Today

- Terrestrial Planets Atmospheres & Climates

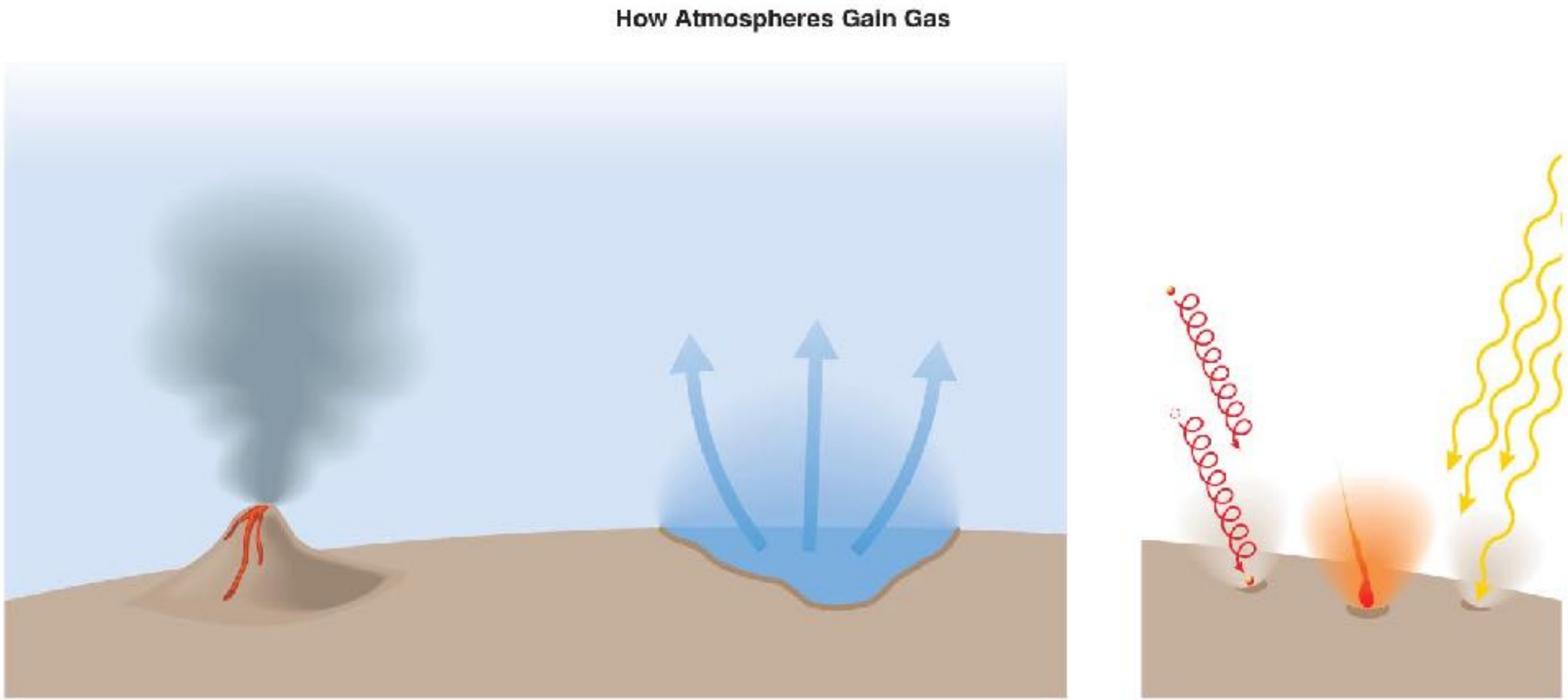
Events

- Homework DUE
- Review next time
- Exam next week

“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

Sources of Gas

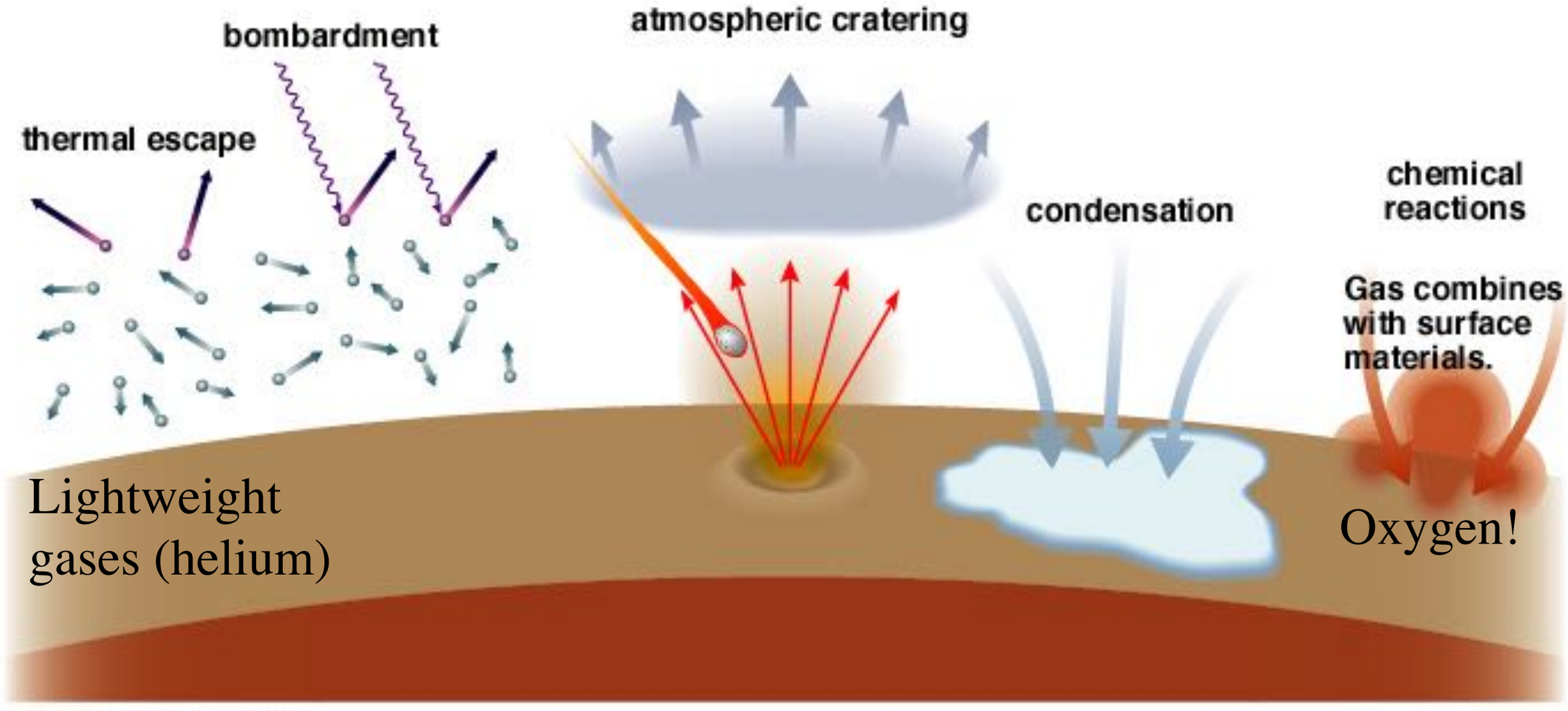


Outgassing from volcanoes

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

Impacts of particles and photons e.g., comets

Factors affecting atmospheres



Can break up water vapor; hydrogen escapes

Water can freeze out

Weather and Climate

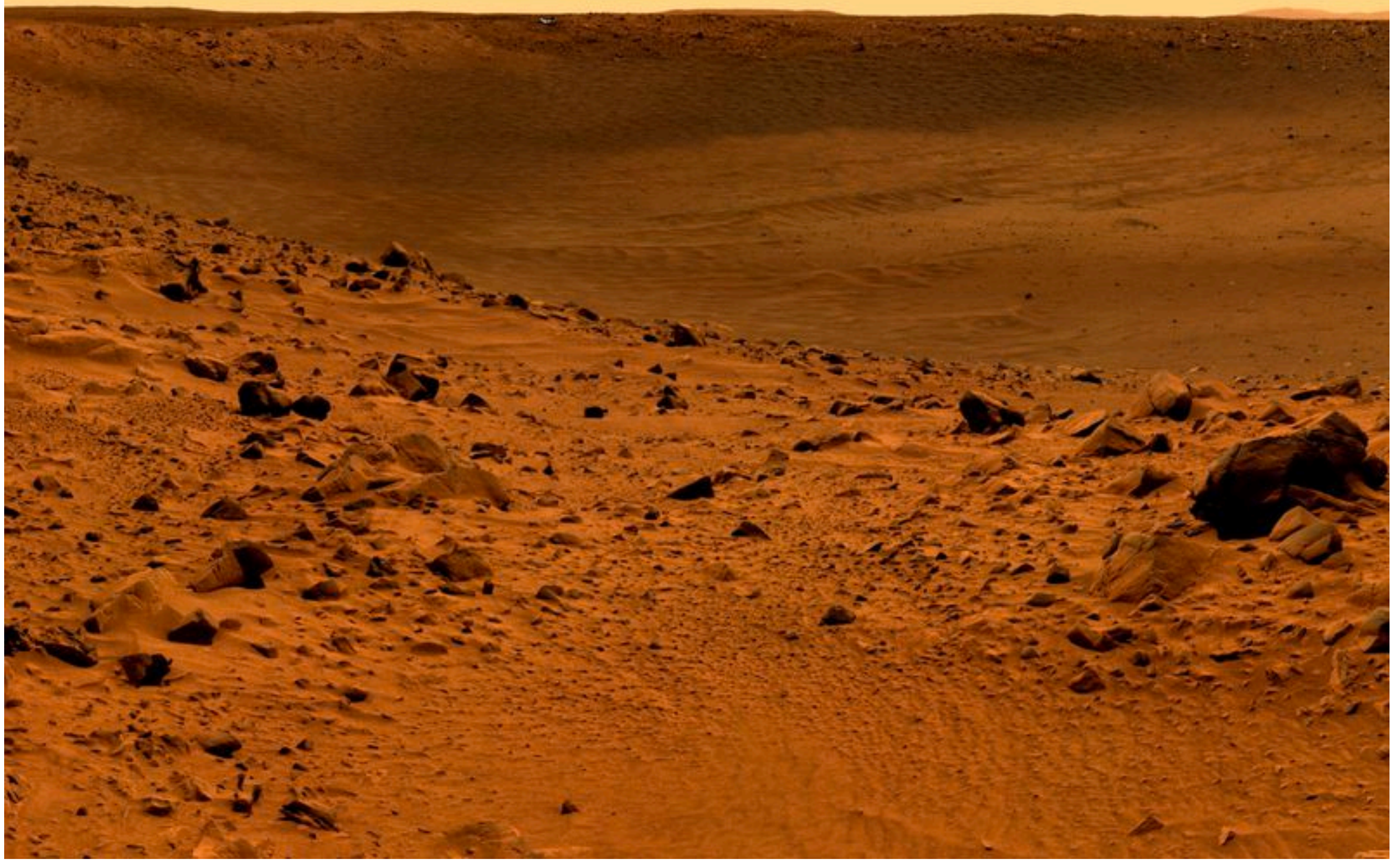
- **Weather** is the ever-varying combination of wind, clouds, temperature, and pressure.
  - Local complexity of weather makes it difficult to predict.

- **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)

Climate is what you expect

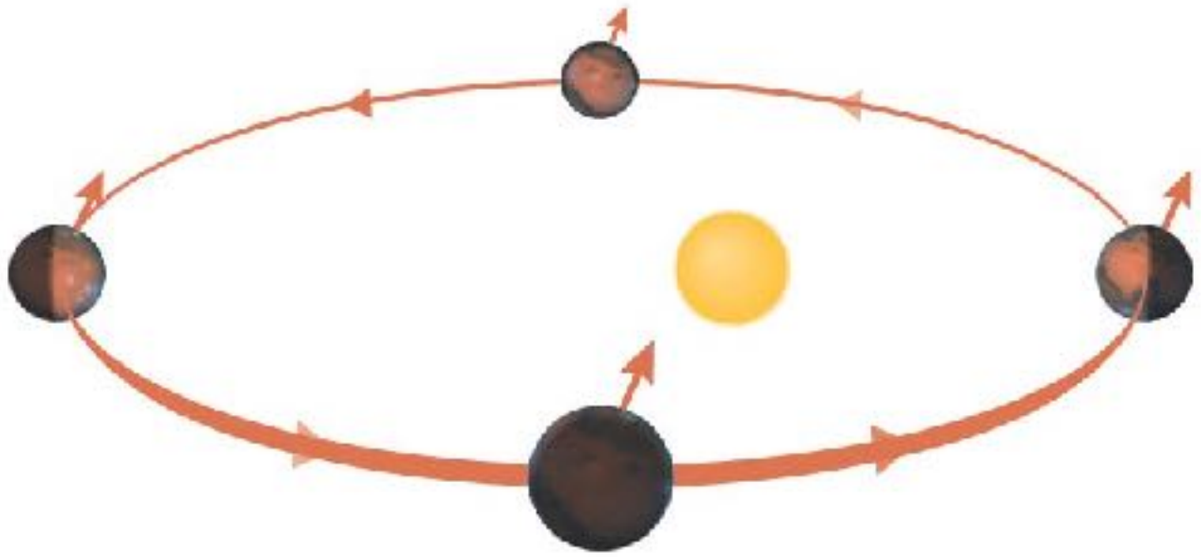
Weather is what you get

Mars: runaway icebox



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

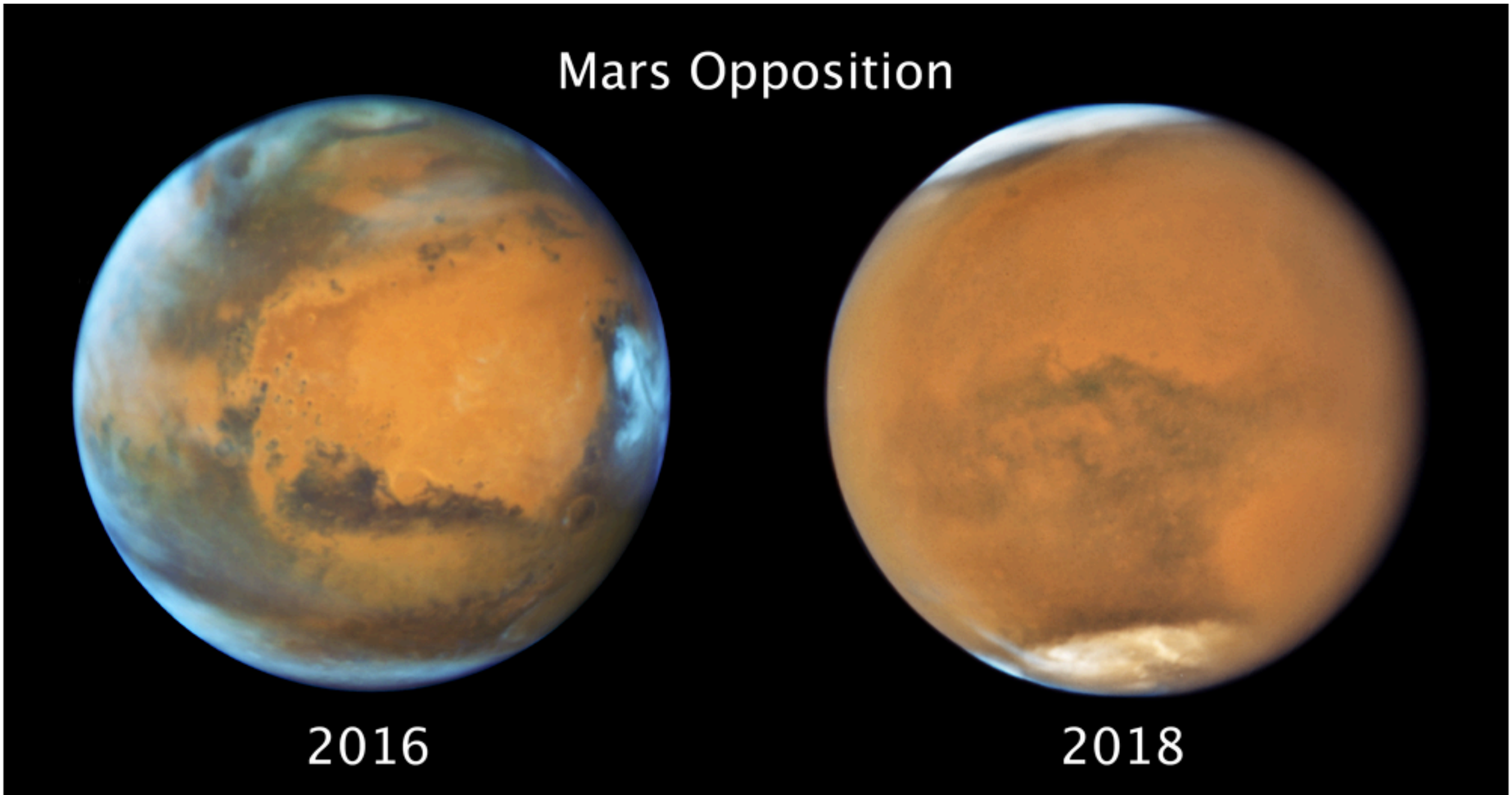
Seasons on Mars



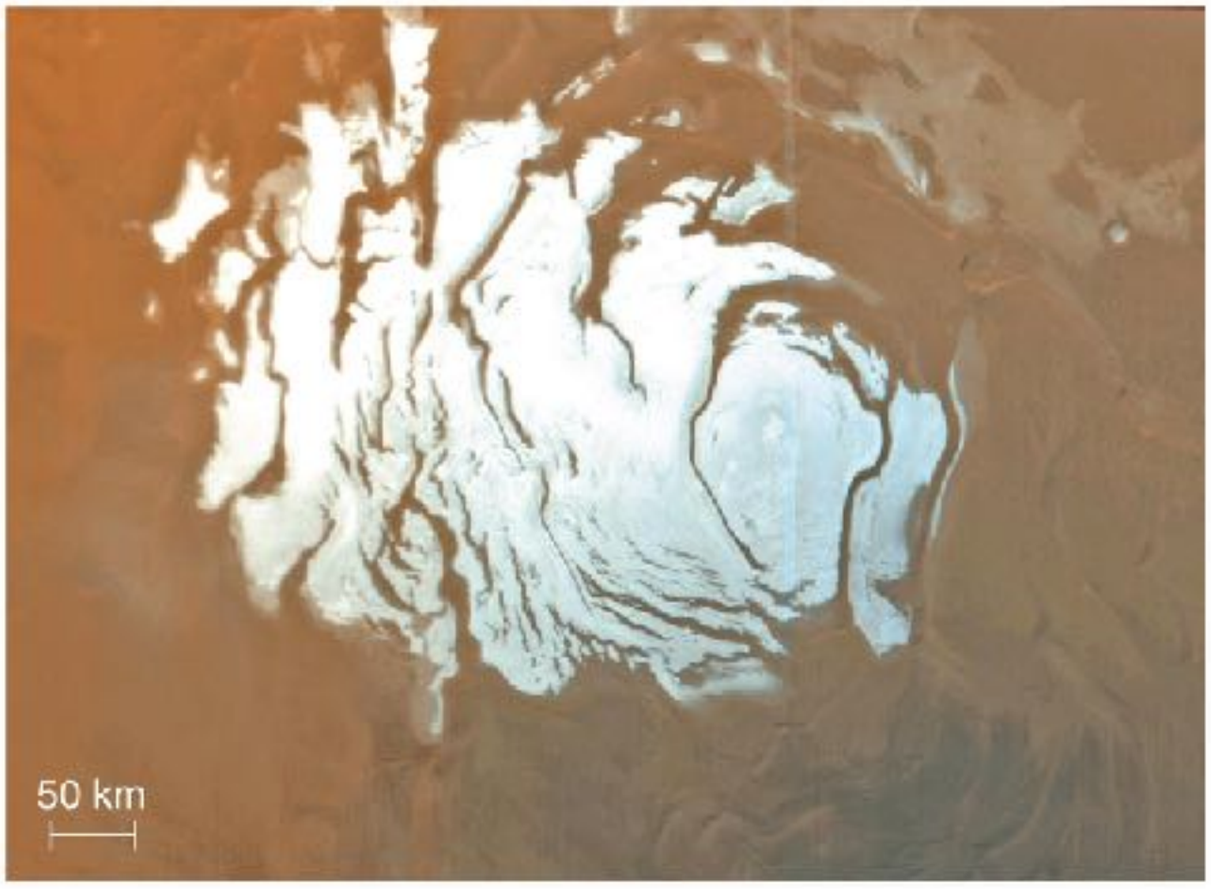
- Mars does have seasons; both axial tilt and distance from the sun matter.
- Seasons on Mars are more extreme in the southern hemisphere because of its elliptical orbit.

Storms on Mars

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

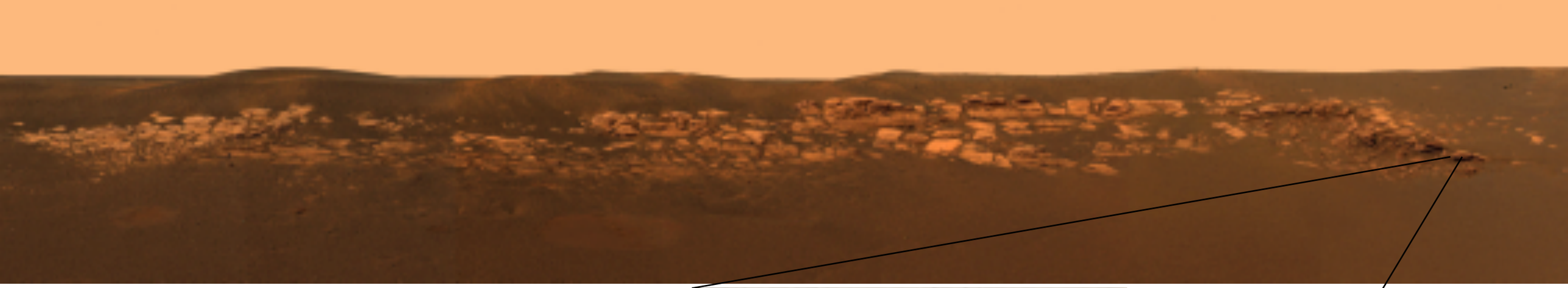


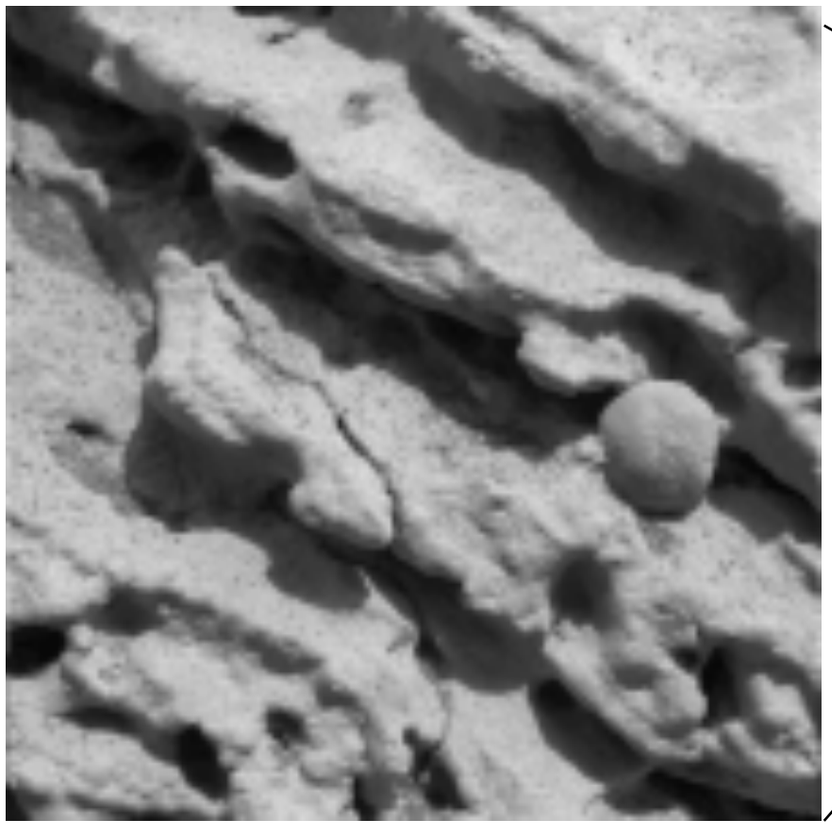
Polar Ice Caps of Mars



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

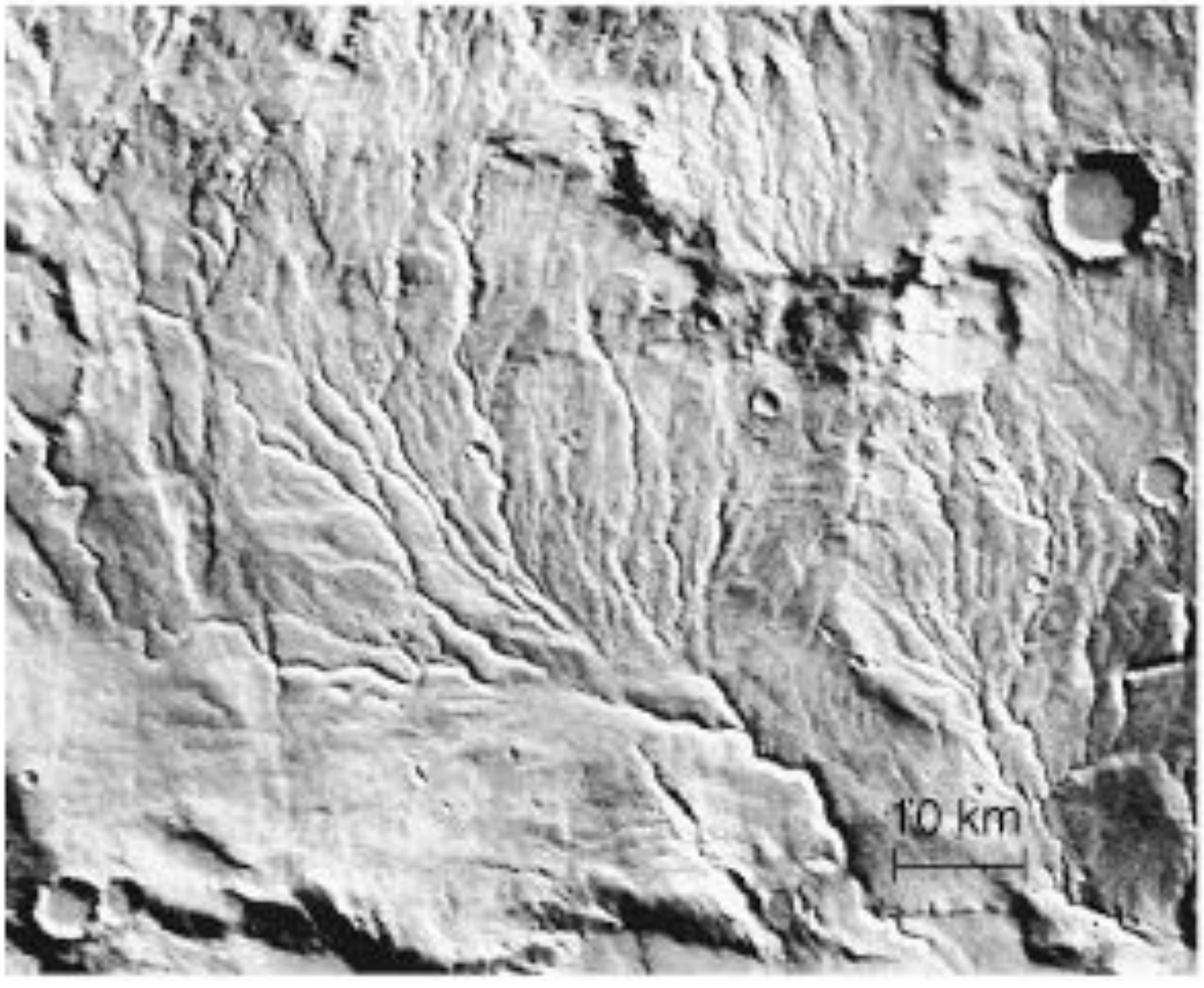
- Carbon dioxide ice of polar cap sublimates as summer approaches and condenses at opposite pole.





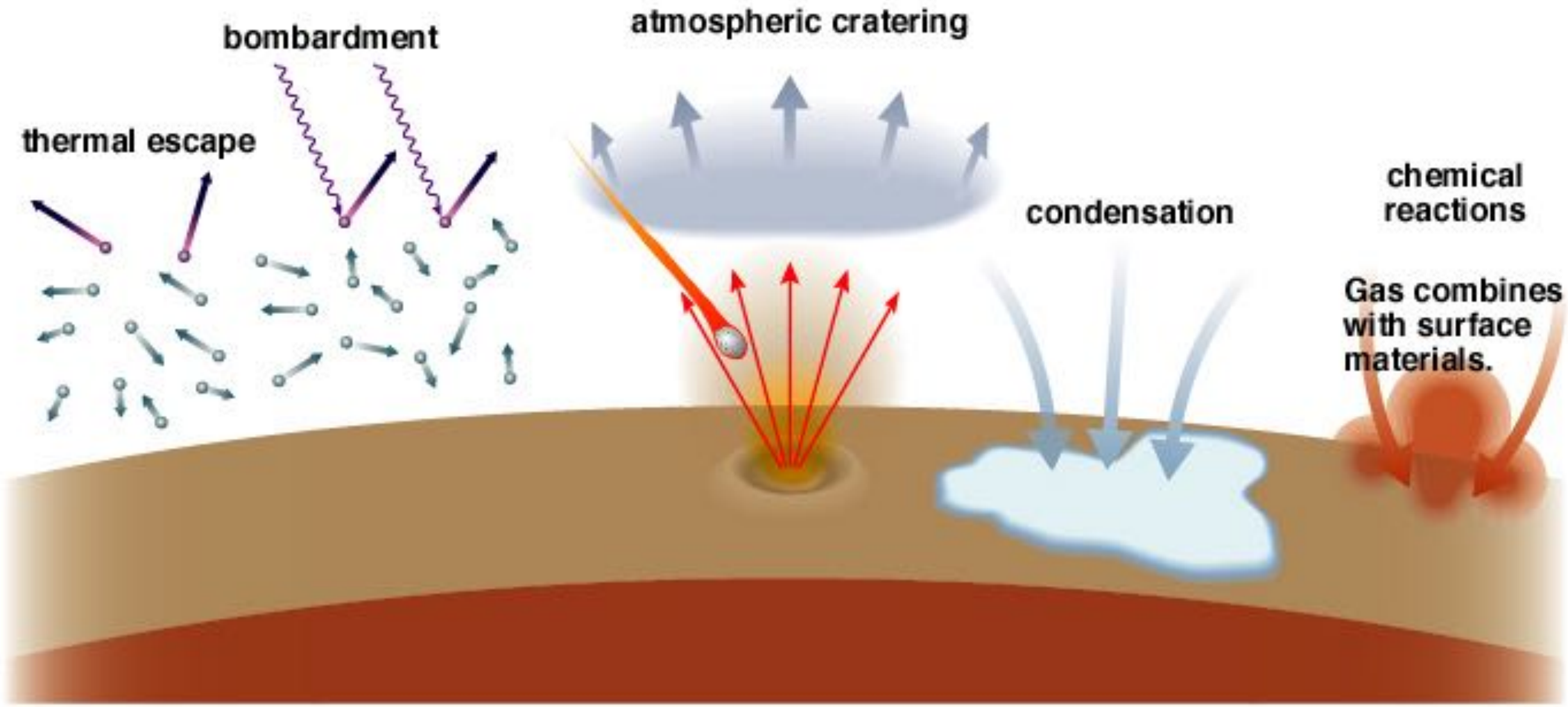
- 2004 *Opportunity* Rover provided strong evidence for abundant liquid water on Mars in the distant past.
- How could Mars have been warmer and wetter in the past?

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.

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



Climate change on Mars

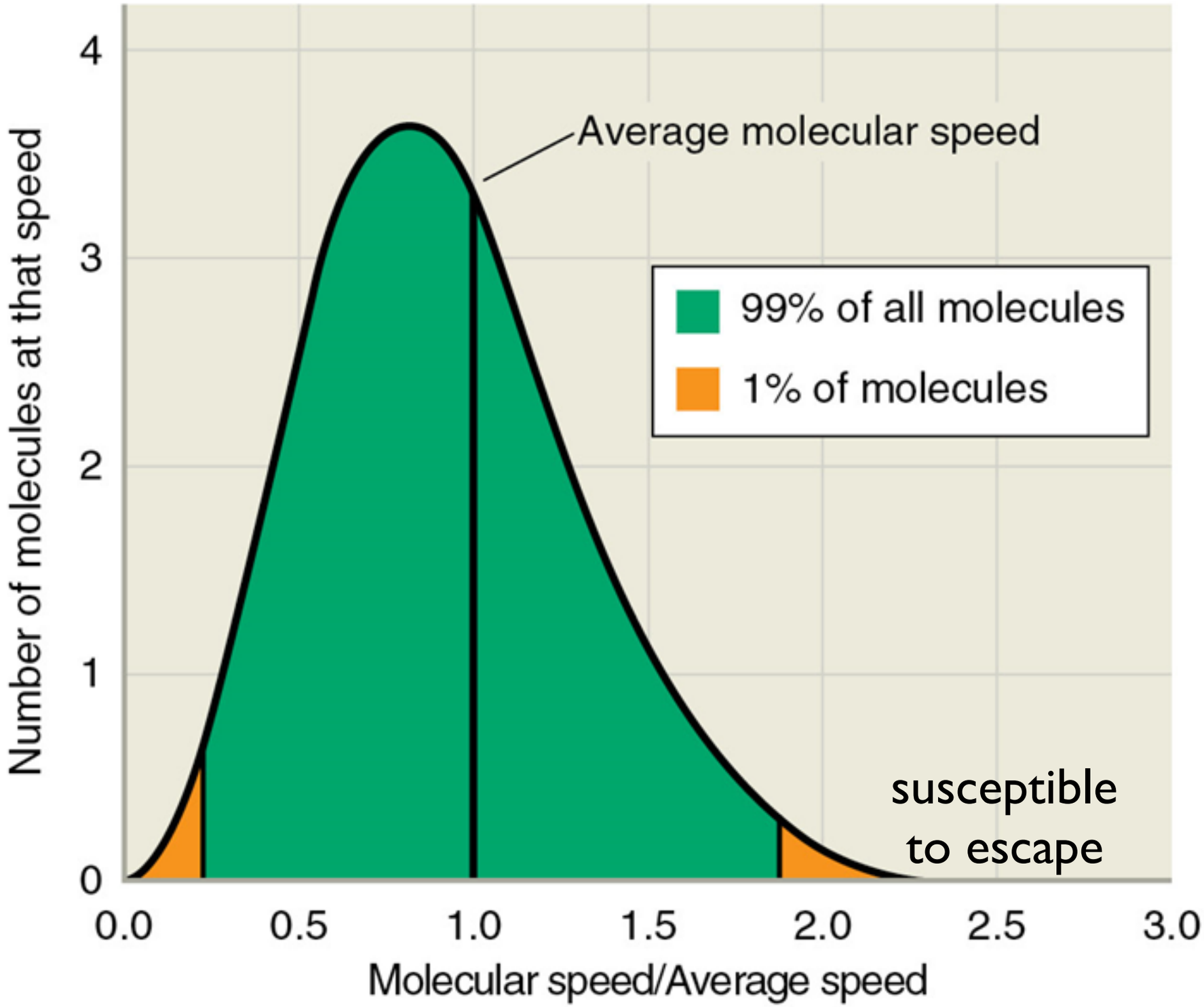
- Early Mars had thicker atmosphere
  - warmer climate
  - liquid water on surface (> 3 billion years ago!)

- 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

Thermal escape

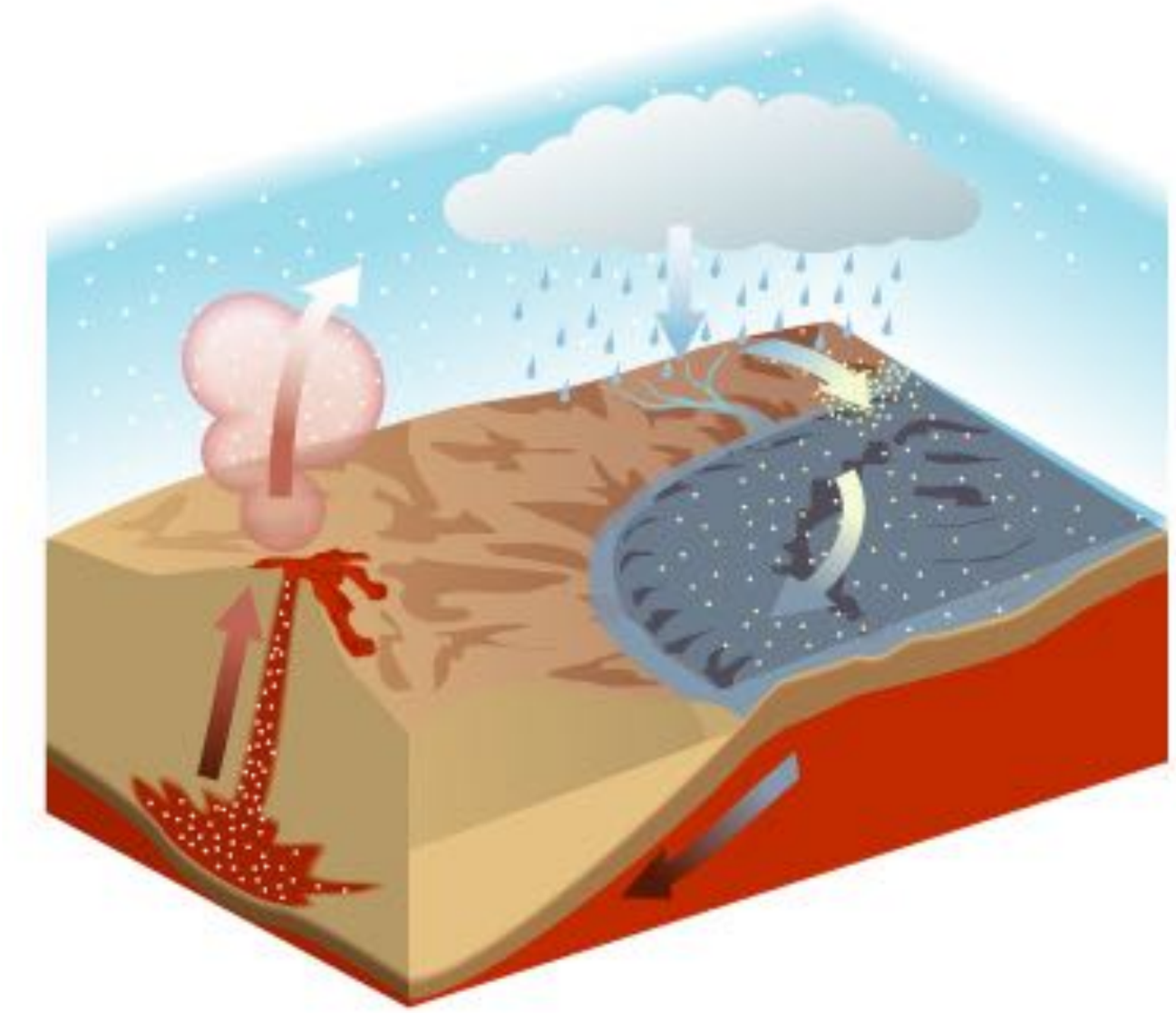
If atmospheric gas is hot enough, some of it exceeds escape velocity and leaks into space.



Factors affecting atmospheres

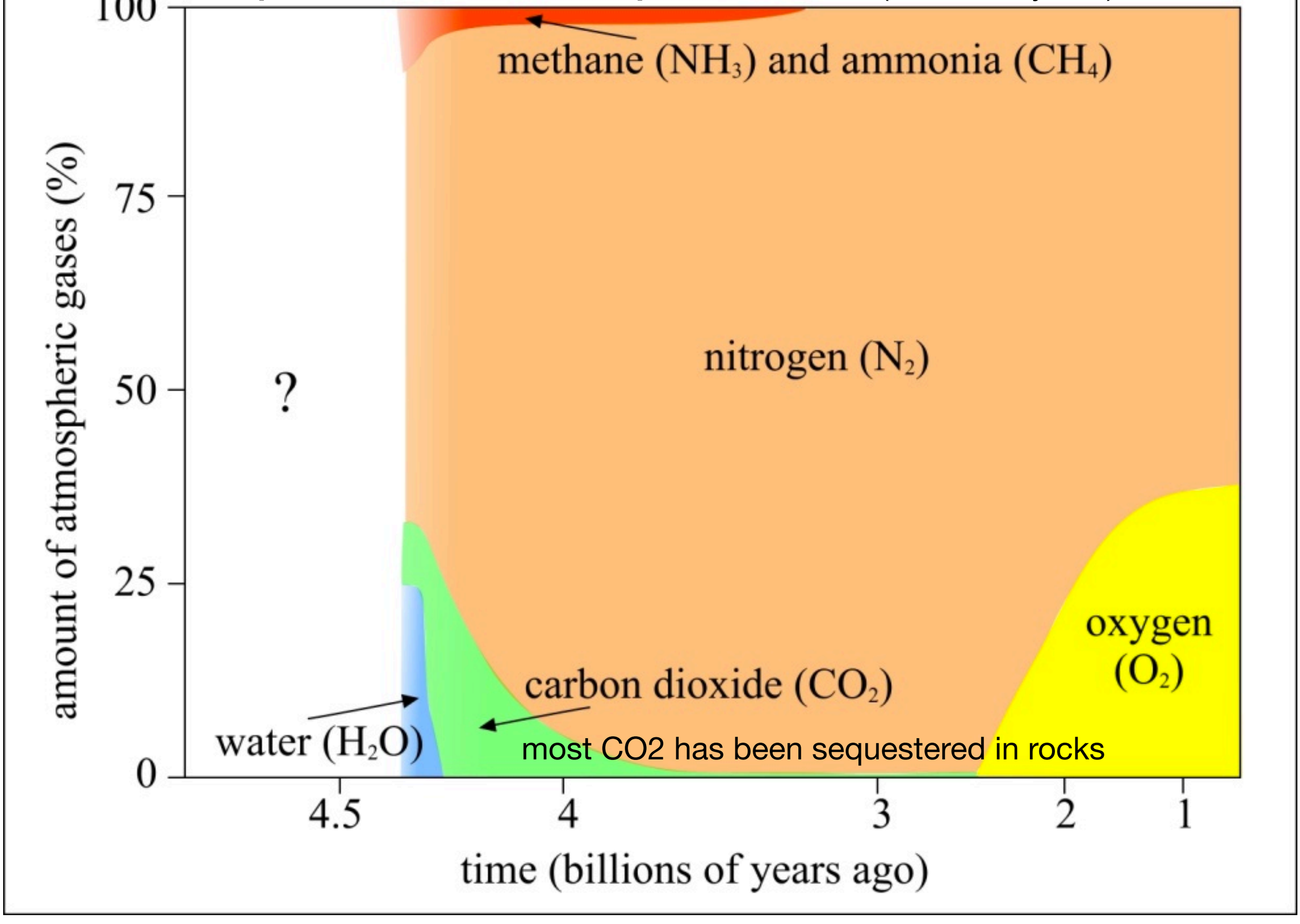
- Thermal Escape
- Bombardment (escape enhanced by molecular disintegration caused by energetic particles)
- Atmospheric cratering (important for thin atmospheres and/or major impact)
- Condensation (e.g., Martian polar caps; permafrost)
- Chemical Reactions (O_2 very reactive - won't last without replenishment. E.g., Permian-Triassic mass extinction)

Back on Earth
Carbon Dioxide Cycle

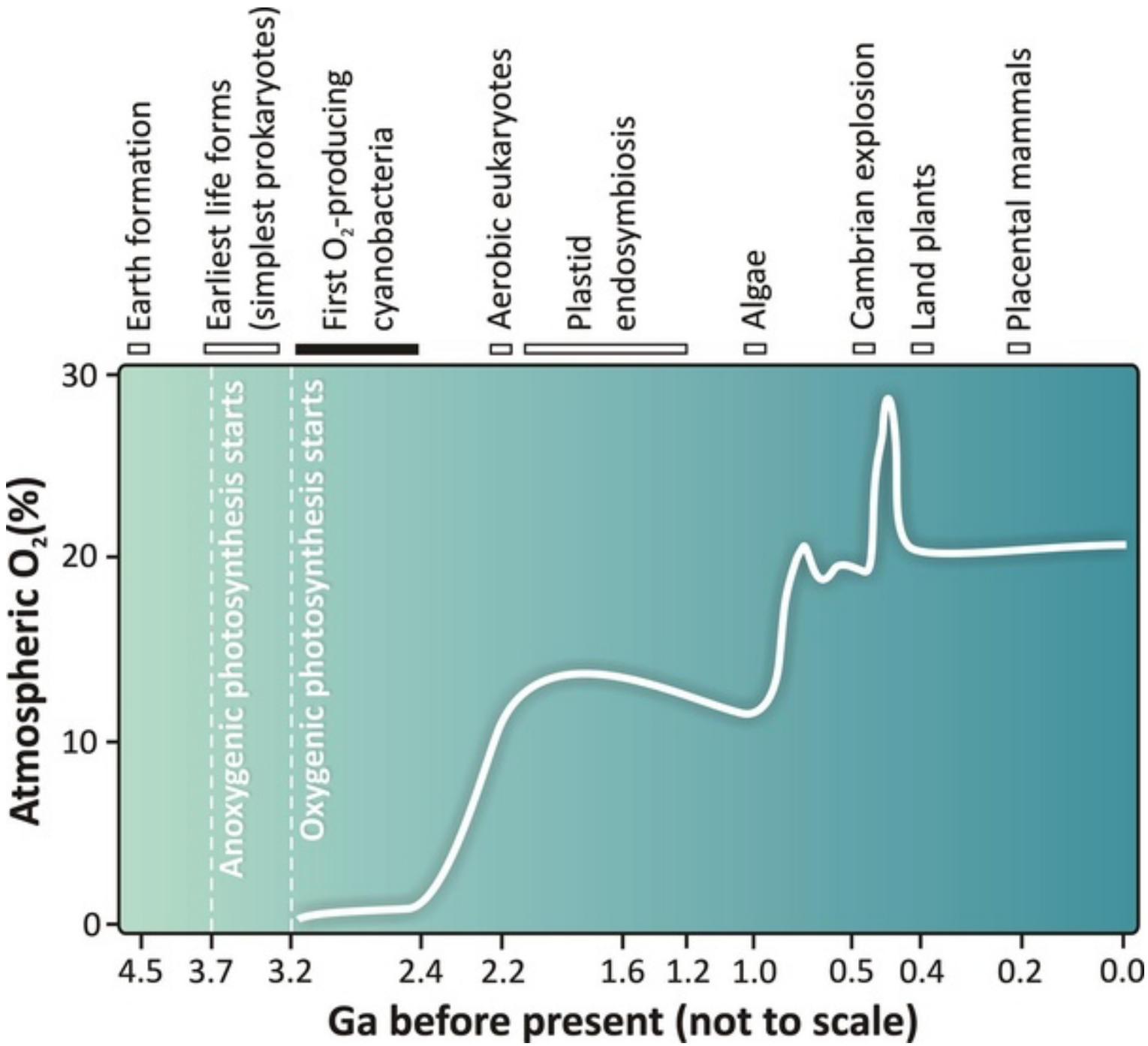


CO2 is washed out of the atmosphere by rain.
Over time, this has depleted most of the CO2

Composition of Earth's Atmosphere over time (billions of years)



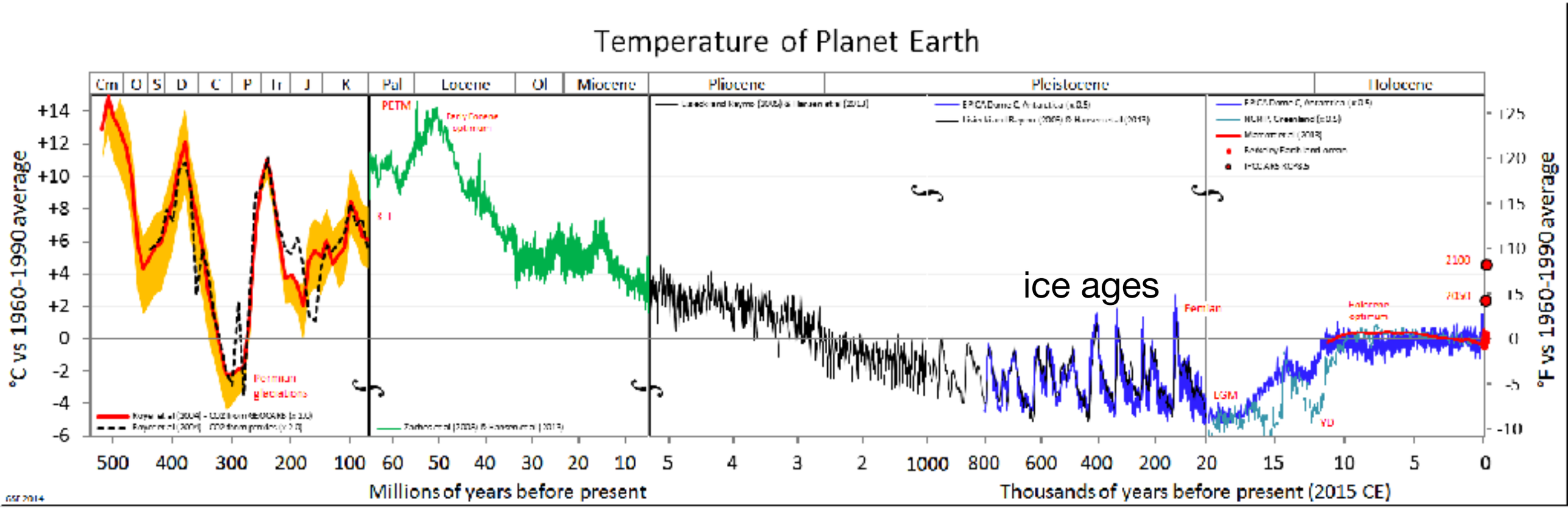
Oxygen in Earth's atmosphere built up over time as a byproduct of photosynthesis



The oxygen content doesn't approach modern levels until the last billion years or so. You would not have been able to breathe at most times in the distant past

Climate change over time

The average temperature has gradually decreased as the CO_2 content of atmosphere declined



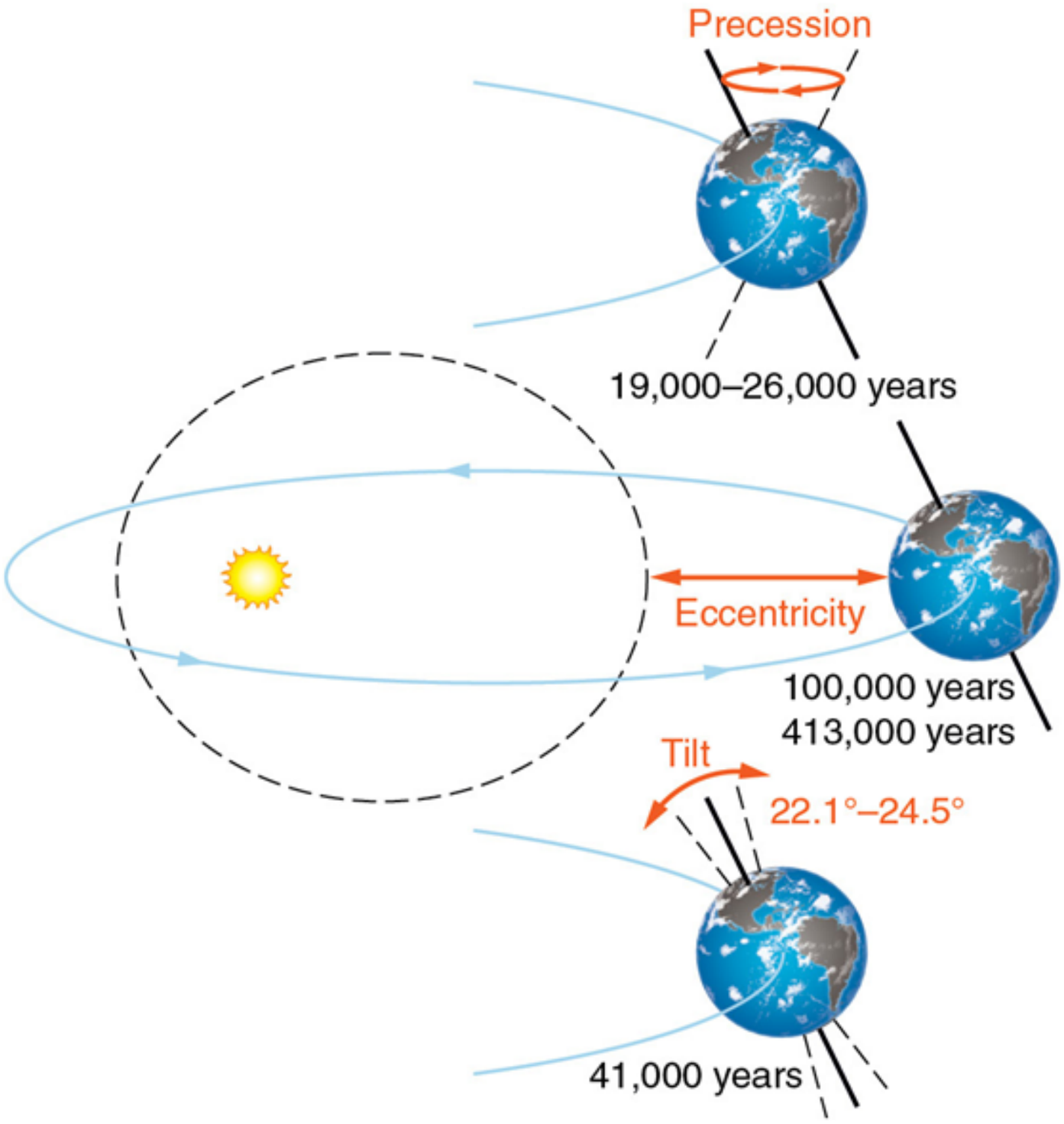
dinosaurs appear

dinosaurs disappear

Note highly variable time axis

humans appear

https://statmodeling.stat.columbia.edu/2014/05/05/can-make-better-graphs-global-temperature-history/



Subtle variations in Earth's orbit can impact long term climate.

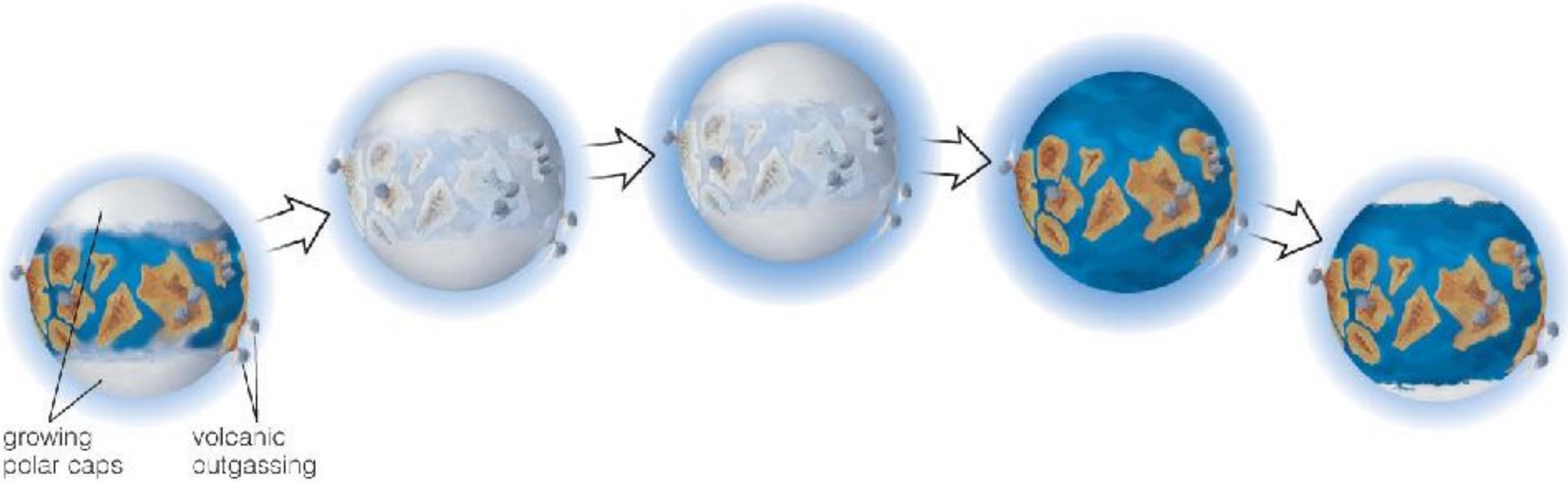
Precession means the north pole isn't always tipped towards the sun when the earth is farthest from it.

The tilt of the Earth's axis oscillates between 22 and 24.5 degrees, slightly varying seasonal extremity.

Though subtle, it is thought that these effects could contribute to the coming and going of the ice ages.

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

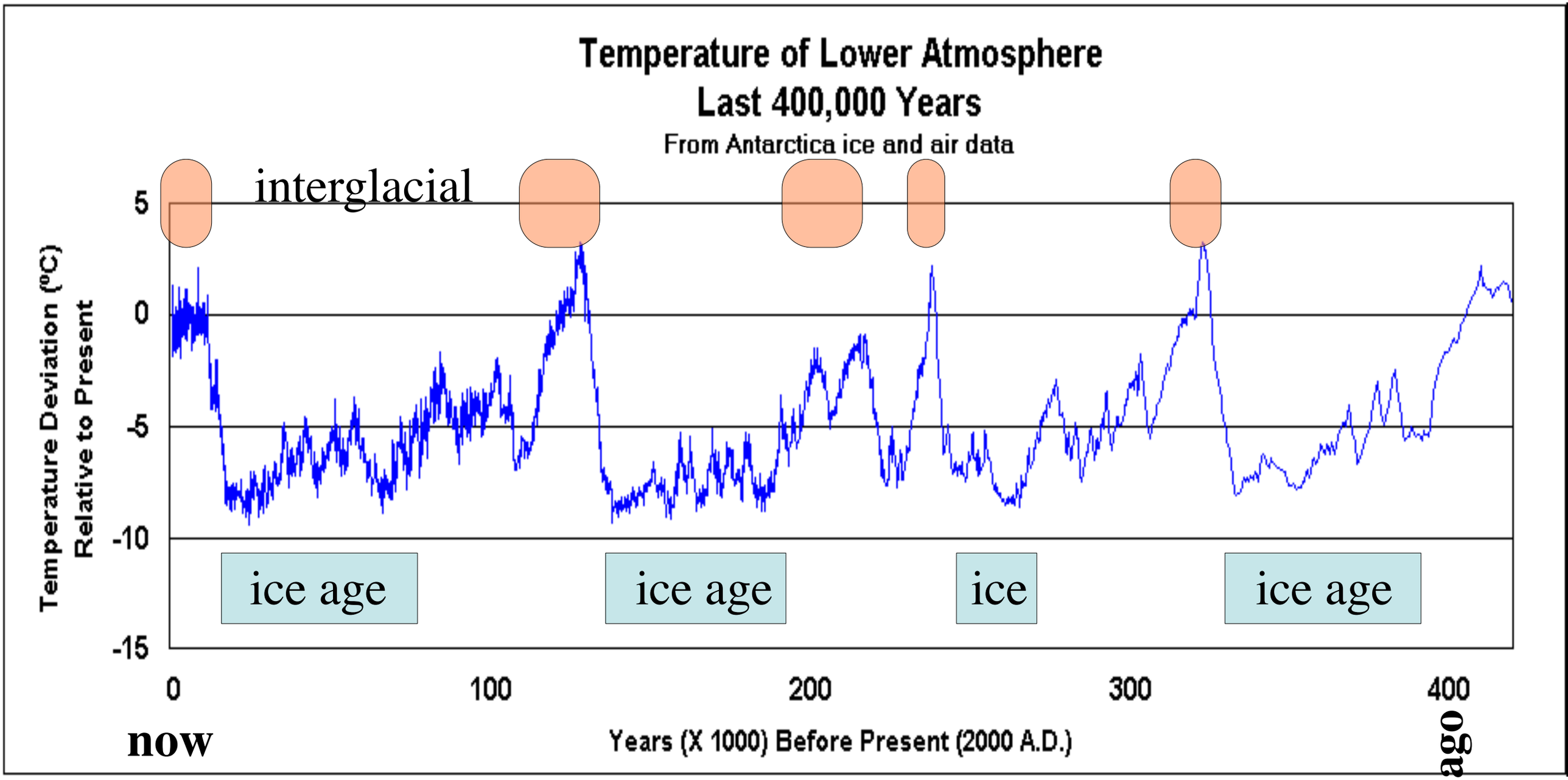
over 10,000s & 100,000s years



- 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.

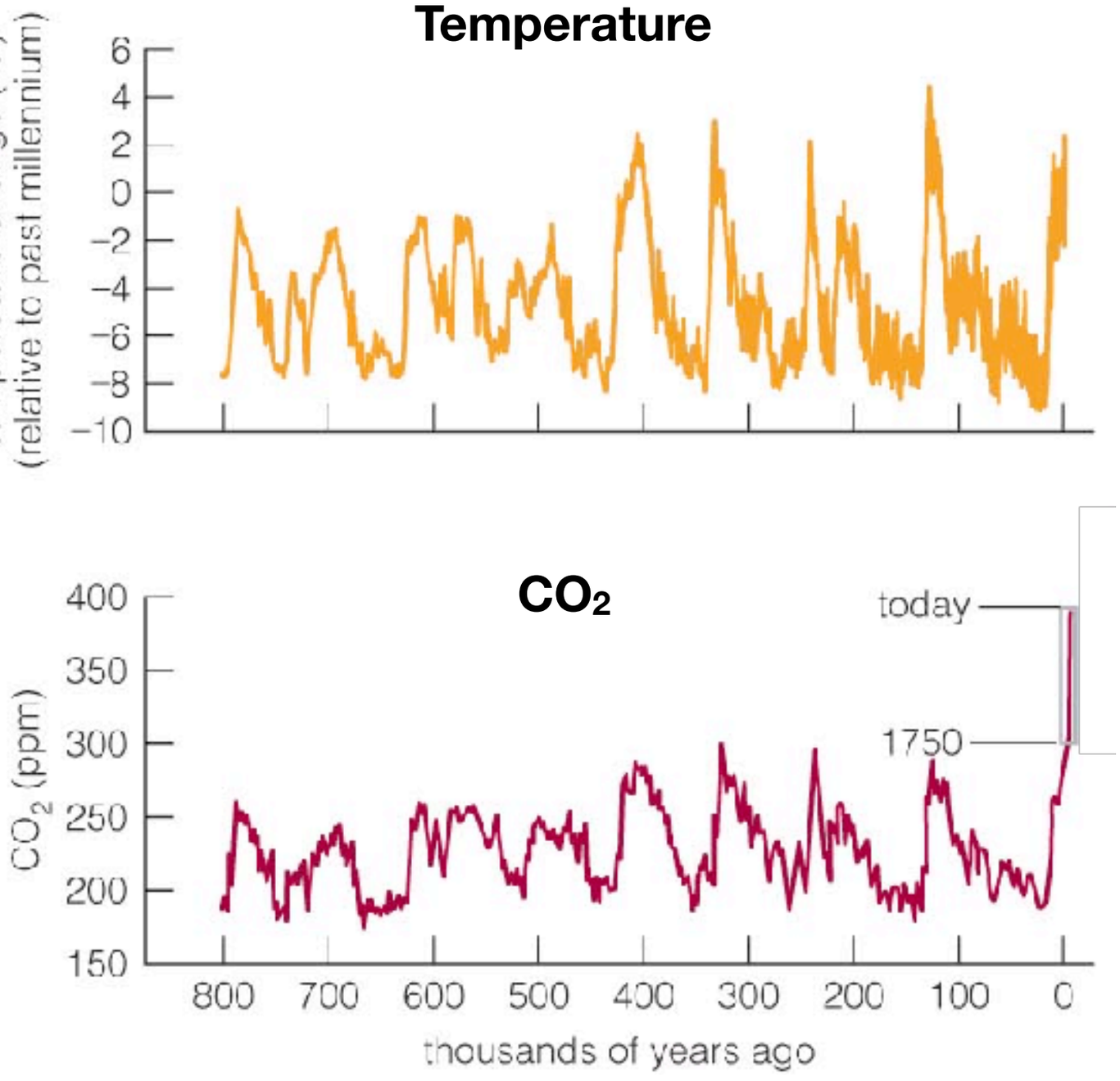
Earth's climate variable on ~10,000 yr timescale: ice ages

Humans have been around > 100,000 years, but civilization only arose at the end of the last ice age



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

CO_2 Concentration



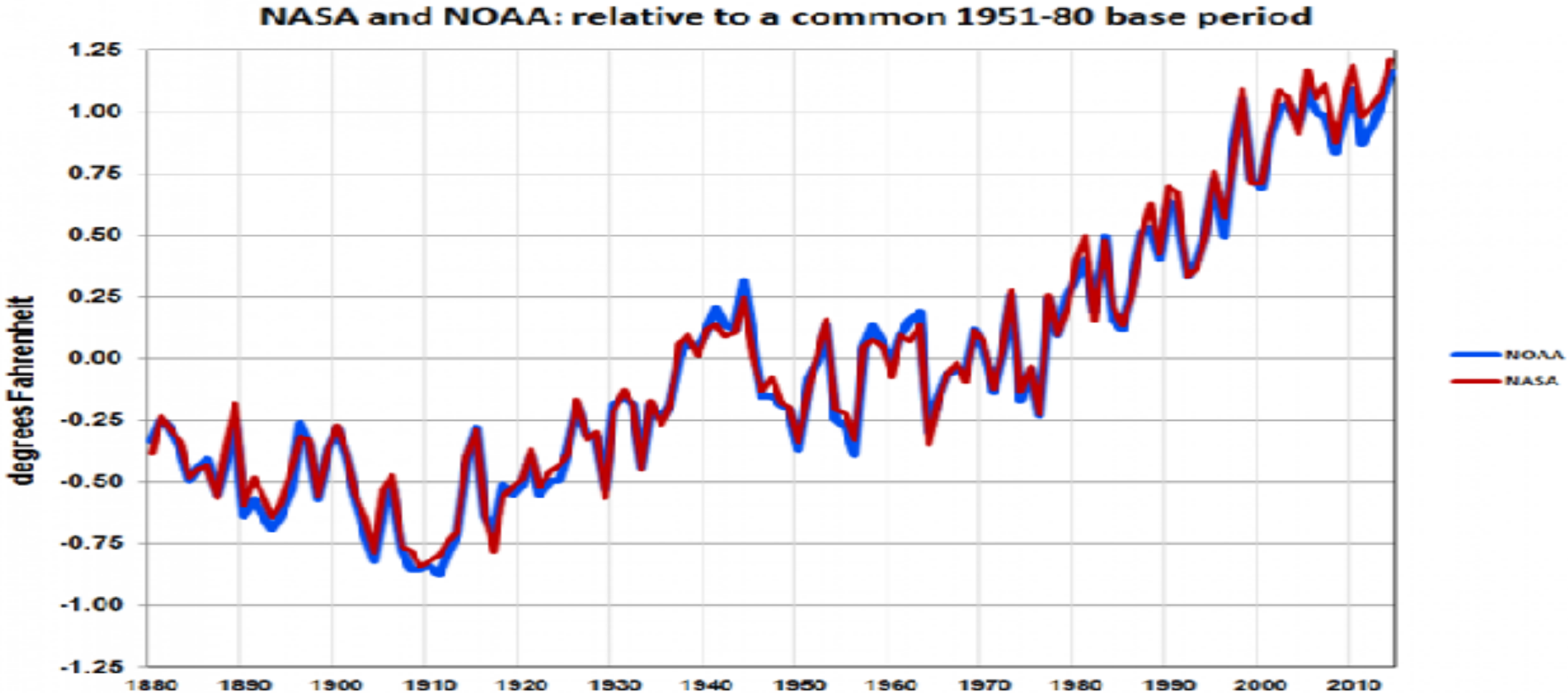
- Temperature and CO_2 concentration vary in lockstep

- This coupling is expected from known physics

- Current CO_2 concentration is the highest it's been in at least 500,000 years.
  - All of human existence

The anthropogenic greenhouse effect (Global Warming and human activity)

What is real information?
What is misleading?
Should we be worried?



News clipping from 1912:

The potential for human-driven climate change has been known for a long time

In an **1827** paper **Fourier** stated, *"The establishment and progress of human societies, the action of natural forces, can notably change, and in vast regions, the state of the surface, the distribution of water and the great movements of the air.* ***Such effects are able to make to vary, in the course of many centuries, the average degree of heat****; because the analytic expressions contain coefficients relating to the state of the surface and which greatly influence the temperature.*

The Rodney & Otamatea Times
WAITEMATA & KAIPARA GAZETTE.
PRICE—10s per annum in advance
WARKWORTH, WEDNESDAY, AUGUST 14, 1912.
3d per Copy.

Science Notes and News.

COAL CONSUMPTION AFFECTING CLIMATE.

The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

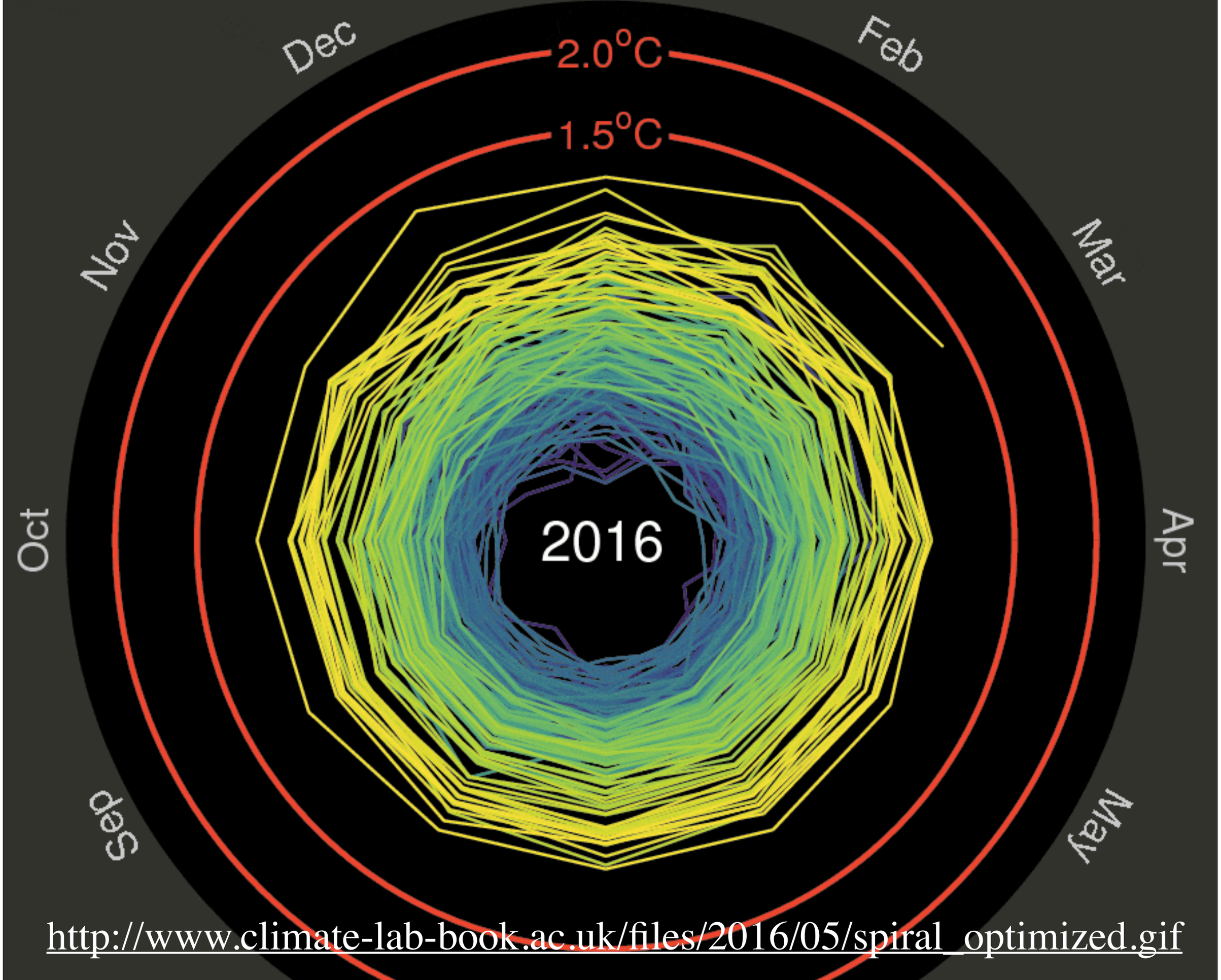
Basic facts

(non-partisan)

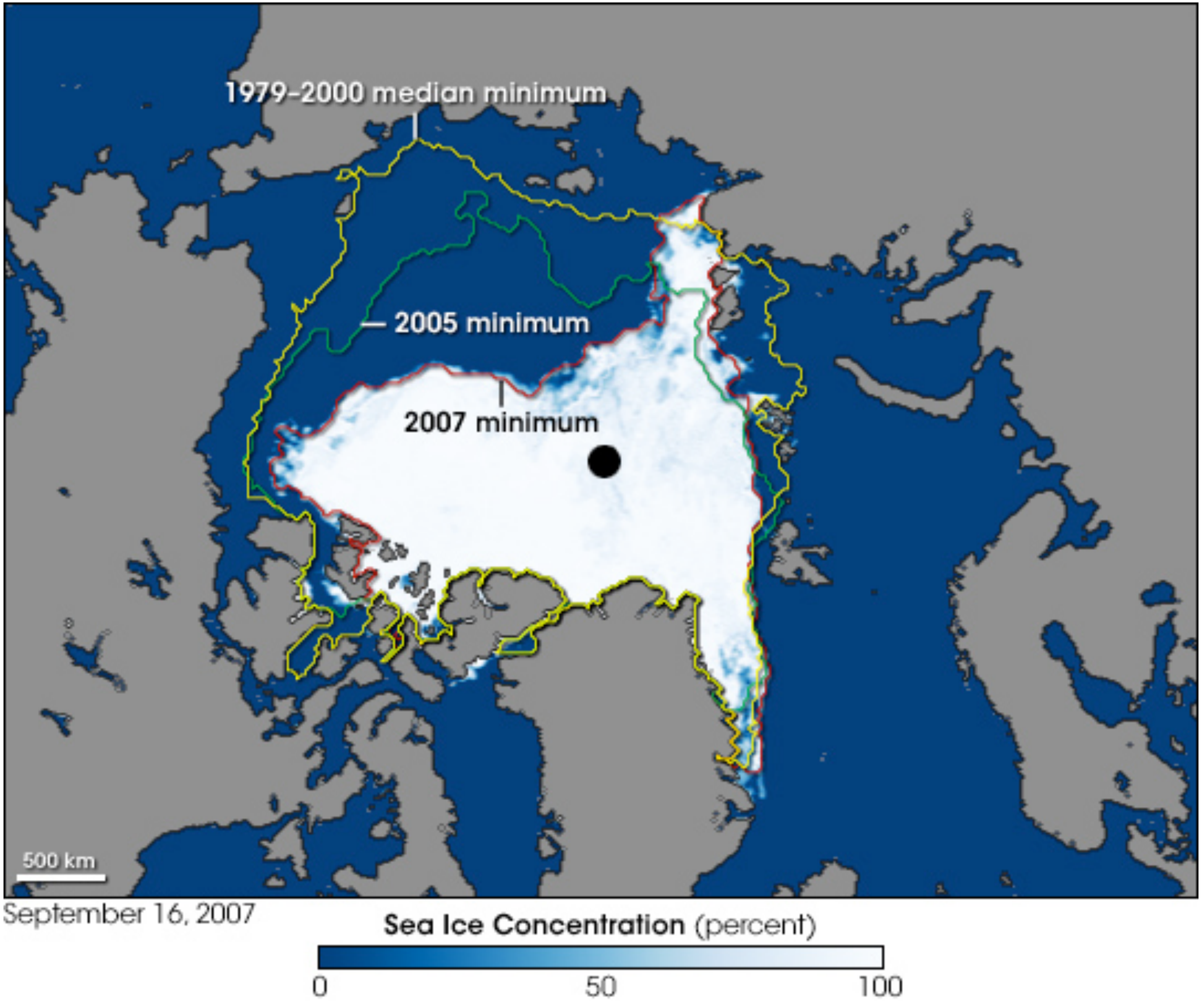
- The globe is warming (*measured*)
- The concentration of CO_2 in the atmosphere is increasing (*measured*)
- The CO_2 increase is roughly equal to the amount of fossil fuel we've burned (*measured*)
- Climate change is the expected result of changing greenhouse gases in the atmosphere
  – (e.g., Venus, Mars)

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; floods & draughts; extreme storms, hurricanes, etc
- Melting permafrost

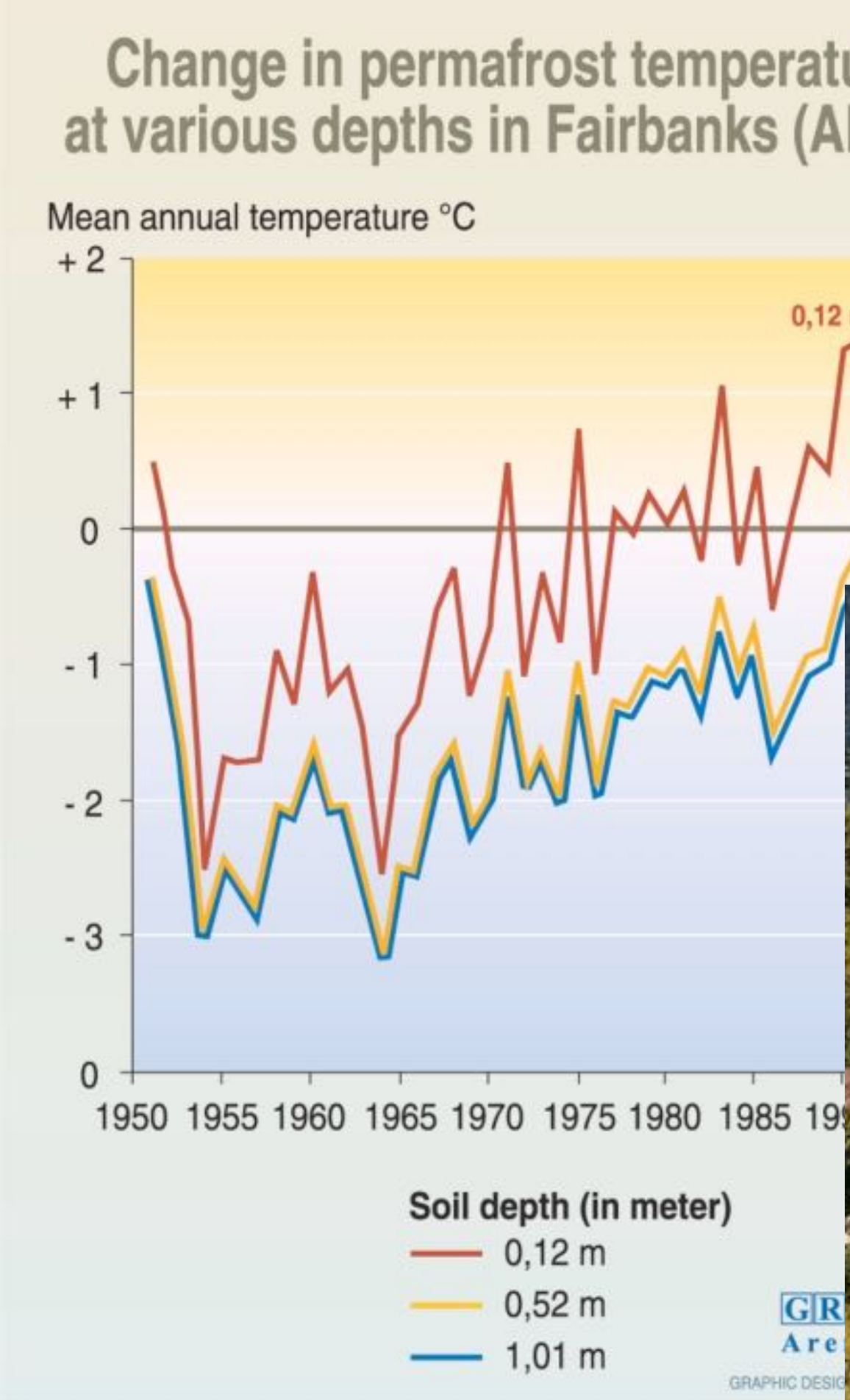


http://www.climate-lab-book.ac.uk/files/2016/05/spiral_optimized.gif



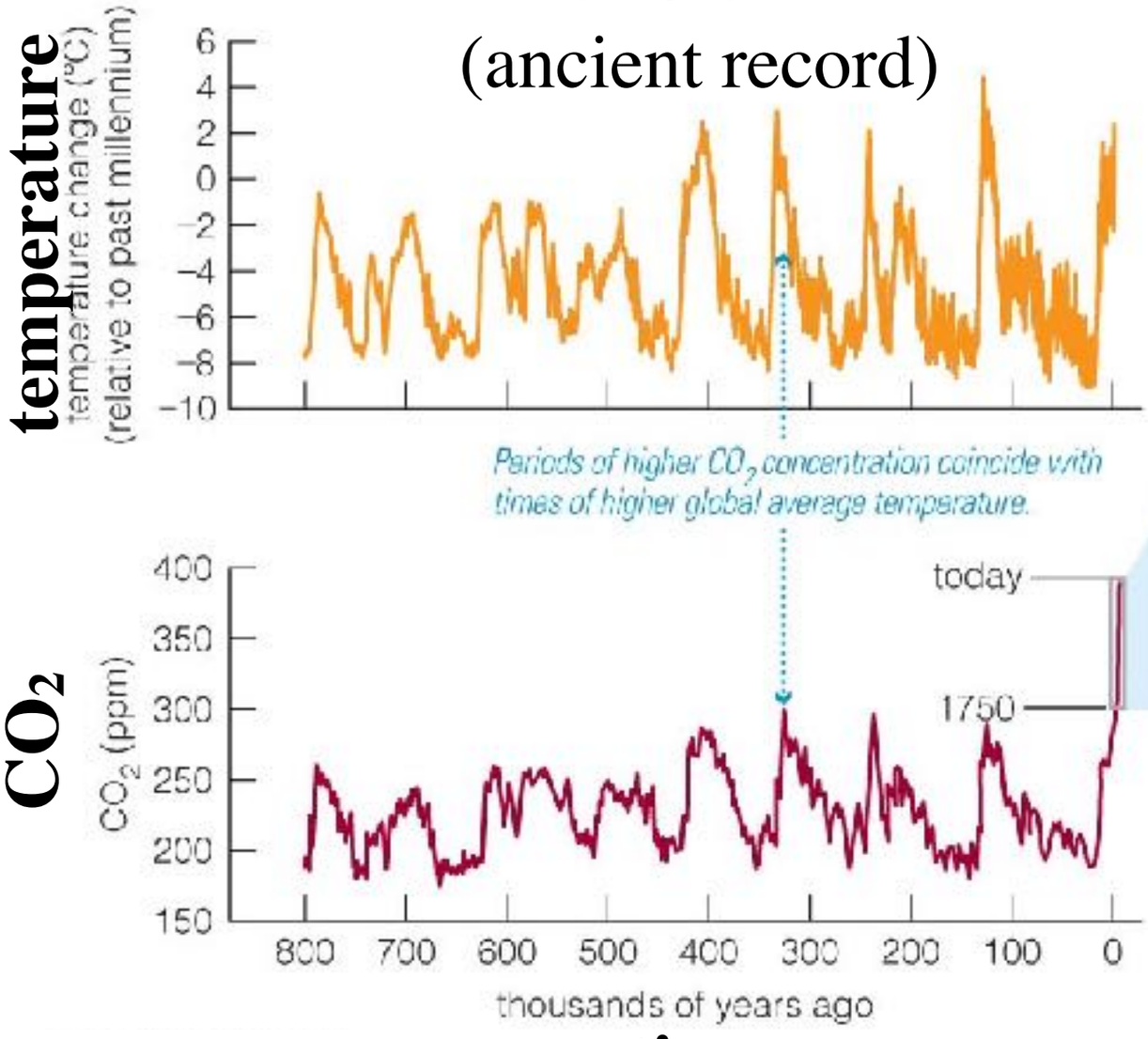
Fabled Northwest passage opened for first time in history in 2007

Arctic
permafrost
is melting



CO_2 Concentration

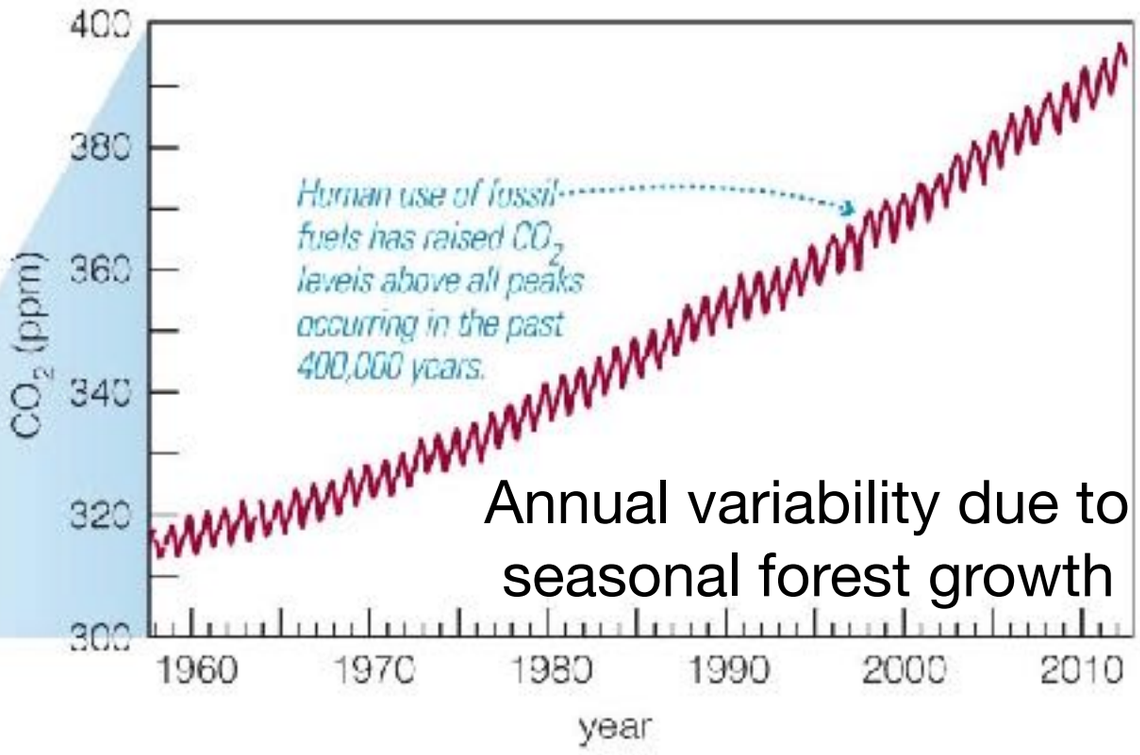
Ice core data
(ancient record)



time

(thousands of years)

Mauna Loa Observatory
(modern record)

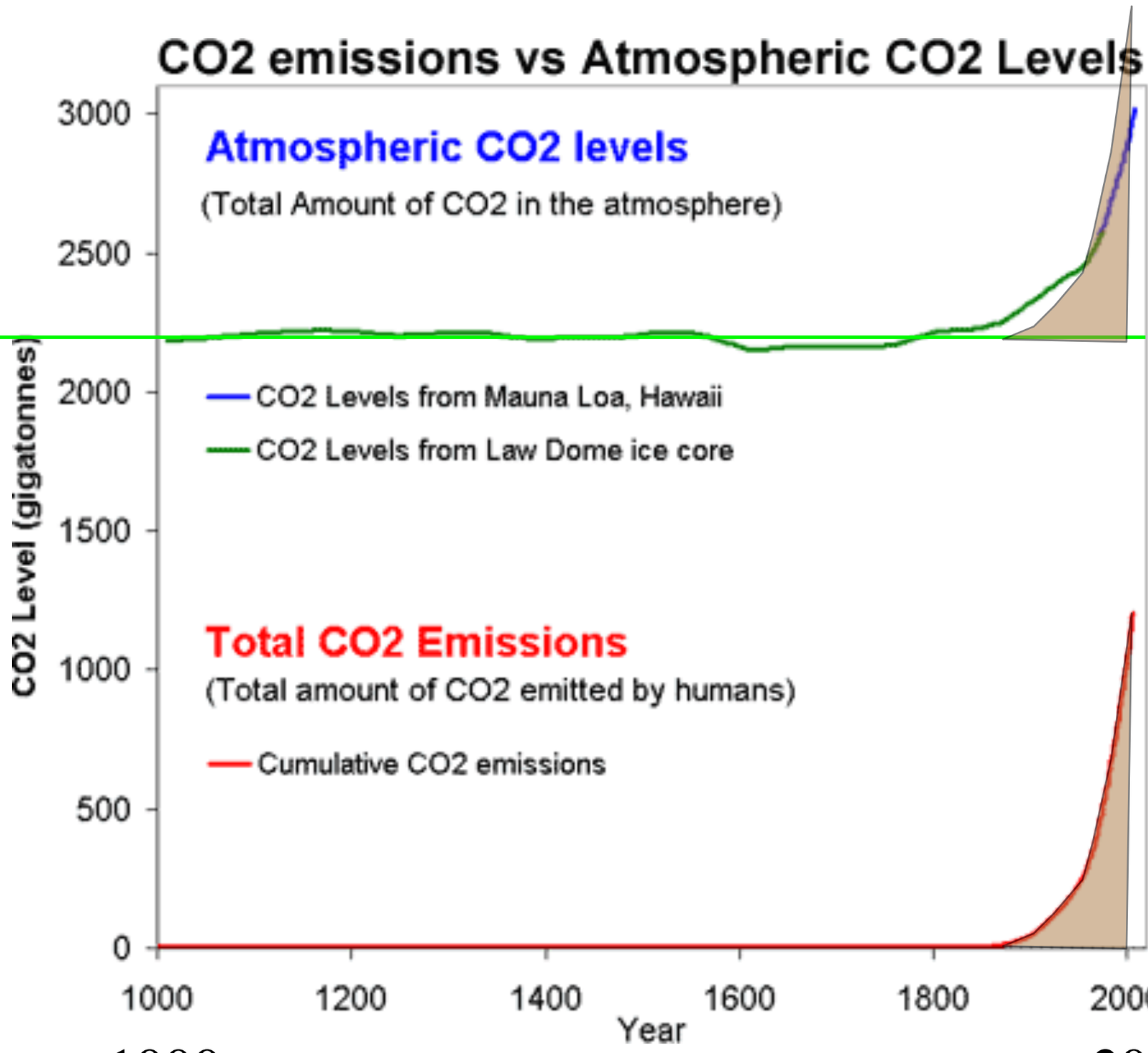


time

(years)

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

Pre-industrial CO_2 concentration: 280 ppm. Current level: 410 ppm



Pre-industrial CO_2 level

CO2 added to atmosphere

Human activity

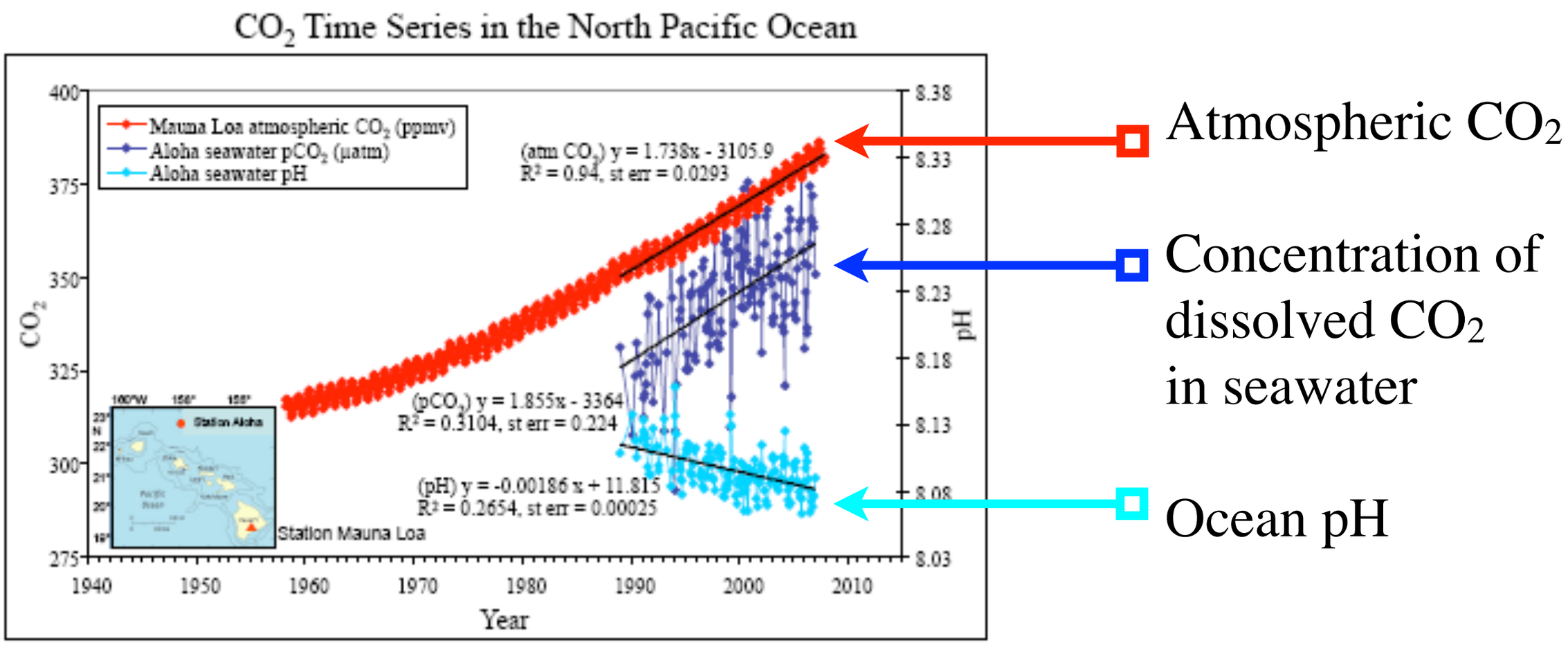
Carbon burned

1000

Year (A.D.)

2000

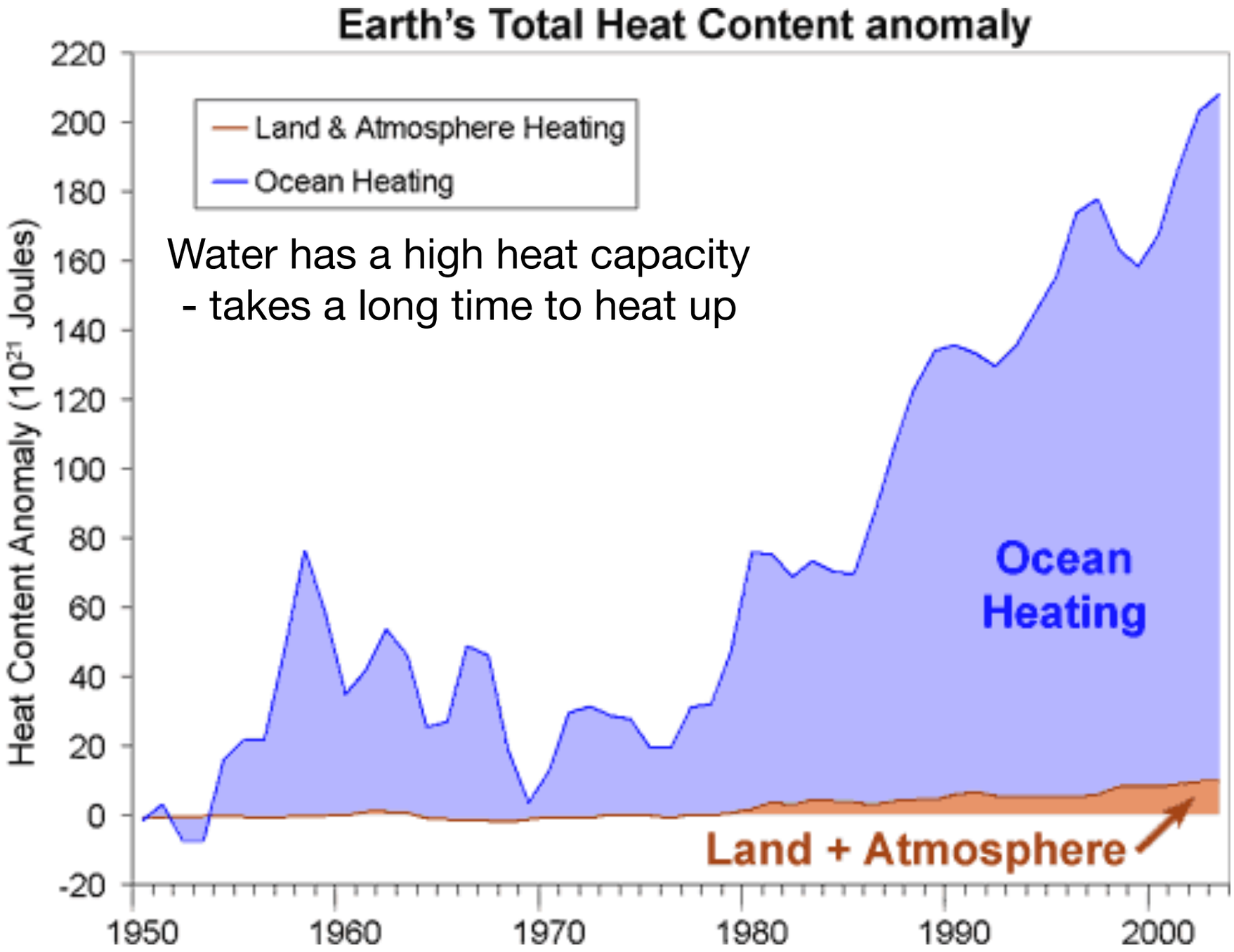
- Should be more CO_2 in atmosphere than there is
  - Some of what we've burned is missing
- Some CO_2 being sequestered in the ocean
  - Ocean acidity up due to increased amounts of CO_2 dissolved in seawater
  - pH = 8.25 to 8.14 over last two centuries



Atmospheric CO_2

Concentration of dissolved CO_2 in seawater

Ocean pH



The Earth's climate is out of equilibrium - heat is accumulating in the ocean faster than it is being radiated into space.

This disequilibrium is expected to drive extreme weather events

Climate Change Forecasts

- Gradual increase of average temperature
  - – average increase modest but noticeable
  - – winter not cancelled by 2^{o} 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

Could be more, especially with ice melt

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