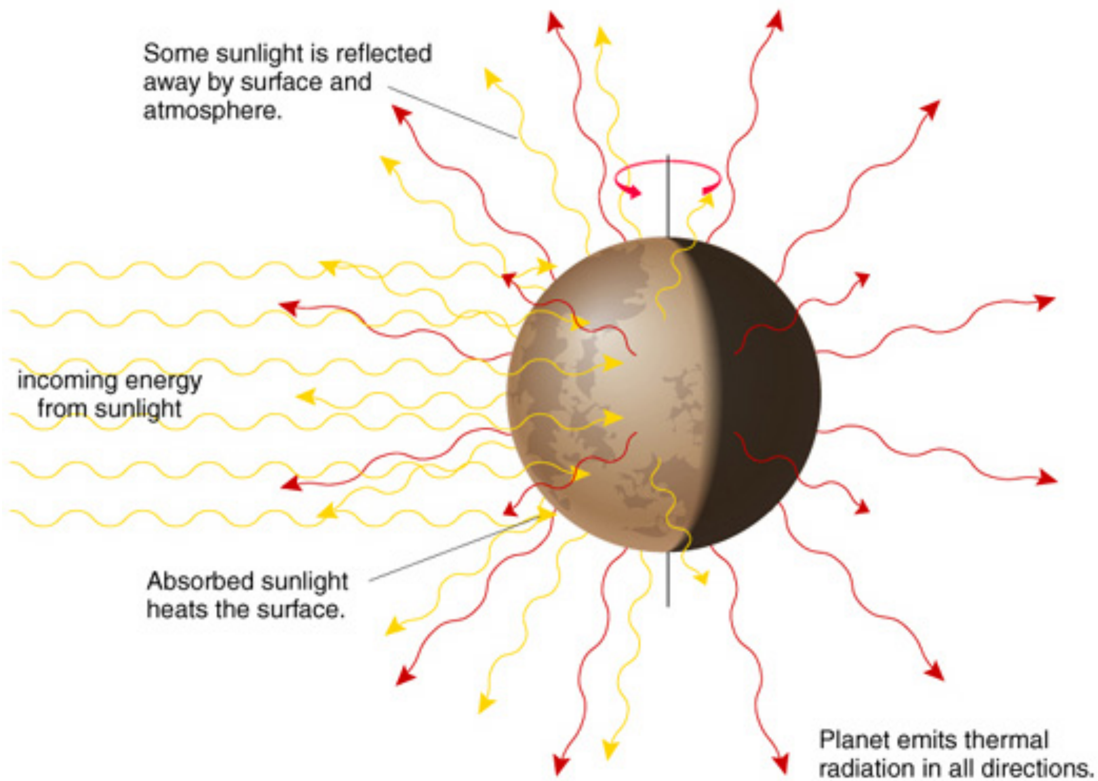


- Visible light passes through the atmosphere and warms a planet's surface.
- The atmosphere absorbs infrared light from the surface, trapping heat.

Planetary Temperature

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

Source: LASP



Temperature and Distance

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

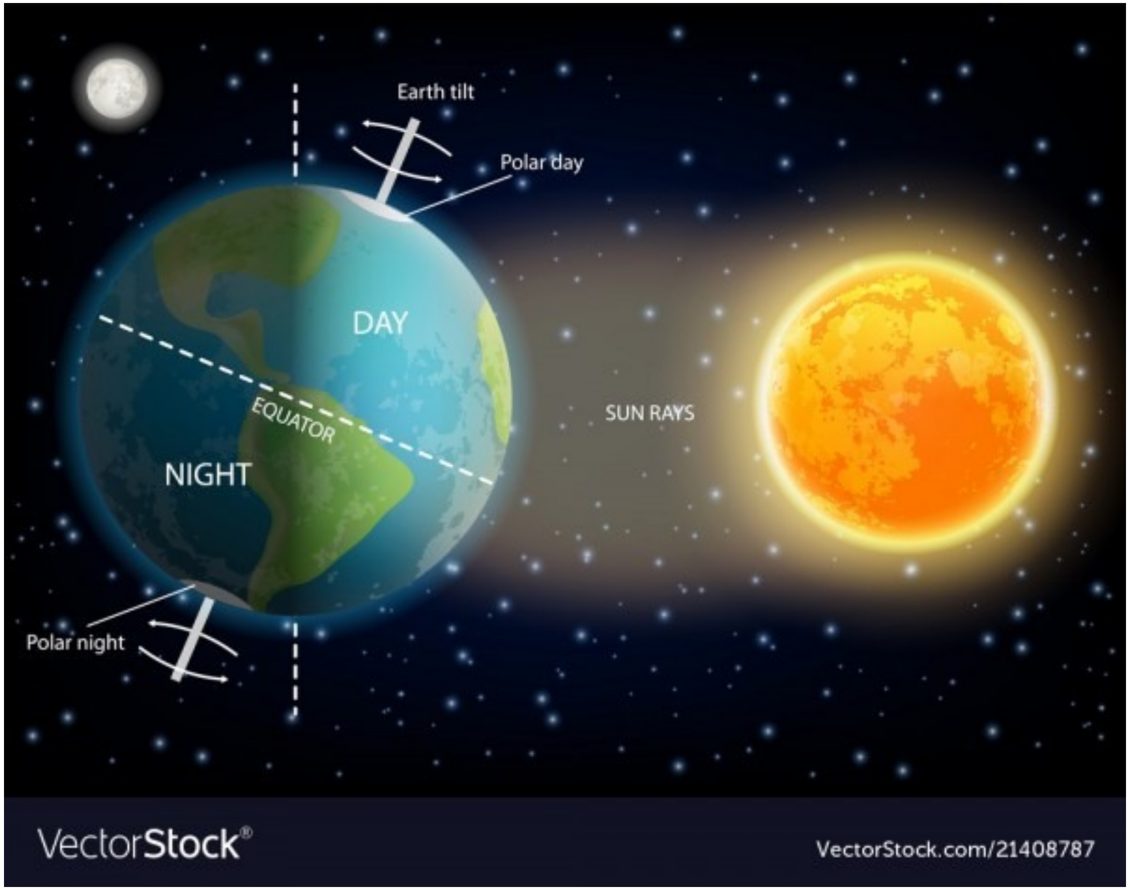
For Earth:

- ~1,360 Watt / m^2 at the top of the atmosphere
- ~1,000 Watt / m^2 at sea level

Why do we see this difference?

Temperature and Rotation

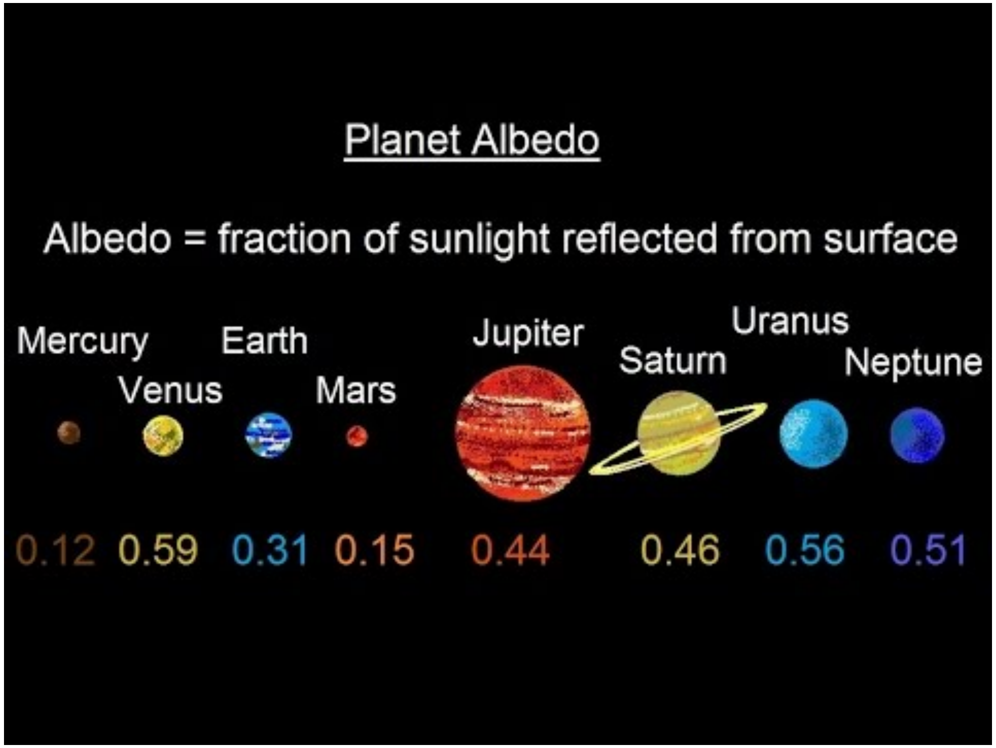
- A planet's rotation rate affects the temperature differences between day and night.



Temperature and Reflectivity

- A planet's reflectivity (or *albedo*) is the fraction of incoming sunlight it reflects.
- Planets with low albedo absorb more sunlight, leading to hotter temperatures.

Credit: lectureonline.com



"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.

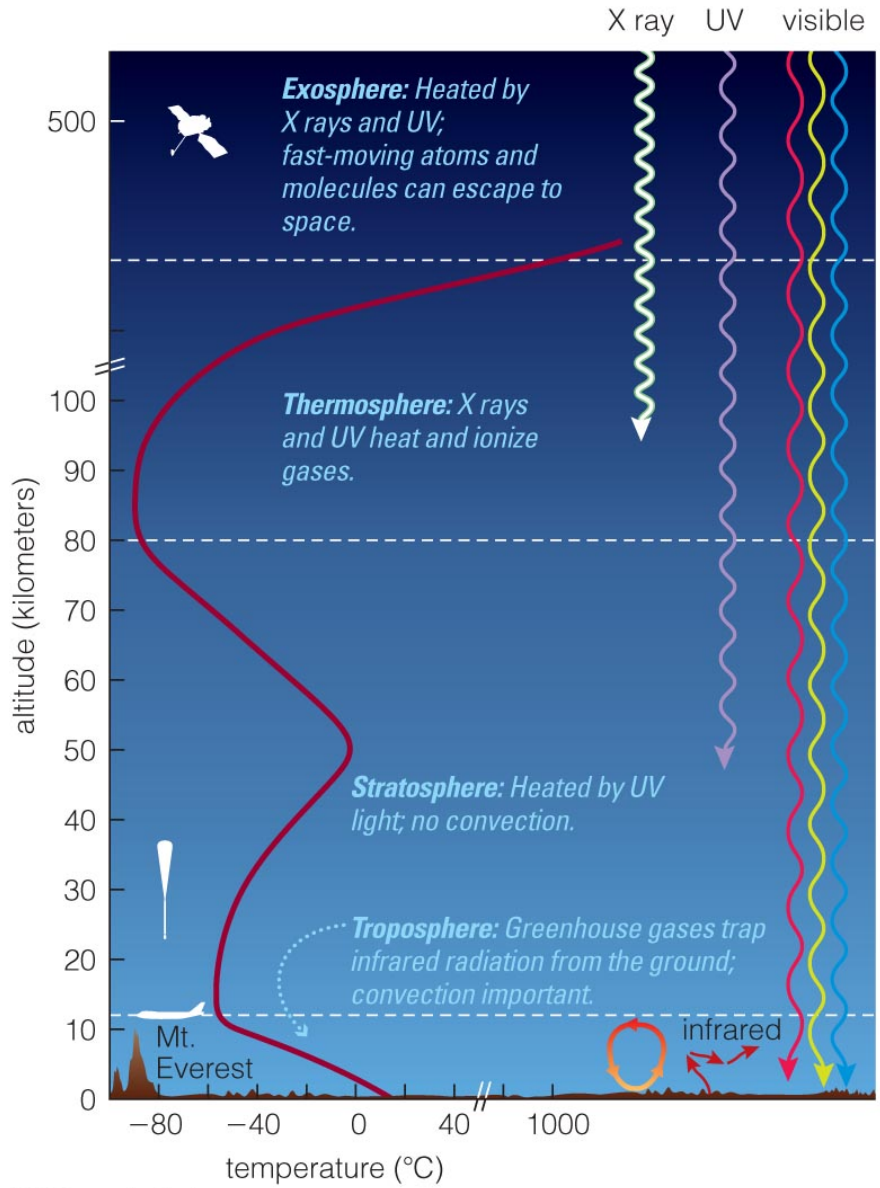
Thought Question

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

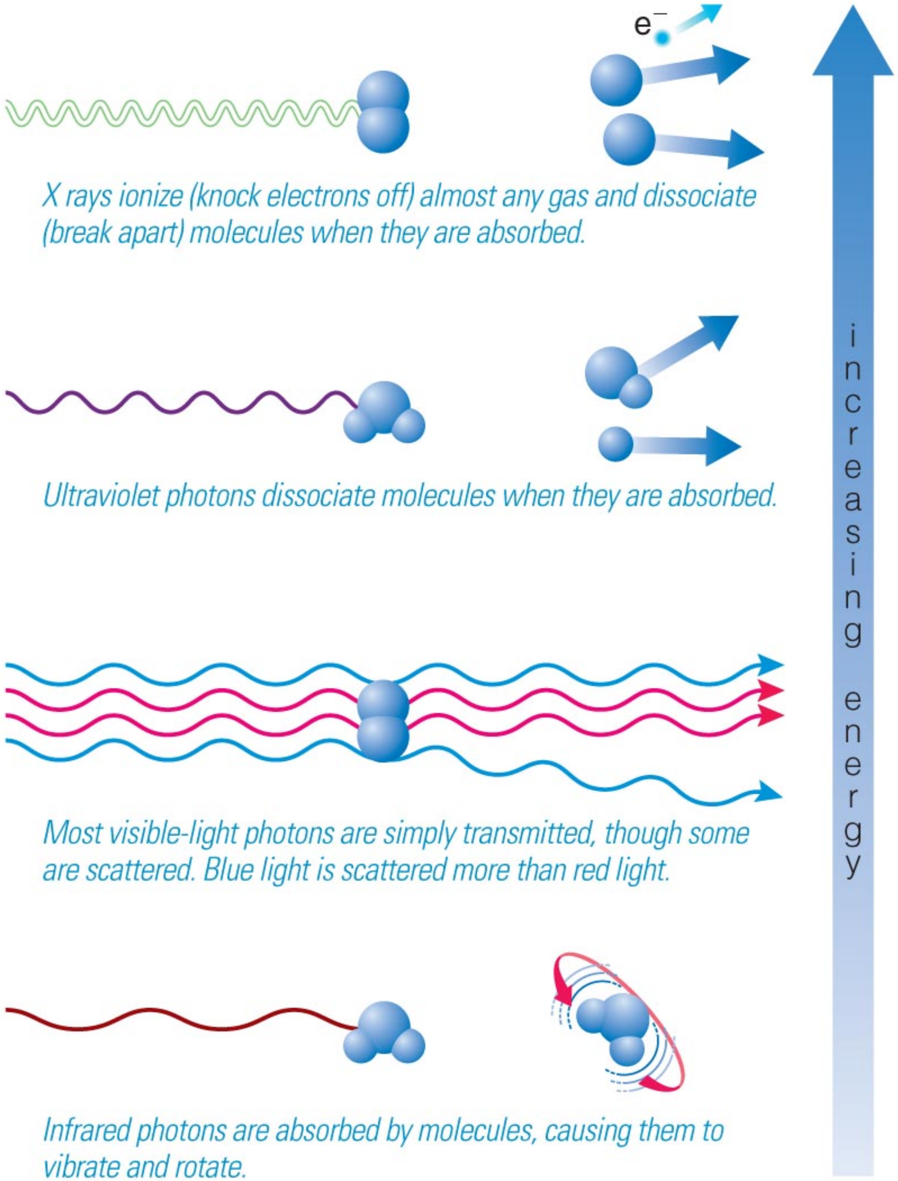
a) It would go up a little (less than 10° C).
b) It would go up a lot (more than 10° C).
c) It would go down a little (less than 10° C).
d) It would go down a lot (more than 10° C).
e) It would not change.

No atmosphere: no greenhouse effect!

Why do atmospheric properties vary with altitude?

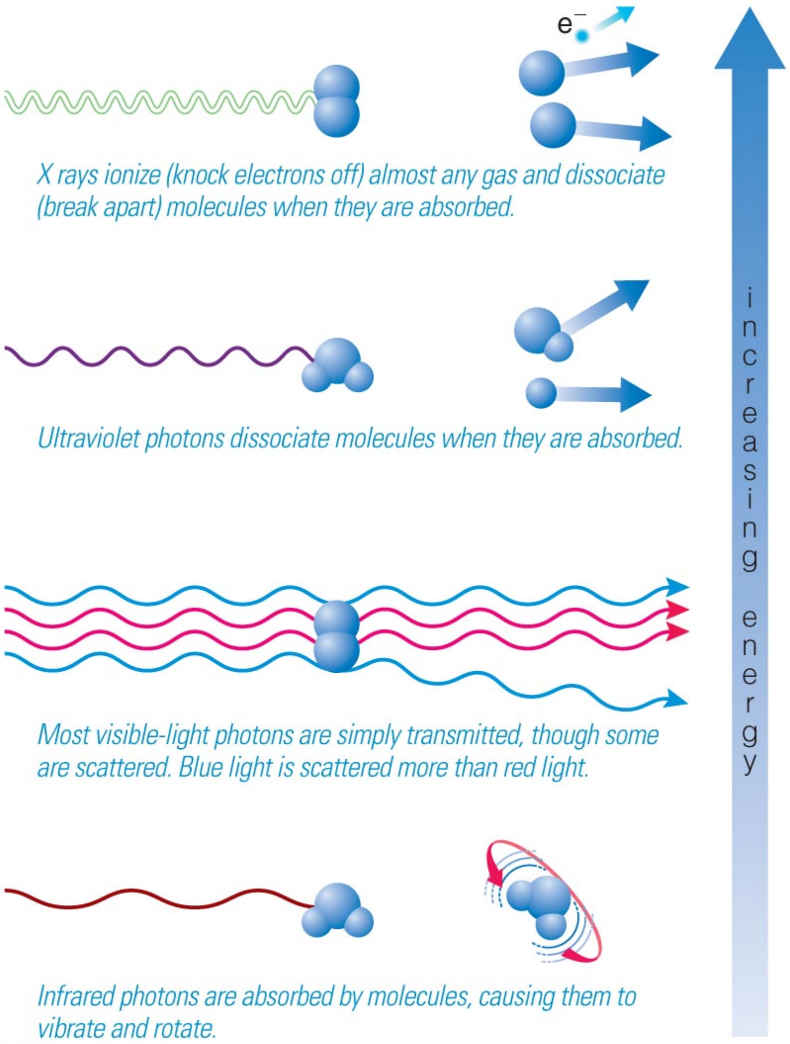


Light's Effects on Atmosphere



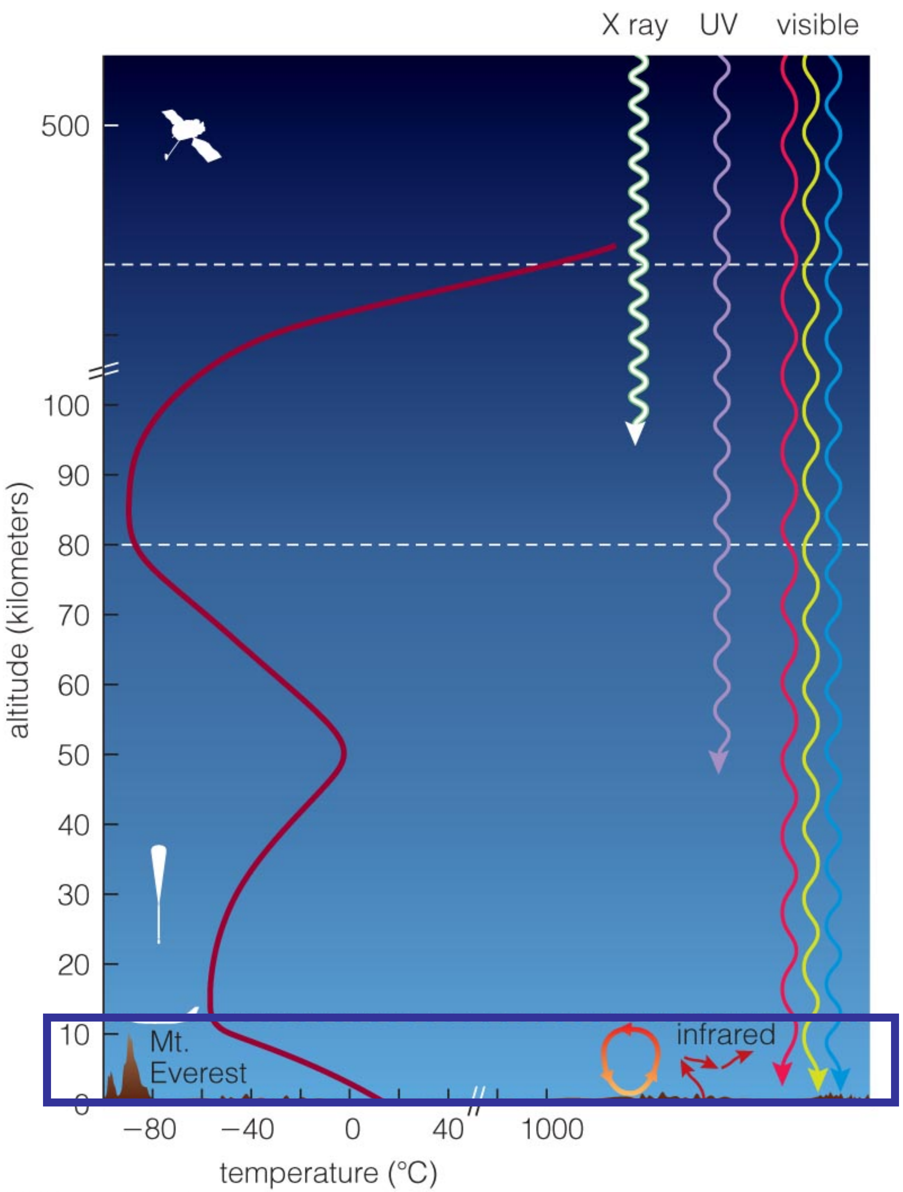
- **Ionization:** removal of an electron
- **Dissociation:** destruction of a molecule
- **Scattering:** change in photon's direction
- **Absorption:** photon's energy is absorbed.

Light's Effects on Atmosphere



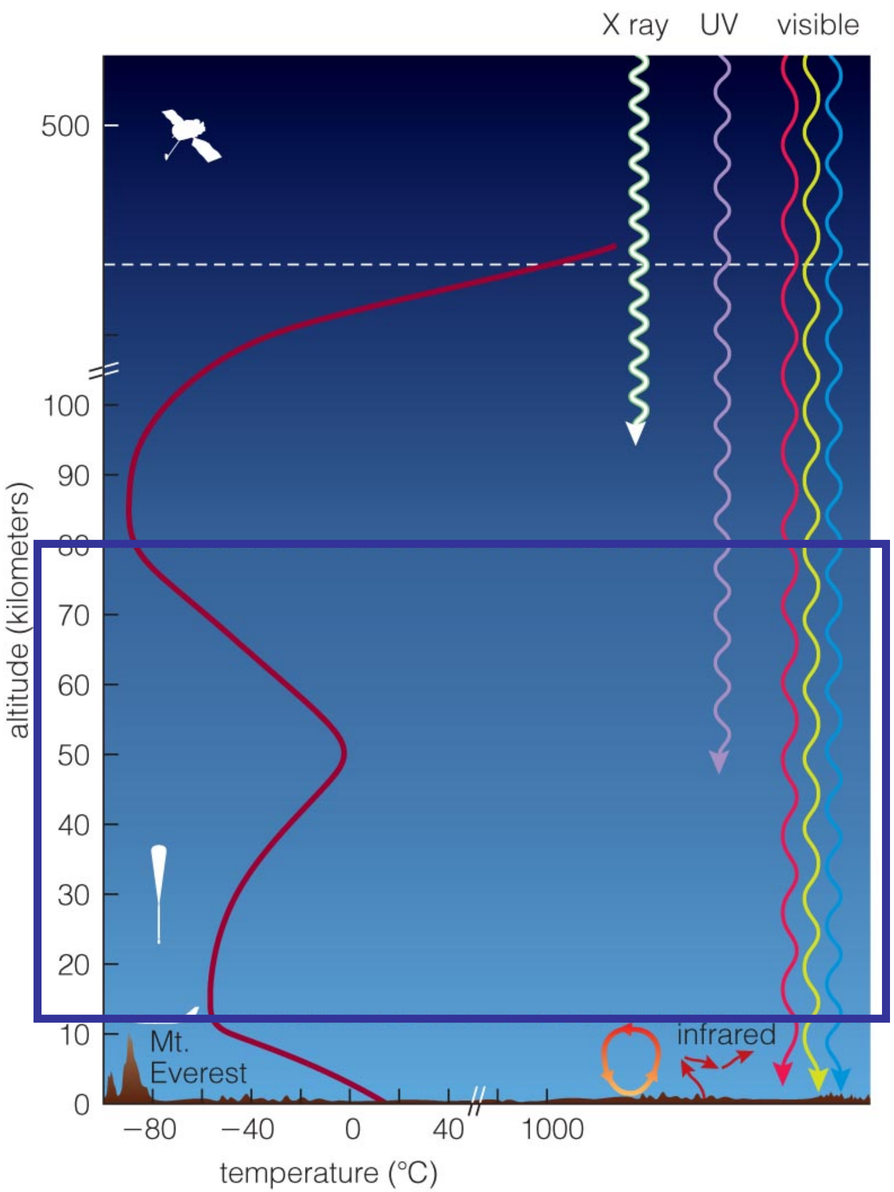
- X rays and UV light can ionize and dissociate molecules.
- Molecules tend to scatter blue light more than red.
- Molecules can absorb infrared light.

Earth's Atmospheric Structure



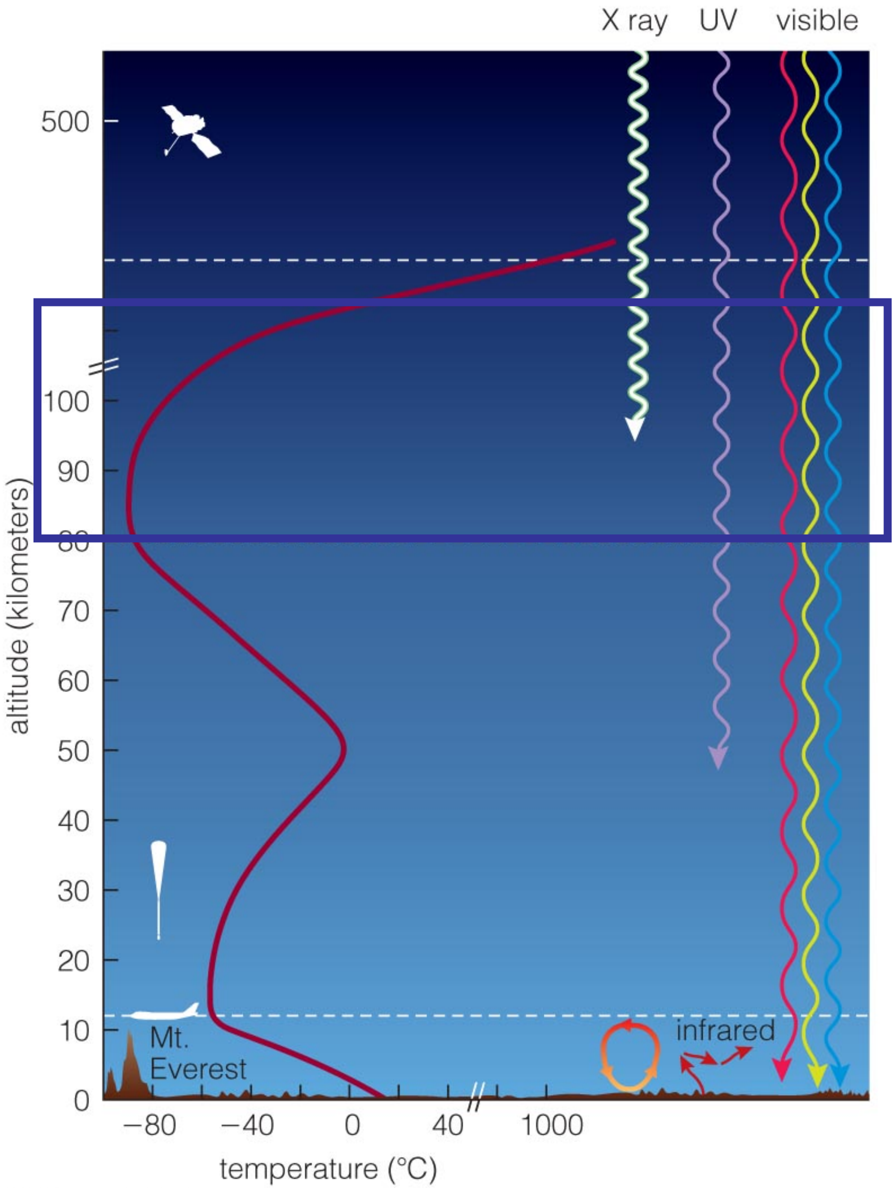
- **Troposphere:** lowest layer of Earth's atmosphere
- Temperature drops with altitude.
- Warmed by infrared light from surface and convection

Earth's Atmospheric Structure



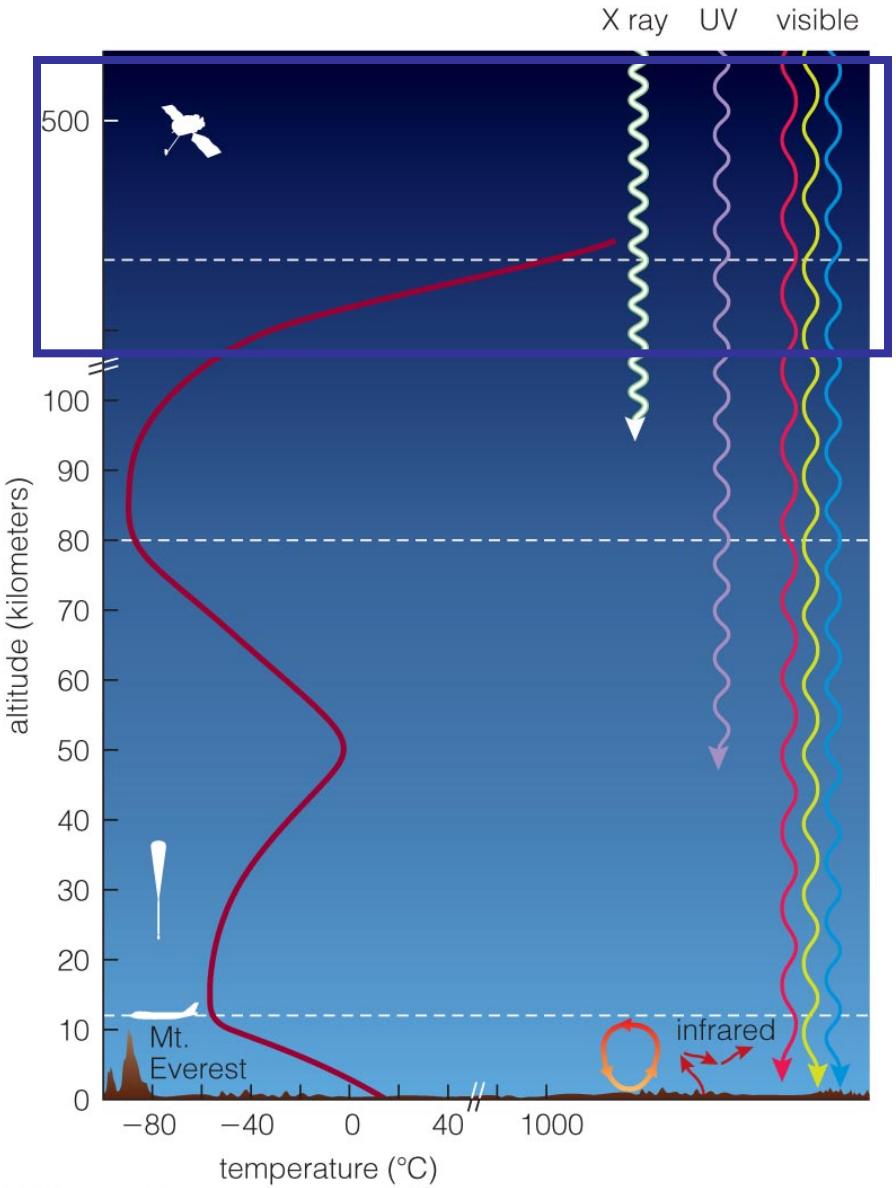
- **Stratosphere:** layer above the troposphere
- Temperature rises with altitude in lower part, drops with altitude in upper part.
- Warmed by absorption of ultraviolet sunlight

Earth's Atmospheric Structure



- **Thermosphere:** layer at about 100 kilometers altitude
- Temperature rises with altitude.
- X rays and ultraviolet light from the Sun heat and ionize gases.

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?

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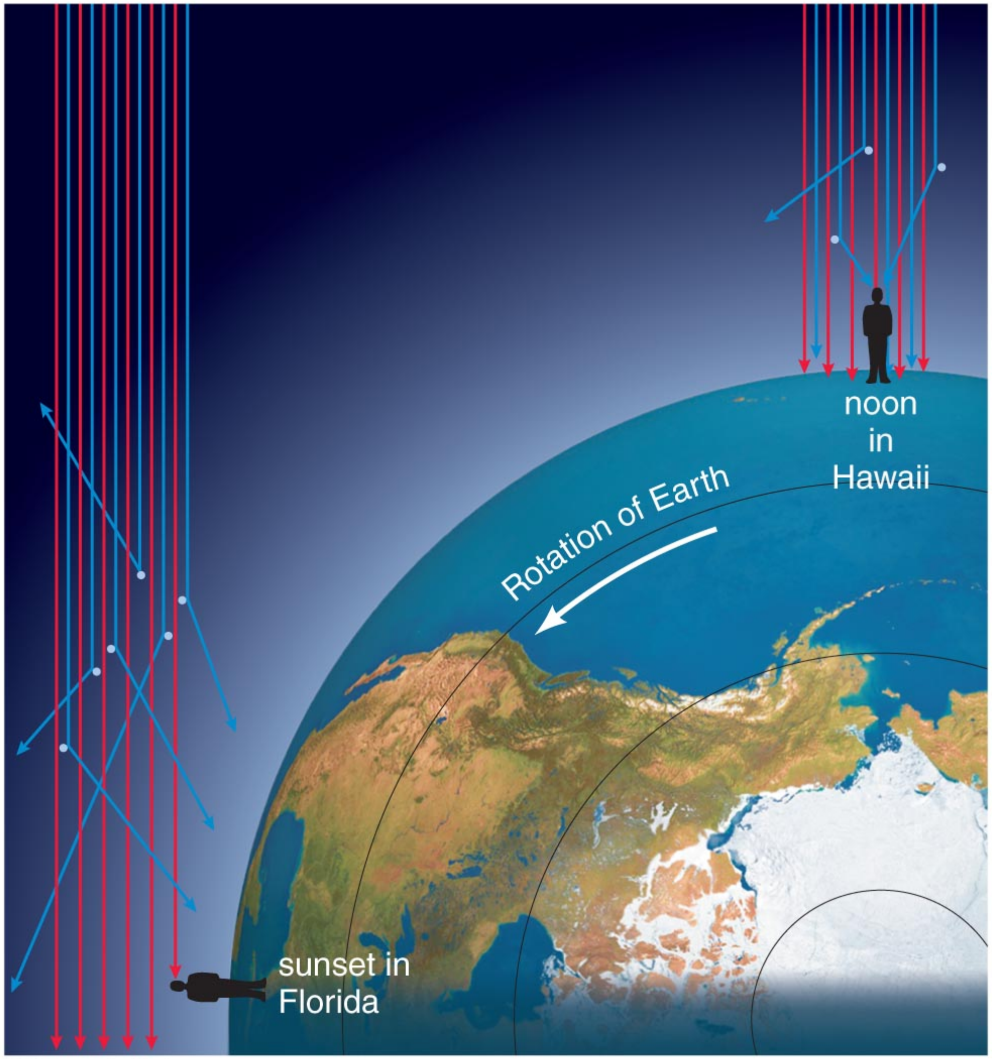
Why the Sky Is Blue



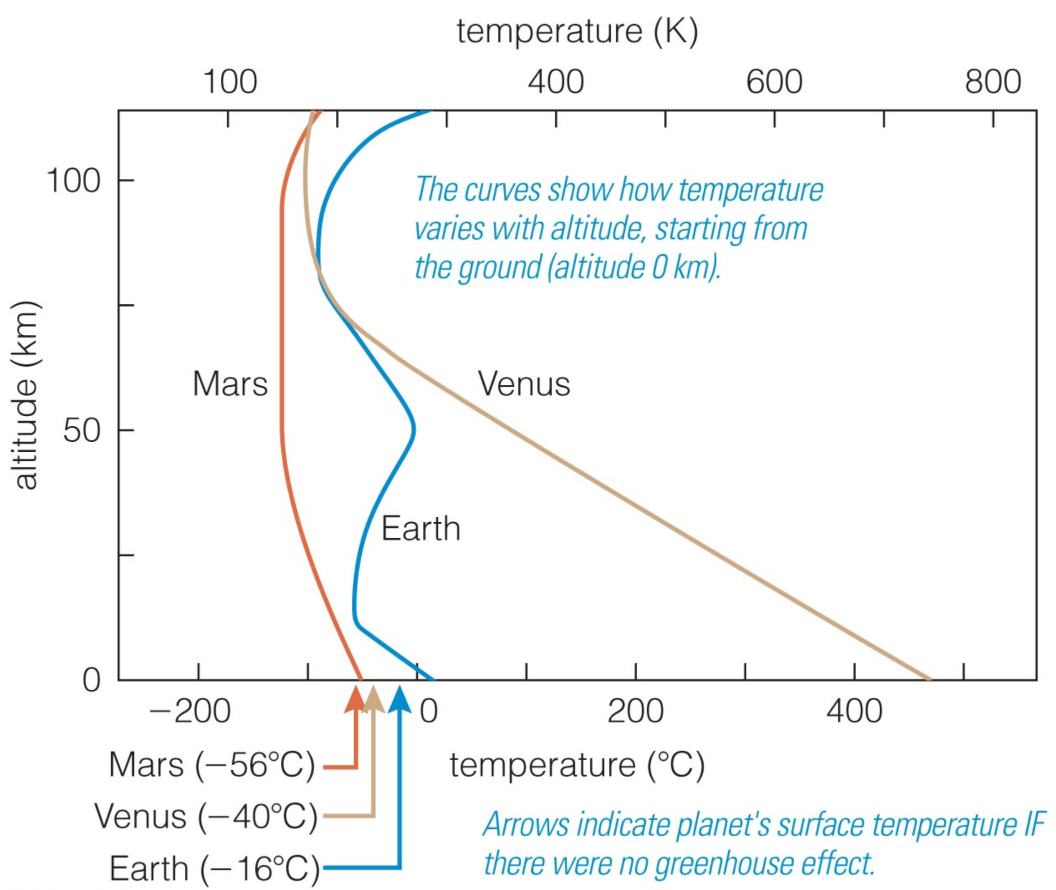
- Atmosphere scatters blue light from Sun, making it appear to come from different directions.
- Sunsets and sunrises are red because the blue light has been already scattered out before reaching your eyes.

Obviously the blue color is due to the atmosphere

The sky from Moon

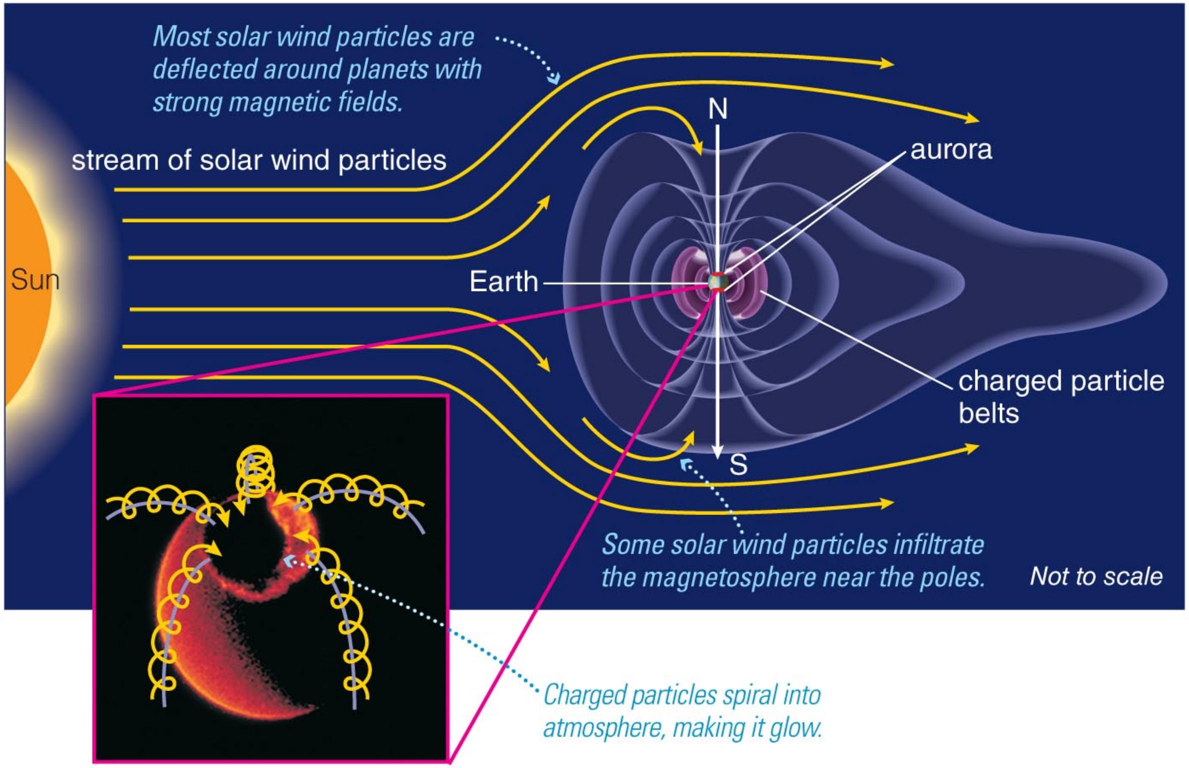
The sky from Earth

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.

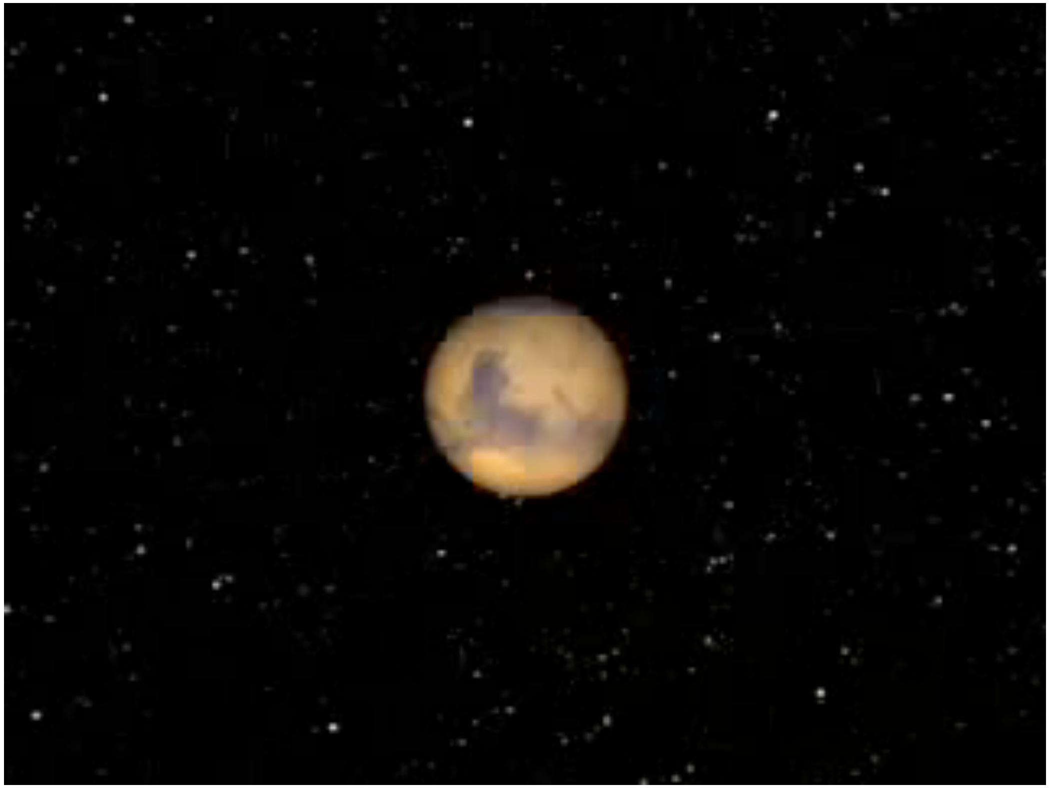
Earth's Magnetosphere



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.

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

The solar wind in case the atmosphere is basically lacking



A simulation of Mars

Aurora

b This photograph shows the aurora near Yellowknife, Northwest Territories, Canada. In a video, you would see these lights dancing about in the sky.

- Charged particles from solar wind energize the upper atmosphere near magnetic poles, causing an aurora.

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

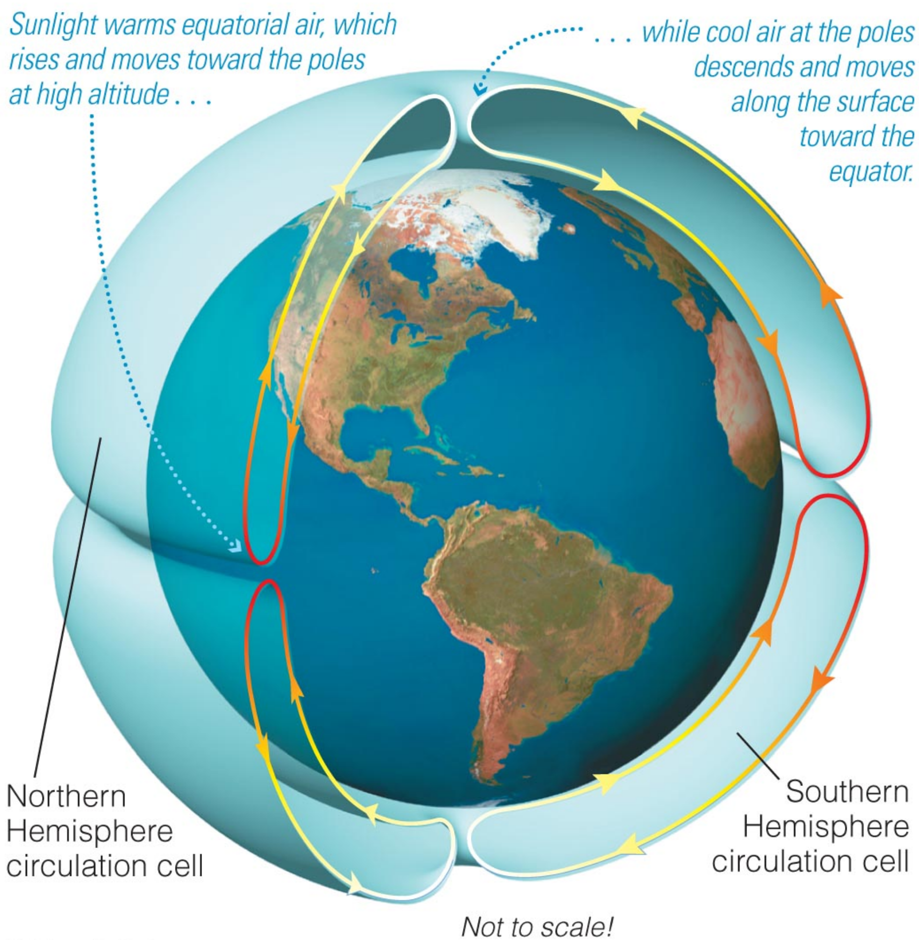
- **Weather** is the ever-varying, short-term combination of wind, clouds, temperature, and pressure.
  - Local complexity of weather makes it difficult to predict.
- **Climate** is the long-term average of weather.
  - Long-term stability of climate depends on global conditions and is more predictable.

"short term" → hours to days
"long term" → years to centuries

Global Wind Patterns

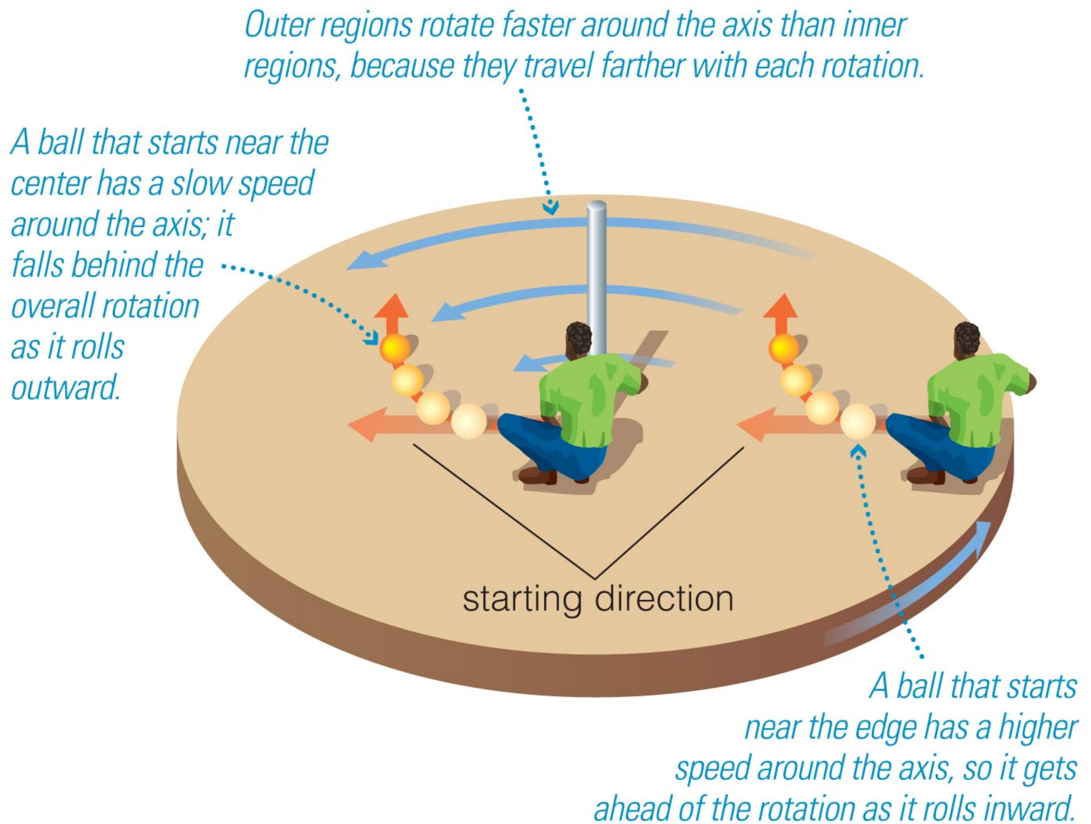
- Global winds blow in distinctive patterns:
  - Equatorial: E to W
  - Mid-latitudes: W to E
  - High latitudes: E to W

Circulation Cells: No Rotation



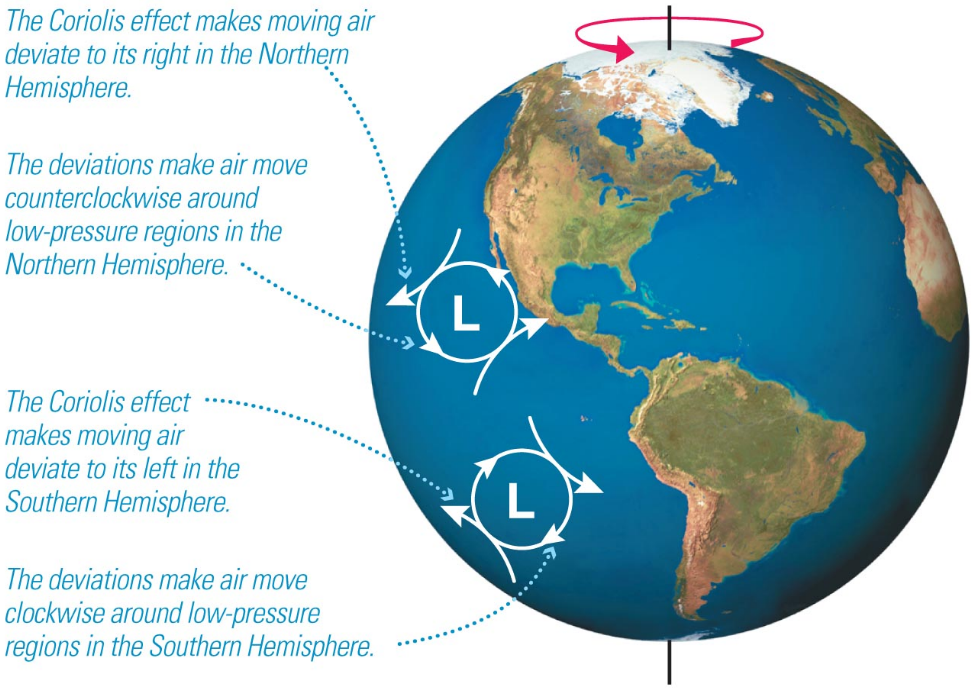
- Heated air rises at equator.
- Cooler air descends at poles.
- Without rotation, these motions would produce two large circulation cells.

Coriolis Effect



- Conservation of angular momentum causes a ball's apparent path on a spinning platform to change direction.

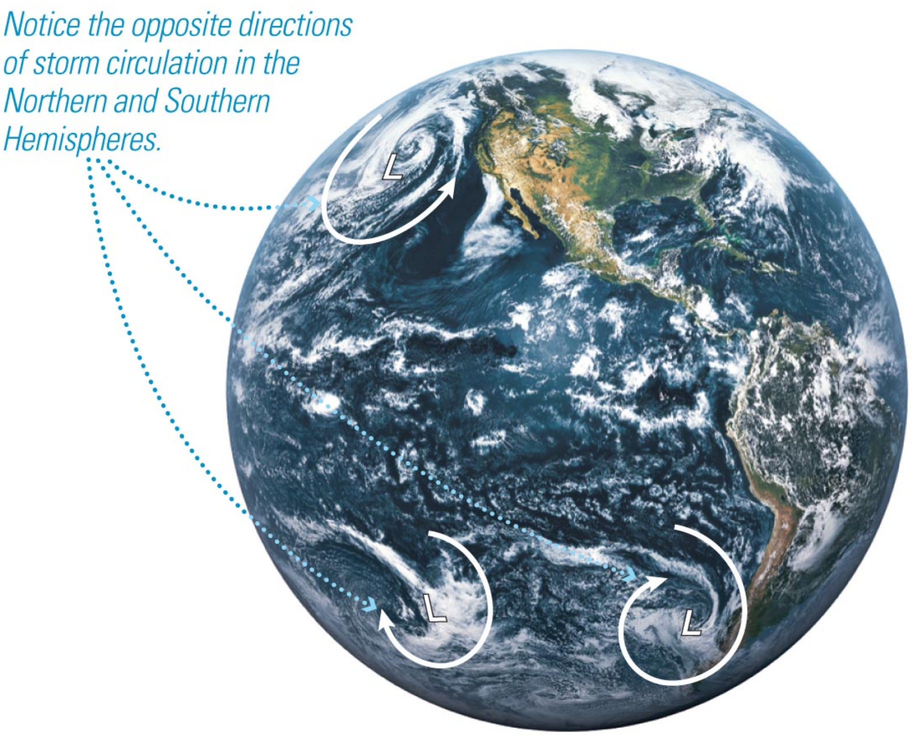
Coriolis Effect on Earth



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.

- 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.

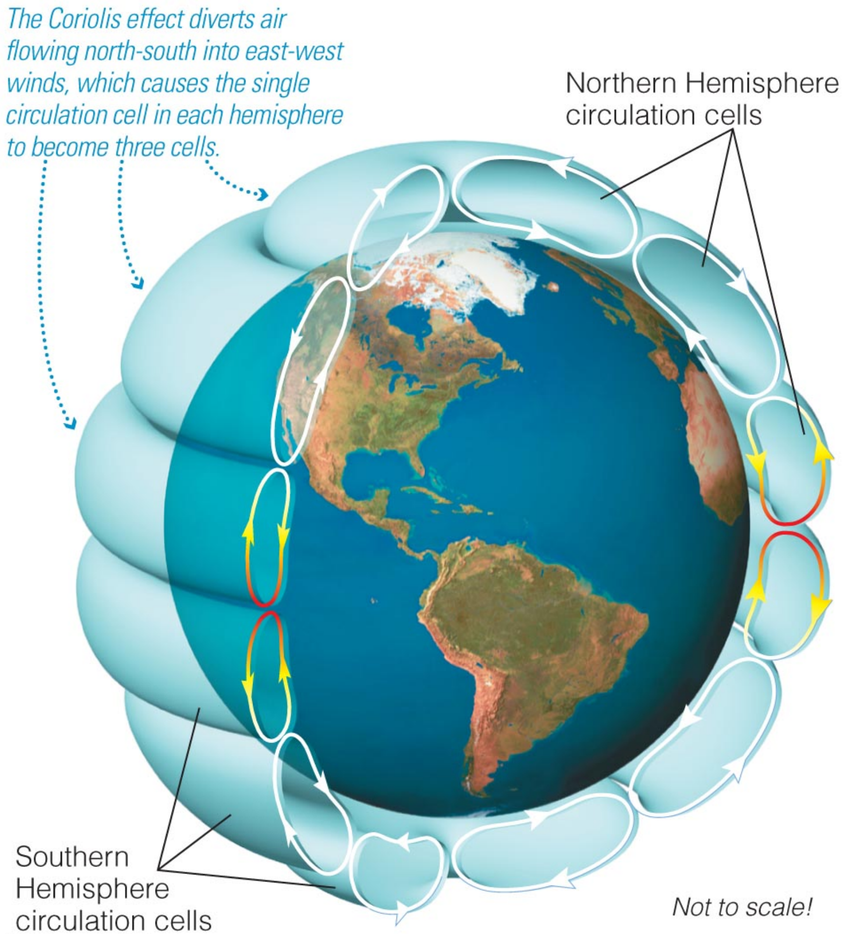
Coriolis Effect on Earth



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

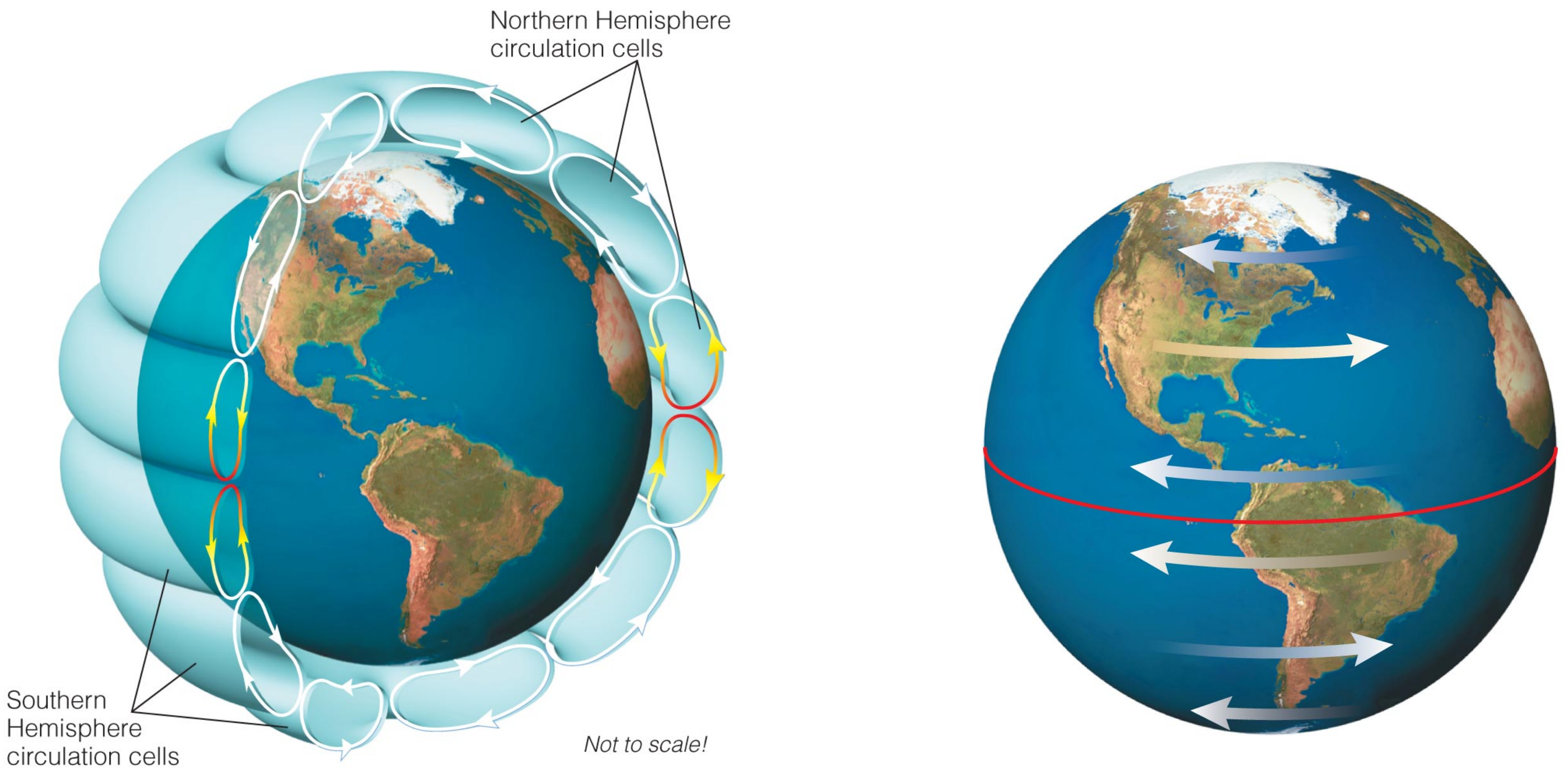
- Conservation of angular momentum causes large storms to swirl.
- Direction of circulation depends on hemisphere:
  - N: counterclockwise
  - S: clockwise

Circulation Cells with Rotation



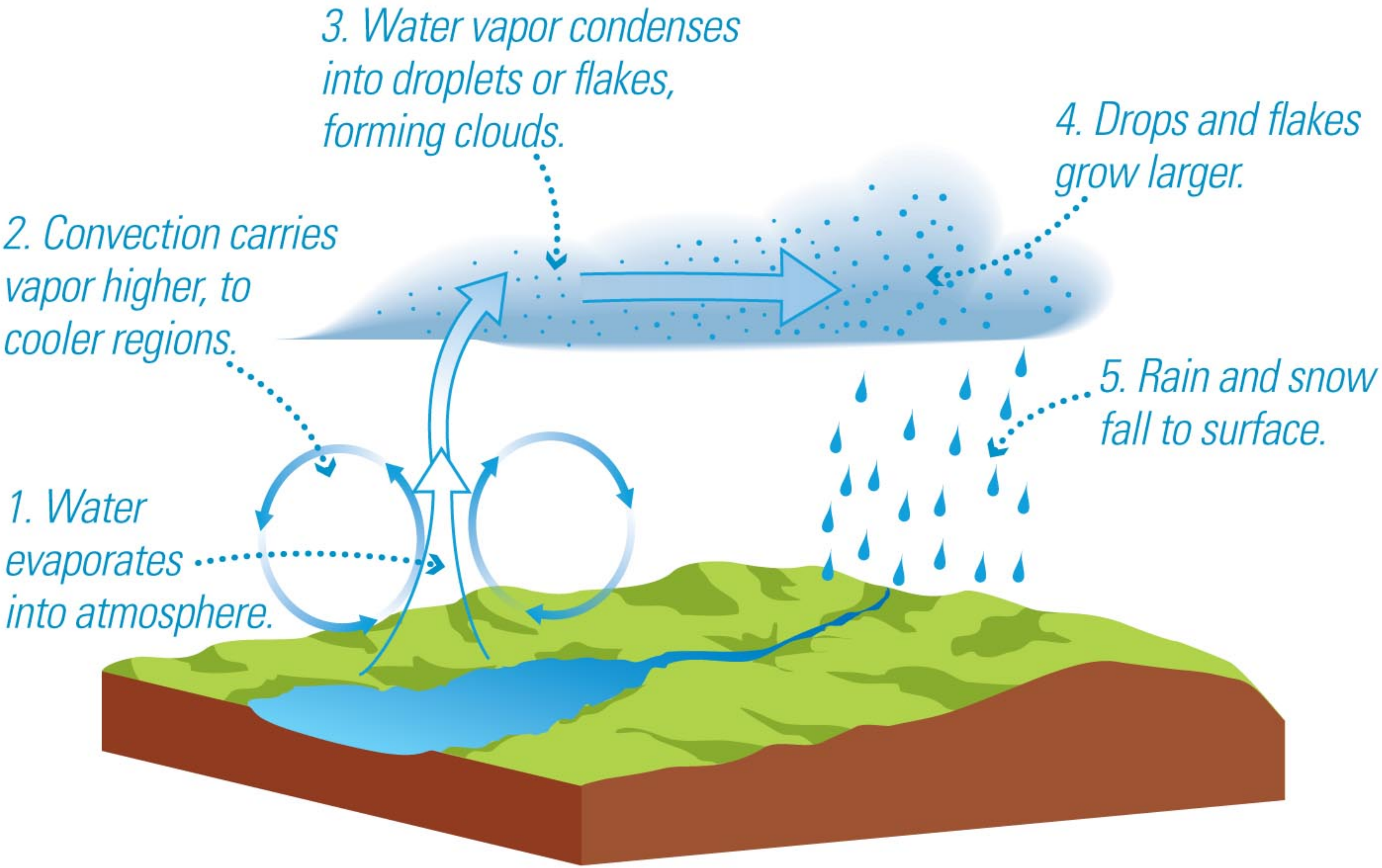
- Coriolis effect deflects north-south winds into east-west winds.
- Deflection breaks each of the two large "no-rotation" cells into three smaller cells.

Prevailing Winds

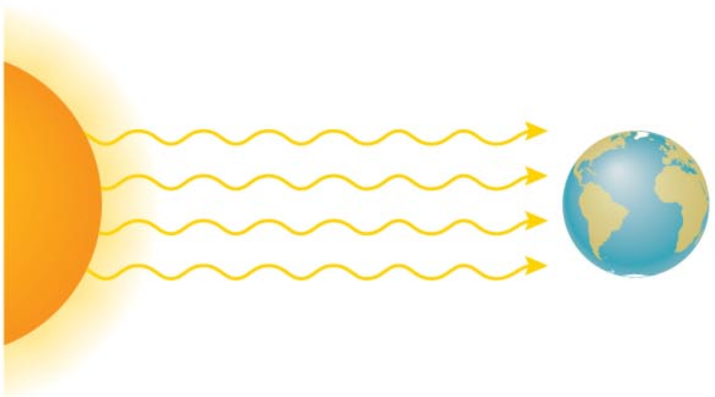


- Prevailing surface winds at mid-latitudes blow from W to E because the Coriolis effect deflects the S to N surface flow of mid-latitude circulation cells.

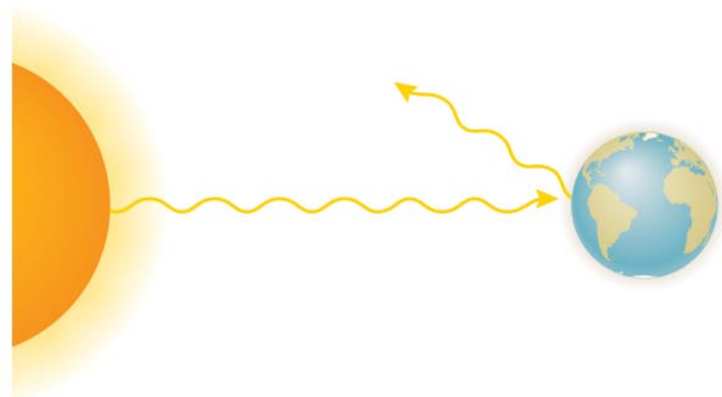
Clouds and Precipitation



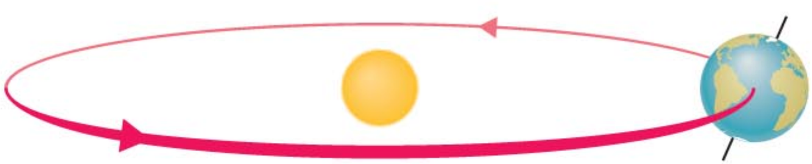
What factors can cause long-term climate change?



Solar brightening: *As the Sun brightens with time, the increasing sunlight tends to warm the planets.*



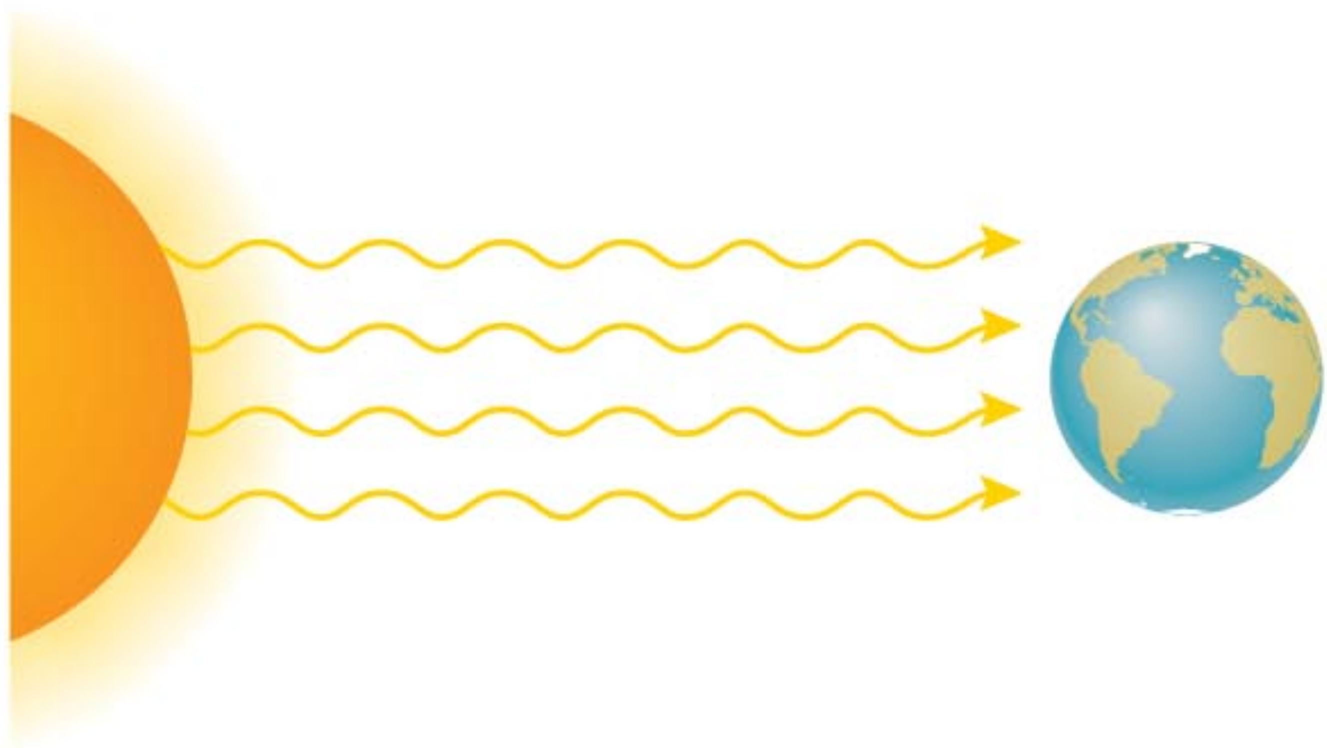
Changes in reflectivity: *Higher reflectivity tends to cool a planet, while lower reflectivity leads to warming.*



Changes in axis tilt: *Greater tilt makes more extreme seasons, while smaller tilt keeps polar regions colder.*

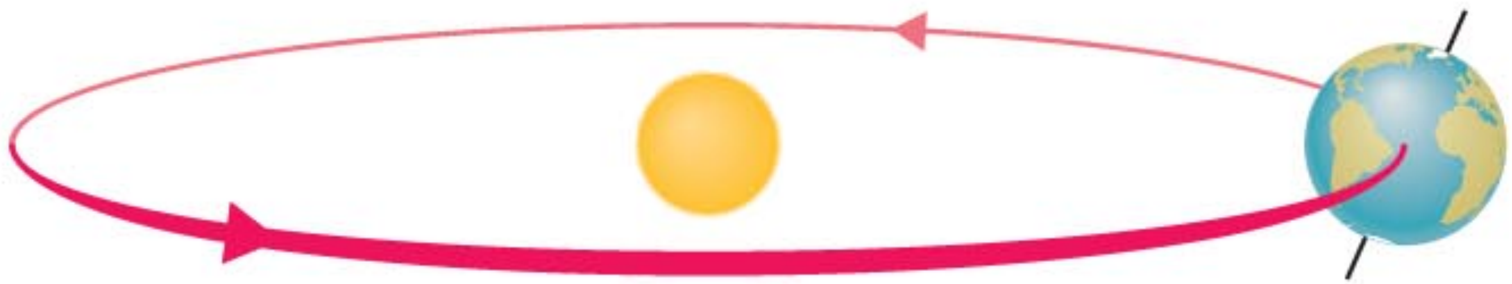
Changes in greenhouse gas abundance: *An increase in greenhouse gases slows escape of infrared radiation, warming the planet, while a decrease leads to cooling.*

Solar Brightening



- The Sun very gradually grows brighter with time, increasing the amount of sunlight warming the planets.

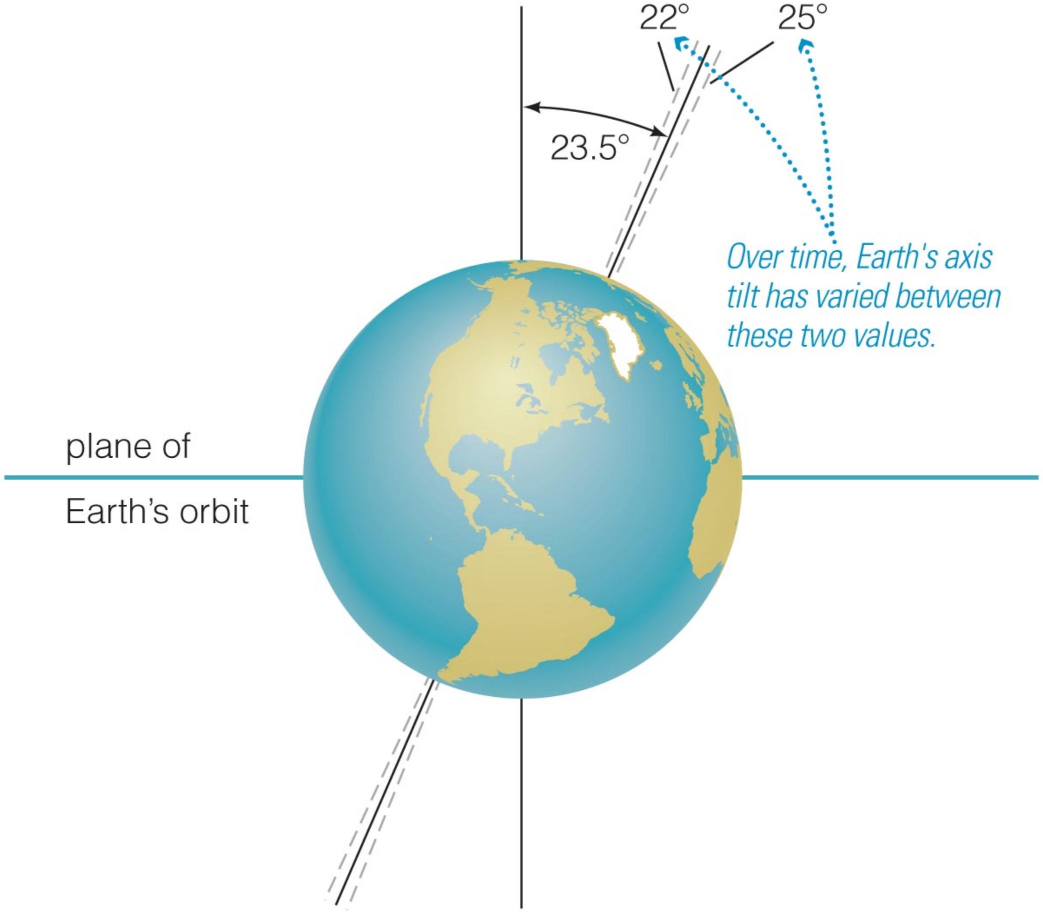
Changes in Axis Tilt



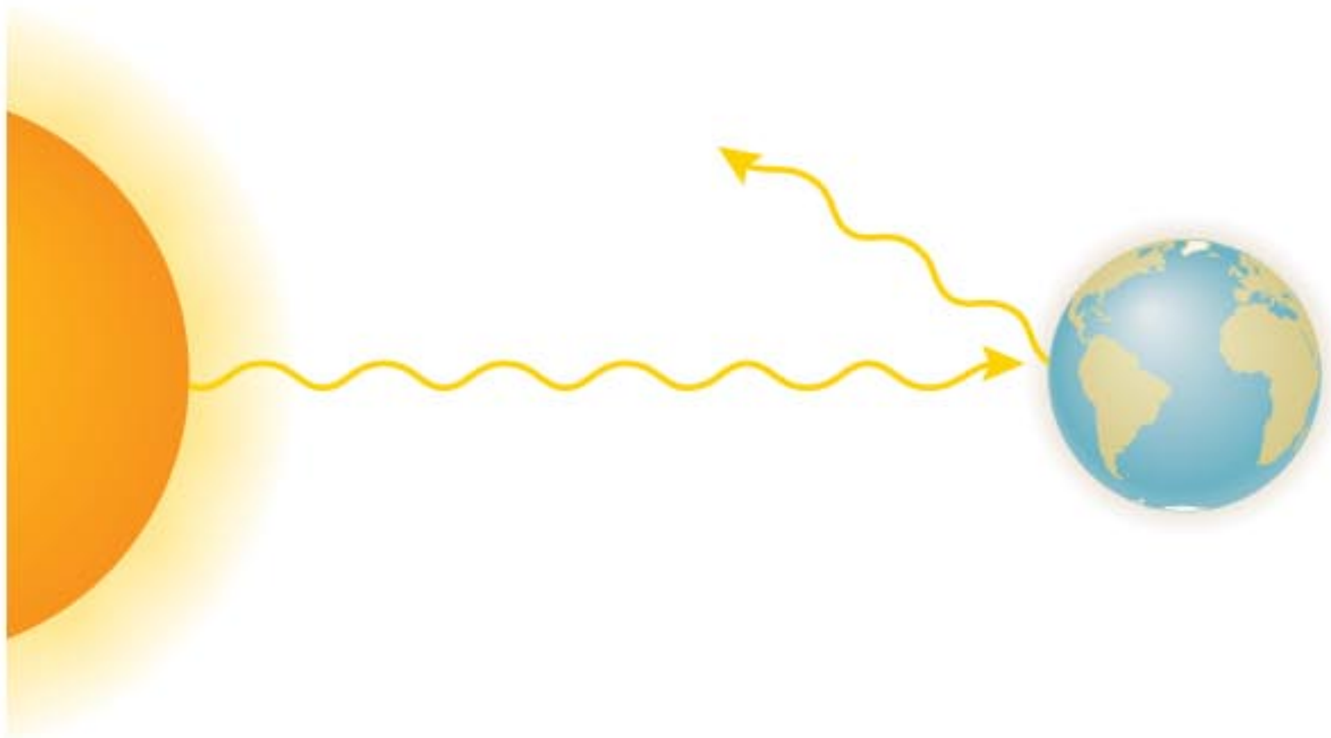
- Greater tilt creates more extreme seasons, while smaller tilt keeps polar regions colder.

Changes in Axis Tilt

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



Changes in Reflectivity



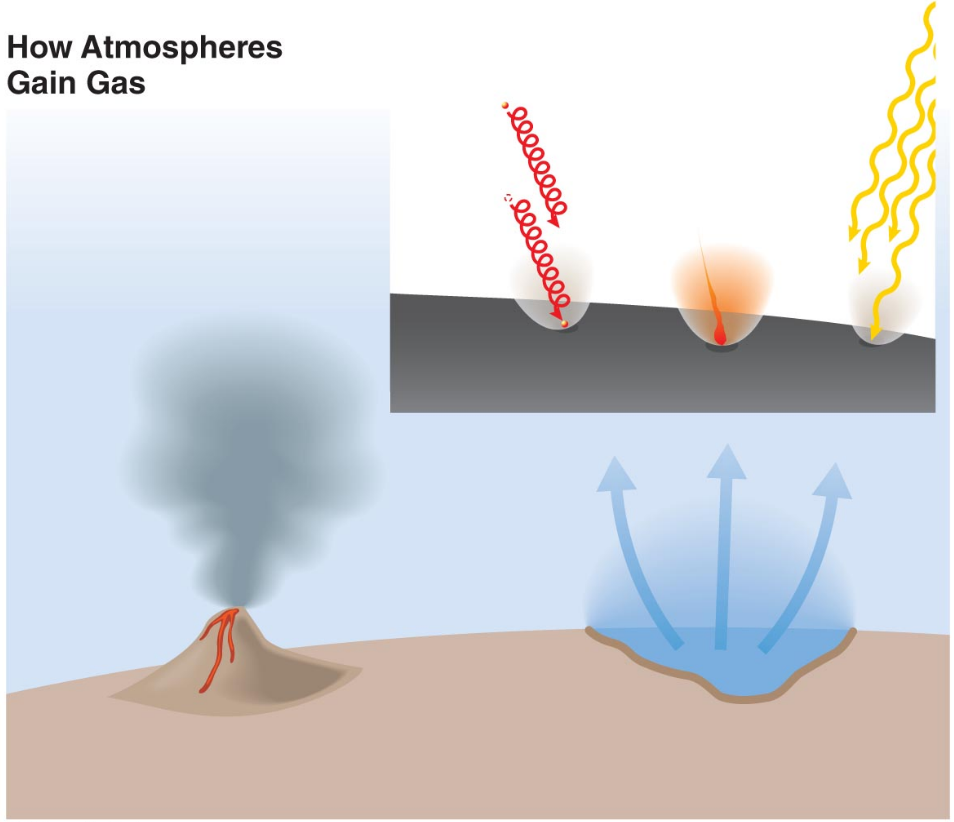
- Higher reflectivity tends to cool a planet, while lower reflectivity leads to warming.

Changes in Greenhouse Gases

- An increase in greenhouse gases leads to warming, while a decrease leads to cooling.

How does a planet gain or lose atmospheric gases?

Sources of Gas



Impacts of particles and photons

Outgassing from volcanoes

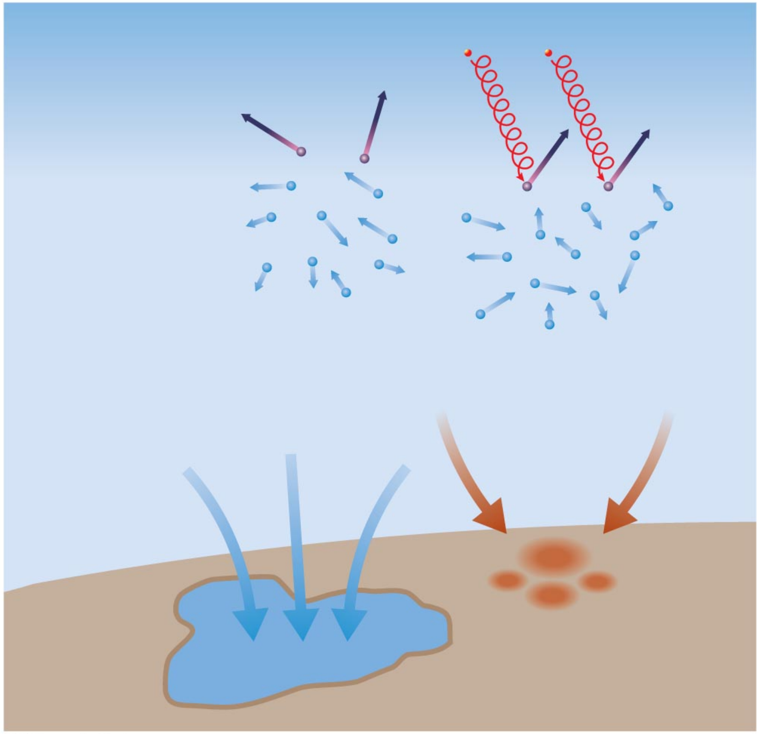
Evaporation of surface liquid; sublimation of surface ice

Losses of Gas

Thermal escape of atoms

Sweeping by solar wind

How Atmospheres Lose Gas

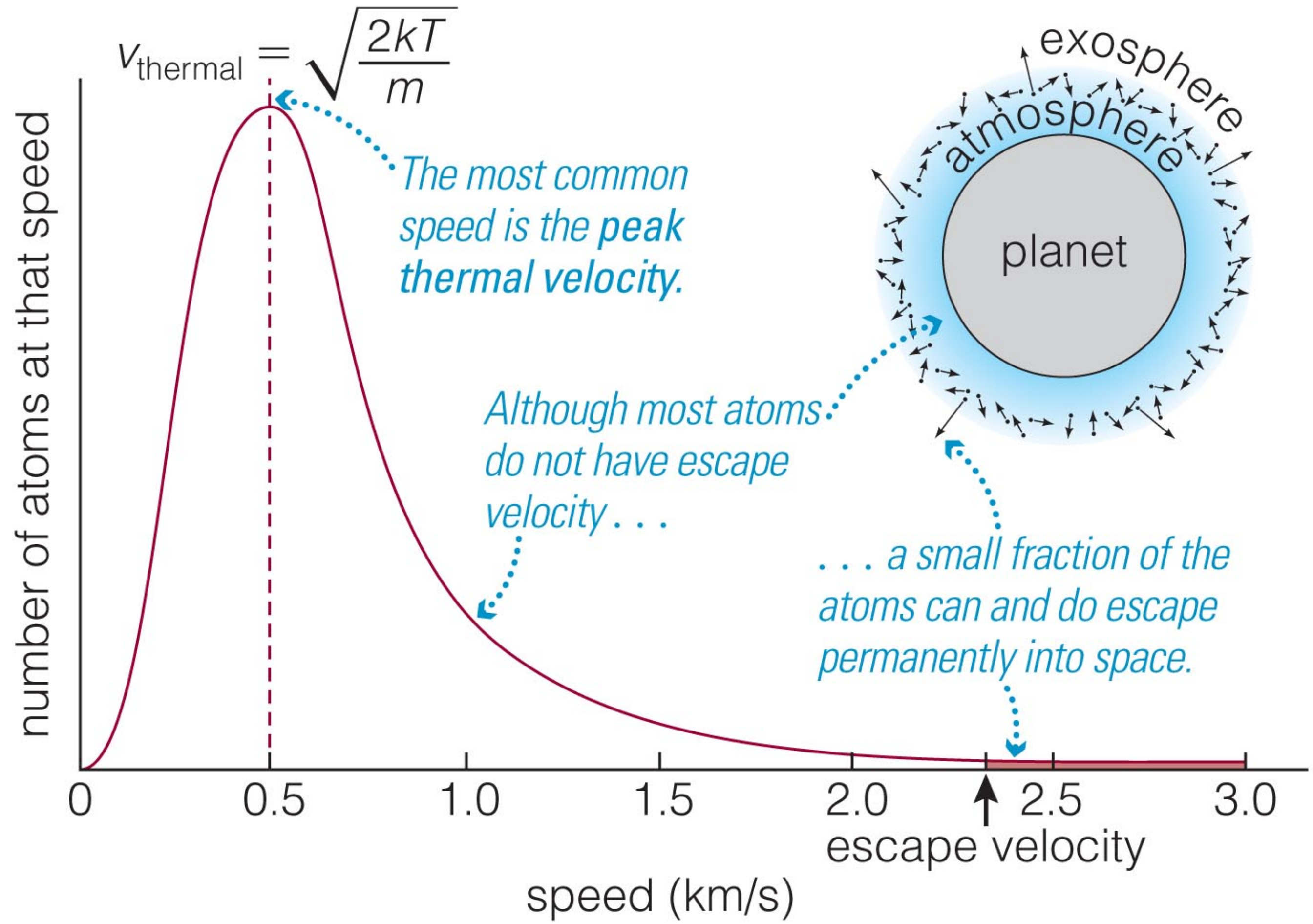


Condensation onto surface

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
  - Changes in reflectivity
  - Changes in greenhouse gases

What have we learned?

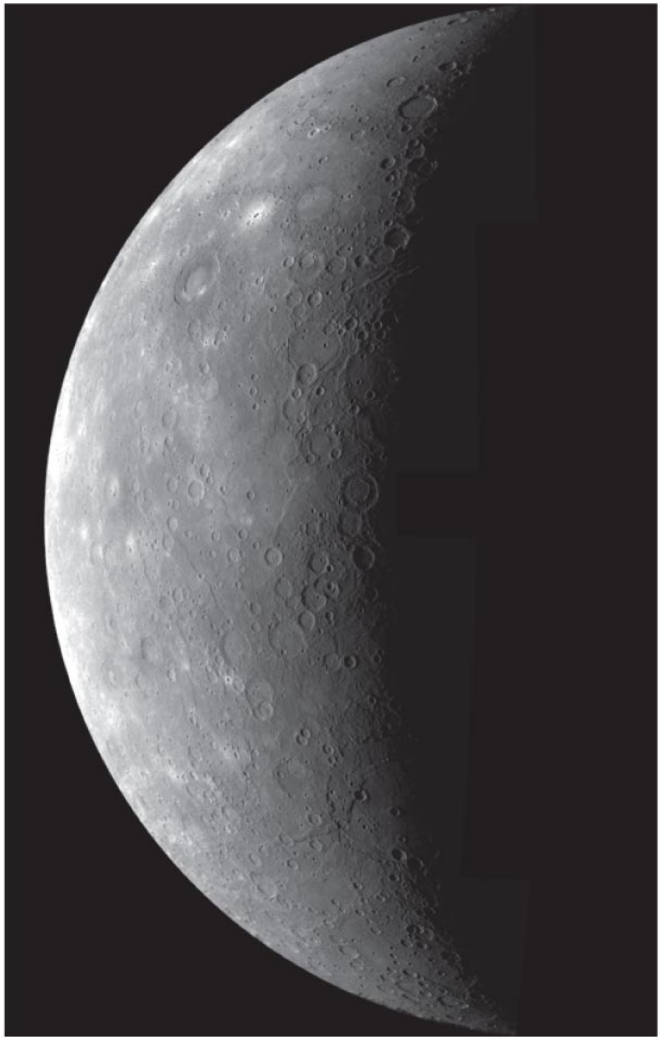
- **How does a planet gain or lose atmospheric gases?**
  - Gains: outgassing, evaporation/sublimation, and impacts by particles and photons
  - Losses: condensation, chemical reactions, blasting by large impacts, sweeping by solar winds, and thermal escape

10.3 Atmospheres of the Moon and Mercury

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

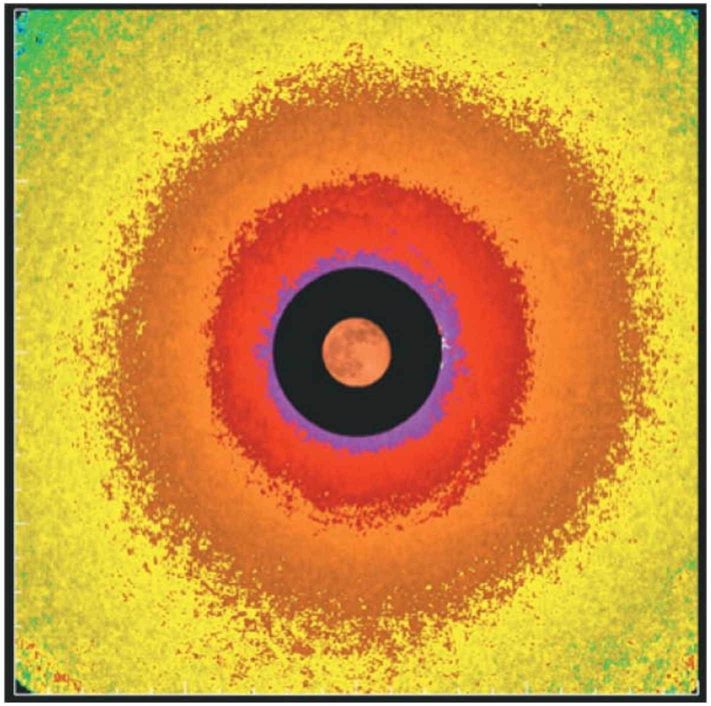
Do the Moon and Mercury have any atmosphere?

Moon

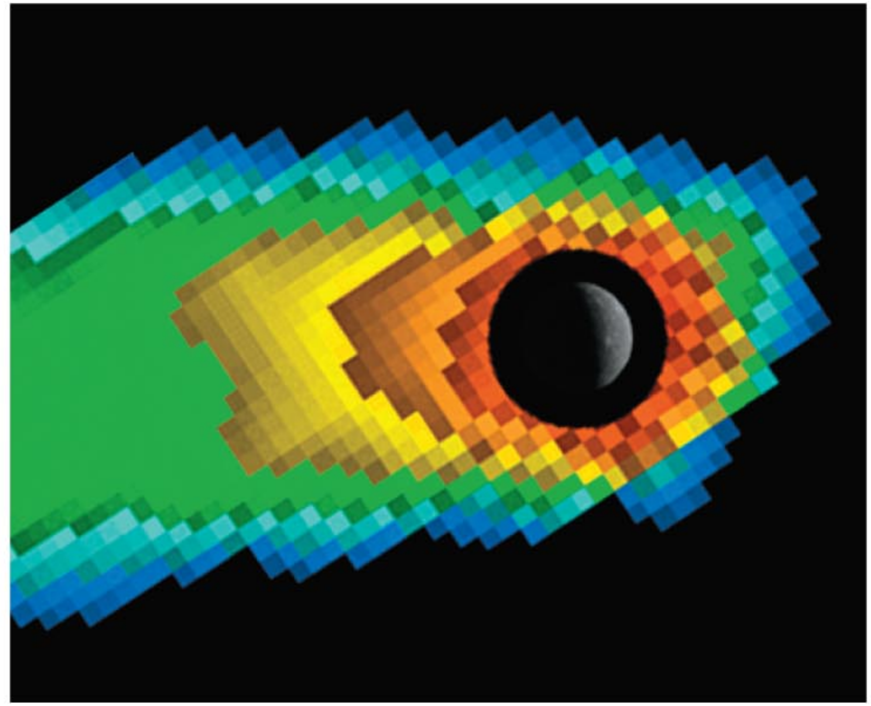


Mercury

Exospheres of the Moon and Mercury



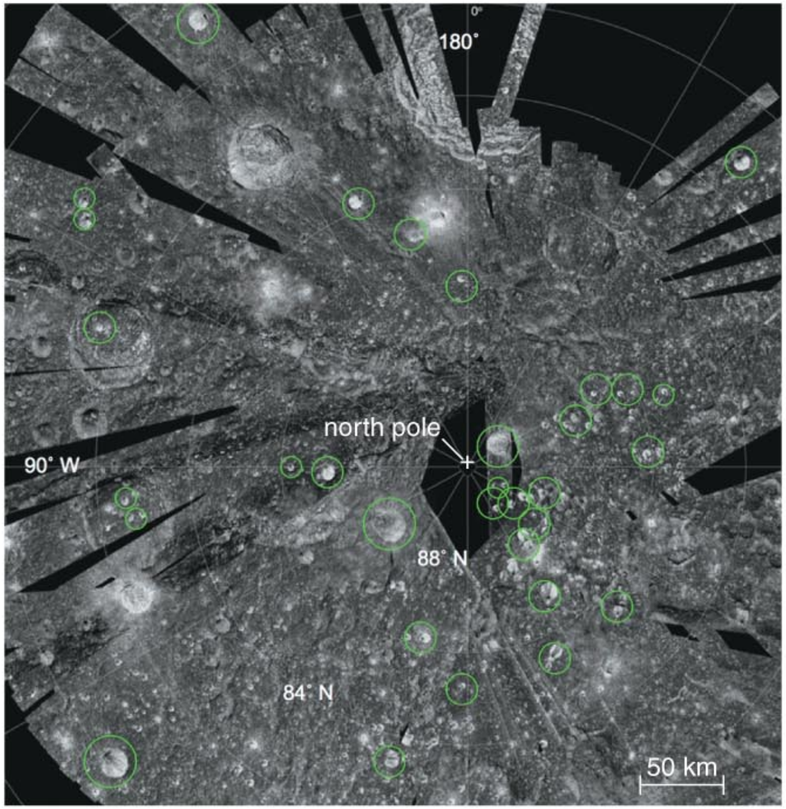
a The Moon's exosphere, which extends high above the surface.

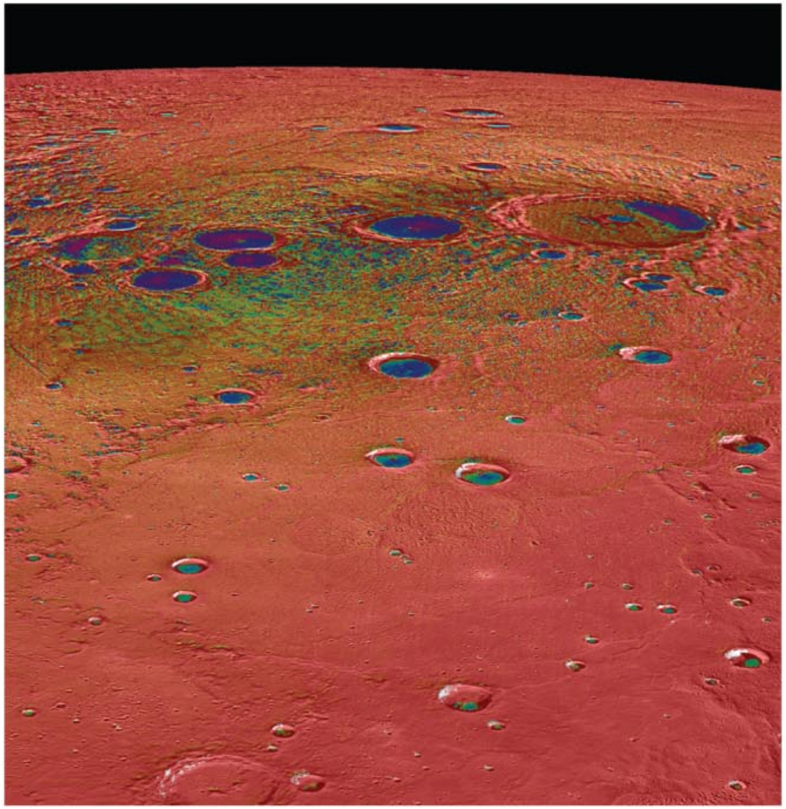


b Mercury's exosphere, much of which is escaping in this image.

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

Ice in Polar Craters





Near the Moon's north pole. Green circles indicate craters with ice.

Near the Mercury's north pole. Purple regions have ice.

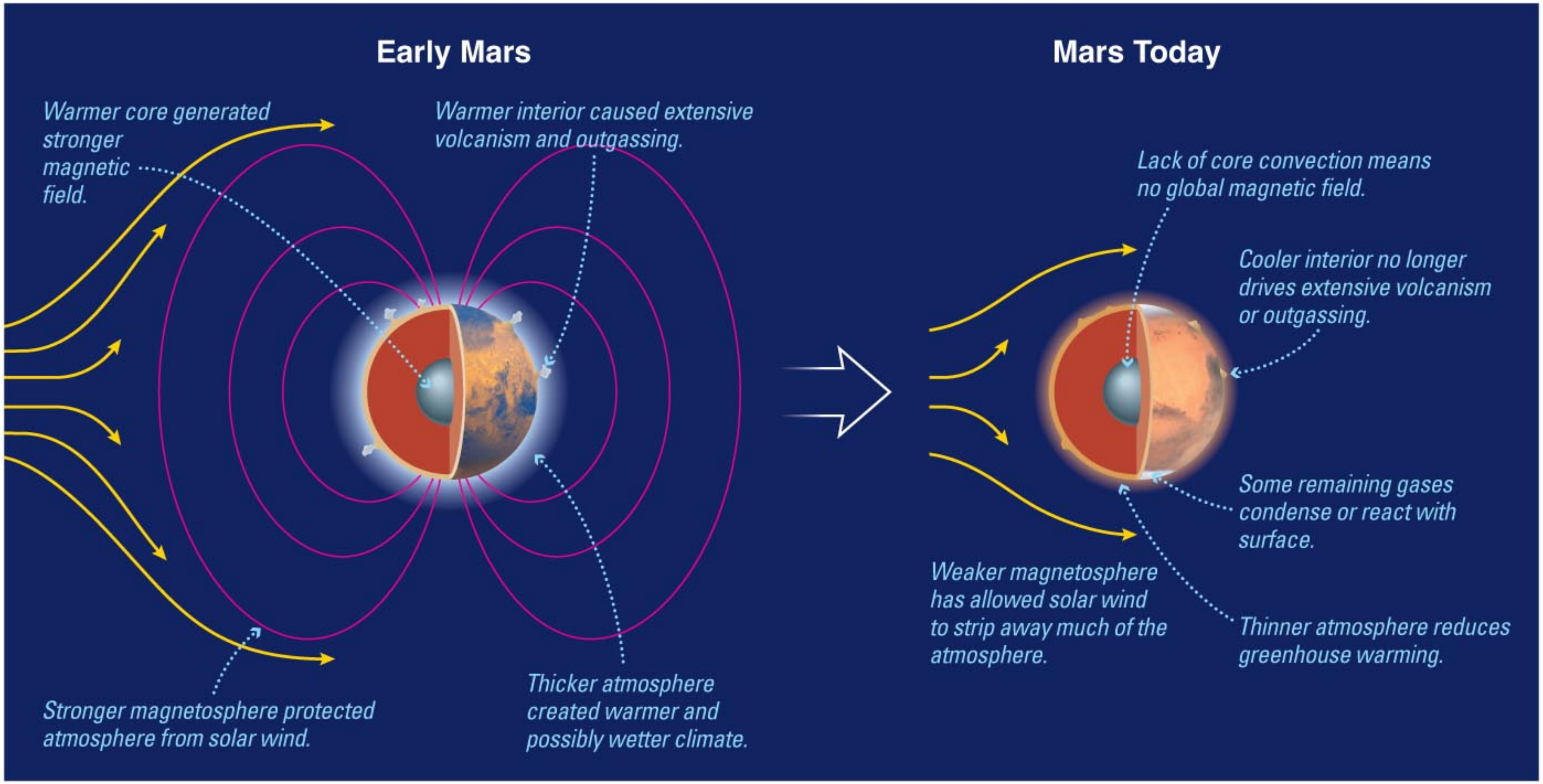
What have we learned?

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

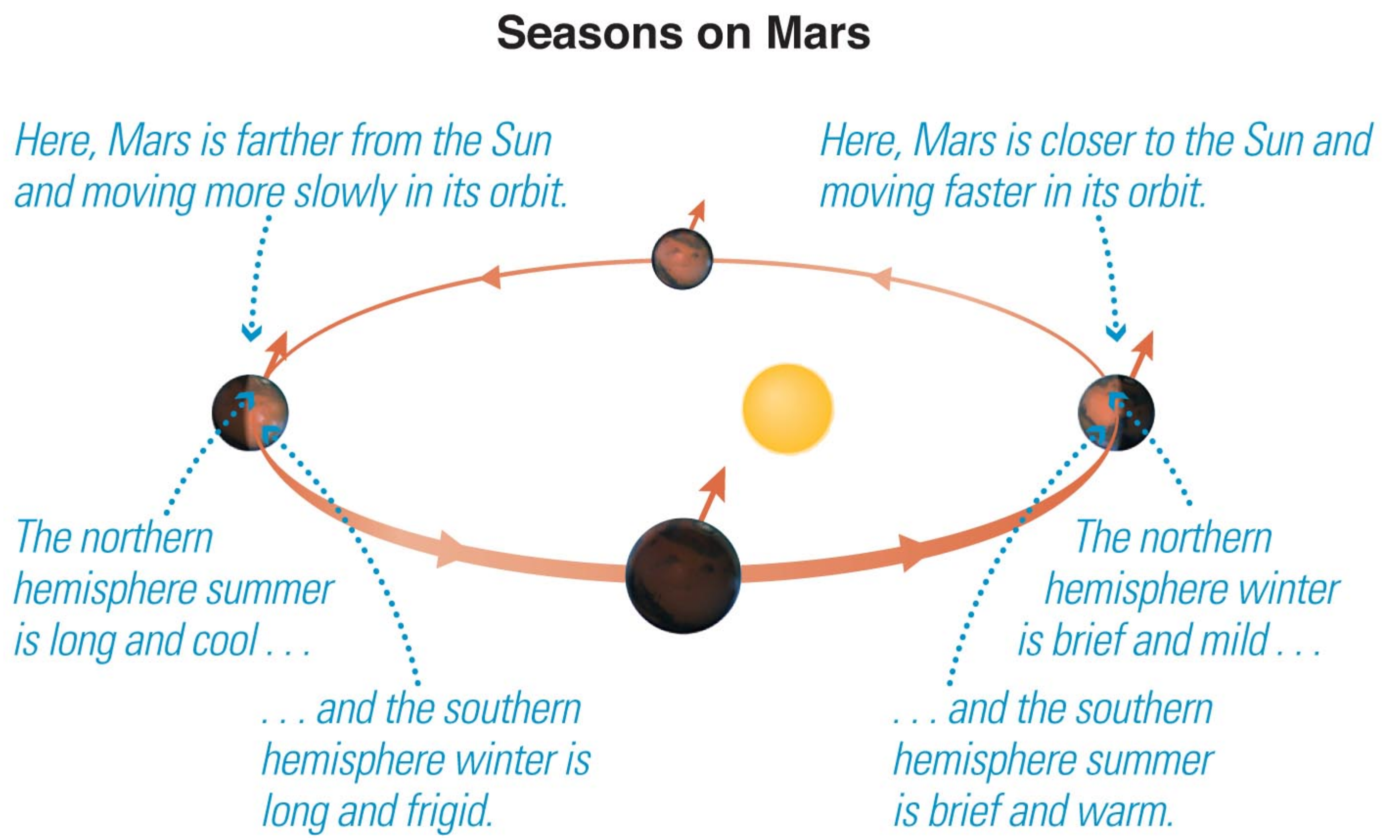
10.4 The Atmospheric History of Mars

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

What is Mars like today?

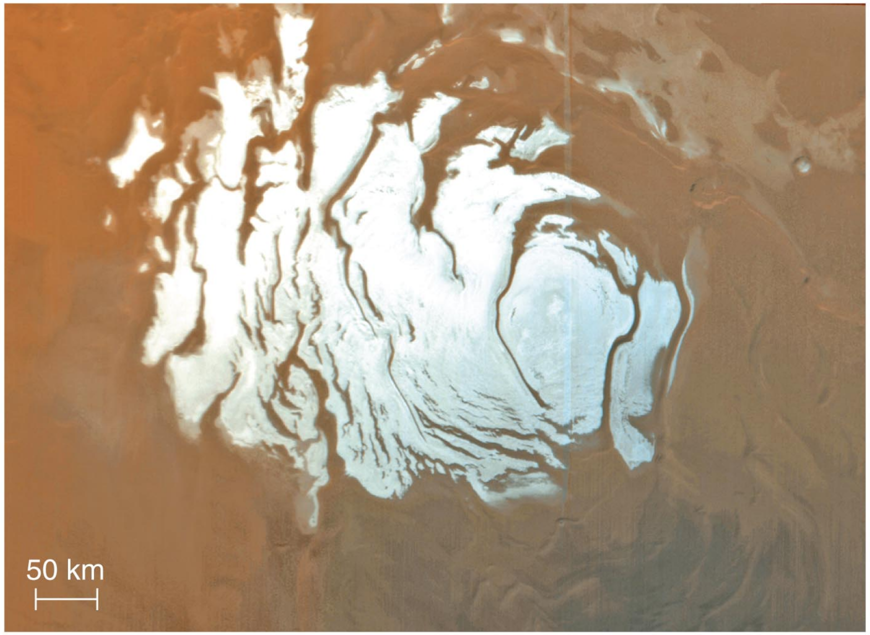


Seasons on Mars



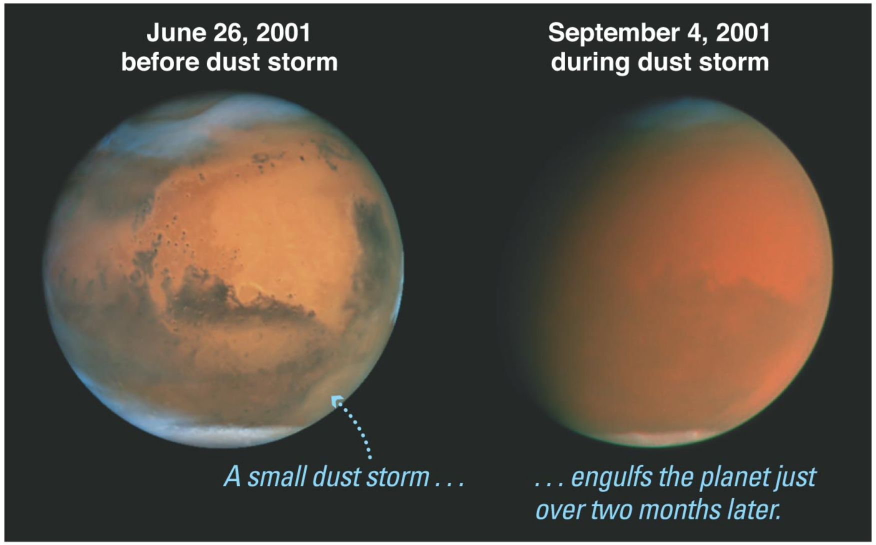
- The ellipticity of Mars's orbit makes seasons more extreme in the southern hemisphere.

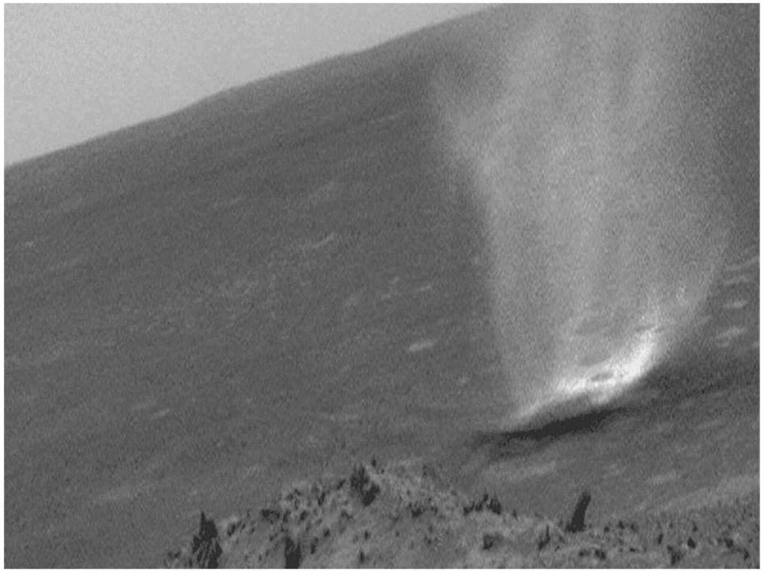
Polar Ice Caps of Mars



- 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.

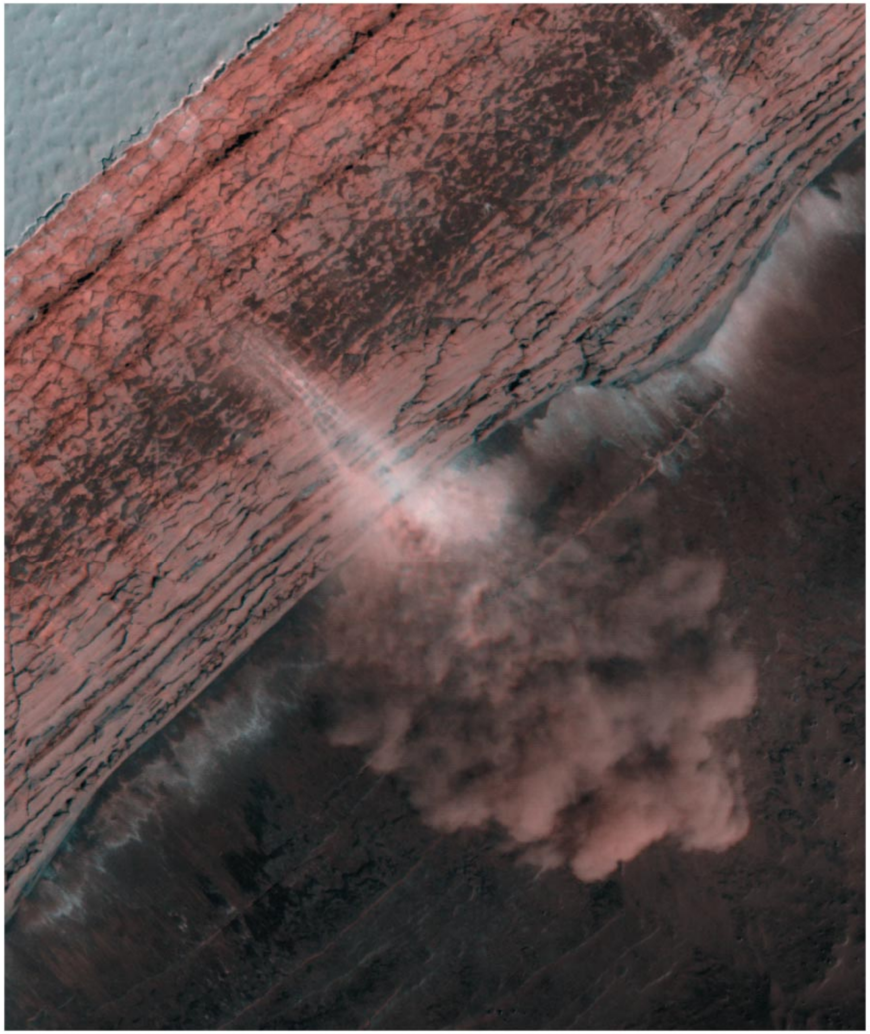
Dust Storms: extreme weather on Mars





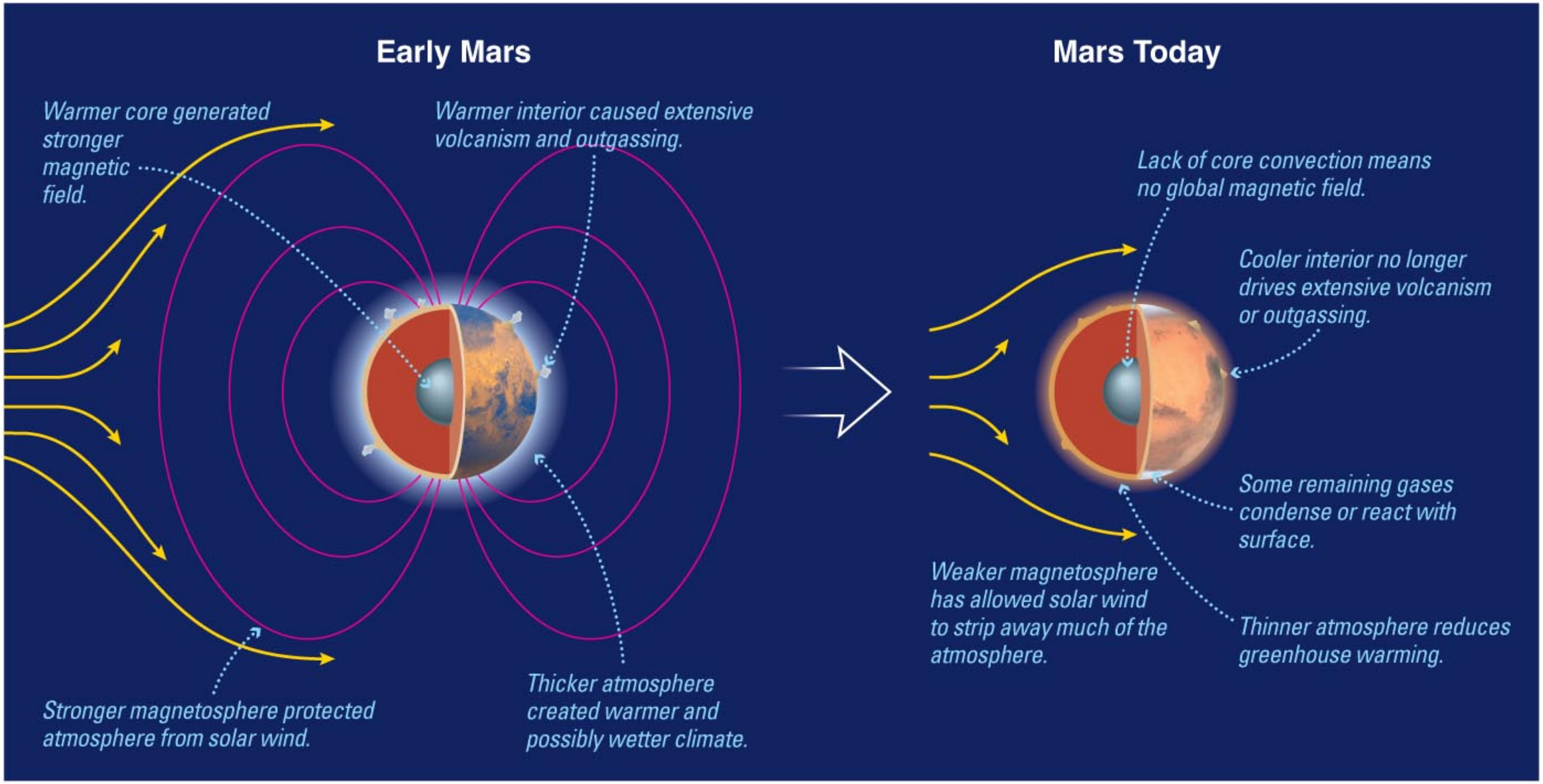
- Seasonal winds can drive dust storms on Mars.
- Dust in the atmosphere absorbs blue light, sometimes making the sky look brownish-pink.

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?

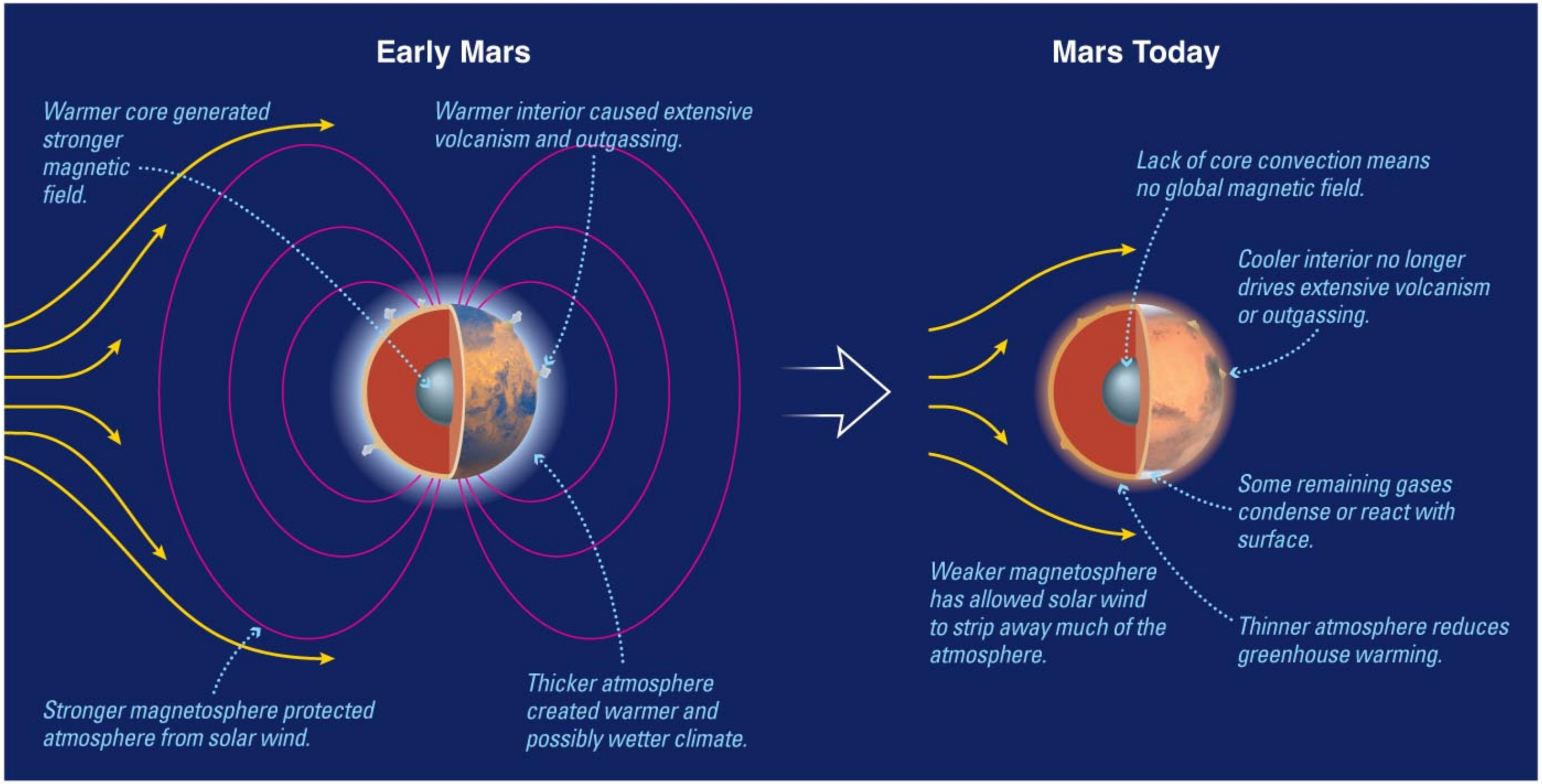


Climate Change on Mars

- 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.

Recent results by NASA’s MAVEN mission attribute atmospheric loss in Mars to the solar wind, due to the lack of a proper magnetosphere from some point onwards.

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.

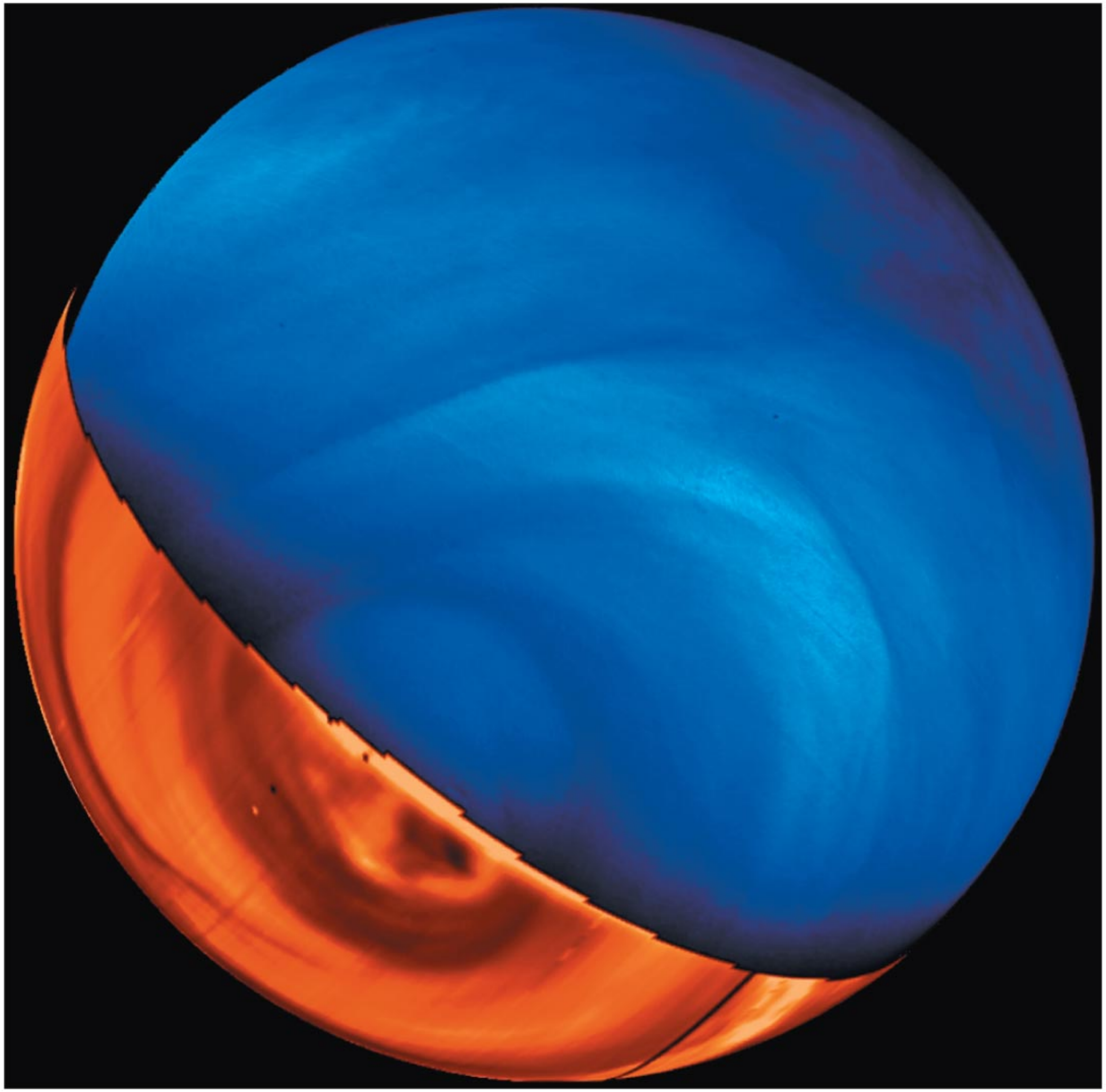
What have we learned?

- **What is Mars like today?**
  - Mars is cold, dry, and frozen.
  - Strong seasonal changes cause CO_2 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?



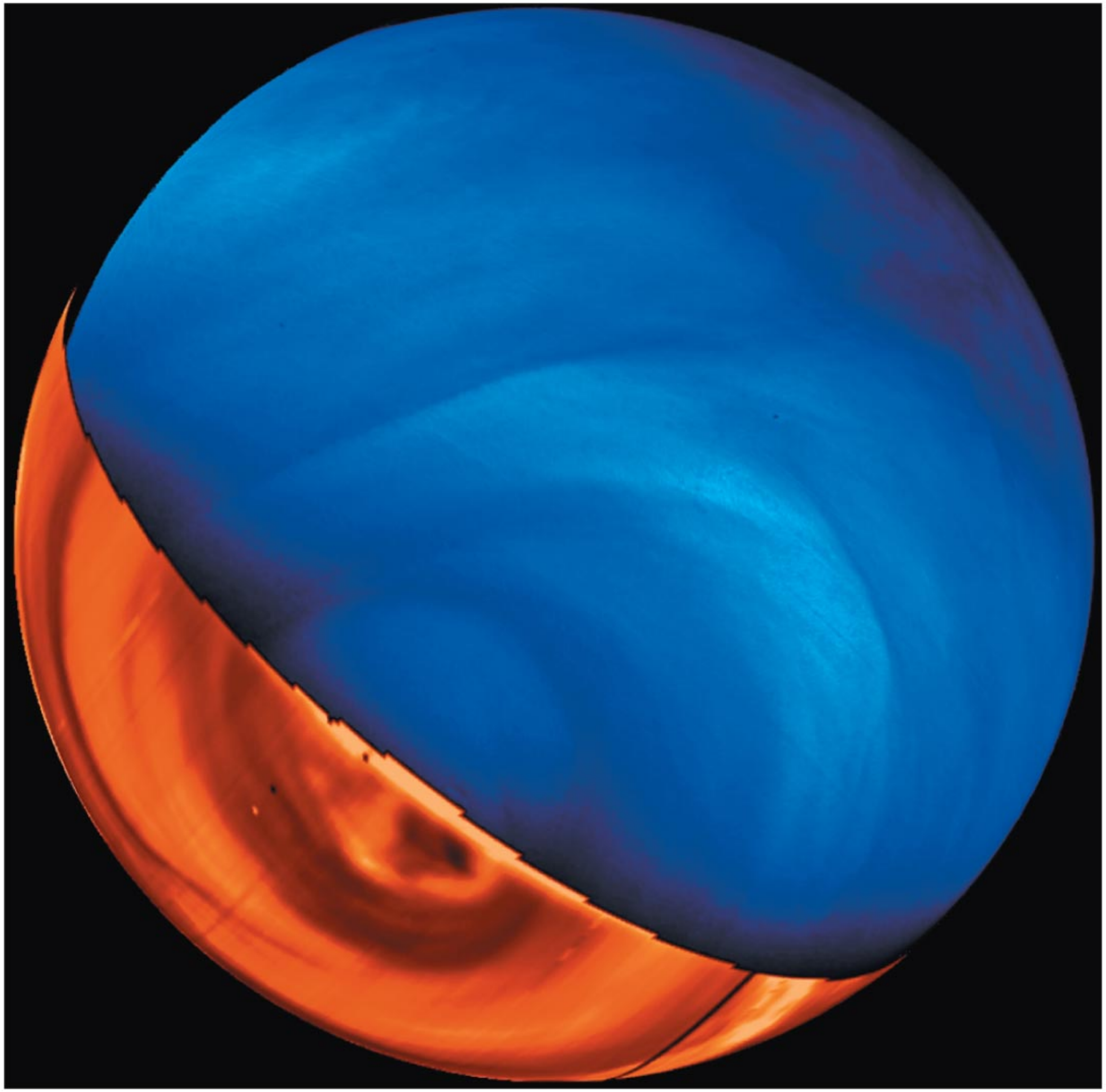
Atmosphere of Venus

- Venus has a very thick carbon dioxide atmosphere with a surface pressure 90 times that of Earth.
- Slow rotation produces a very weak Coriolis effect and little weather.

Greenhouse Effect on Venus

- Thick carbon dioxide atmosphere produces an extremely strong greenhouse effect.
- Earth escapes this fate because most of its carbon and water is in rocks and oceans.

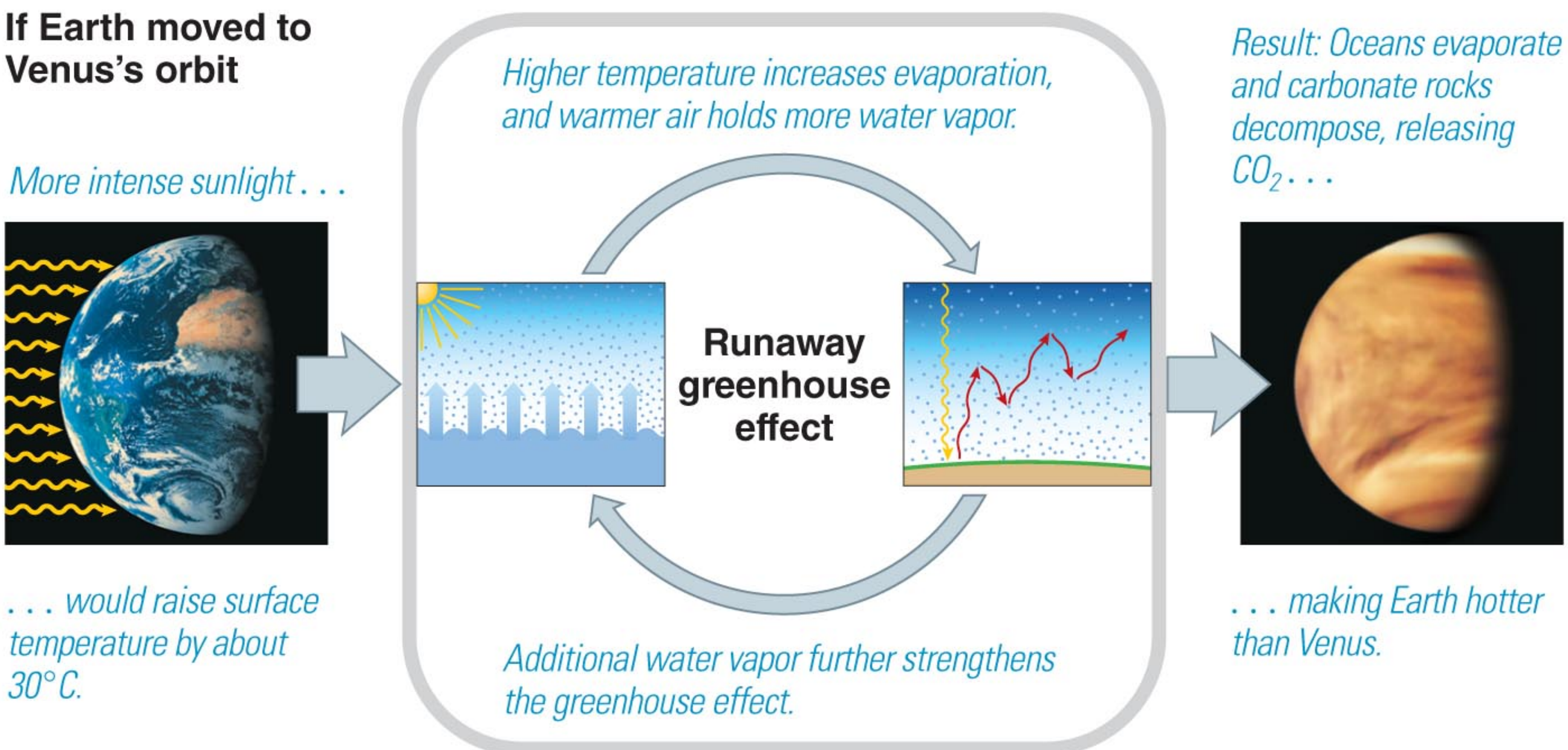
How did Venus get so hot?



Atmosphere of Venus

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

Runaway Greenhouse Effect



- 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 CO_2 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?

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 CO_2

- Earth's temperature remained cool enough for liquid oceans to form.
- Oceans dissolve atmospheric CO_2, enabling carbon to be trapped in rocks.

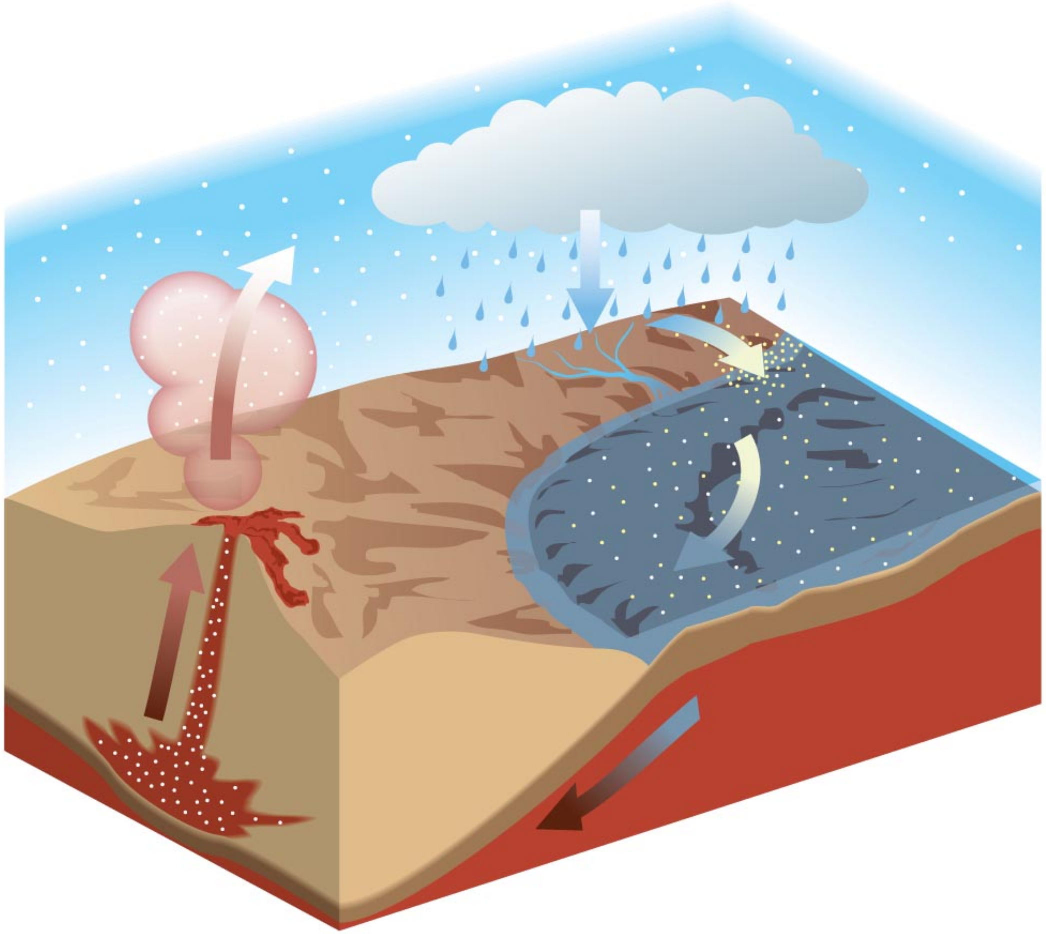
Nitrogen and Oxygen

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

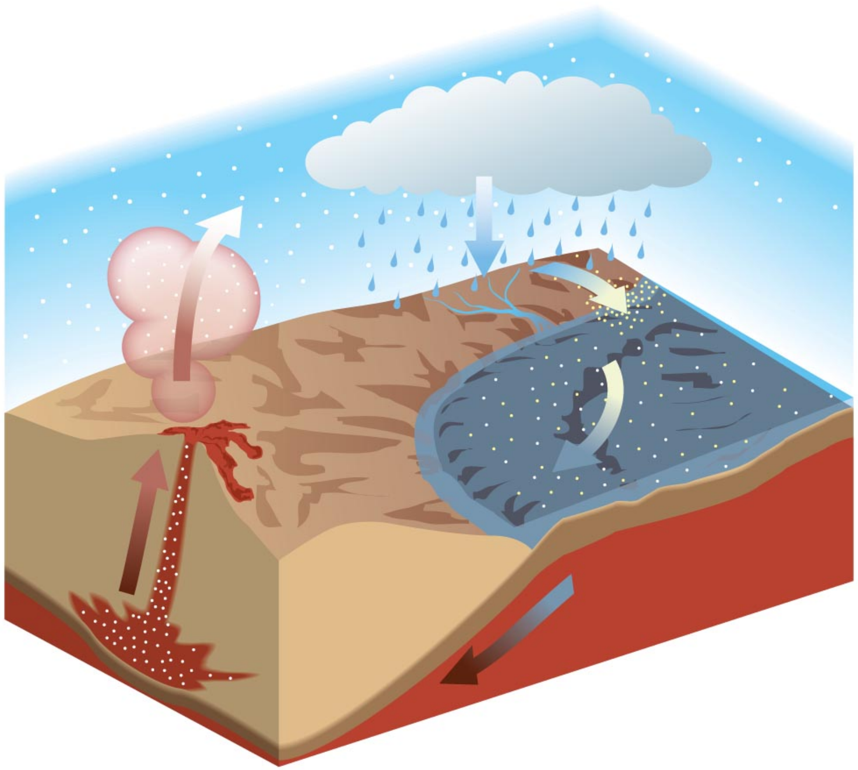
Ozone and the Stratosphere

- 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?

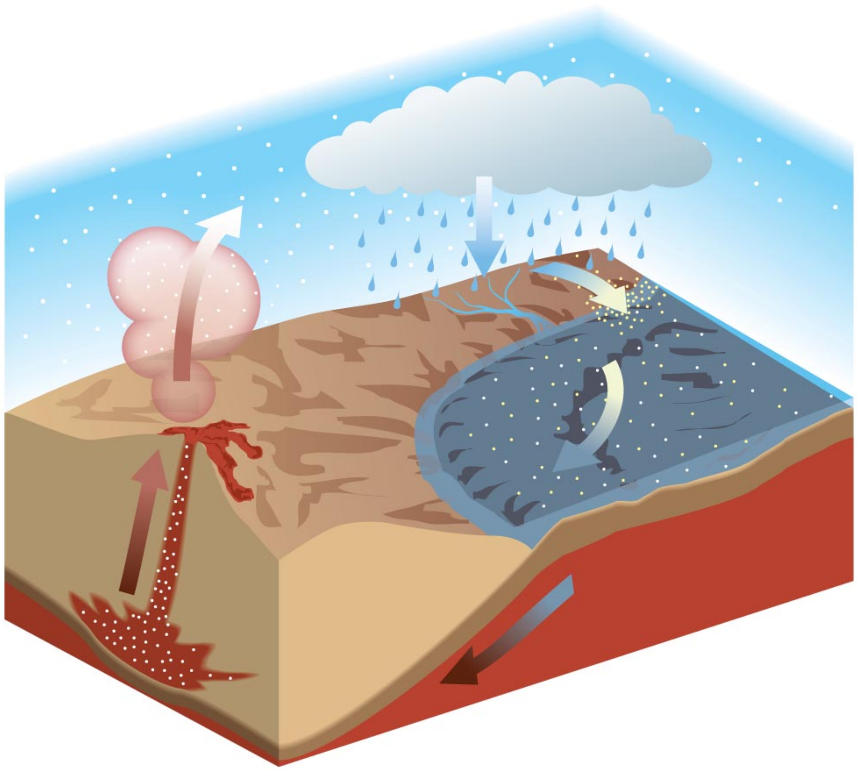


Carbon Dioxide Cycle



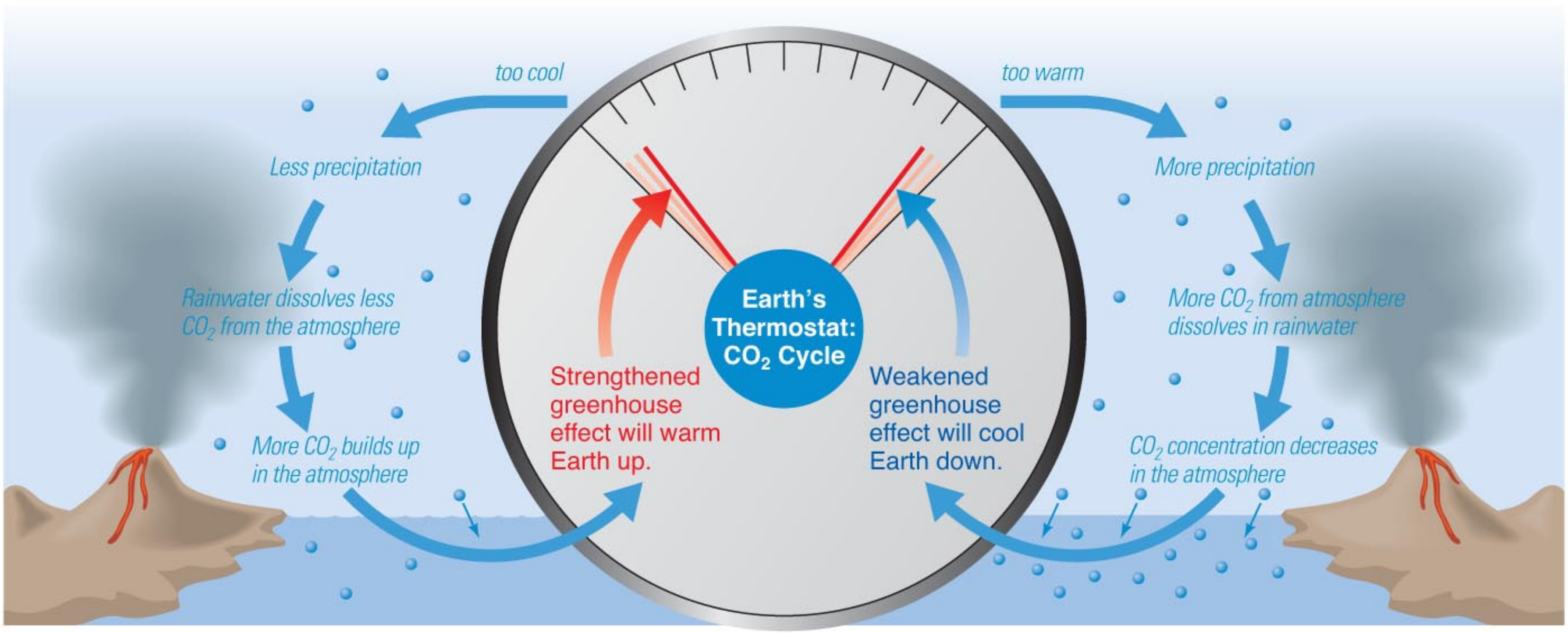
1. Atmospheric CO_2 dissolves in rainwater.
2. Rain erodes minerals that flow into ocean.
3. Minerals combine with carbon to make rocks on ocean floor.

Carbon Dioxide Cycle



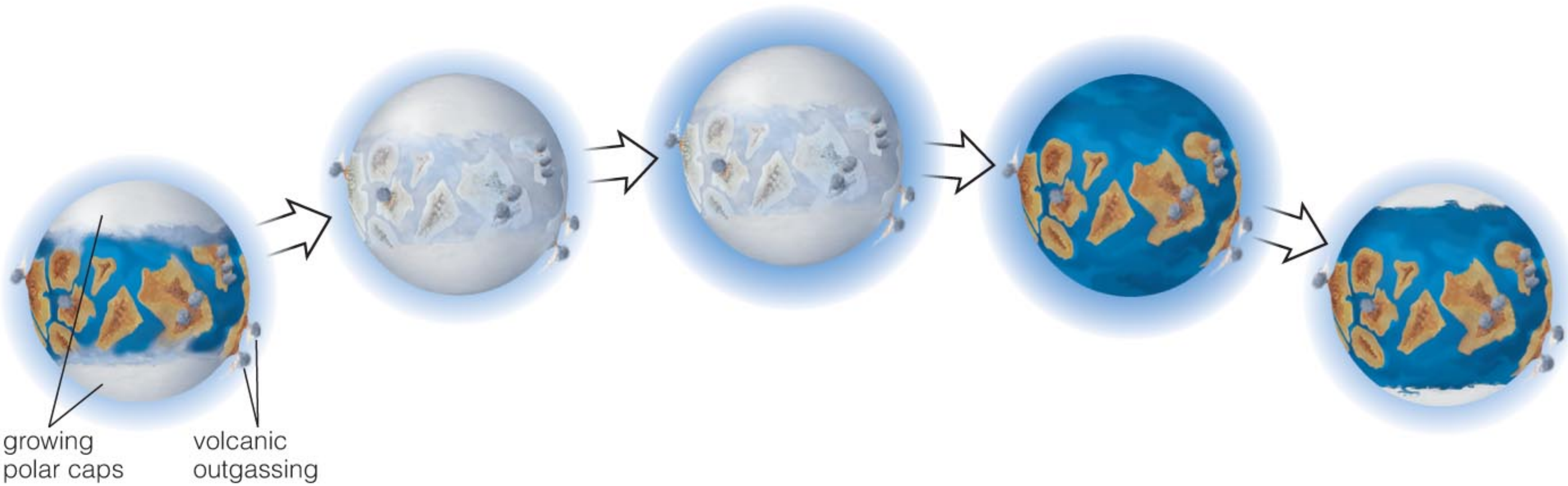
4. Subduction carries carbonate rock down into mantle.
5. Rock melts in mantle and CO_2 is outgassed back into atmosphere through volcanoes.

Earth's Thermostat



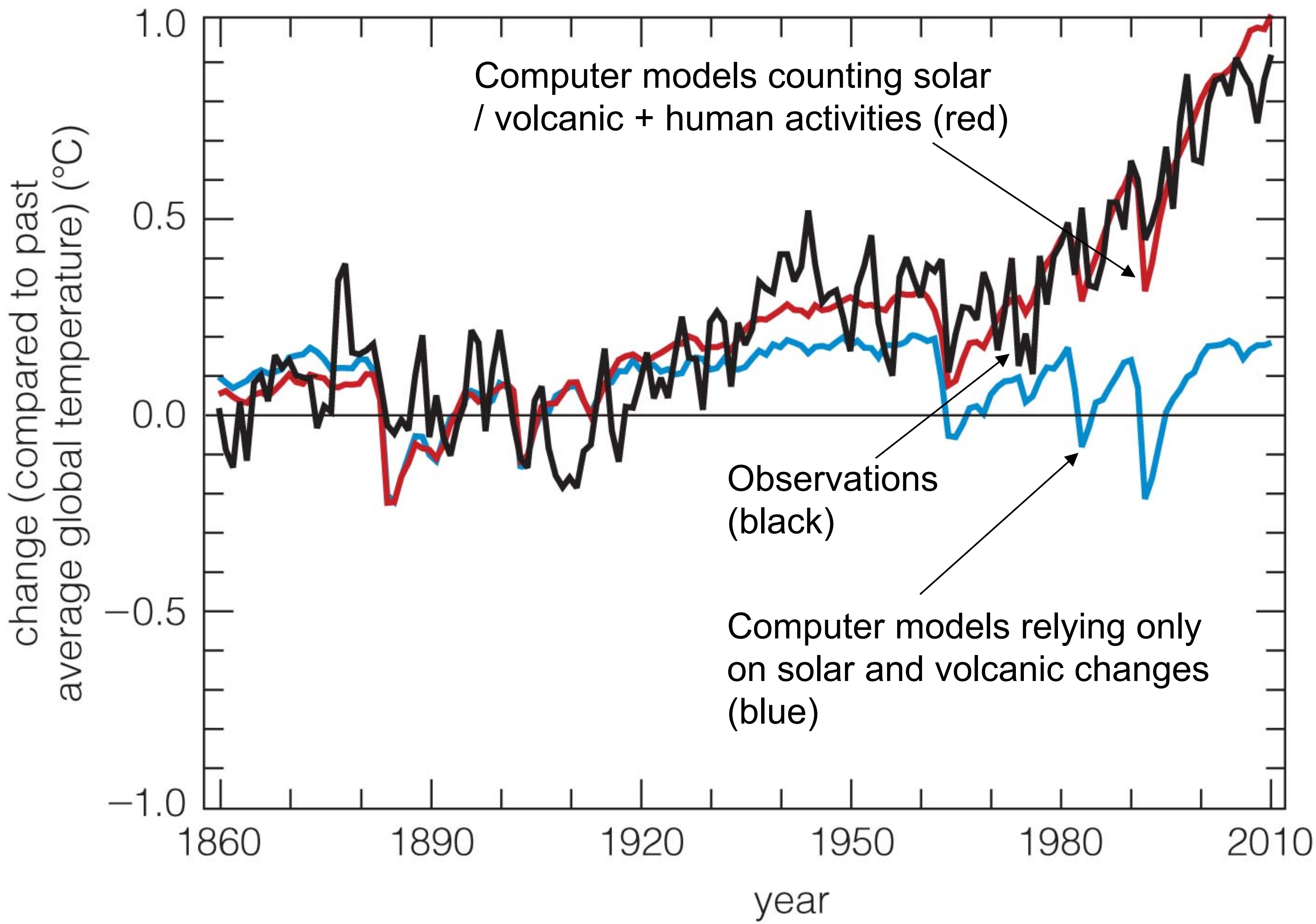
- Cooling allows CO_2 to build up in atmosphere.
- Heating causes rain to reduce CO_2 in atmosphere.

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.
- CO_2 from outgassing will build up if oceans are frozen, ultimately raising global temperatures again.

How is human activity changing our planet?



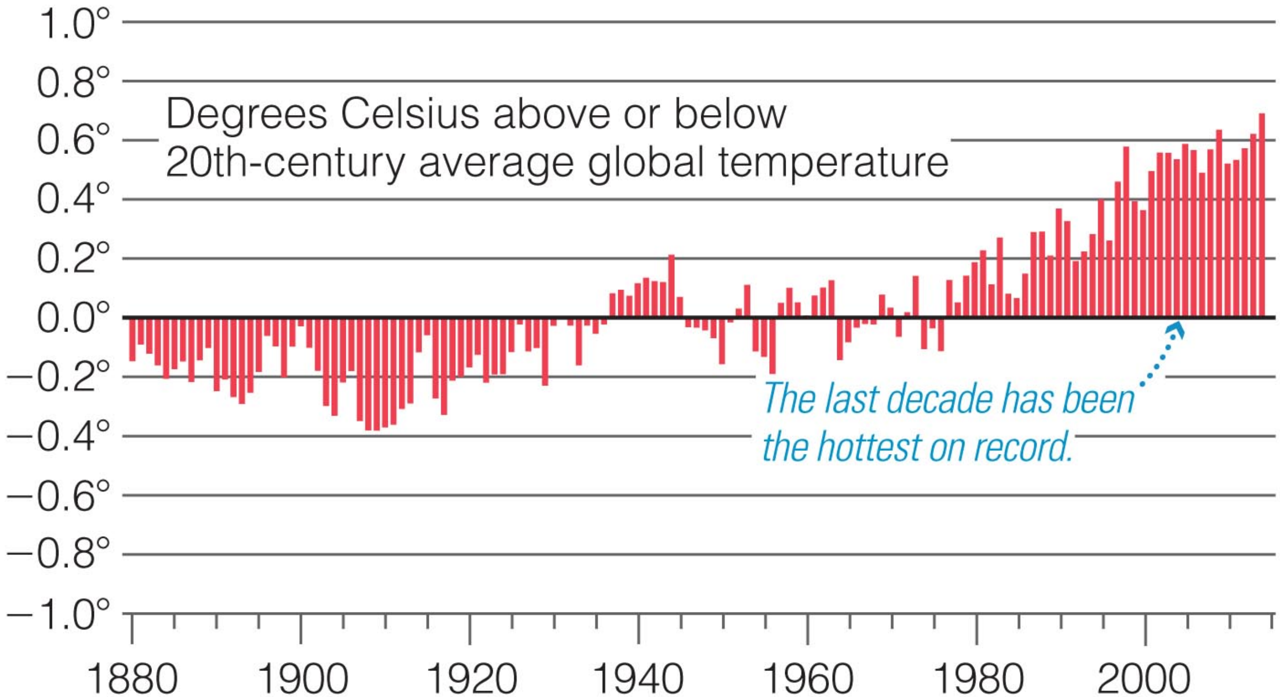
Human activity behind global warming!

Dangers of Human Activity

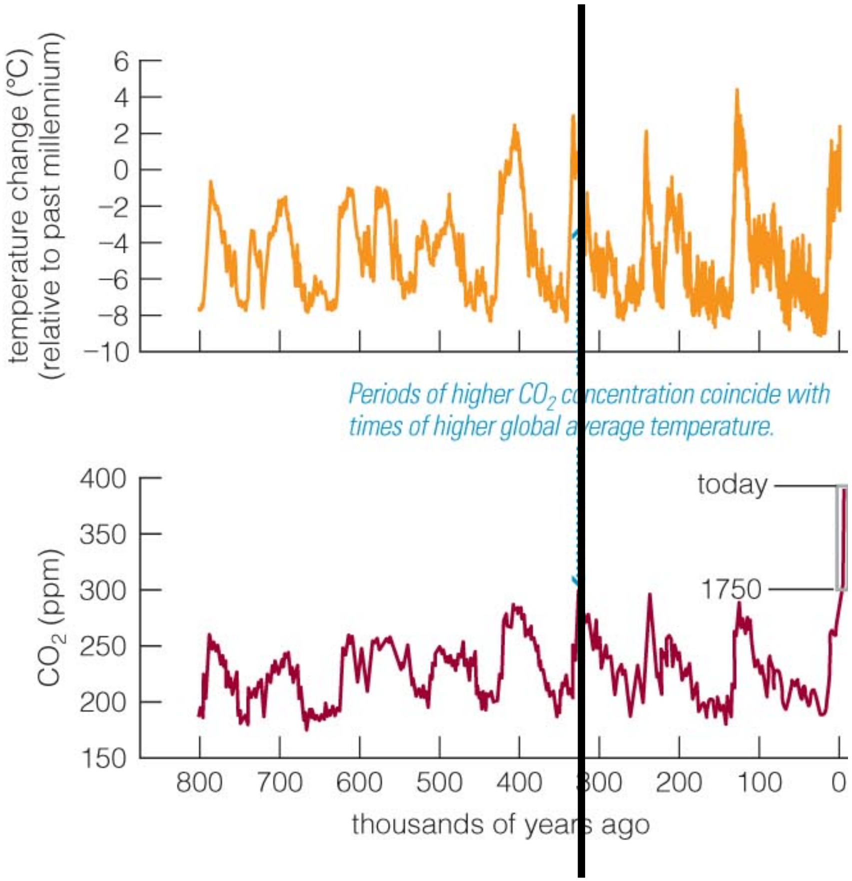
- Human-made CFCs (Chlorofluorocarbons) in the atmosphere destroy ozone, reducing protection from ultraviolet radiation.
- Human activity is driving many species to extinction.
- Human use of fossil fuels produces greenhouse gases that can cause global warming.

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.



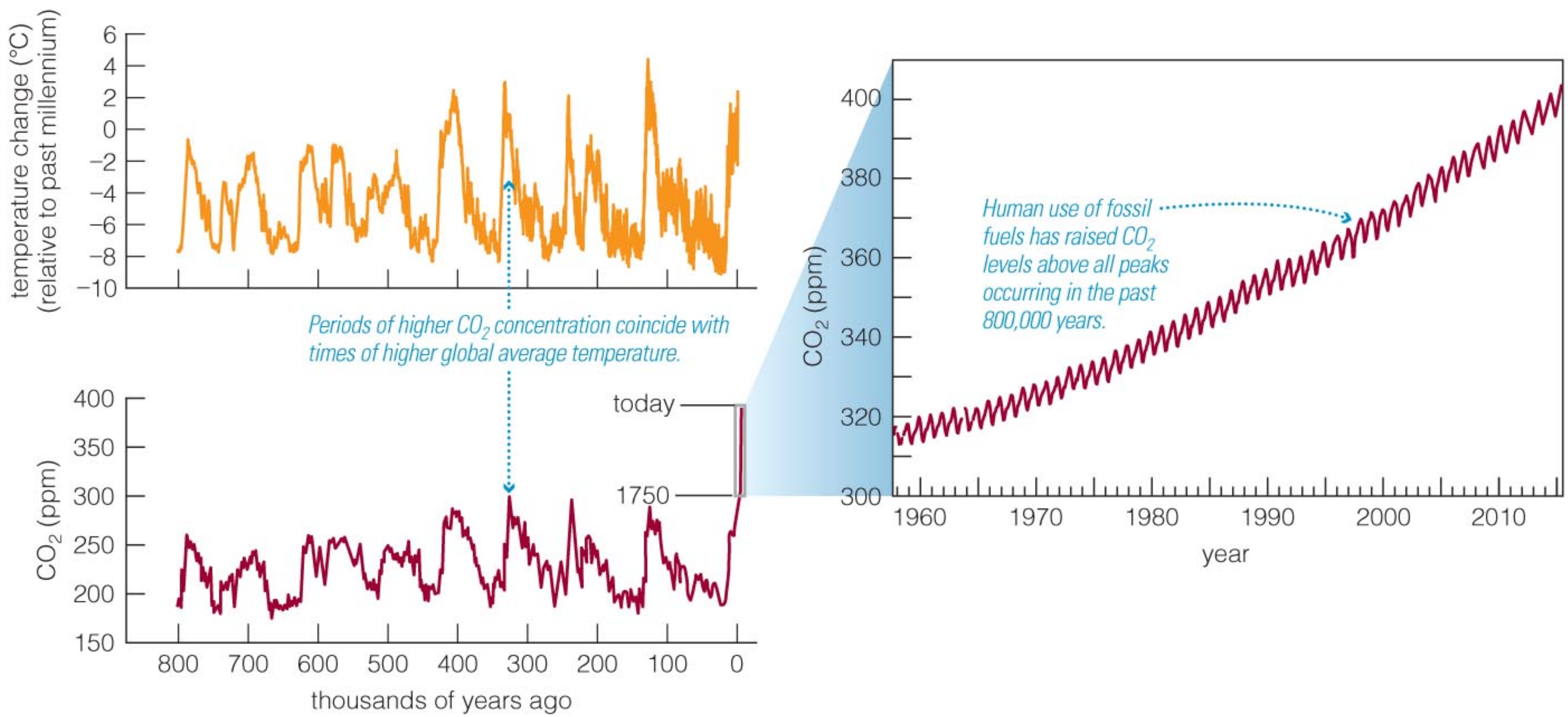
CO_2 Concentration



Start of the industrial revolution

- Global temperatures have tracked CO_2 concentration for last 500,000 years.
- Current CO_2 concentration is the highest it's been in at least 500,000 years.

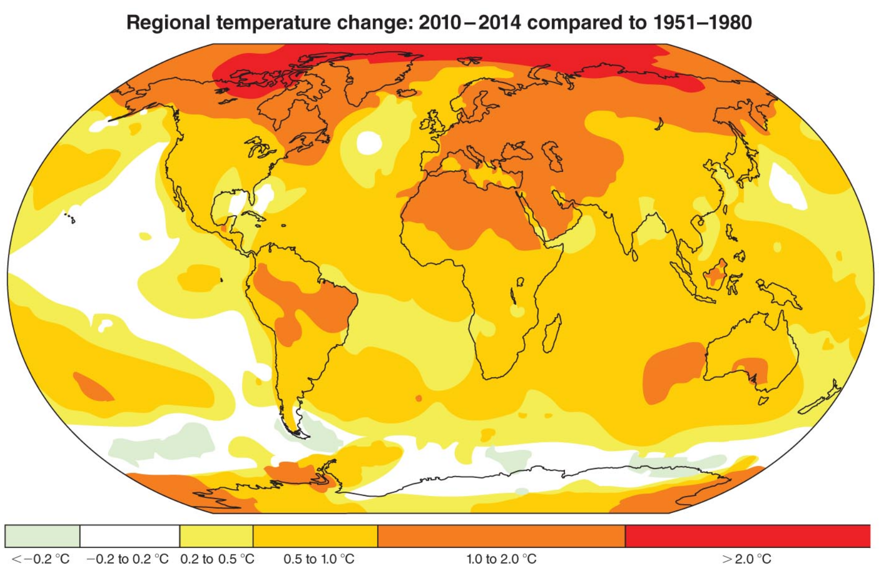
CO_2 Concentration



- Most of the CO_2 increase has happened in last 50 years!

Consequences of Global Warming

- Storms more numerous and intense
- Rising ocean levels; melting glaciers
  - Sea level has risen 20 centimeters in past century; expected to rise another 30 centimeters by 2100.
- 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 CO_2 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