Definitions

Climate: the composite or generally prevailing weather conditions of a region, throughout the year, averaged over a series of years.

Weather: the state of the atmosphere at a place and time with respect to wind, temperature, cloudiness, moisture, pressure, etc.

Definitions

Climate: your personality

Weather: your mood today

(Dr. Marshall Shepherd, former President AMS)

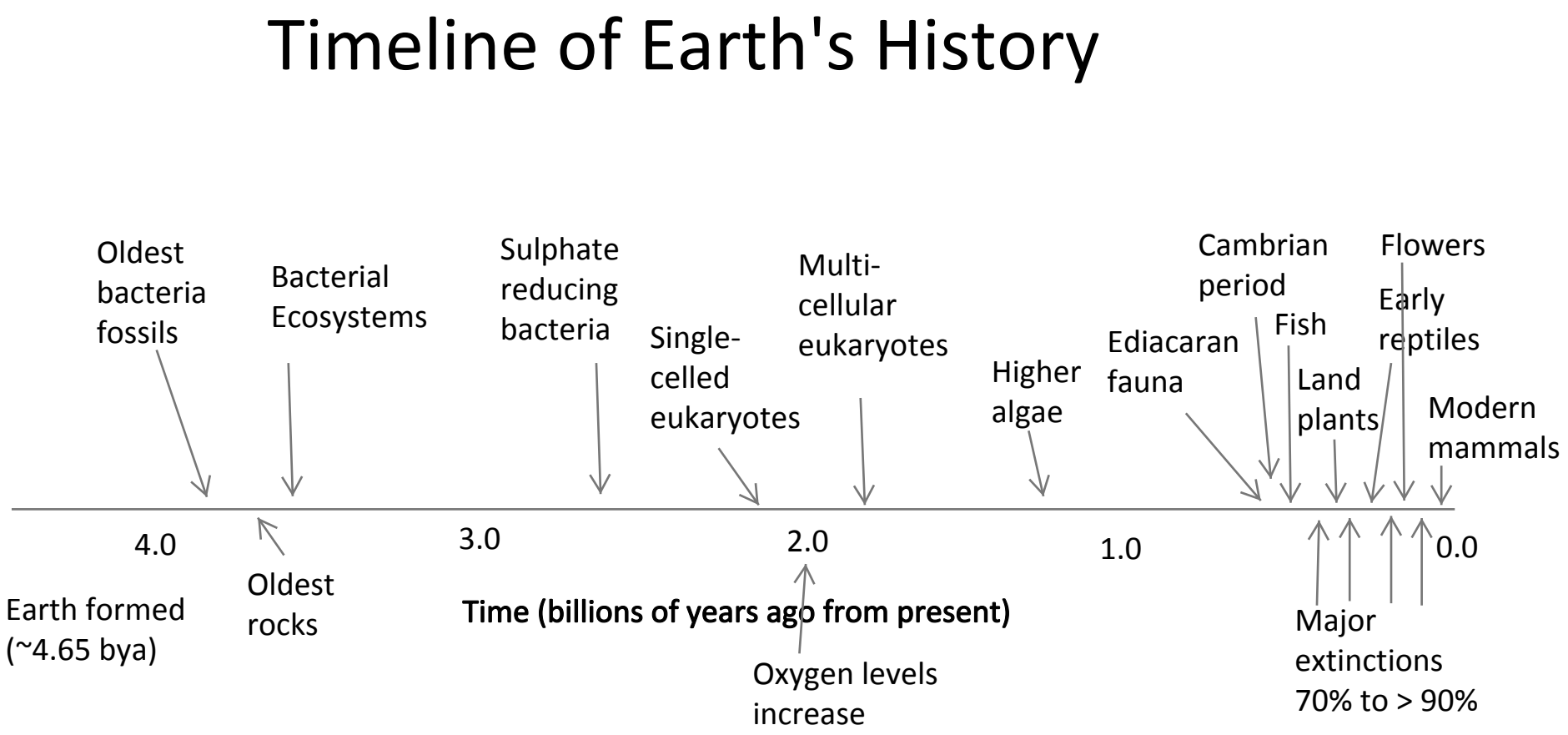
Earth is 4.5 billion years old (ish)

A timeline, in billions of years ago:

- 3.8: solid rocks and archaea
- 3.5: cyanobacteria and photosynthesis (anoxygenic)
- by 2.3: first eukaryotes appear and oxygen begins to accumulate ("Great Oxidation Event“ – rust layers in sea floor)
- 1.0: first multicellular life (oxygen dependent)
- by 0.5: first vertebrates, trilobites, vascular plants

Living stromatolites in Shark Bay, Western Australia

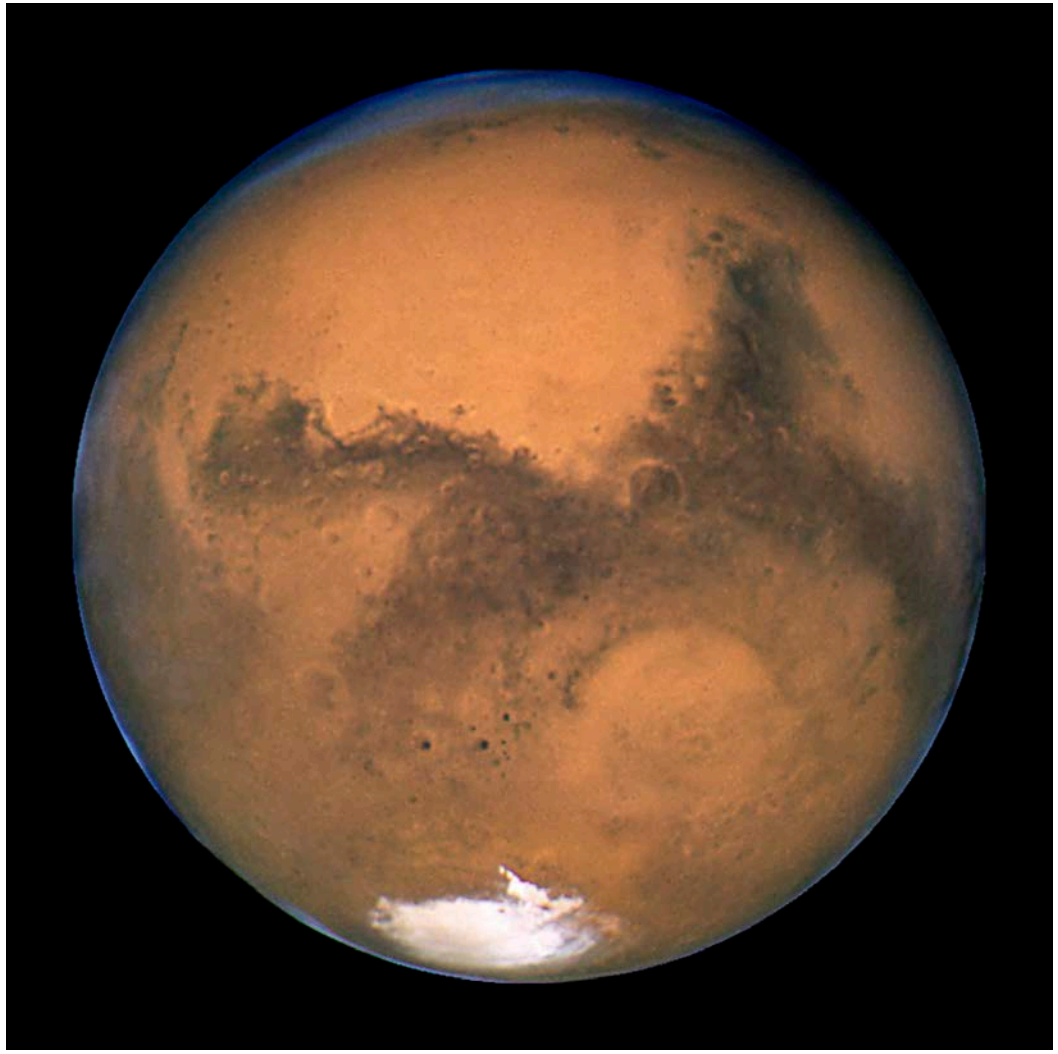
Earth is 4.5 billion years old (ish)



Apollo 8 image of Earth by William Anders, AS8-14-2383

We are on a rock hurtling through space.

What makes life possible?



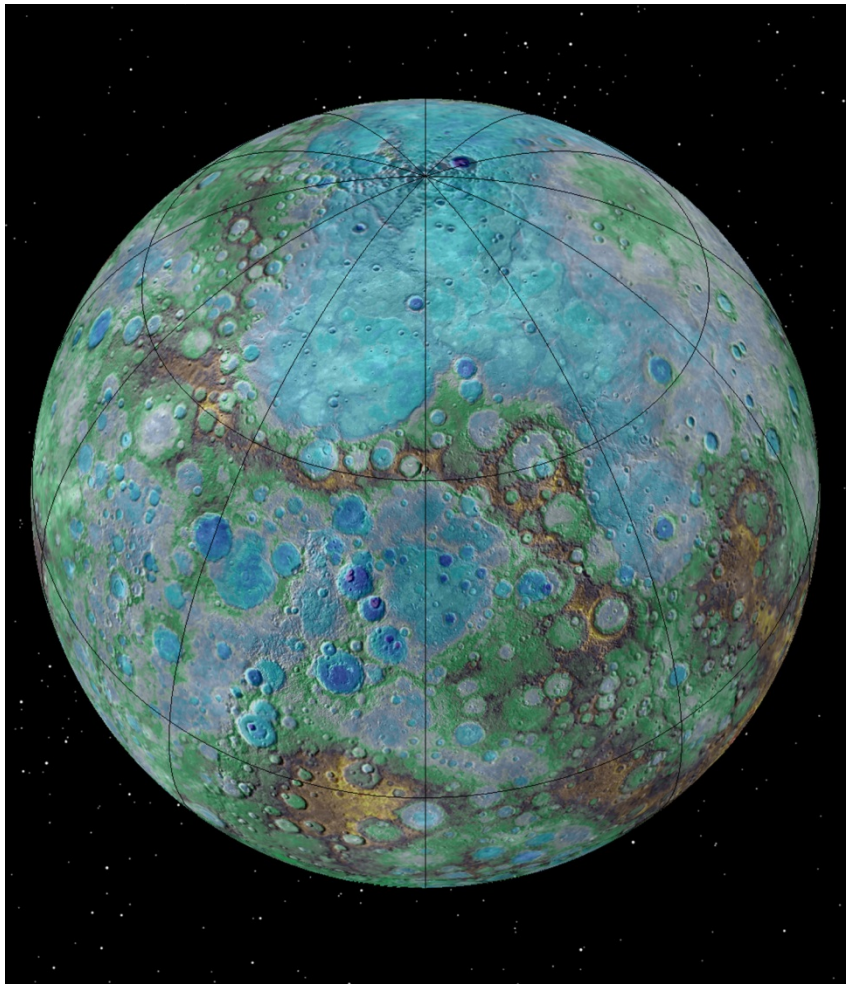
We are on a rock hurtling through space.

What makes life possible?

Compare Mars: diurnal temperature varies from 0 to -80°C (32 to -112°F).

Courtesy of NASA, J. Bell (Cornell U.) and M. Wolff (SSI). Images are in the public domain.

NASA



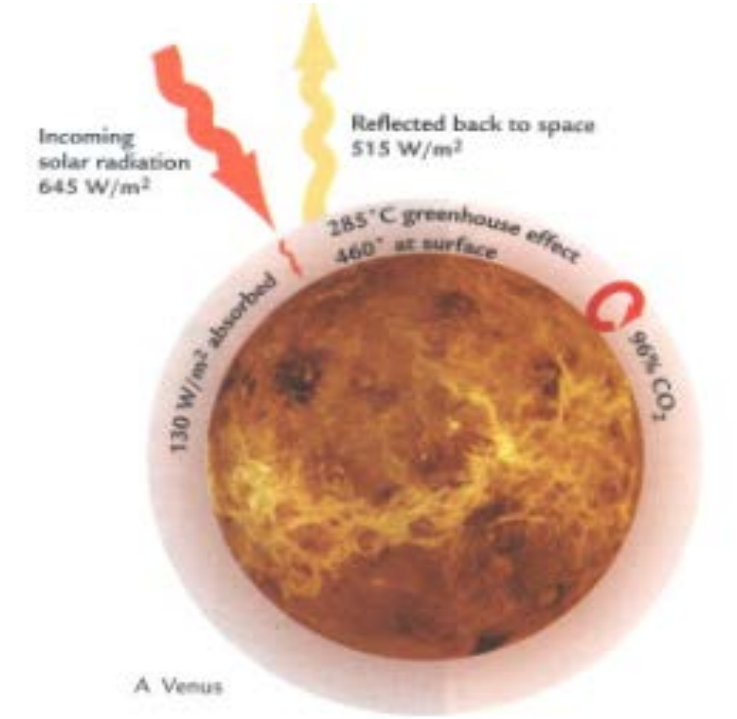
NASA

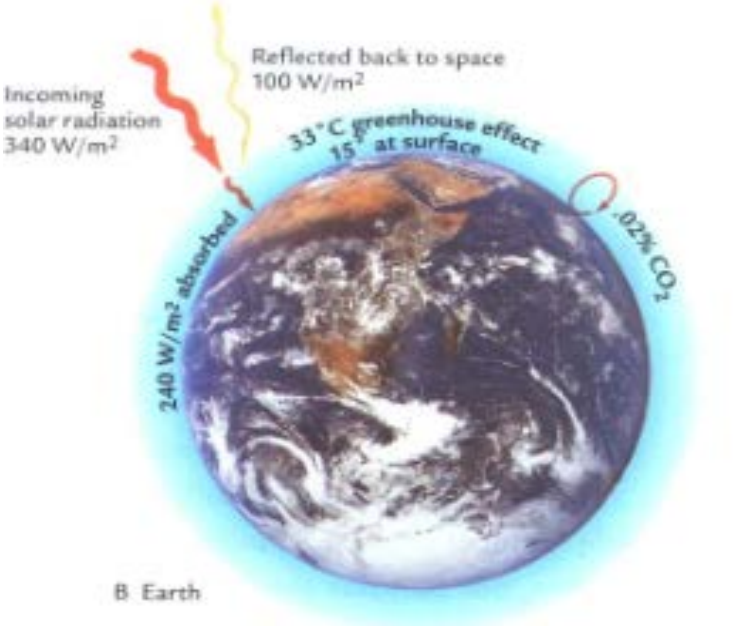
We are on a rock hurtling through space.

What makes life possible?

Compare Mars: diurnal temperature varies from 0 to -80°C (32 to -112°F).

Or Mercury: 430°C during day, -170°C at night



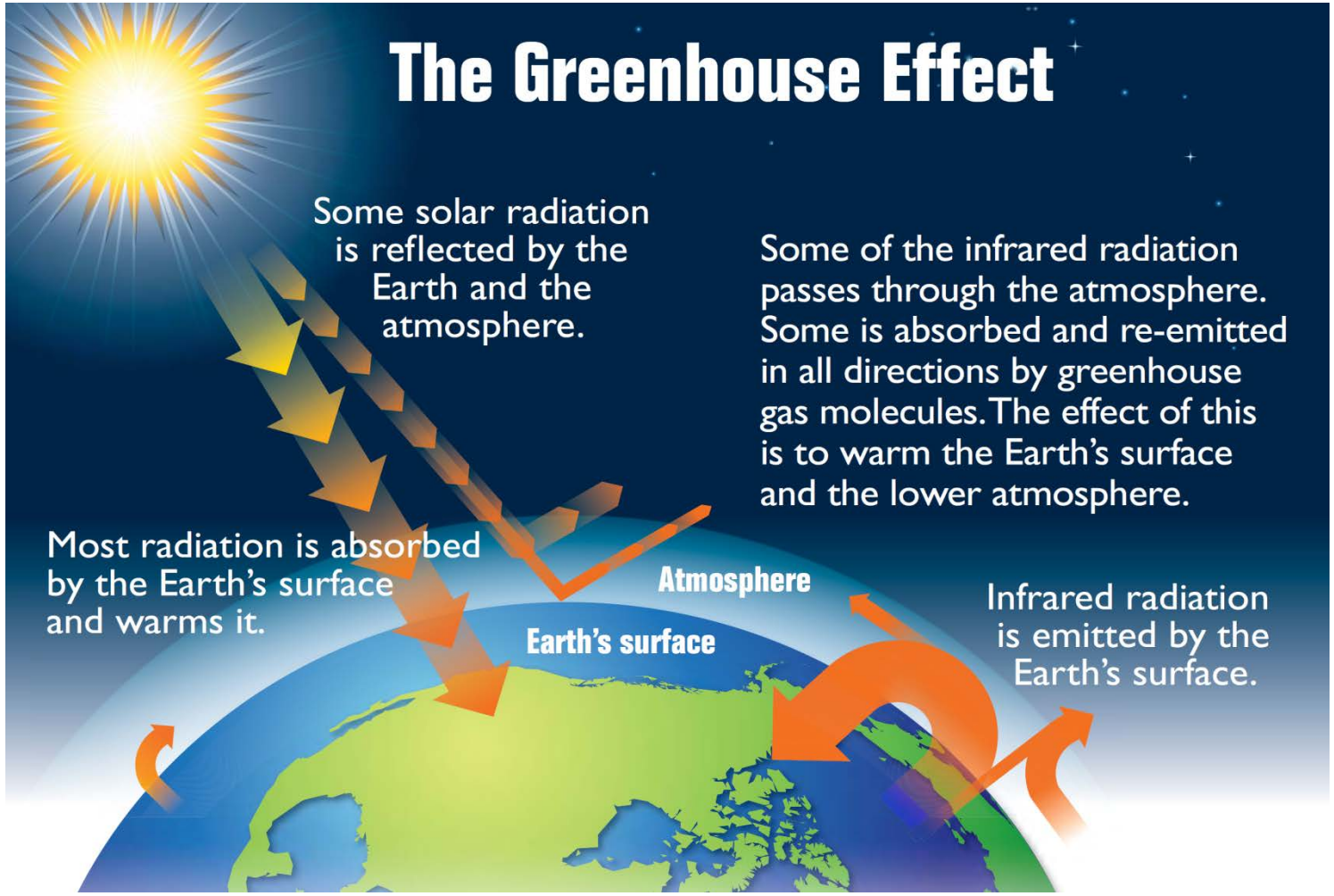


Venus vs. Earth: the greenhouse effect

- Venus' surface temperature is 460° C (860° F)
- Earth's surface temperature is 14°C (57° F).
- Venus receives almost twice as much solar radiation from the Sun as Earth; 80% is reflected by dense clouds, vs. 26% from Earth.

- CO_2 on Venus: 96.5%; CO_2 on Earth = 0.04%.

Greenhouse gases act as a blanket, trapping the sun's energy.



US EPA, 2014

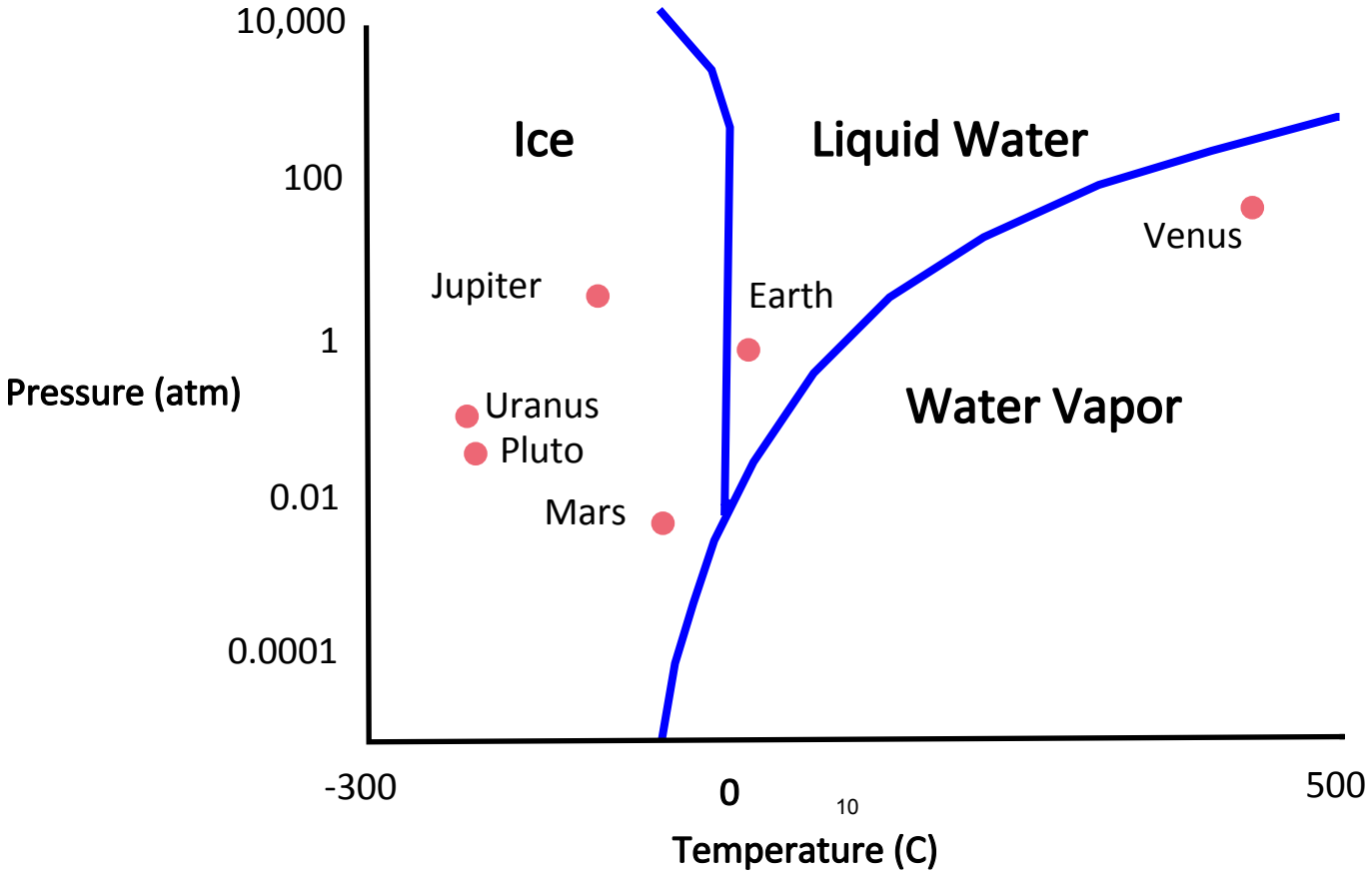
Major greenhouse gases:

Carbon dioxide
Methane
Nitrous oxides
CFCs

water vapor

Because Earth is warm and temperate, we have liquid water.

Because we have liquid water, we have life (as we know it).



A quick introduction to global carbon cycling

- most carbon in sediments and rocks
- “fast” cycling through surface pools, atmosphere, biosphere (months to centuries)
- slow cycling between rocks and surface (millions to billions of years)

[Figure removed due to copyright restrictions. Ruddiman, William F. Earth’s Climate: Past and Future. 3rd Edition. W.F. Freeman and Co., New York. 2014.]

A quick introduction to global carbon cycling

Slow cycling between rocks and surface pools:

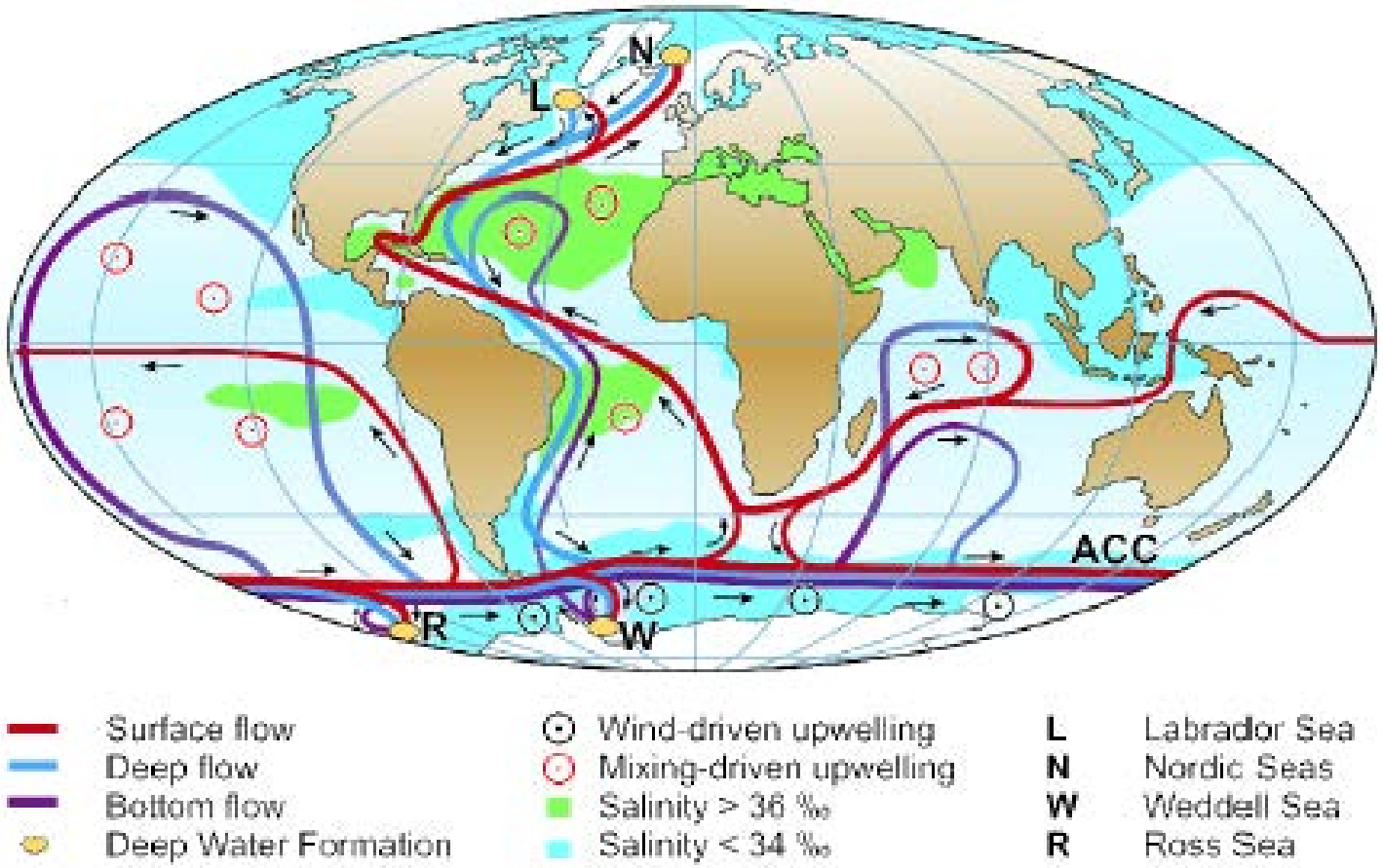
[Figure removed due to copyright restrictions. Ruddiman, William F. Earth's Climate: Past and Future. 3rd Edition. W.F. Freeman and Co., New York. 2014.]

Carbon enters atmosphere through volcanoes, hot springs

Carbon leaves surface pools via rock weathering, transport, deposition

This process is climate-dependent

Oceans are major heat transport systems

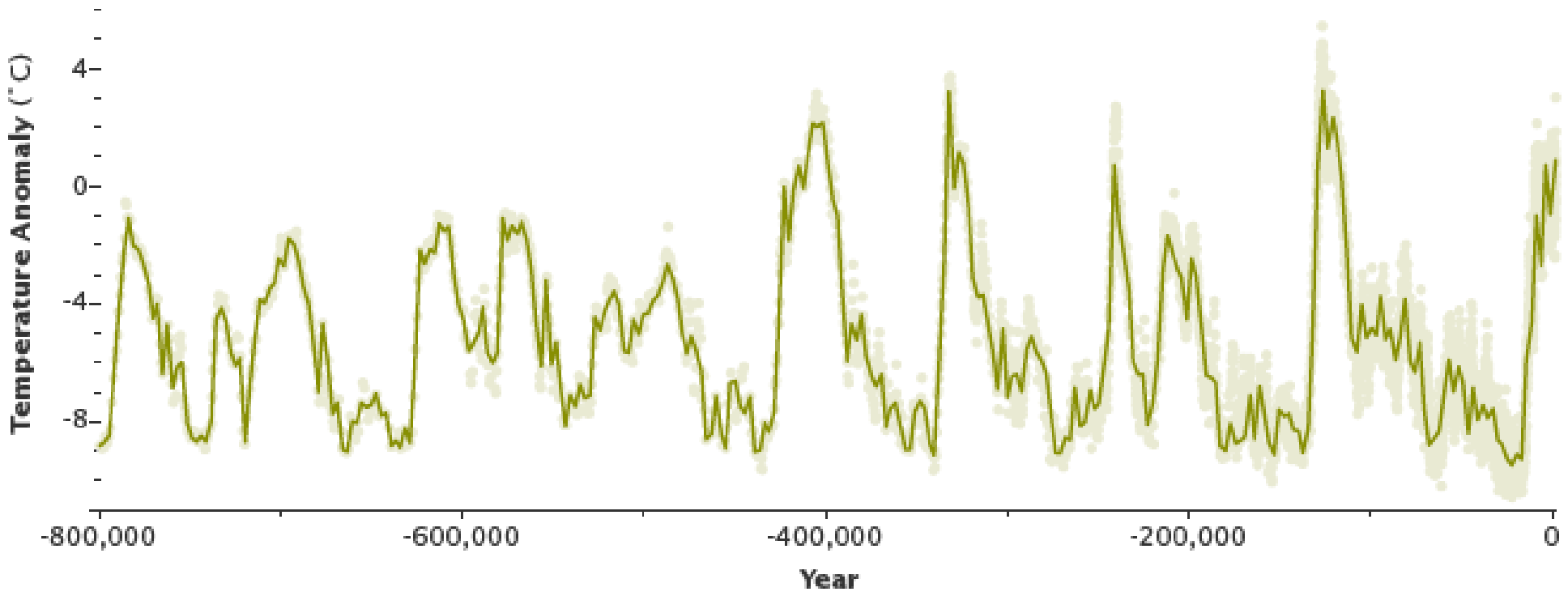


- Water warms at equator
- Evaporation increases salinity
- Surface water flows north, releases heat at higher latitudes

- Dense, cold, high-salinity water sinks and flows south toward Antarctica.

Schematic of global ocean circulation associated with the Meridional Overturning Circulation, a.k.a. thermohaline circulation. From Kuhlbrodt et al. 2007 via Delworth et al., 2008

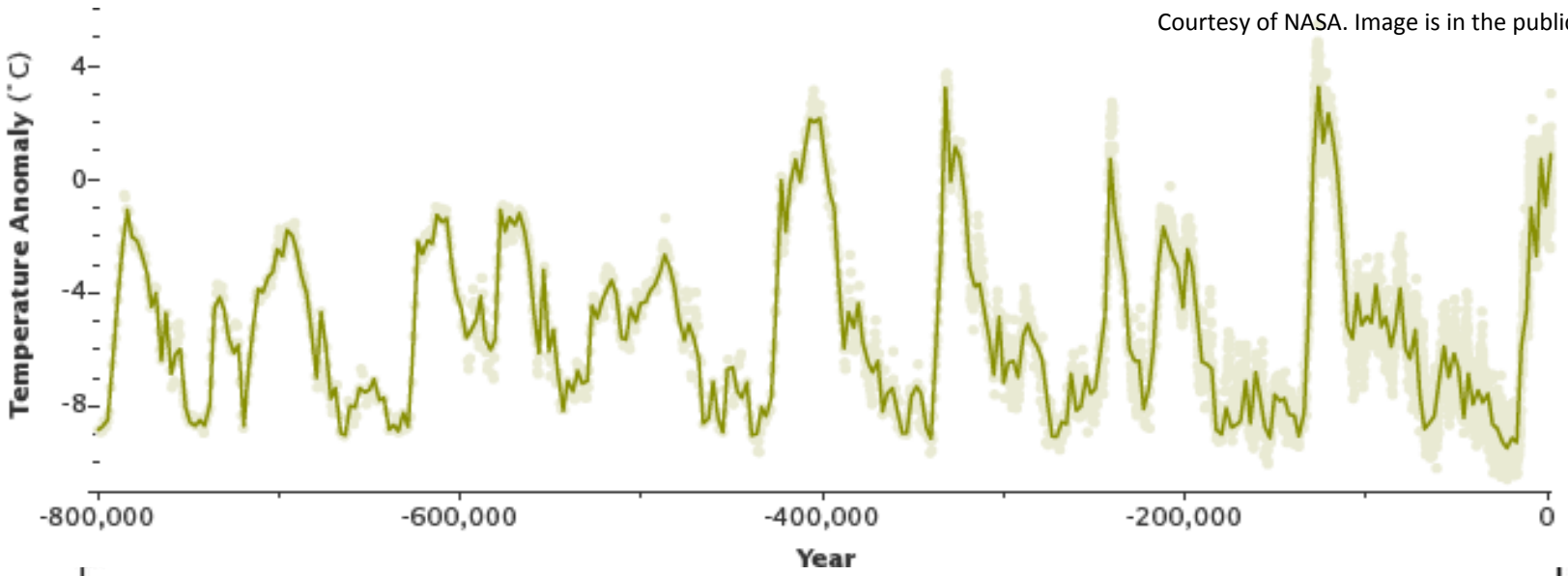
Earth's temperature and climate have always changed.

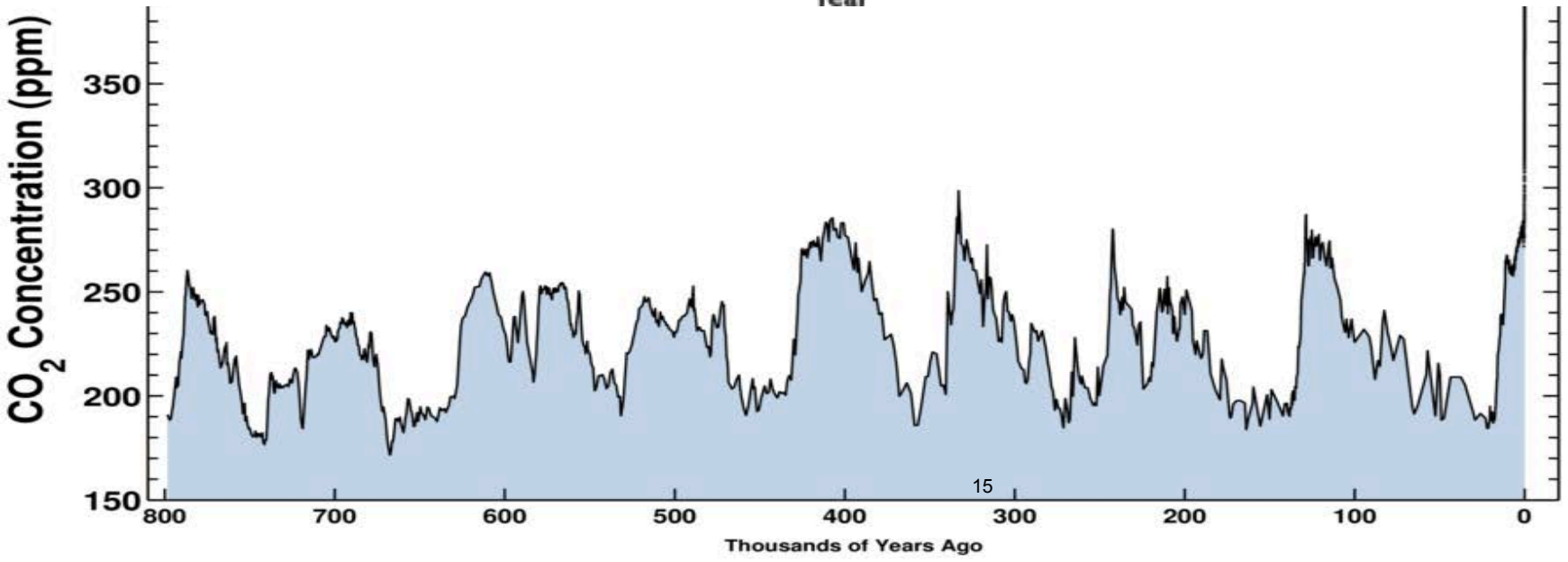


NASA graph by Robert Simmon, based on data from Jouzel et al., 2007

And CO_2 concentrations correlate with temps

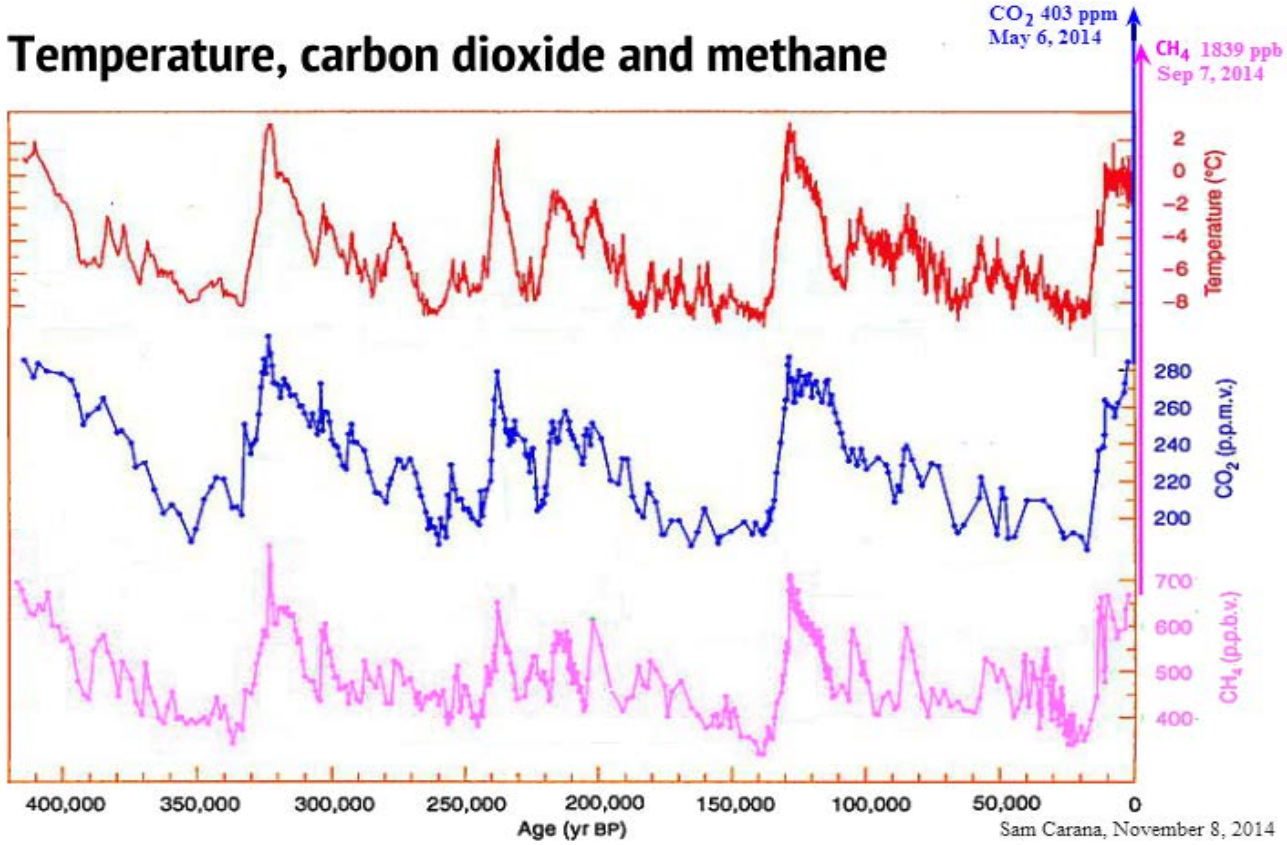
Courtesy of NASA. Image is in the public domain.



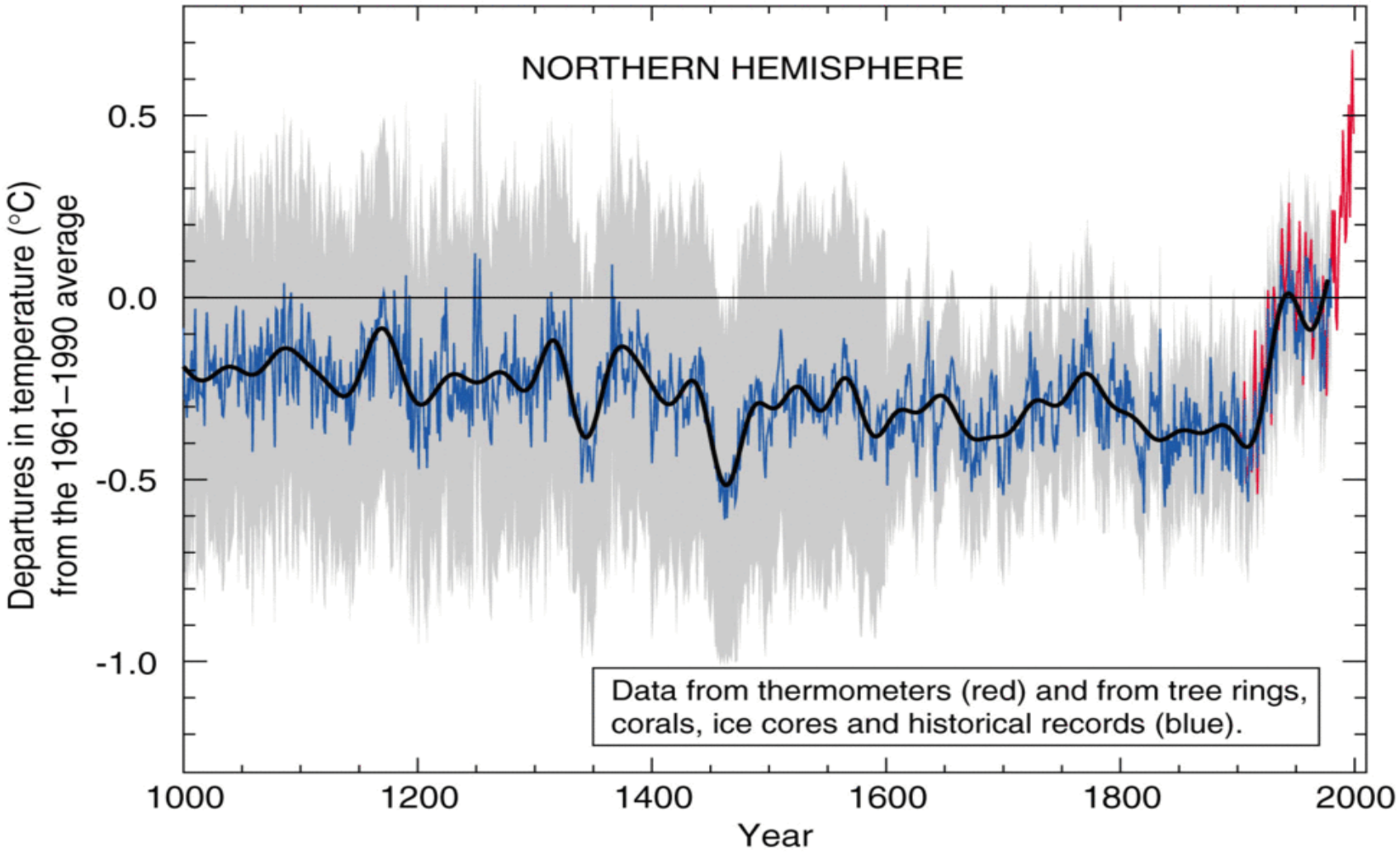


Ice core samples show close correlation between CO_2, CH_4, and atmospheric temperature

(100,000 year time scales)



Overall trend toward cooling, until industrialization:



IPCC/Michael Mann, 2015

Overall trend toward cooling, particularly pronounced in the Arctic

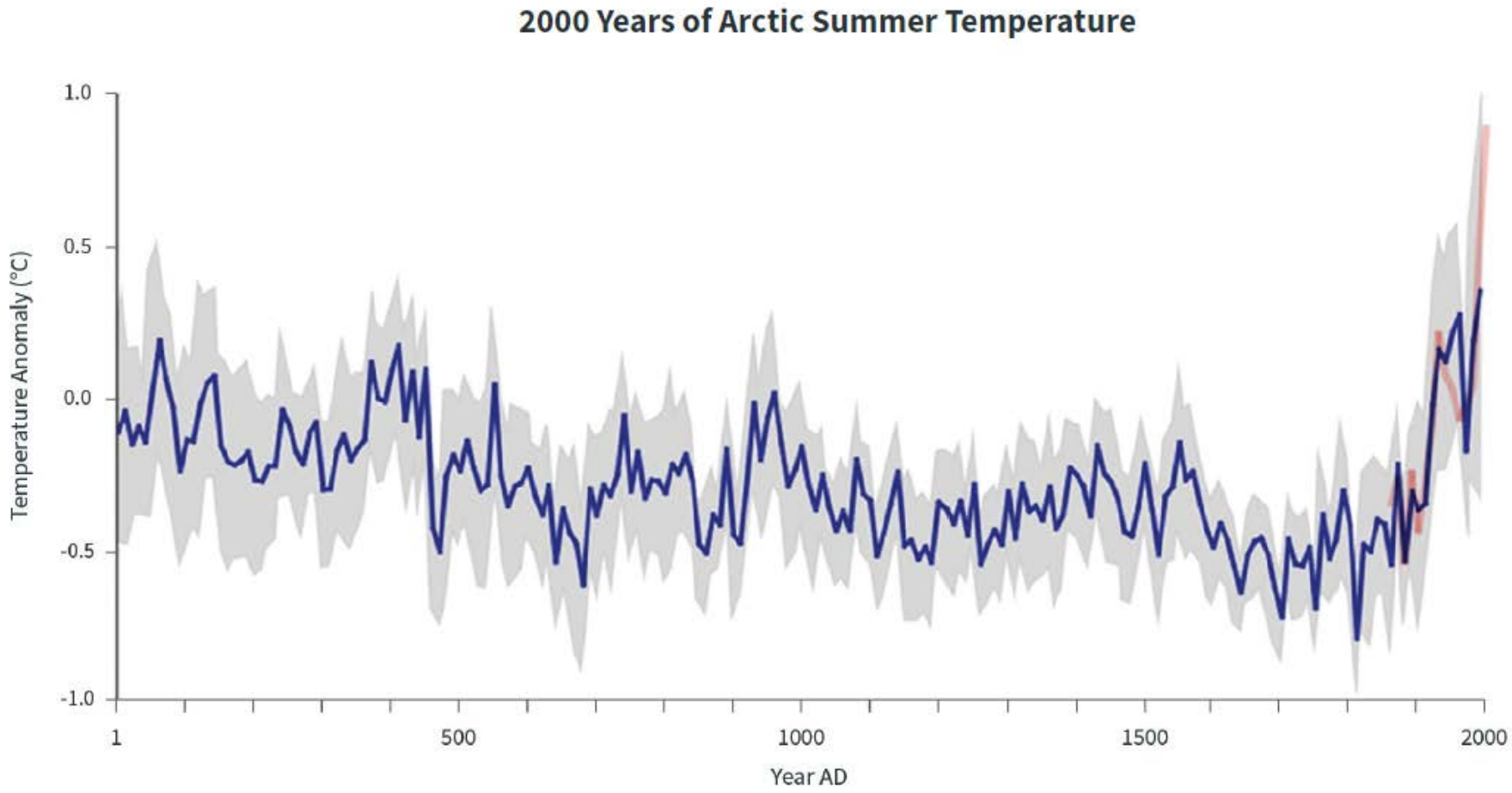


FIGURE 6: Estimated Arctic average summer temperature (°C) over the last 2000 years, based on proxy records from lake sediments, ice cores, and tree rings (blue). The gray shading represents the scatter among the 23 sites used to make this graph. The red line on the right side shows the instrumental Arctic temperature record over roughly the last century. From Kaufman et al., 2009, Science 325: 1236–1239.

How do we know what we know?

Early climate research:

Joseph Fourier, 1827: visible light ➞ infrared when absorbed by a surface; atmosphere is transparent to visible but opaque to IR (light comes in but heat can't get out).

Eunice Newton Foote, 1856: water vapor and CO_2 warm more than other gases, composition of atmosphere affects temperature

John Tyndall, 1861: expanded on Foote's work, didn't cite her, gets all the credit

Svante Arrhenius, 1896: calculated climate sensitivity, described water vapor and ice albedo feedback mechanisms, thought a warmer world would be kind of nice

Charles David Keeling, 1957-2005: invented atmospheric CO_2 analyzer, started measurement program on Mauna Loa

Wally Broeker, 1975 – 2019: developed theory of thermohaline circulation, popularized term "global warming"

Eunice Newton Foote (1819 – 1888)

- Conducted experimental work on the warming effect of the sun on air, and how warming increased by water vapor and carbonic acid gas (carbon dioxide).
- Her experimental work was presented by Prof. Joseph Henry at the 8th annual American Association for the Advancement of Science (AAAS) meeting in 1856, (because women weren't allow to present).
- Foote was the 2nd female member of AAAS.
- The 1st was the famous astronomer Maria Mitchell, who was Ellen Swallow Richard's professor at Vassar.

No known photo exists of Eunice Newton Foote. But there is a photo of her daughter, Mary Foote Henderson

John Tyndall (1820 – 1893)

- Tyndall explained the heat in the Earth's atmosphere in terms of the capacities of the various gases in the air to absorb radiant heat, also known as infrared radiation. His measuring device, which used thermopile technology, is an early landmark in the history of absorption spectroscopy of gases.
- He was the first [or 2nd if credit goes to Eunice Foote] to correctly measure the relative infrared absorptive powers of the gases nitrogen, oxygen, water vapour, carbon dioxide, ozone, methane, in the 1859 (four years after Eunice Foote's work).
- He concluded that water vapor is the strongest absorber of radiant heat in the atmosphere and is the principal gas controlling air temperature. Absorption by the other gases is not negligible but relatively small.
- Prior to Tyndall it was widely surmised that the Earth's atmosphere has a Greenhouse Effect, but he was considered to be the first to prove it. The proof was that water vapor strongly absorbed infrared radiation.
- [Eunice Newton Foote's experimental work is only recently discovered].

Image courtesy of the Smithsonian. Image is in the public domain.

“Like written chronicles of human history, climate archives hold the story of climate change for those who can read them.”

Major climate archives, data from:

- Sediments
- Ice cores
- Corals
- Trees
- Historical
- Instrumental

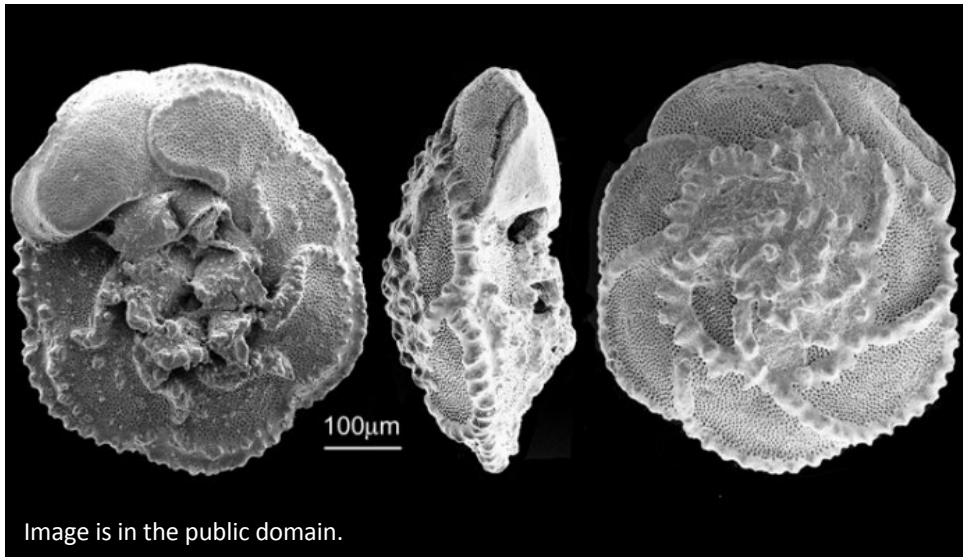
Questions:
1. Why does the importance of different climate archives change for different time scales?
2. How does the method of dating climate records vary with the type of archive?

Ruddiman, W. F. Earth's Climate: Past and Future, 2014.

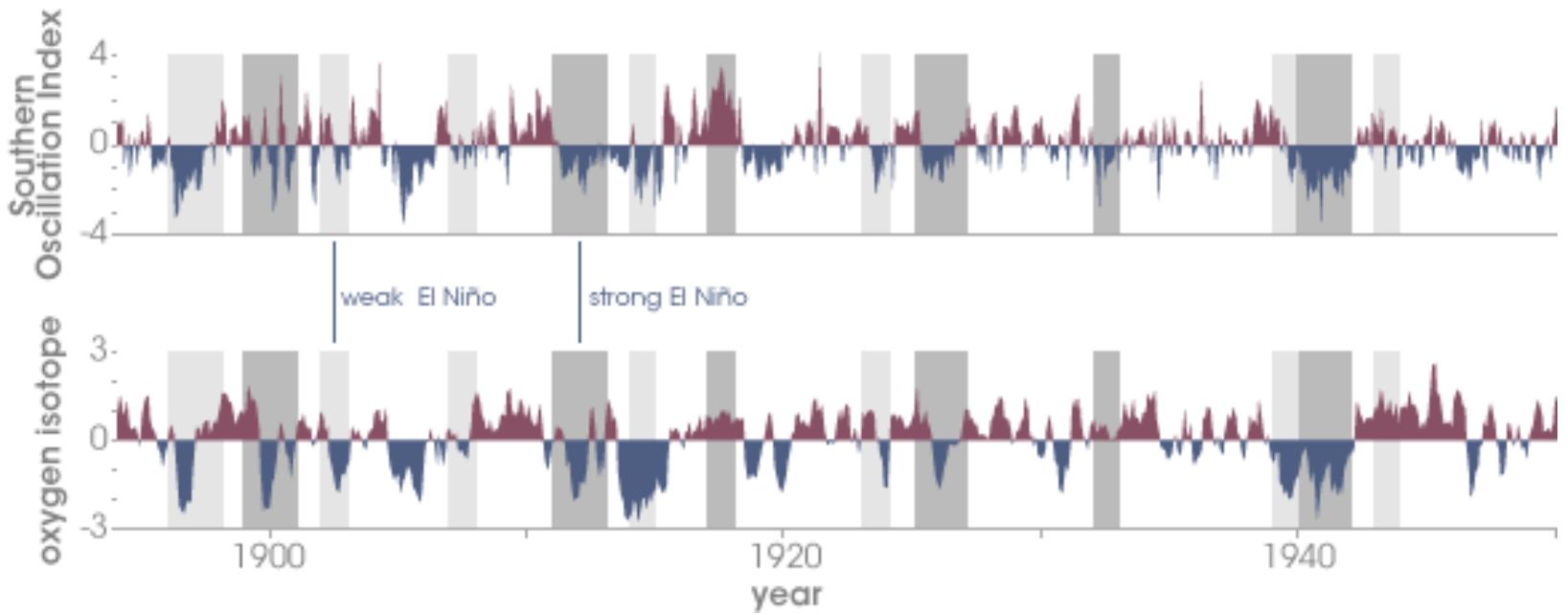
Sediments:

- Lakes, coastal ocean, deep ocean
- Pollen record, diatoms and foraminifera represent climate conditions (temperature, O_2 availability, ocean circulation)
- Dated with radioisotopes, volcanic ash

Globotruncana falsostuarti, 75 million years old. Brian Huber/Smithsonian



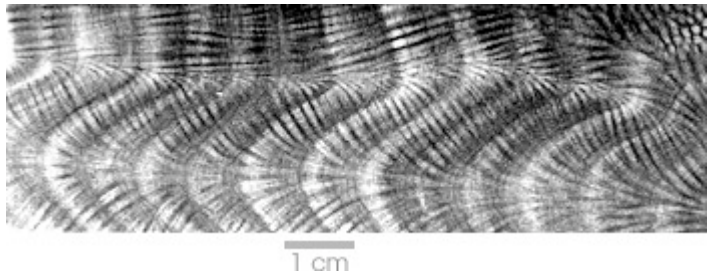
Coral reefs:



- Corals form annual bands like tree rings
- Thickness represents temperature, water clarity, nutrient availability
- Chemistry represents temperature, rainfall

Oxygen isotope ratios in corals correlate well with the Southern Oscillation Index ("El Niño"). Cole et al., Science, 1993

X-ray image Thomas Felis, Research Center Ocean Margins, Bremen



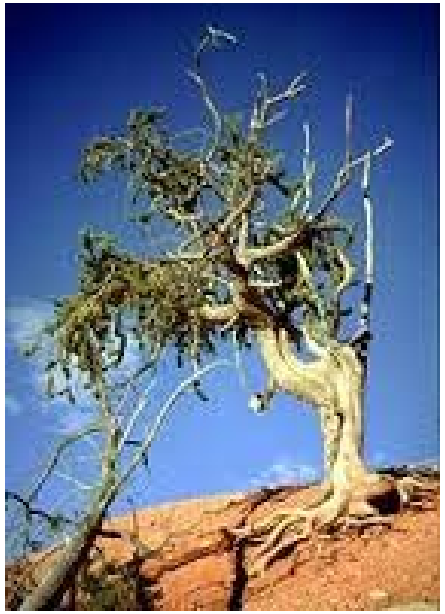
Ice cores:

- Mountain glaciers, Greenland, Antarctica; gas bubbles trapped in ice
- Dated by counting layers, volcanic ash, radioisotopes, ice flow models
- Directly measure gas concentrations, infer climate from stable isotopes
- Hundreds to 800,000 years BP

Tree rings:

- Annual rings, width represents temperature, water availability
- Can build records up to 9,000 year BP

NASA



Bristlecone pines can live >4,000 years. Image: National Park Service

Instrumental and Historical

- 100 years of reliable instrumental data (weather stations, buoys)
- Satellites since 1970s
- Several hundred years of historical records, often require calibration

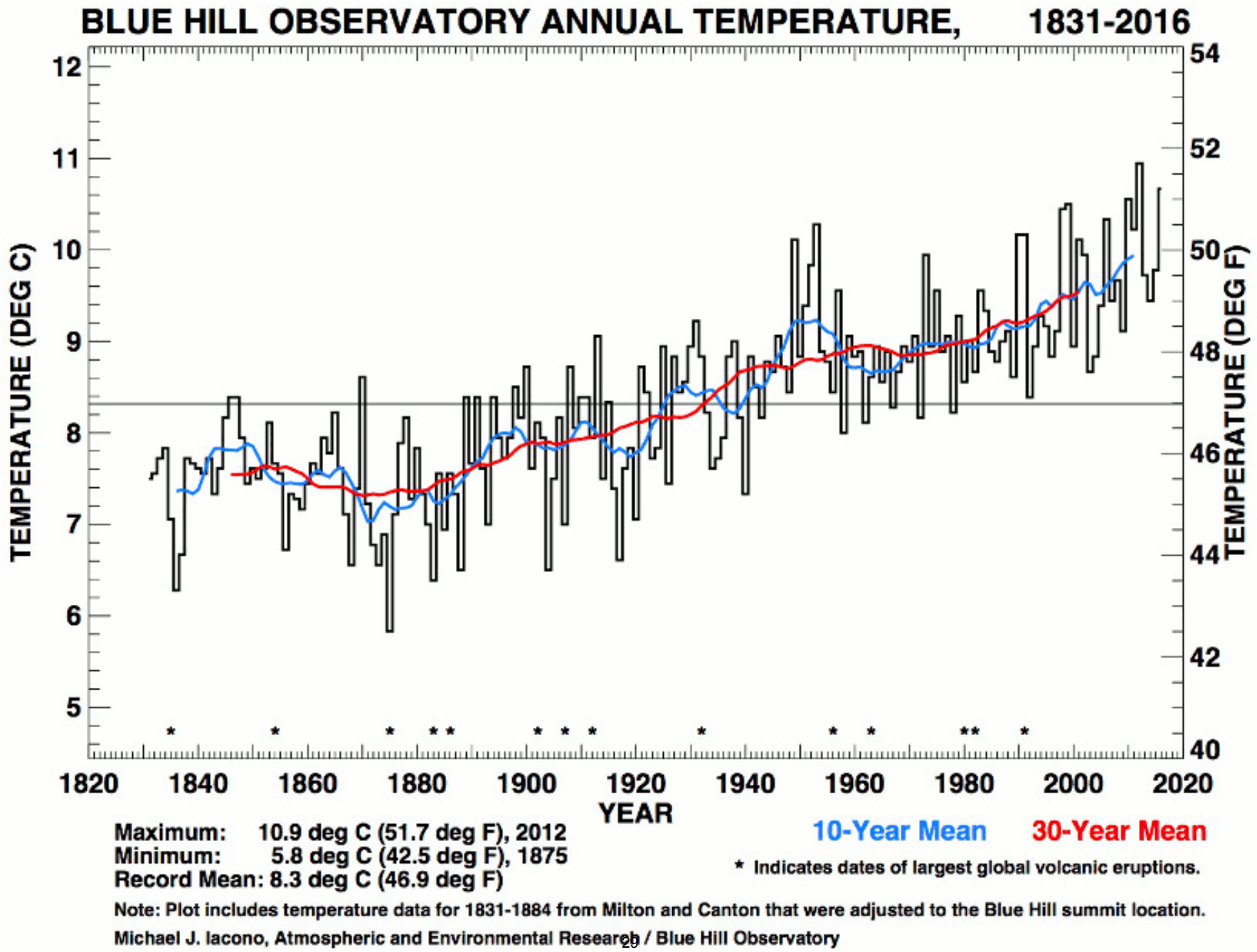
Example 1: Historical Archives
Massachusetts – Blue Hill Observatory

"Home of the Oldest Climate Record in the USA"

Courtesy of John Phelan (Faolin42) on Wikipedia. Used under CC BY.

Built: 1885. Oldest, continuously operated weather Observatory in the United States

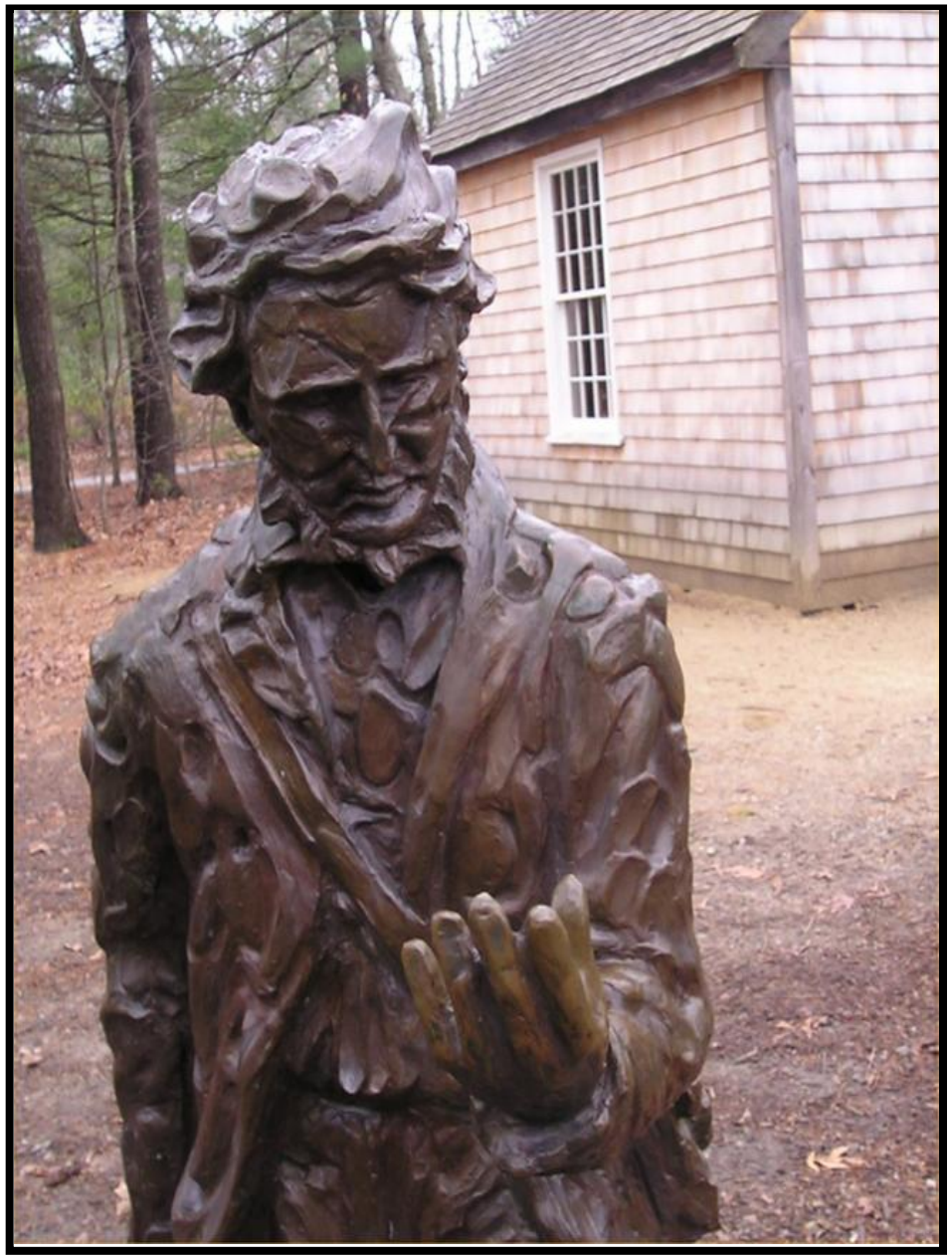
http://bluehill.org/observatory/about-us/history/



Example 2: Historical Archives from: Henry David Thoreau's detailed records of the 1850s

"I often visited a particular plant four or five miles distant, half a dozen times within a fortnight, that I might know exactly when it opened."

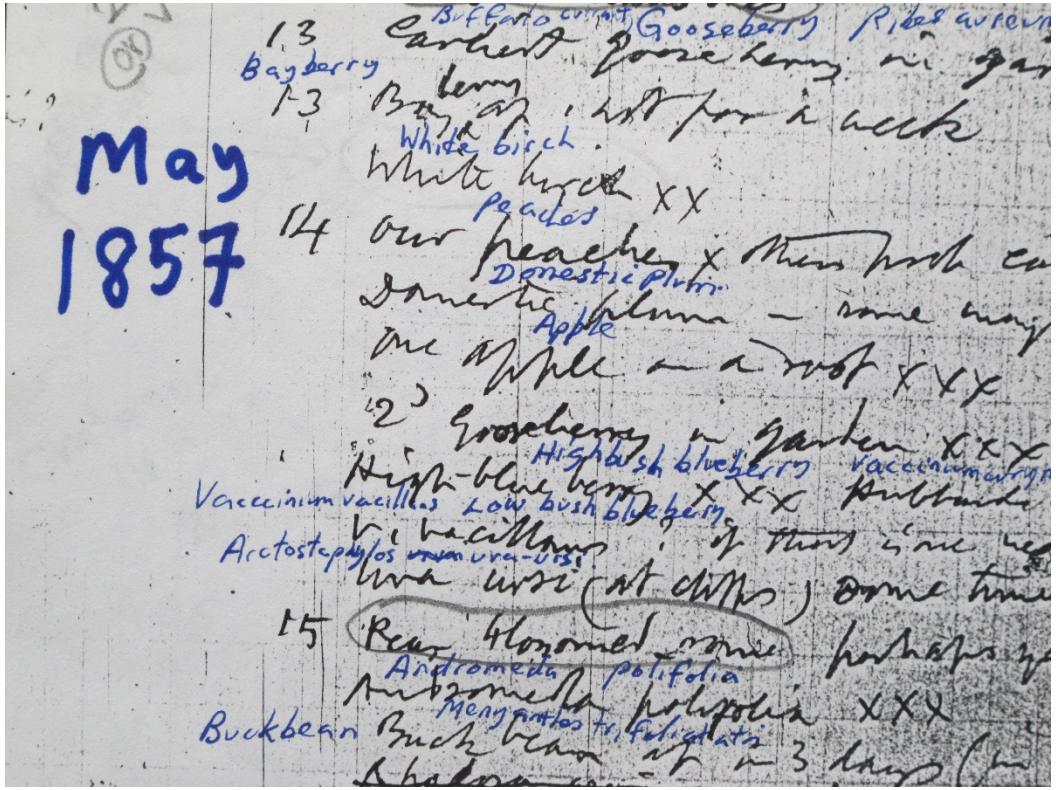
H.D. Thoreau *Journal*, Dec.1856



Henry David Thoreau's journals from 1851-1858

Highbush blueberry
Vaccinium corymbosum

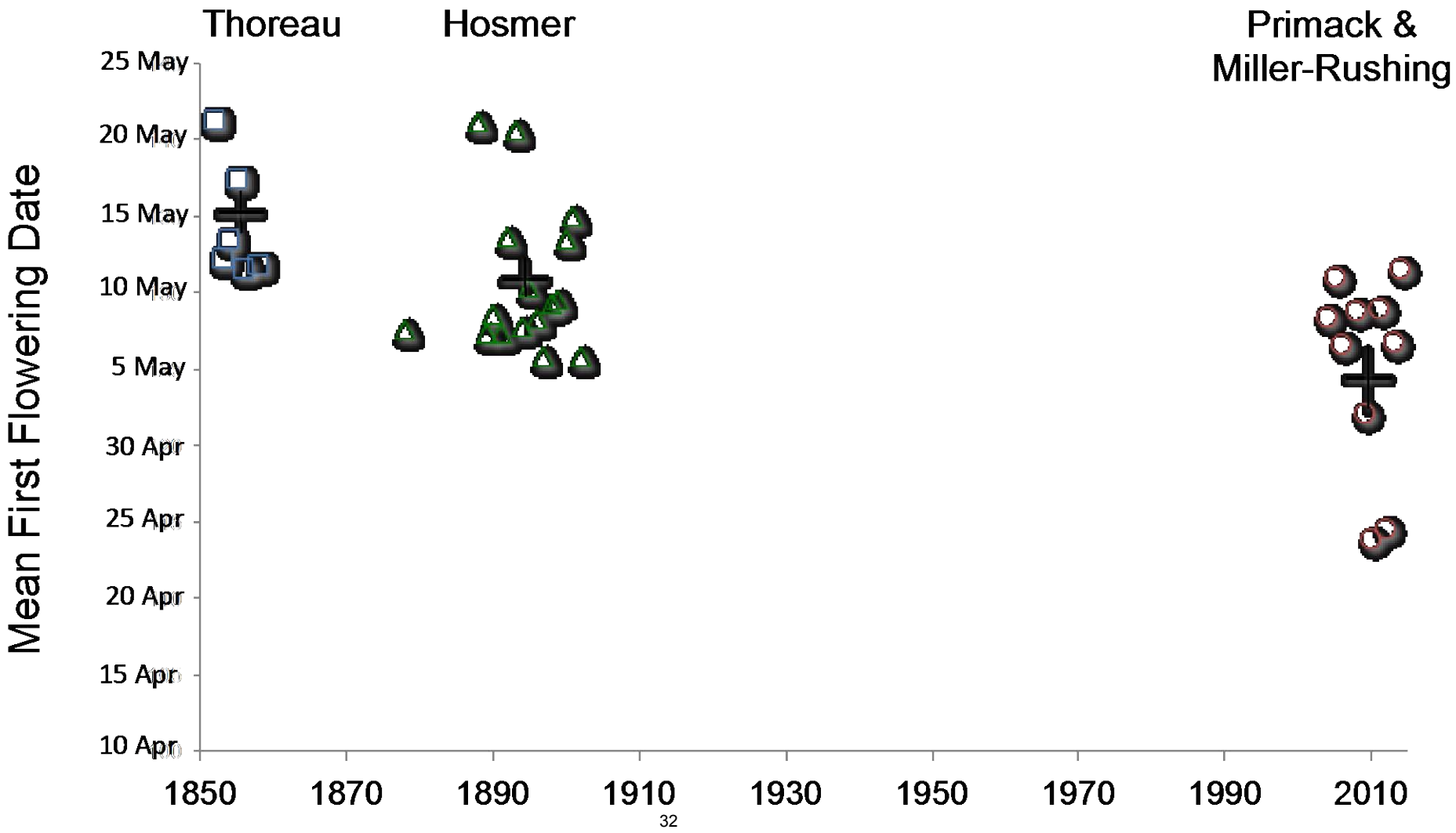
Thoreau's writing is in black and Richard Primack's notes are in blue.



Courtesy of Richard Primack. Used with permission. "Climate Change Comes to Concord." Arnold Arboretum Presentation 3/26/16

First Flowering Day in Concord;

Thoreau (1850s), Hosmer (1890s), Primack & Miller-Rushing (2004-2012)
from a paper by Elizabeth Ellwood published in PLOS One in 2013



Courtesy of Richard Primack. Used with permission. “Climate Change Comes to Concord.” Arnold Arboretum Presentation 3/26/16

Topex Poseidon

"Topex/Poseidon revolutionized the study of Earth's oceans, providing the first continuous, global coverage of ocean surface topography and allowing us to see important week-to-week oceanic variations," said Dr. Mary Cleave, associate administrator for NASA's Science Mission Directorate. "Its data made a huge difference in our understanding of the oceans and their effect on global climatic conditions."

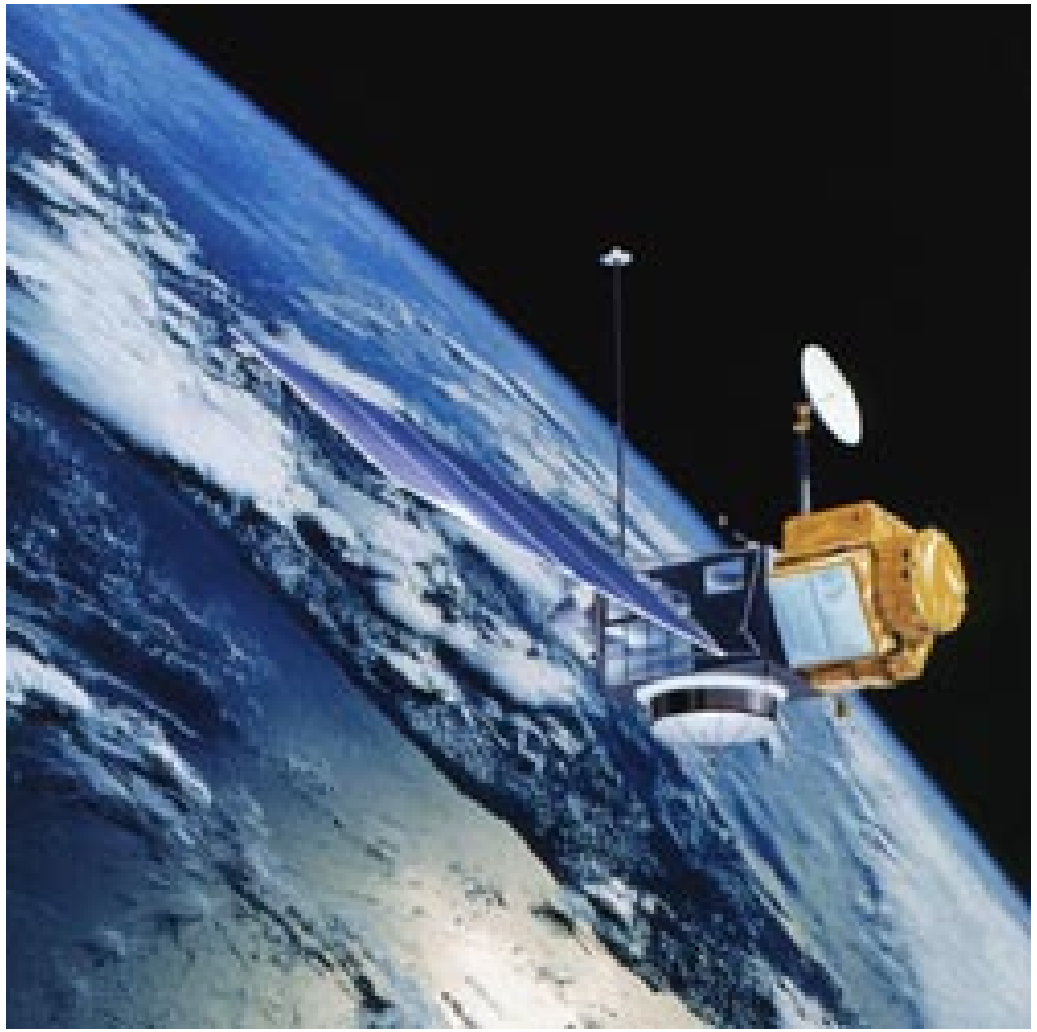


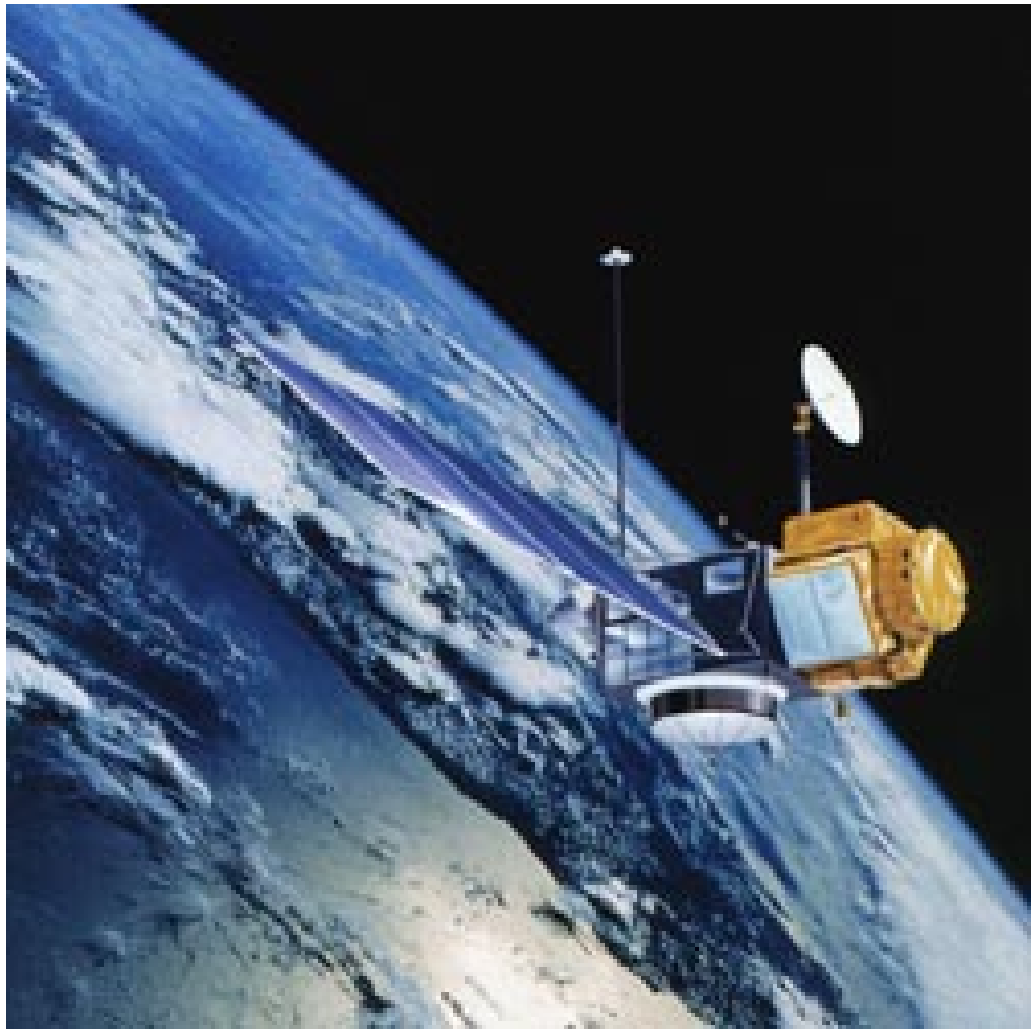
Image is in the public domain.

Artist's concept of Topex/Poseidon. Image credit: NASA/JPL

Topex Poseidon

- Verified and corrected ocean circulation models
- Accurately measured global sea levels

- Planned 3 year mission, operated for >10 years
- Mission continues with Jasons 1, 2, and 3

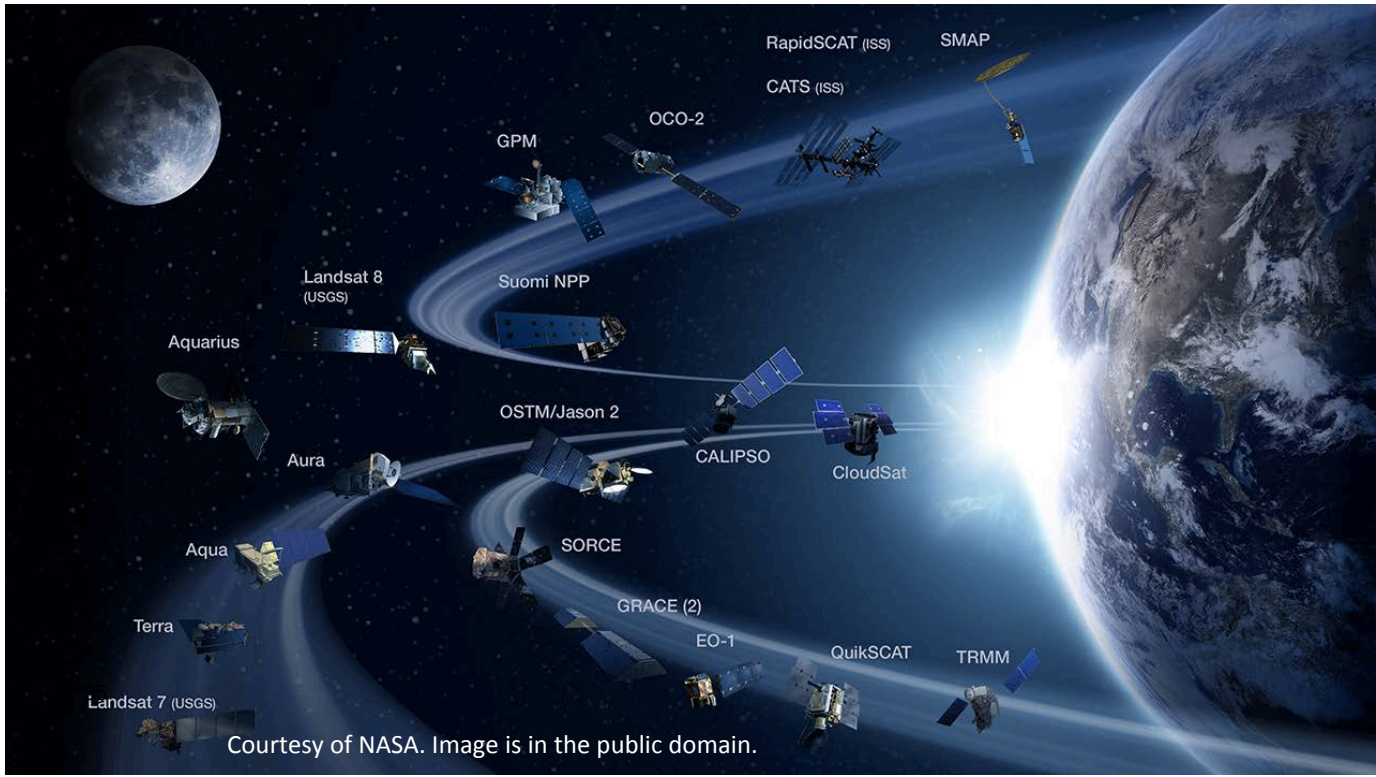


Artist's concept of Topex/Poseidon. Image credit: NASA/JPL

NASA Earth Observing System (partnership with space agencies of Japan, France, Germany, Argentina, E.U., others), includes:

- GRACE – presence and movement of water and ice
- CALIPSO – clouds and aerosols
- OCO-2 (Orbiting Carbon Observatory) – atmospheric CO_2
- Aqua and Terra – clouds and radiative energy, sea surface temperature (and gorgeous images)

Galapagos Islands as viewed by Aqua MODIS, image: Jeff Schmalz, NASA. Image is in the public domain.



Courtesy of NASA. Image is in the public domain.

Most data curated and freely accessible!

NOAA Paleoclimate Data

https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets

Courtesy of NOAA. Image is in the public domain.

Carbon Dioxide Information Analysis Center

http://cdiac.ornl.gov/mission.html

Data Focus Areas:

Fossil-Fuel CO_2 Emissions
Trace Gas Emissions
Atmospheric Trace Gases & Aerosols
Oceanic Trace Gases
Carbon Cycle
Terrestrial Carbon Management
Vegetation Response to CO_2 & Climate
Climate
Land-Use & Ecosystems

EC.719 D-Lab: Weather, Climate Change, and Health

Spring 2019