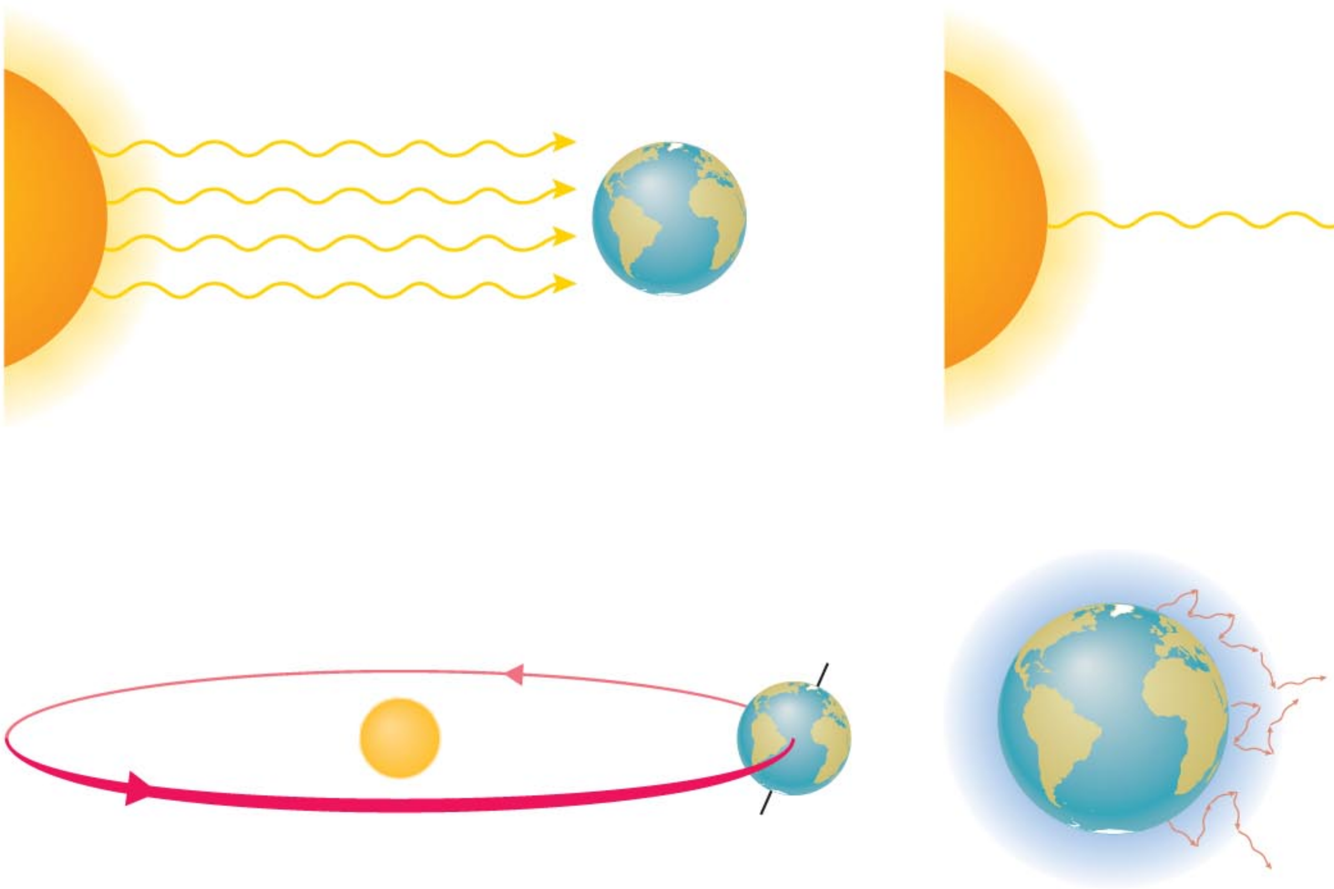
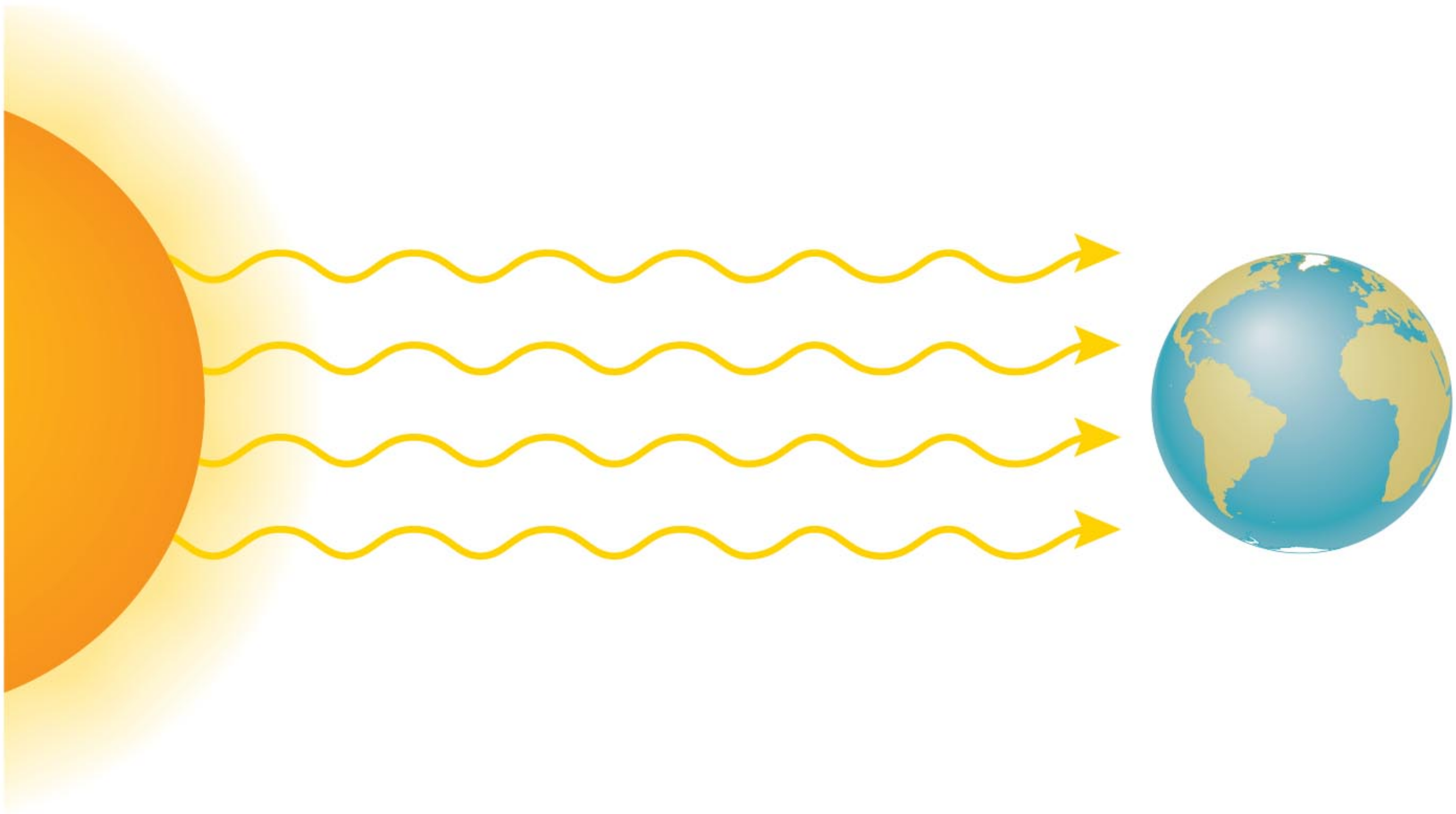
What factors can cause long-term climate change?

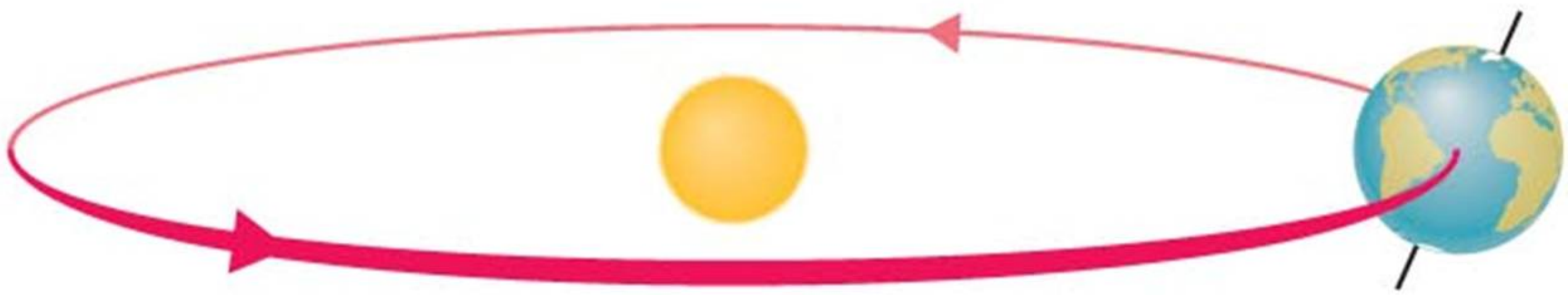


Solar Brightening



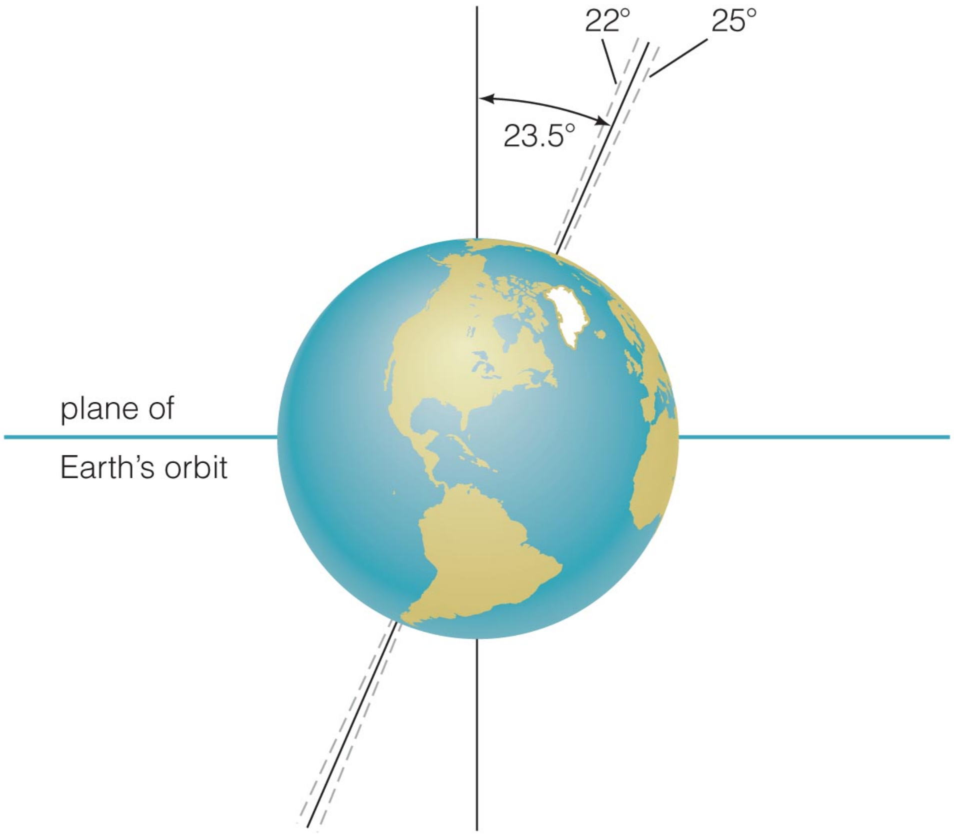
- The Sun very gradually grows brighter with time, increasing the amount of sunlight warming the planets.

Changes in Axis Tilt



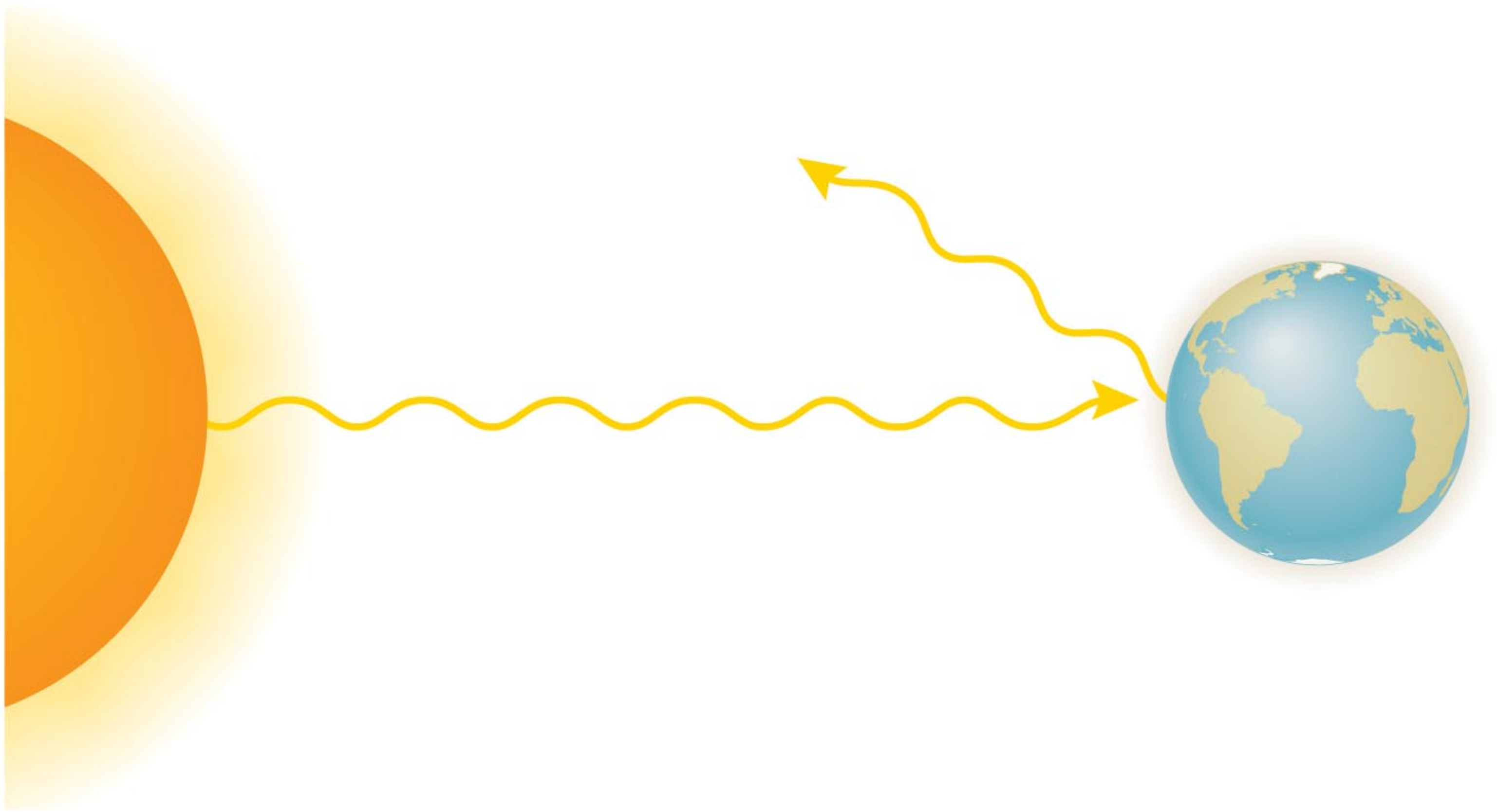
- Greater tilt creates more extreme seasons, while smaller tilt keeps polar regions colder.

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

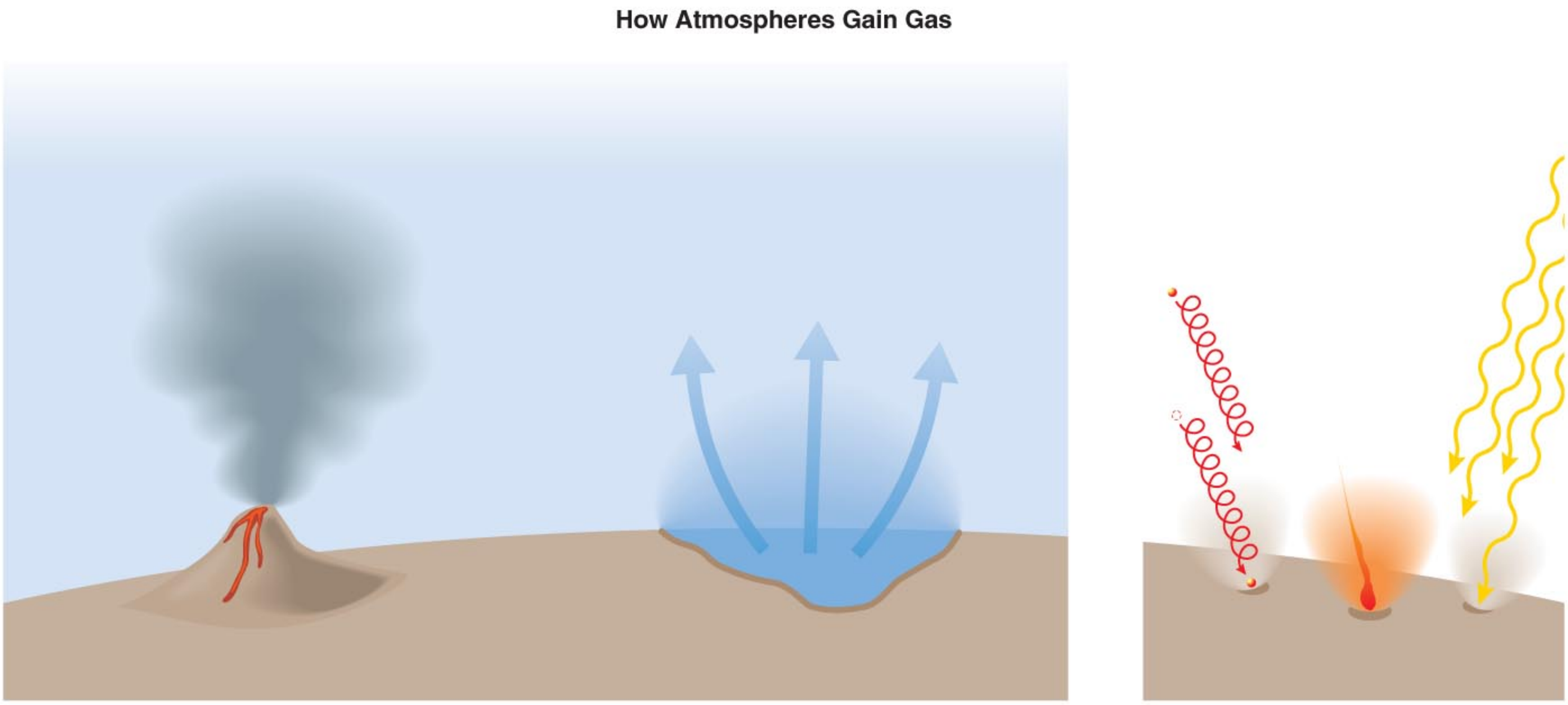


- Higher reflectivity tends to cool a planet, while lower reflectivity leads to warming.

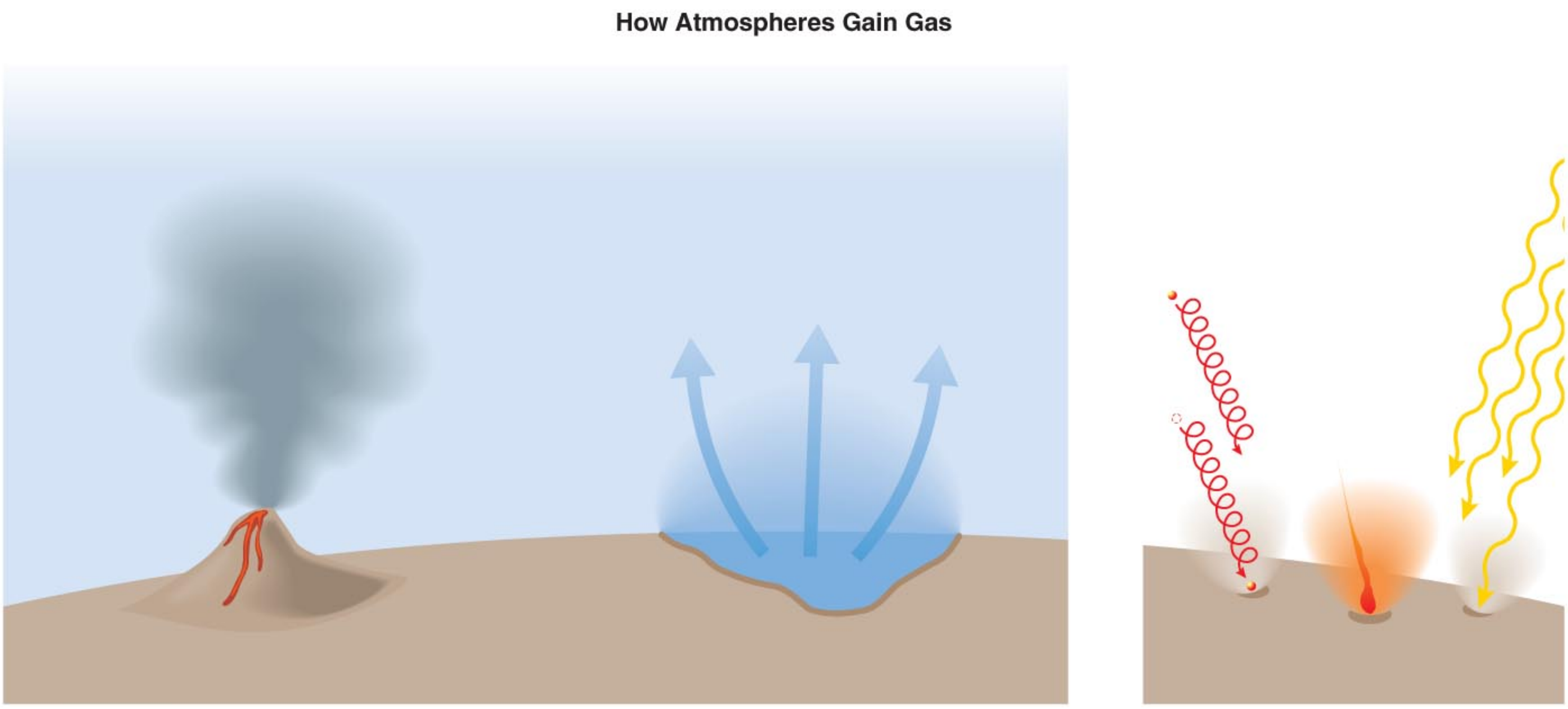
Changes in Greenhouse Gases

- 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

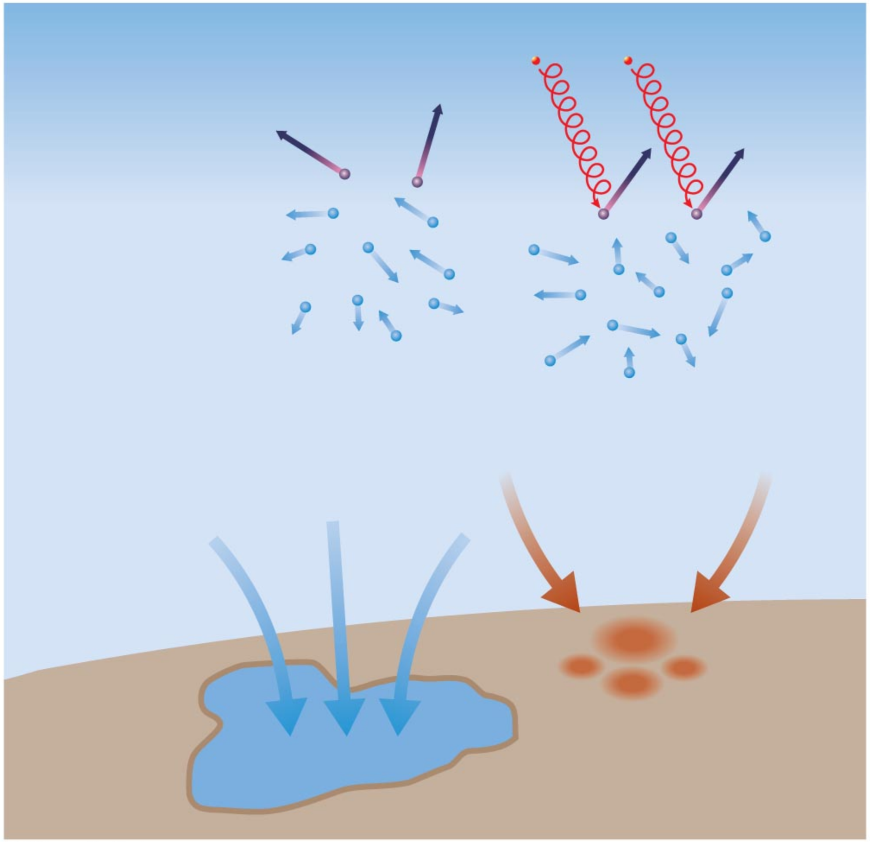
Impacts of particles and photons

Losses of Gas

Thermal escape of atoms

Sweeping by solar wind

How Atmospheres Lose Gas

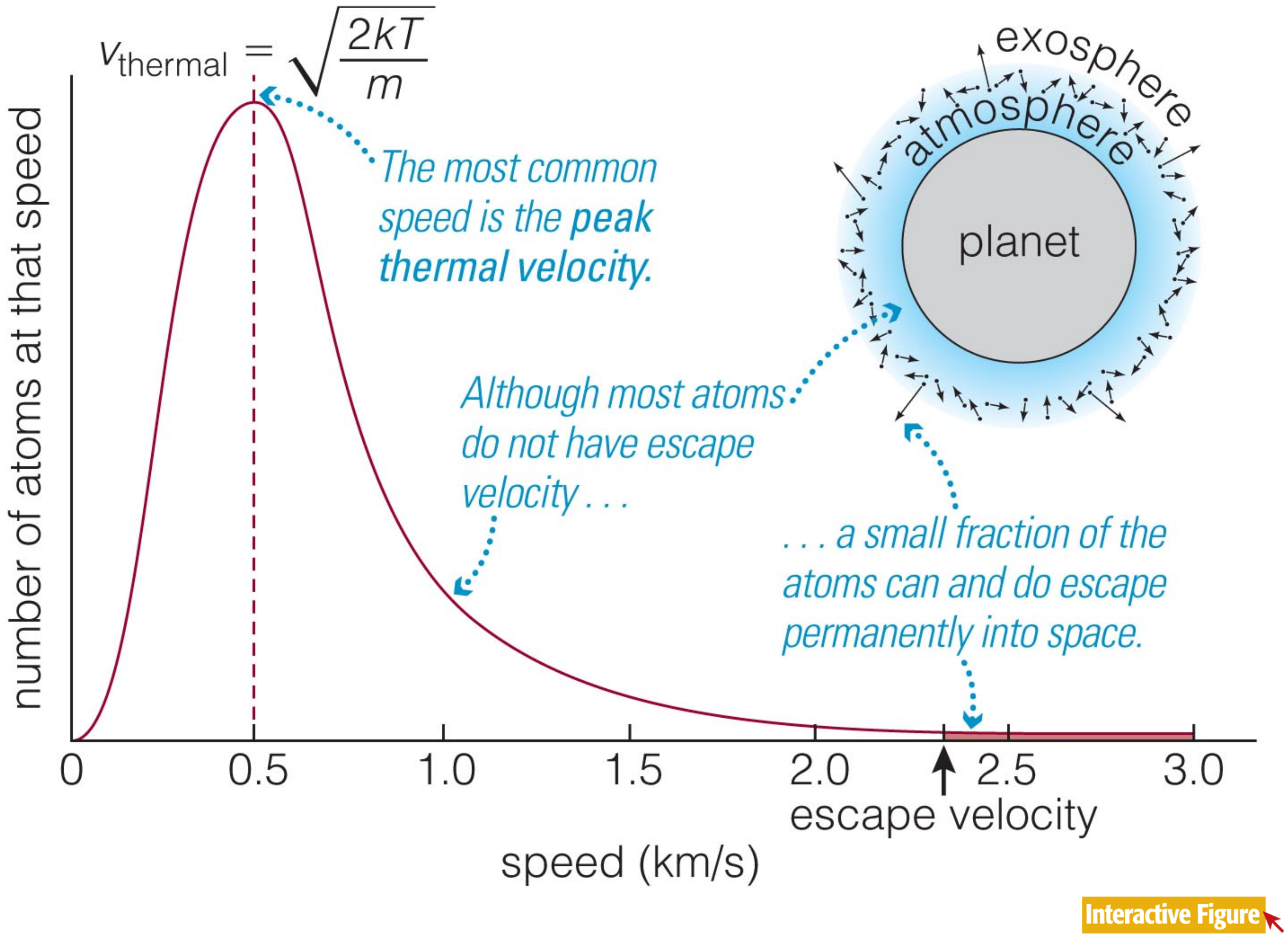


Condensation onto surface

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

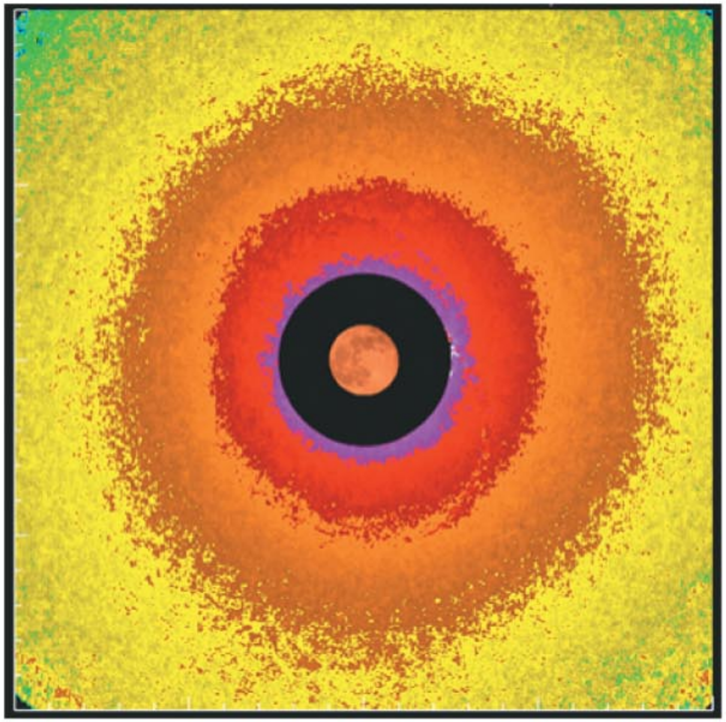
10.3 Atmospheres of Moon and Mercury

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

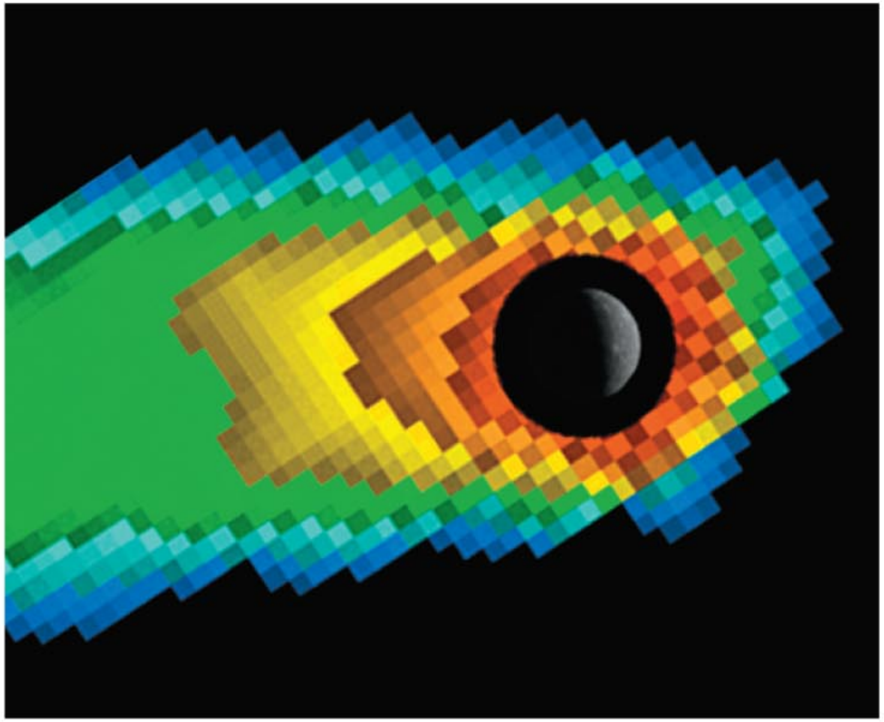
Do the Moon and Mercury have any atmosphere?

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.

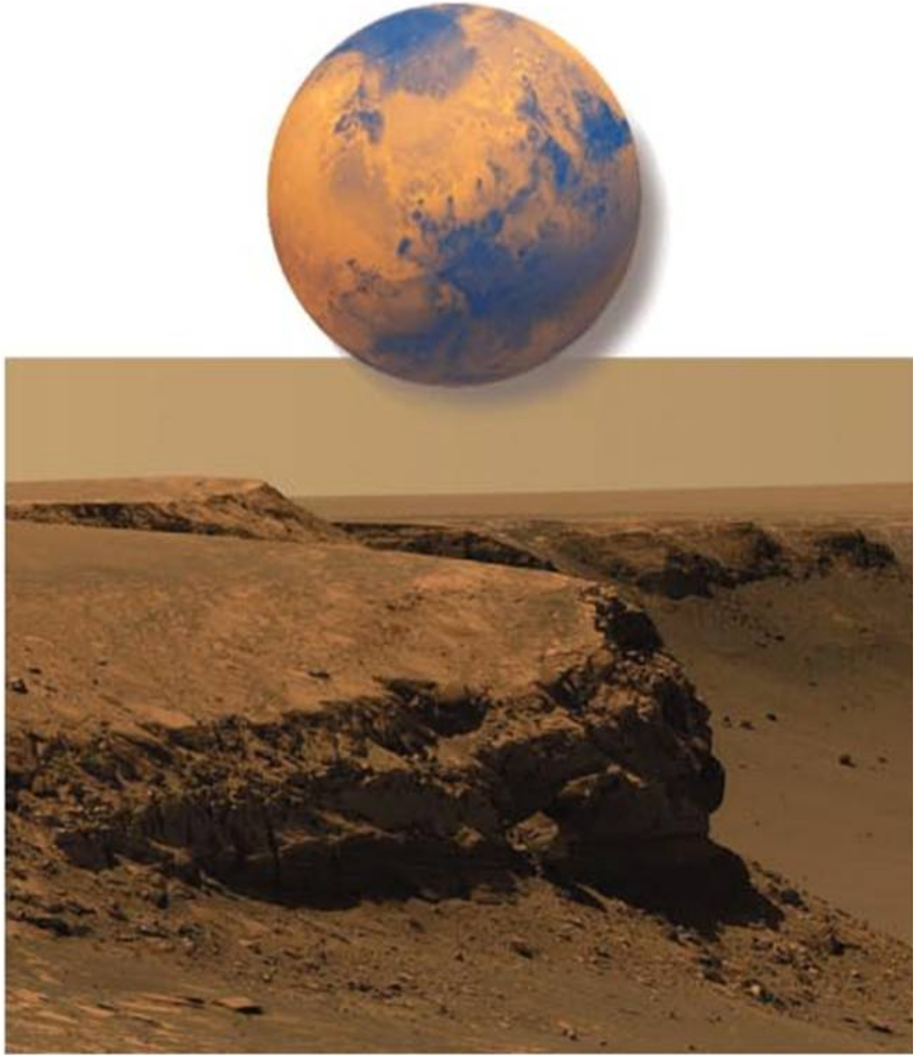
What have we learned?

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

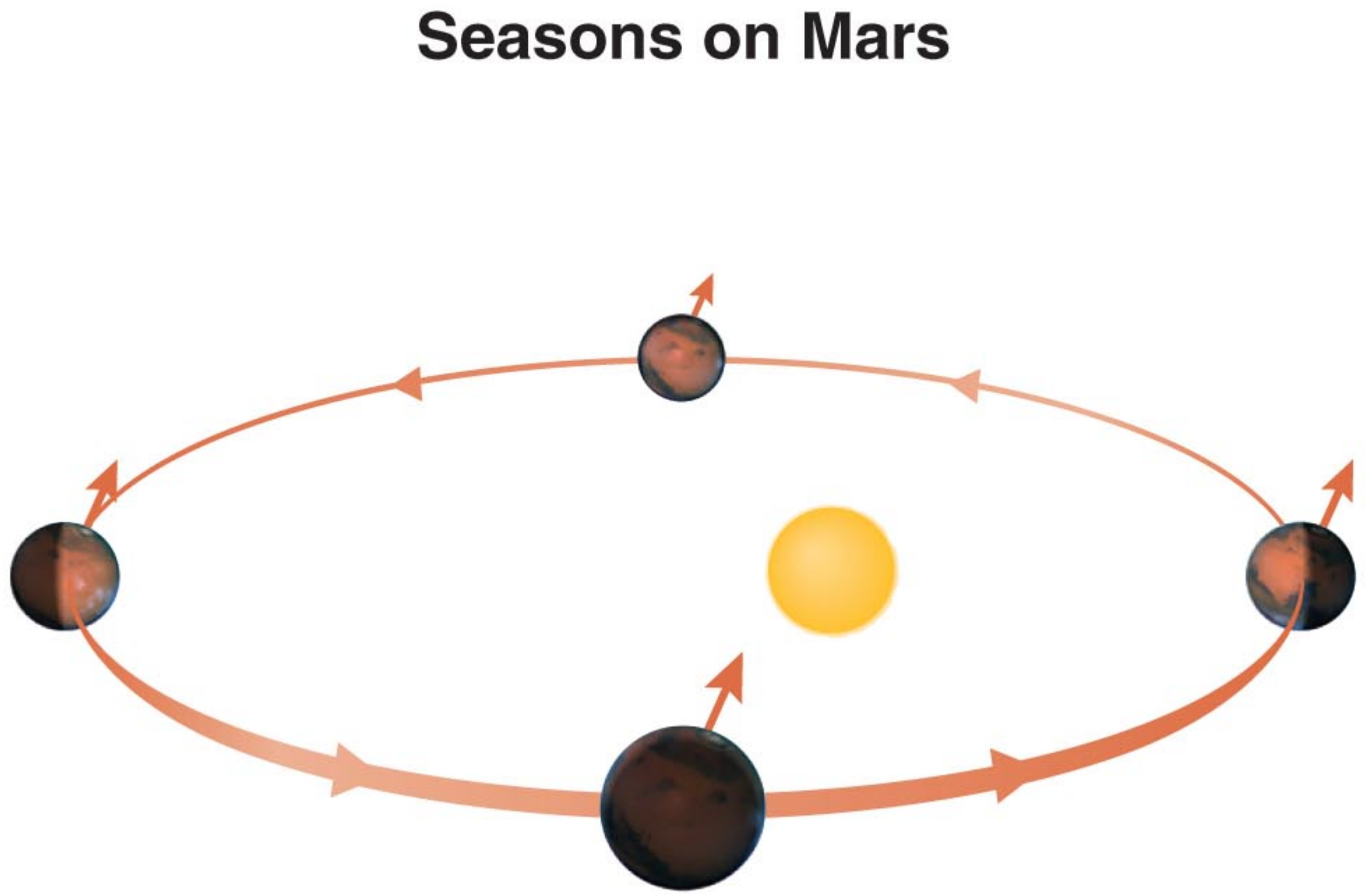
10.4 The Atmospheric History of Mars

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

What is Mars like today?

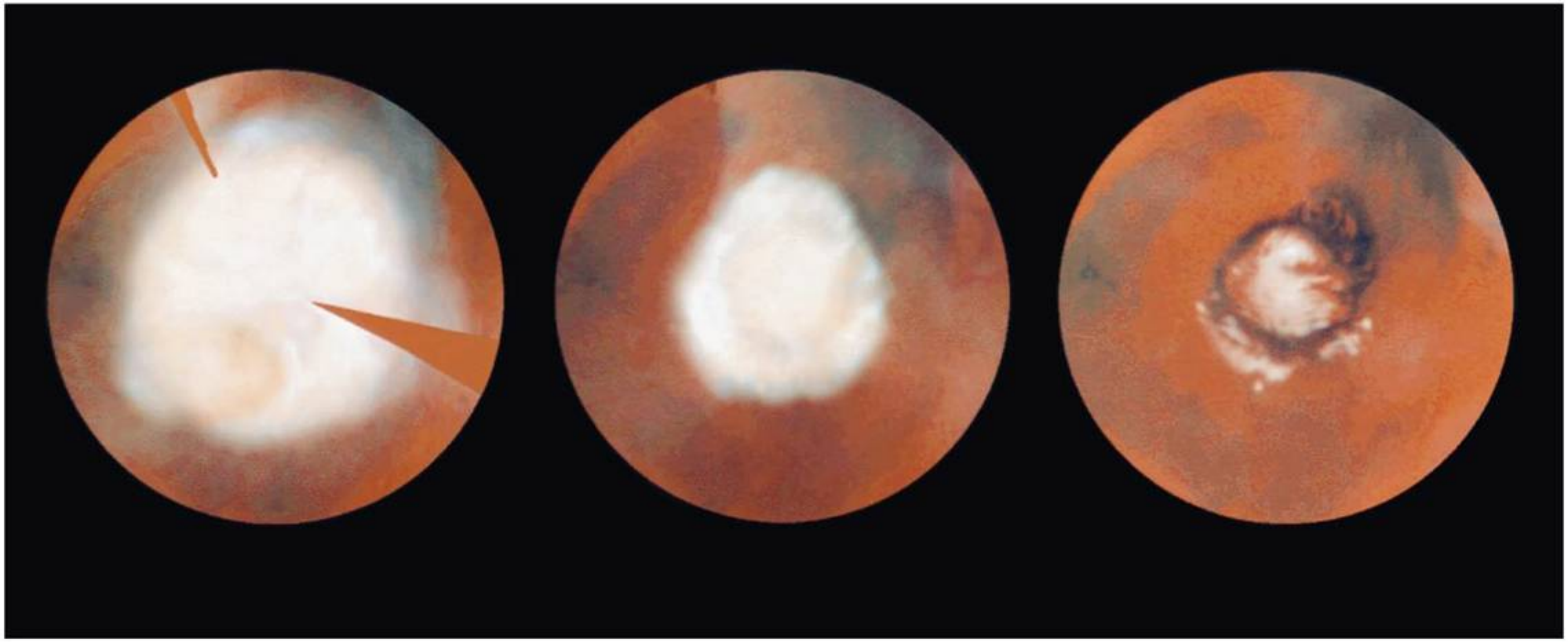


Seasons on Mars



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

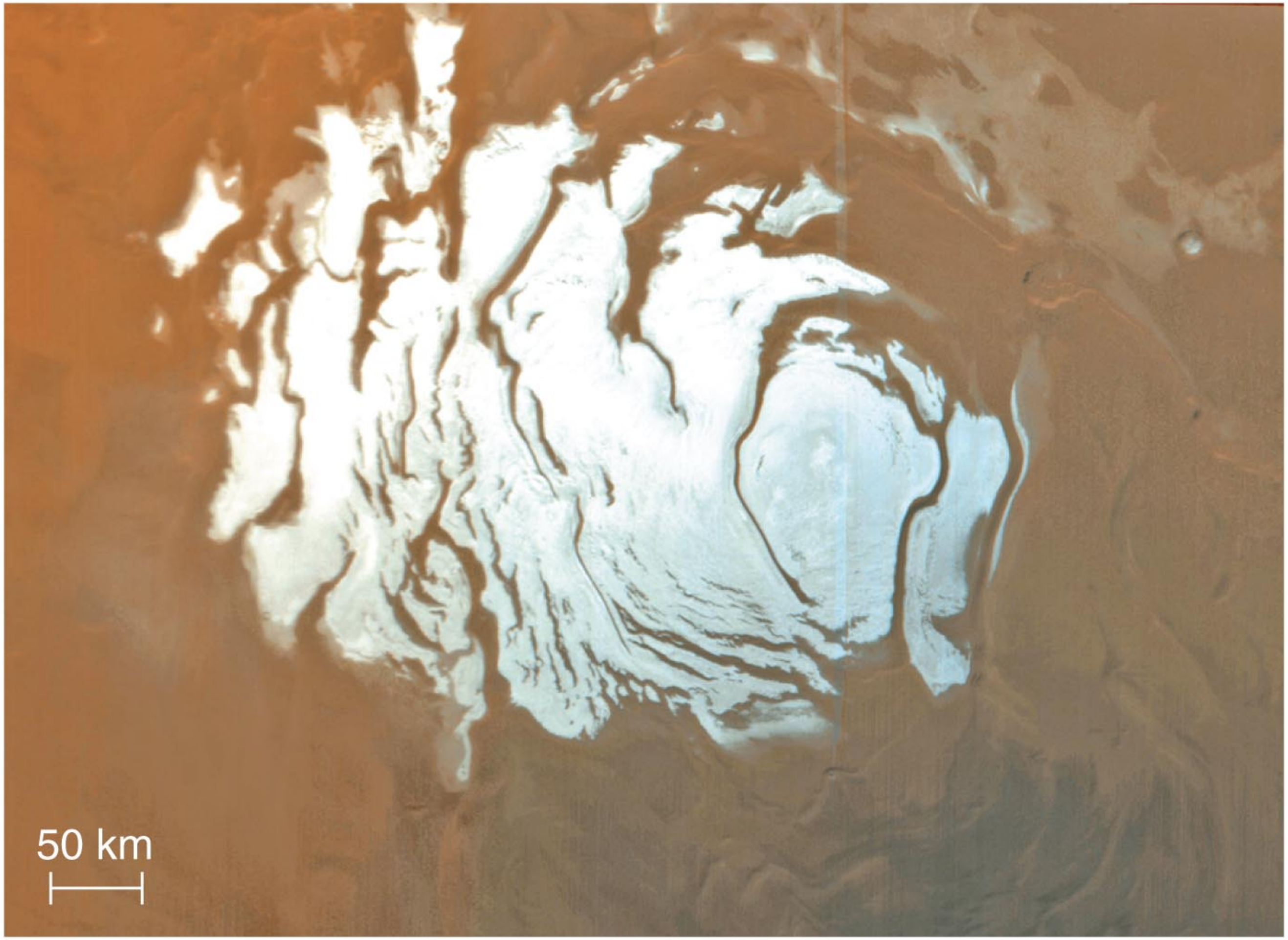
Polar Ice Caps of Mars



Late winter	Mid-spring	Early summer

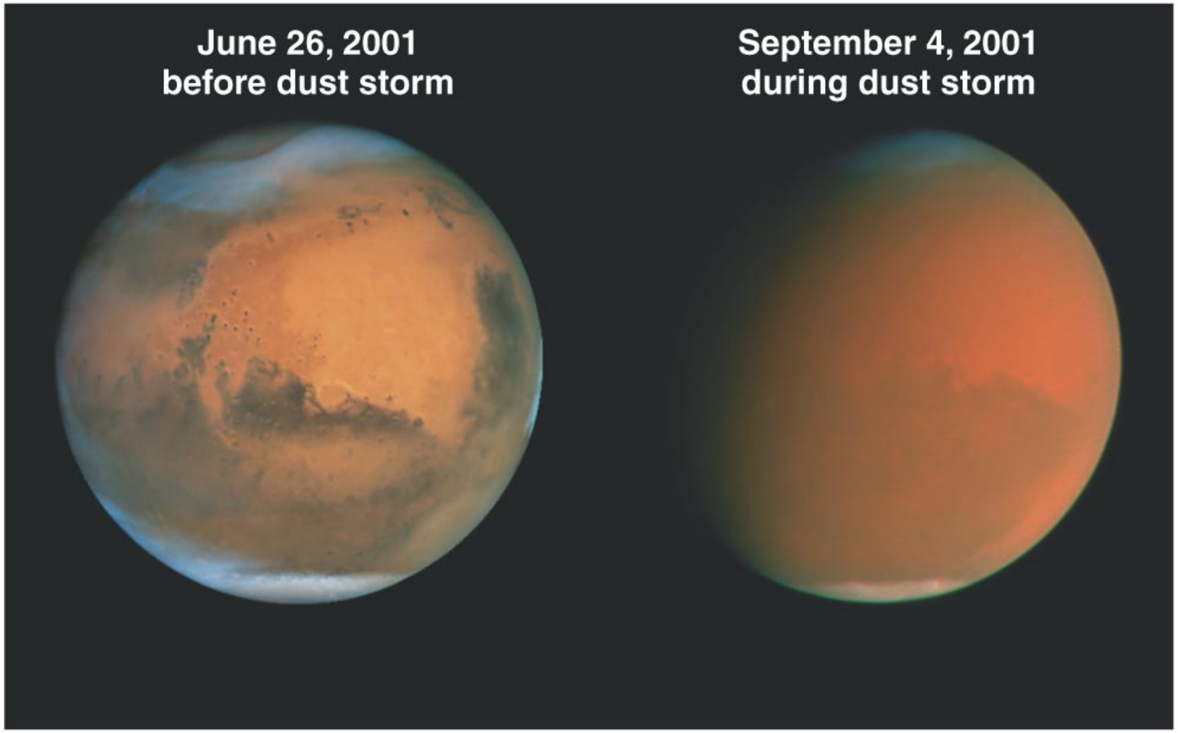
Carbon dioxide ice of polar cap sublimates as summer approaches and condenses at opposite pole.

Polar Ice Caps of Mars



Residual ice of the south polar cap remaining during summer is primarily water ice.

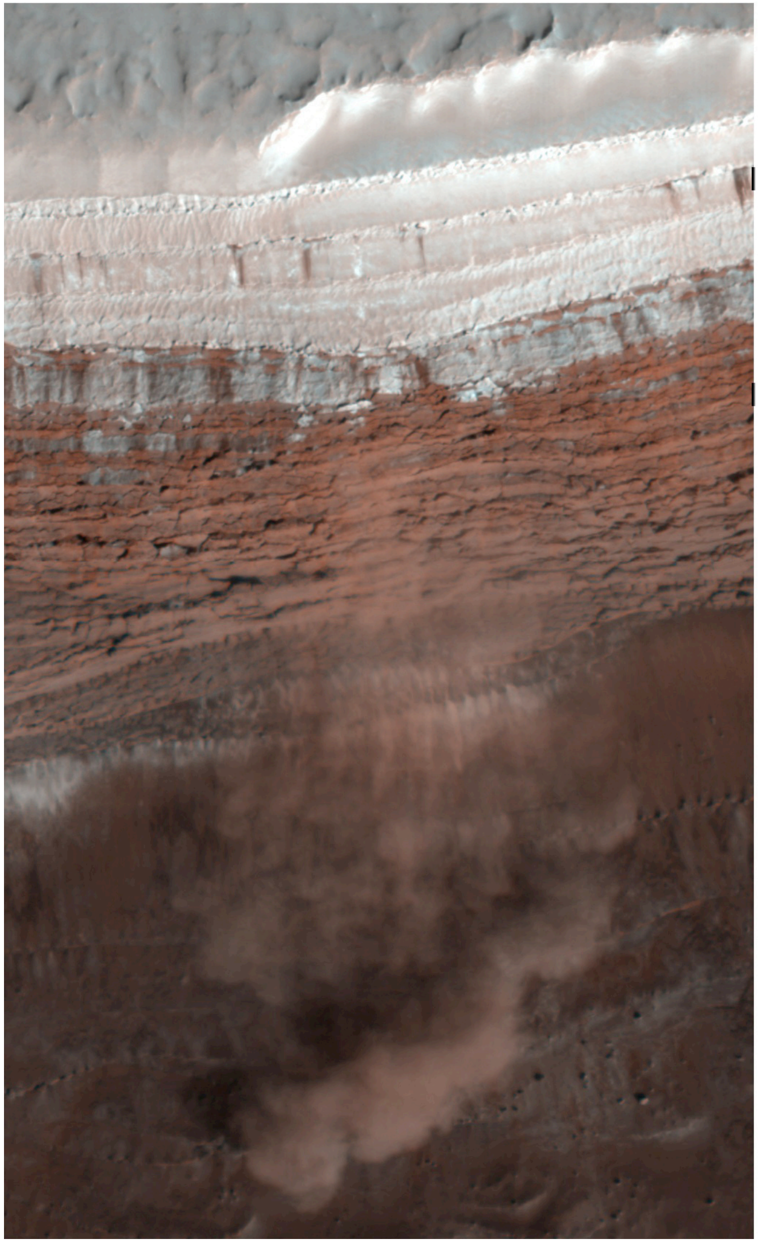
Dust Storms on Mars



Martian Dust Devil

- 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

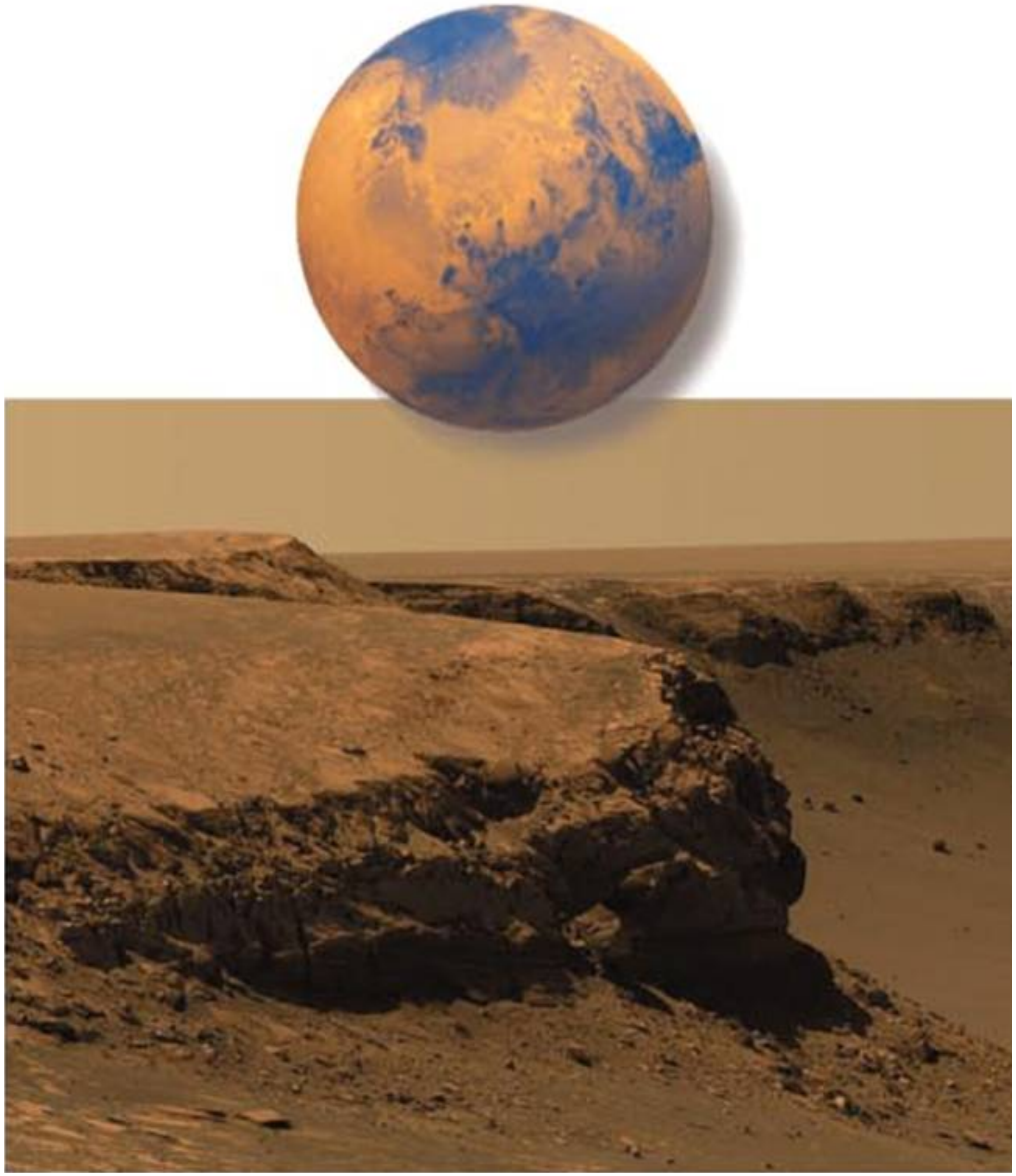


Calculations suggest Mars's axis tilt ranges from 0° to 60°.

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.

- Magnetic field may have preserved early Martian atmosphere.
- Solar wind may have stripped atmosphere after magnetic field decreased because of interior cooling.
- No more volcanoes, no more outgassing, no more atmosphere

What have we learned?

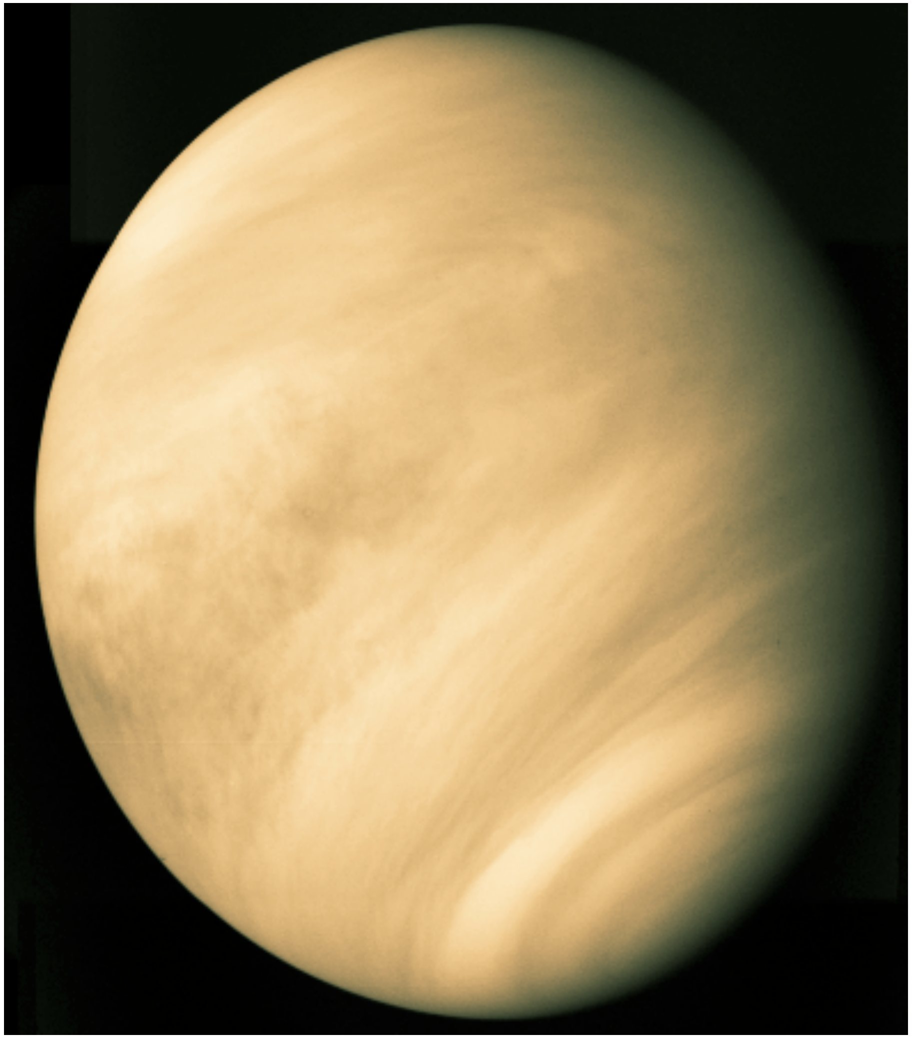
- **What is Mars like today?**
  - Mars is cold, dry, and frozen.
  - Strong seasonal changes cause CO_2 to move from pole to pole, leading to dust storms.
- **Why did Mars change?**
  - Its atmosphere must have once been much thicker for its greenhouse effect to allow liquid water on the surface.
  - 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?

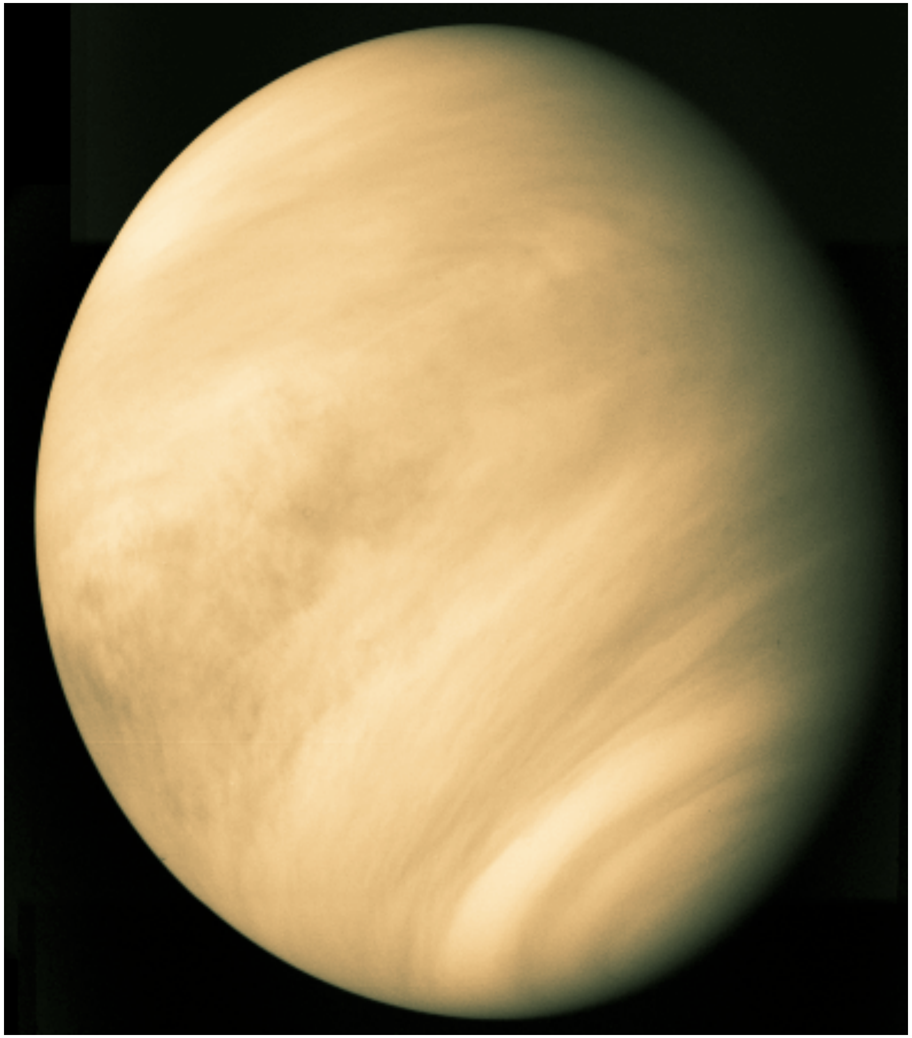
Atmosphere of Venus



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.

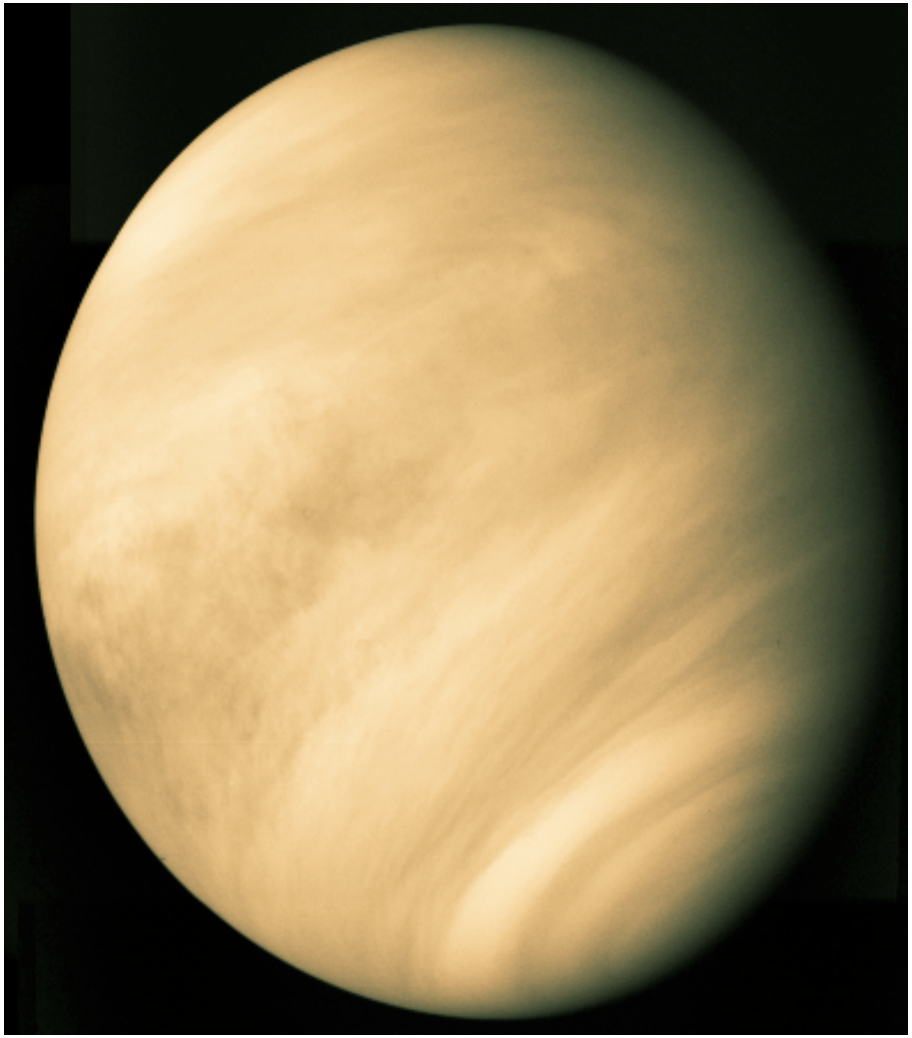
Greenhouse Effect on Venus



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?

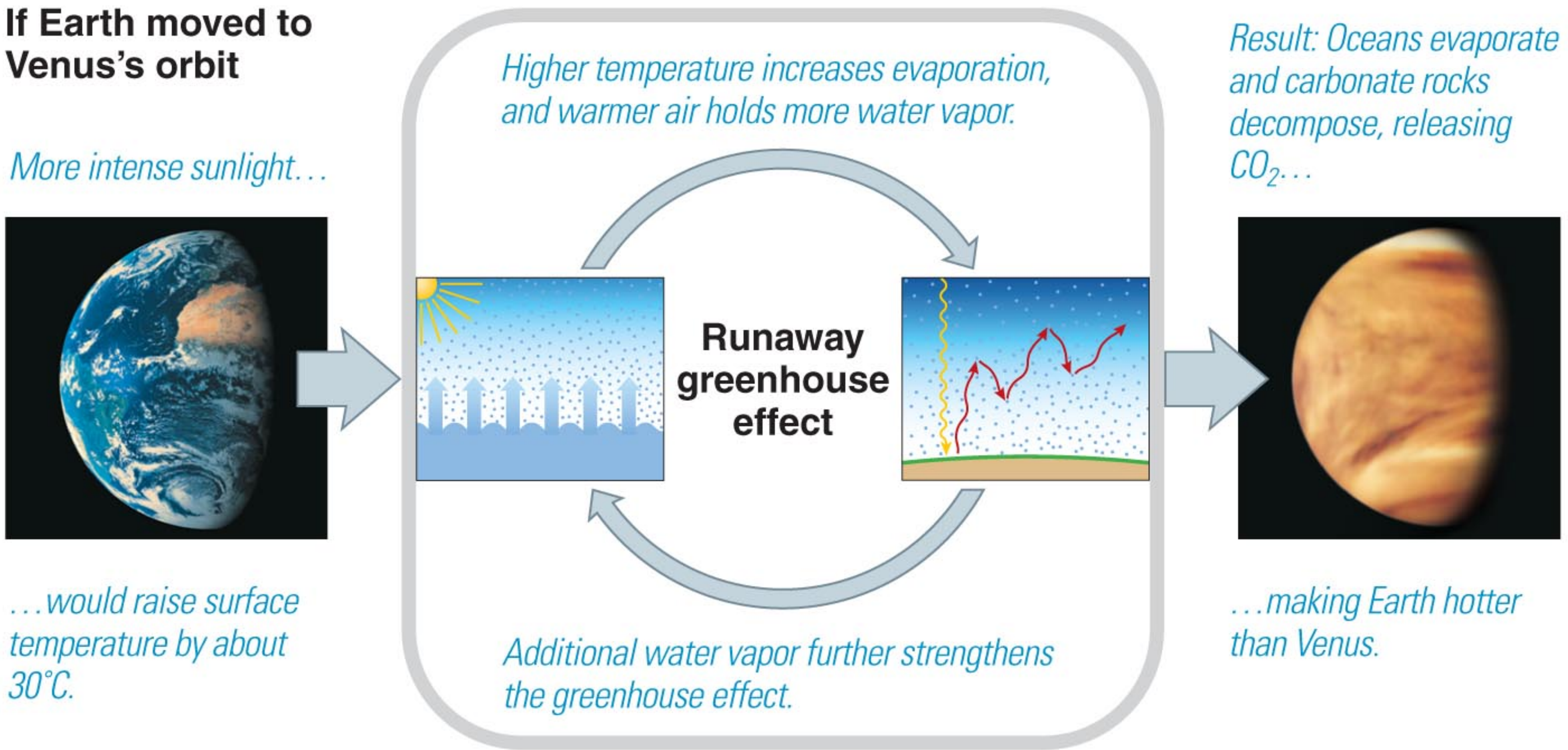


Runaway Greenhouse Effect

Imagine moving Earth closer to the Sun, where Venus is. What would happen?

1. Temps would rise (closer to Sun)
2. Water would evaporate, leading to increased water vapor – a greenhouse gas.
3. Temps would rise more.
4. More water would evaporate, more greenhouse, temps rise more.
5. Without liquid water, carbon dioxide doesn't get washed out of the atmosphere. So carbon dioxide levels rise – another greenhouse gas. So the temps rise even more!
6. Eventually, strong UV light from the Sun would break up the water molecules in the atmosphere into hydrogen and oxygen, and the oxygen would be lost via thermal escape – no more water molecules, just carbon dioxide.

Runaway Greenhouse Effect



- A runaway greenhouse effect would account for why Venus is so hot with so little water.

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 (O_2) from CO_2 into atmosphere.

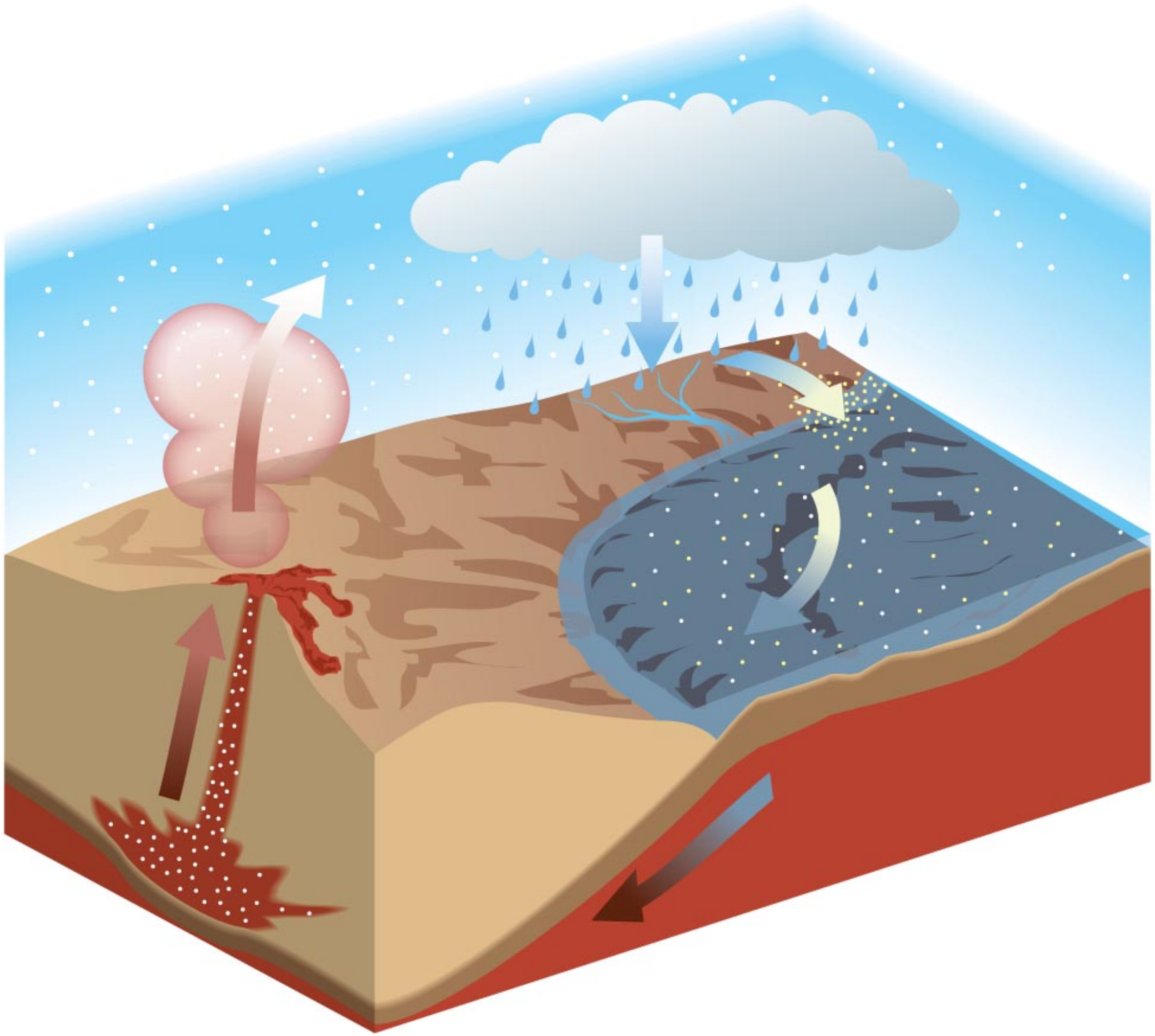
Ozone and the Stratosphere

Ultraviolet light can break up O_2 molecules, allowing ozone (O_3) to form.

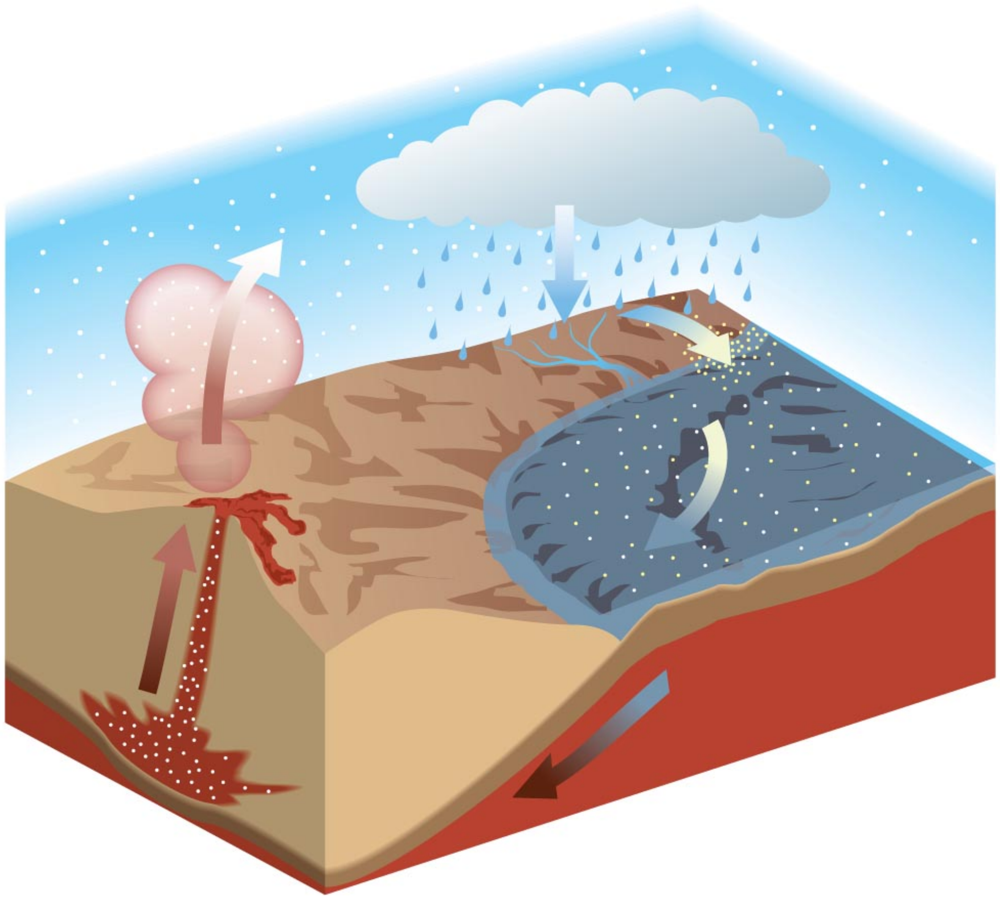
Without plants to release O_2, there would be no ozone in stratosphere to absorb ultraviolet light.

Only Earth has a stratosphere!

Why does Earth's climate stay relatively stable?

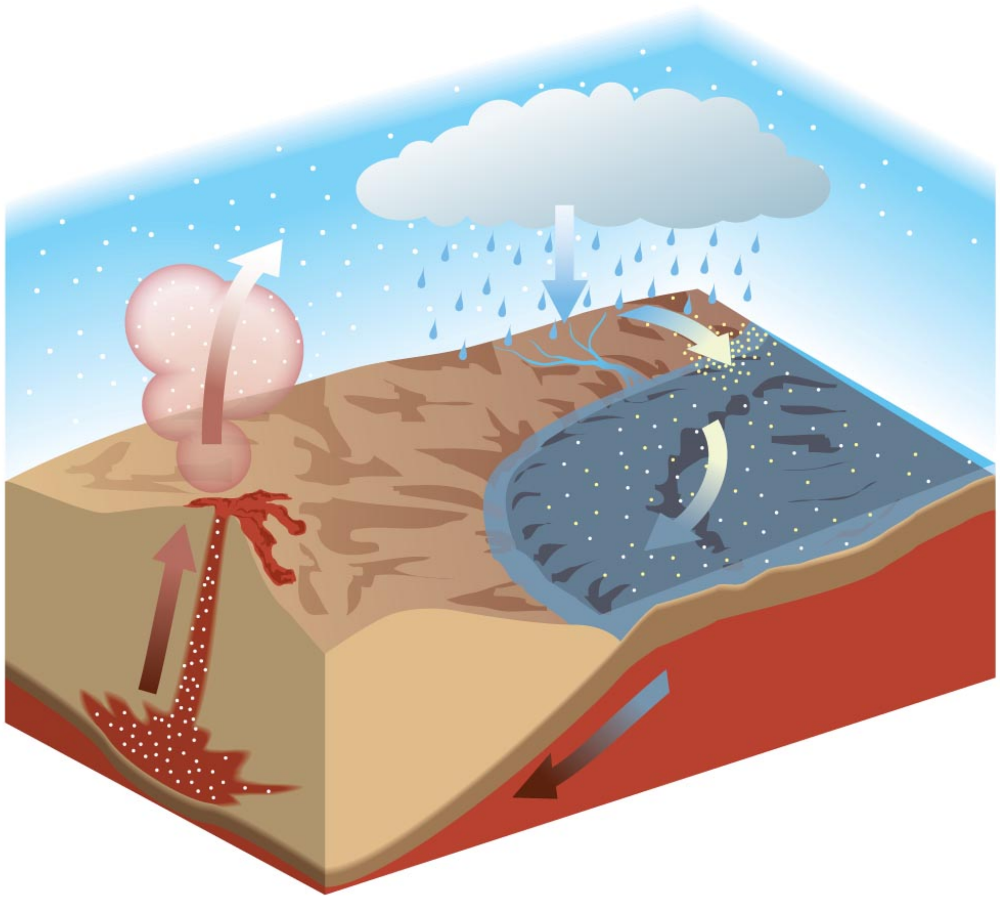


Carbon Dioxide Cycle



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.

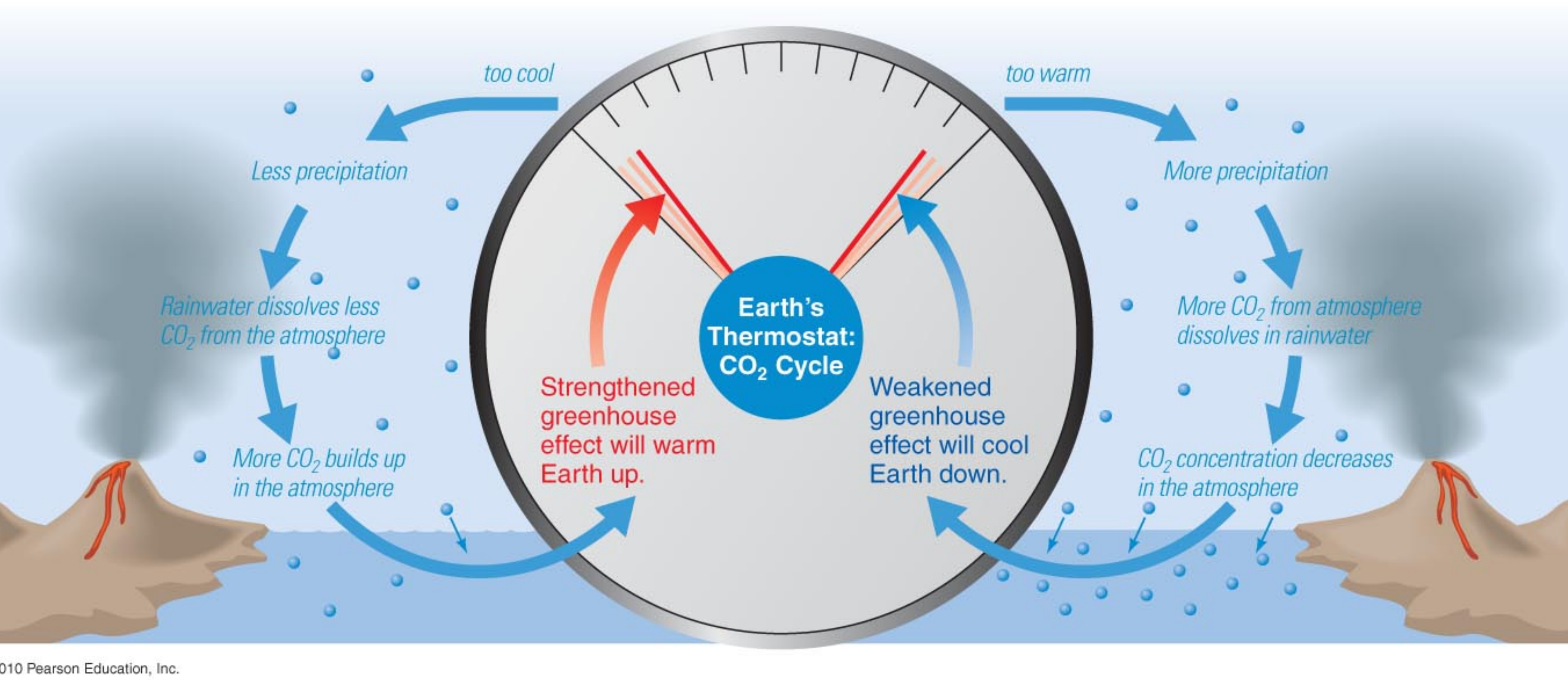
Carbon Dioxide Cycle



4. Subduction carries carbonate rock down into mantle.

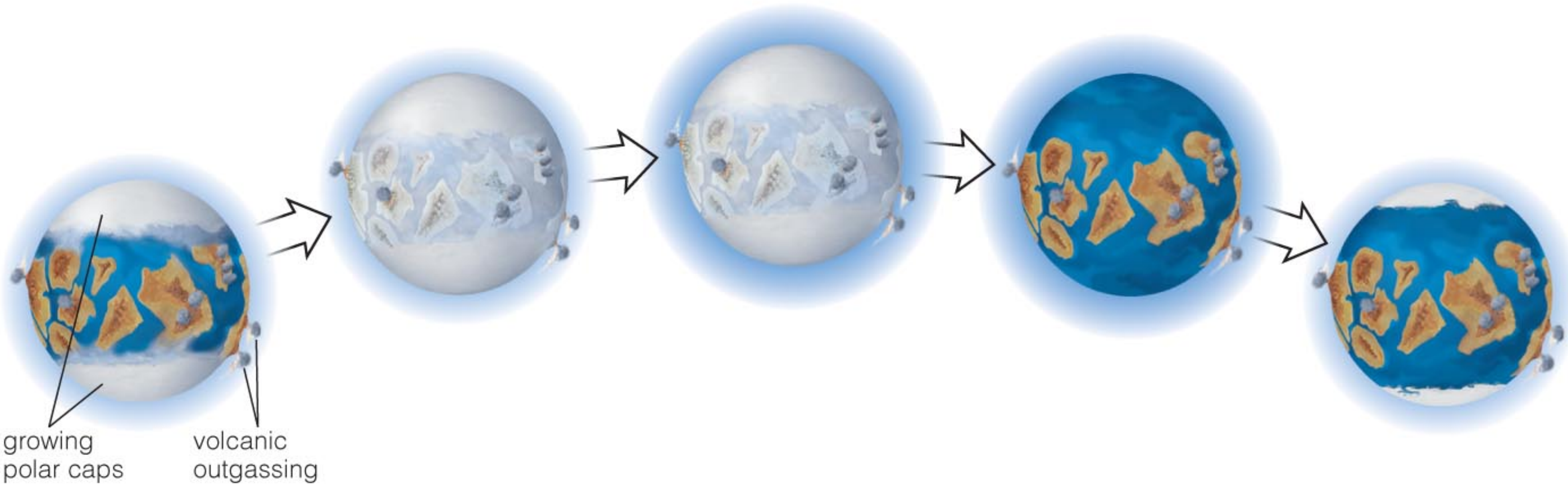
5. Rock melts in mantle and CO_2 is outgassed back into atmosphere through volcanoes.

Earth's Thermostat



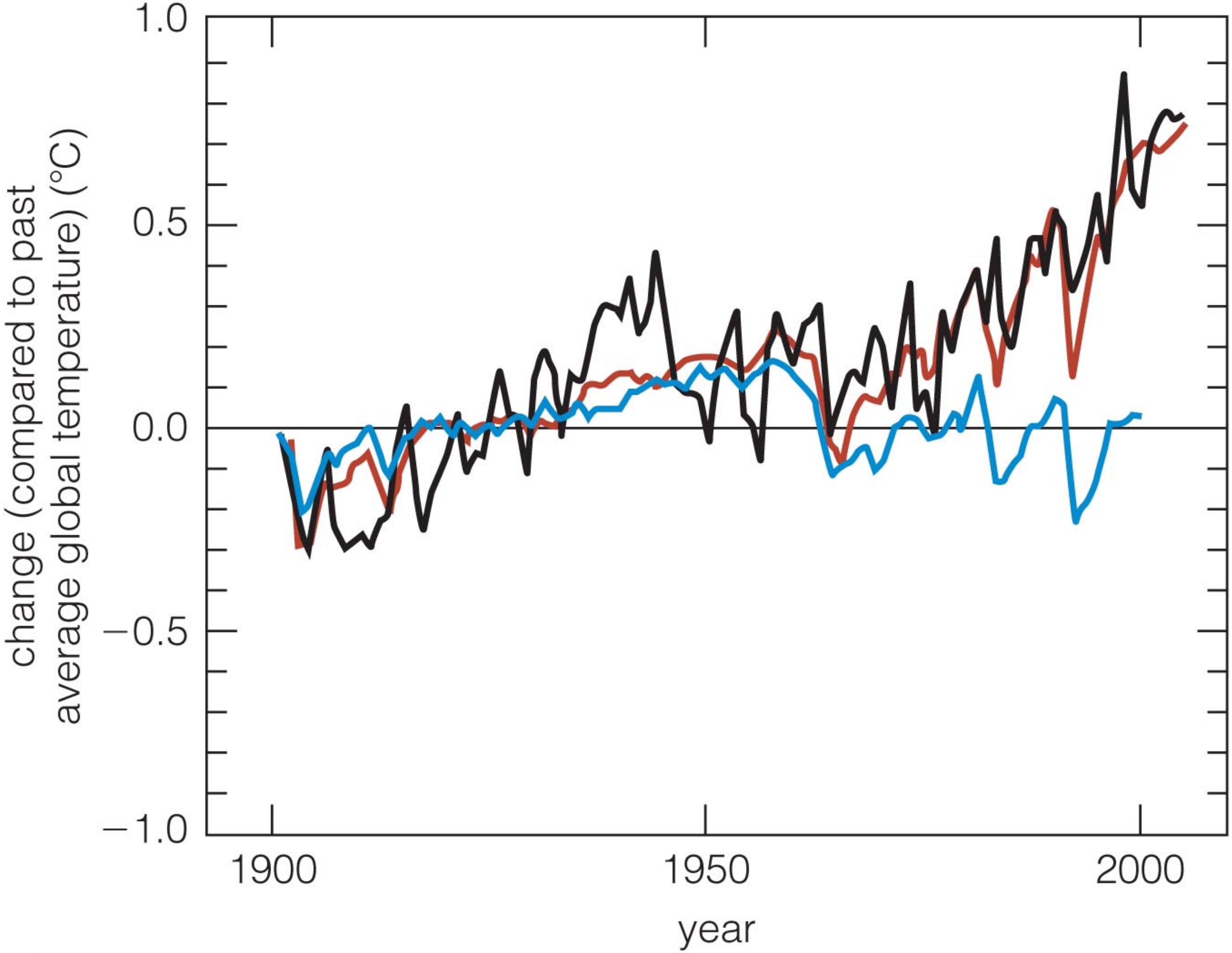
- Cooling allows CO_2 to build up in atmosphere.
- Heating causes rain to reduce CO_2 in atmosphere.

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.

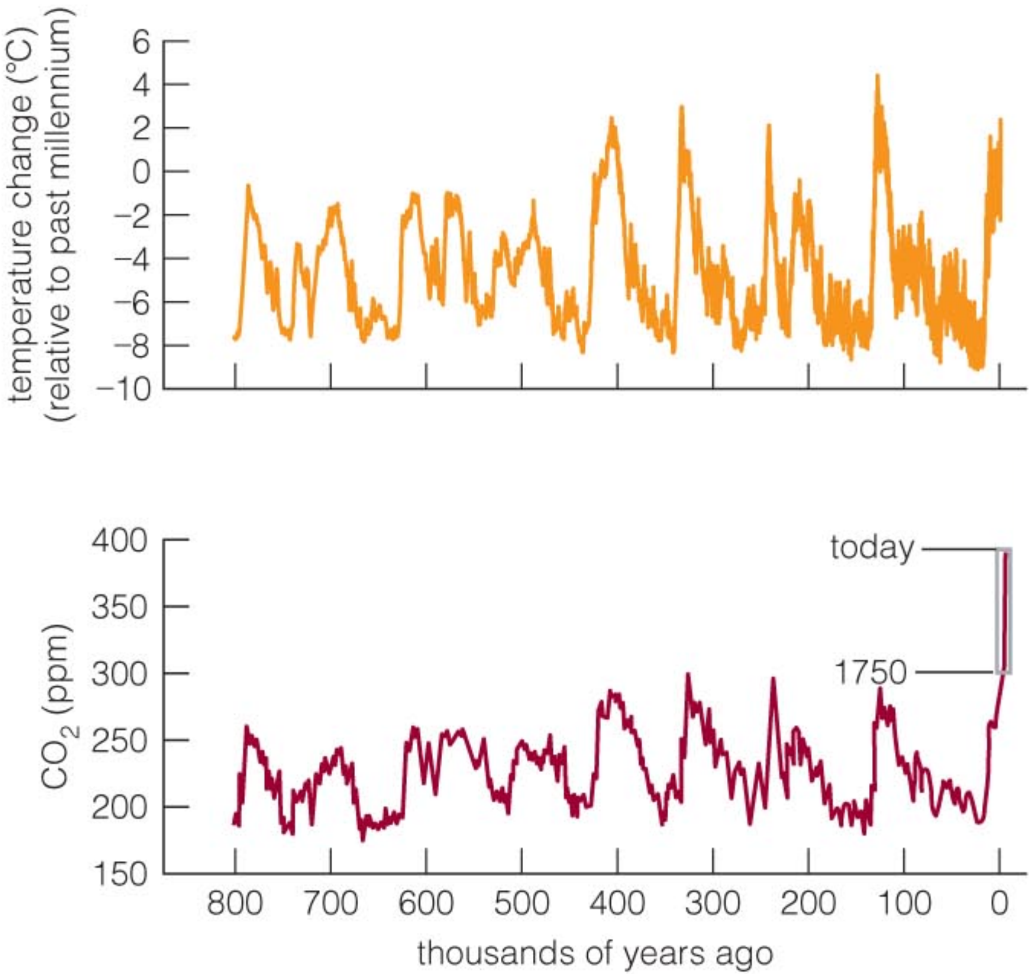
How is human activity changing our planet?



Global Warming

- Earth's average temperature has increased by about 1° 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.

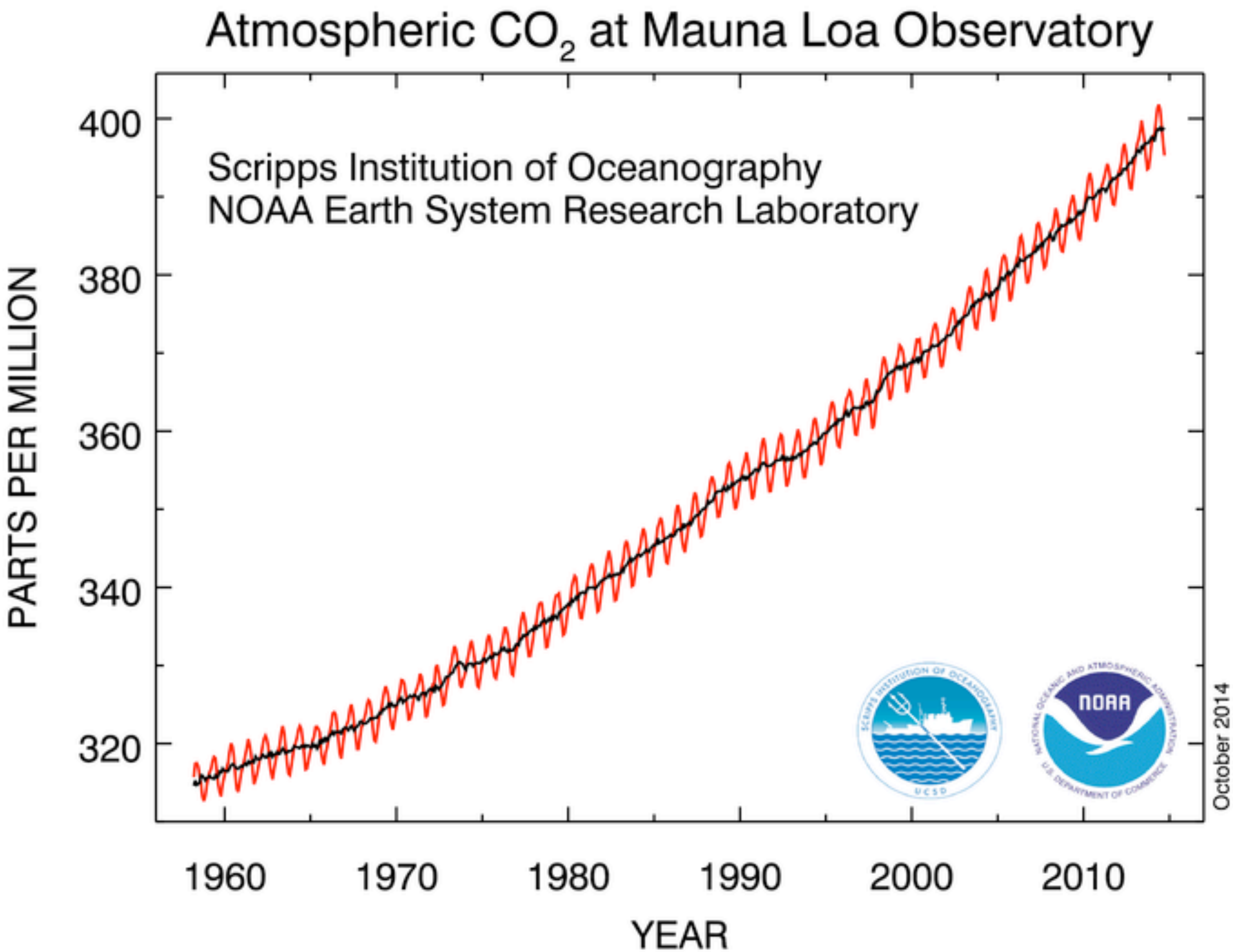
CO_2 Concentration



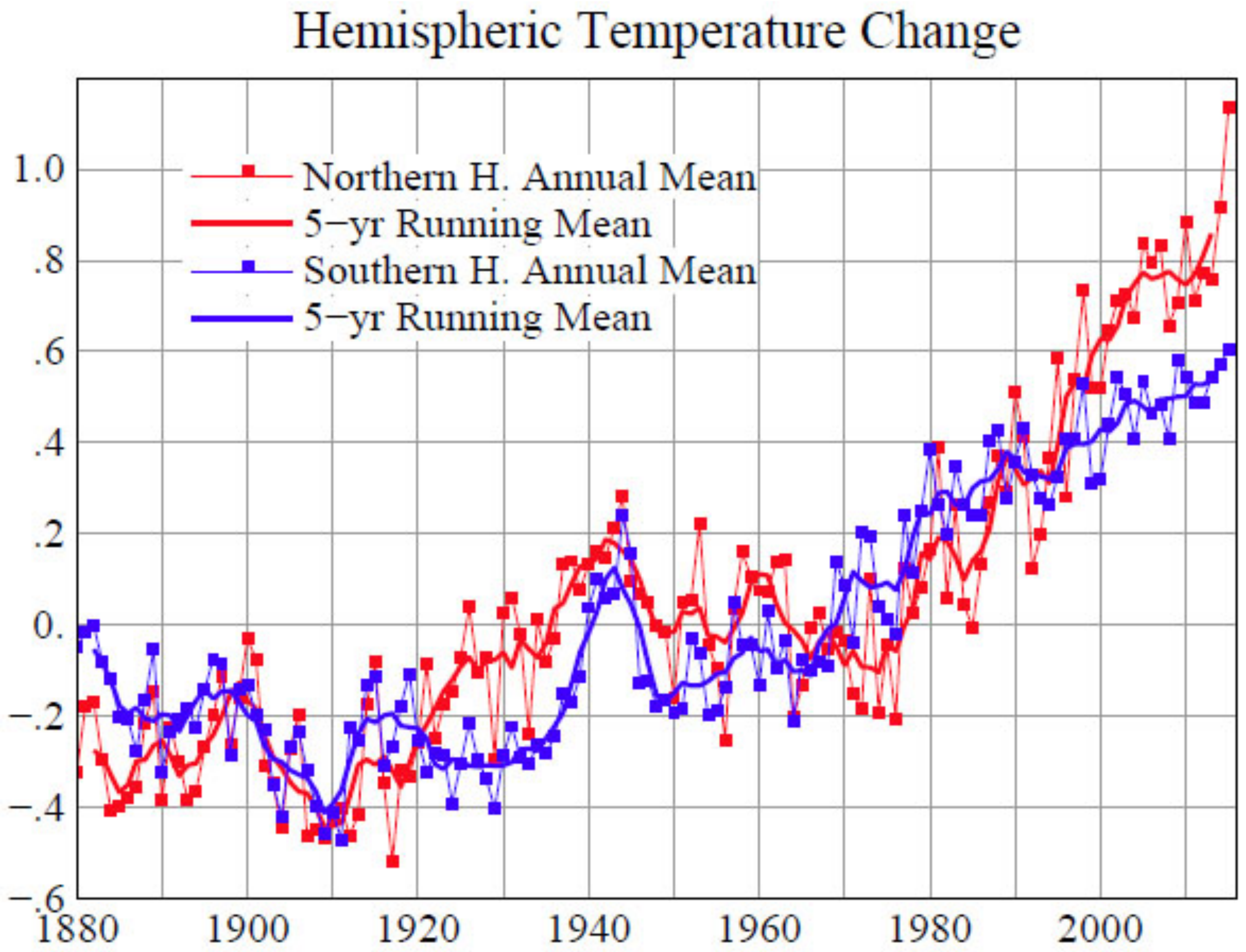
NOAA paleo data

- 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.

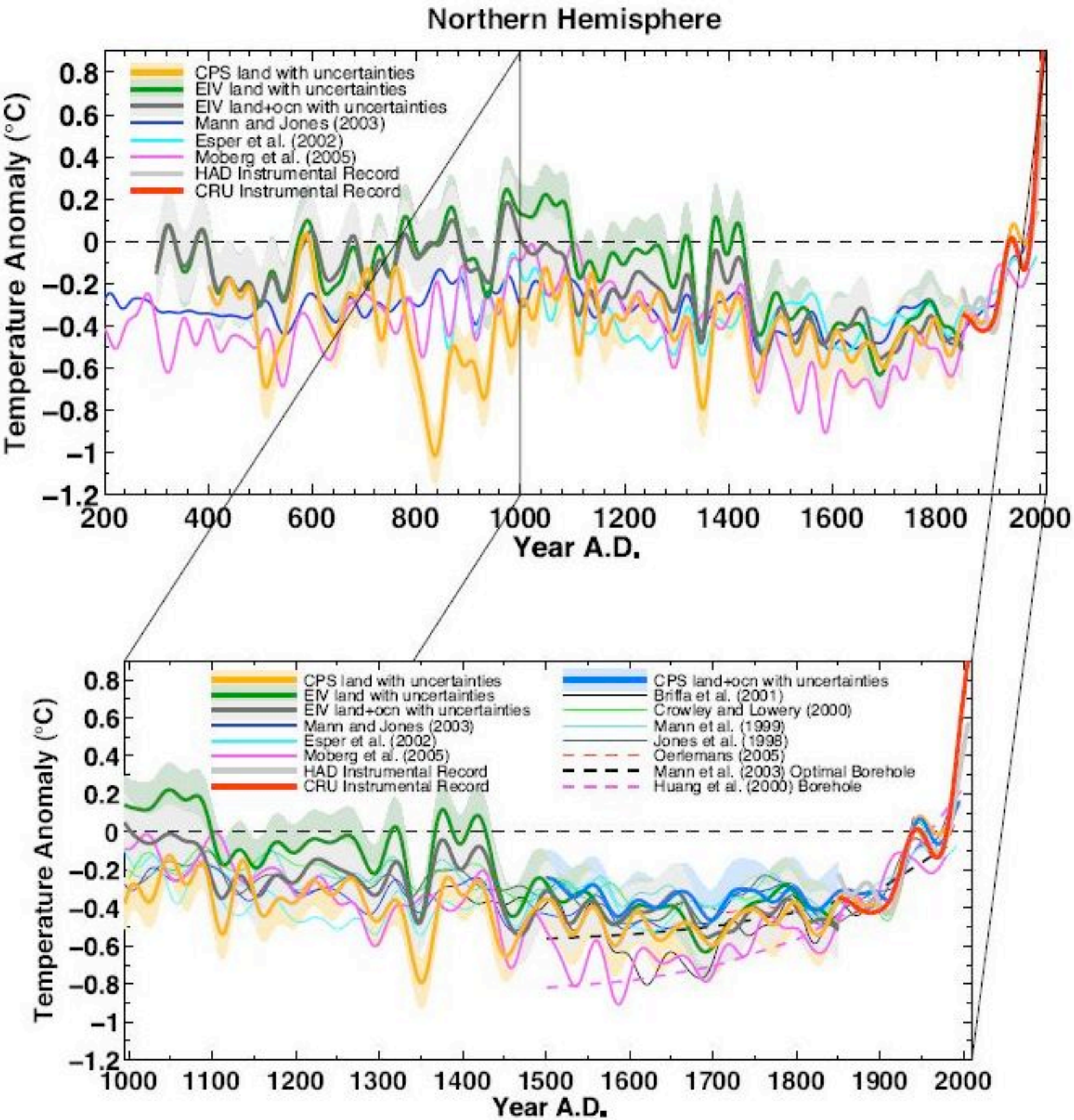
CO_2 Concentration



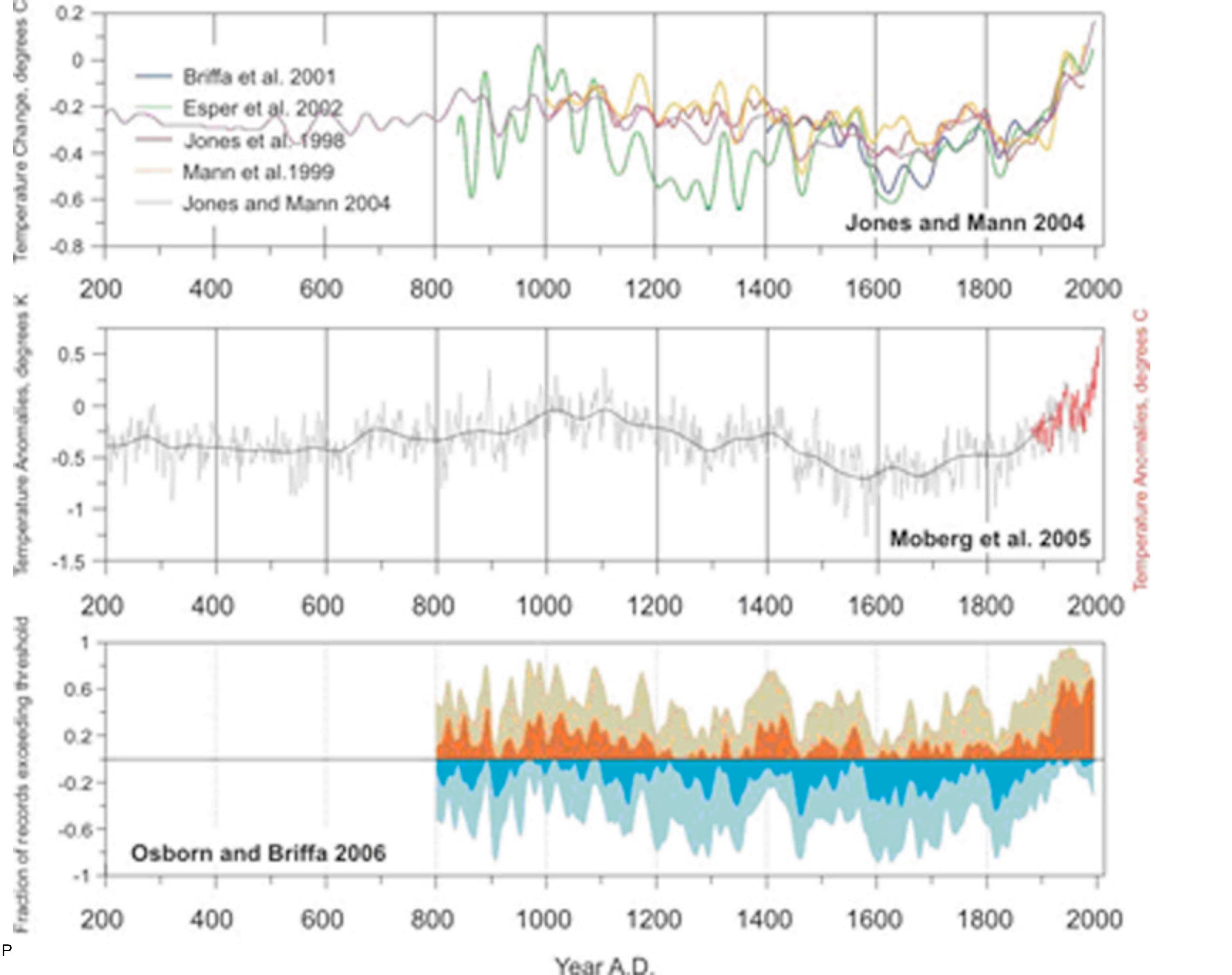
Temperature



https://data.giss.nasa.gov/gistemp/graphs/

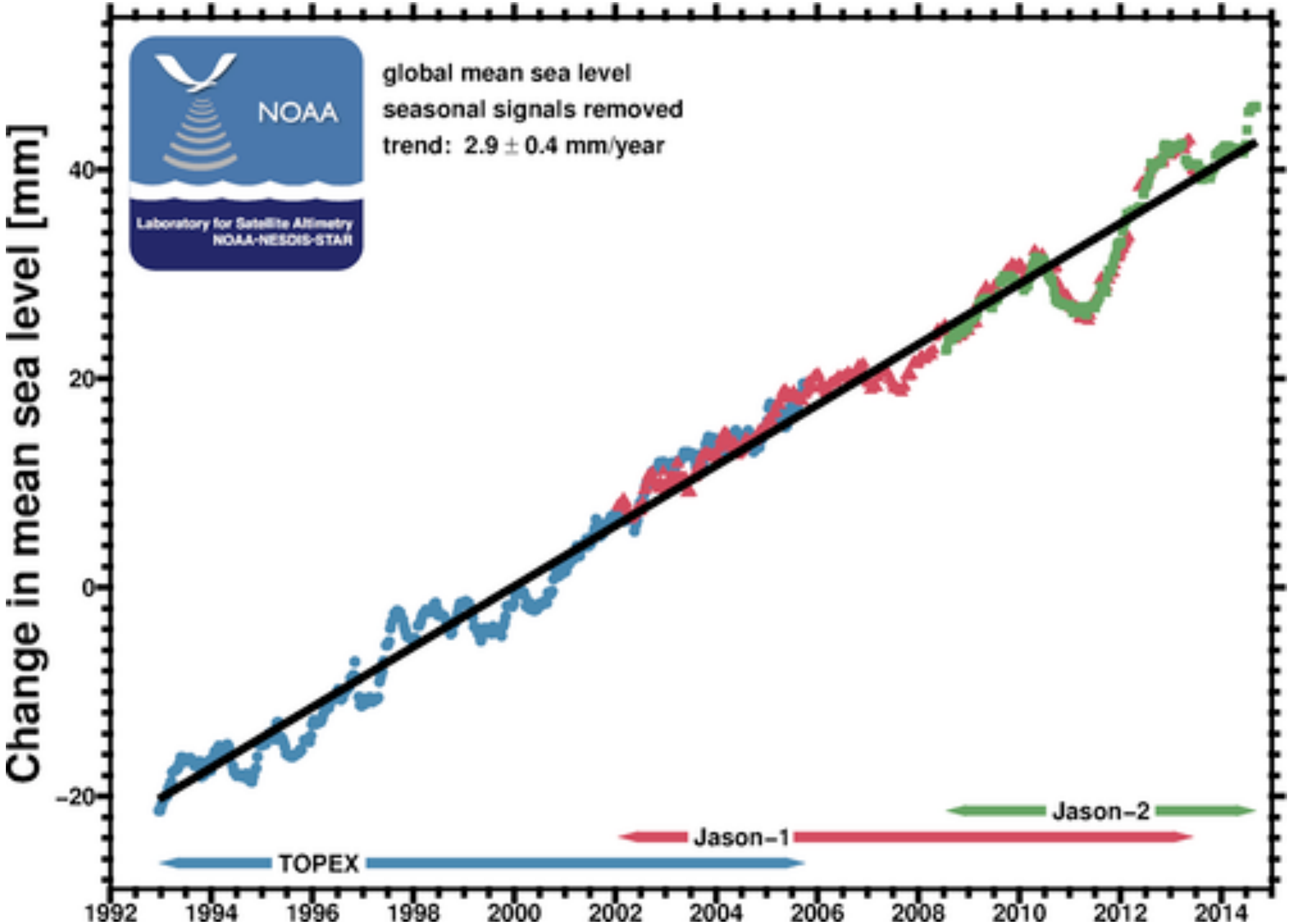


Northern Hemisphere
CPS land with uncertainties
EIV land with uncertainties
EIV land+ocn with uncertainties
Mann and Jones (2003)
Esper et al. (2002)
Moberg et al. (2005)
HAD Instrumental Record
CRU Instrumental Record
Temperature Anomaly (°C)
Year A.D.
CPS land+ocn with uncertainties
Briffa et al. (2001)
Crowley and Lowery (2000)
Mann et al. (1999)
Jones et al. (1998)
Oerlemans (2005)
Mann et al. (2003) Optimal Borehole
Huang et al. (2000) Borehole



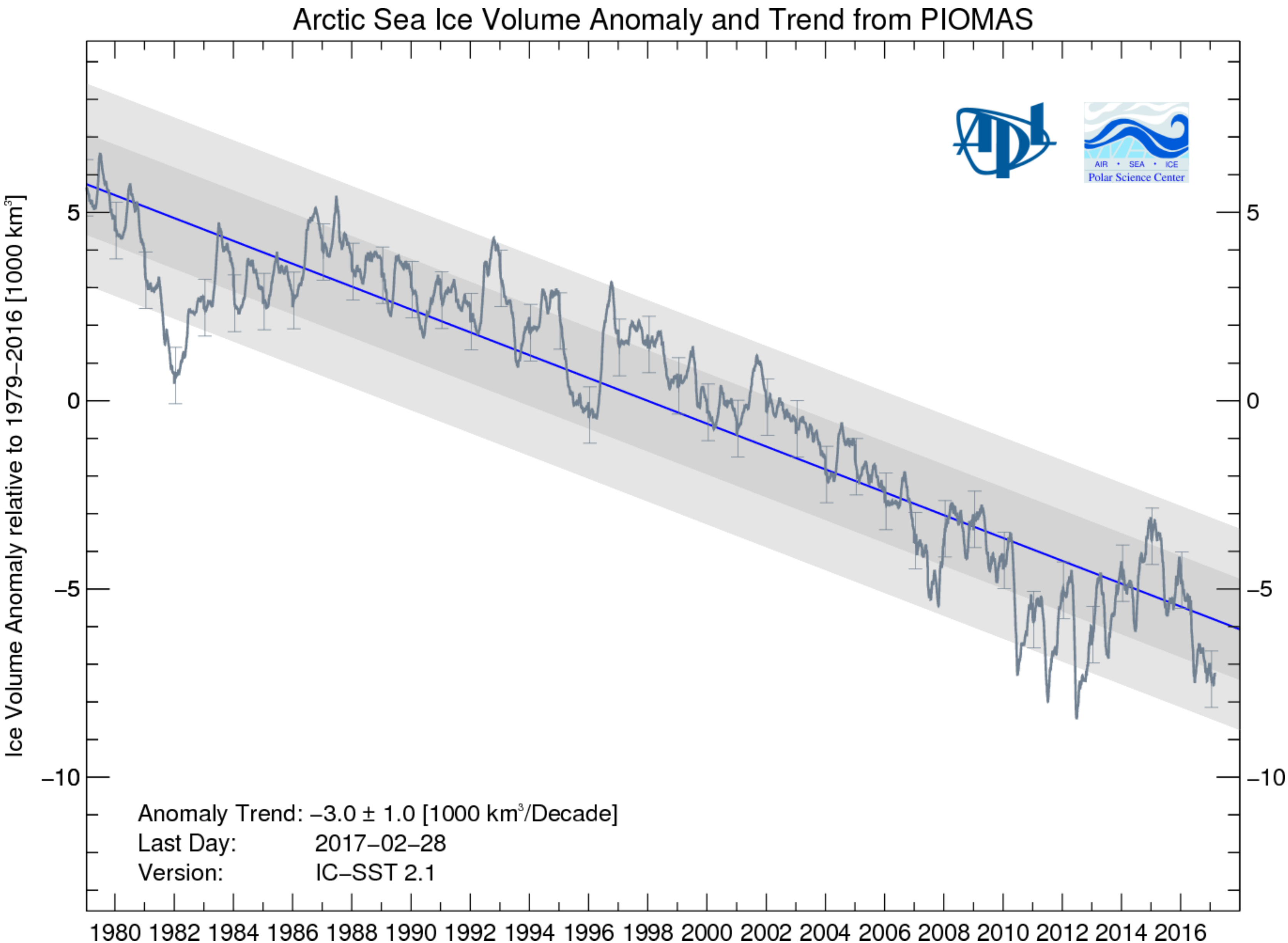
Briffa et al. 2001
Esper et al. 2002
Jones et al. 1998
Mann et al.1999
Jones and Mann 2004
Jones and Mann 2004
Temperature Change, degrees C
Moberg et al. 2005
Temperature Anomalies, degrees K
Temperature Anomalies, degrees C
Osborn and Briffa 2006
Fraction of records exceeding threshold
Year A.D.

Sea Level



NOAA
Laboratory for Satellite Altimetry
NOAA-NESDIS-STAR
global mean sea level
seasonal signals removed
trend: 2.9 ± 0.4 mm/year
Change in mean sea level [mm]
40
20
0
-20
Jason-2
Jason-1
TOPEX
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014

Arctic Ice



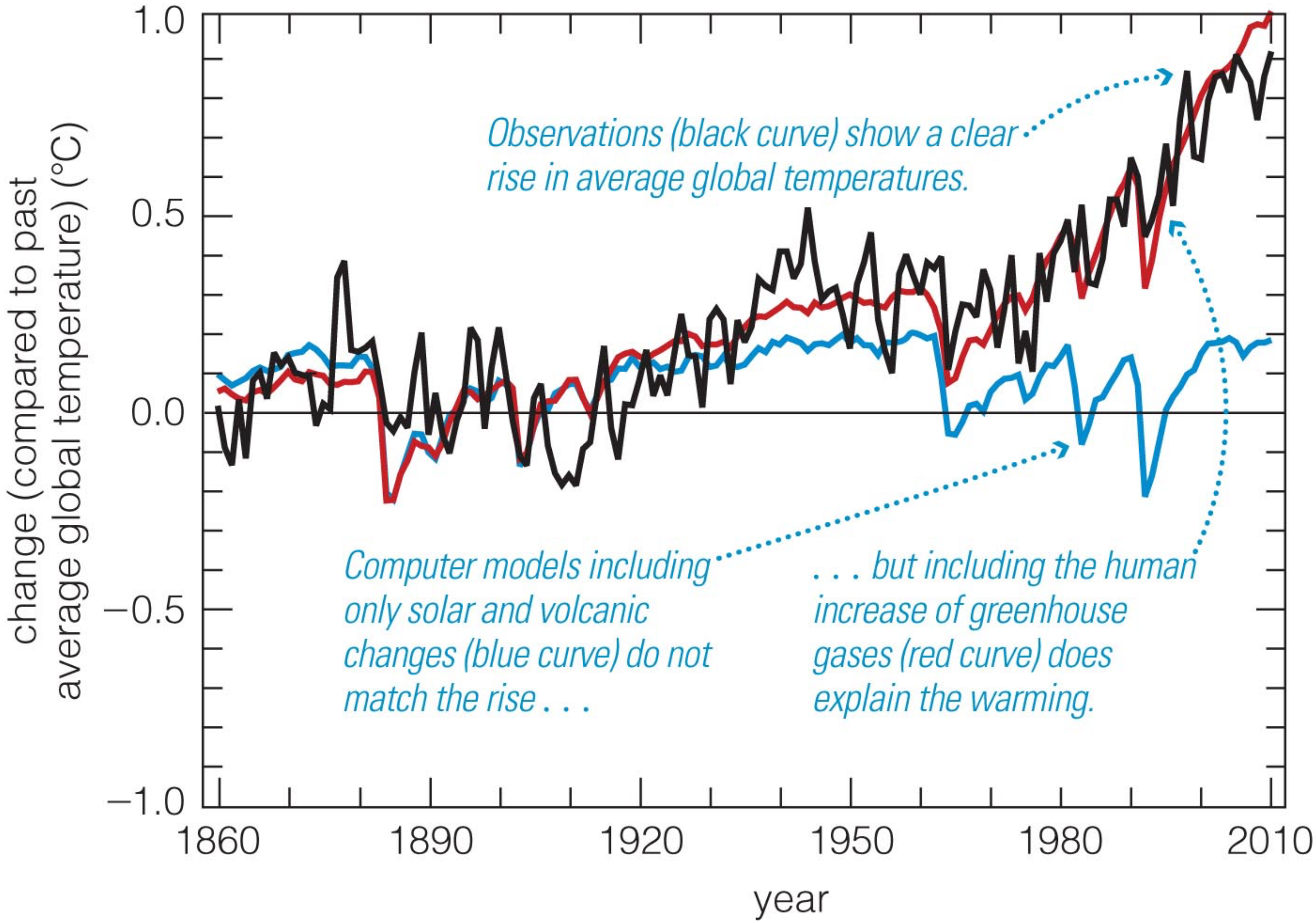
Arctic Sea Ice Volume Anomaly and Trend from PIOMAS
Ice Volume Anomaly relative to 1979–2016 [1000 km³]
5
0
–5
–10
1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016
AIR • SEA • ICE
Polar Science Center
Anomaly Trend: –3.0 ± 1.0 [1000 km³/Decade]
Last Day: 2017–02–28
Version: IC–SST 2.1

Temperature

[Global Visualization of Temperature Change]

[Global Modeling of Temperature Change]

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
- Local climate variations not the same as global response.
- Uncertain effects on food production, availability of fresh water

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