Today

- Terrestrial Planet Atmospheres (continued)

Events

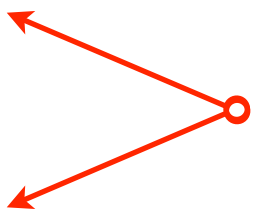
- Homework DUE
- Review next time
- Exam next week
- Vote!

Planetary climates

close to sun

- Mercury (no atmosphere)
  - Hot on day side, cold on night side
- Venus (thick atmosphere)
  - Hot all the time (hotter than Mercury!)
- Earth ("nice" atmosphere)
  - "just right"
- Moon (no atmosphere)
  - Hot on day side, cold on night side
- Mars (thin atmosphere)
  - colder now than in past

far from sun



same distance from sun

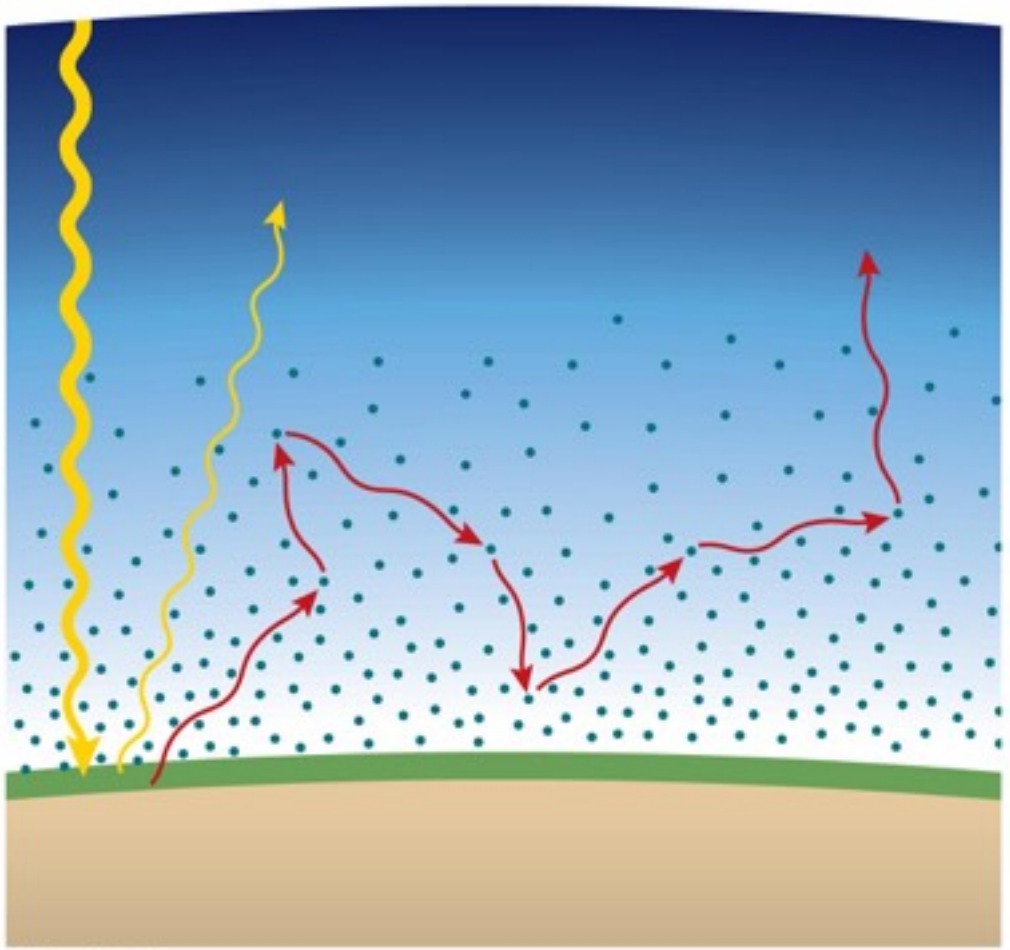
Temperature and Reflectivity

- 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.

- On planets without an atmosphere, like Mercury and the moon, that’s it
  - the surface heats up during the day, and
  - cools off at night

Greenhouse Effect



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

"No Greenhouse" Temperatures

Atmospheres act like blankets, trapping heat.

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).

Greenhouse Gas

- Any gas that absorbs infrared

- Greenhouse gas: molecules with two different types of elements (H_2O, CO_2, CH_4)
  - though a minority of the atmosphere, they provide the bulk of the infrared opacity

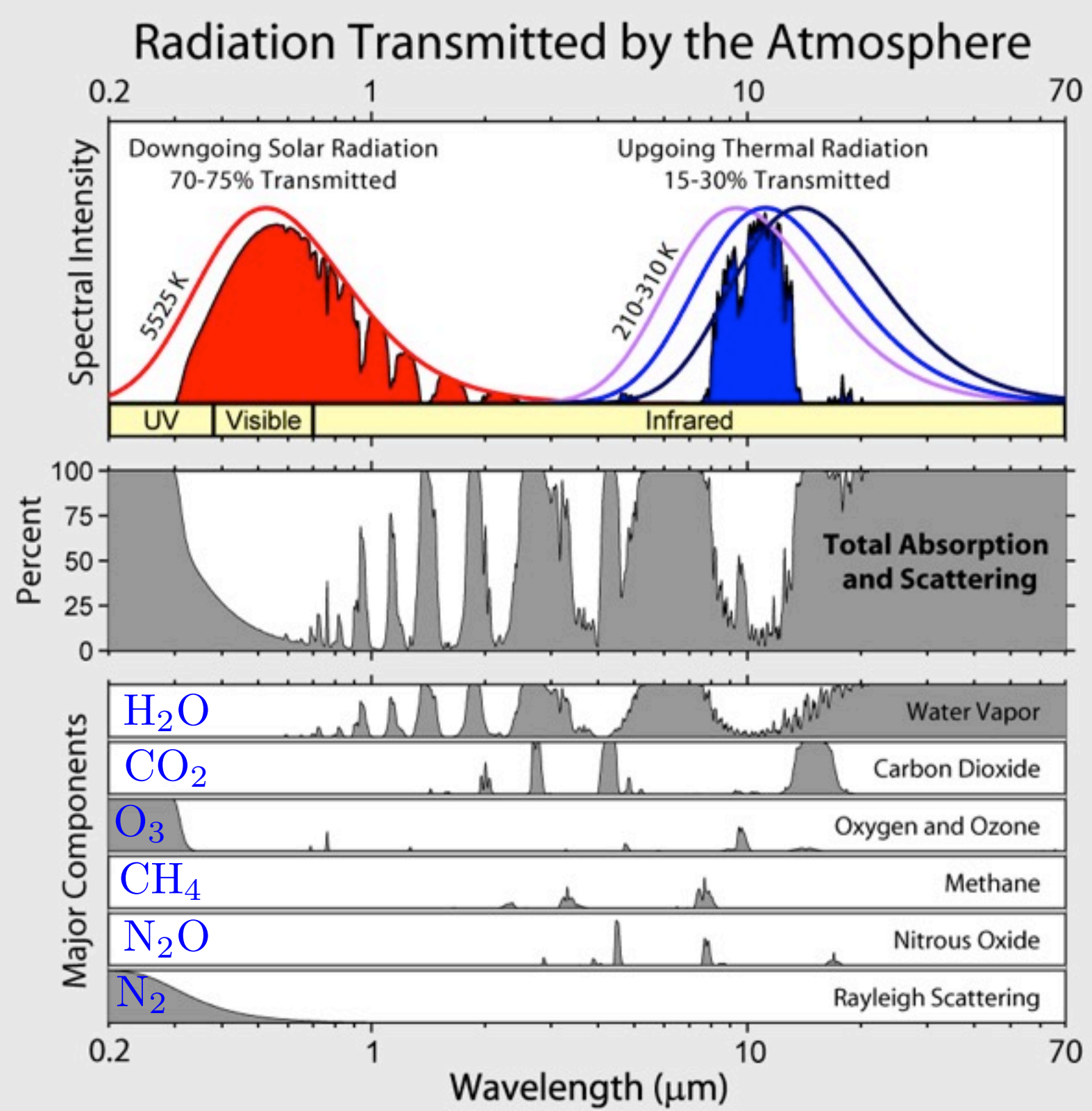
- Not a greenhouse gas: diatomic molecules with two atoms of the same element (O_2, N_2)
  - Though oxygen and nitrogen compose the bulk of the atmosphere, they do not absorb in the infrared so don't contribute to the greenhouse effect

Main greenhouse gases
(on the Earth)

– all are < 1% of atmosphere, but provide

- Water (H_2O) ~60% of infrared opacity
- Carbon dioxide (CO_2) ~22%
- Methane (CH_4) ~7%
- Others (ozone, CFCs, nitrous oxide) ~11%

Note: water vapor absorbs more IR than CO_2!



Atmosphere opaque (gray)

Atmosphere opaque (clear)

Rayleigh scattering makes the sky blue

Greenhouse Effect: Bad?

Just talking about the *natural* Greenhouse effect,
not any man-made addition to it.

The Earth is much warmer than it would be without an atmosphere because of the greenhouse effect. That's good!

(cf. the moon)

Earth's Moon

…the same can be said for Venus,

only more so...

Why is Venus so hot?

The greenhouse effect on Venus keeps its surface temperature at 470°C (878°F). That's higher than Mercury, even though it is farther from the sun.

The difference is the greenhouse effect.

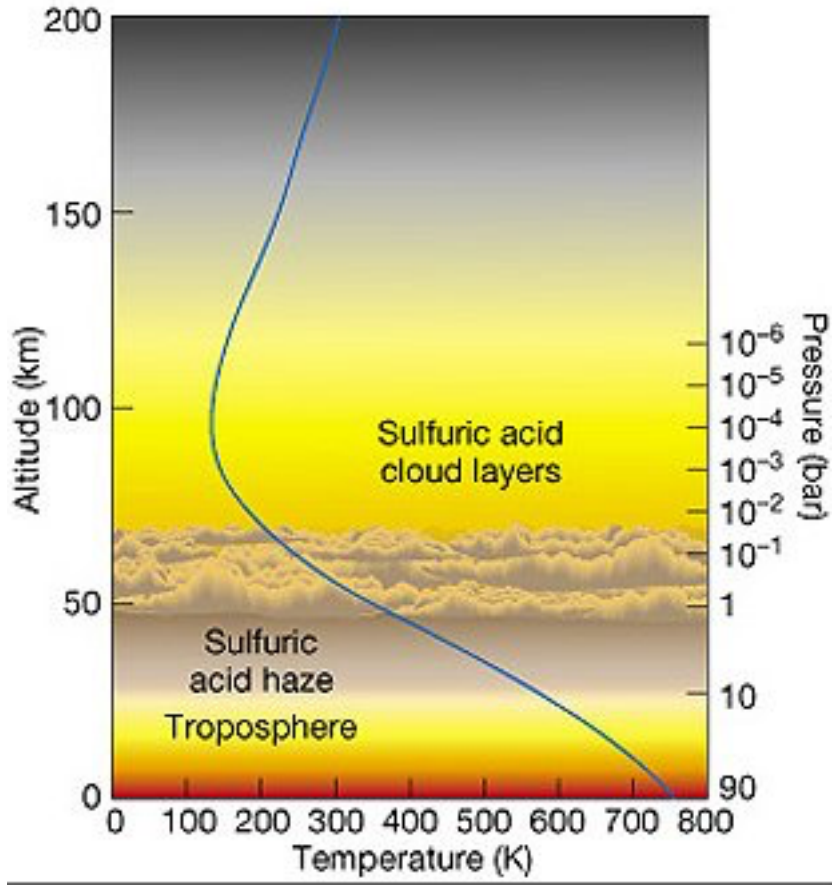
Why is the greenhouse effect on Venus so much stronger than on Earth?

Atmosphere of Venus

- Venus has a very thick carbon dioxide atmosphere with a surface pressure 90 times that of Earth.
- That's equivalent to nearly a kilometer beneath the surface of the ocean.

Venus

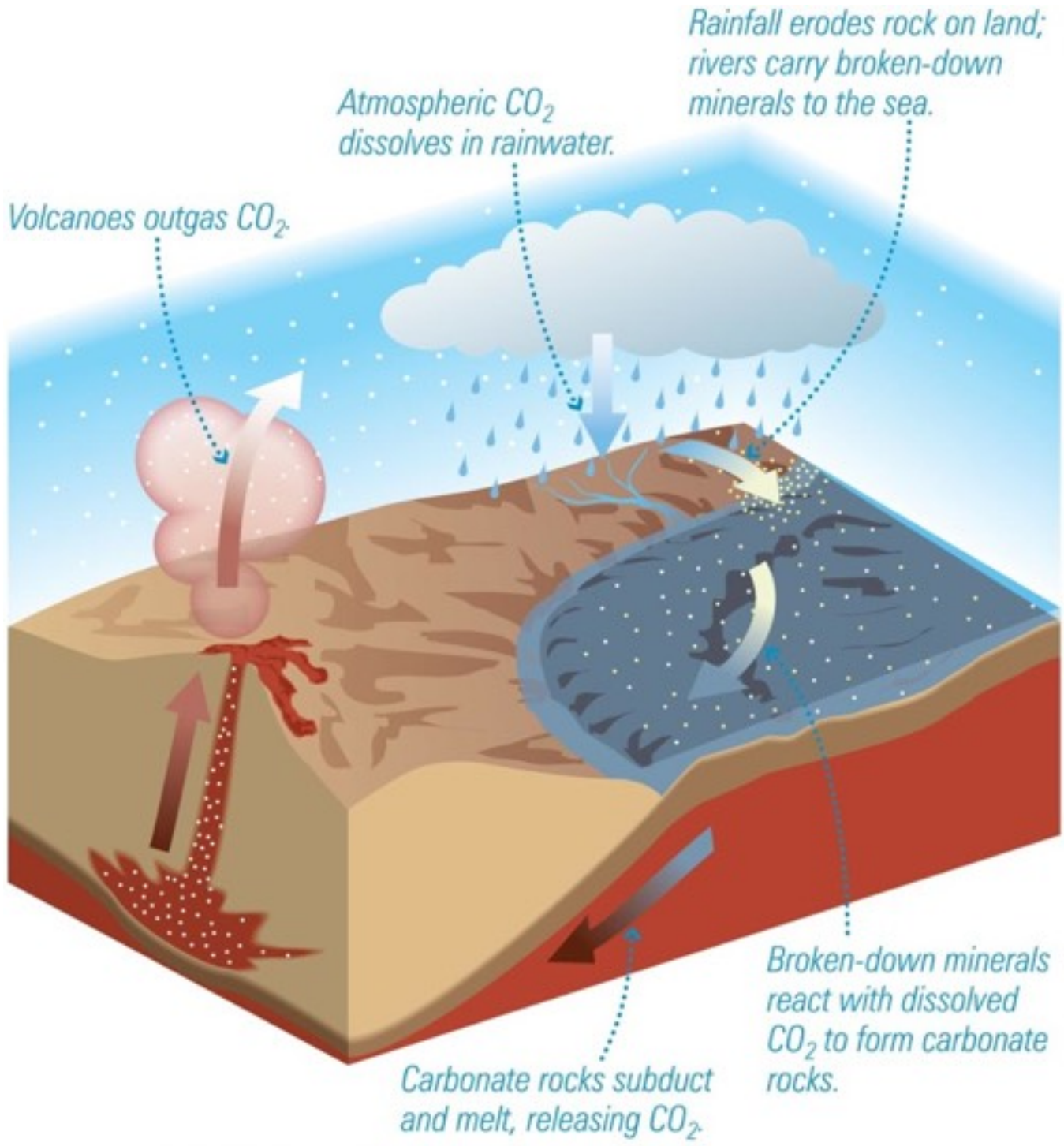
- Permanently shrouded in clouds of sulfuric acid
- Albedo of clouds high
  - little sunlight absorbed
  - yet temperature high
- Earth-like temperature and pressure about 50-60 km altitude



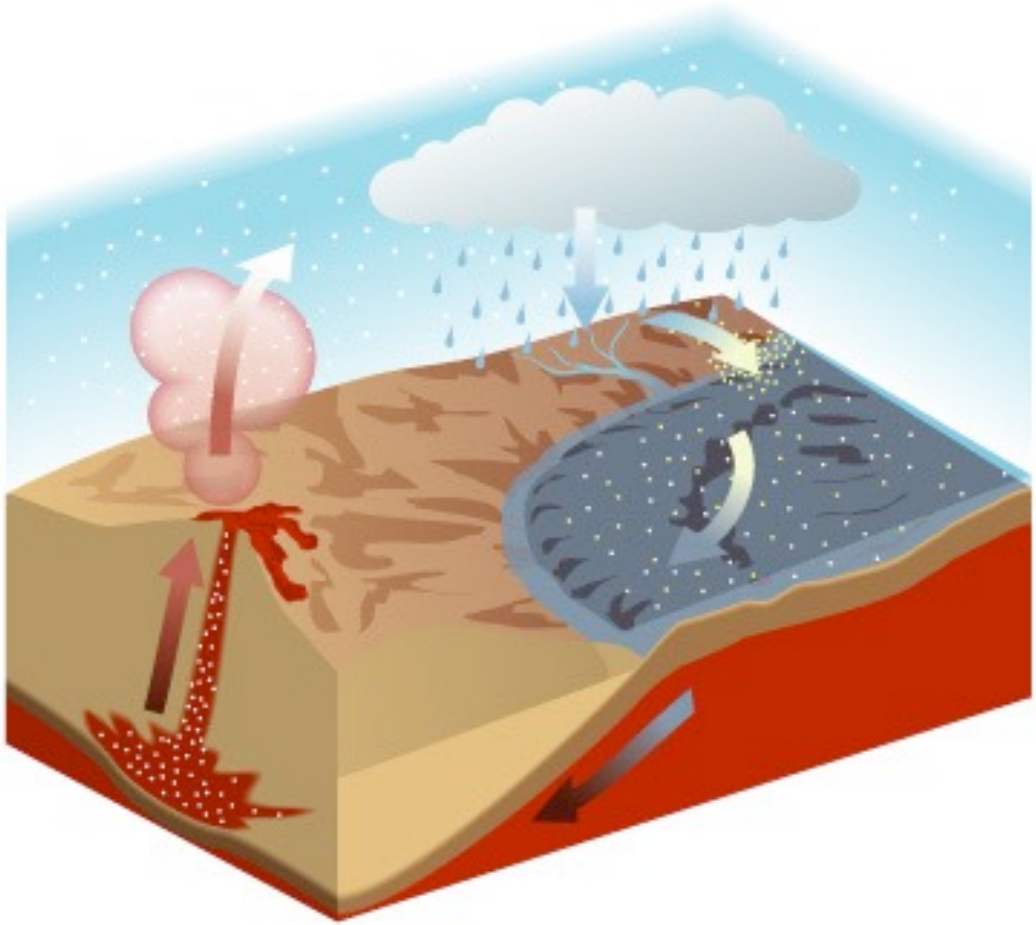
Greenhouse Effect on Venus

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

Carbon cycle on Earth



Carbon Dioxide Cycle

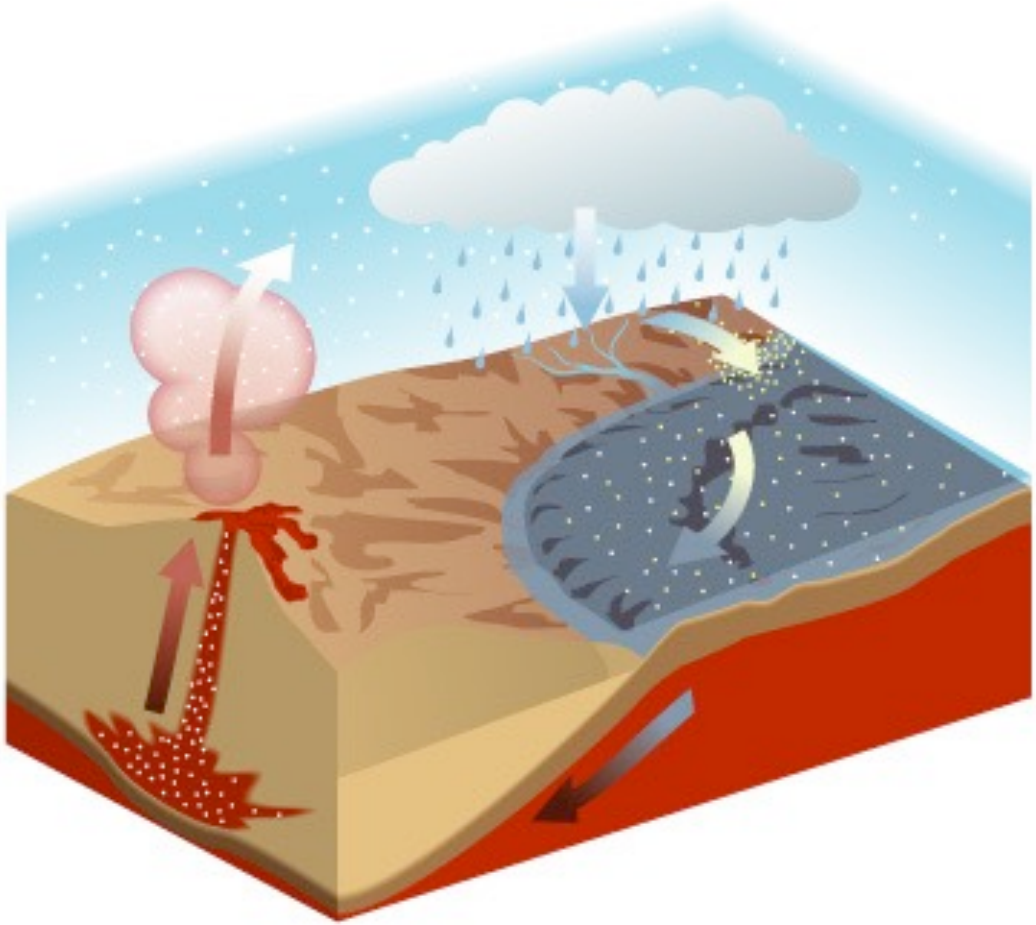


1. Atmospheric CO_2 dissolves in rainwater.

2. Rain erodes minerals that flow into the ocean.

3. Minerals combine with carbon to make rocks on ocean floor.

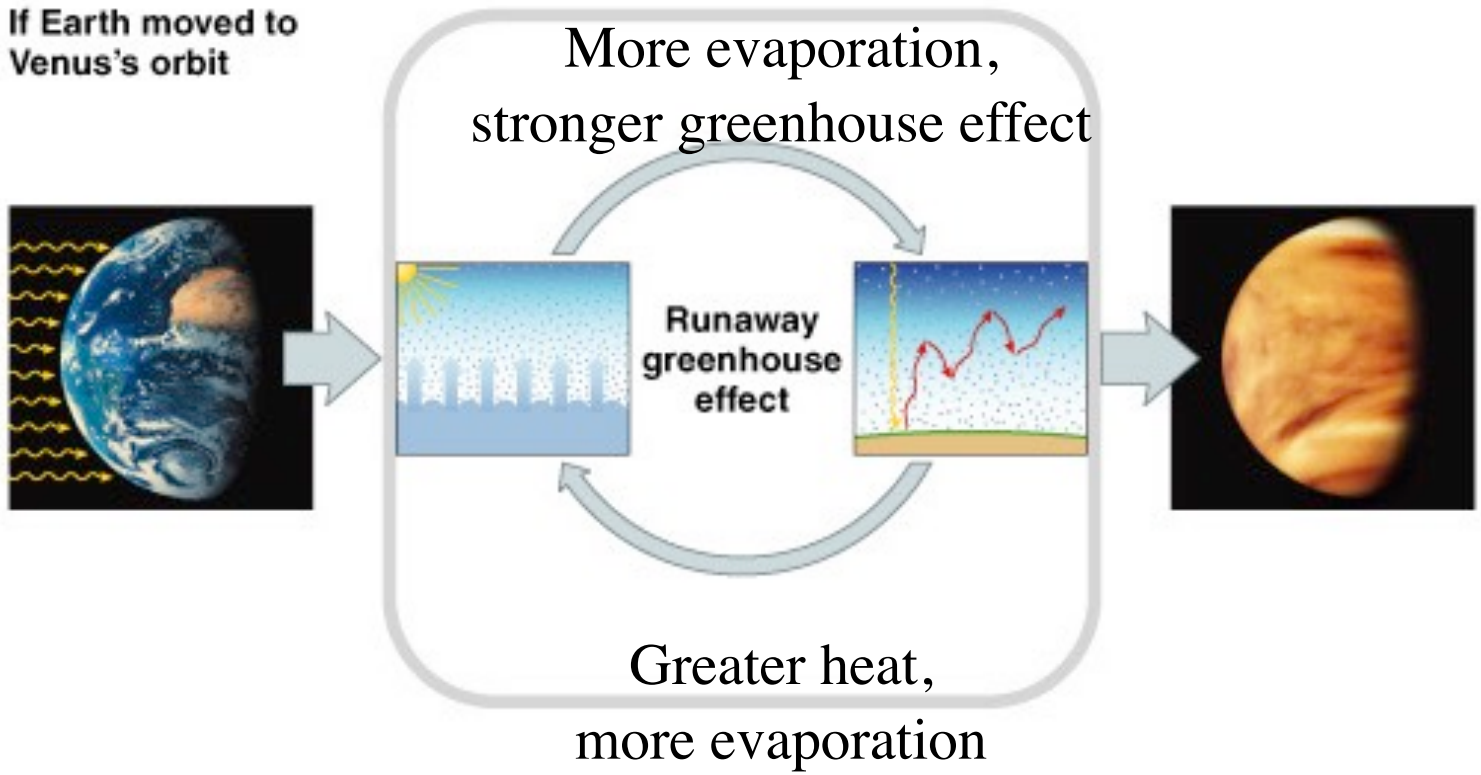
Carbon Dioxide Cycle



4. Subduction carries carbonate rocks down into the mantle.

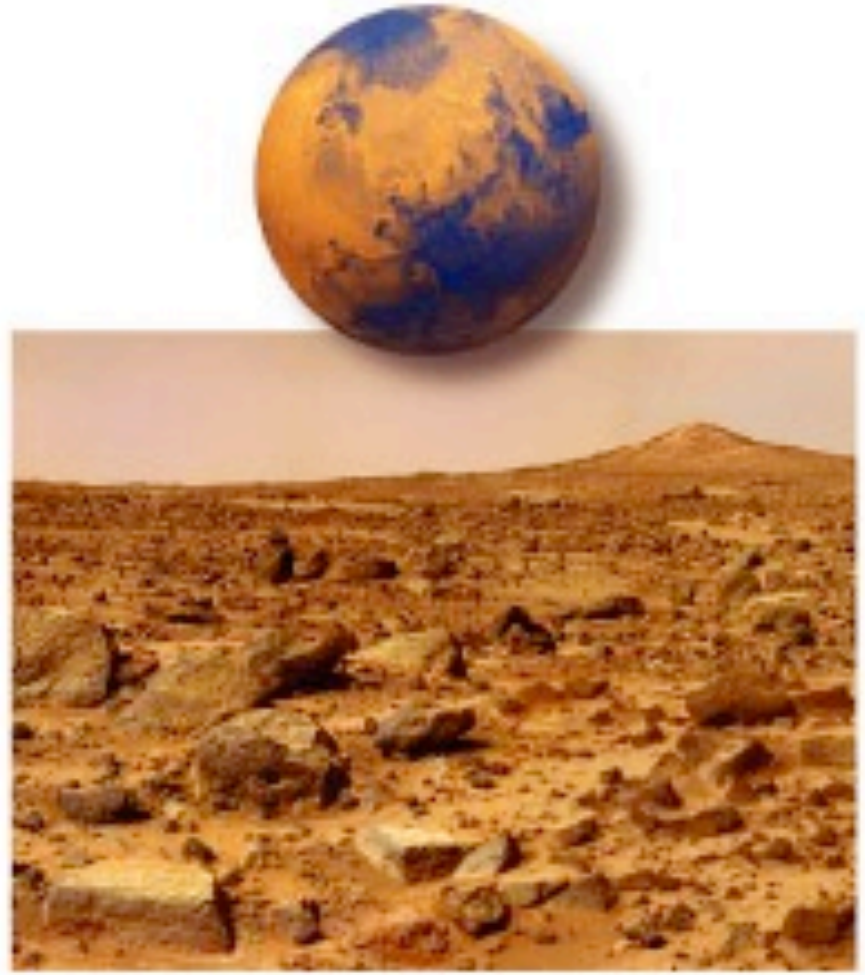
5. Rock melts in mantle and outgases CO_2 back into atmosphere through volcanoes.

Runaway Greenhouse Effect



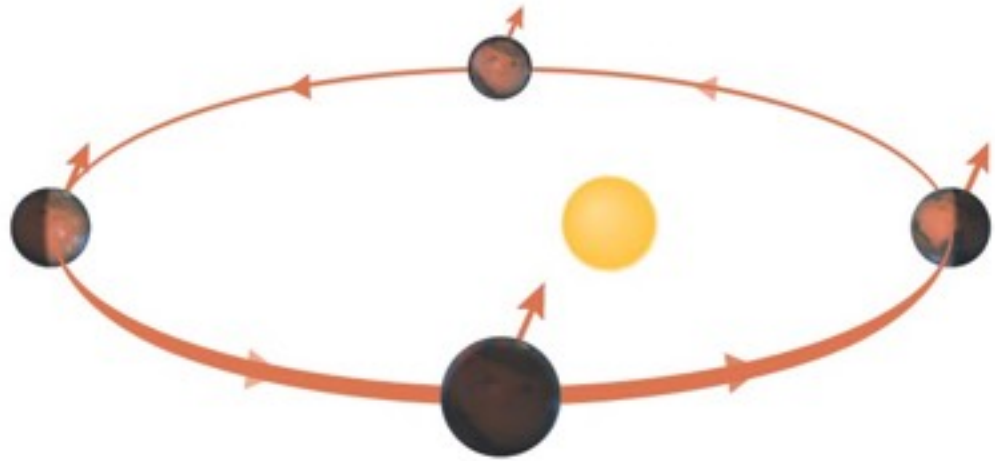
- Oceans evaporate; no longer absorb CO_2.
  - CO_2 builds up in atmosphere unchecked
  - "runaway greenhouse"

Mars: the opposite extreme



- Low gravity and a thinning atmosphere led to a runaway icehouse.
- Mars atmosphere currently ~1% as thick as Earth's

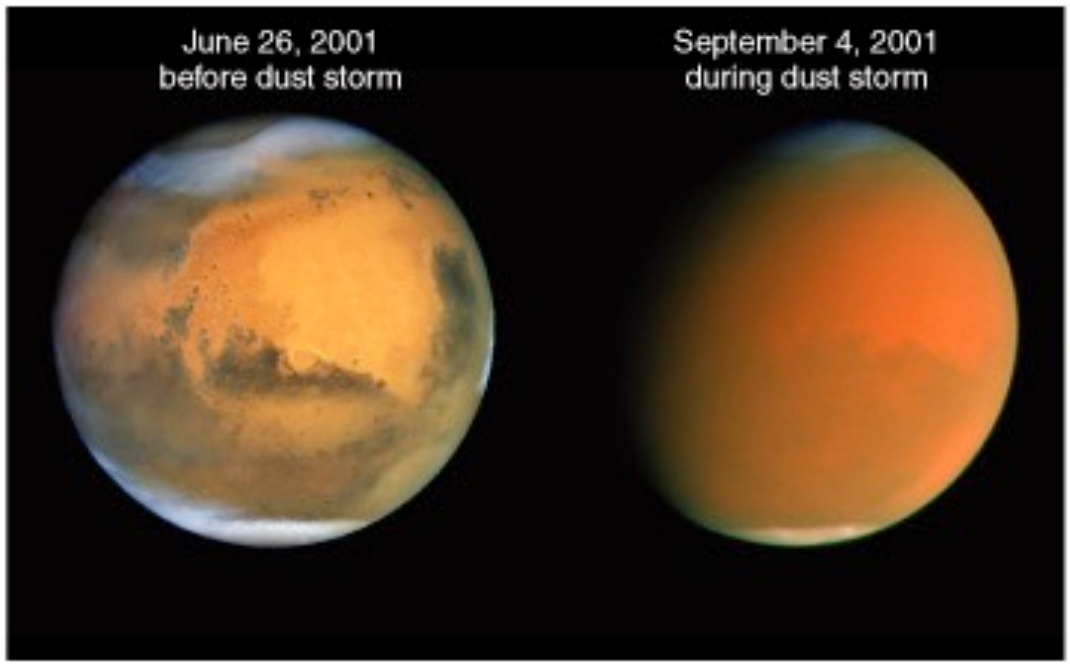
Seasons on Mars

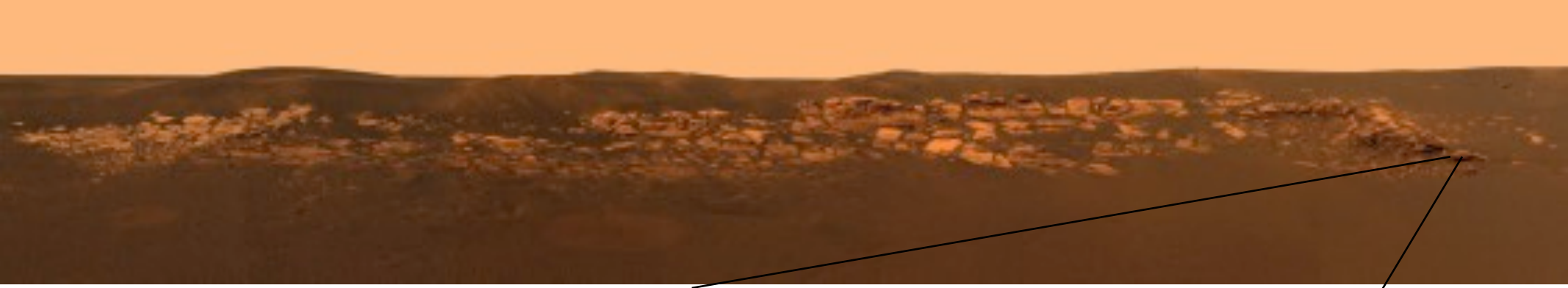


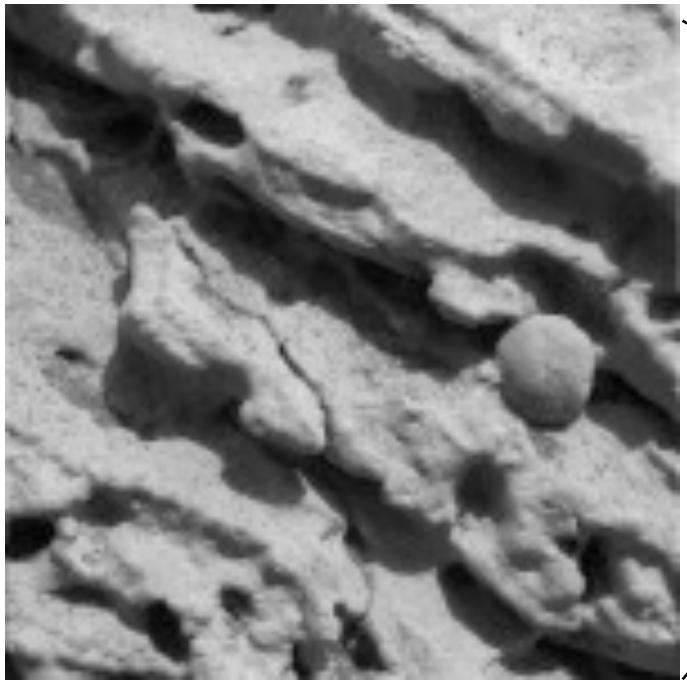
- Mars does have seasons; both axial tilt and distance from the sun matter.
- Seasons on Mars are more extreme in the southern hemisphere because of its elliptical orbit.

Storms on Mars

- Seasonal winds on Mars can drive huge dust storms.
- Drive ongoing wind erosion

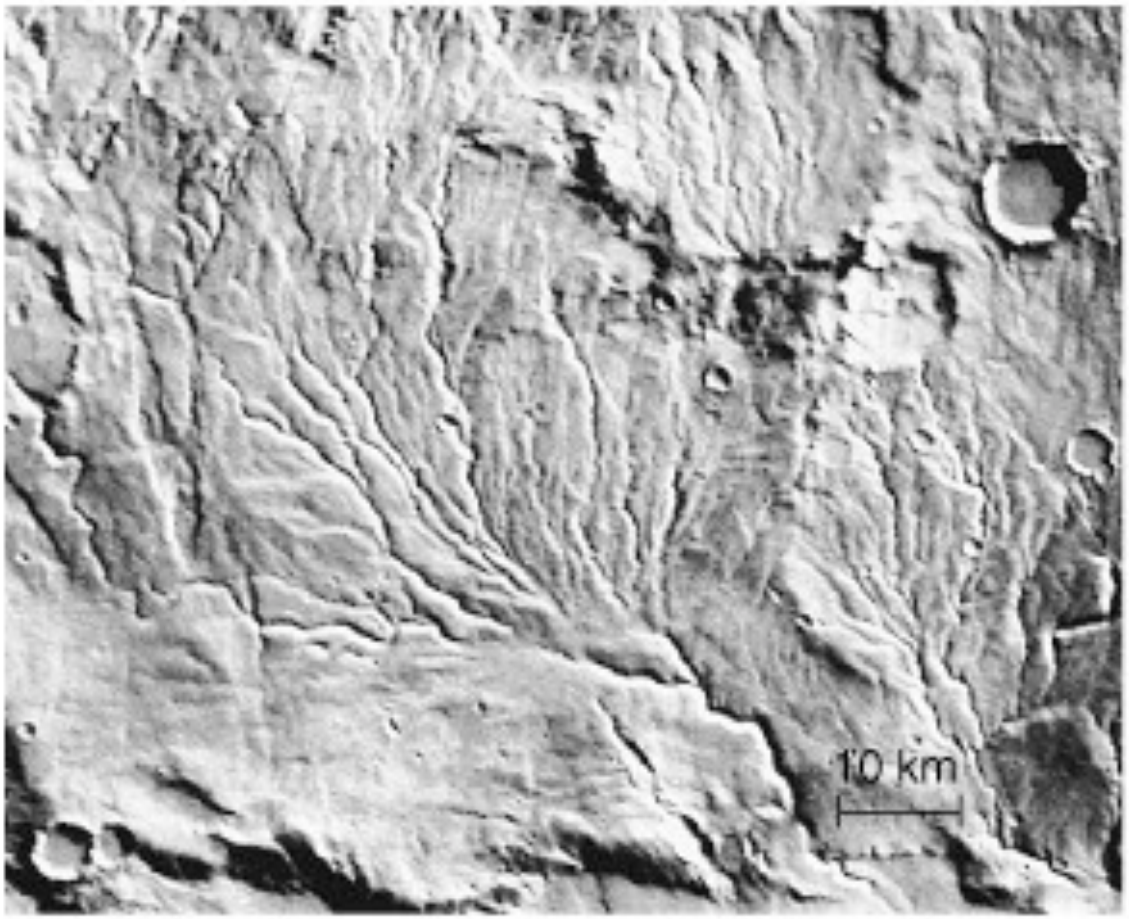






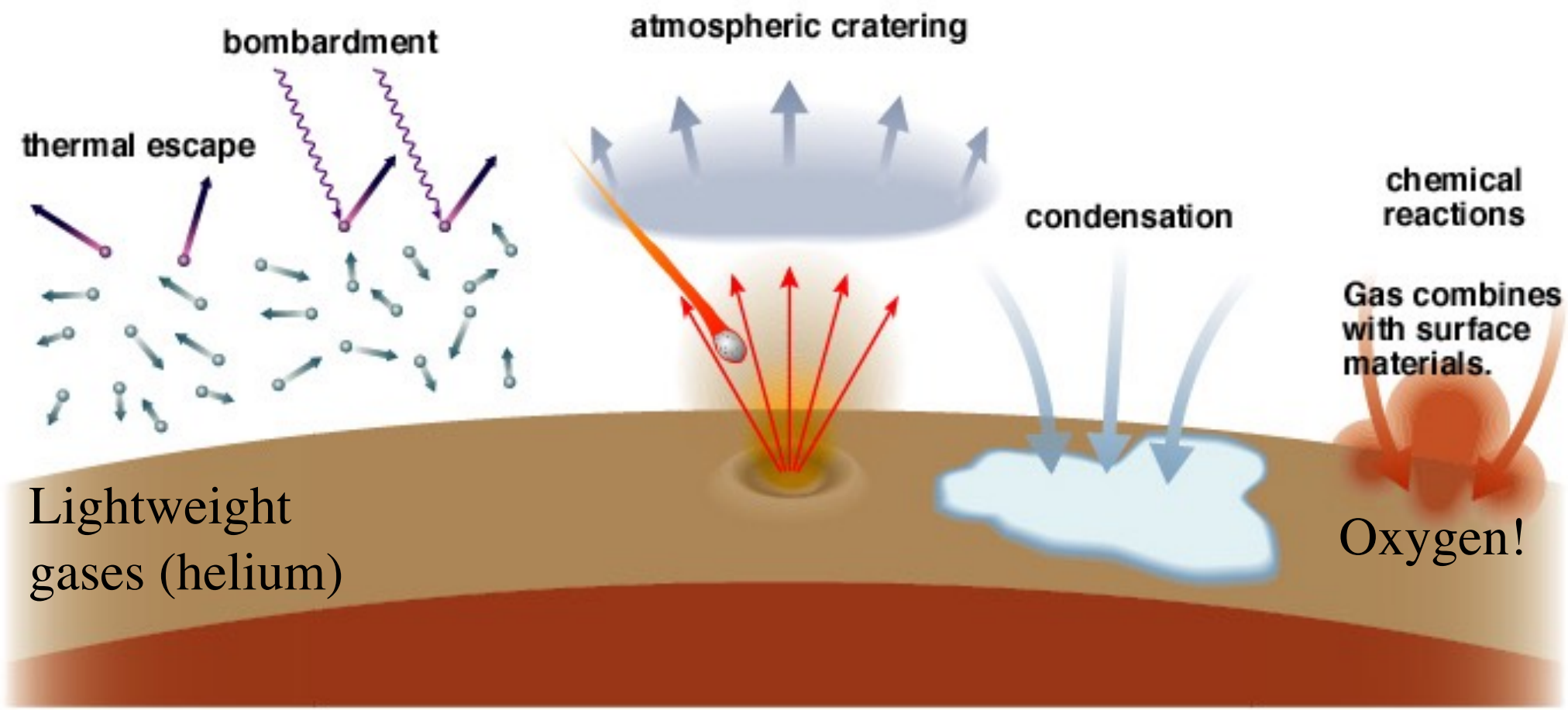
- 2004 *Opportunity* Rover provided strong evidence for abundant liquid water on Mars in the distant past.
- How could Mars have been warmer and wetter in the past?

Climate Change on Mars



- Mars has not had widespread surface water for 3 billion years.
- The greenhouse effect probably kept the surface warmer before that.
- Over time, Mars lost most of its atmosphere.

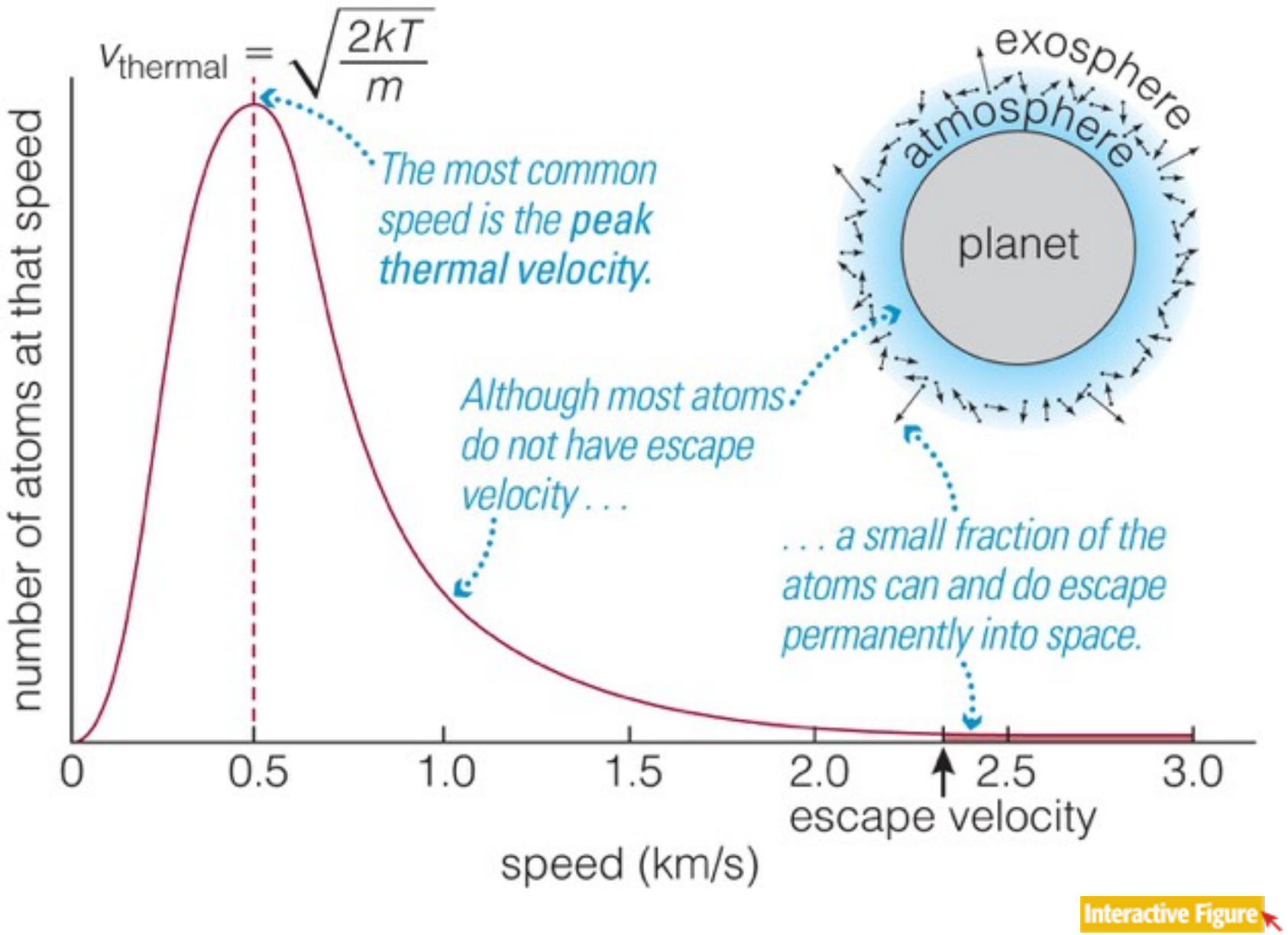
Factors affecting atmospheres



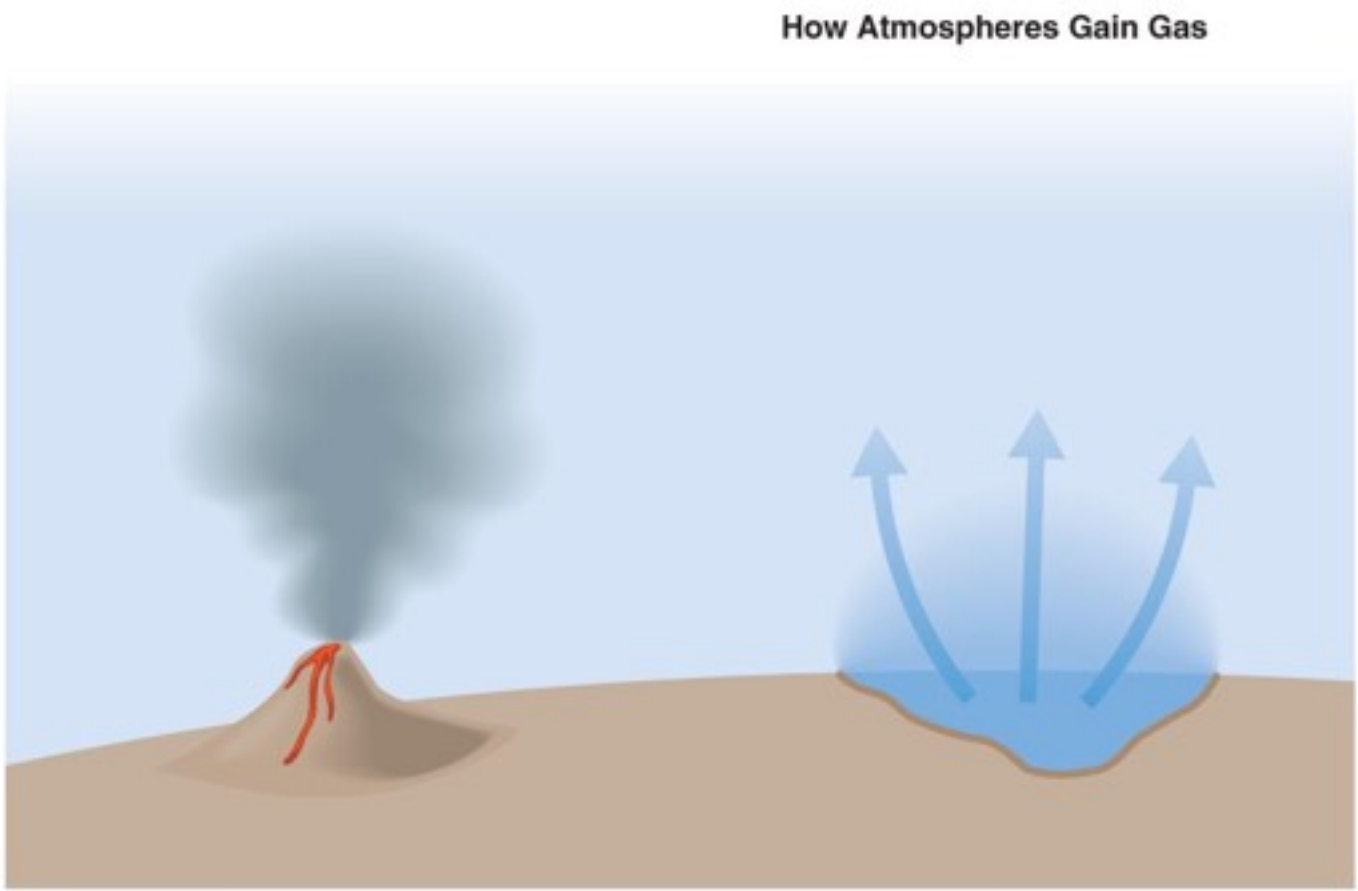
Can break up water vapor; hydrogen escapes

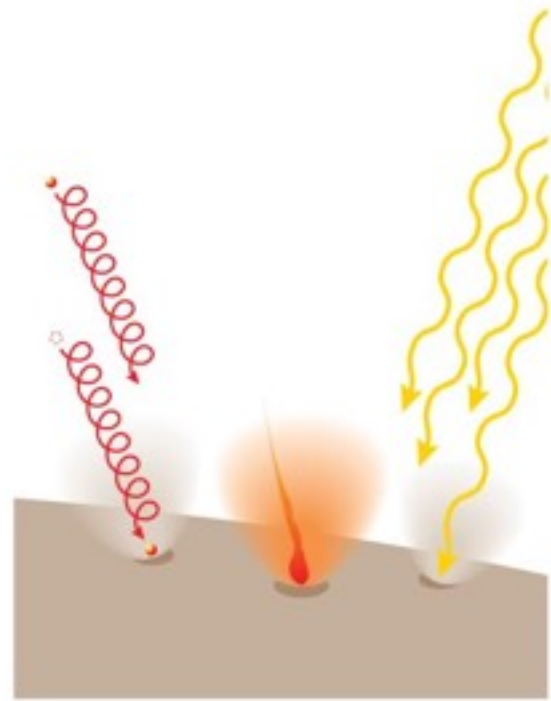
Water can freeze out

Thermal Escape



Sources of Gas



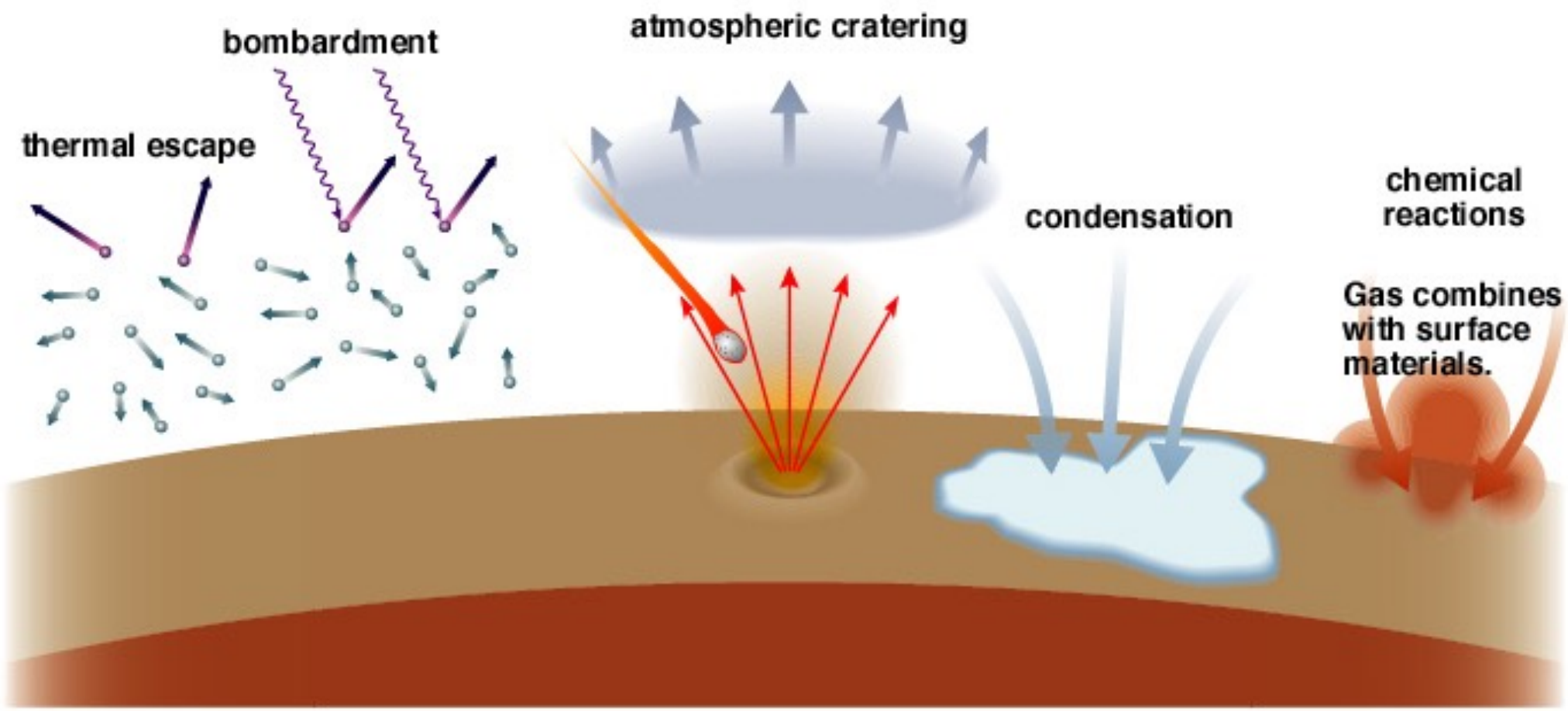


Outgassing from volcanoes

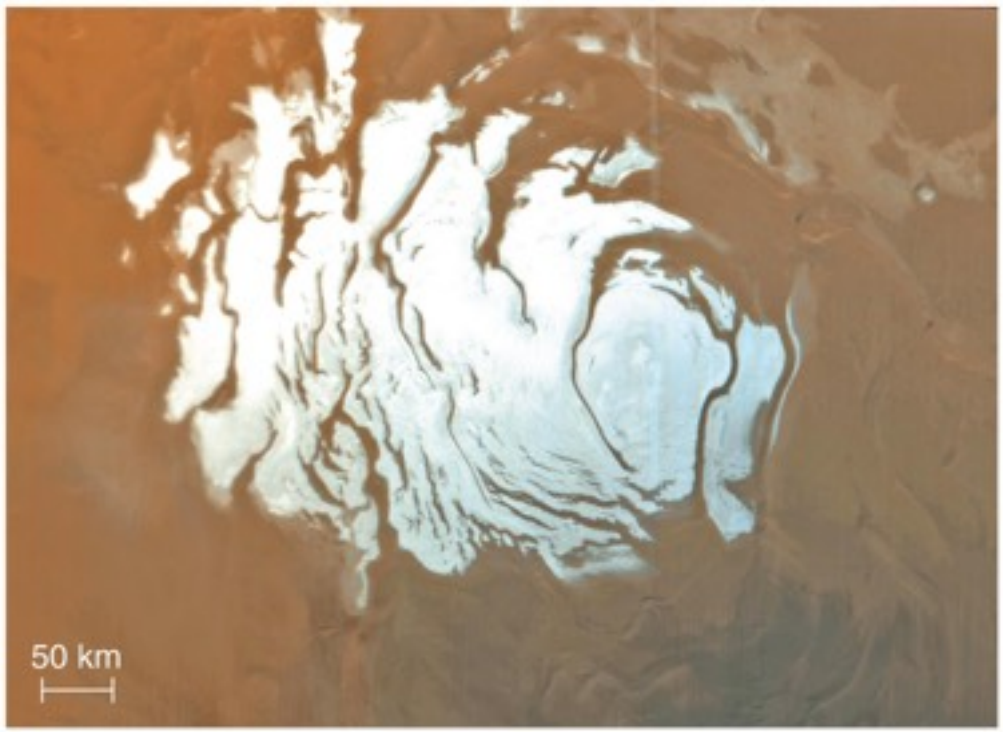
Evaporation of surface liquid; sublimation of surface ice (cometary coma)

Impacts of particles and photons e.g., comets

Loss of gas

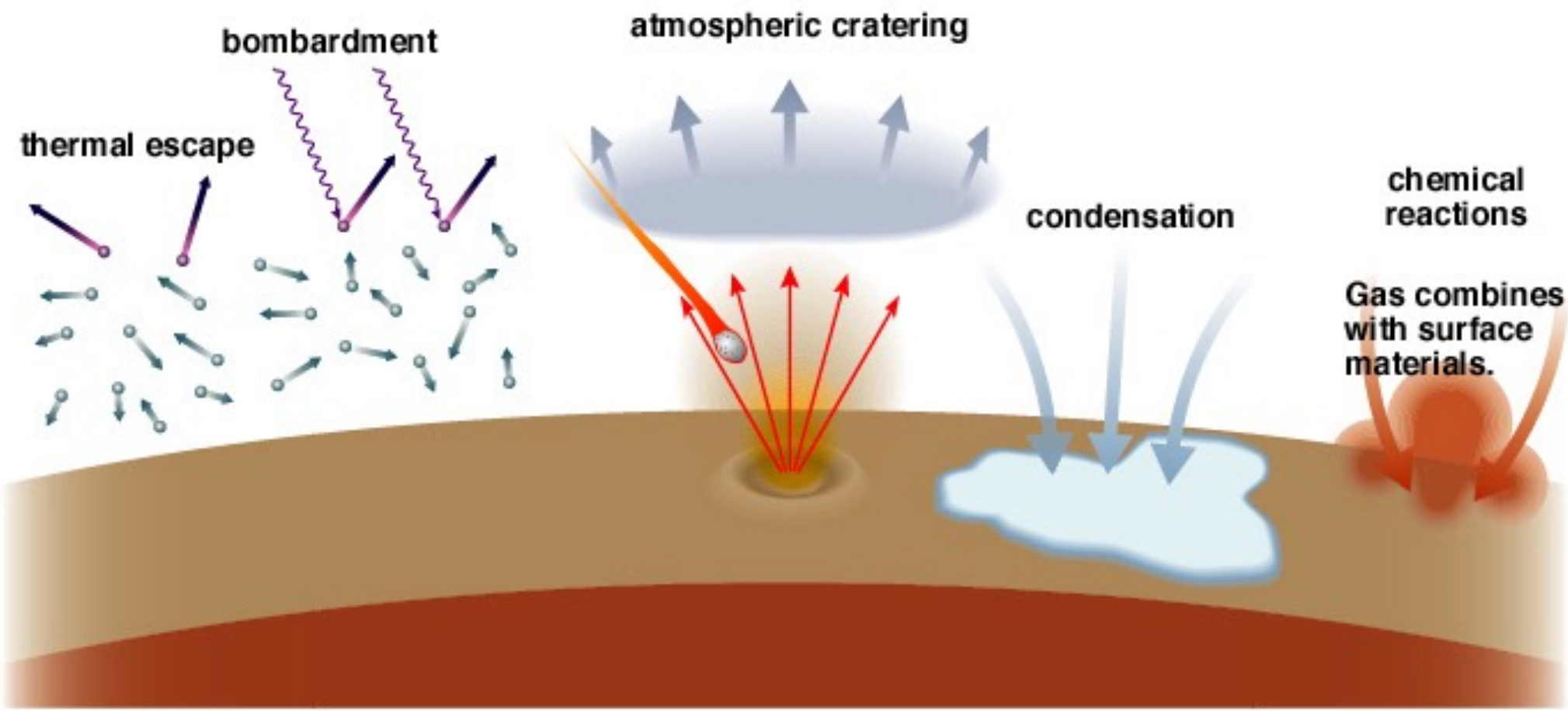


Polar Ice Caps of Mars

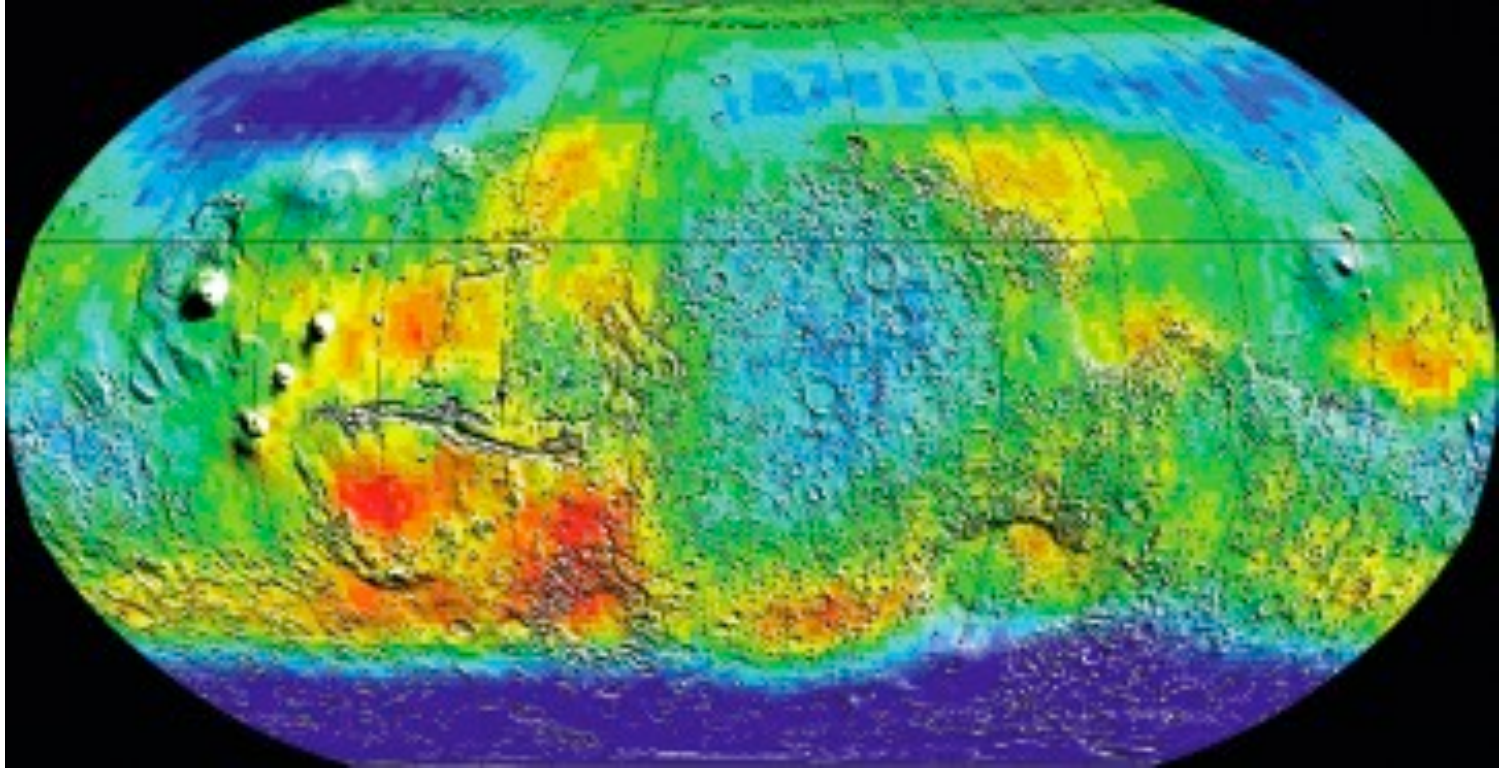


- Residual ice of the south polar cap remaining during summer is primarily water ice.
- Carbon dioxide ice of polar cap sublimates as summer approaches and condenses at opposite pole.

- Mars atmosphere was thicker in the past; its climate was warmer - liquid water!
- The atmosphere was gradually lost to space or frozen onto surface

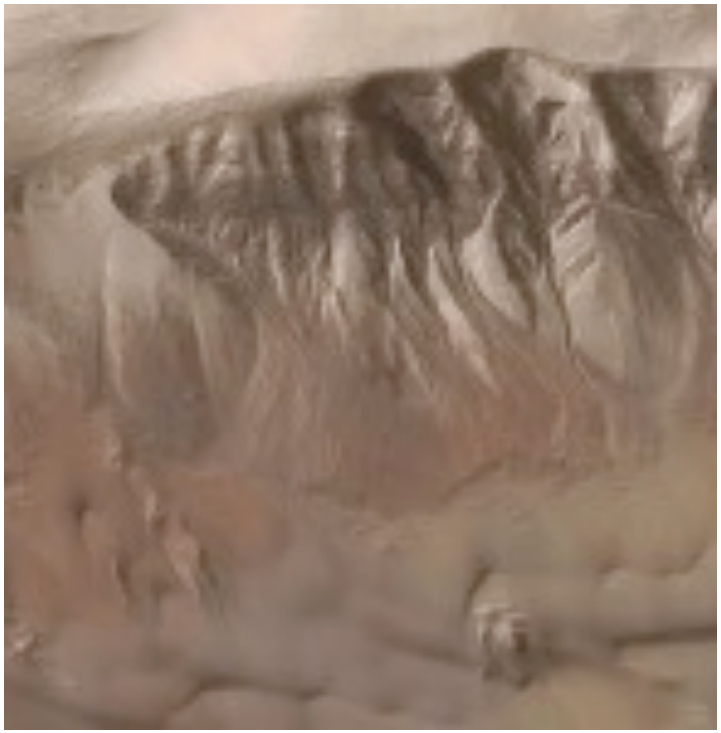


Today, most water lies frozen underground (blue regions) "permafrost"



Some scientists believe accumulated snowpack melts carve gullies even today.

Could see this happening in 2015!



Observed in 2015

https://cdn.theatlantic.com/assets/media/img/posts/2015/09/577359main_pia14472_946b/28ec00e1c.gif

Climate change on Mars

- Early Mars had thicker atmosphere
  - warmer climate
  - liquid water on surface (> 3 billion years ago!)
- Over time, most of Mars's atmosphere either
  - escaped into space
  - froze out onto surface
- Current atmosphere thin
  - Mostly CO_2, but not much of a greenhouse effect

“Normal” terrestrial atmosphere

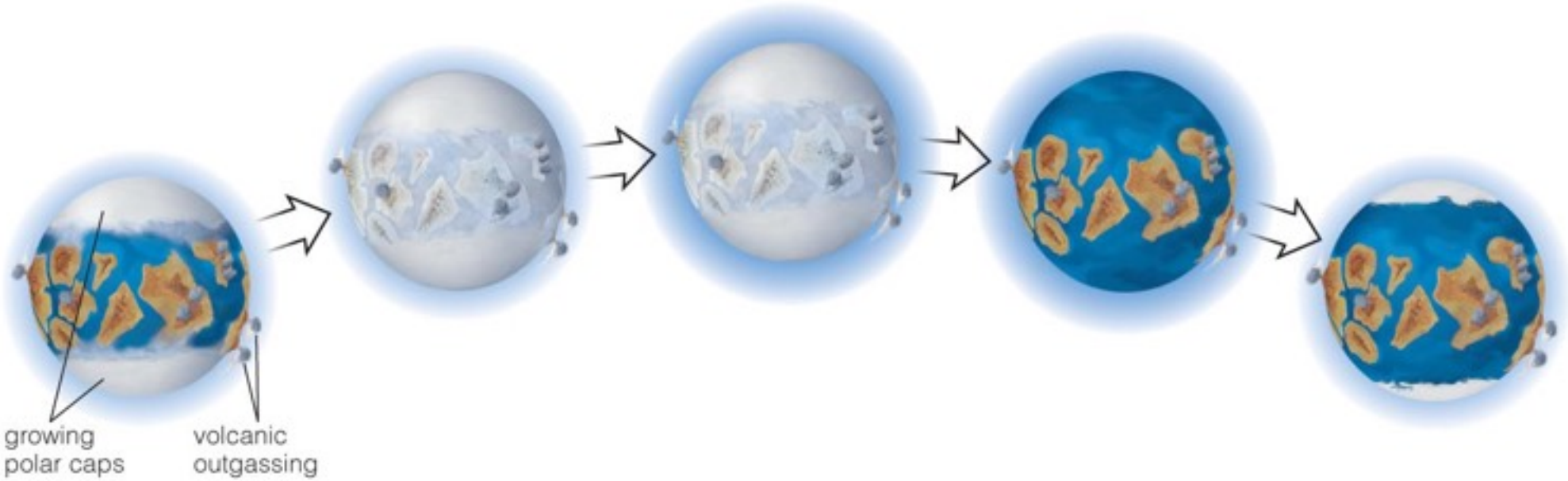
- Atmospheric retention depends on
  - surface gravity
  - temperature
- Most common atmospheric composition
  - CO_2, N_2 (Venus, Mars)
  - or none at all (Mercury, Moon)
- Earth is the exception
  - H_2O plays crucial role in Carbon cycle
  - O_2 a biological byproduct

Weather and Climate

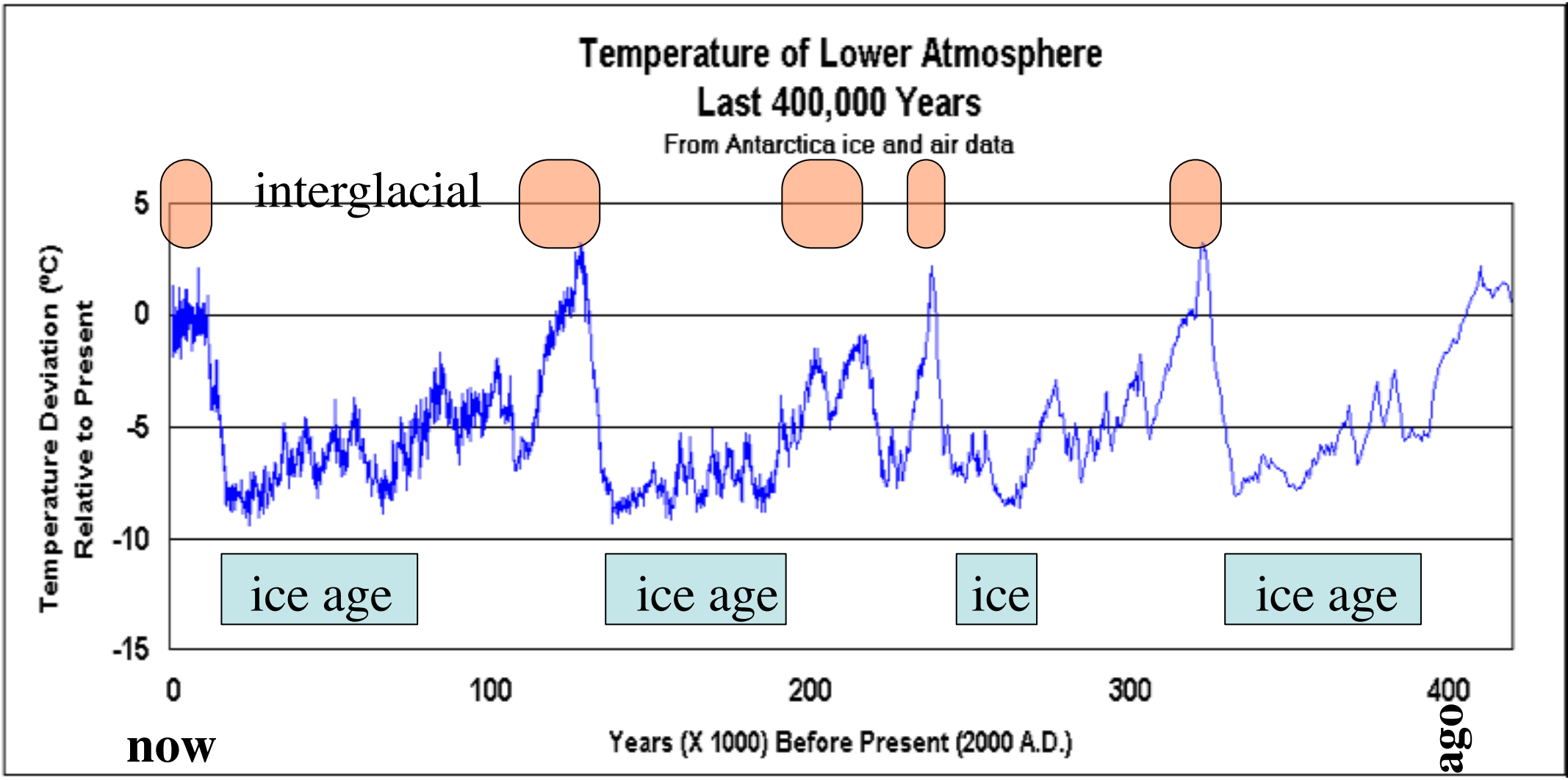
- Weather is the ever-varying combination of wind, clouds, temperature, and pressure.
  - Local complexity of weather makes it difficult to predict.

- Climate is the long-term average of weather.
  - generally more predictable than weather
  - Stability of climate depends on global conditions
  - Long term climate prone to instability
    - Venus, Mars evolved to stable points
    - Earth still varying (e.g., ice ages come & go)

Long-Term Climate Change (e.g., Ice Ages)



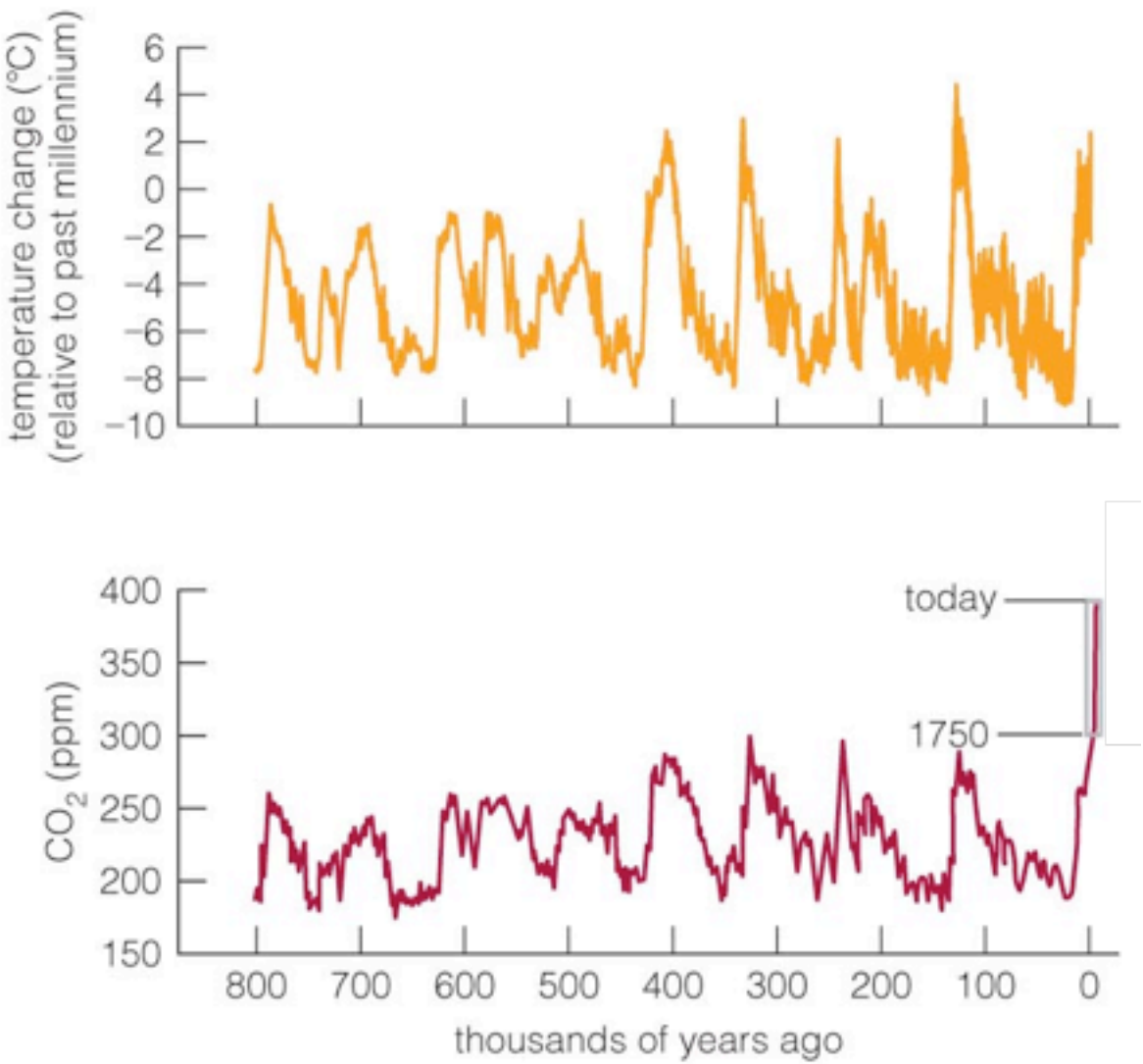
- Changes in Earth's axis tilt might lead to ice ages.
- Widespread ice tends to lower global temperatures by increasing Earth's reflectivity.
- CO_2 from outgassing will build up if oceans are frozen, ultimately raising global temperatures again.



Good global climate record for past half million years from Antarctic ice core measurements

400,000 yr ago

CO_2 Concentration



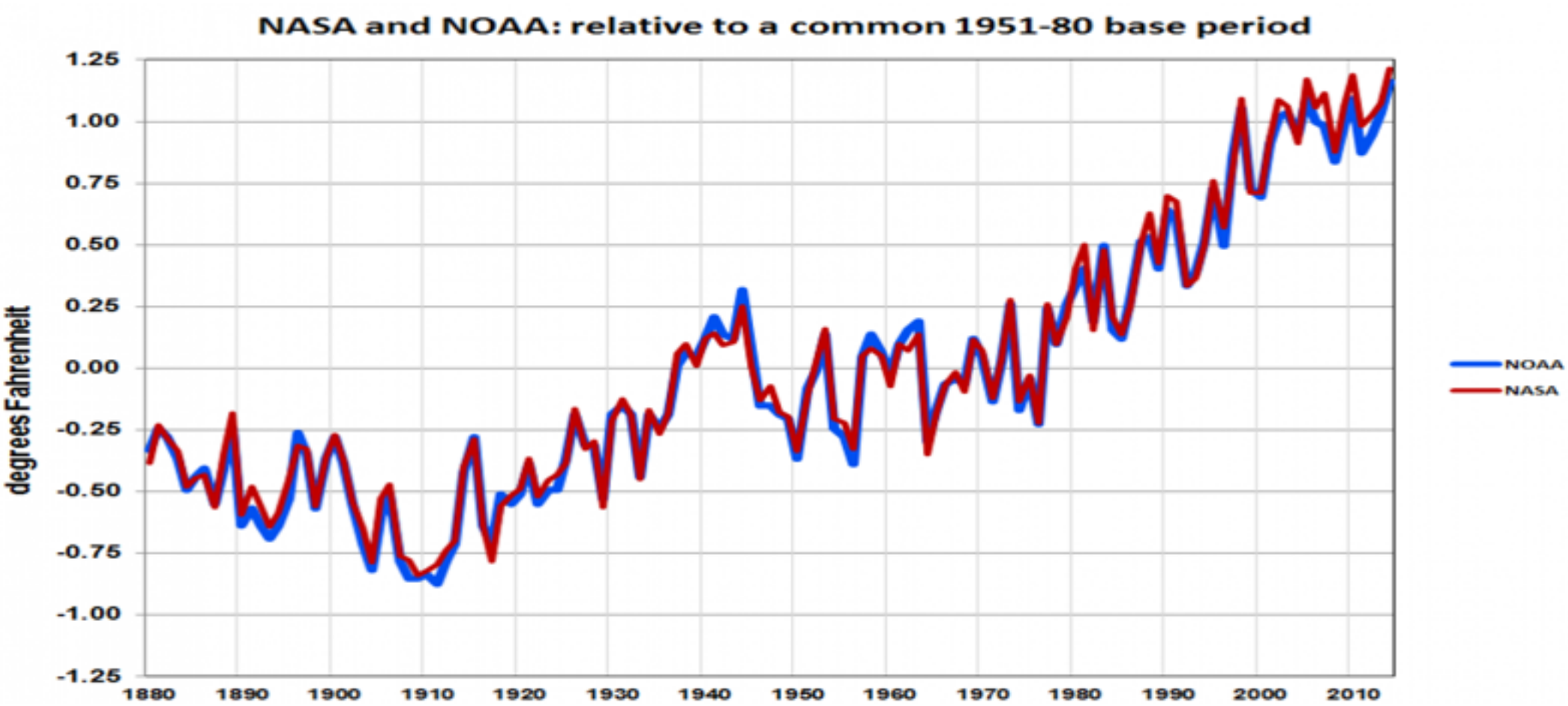
- Temperature and CO_2 concentration vary in lockstep
- This coupling is expected from known physics
- Current CO_2 concentration is the highest it's been in

The anthropogenic greenhouse effect (Global Warming and human activity)

What is real information?

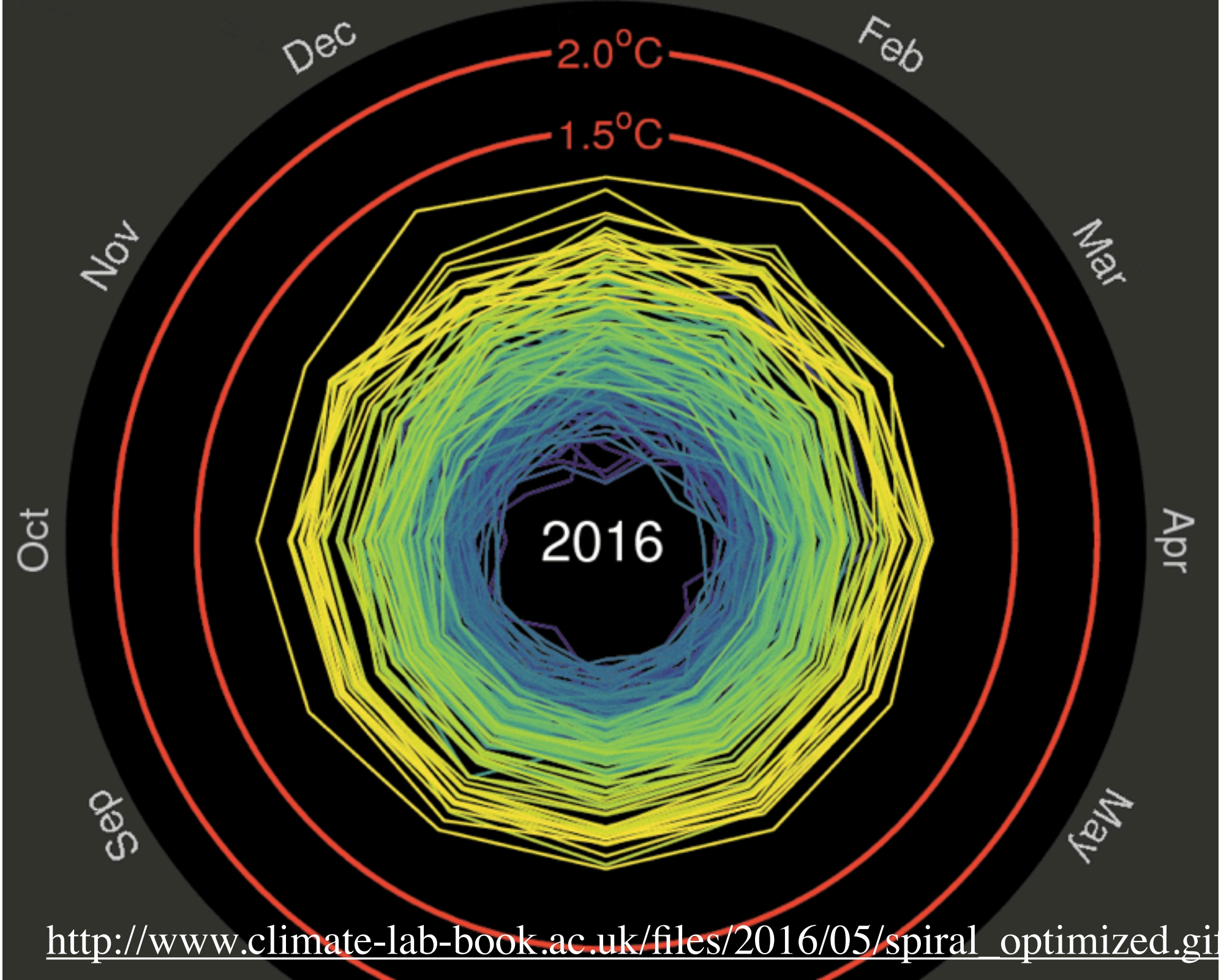
What is misleading?

Should we be worried?

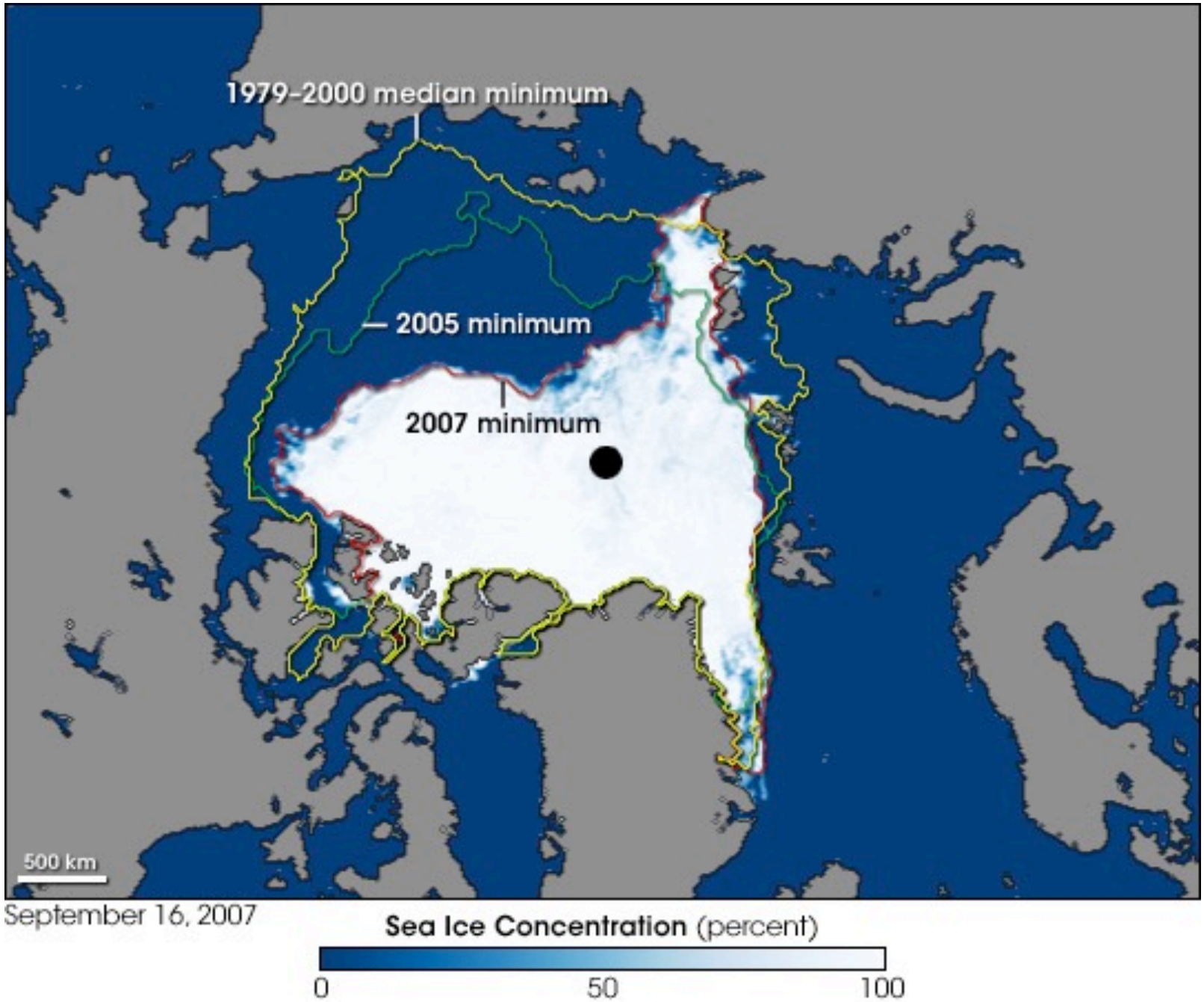


Evidence of global warming

- Increase in greenhouse gas concentrations
- Surface temperature measurements
- Ocean temperature measurements
- Sea level rise (water expands as it warms)
- Melting arctic icecap; retreating glaciers
- Poleward migration of species
- More extreme weather events
  - both warm & cold; hurricanes; snowmageddon
- Melting permafrost

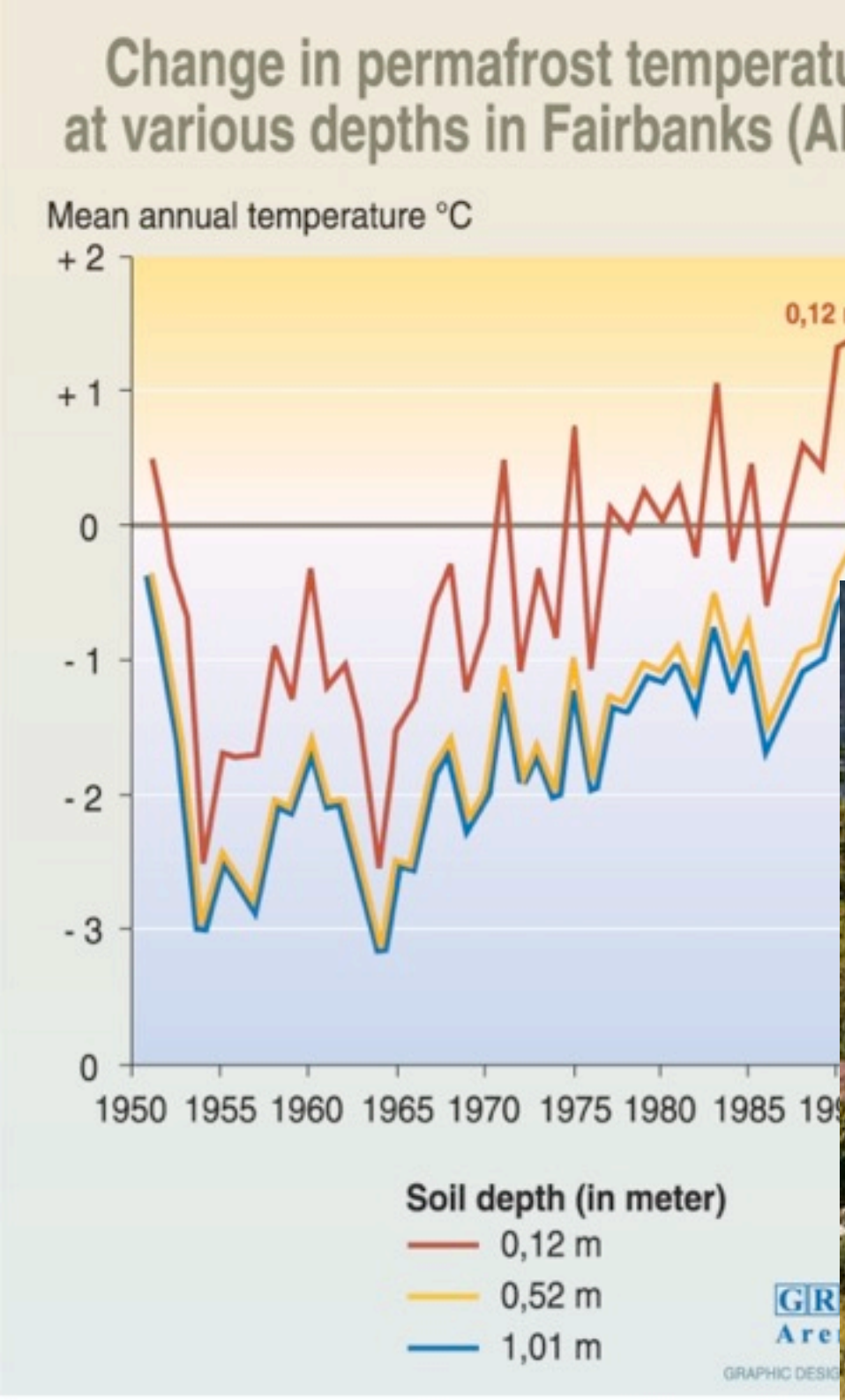


http://www.climate-lab-book.ac.uk/files/2016/05/spiral_optimized.gi



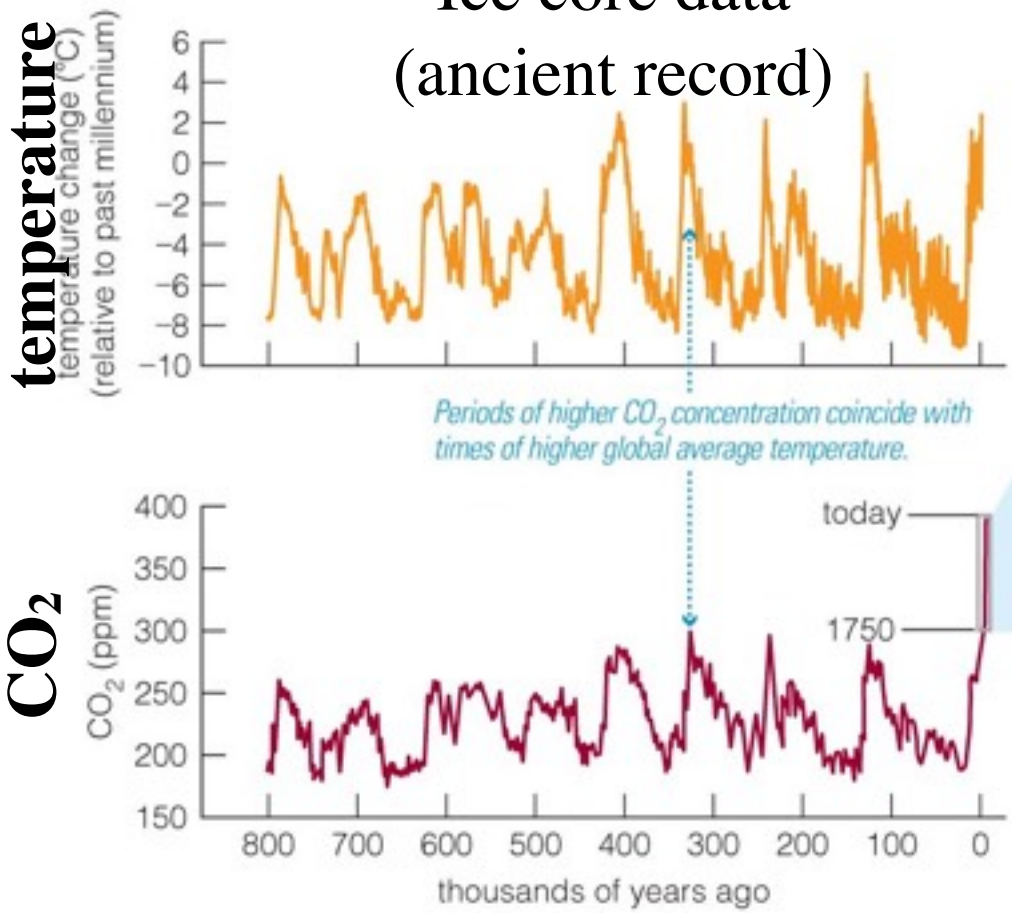
Fabled Northwest passage opened for first time in history in 2007

Arctic
permafrost
is melting



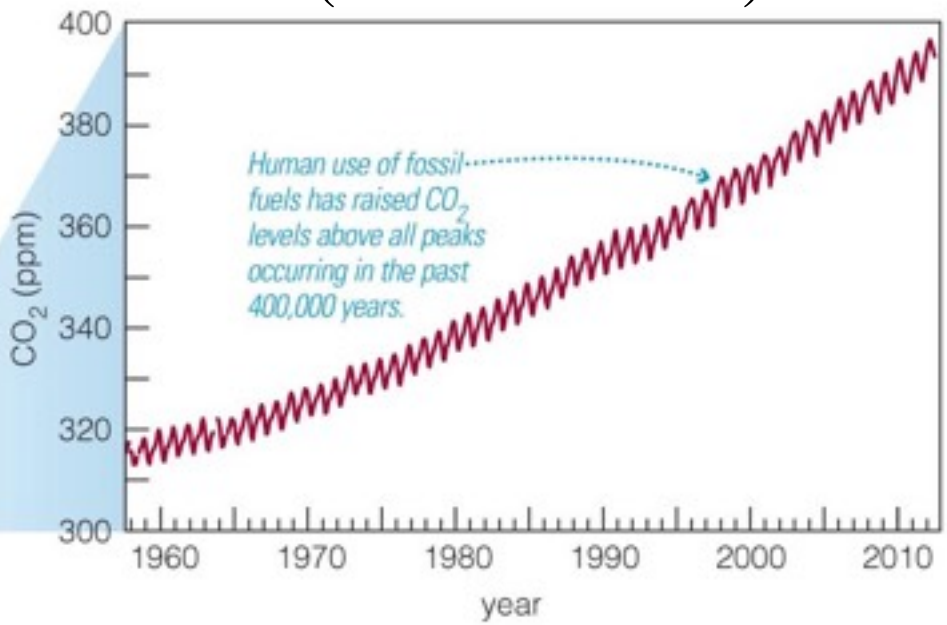
CO_2 Concentration

Ice core data
(ancient record)



time
(thousands of years)

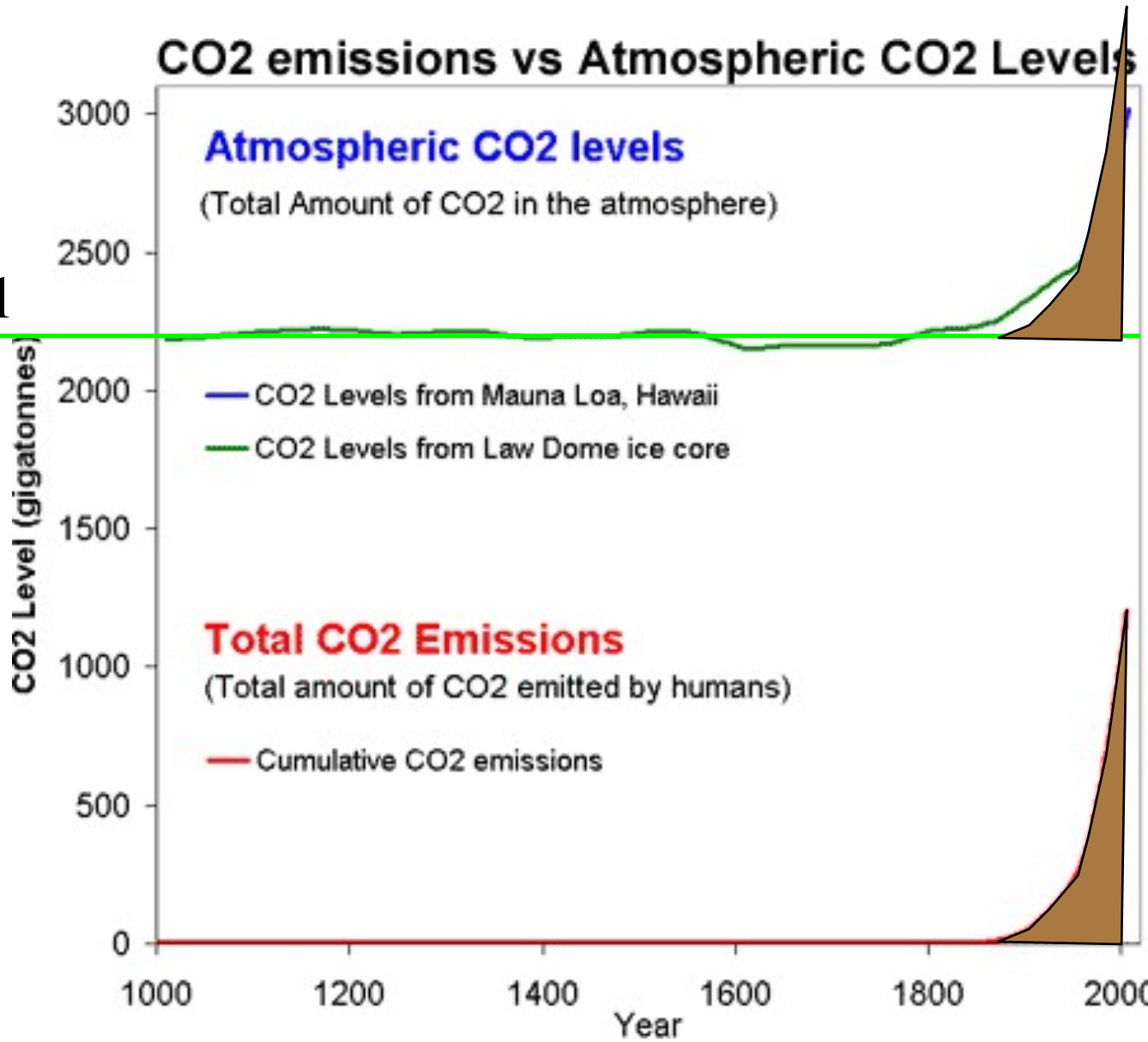
Mauna Loa Observatory
(modern record)



time
(years)

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

Pre-industrial CO_2 concentration: 280 ppm. Current level: 400 ppm



Pre-industrial CO_2 level

CO_2 added to atmosphere

Human activity

Carbon burned

1000

Year (A.D.)

2000

Basic facts

(non-partisan)

- The globe is warming (measured)
- The concentration of CO2 in the atmosphere is increasing (measured)
- The measured increase is roughly equal to the amount of fossil fuel we've burned (measured)
- Climate change is the expected result of adding greenhouse gases to the atmosphere (cf. Venus, Mars)

Climate Change Forecasts

- Gradual increase of average temperature
  - average increase modest but noticeable
  - winter not cancelled by 2° of warming
- More wild swings in weather events
  - Heat waves *and* cold waves more extreme
  - Same for rainfall/snowfall
- Ocean levels rise
  - 8" since 1880 (measured)
  - 3' forecast by 2100 - mostly thermal expansion

adios, Miami Beach

- Drought

model dependent

  - California, southwest dry out (more)
  - due to enhanced evaporation, smaller snowpack

Policy implications

- Basic trend clear but detailed long range forecast challenging.
  - Probably some winners as well as losers
- Probably a bad idea to conduct an uncontrolled experiment on the atmosphere we all breathe & climate we depend on.
- There is finite energy available in coal, oil, natural gas, uranium...
  - Are we ***NOT*** going to use these resources?