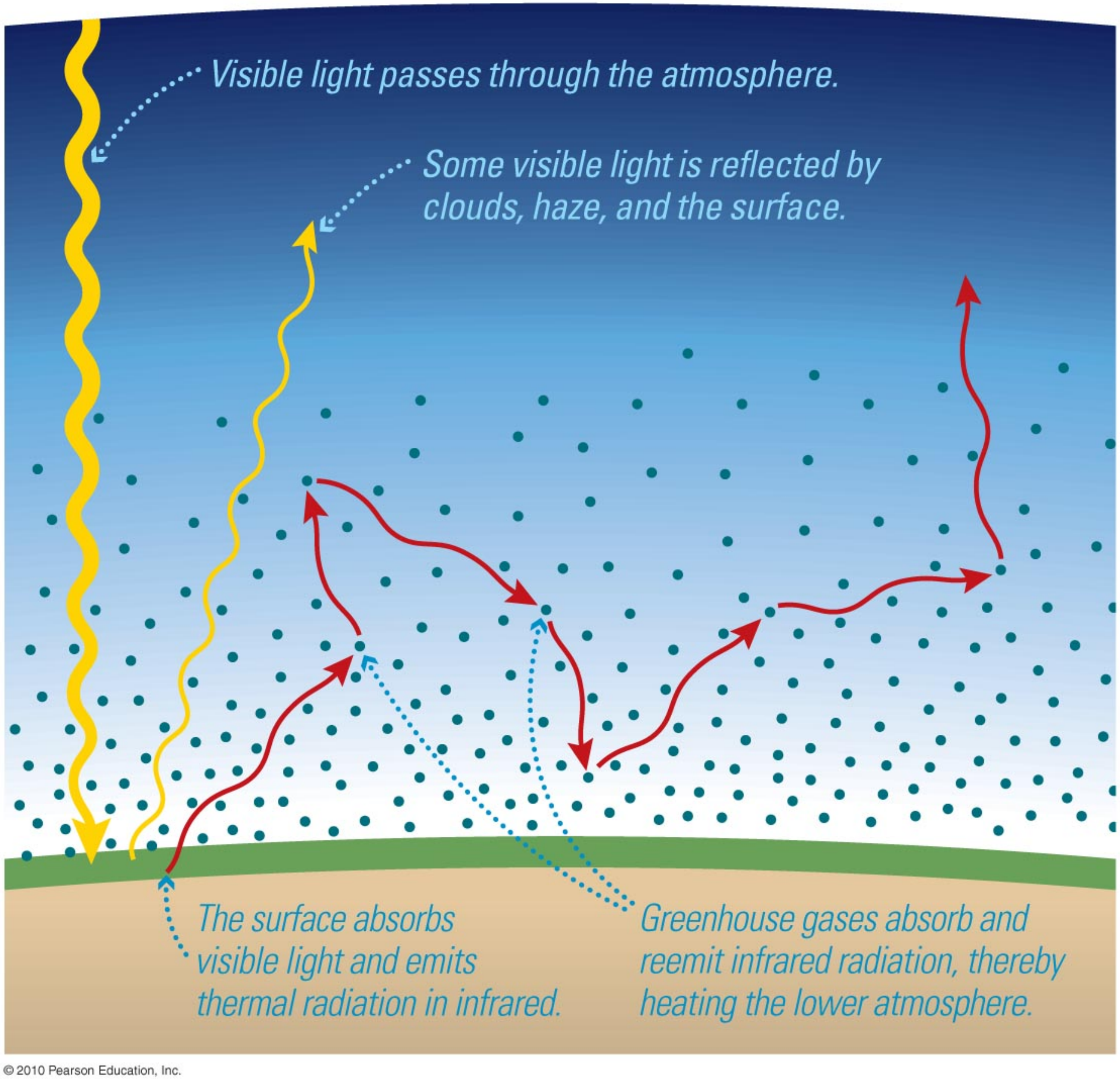
What have we learned?

- 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.

How does the greenhouse effect warm a planet?



"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).

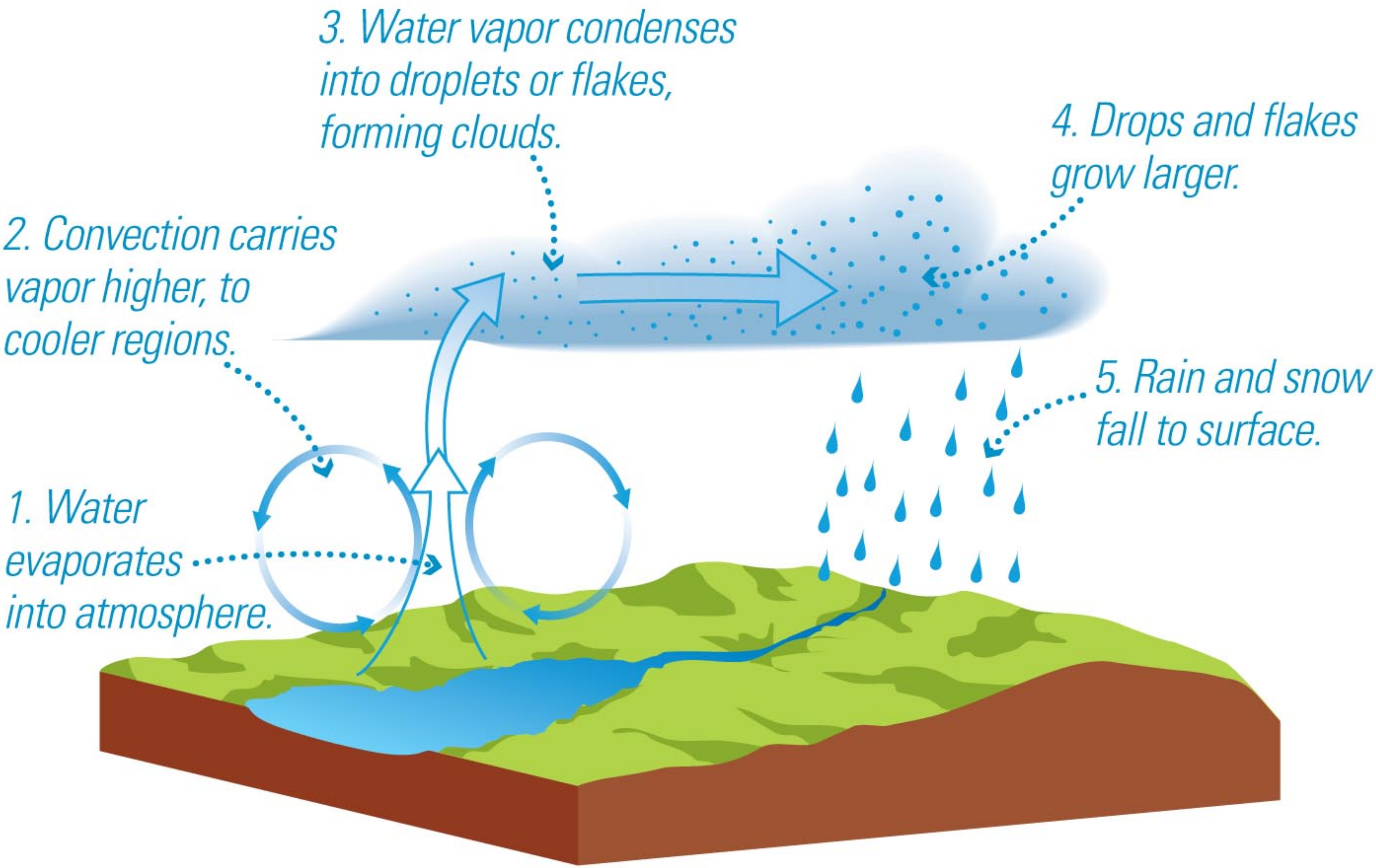
10.2 Weather and Climate

Our goals for learning:

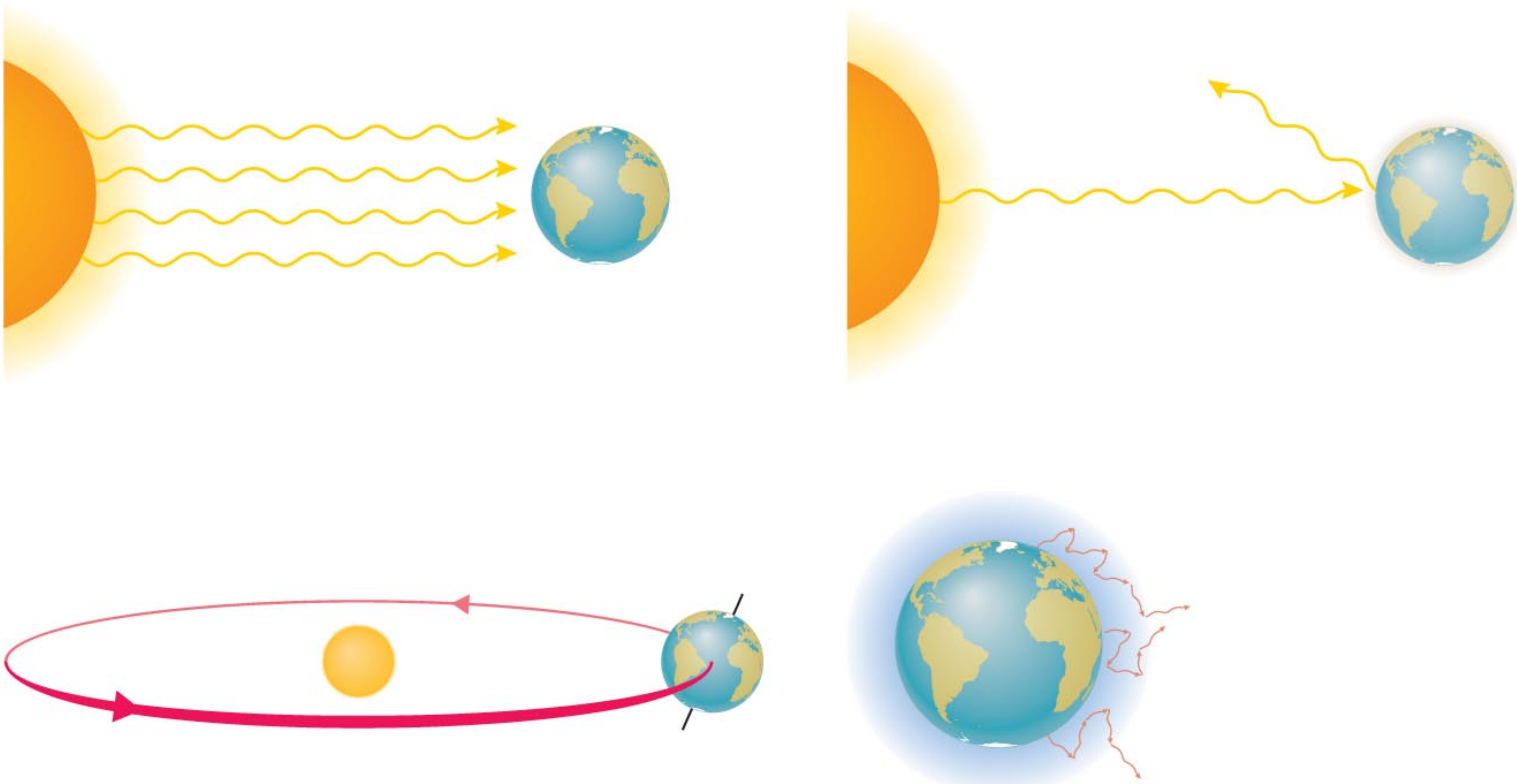
- What factors can cause long-term climate change?
- How does a planet gain or lose atmospheric gases?

- We’ll skip over Earth atmospheric circulation and the Coriolis force

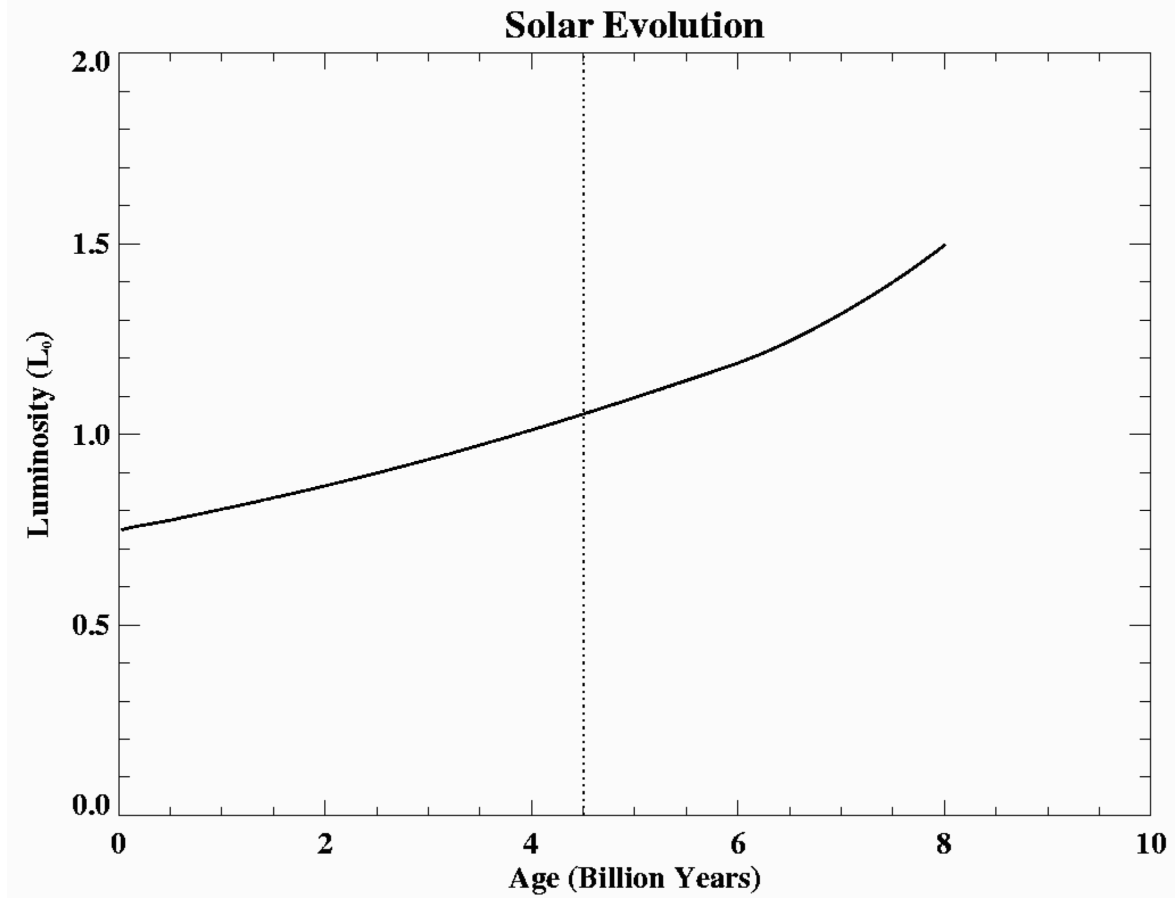
Clouds and Precipitation

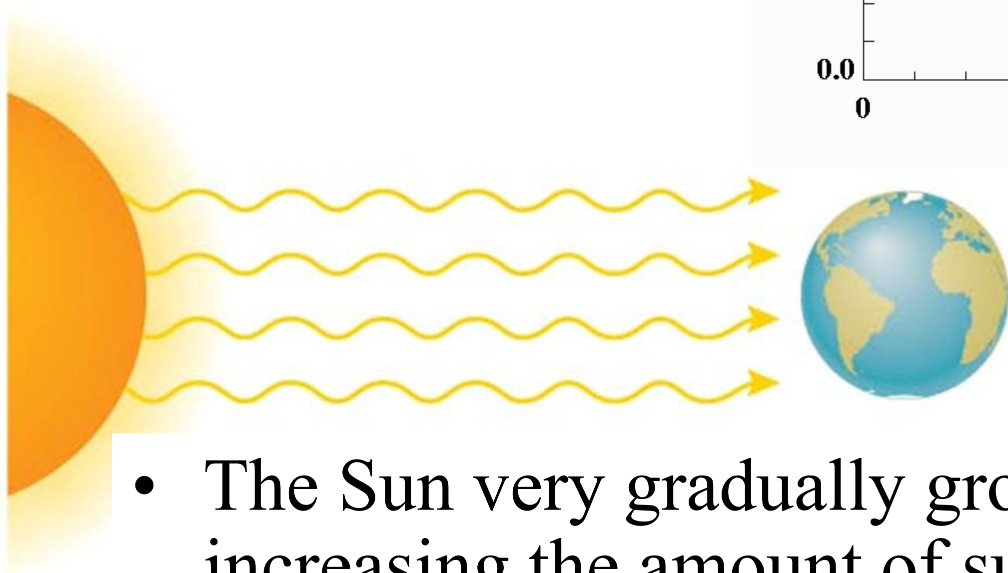


What factors can cause long-term climate change?



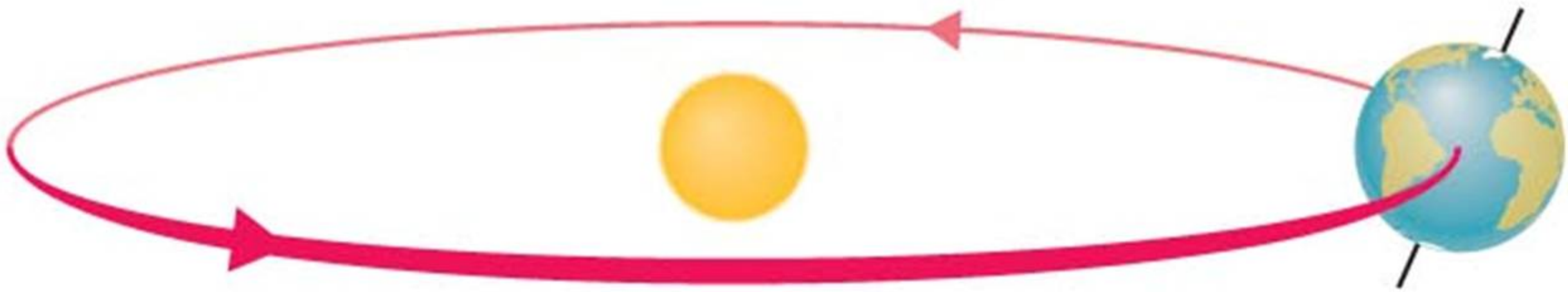
Solar Brightening





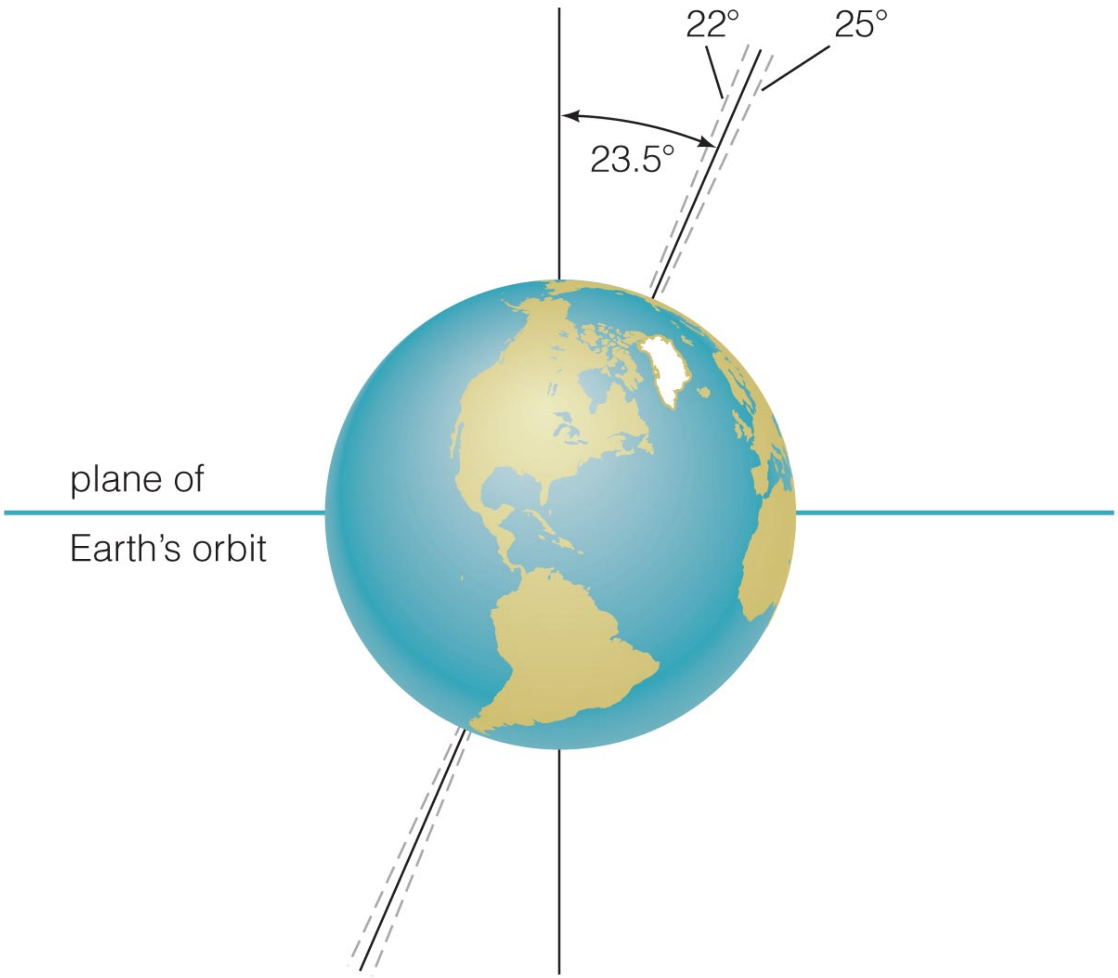
- The Sun very gradually grows brighter with time, increasing the amount of sunlight warming the planets.

Changes in Axis Tilt



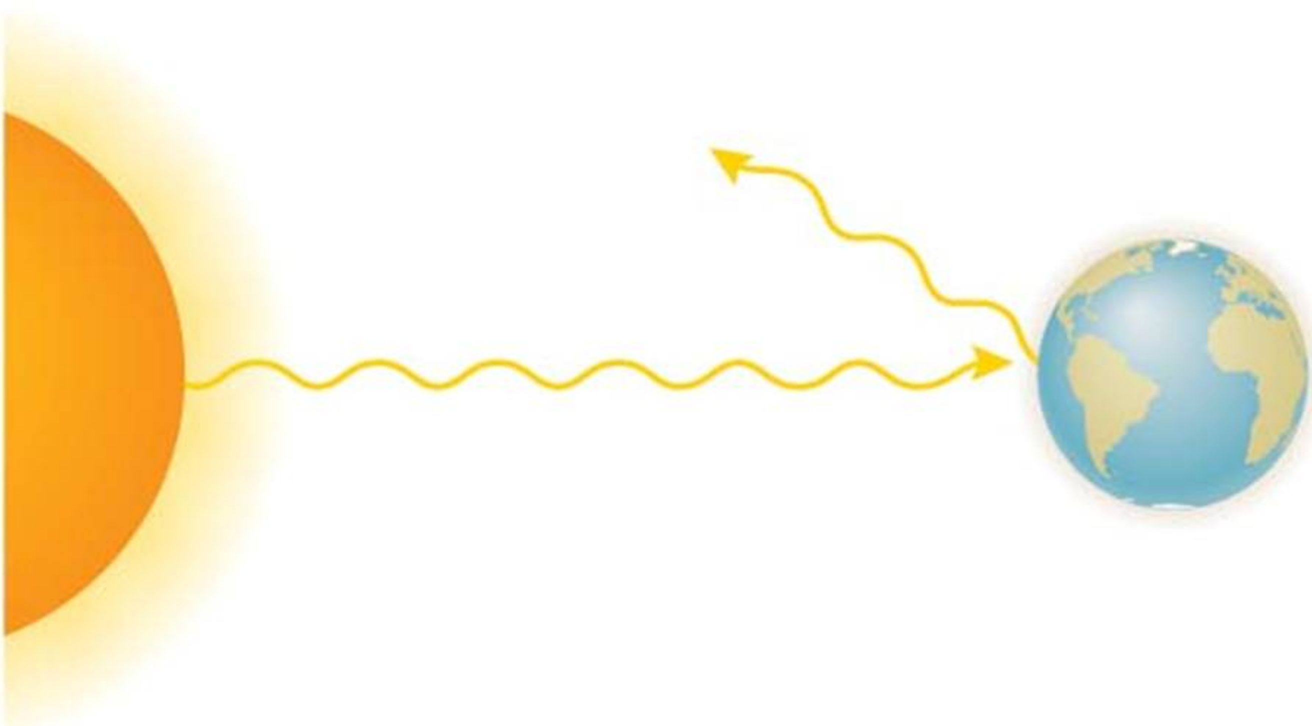
- Greater tilt creates more extreme seasons, while smaller tilt keeps polar regions colder.
- Tens of thousands of years timescale for Earth

Changes in Axis Tilt



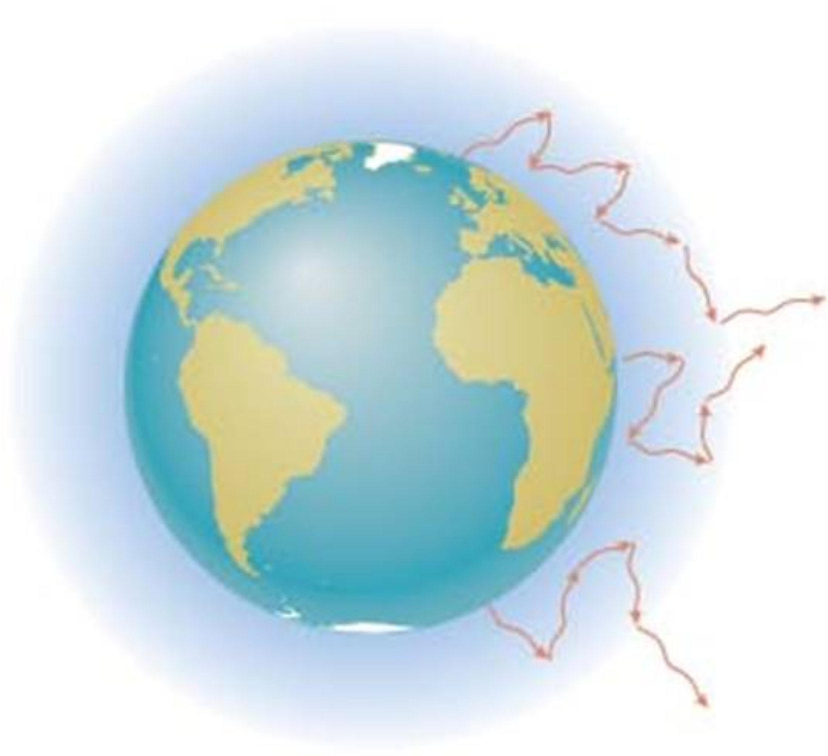
- Small gravitational tugs from other bodies in solar system cause Earth's axis tilt to vary between 22° and 25°.

Changes in Reflectivity



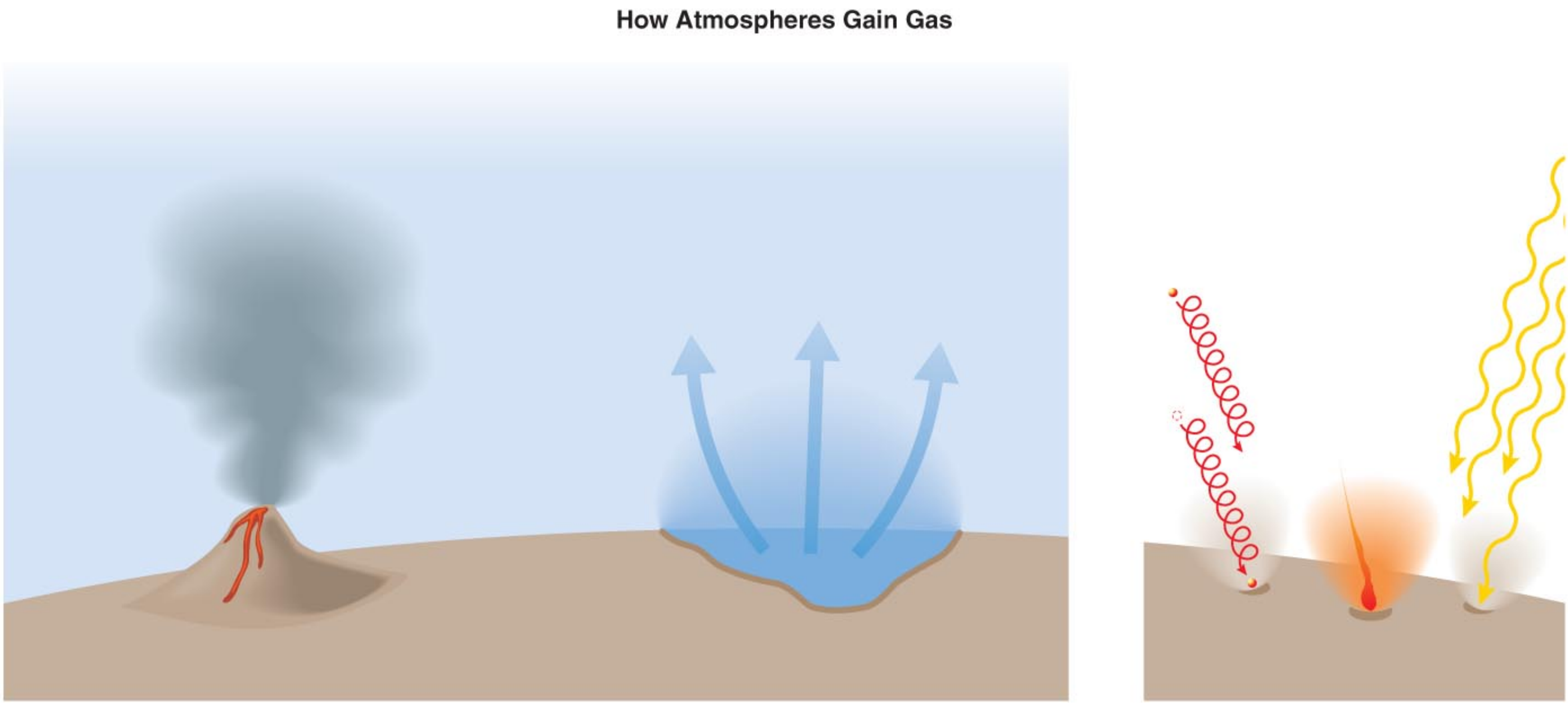
- Higher reflectivity tends to cool a planet, while lower reflectivity leads to warming.

Changes in Greenhouse Gases

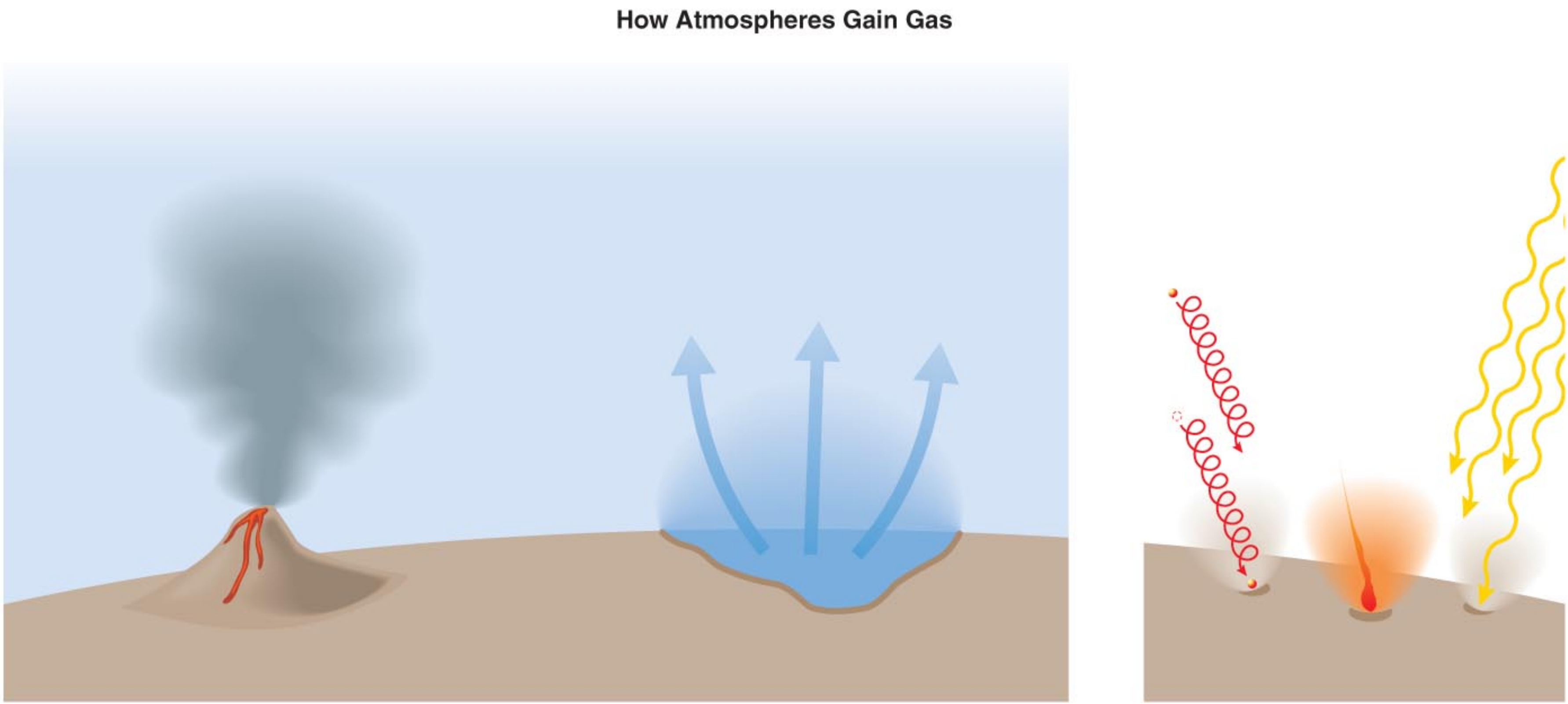


- An increase in greenhouse gases leads to warming, while a decrease leads to cooling.

How does a planet gain or lose atmospheric gases?



Sources of Gas

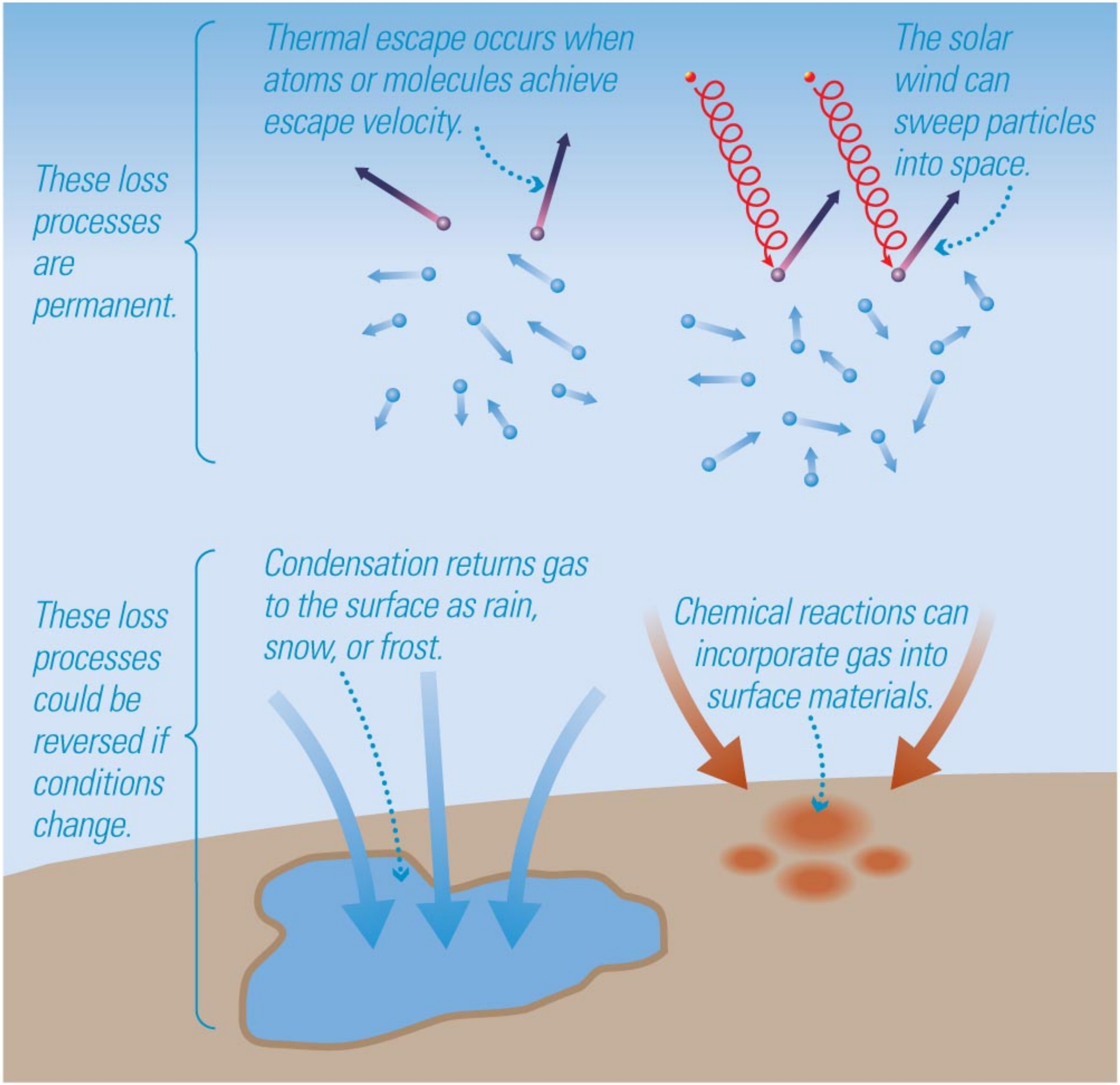


Outgassing from volcanoes

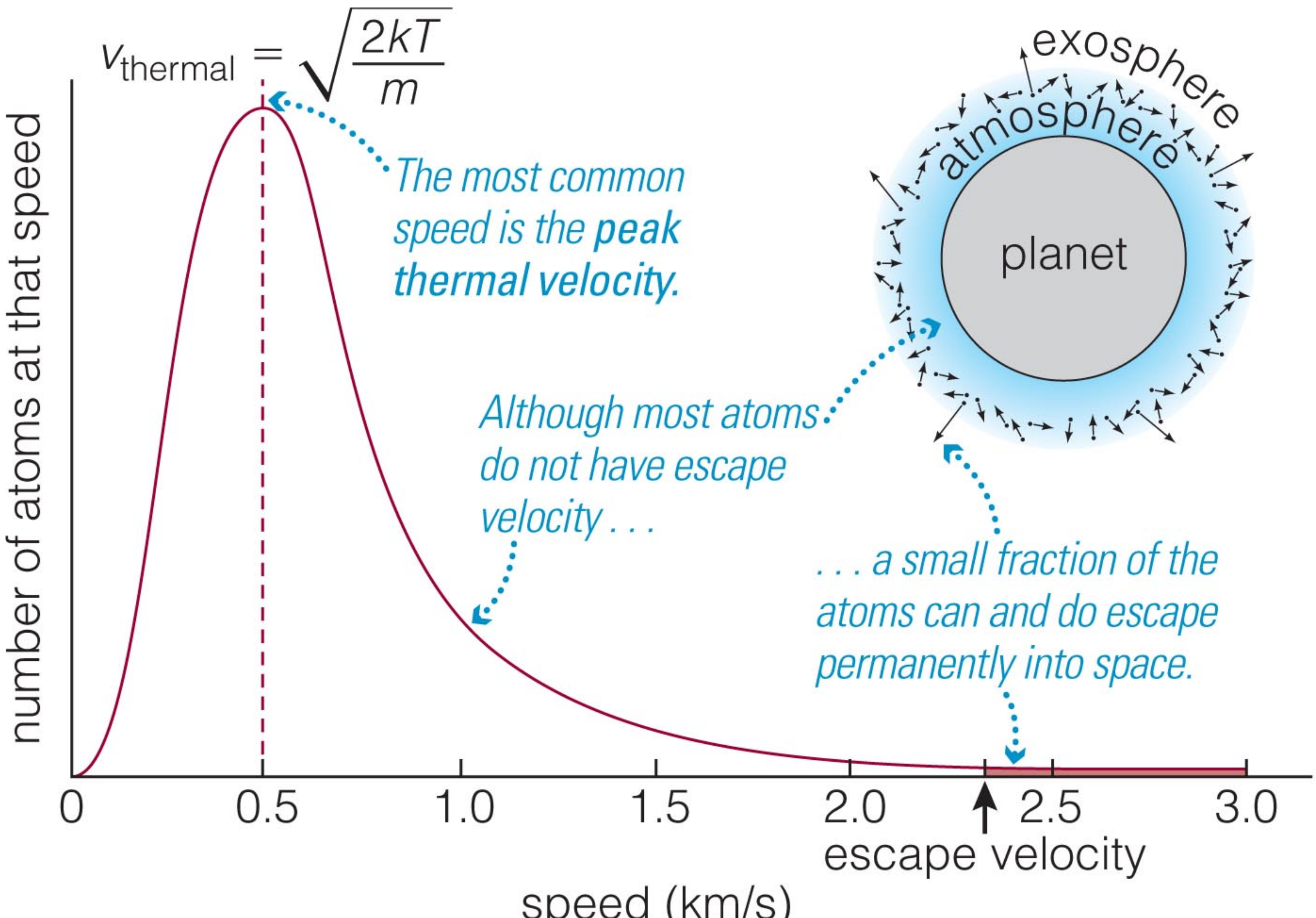
Evaporation of surface liquid; sublimation of surface ice

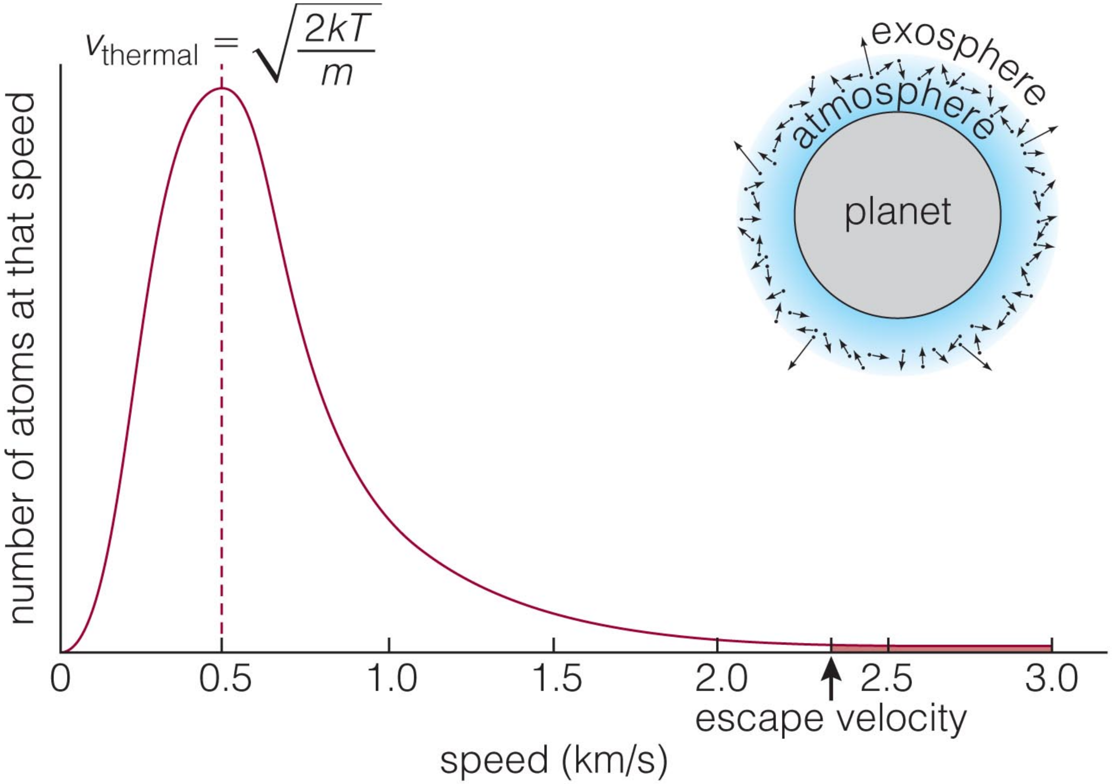
Impacts of particles and photons

How Atmospheres Lose Gas



Thermal Escape





Thermal Escape

$$v_{esc} = (2GM_p/R_p)^{1/2}$$

- If $v_{thermal} > 0.2\ v_{esc}$, atmosphere will be lost on Gyr timescales
- Low molecular mass, high temperatures, low planet mass, favors loss
- Terrestrial planets have lost H/He atmospheres, if they had them after formation

What have we learned?

- 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 Moon and Mercury

Our goals for learning:

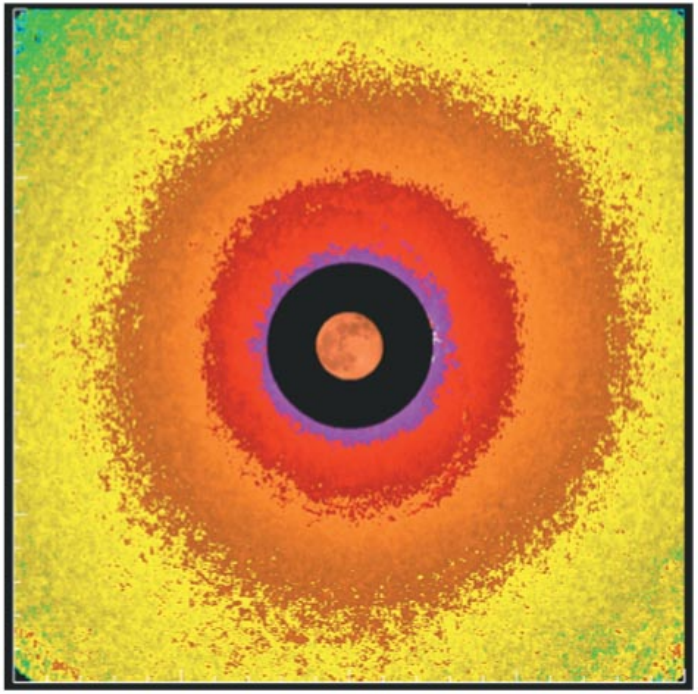
- Do the Moon and Mercury have any atmosphere?

Do the Moon and Mercury have any atmosphere?

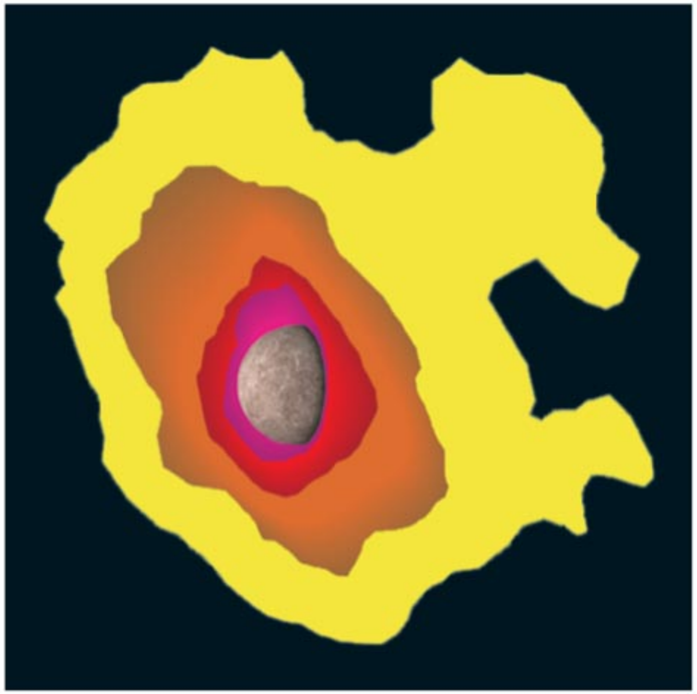
Moon

Mercury

Exospheres of the Moon and Mercury



Earth's Moon



Mercury

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

Where did the hydrogen in Earth's atmosphere go?

A. We never had any.
B. It escaped into space.
C. It dissolved in the oceans and was incorporated into rocks.
D. none of the above

Where did the hydrogen in Earth's atmosphere go?

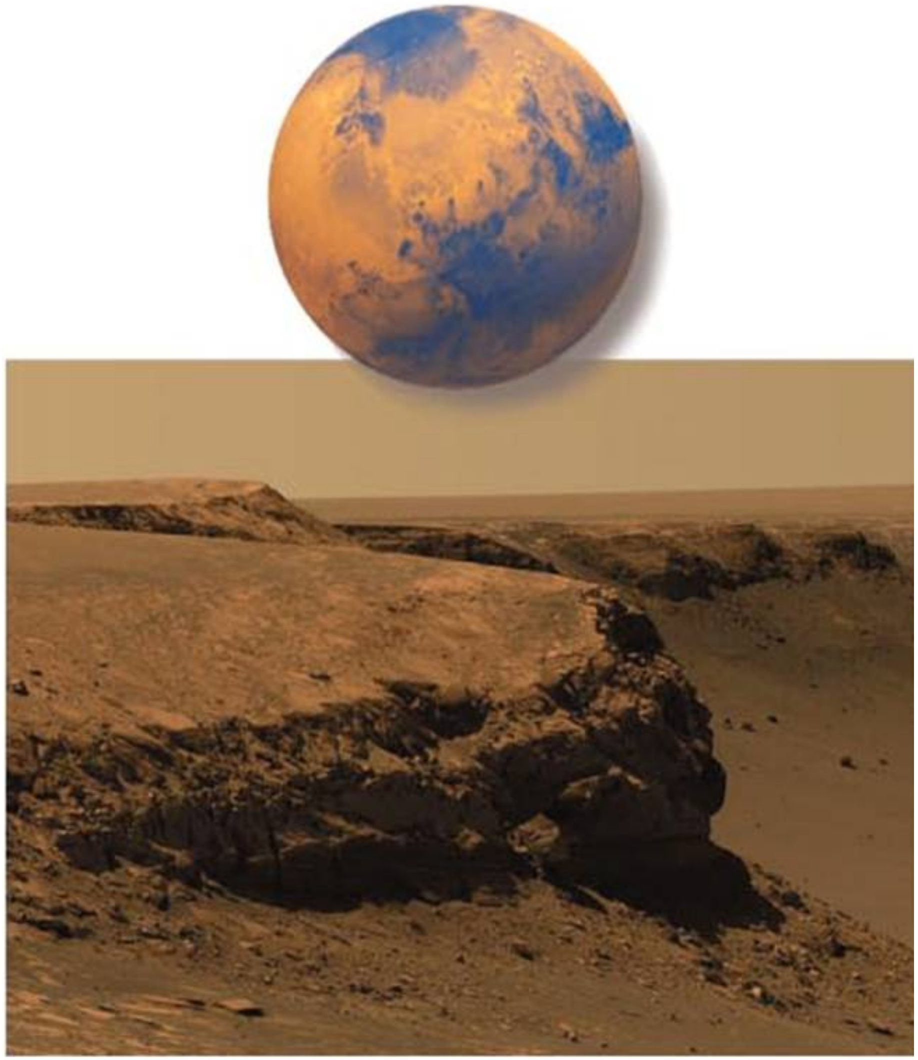
A. We never had any.
B. It escaped into space.
C. It dissolved in the oceans and was incorporated into rocks.
D. none of the above

10.4 The Atmospheric History of Mars

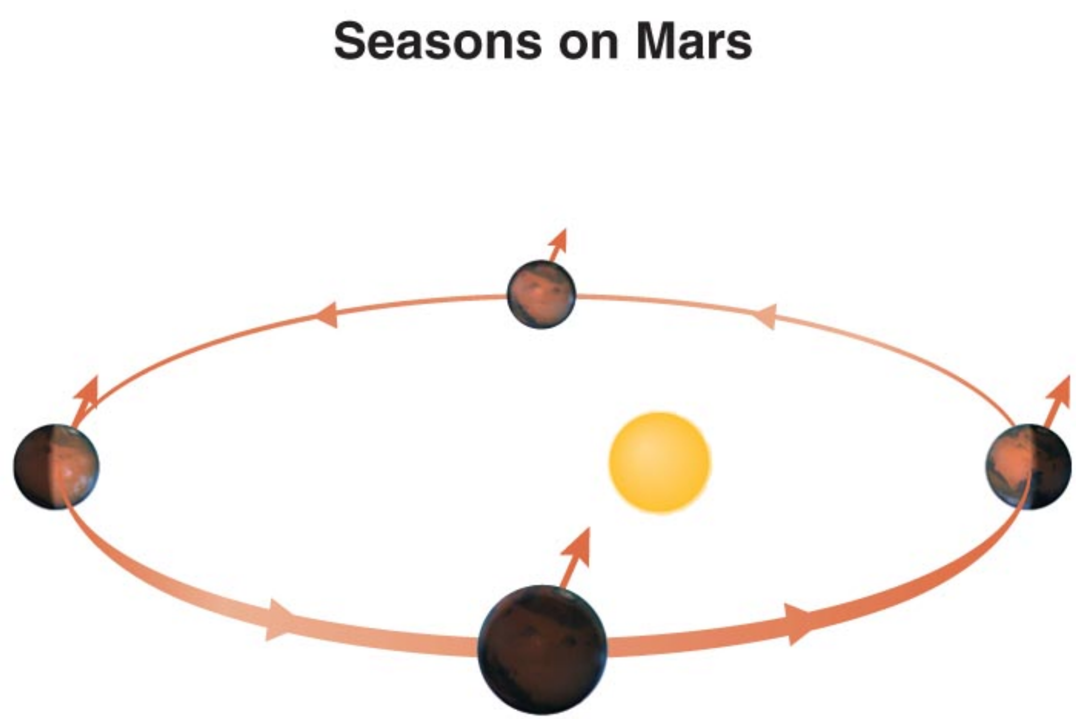
Our goals for learning:

- What is Mars like today?
- Why did Mars change?

What is Mars like today?

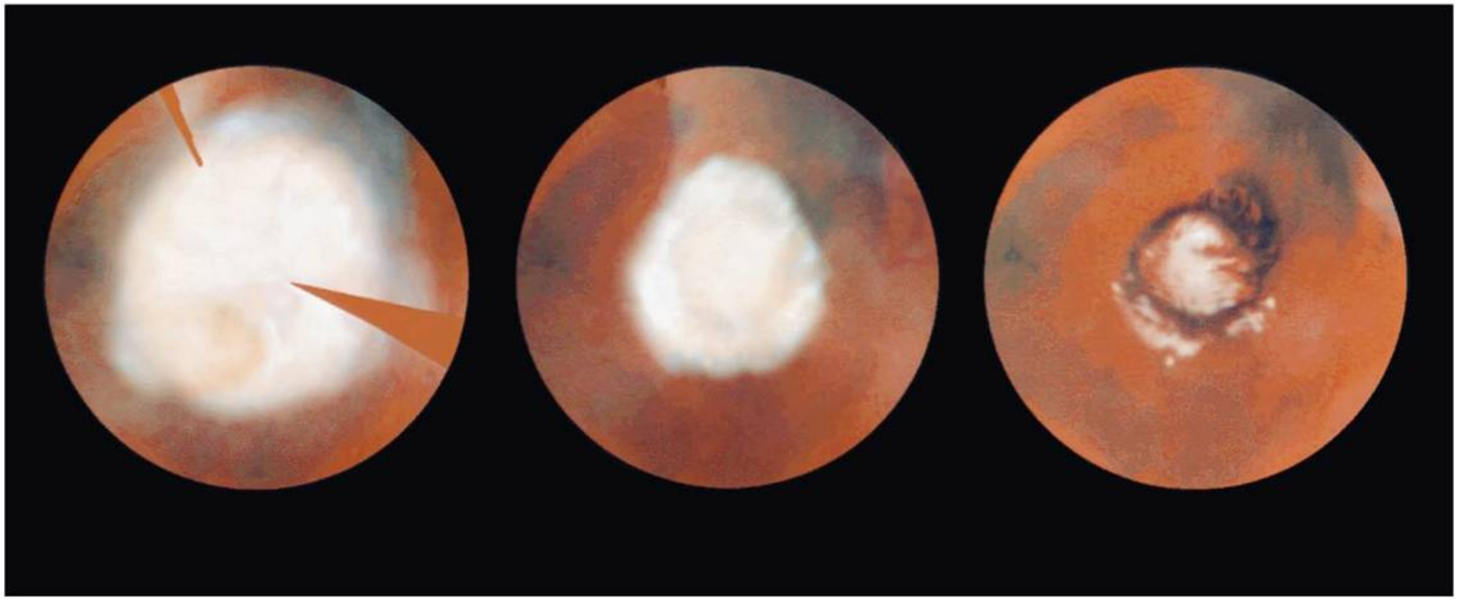


Seasons on Mars



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

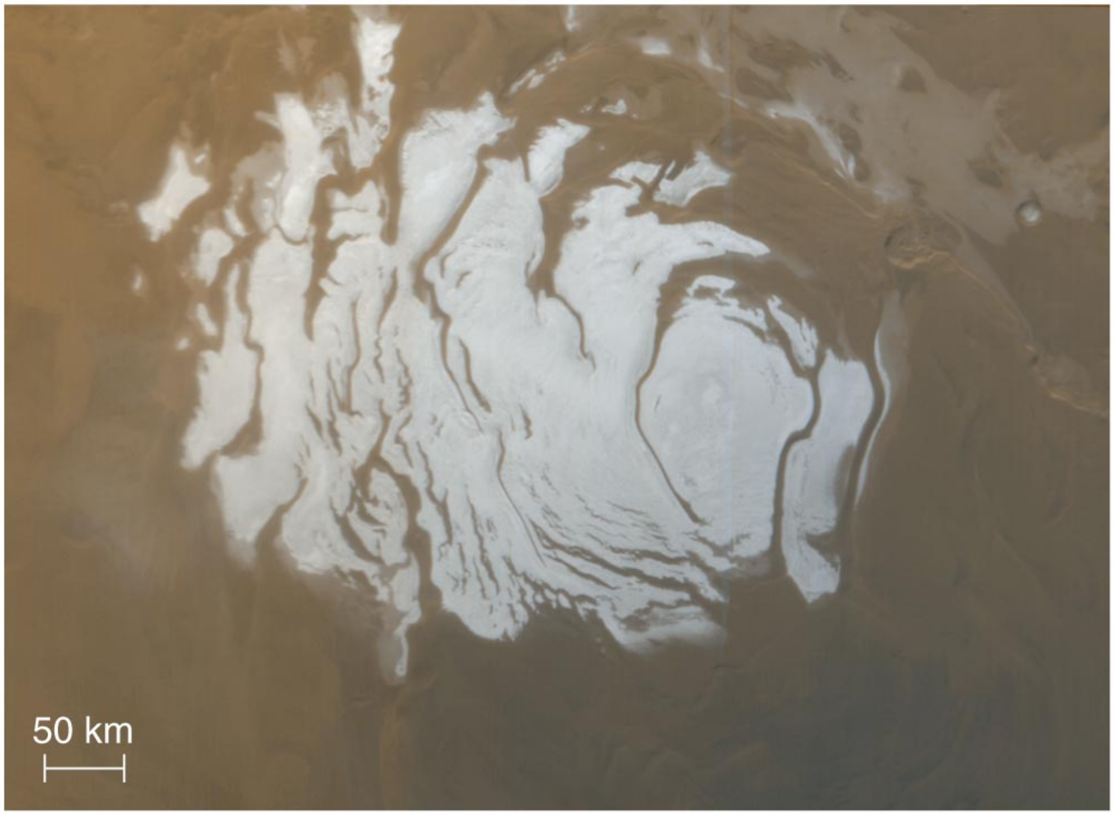
Polar Ice Caps of Mars



Late winter Mid-spring Early summer

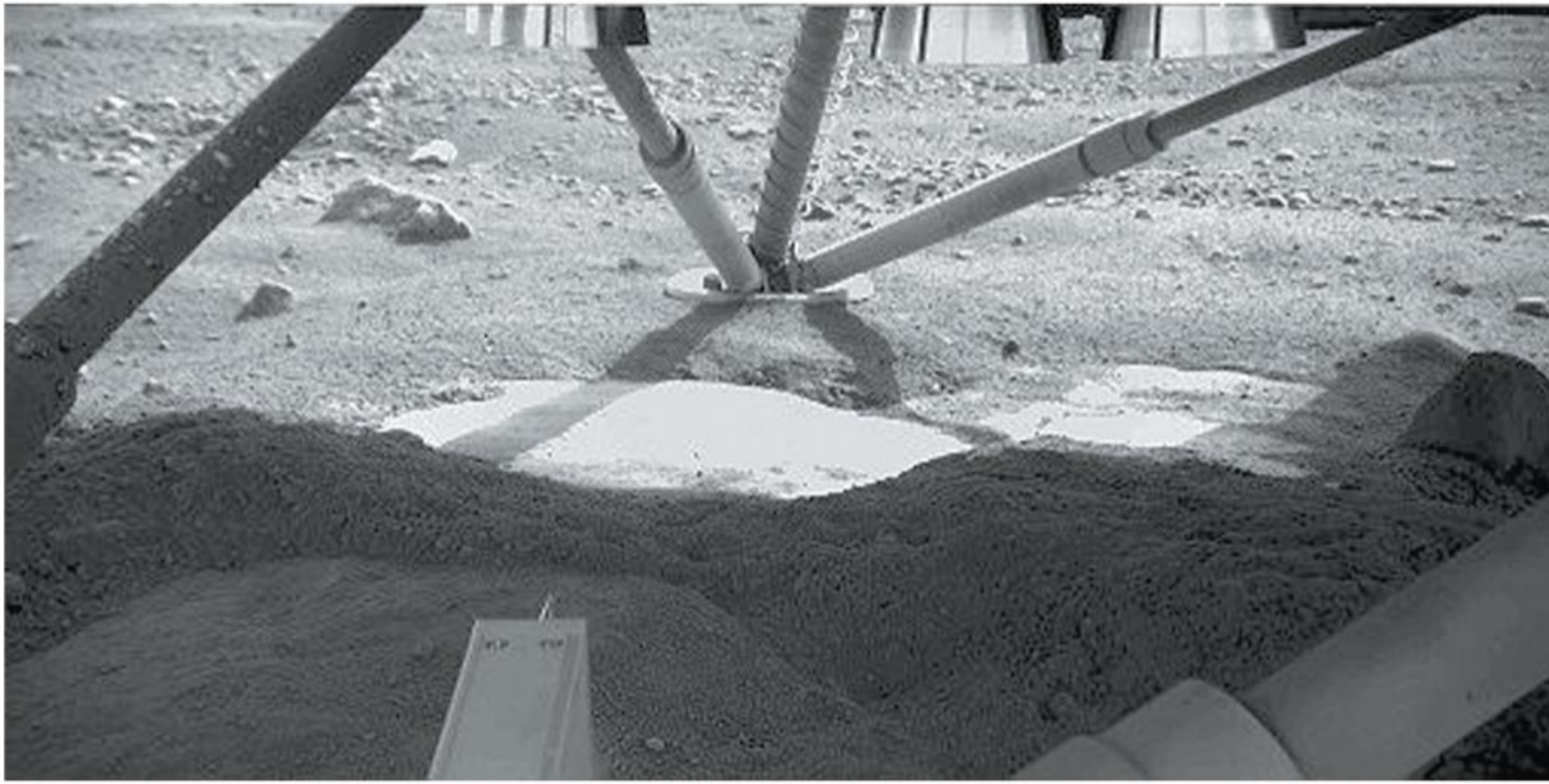
- Carbon dioxide ice of polar cap sublimates (turns from solid to gas) as summer approaches and condenses at opposite pole.

Polar Ice Caps of Mars



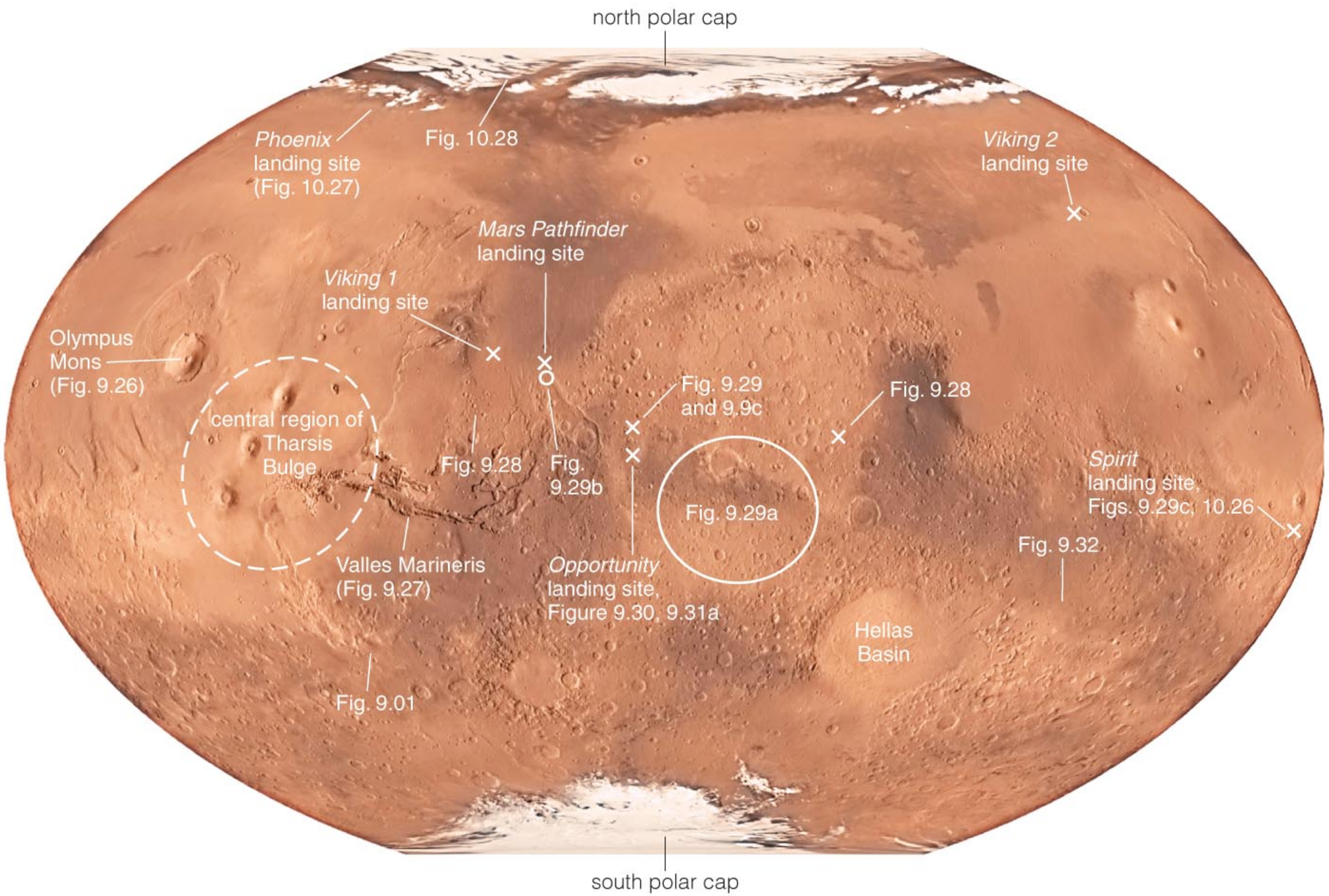
- Residual ice of the polar cap remaining during summer is primarily water ice.
- CO_2 ice sublimates into the atmosphere
- Weird direct exchange of mass between the main component of the poles and the atmosphere

Figure 10.27B



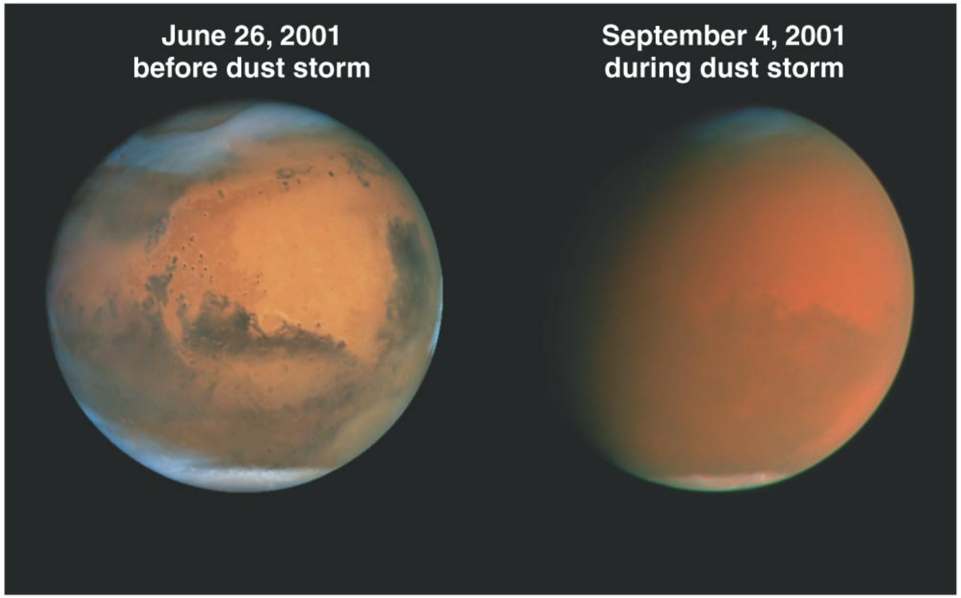
b The robotic arm camera of the *Phoenix* lander found a bright patch of water ice underneath it. The spacecraft's landing rockets (visible at top) blasted away an overlying layer of dust.

What are the major geological features of Mars?



Enough known water ice on Mars to make a global ocean 11 m deep

Dust Storms on Mars



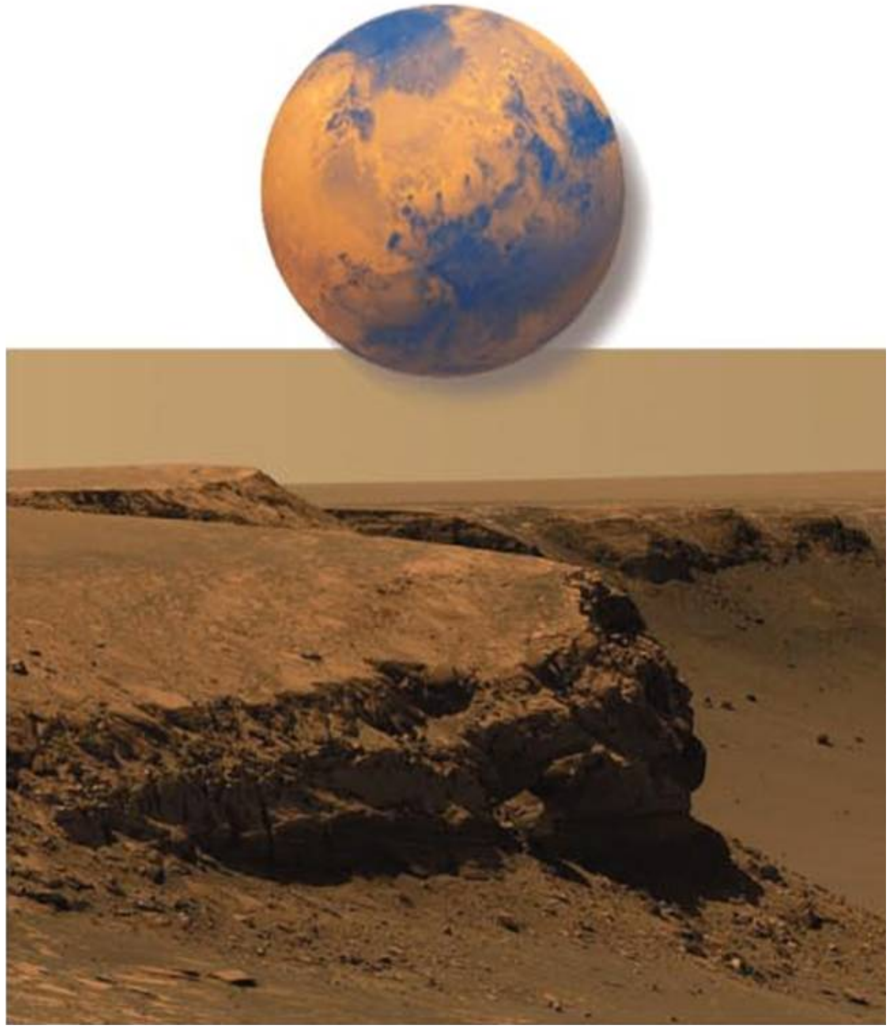
Interactive Figure

- 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.

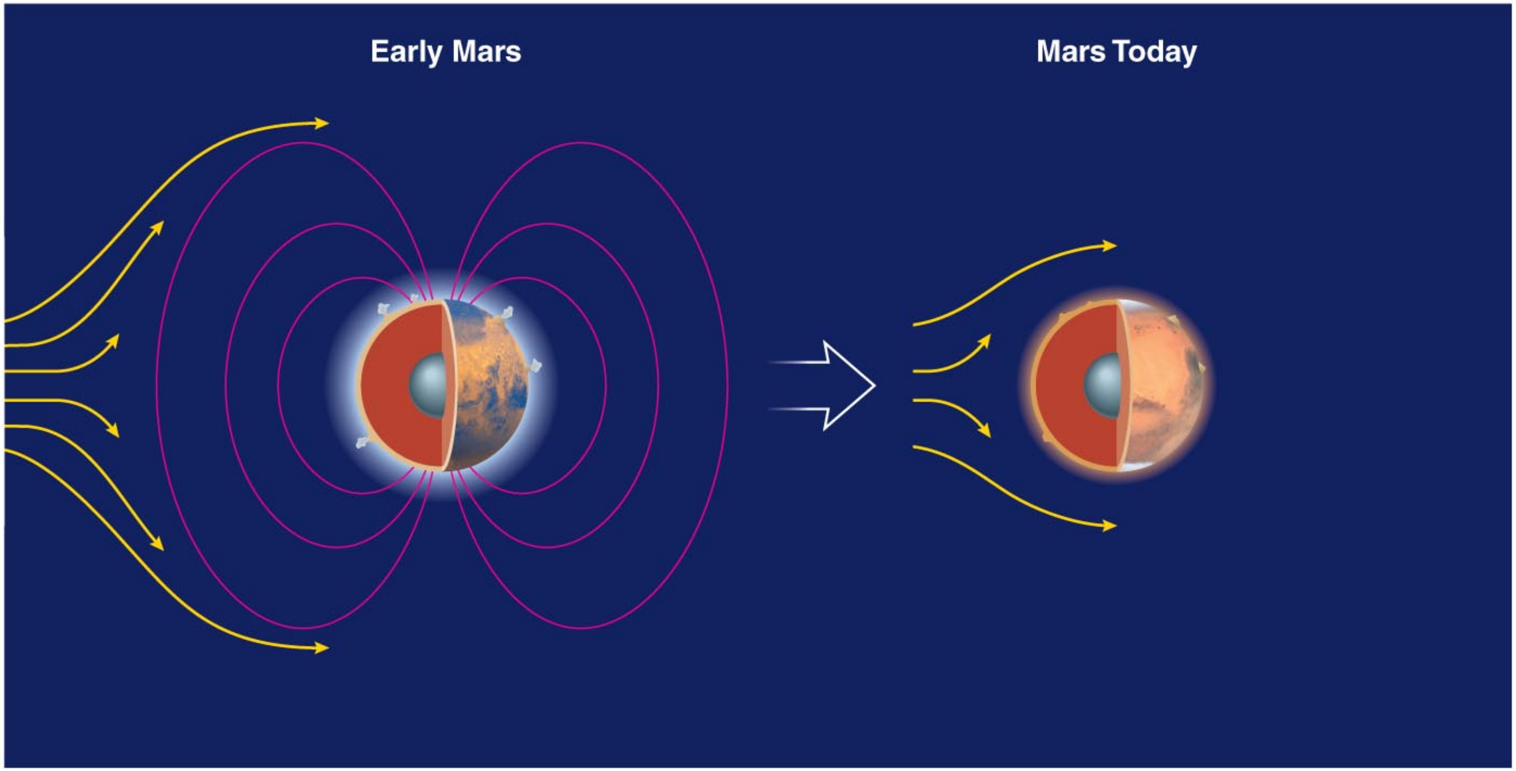
Why did Mars change?



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.

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.
- UV may have broken up water as well

What have we learned?

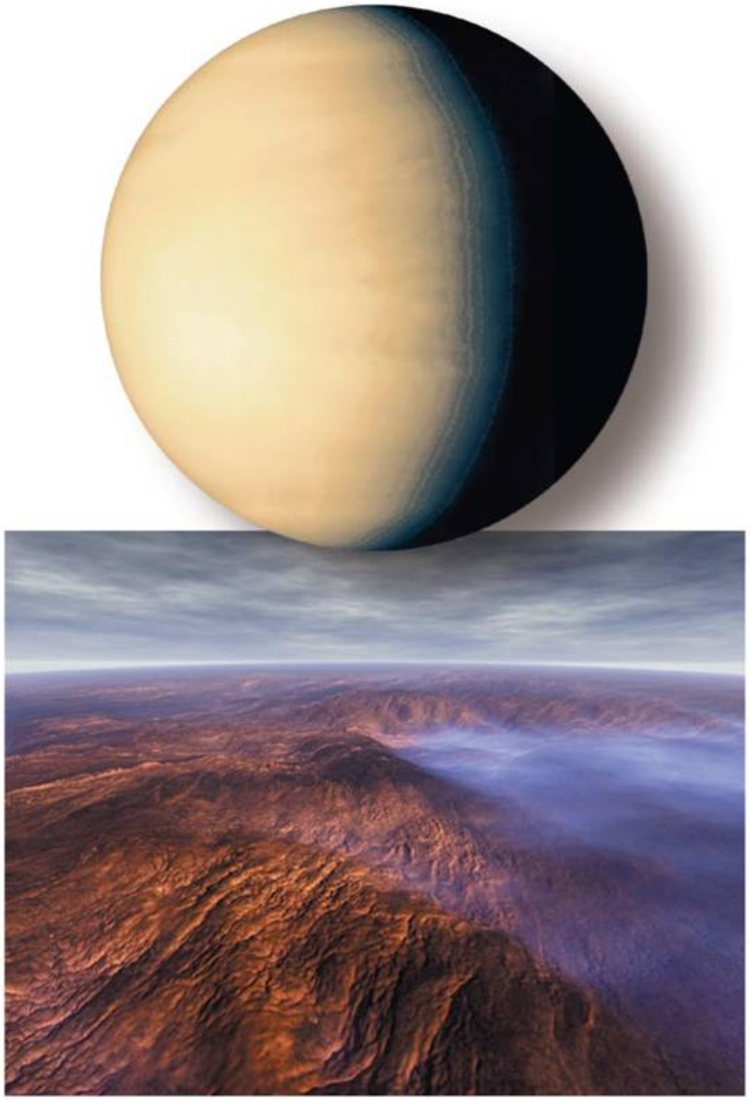
- What is Mars like today?
  - Mars is cold, dry, and frozen.
  - Strong seasonal changes cause CO_2 to move from pole to pole, leading to dust storms.
- Why did Mars change?
  - Its atmosphere must have once been much thicker for its greenhouse effect to allow liquid water on the surface.
  - Somehow 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.
  - Same pressure as 1km down in ocean
- Slow rotation produces little weather.
  - Fastest winds 6 km/hr

Atmosphere of Venus

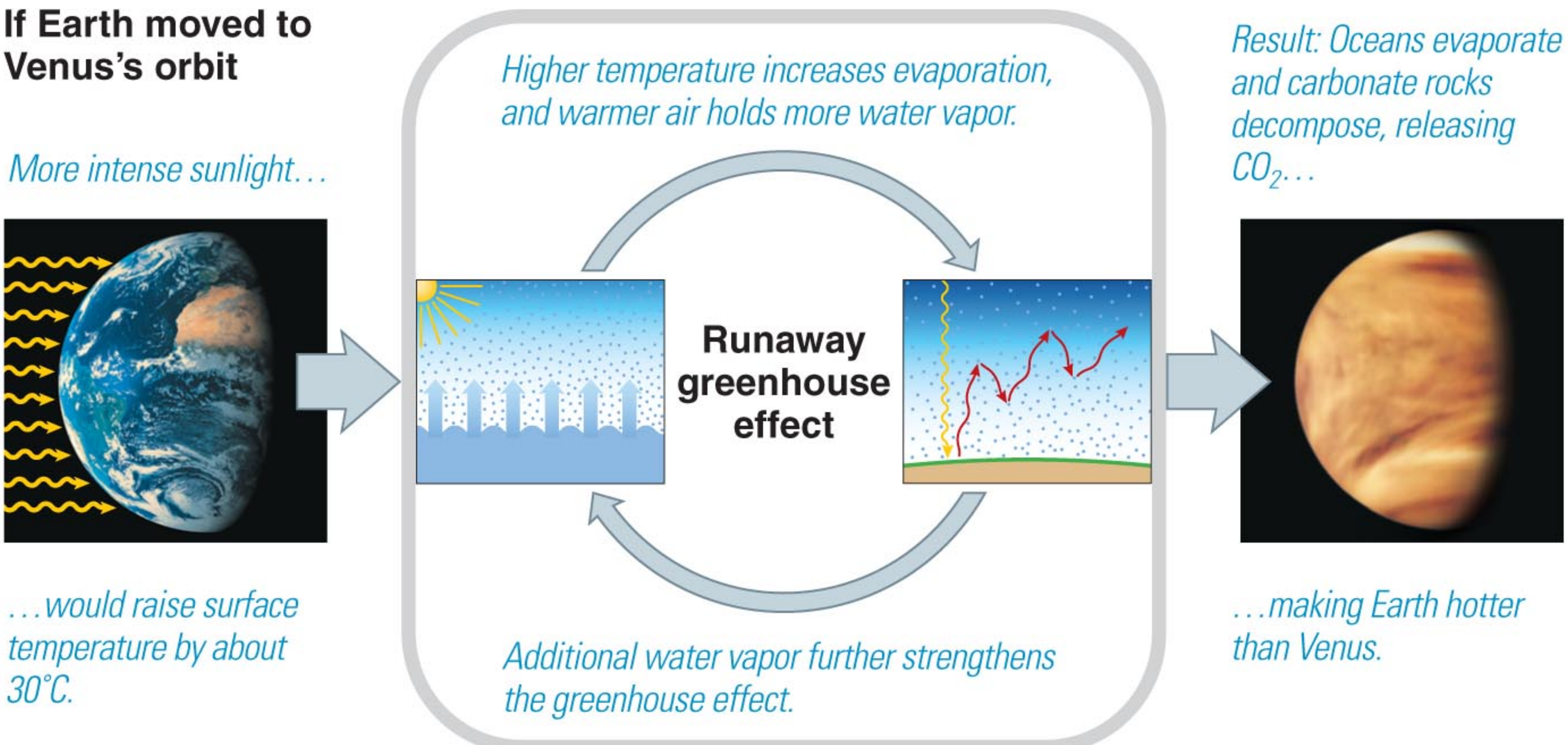
- No axis tilt, so no seasons
- Thick atmosphere homogenizes surface temperature
- Sulfuric acid clouds and rain (but it doesn't reach the surface)

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?

Runaway Greenhouse Effect



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

Runaway Greenhouse Effect

Earth at 1 AU

- Cool enough that water is liquid
- CO_2 dissolves in water, makes carbonate rocks at ocean floor
- 170,000 more CO_2 in rocks than in atmosphere

Earth at 0.7 AU

- Hotter temps lead to more water in vapor form
- Water vapor leads to strong greenhouse effect, evaporates all water – then lost to solar UV
- Hot carbonate rocks release all their CO_2 into the atmosphere
- 10,000X less water than Earth 1 AU

Clicker 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.

Clicker 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 Atmosphere

- About 10 kilometers thick
- Consists mostly of molecular nitrogen (N_2) and oxygen (O_2).
- Thickness of a dollar bill on a 12" globe

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.

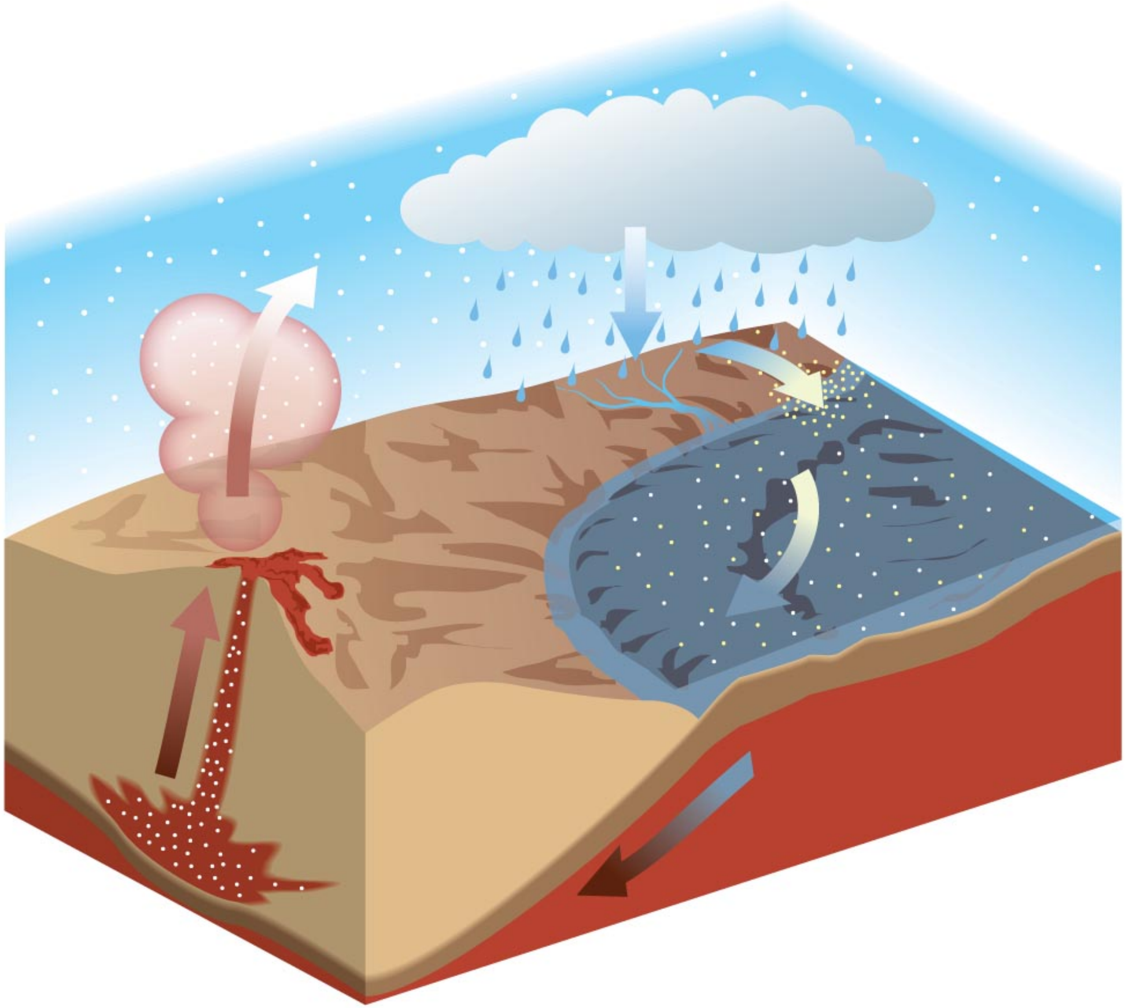
Nitrogen and Oxygen

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

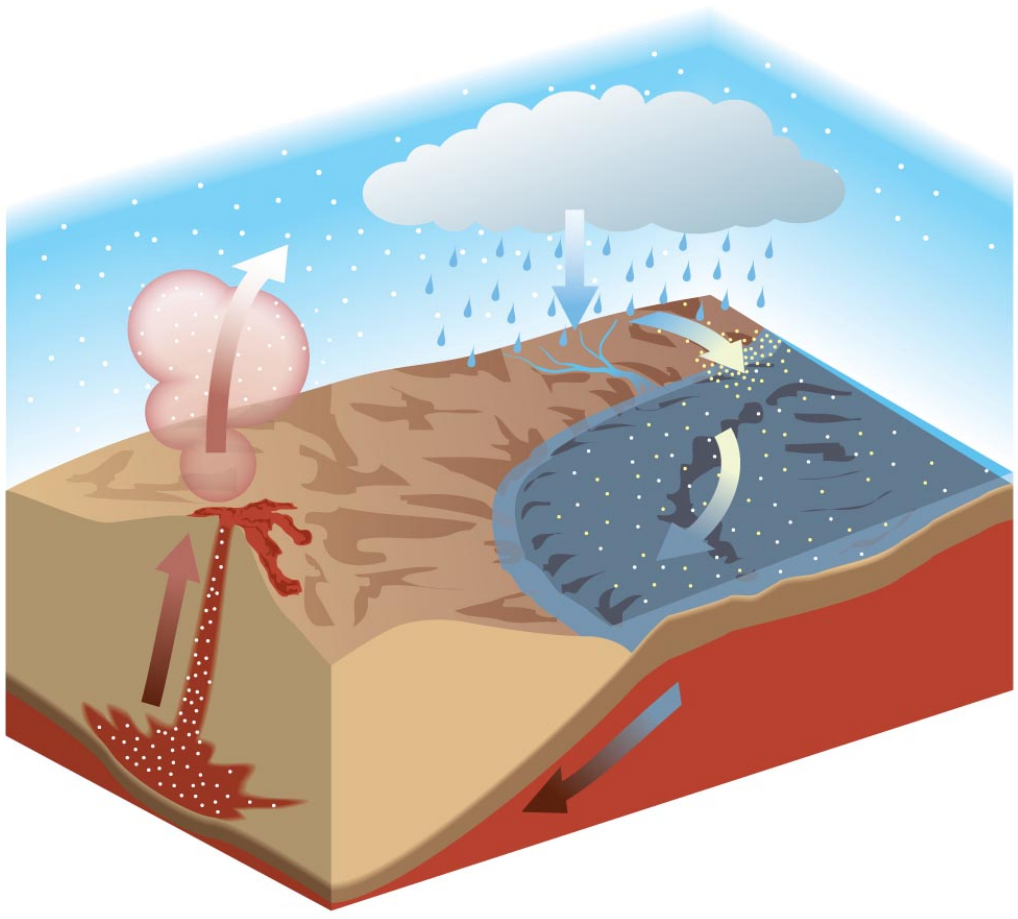
Ozone and the Stratosphere

- 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?

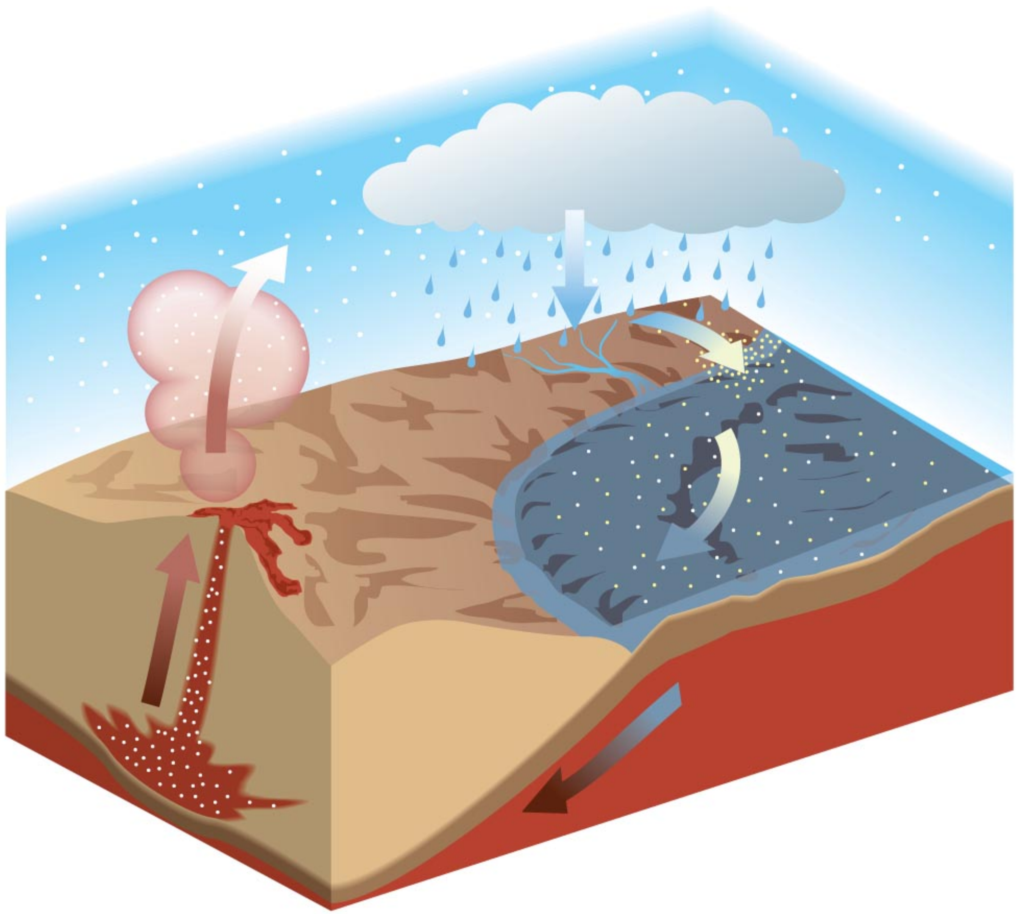


Carbon Dioxide Cycle



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.

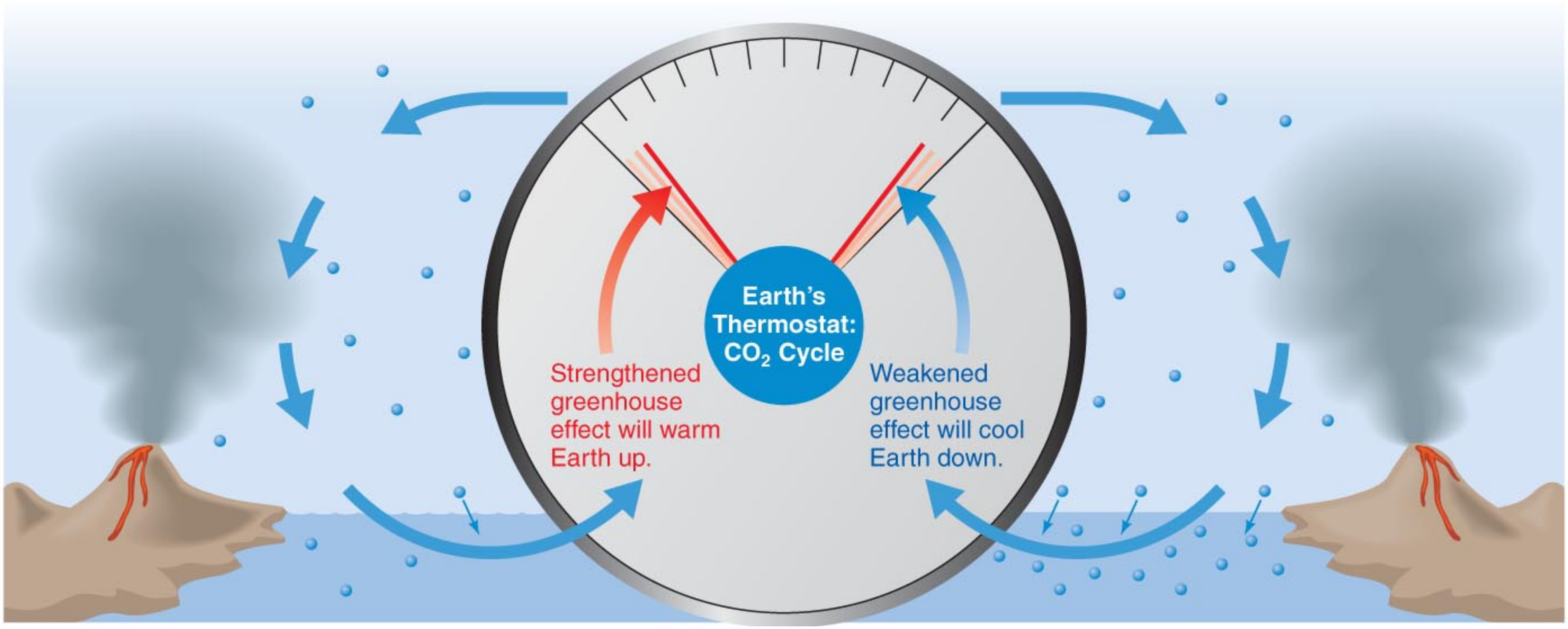
Carbon Dioxide Cycle



4. Subduction carries carbonate rock down into mantle.

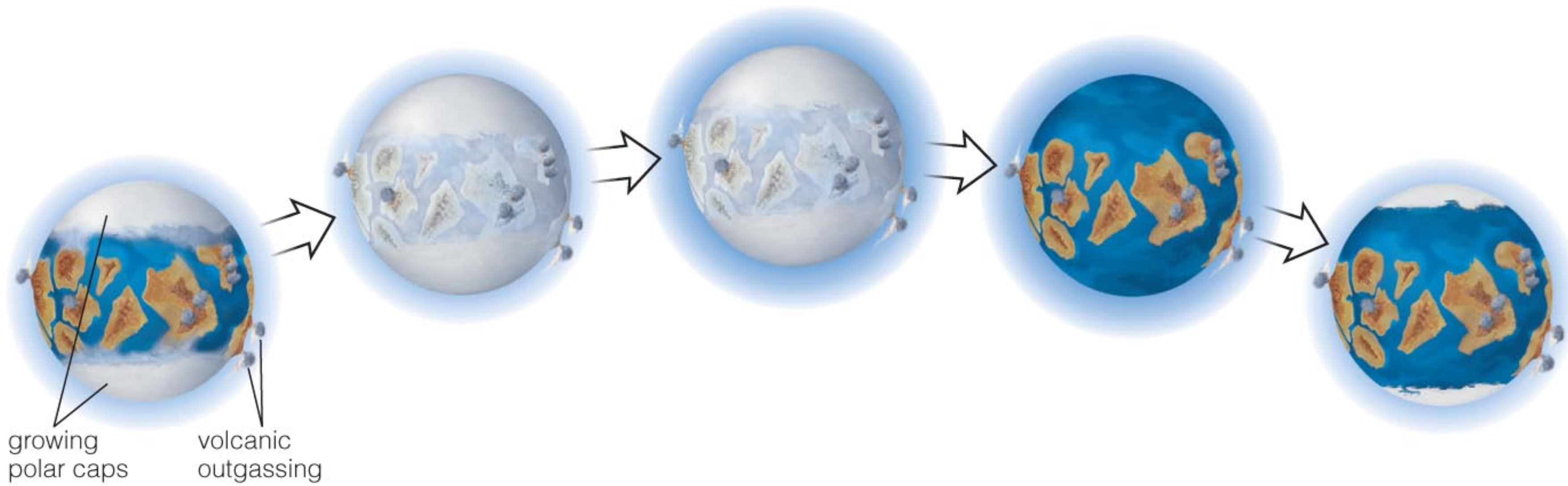
5. Rock melts in mantle and CO_2 is outgassed back into atmosphere through volcanoes.

Earth's Thermostat



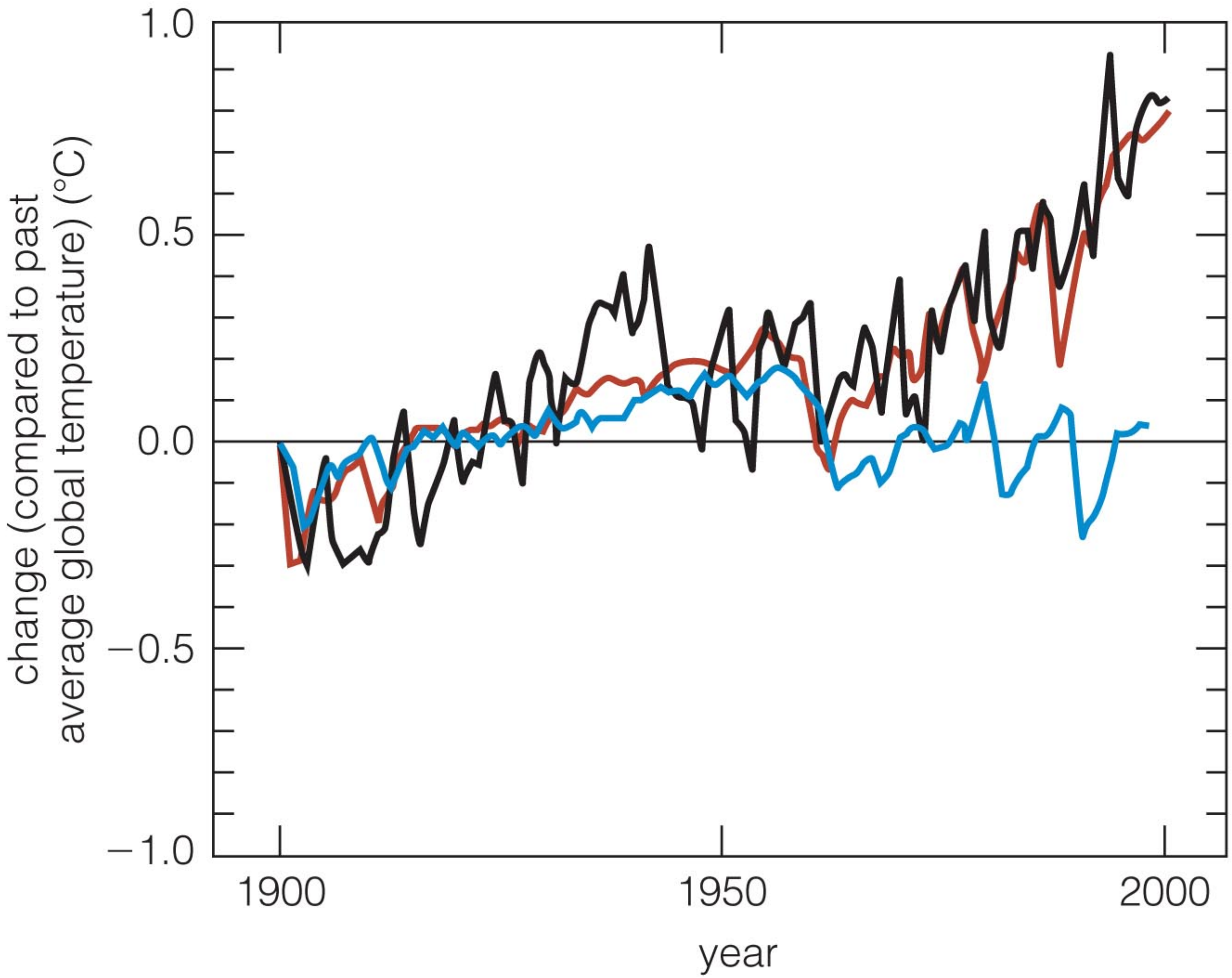
- Cooling allows CO_2 to build up in atmosphere.
- Heating causes rain to reduce CO_2 in atmosphere.

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?

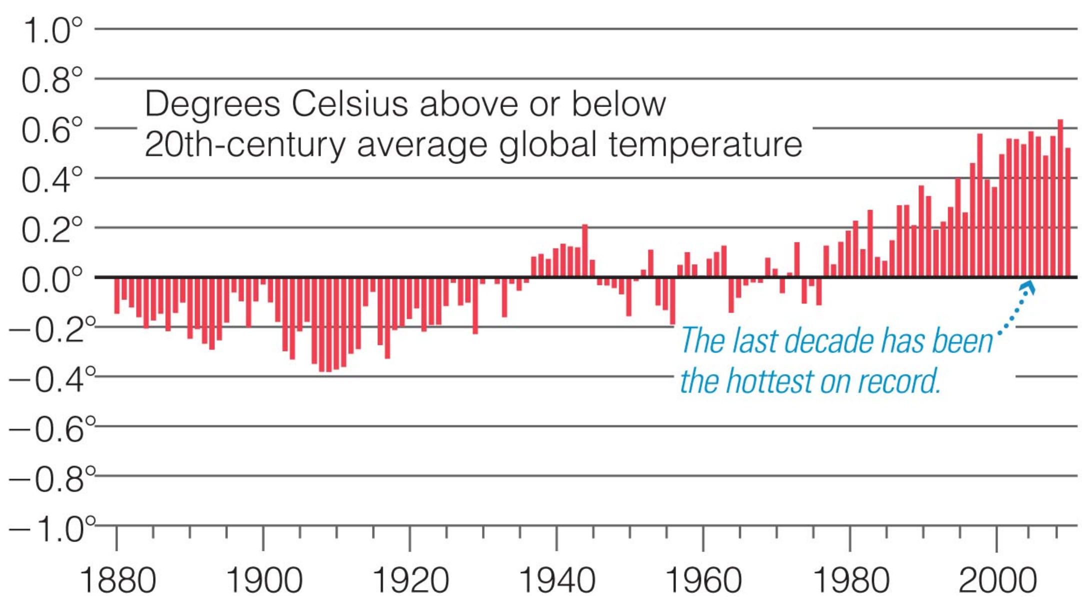


Dangers of Human Activity

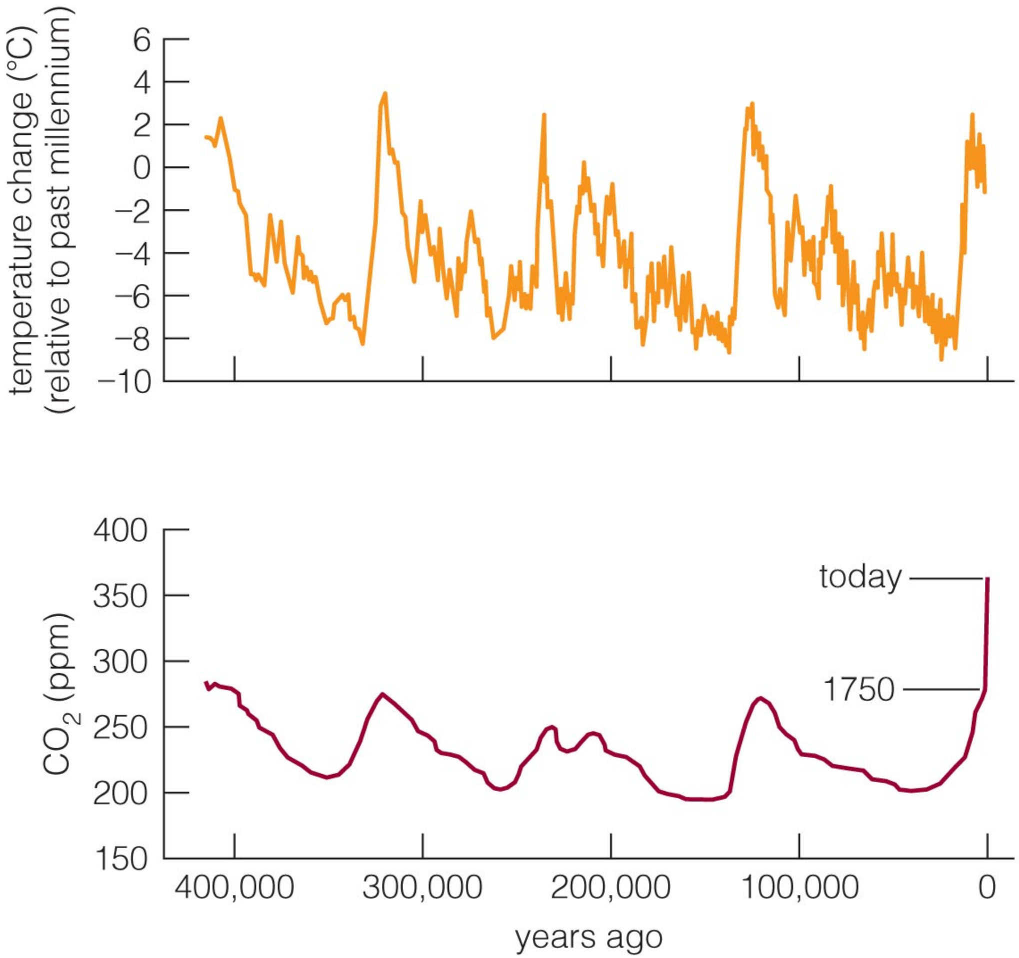
- Human-made CFCs in the atmosphere destroy ozone, reducing protection from ultraviolet radiation.
- Human activity is driving many species to extinction.
- Human use of fossil fuels produces greenhouse gases that can cause global warming.

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.

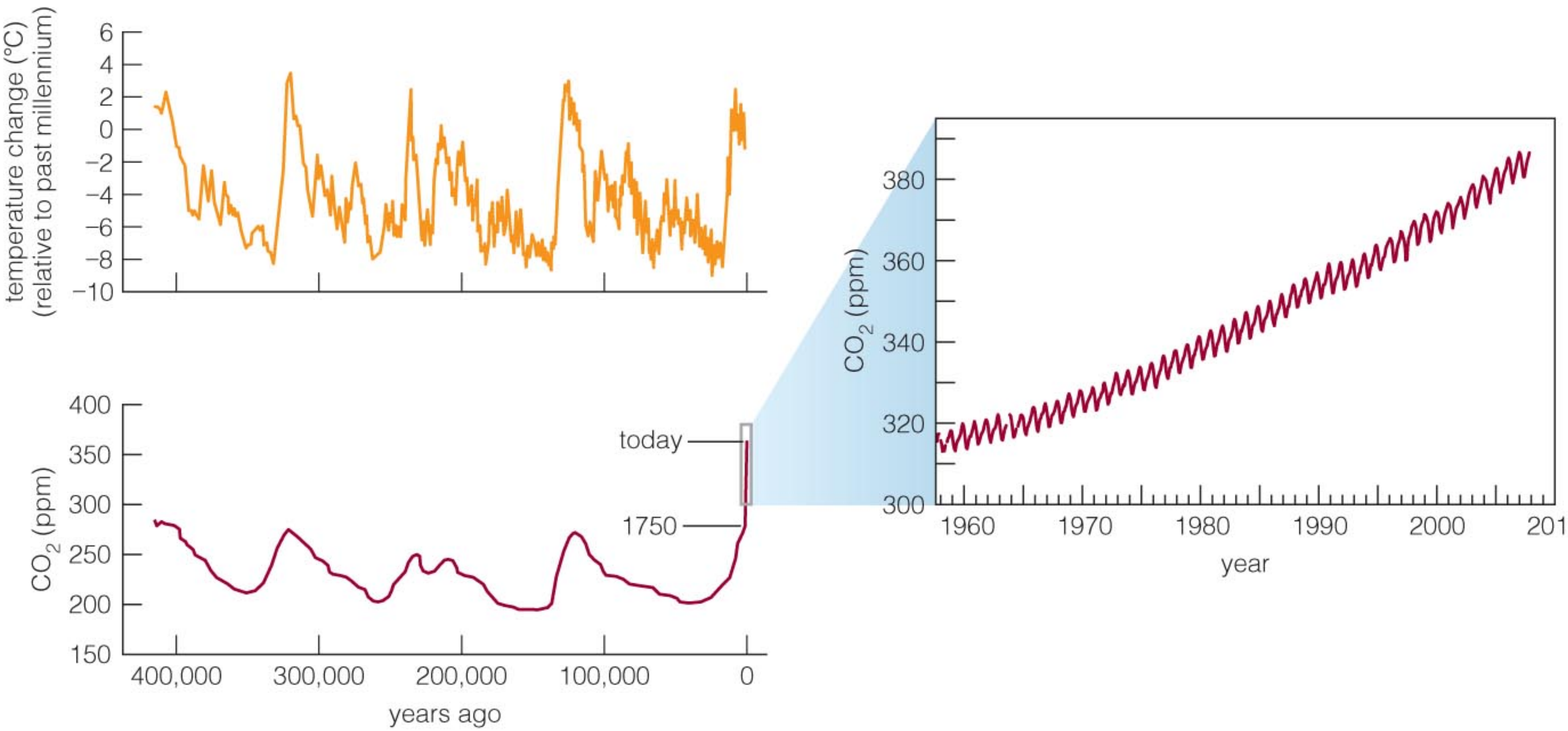


CO_2 Concentration



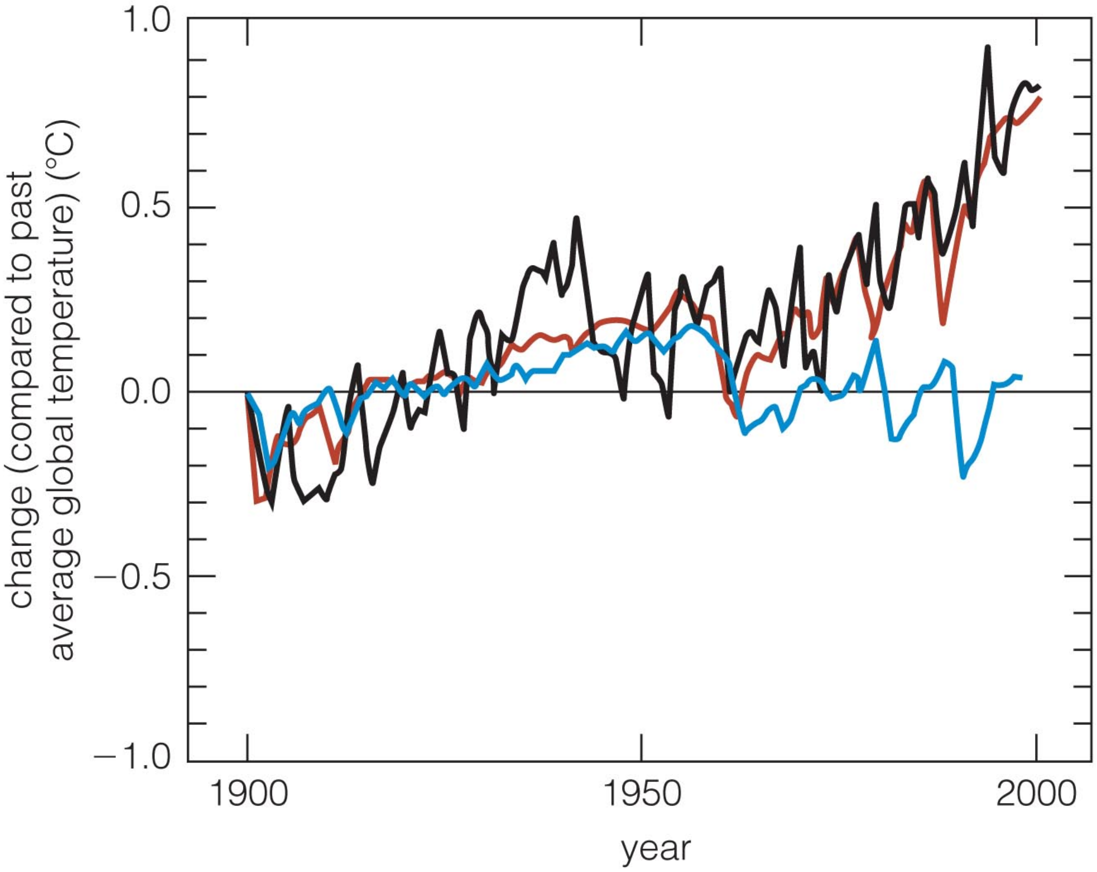
- Global temperatures have tracked CO_2 concentration for last 500,000 years.
- Current CO_2 concentration is the highest it's been in at least 500,000 years.

CO_2 Concentration



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

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 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