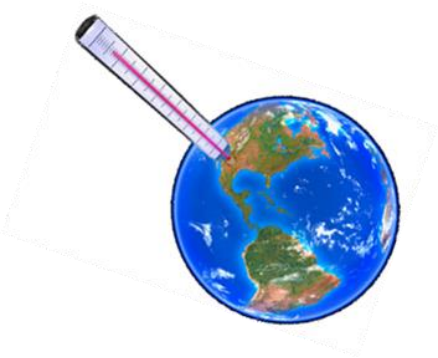
OSHER LIFELONG LEARNING INSTITUTE

Demystifying Climate Change



Boneyard Creek, Champaign *ca.* 20,000 B.C.E. ?

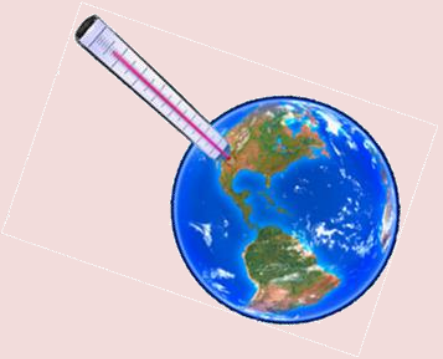
Session 5

Natural Variability of the Climate

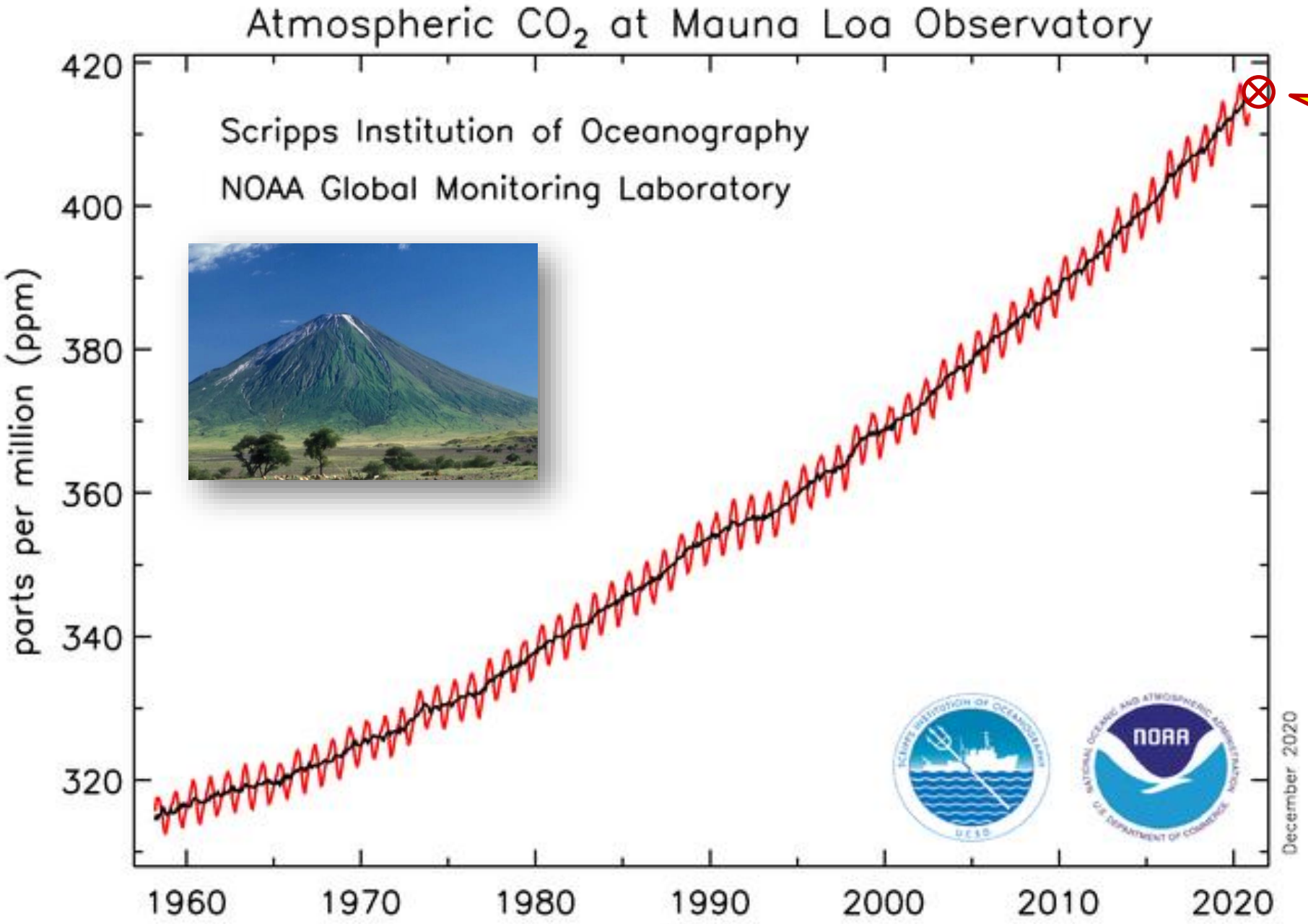
OLLI at Illinois
Spring 2021

D. H. Tracy
DavidHTracy@gmail.com

Reminder



- OLLI Course Download site has
  - Each slide set (with annotations) posted a day after session
  - Syllabus
  - Reference List



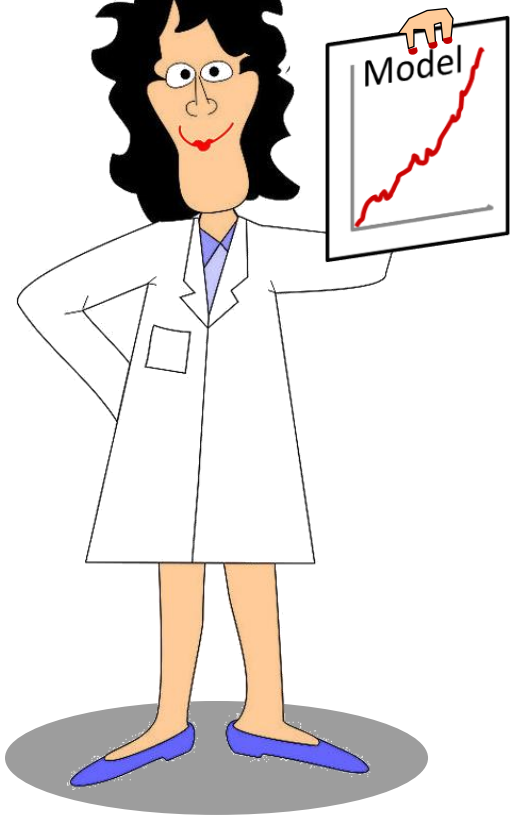
416.67 ppm
Feb 28, 2021

Course Outline

1. Building Blocks: Some important concepts
2. Our Goldilocks Earth: a Radiative Balancing Act
3. The Role of the Atmosphere: Greenhouse Gases & Clouds
4. Global Circulation and Dynamics of the Earth System:
   Oceans, Atmosphere, Biosphere, Cryosphere, People, Lithosphere
5. **Natural Variability of the Climate, short and long term. Ice Ages**
6. Carbon Dioxide and other Greenhouse Gases: where do they come from, where do they go, how are they regulated?
7. Impacts and Future Projections for Global Warming -- Uncertainties
8. Adaptation and Amelioration Strategies. The Climate debate. Policy options.

Theory *vs.* Empiricism

According to my calculations….

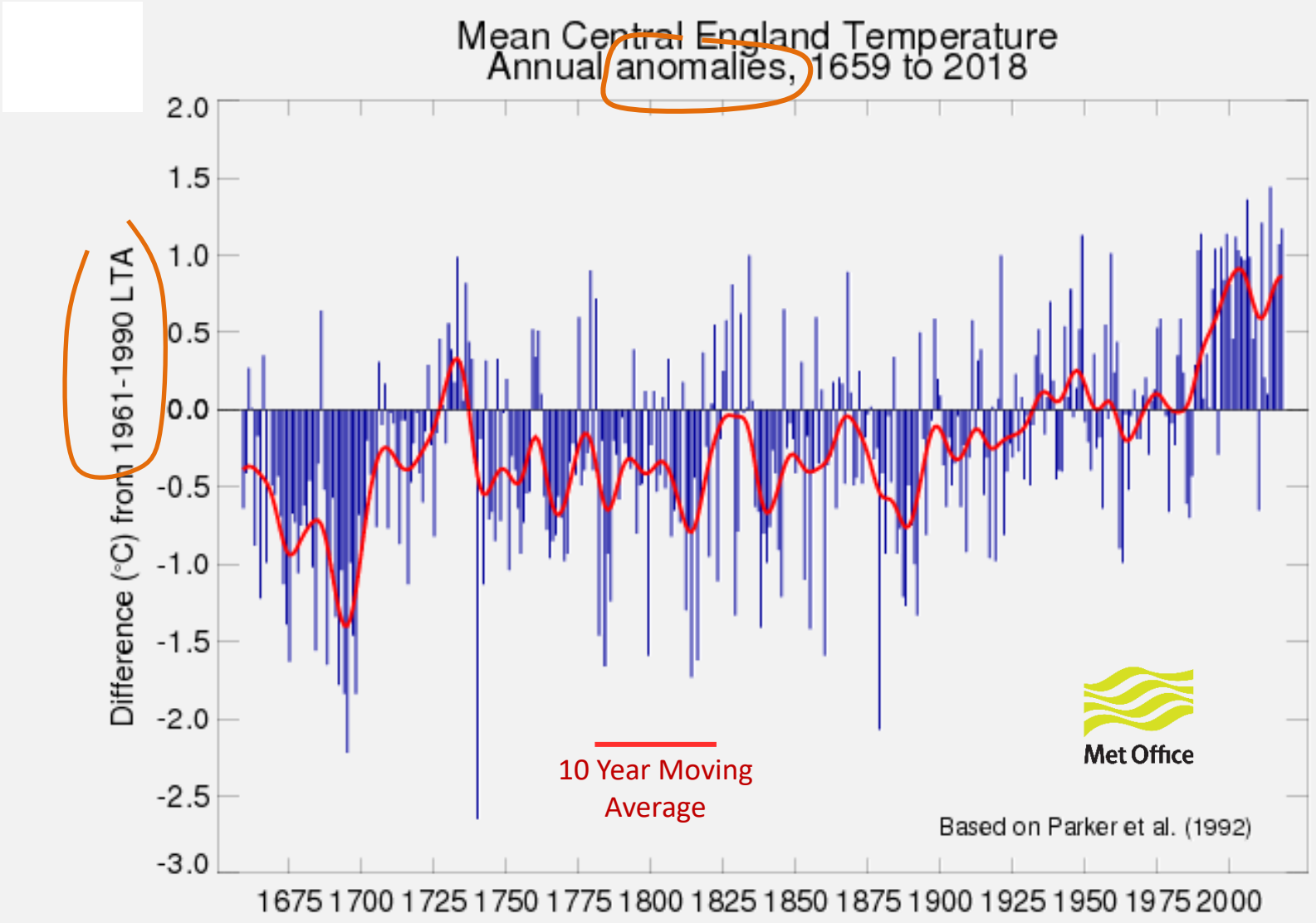


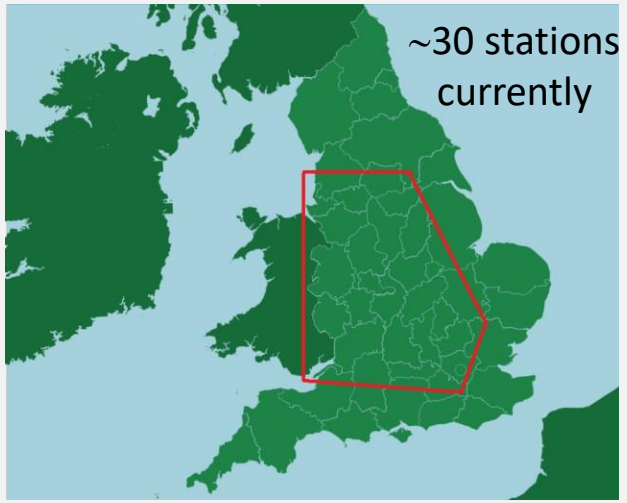
Balderdash! Show me the actual data…

Reconstructing Past Climates

- Recent Past: Instrumental Records
- More Distant Past: Inference from Proxies
  - Paleoclimatology

Oldest Continuous Instrumental Temperature Record





- Anomalies relative to a baseline period:
  - 1961-1990 WMO recommendation
- Small Region

4 Global Instrumental Surface Temperature Records

NASA Goddard Institute for Space Studies (v4)
Hadley Center/Climatic Research Unit (v5)
NOAA National Center for Environmental Information (v5)
Berkeley Earth

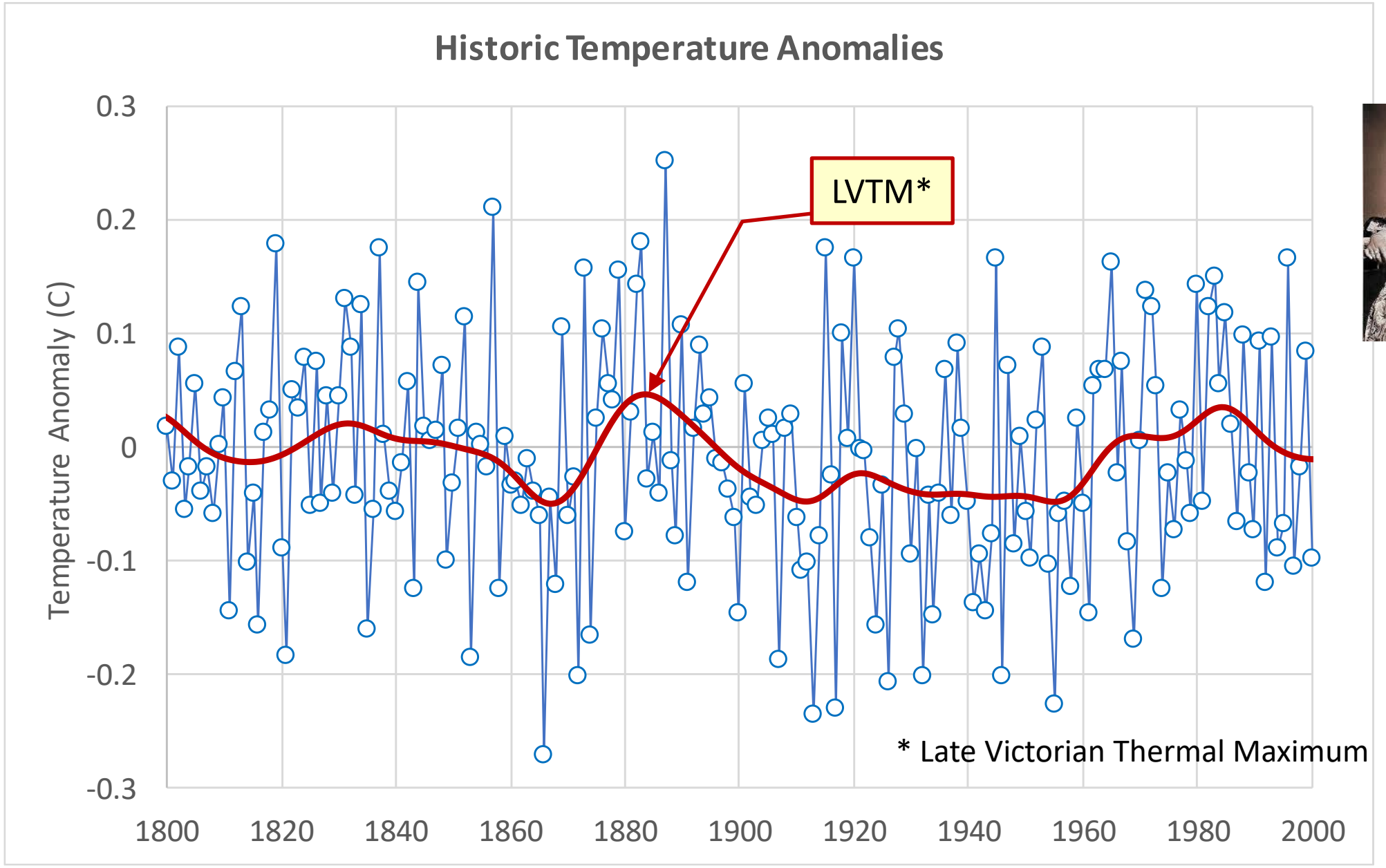
Met Office

Many Difficulties!

Temperature Anomaly (ºC)
Common Baseline 1951-1980

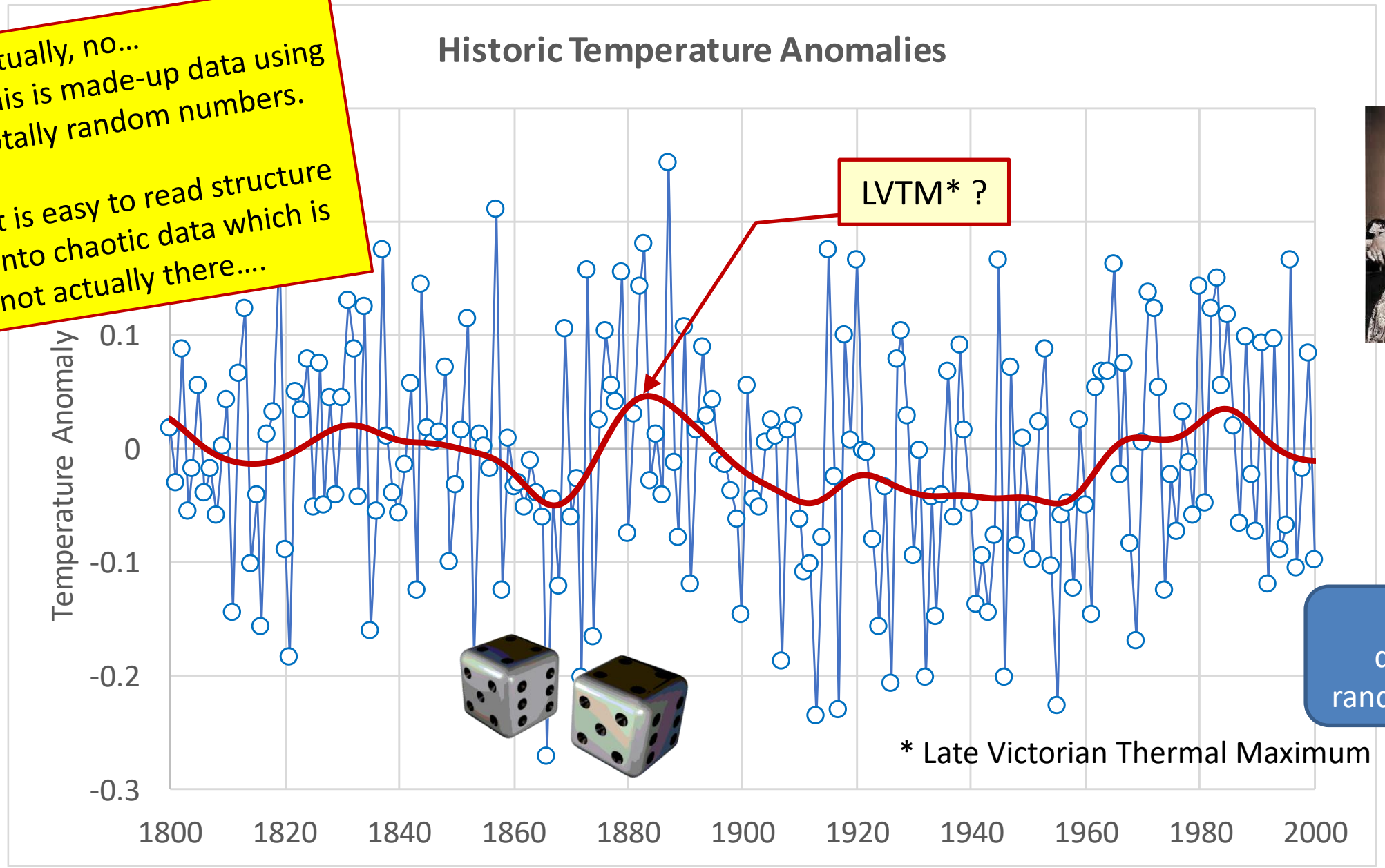
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6

1880 1900 1920 1940 1960 1980 2000 2020


Historic Temperature Anomalies
Temperature Anomaly (C)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
LVTM*
* Late Victorian Thermal Maximum

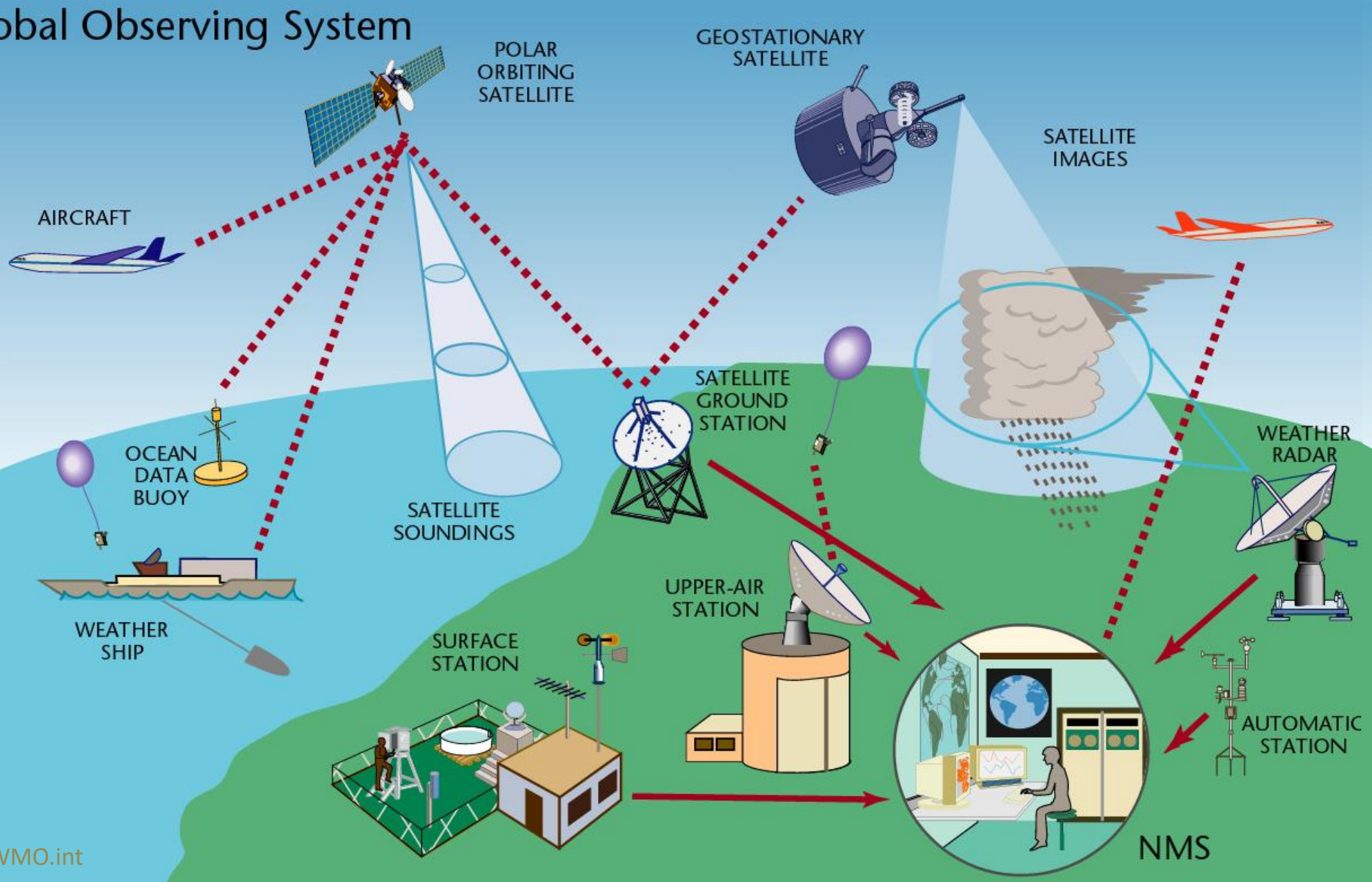
Actually, no…
this is made-up data using totally random numbers.

It is easy to read structure into chaotic data which is not actually there….



Normally distributed random numbers

Modes of Weather Observation

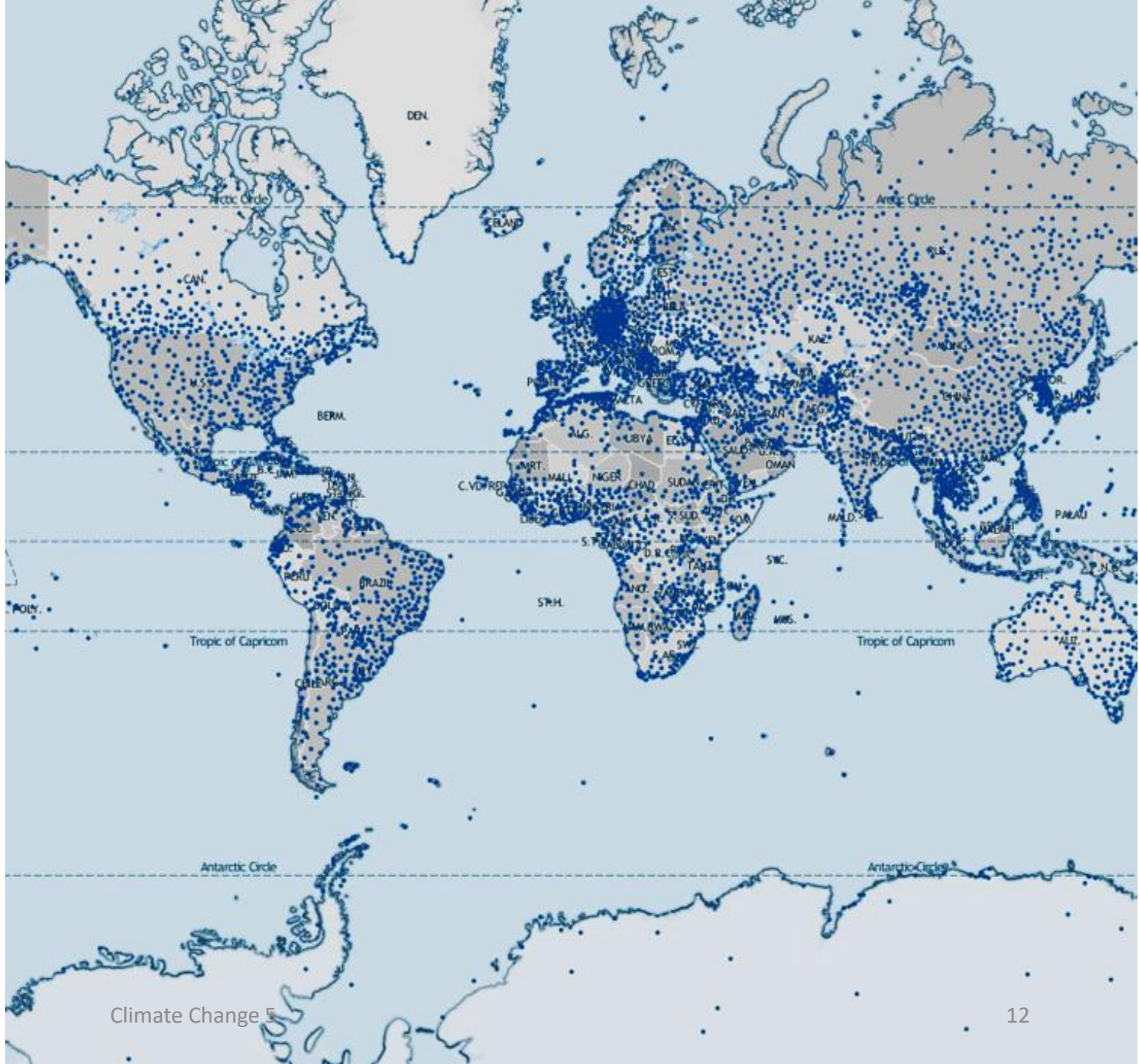


WMO.int

World Meteorological Organization

Weather Station Networks

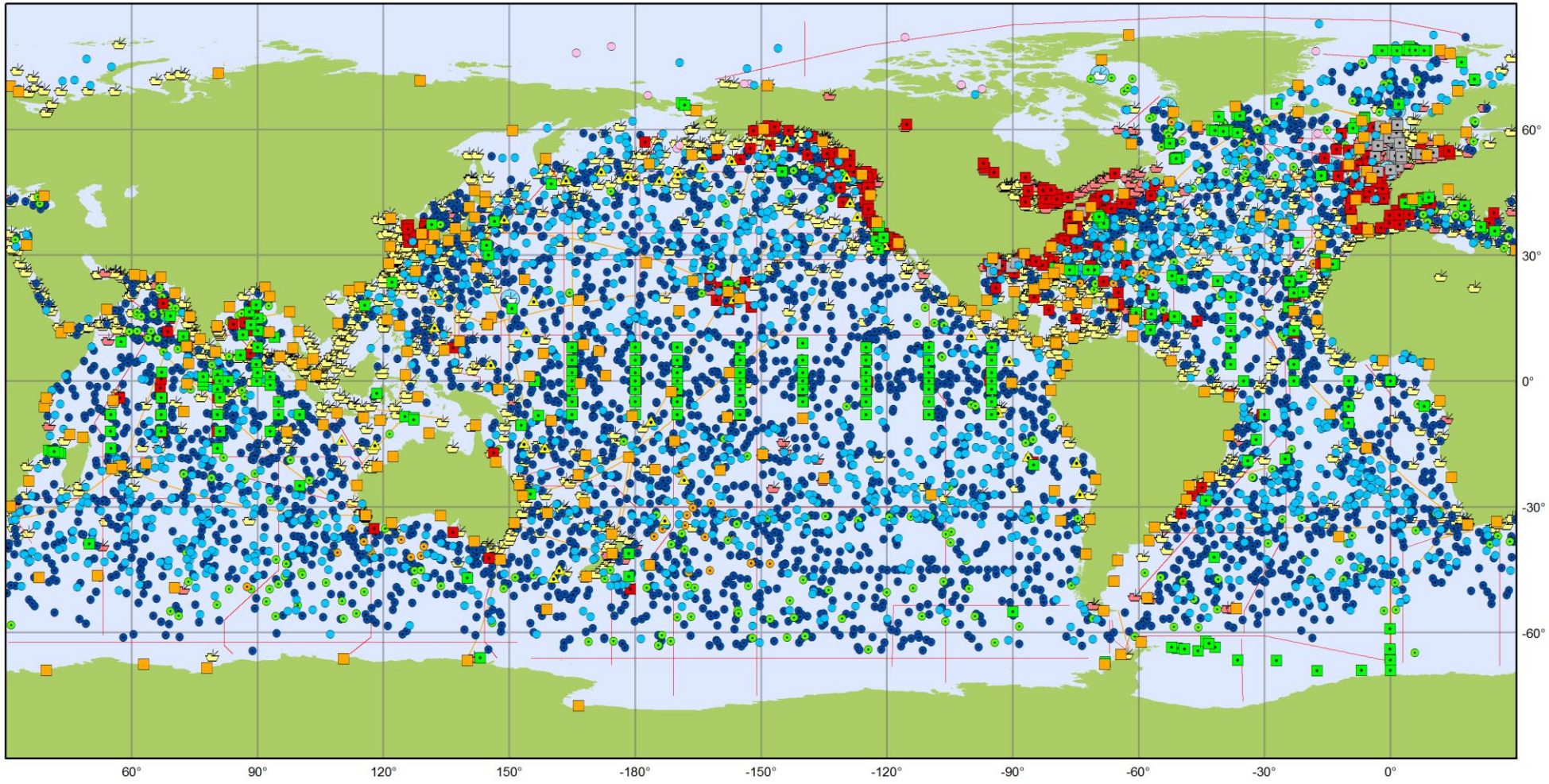
- 3000 in Regional Basic Climatological Networks
- 4000 in Regional Basic Synoptic Networks
- also Antarctic Observing Network
- ~ 4000 additional stations not shown



Global Ocean Observing System

administered by Intergovernmental Oceanographic Commission

- 1400 Surface Drift Buoys
- 700+ Moored Buoys
- 4000 Profiling Floats
- 400+ Voluntary Observing Ships
- Many other platforms



Main in situ Elements of the Global Ocean Observing System — October 2017

Profiling Floats (Argo)
- Core (3836)
- Deep (39)
- BioGeoChemical (287)

Data Buoys (DBCP)
- Surface Drifters (1386)
- Offshore Platforms (103)
- Ice Buoys (15)
- Moored Buoys (399)
- Tsunameters (37)

Timeseries (OceanSITES)
- Interdisciplinary Moorings (332)

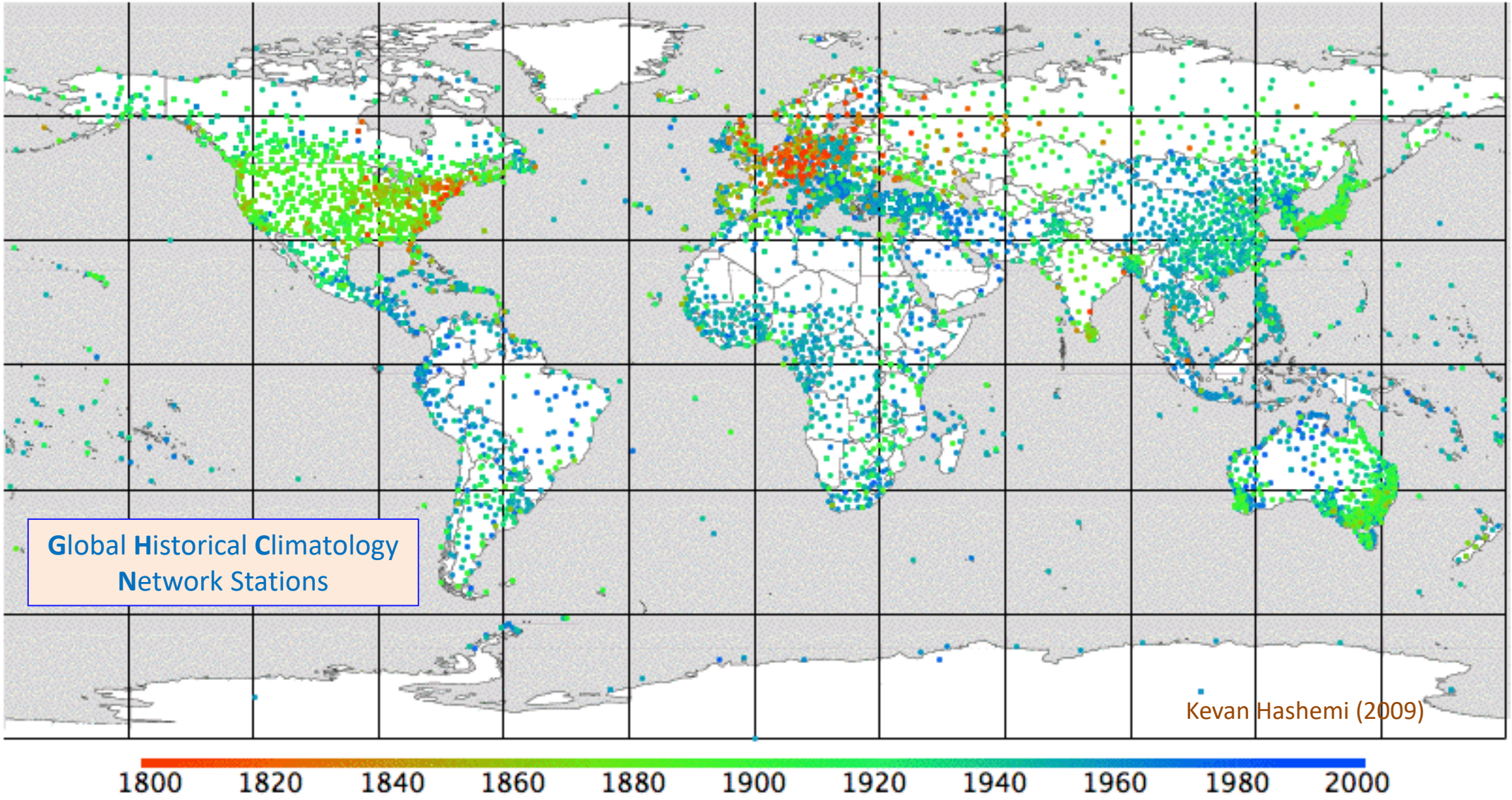
Repeated Hydrography (GO-SHIP)
- Research Vessel Lines (61)

Sea Level (GLOSS)
- Tide Gauges (252)

Ship based Measurements (SOT)
- Automated Weather Stations (247)
- Manned Weather Stations (1601)
- Radiosondes (19)
- eXpendable BathyThermographs (37)

Generated by www.jcommops.org, 13/11/2017

When Did Weather Stations Come Online?



NOAA Weather Stations in CU

- mostly rain gauges only
- 3 provide Temperature, Wind etc.

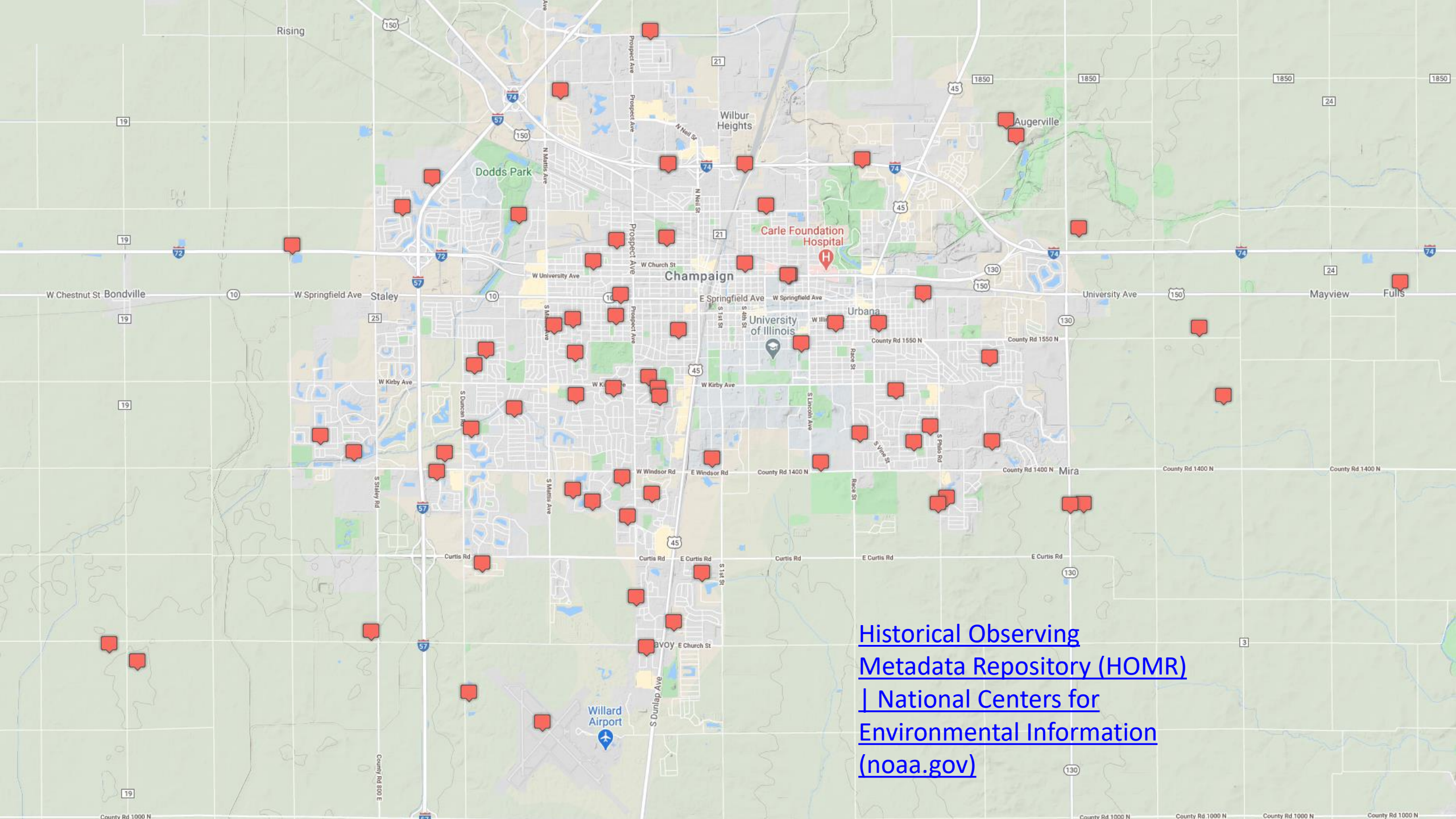
Bondville BEARS site

Willard CMI

“Urbana 4.2 ESE”

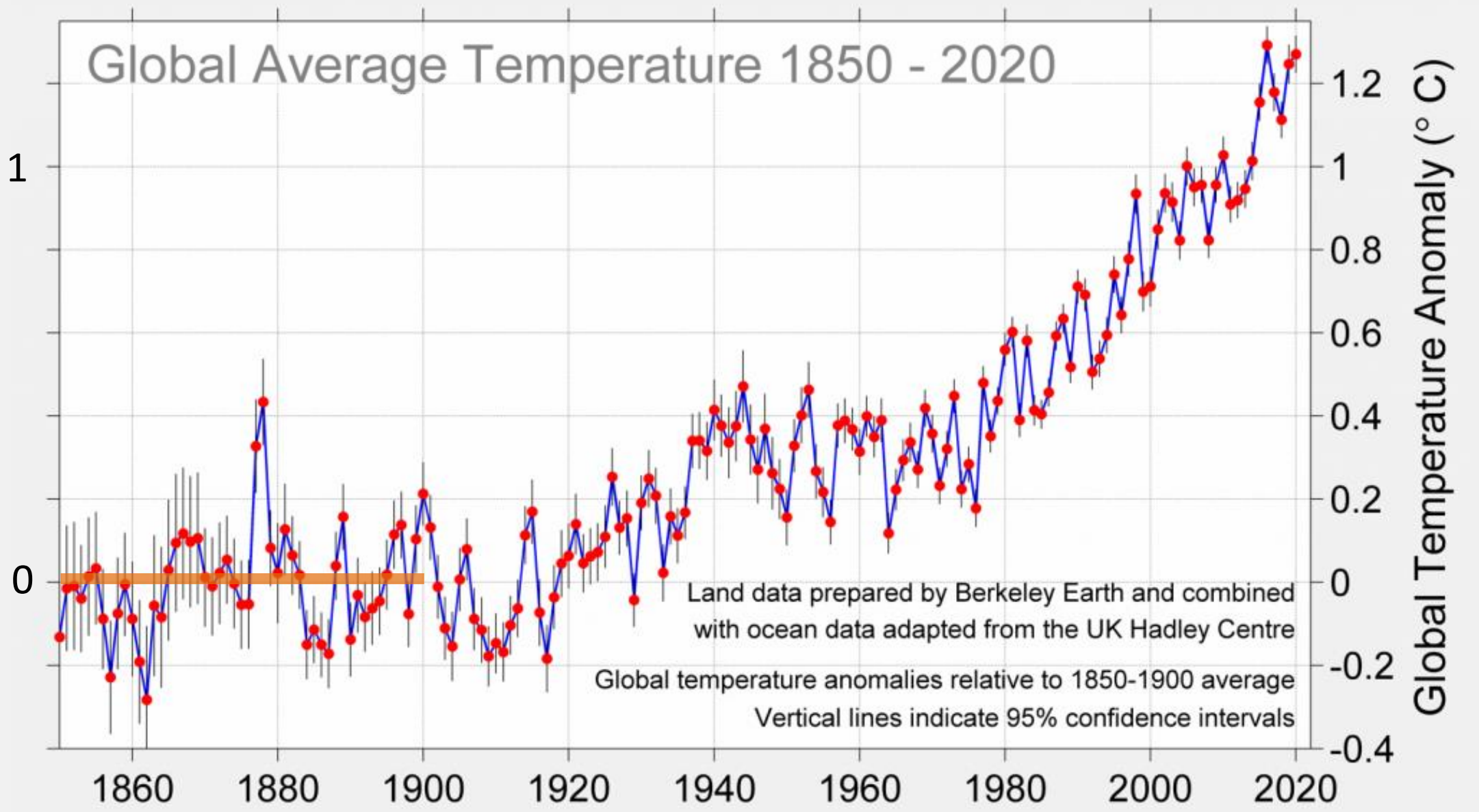
Champaign 3 S
GHCND:USC00118740

North of Windsor Ave



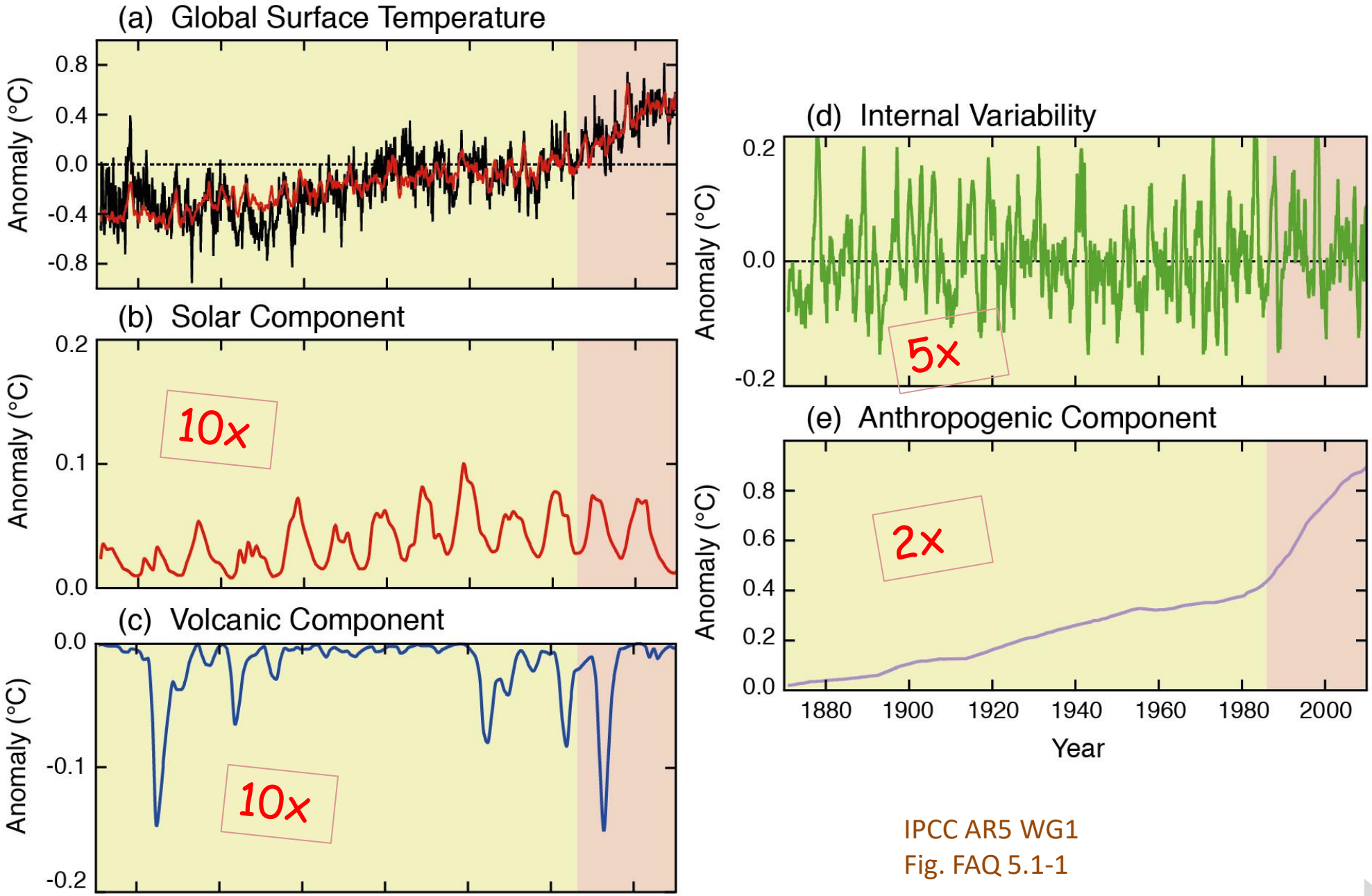
[Historical Observing Metadata Repository (HOMR) | National Centers for Environmental Information (noaa.gov)]

Global Temperature Anomaly (relative to 1850-1900)



IPCC Breakdown of Components of Recent Global Forcings

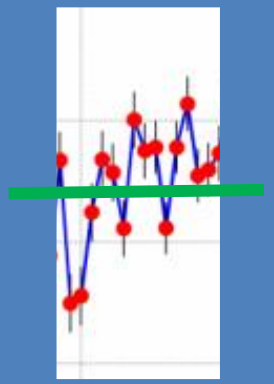
Note widely differing scales. Anthropogenic component is by far the biggest



IPCC AR5 WG1
Fig. FAQ 5.1-1

Global Temperature Anomaly (rela

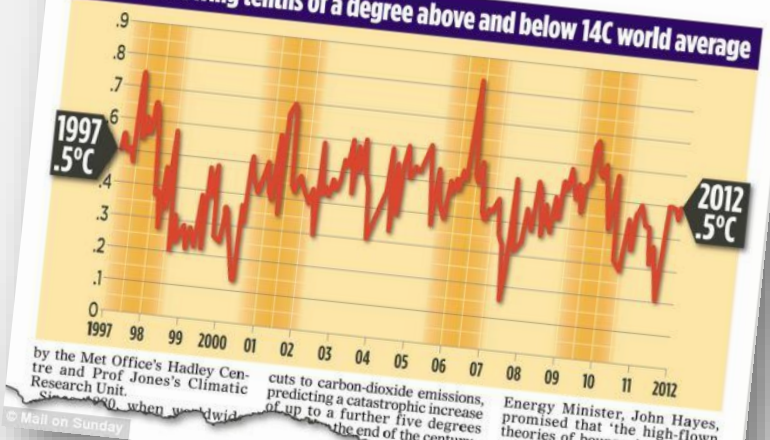
The "Hiatus"



Daily Mail

Global warming stopped 16 years ago, Met Office report reveals

Graph showing tenths of a degree above and below 14C world average

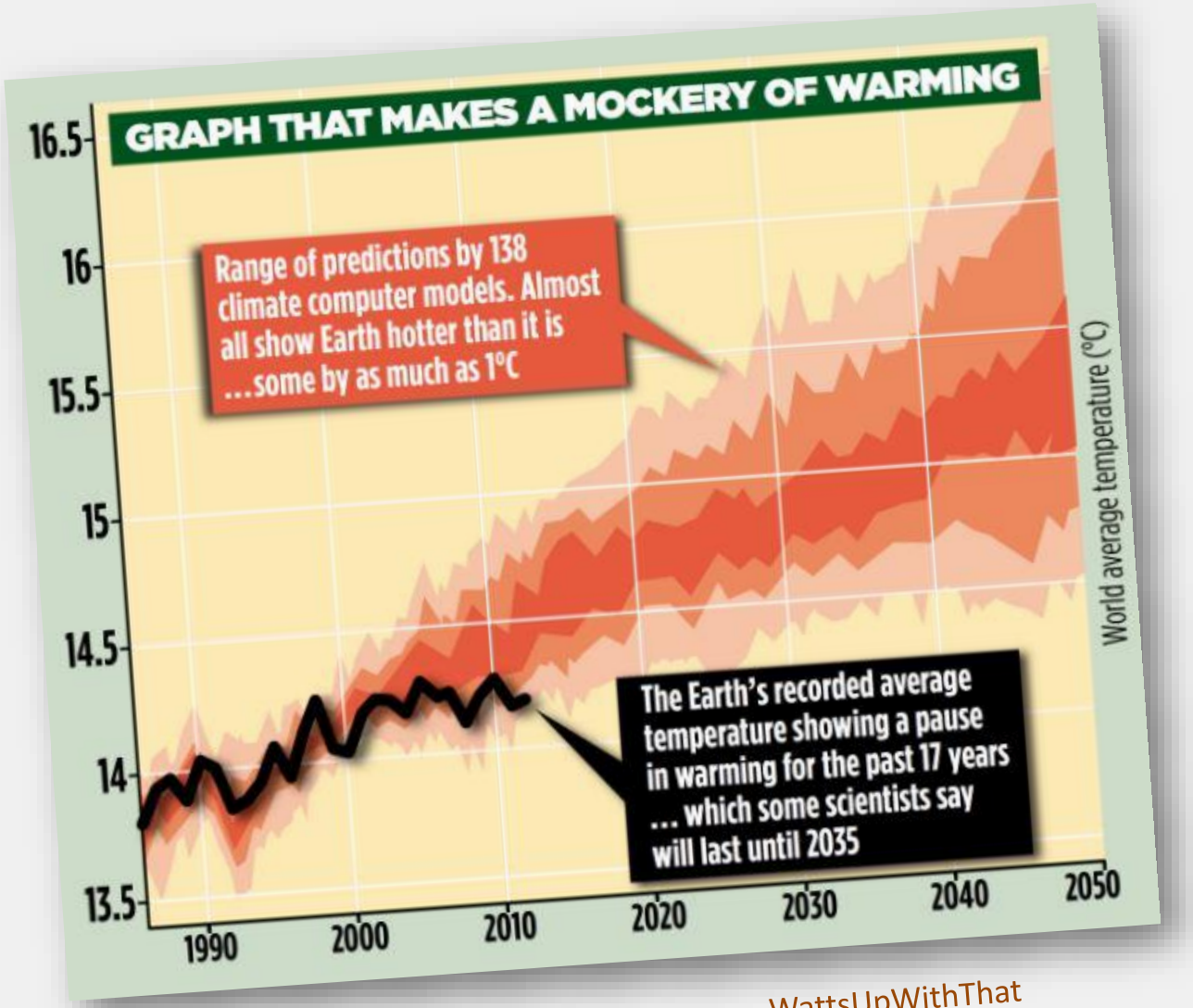


by the Met Office's Hadley Centre and Prof Jones's Climatic Research Unit.

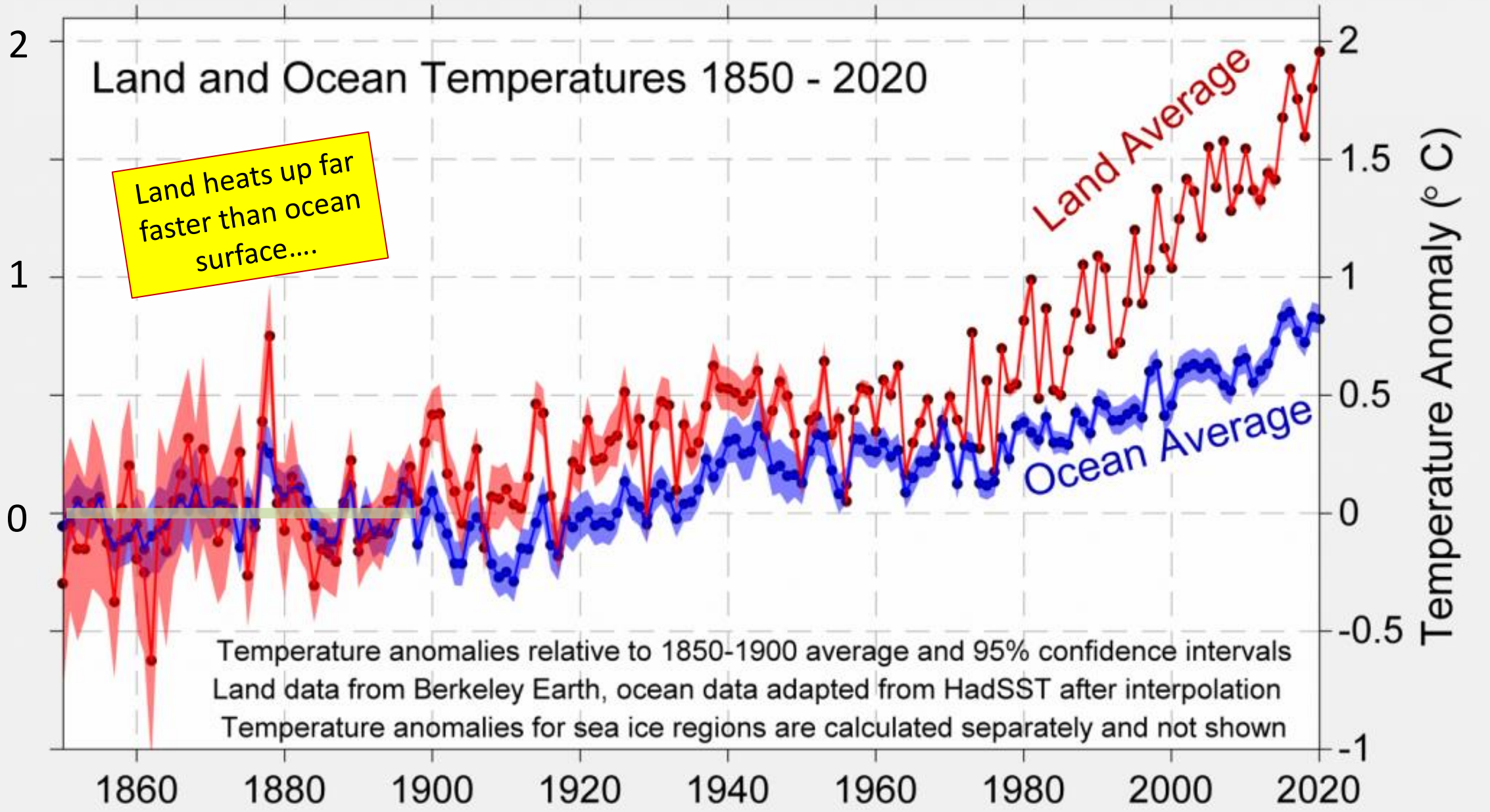
cuts to carbon-dioxide emissions, predicting a catastrophic increase of up to a further five degrees the end of the century.

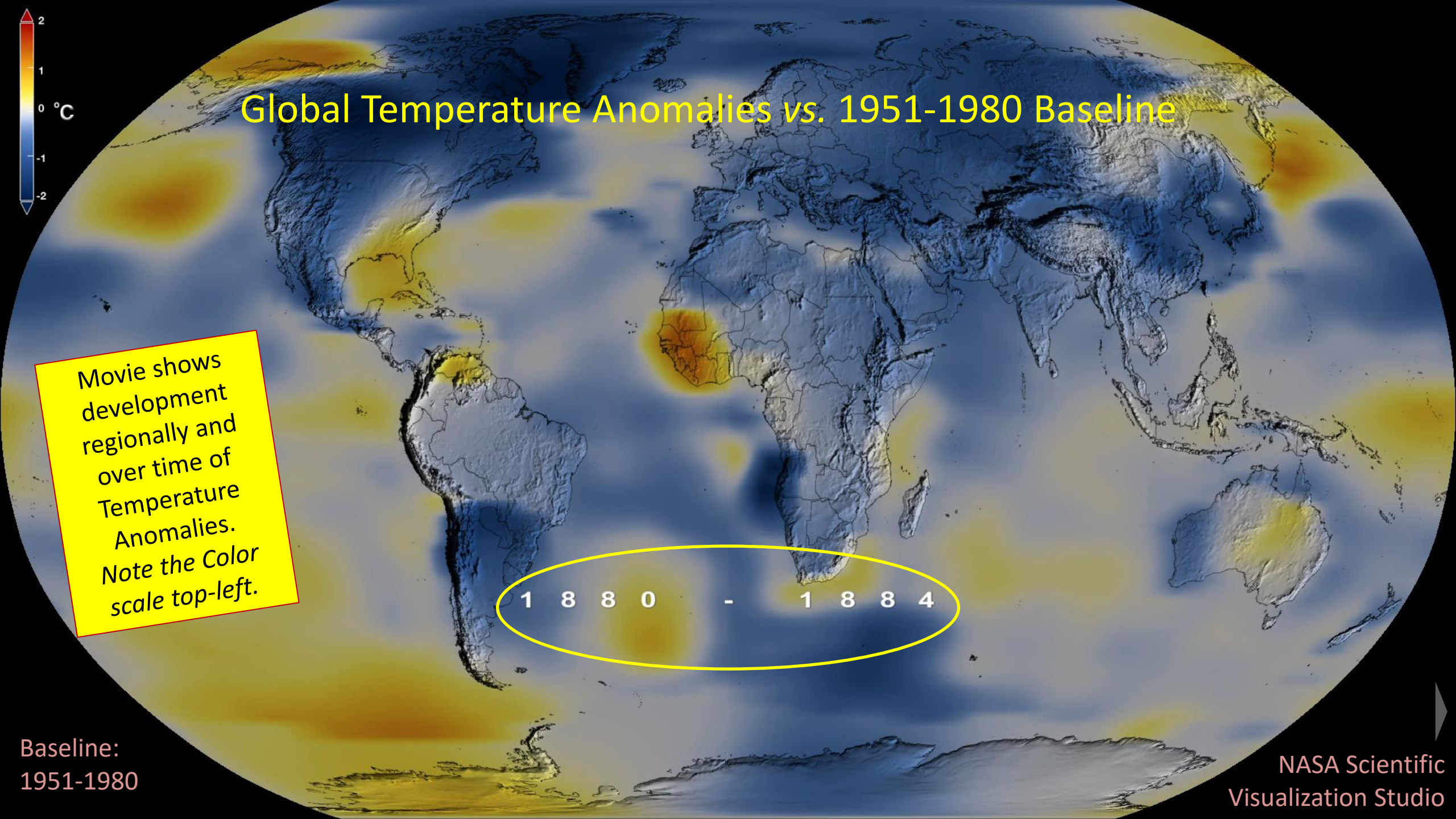
Energy Minister, John Hayes, promised that 'the high-flown theories of bourgeois Left-wing academics will not override the

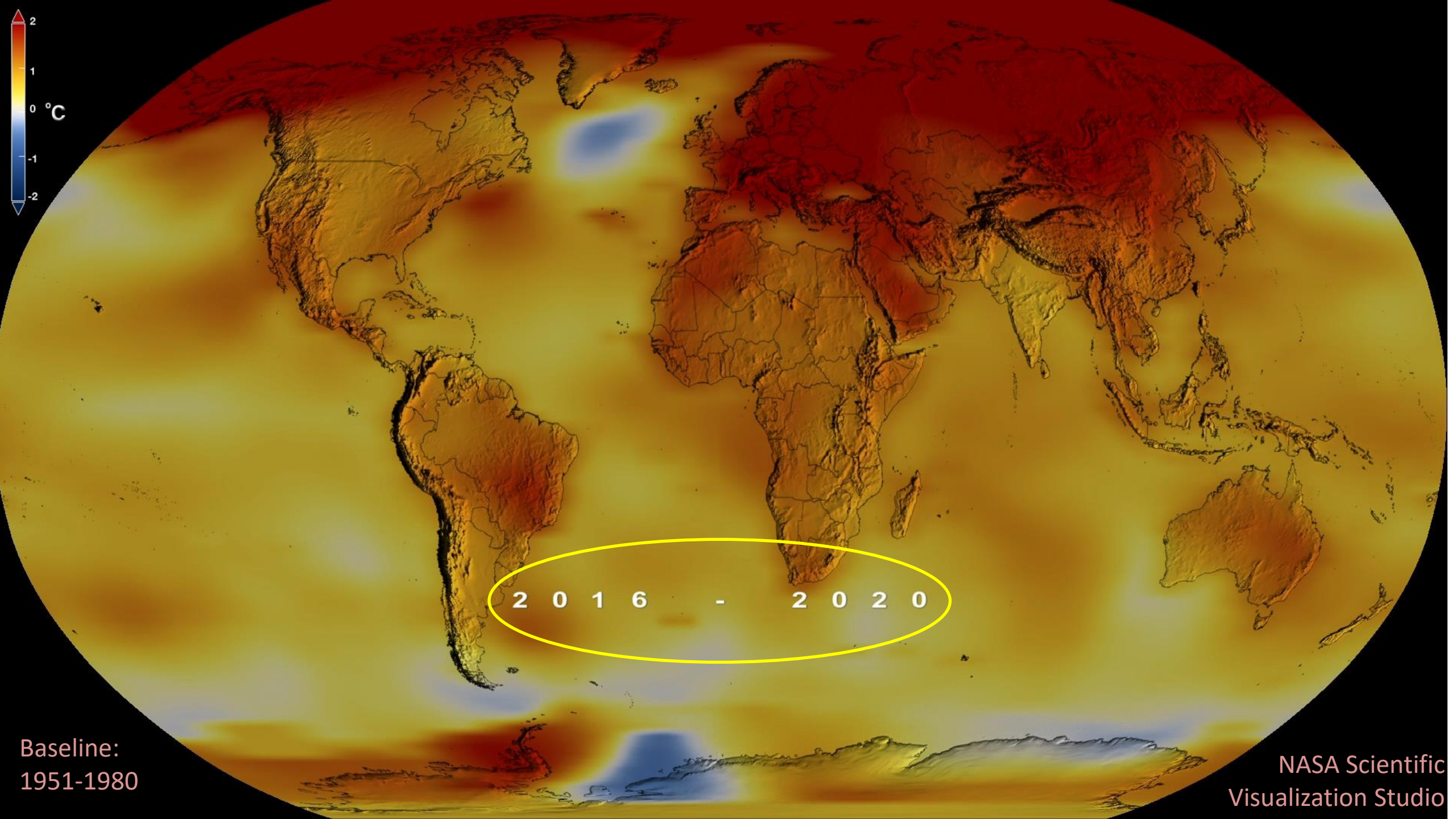
© Mail on Sunday



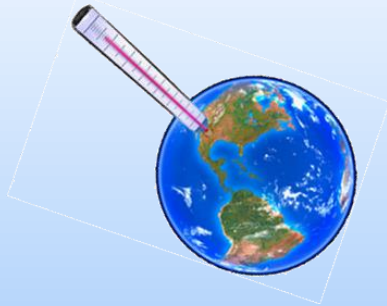
WattsUpWithThat

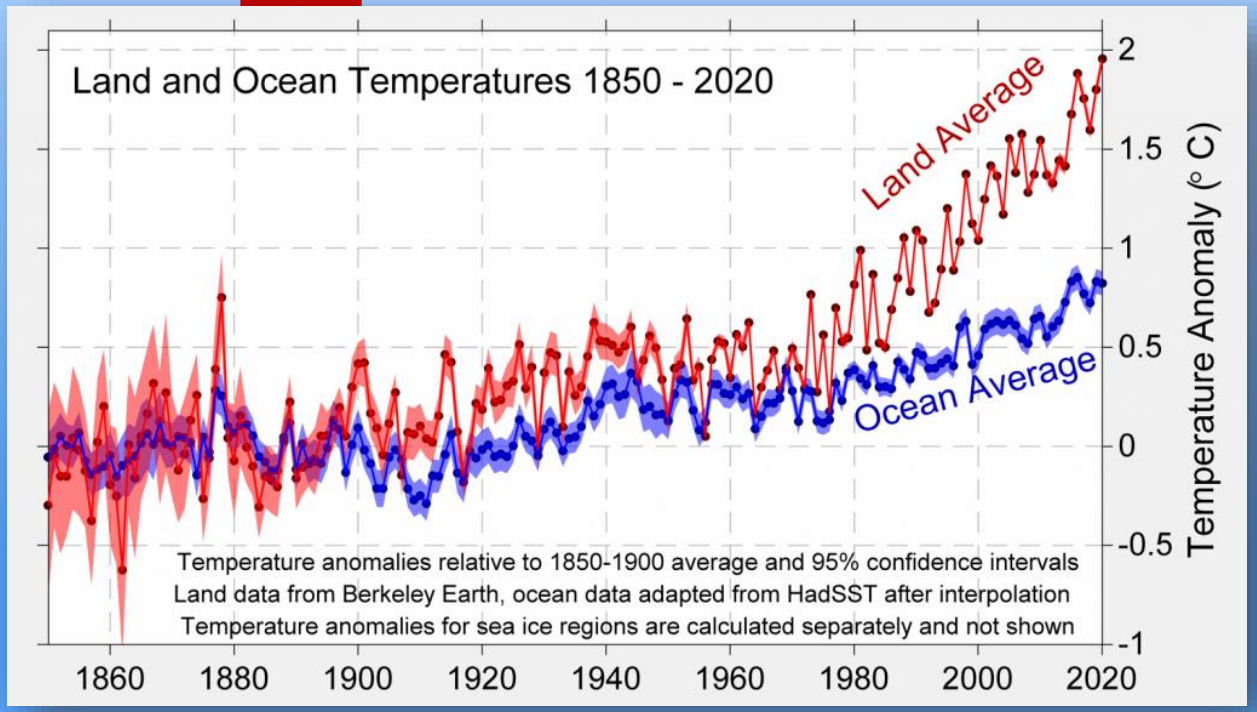

Land and Ocean Temperatures 1850 - 2020
Land heats up far faster than ocean surface….
Land Average
Ocean Average
Temperature anomalies relative to 1850-1900 average and 95% confidence intervals
Land data from Berkeley Earth, ocean data adapted from HadSST after interpolation
Temperature anomalies for sea ice regions are calculated separately and not shown
Temperature Anomaly (° C)
2
1
0
1.5
0.5
-0.5
-1
1860
1880
1900
1920
1940
1960
1980
2000
2020

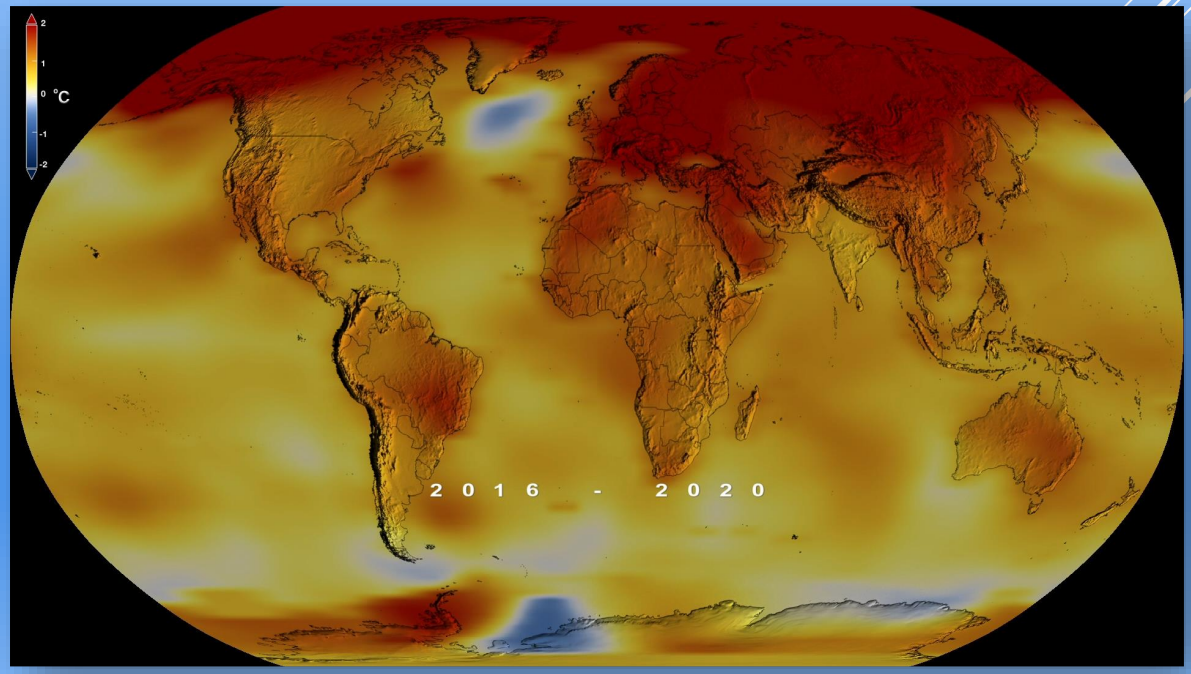

2
1
0 °C
-1
-2
Global Temperature Anomalies *vs.* 1951-1980 Baseline
Movie shows development regionally and over time of Temperature Anomalies. *Note the Color scale top-left.*
1 8 8 0 - 1 8 8 4
Baseline:
1951-1980
NASA Scientific
Visualization Studio


2
1
0 °C
-1
-2
2016 - 2020
Baseline:
1951-1980
NASA Scientific
Visualization Studio

Questions about the Recent Instrumental Global Temperature Record

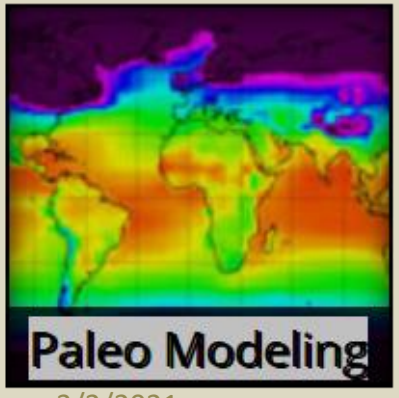






Paleoclimatology Datasets

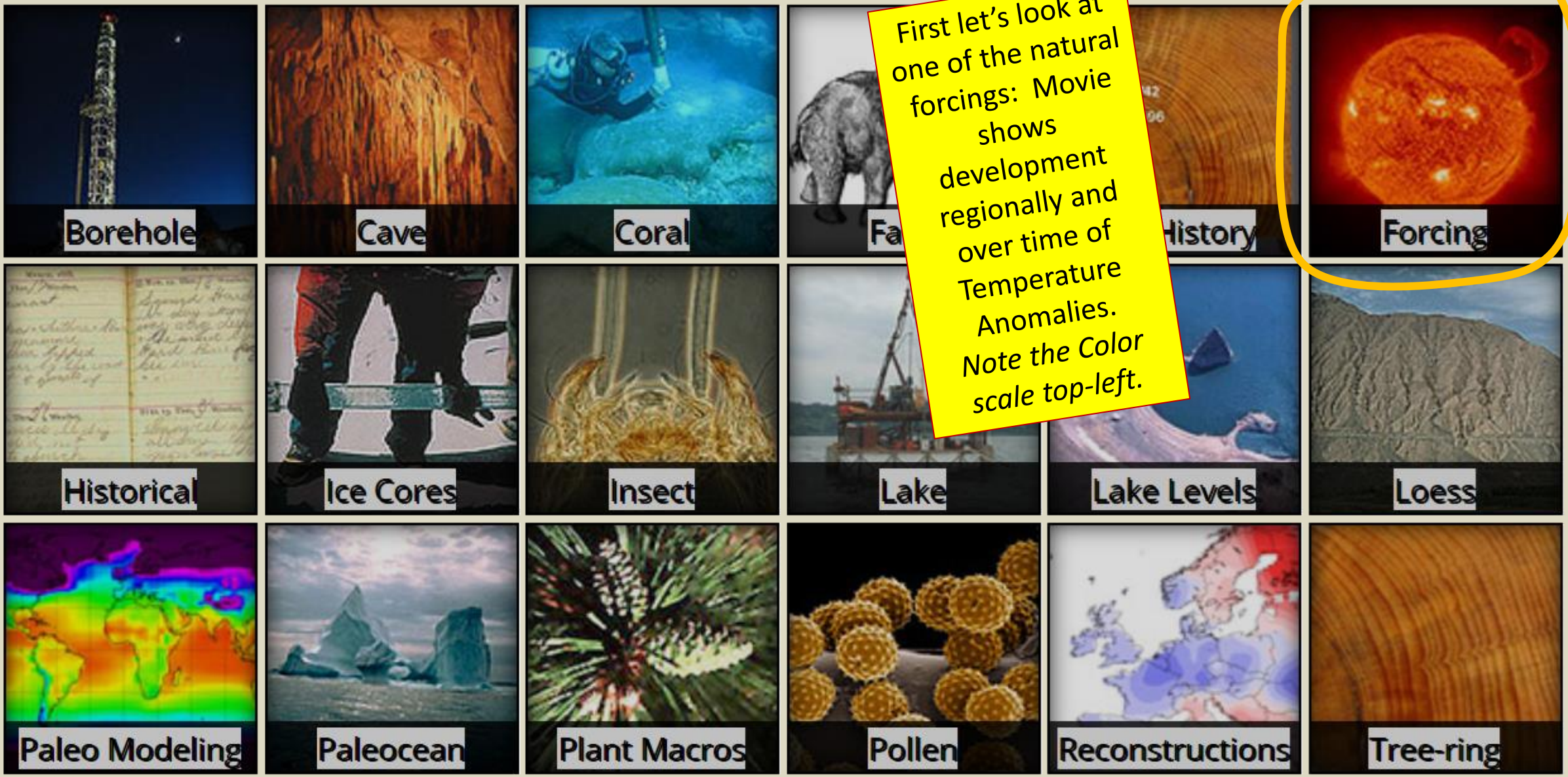
PROXIES



National Climatic Data Center (NOAA)


HITACHI
60 ton trunk of Kauri tree found
in a bog in New Zealand.
42,000 years old, lived 1700 years

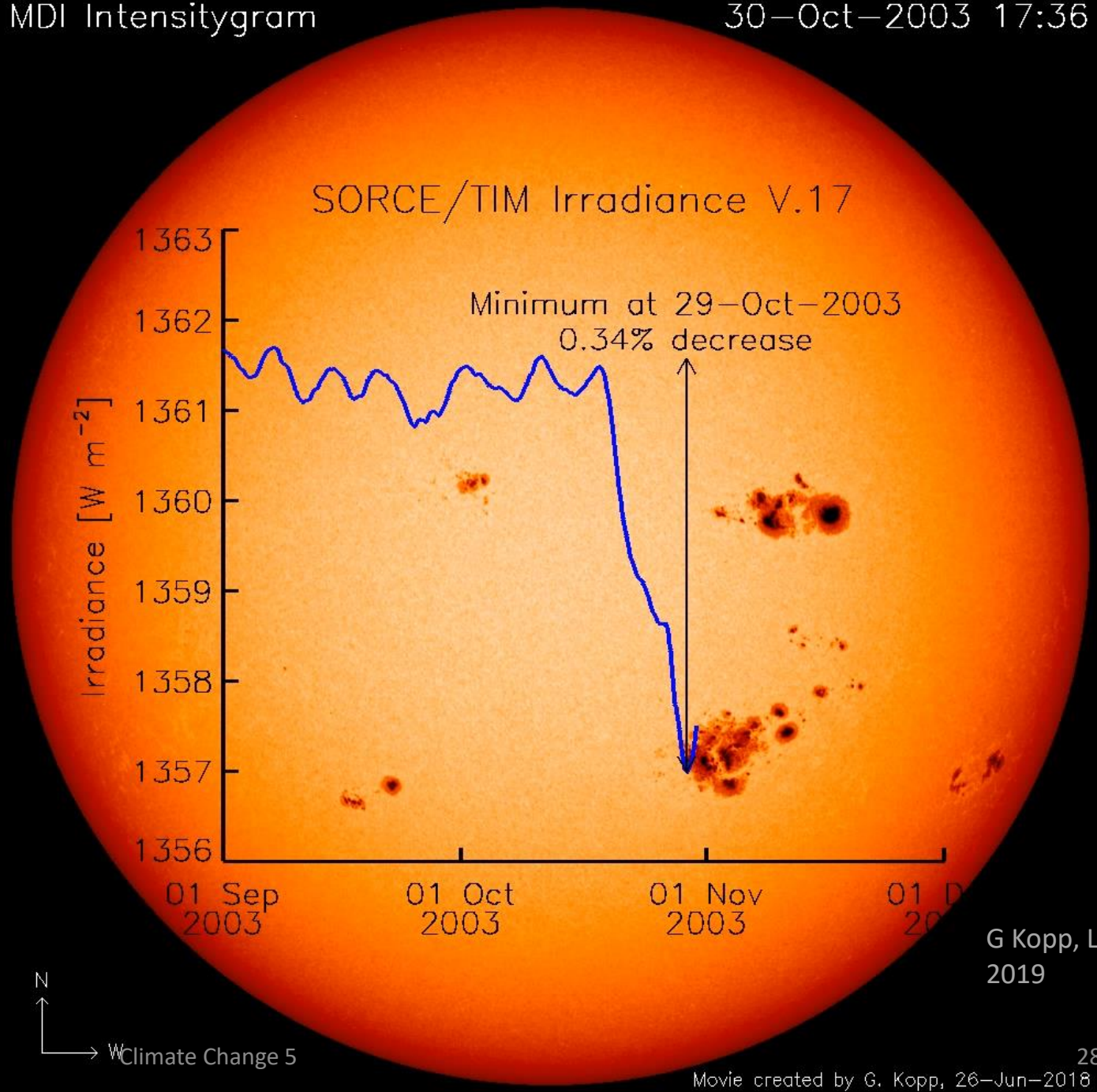
Paleoclimatology Datasets



First let's look at one of the natural forcings: Movie shows development regionally and over time of Temperature Anomalies. *Note the Color scale top-left.*

Fall 2003: High Sunspot Activity

During active sunspot years, overall Irradiance is HIGHER, but it DROPS briefly when a sunspot drifts across



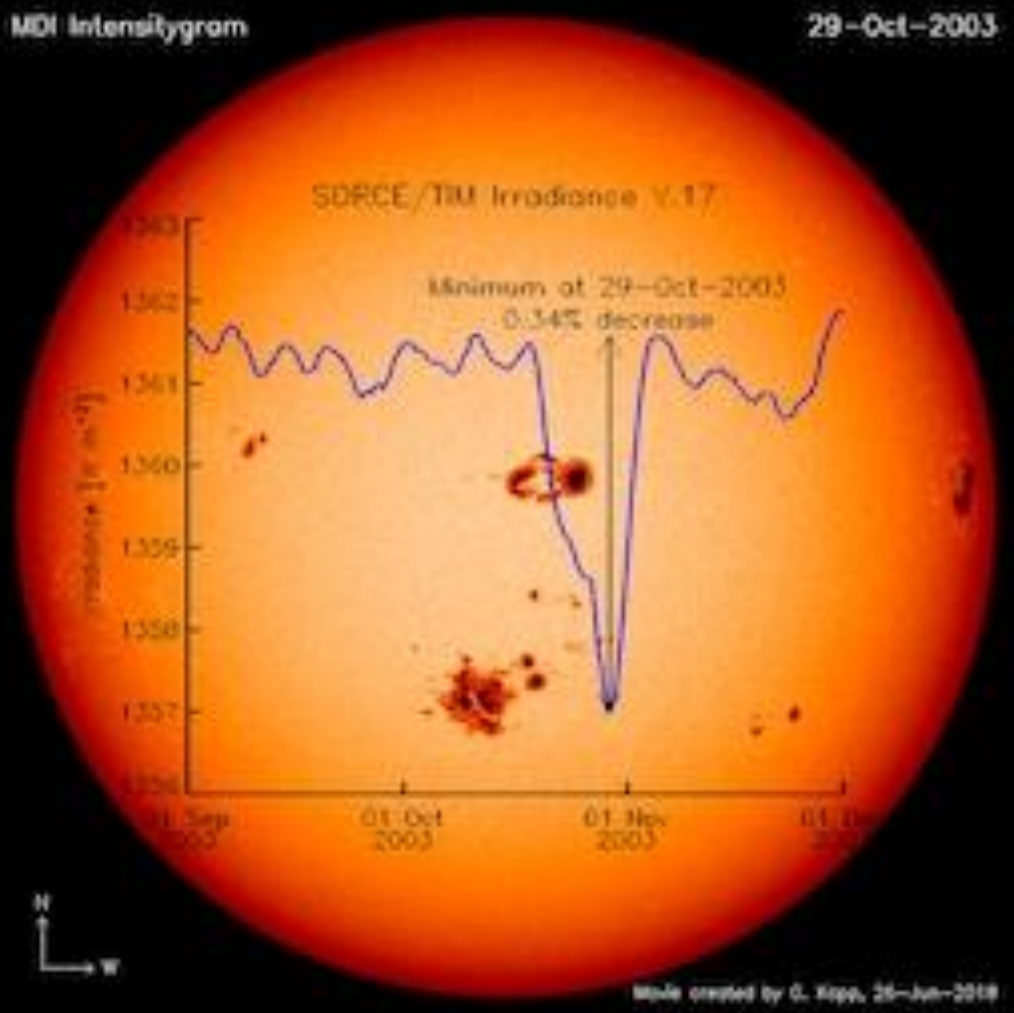
SORCE Solar Radiation & Climate Experiment

Laboratory for Atmospheric and Space Physics
U Colorado (Boulder)

G Kopp, LASP 2019

Fall 2003: High Sunspot Activity

During active sunspot years, overall Irradiance is HIGHER, but it DROPS briefly when a sunspot drifts across

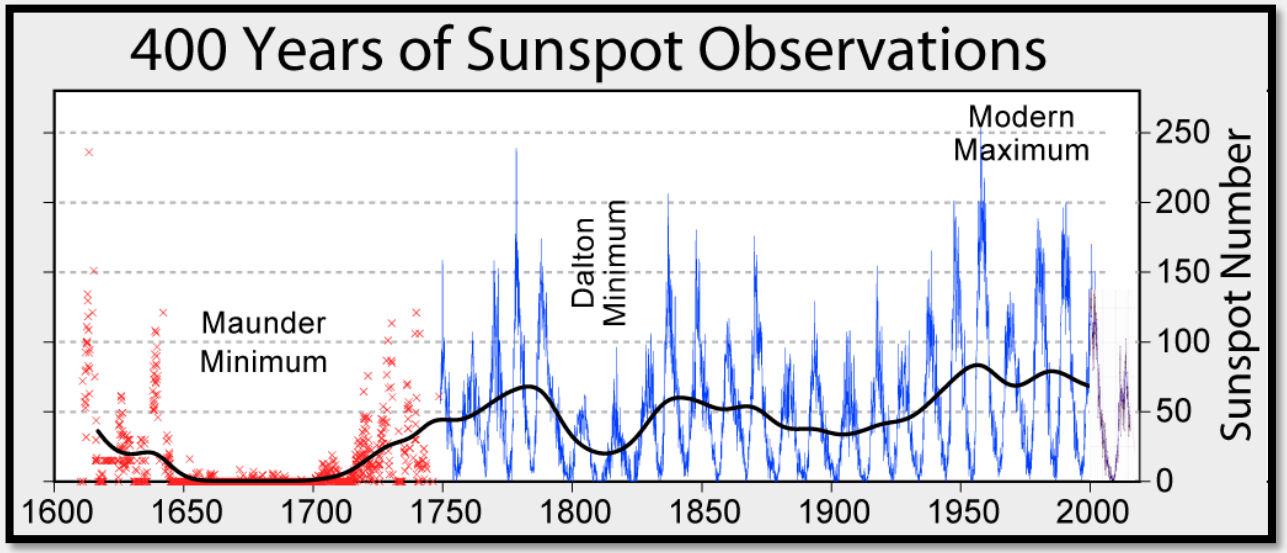


SORCE Solar Radiation & Climate Experiment

Laboratory for Atmospheric and Space Physics
U Colorado (Boulder)

G Kopp, LASP 2019

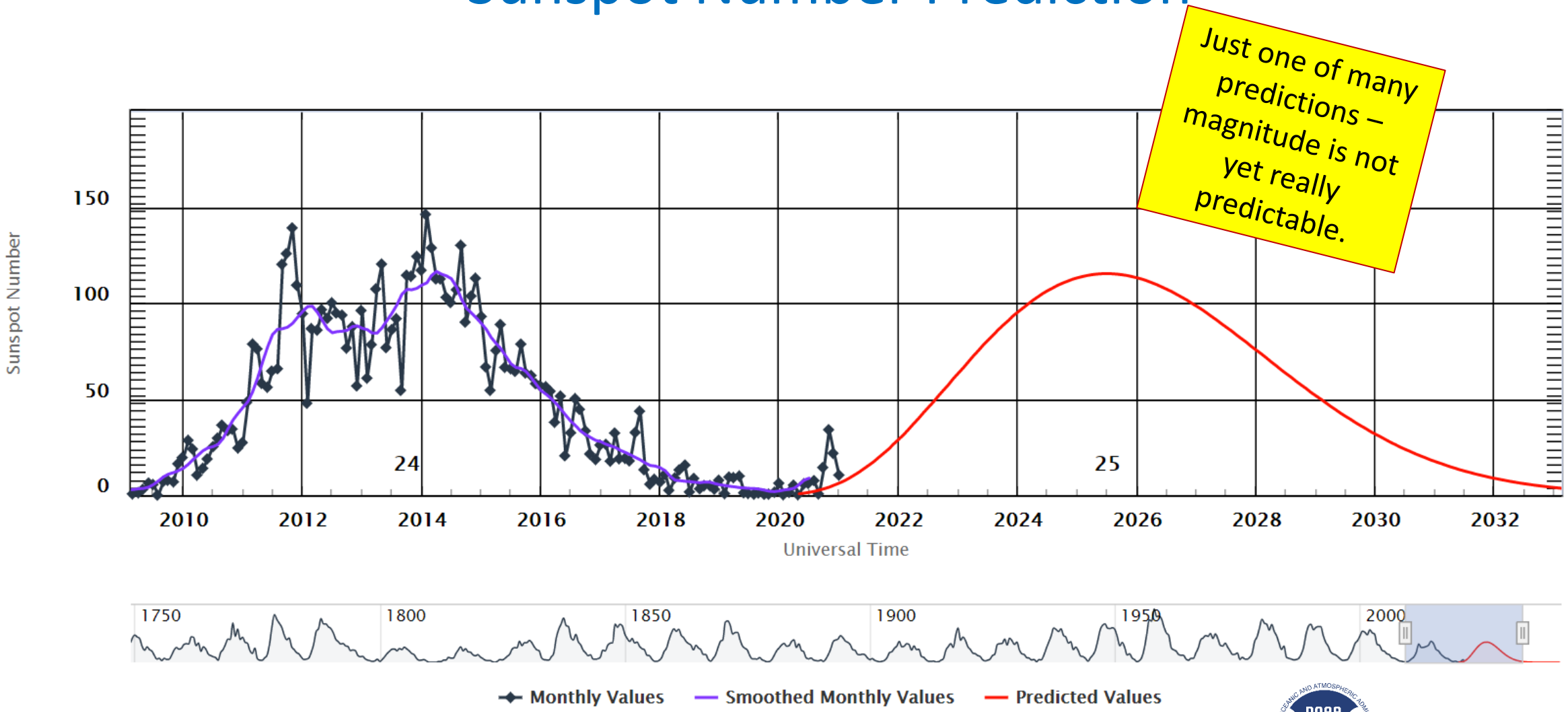
Meet the Maunders



Annie and Walter Maunder in India 1898 for Solar Eclipse expedition

1890's
Dallmeyer Photo-Heliograph at Royal Observatory Greenwich

Sunspot Number Prediction

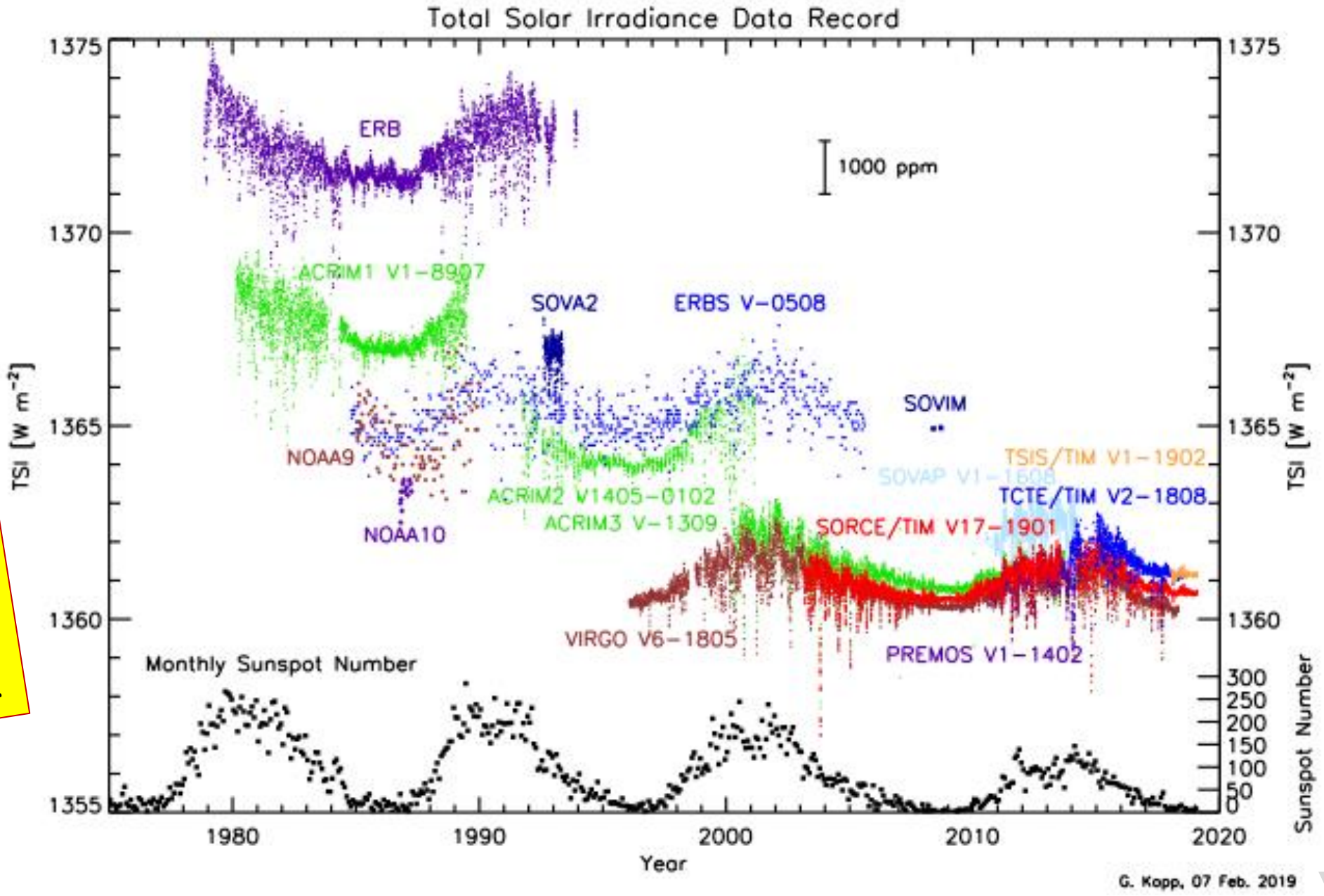


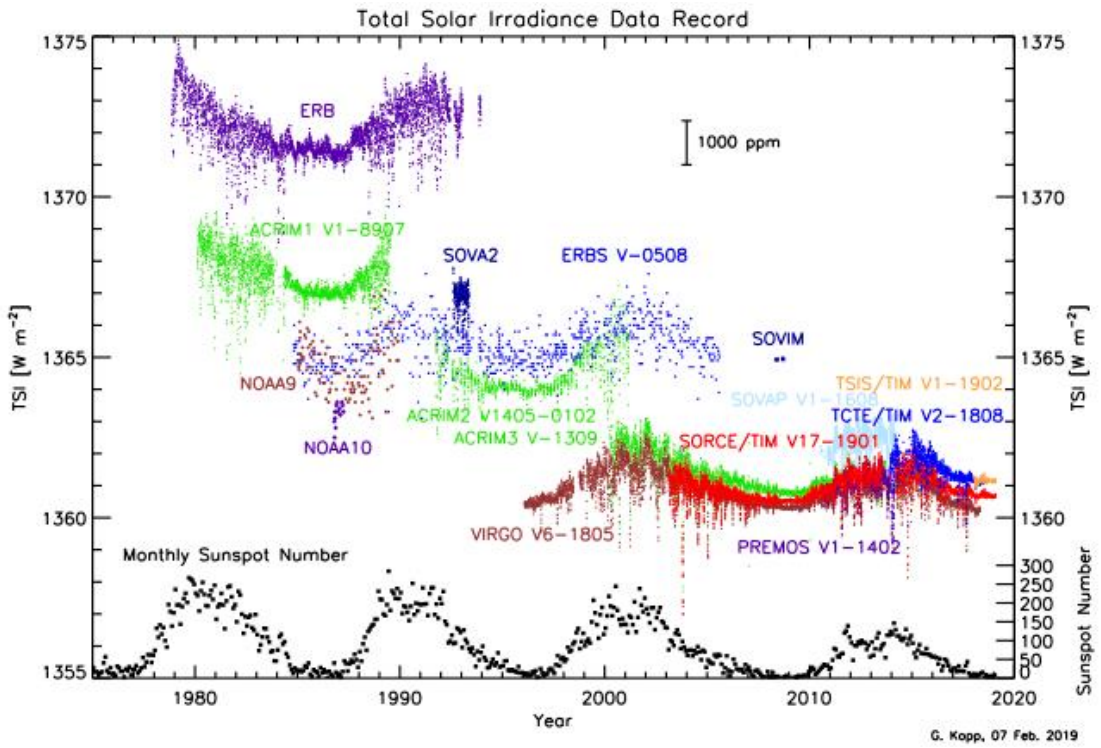
Space Weather Prediction Center

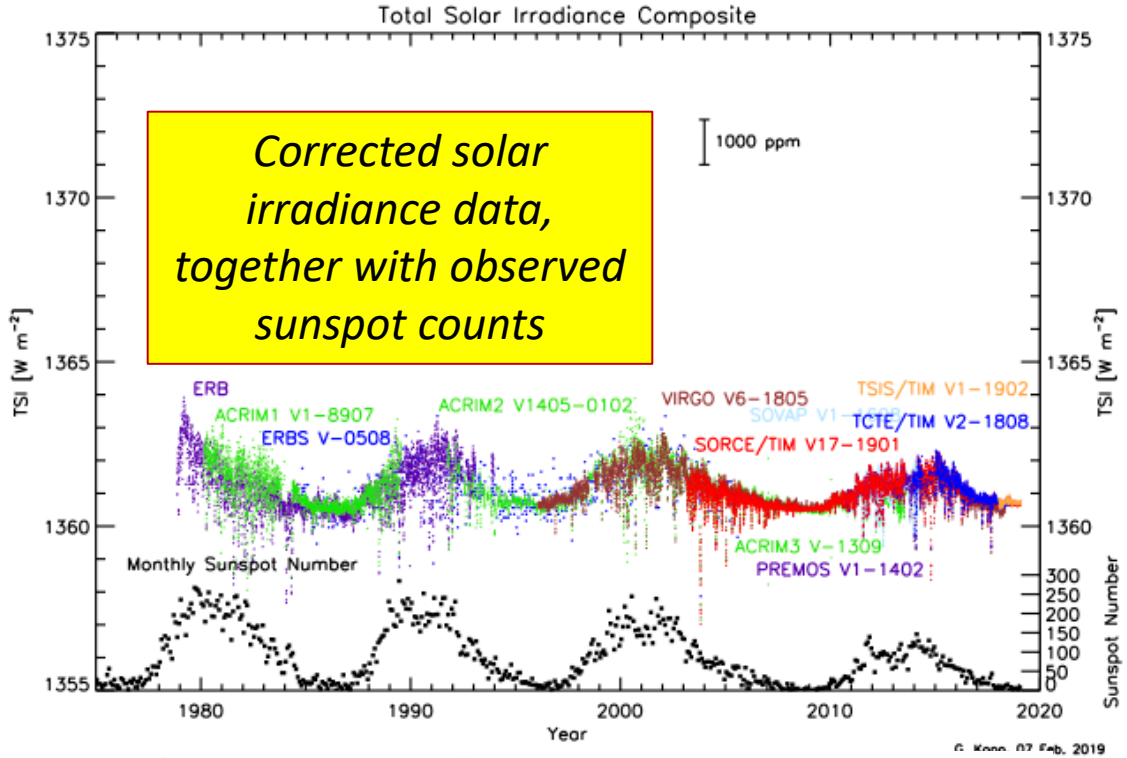
Satellite Solar Irradiance Measurement

Only from orbit, above the atmosphere, can accurate Solar Irradiance measurements be made. Early satellites like ERB had optical design errors which resulted in over-estimates of true irradiance.

These errors were corrected and properly calibrated in later designs.

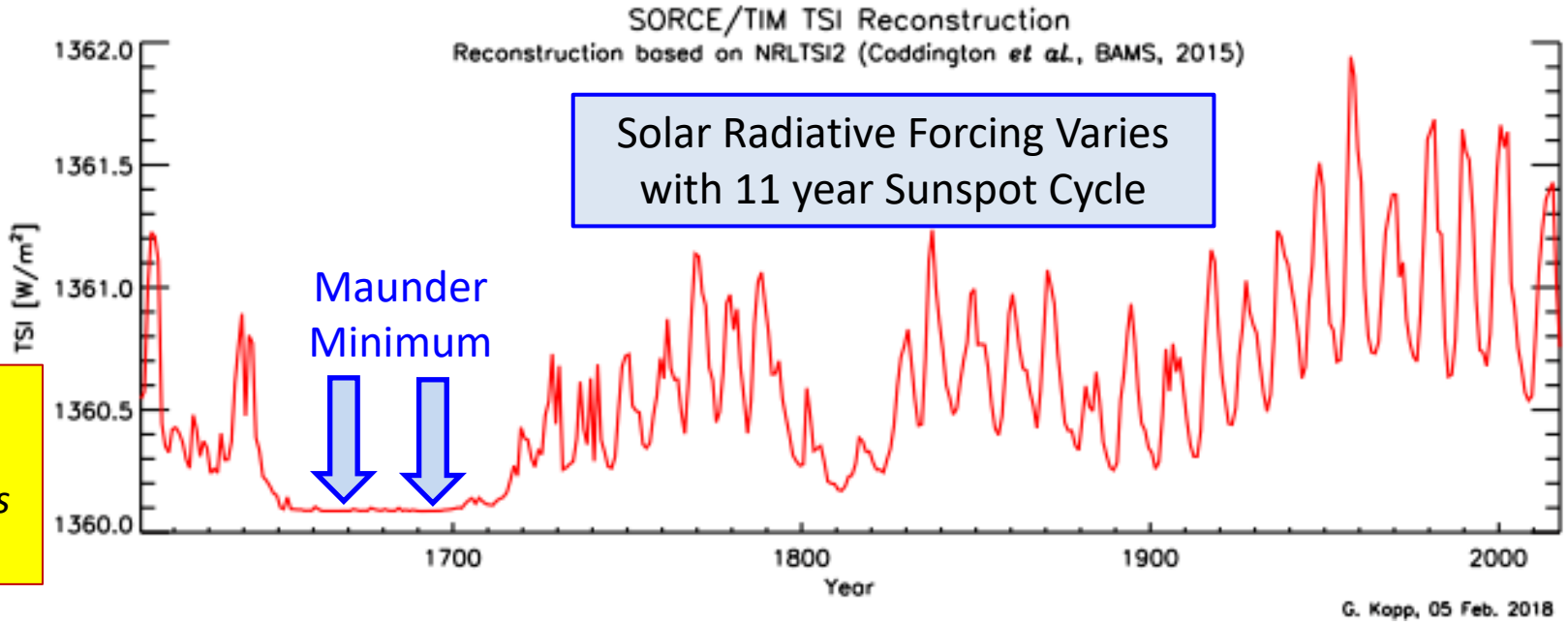




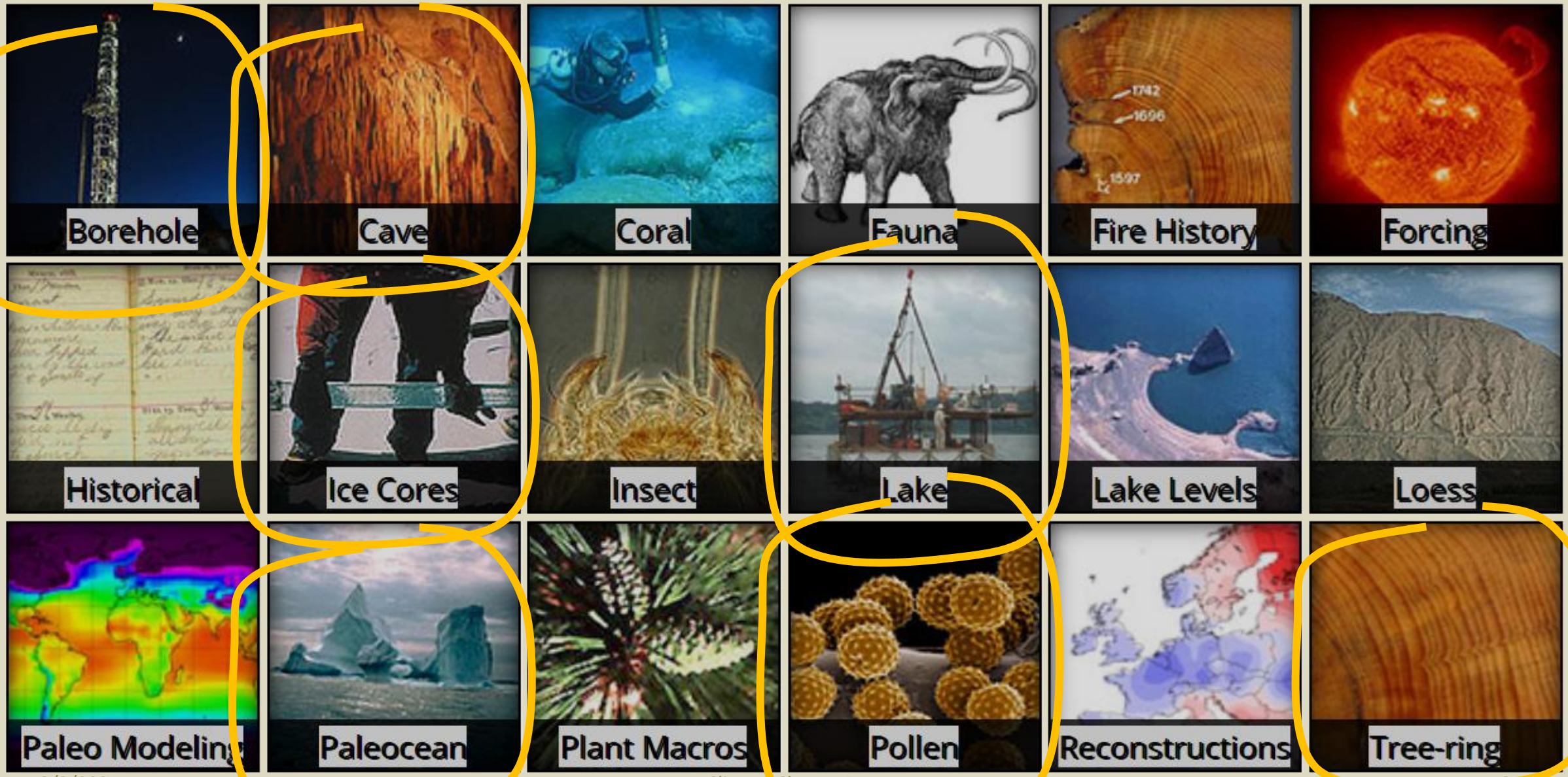


Satellite Solar Irradiance Measurements

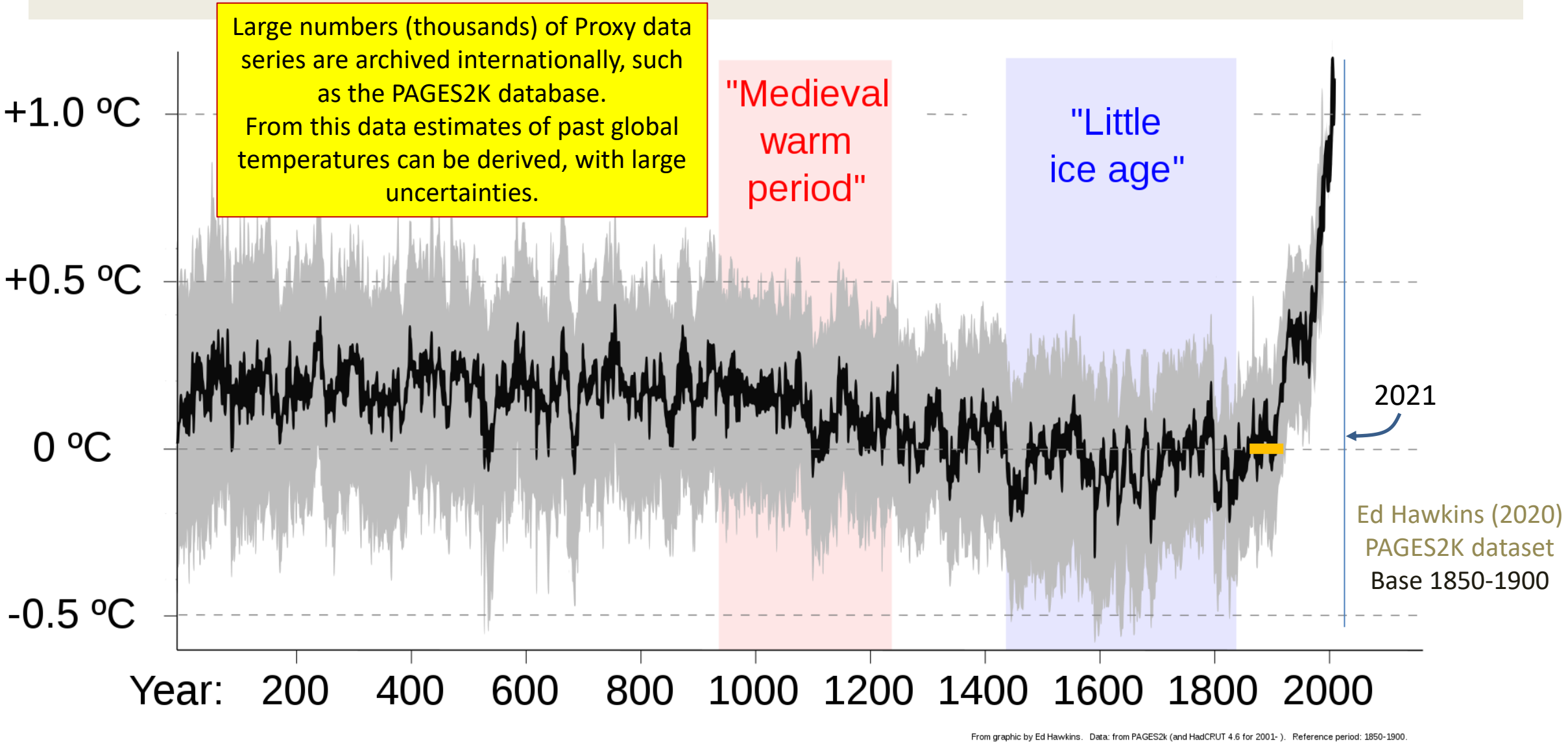
To right: Best estimates of historical Solar Irradiance based on recorded sunspot activity. Total variation is less than 2 W/m2 out of 1360 W/m2.



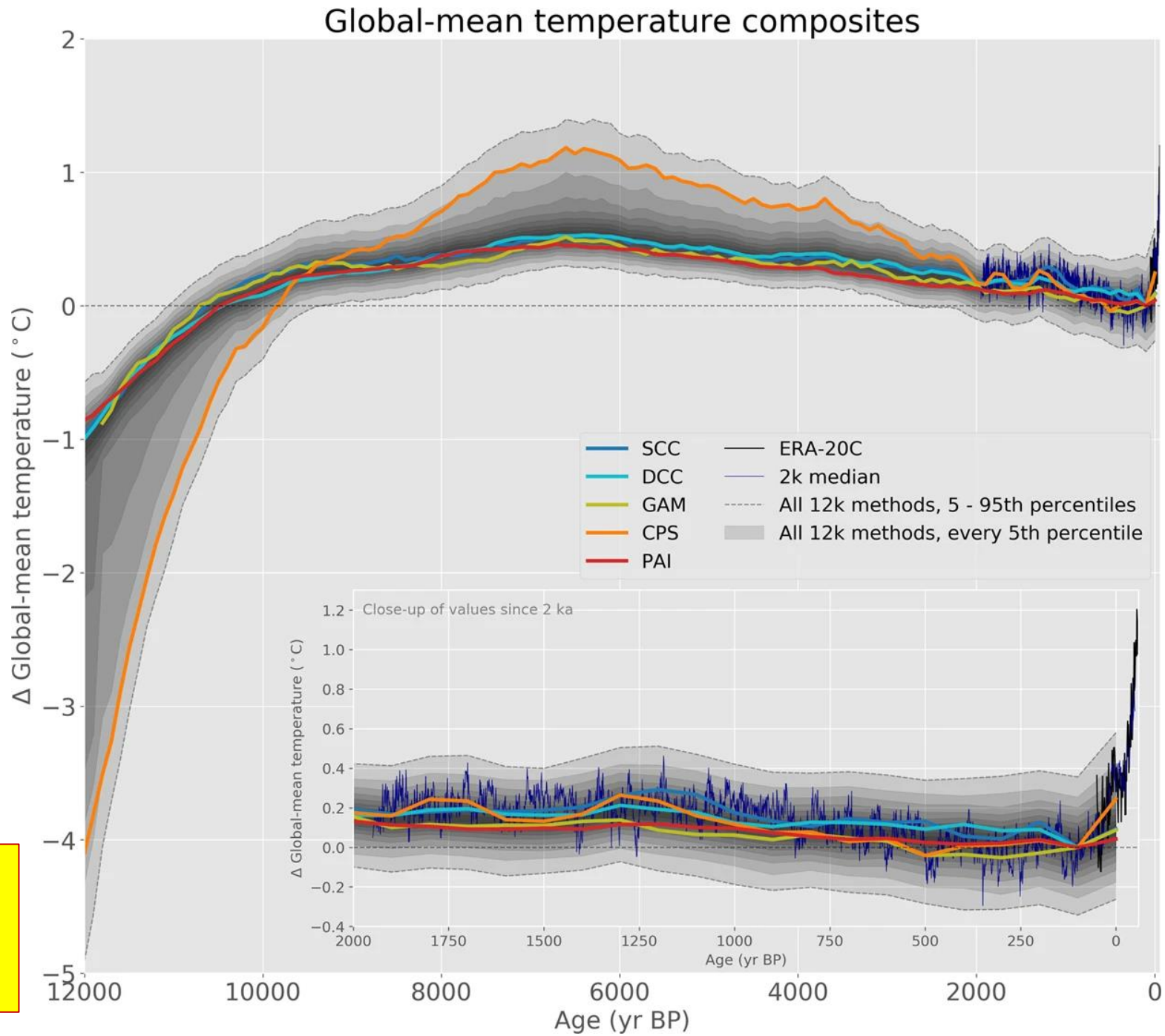
Paleoclimatology Datasets



Global Temperature Anomaly Estimated from Proxy Data



12,000 Year Global Temperature Reconstructions based on ~800 Proxy Records



Kaufman et al,
"Holocene Global Mean Temperature, a Multi-Method Reconstruction Approach",
Nature: Scientific Data (2020)

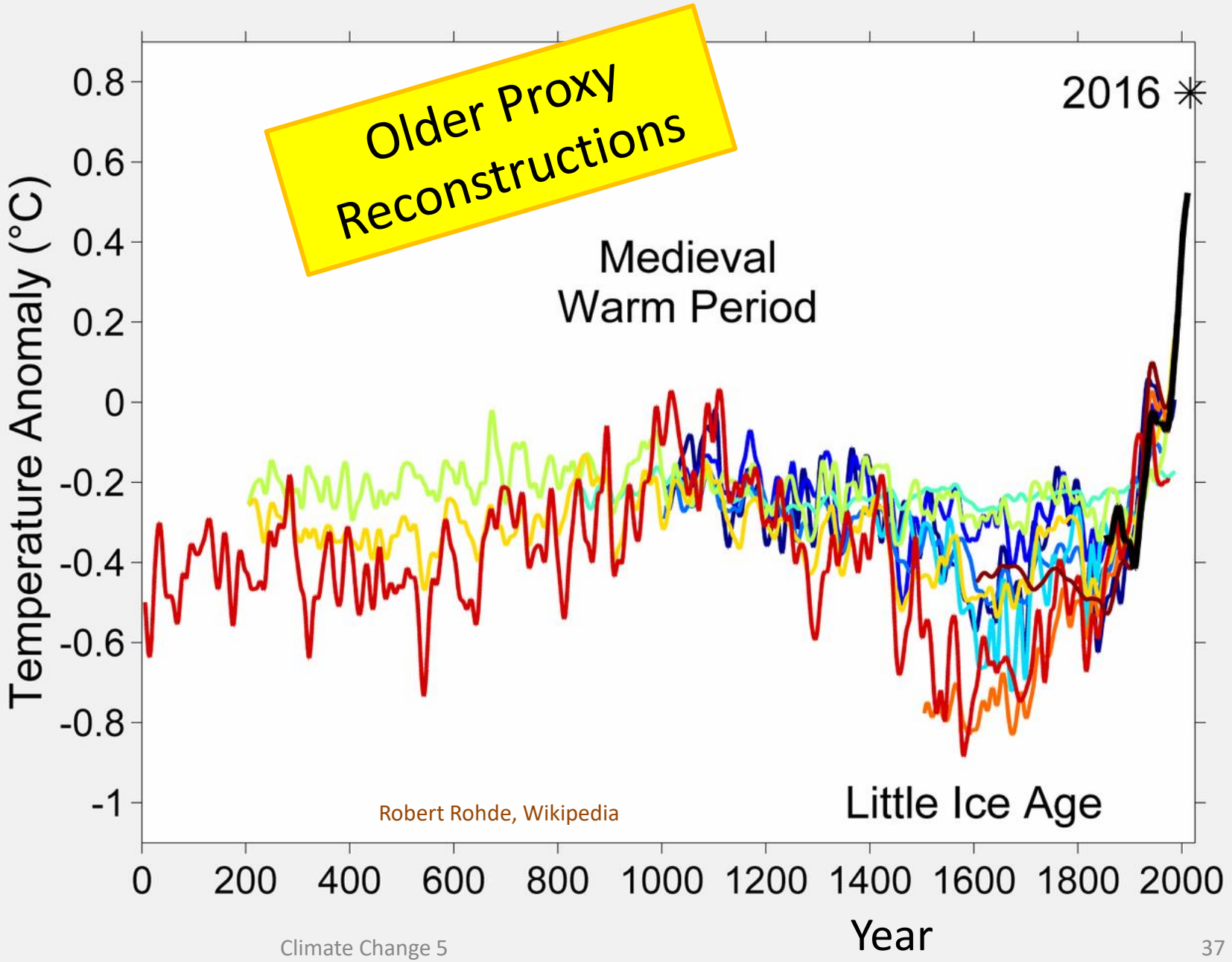
At 1200 years before present (BP), we are coming out of the last ice age. Temperature peaks at ~ 6000 years BP. then slowly falls, until industrial era.

Various Proxy Reconstructions of Global Temperature for Last 2000 Years

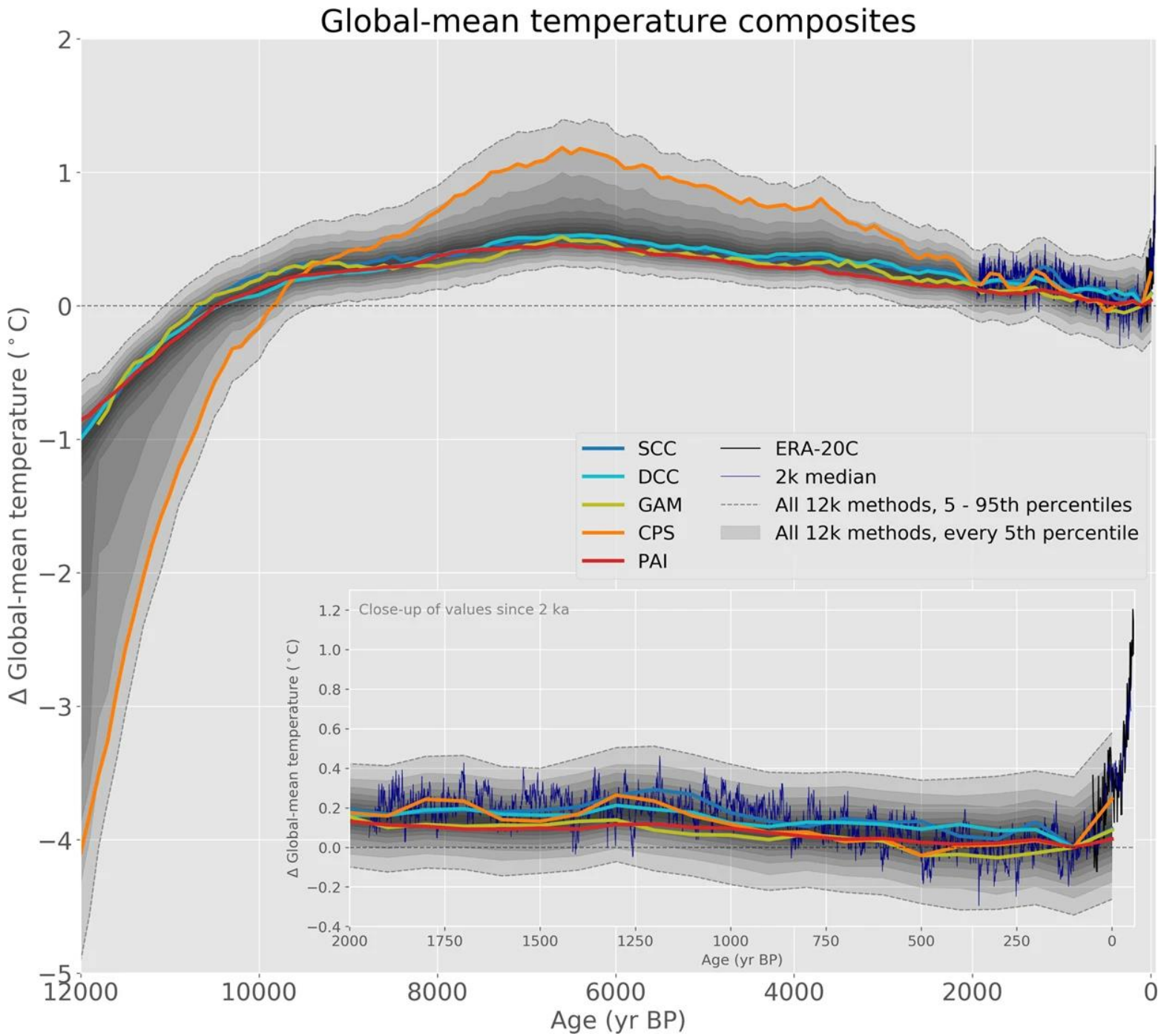
Instrumental Record

Moberg *et. al.* Nature (2005) 11 Proxy Datasets

Early reconstructions were based on regionally biased datasets (European e.g.) which show more variability, including the infamous “Medieval Warm Period” and “Little Ice Age”

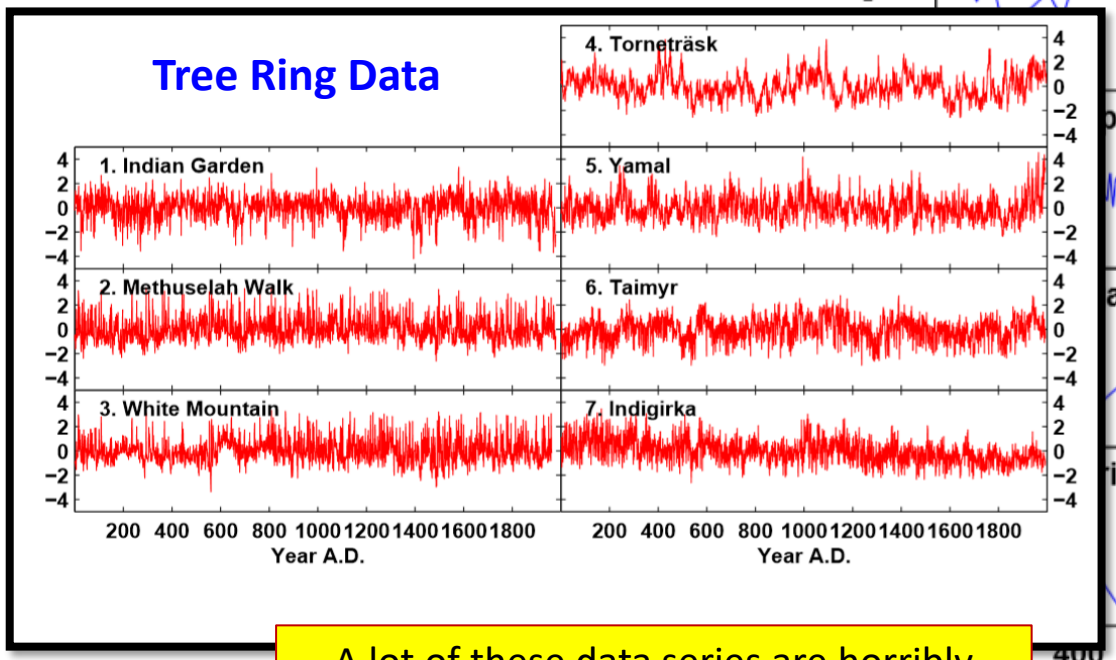


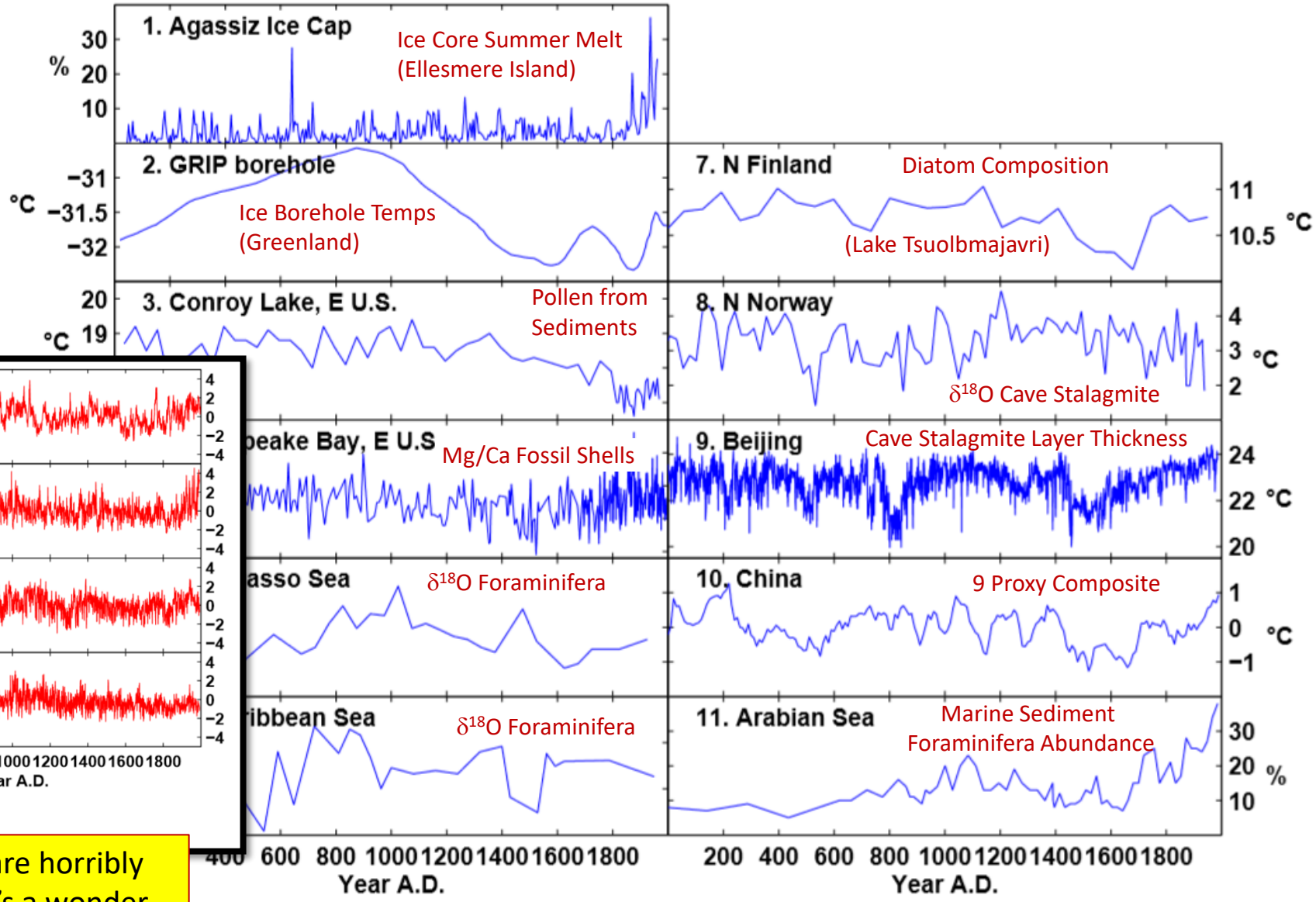
12,000 Year Global Temperature Reconstructions based on ~800 Proxy Records



Kaufman et al,
"Holocene Global Mean Temperature, a Multi-Method Reconstruction Approach",
Nature: Scientific Data (2020)

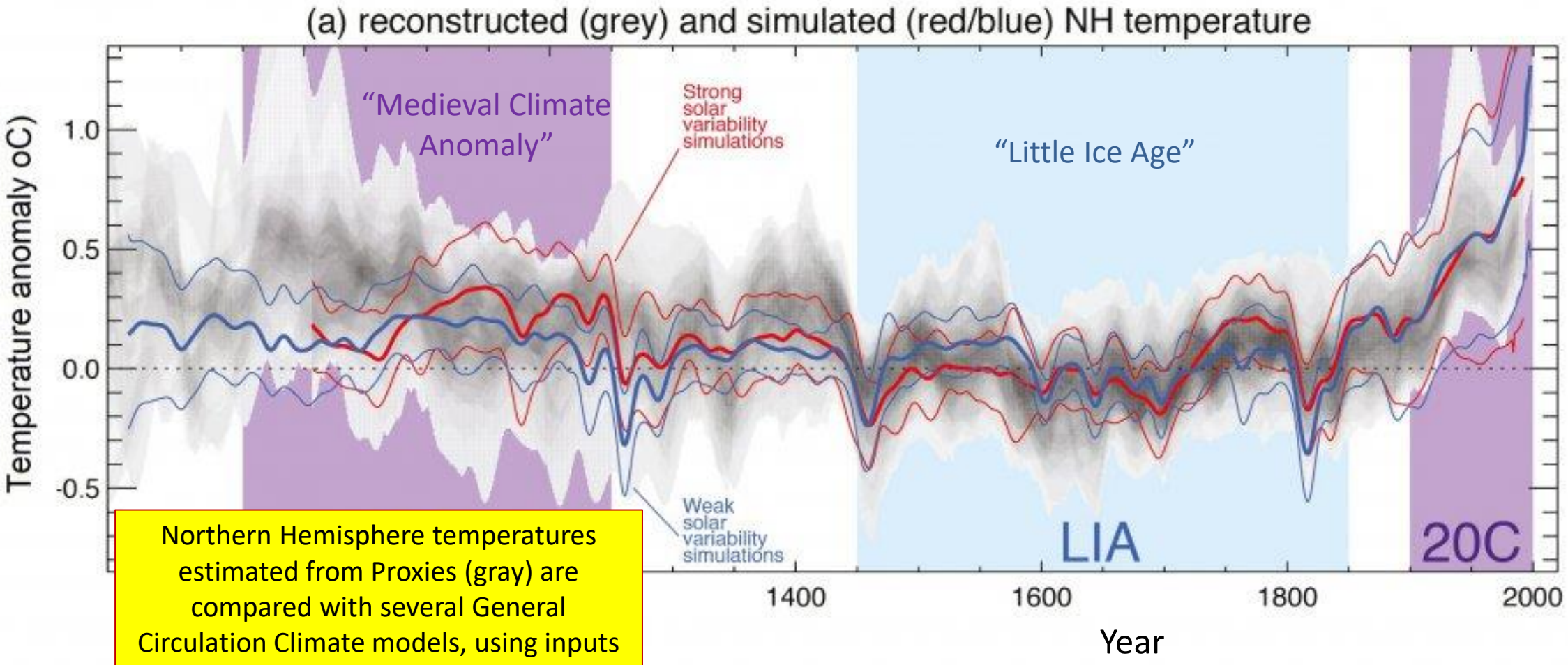
Examples of Proxy Data Used in Climate Reconstruction





A lot of these data series are horribly noisy and uncorrelated. It's a wonder that anything useful can be recovered, and we should be a bit skeptical.

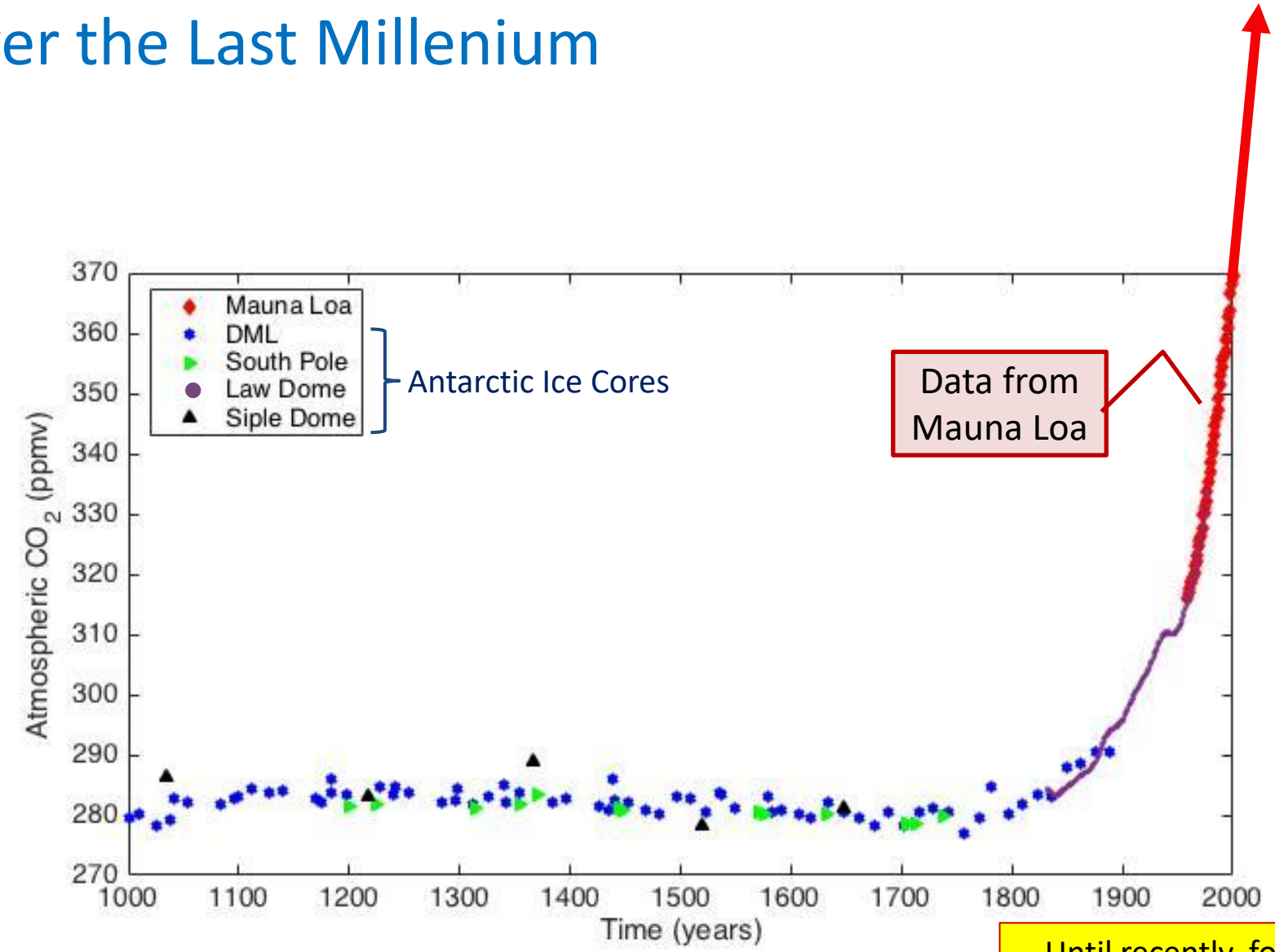
Attempts to Model Recent Northern Hemisphere Climate

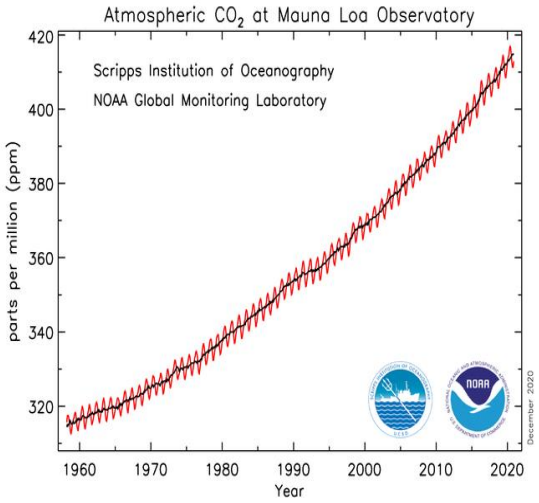


Northern Hemisphere temperatures estimated from Proxies (gray) are compared with several General Circulation Climate models, using inputs such as known CO2 concentrations and volcanic eruptions. Decent agreement is obtained.

IPCC AR5 WG1
Fig 5.08a

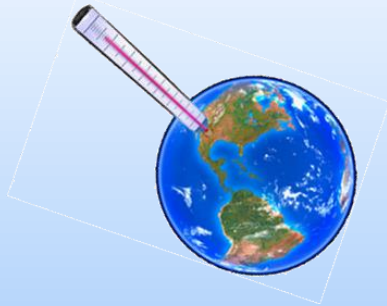
CO_2 in Atmosphere over the Last Millenium

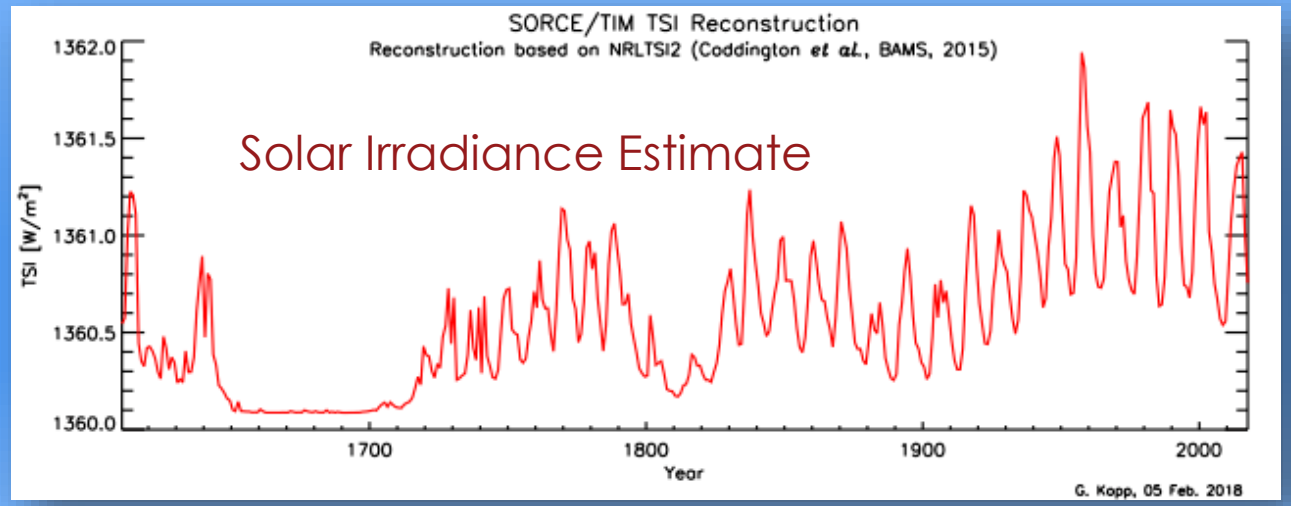


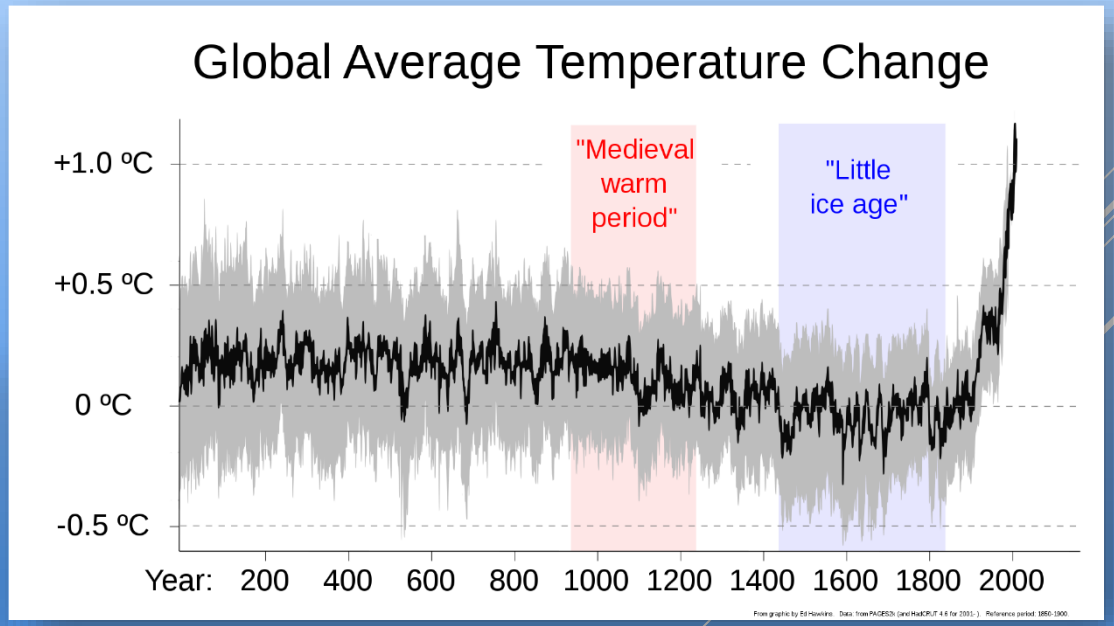


Until recently, for the last 1000 years, CO_2 hovered around 280 ppm.

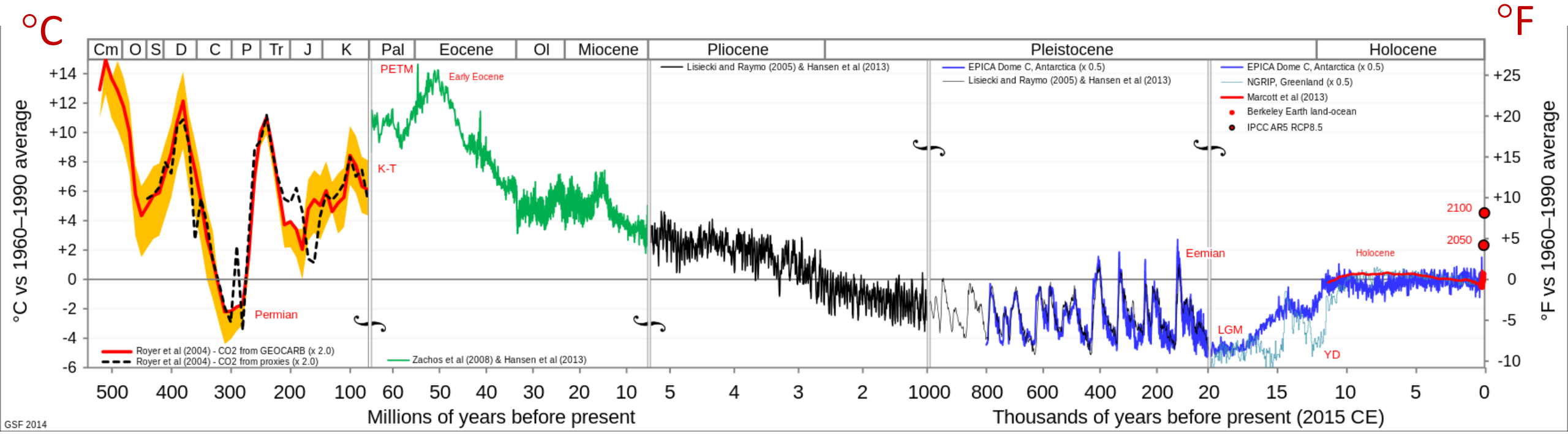
Questions about Sunspots and the Last Millenium?







Preview:
Proxy Estimates of Earth Surface Temperature



Glen Furgus "All Palaeotemps.svg" Wikipedia "Paleoclimatology". Composite from various source data.

The Most Important Temperature Proxy

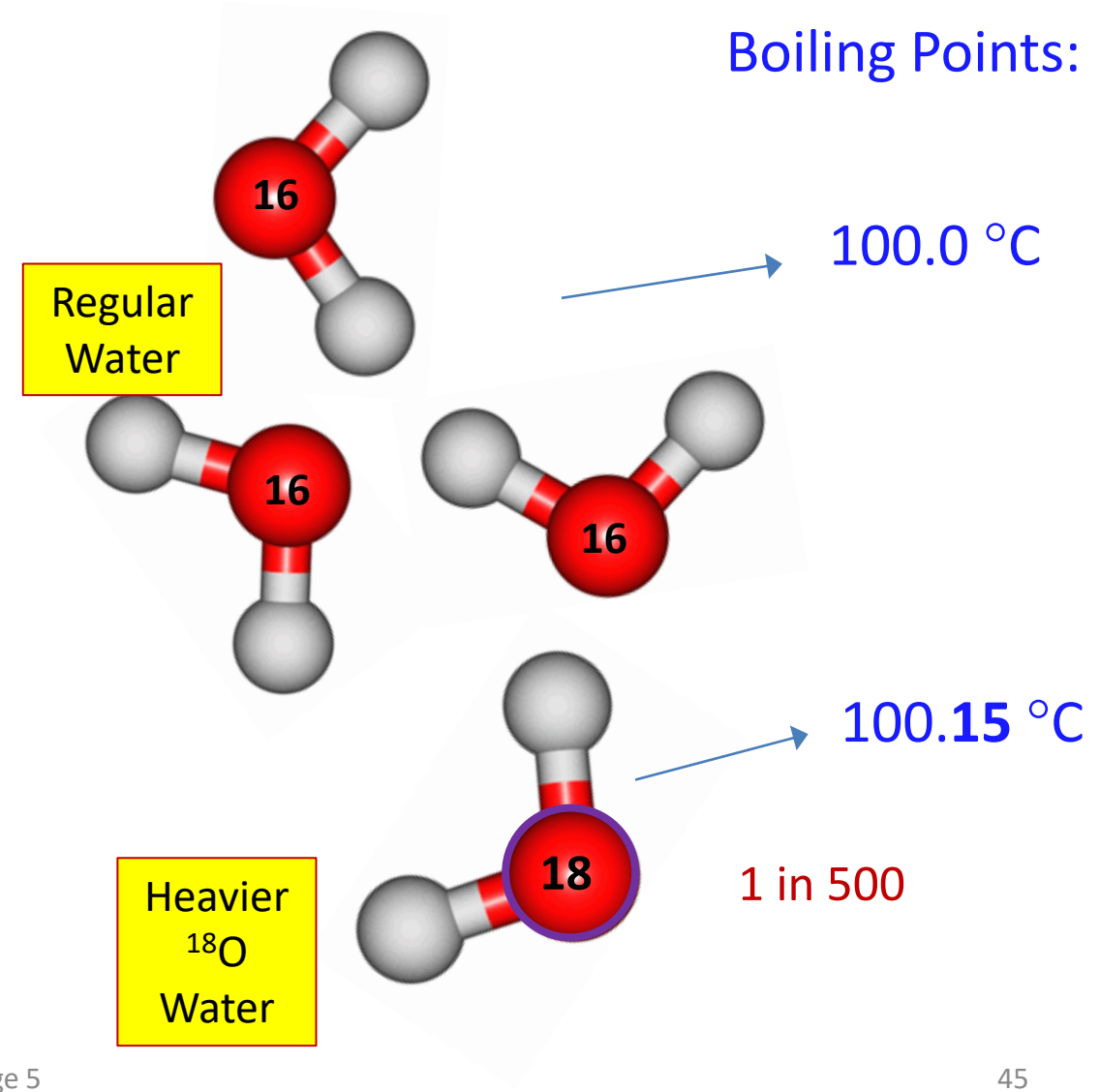
$$\delta^{18}O$$

"Delta Oh Eighteen"

Isotopologues of Water

Oxygen Isotopes			Hydrogen Isotopes		
^{16}O	16	99.75%	^{1}H	1	99.985%
^{17}O	17	0.04%	^{2}H	2	0.015%
^{18}O	18	0.20%		(Deuterium)	

9 Water Isotopologues



Isotopologues of Water

Since Boiling Points are different, regular water and ^{18}O water can be separated by multiple distillation….

Oxygen Isot

^{16}O **16** 99.75%

^{17}O **17** 0.04%

^{18}O **18** 0.20%

9 Water Isc

Boiling Points:

100.0 °C

100.**15** °C

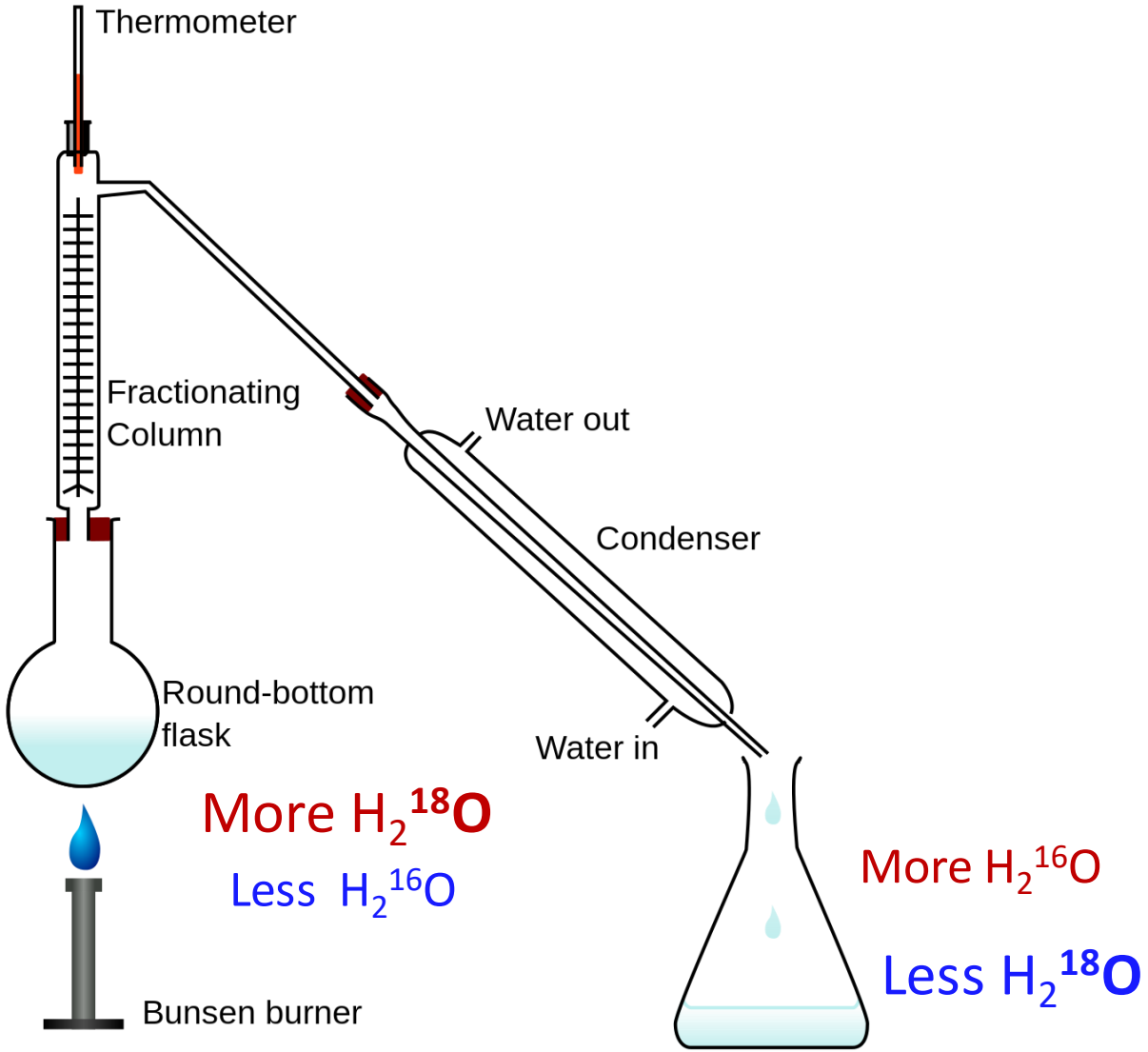
1 in 500

You can buy it…

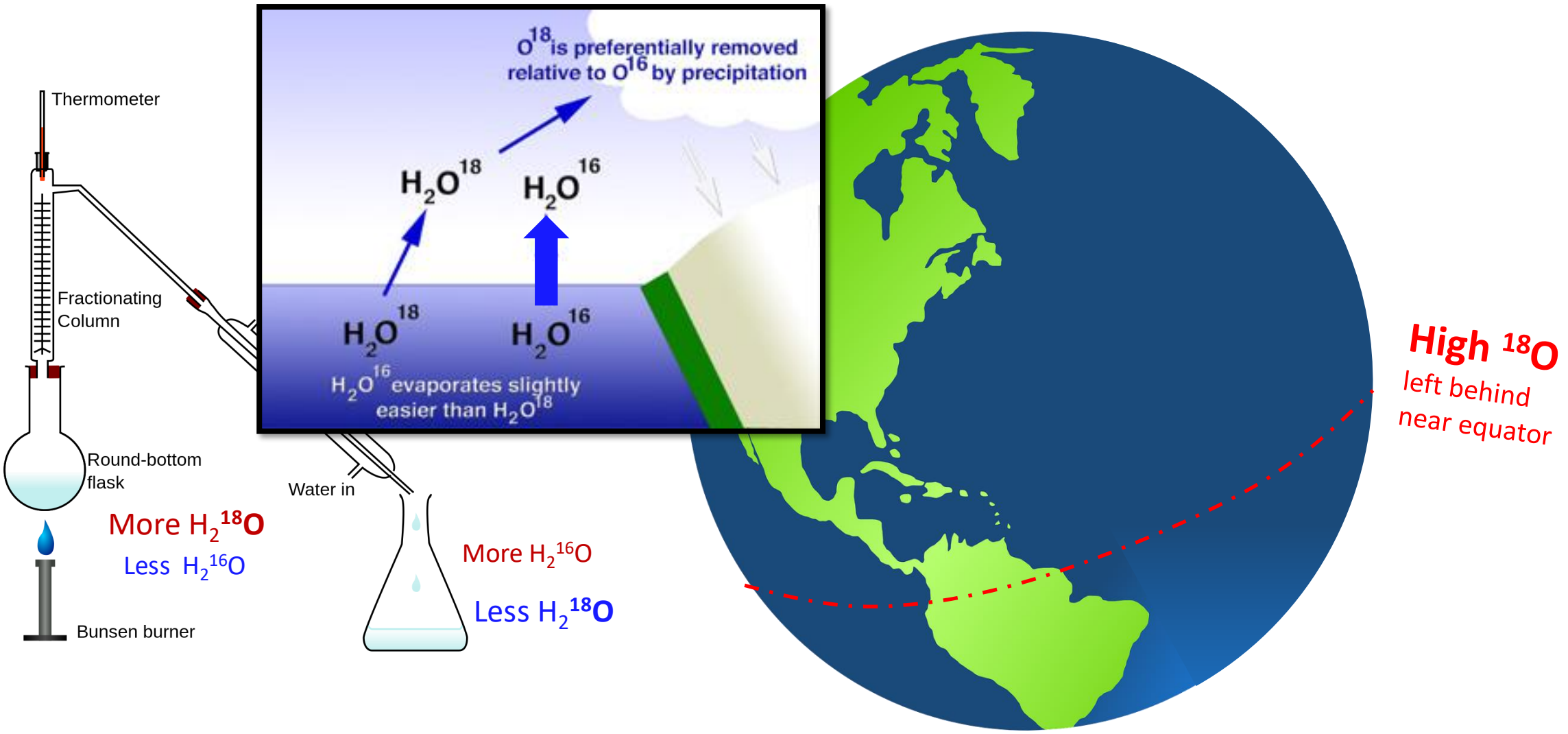
Sigma-Aldrich:

$272,000 per liter

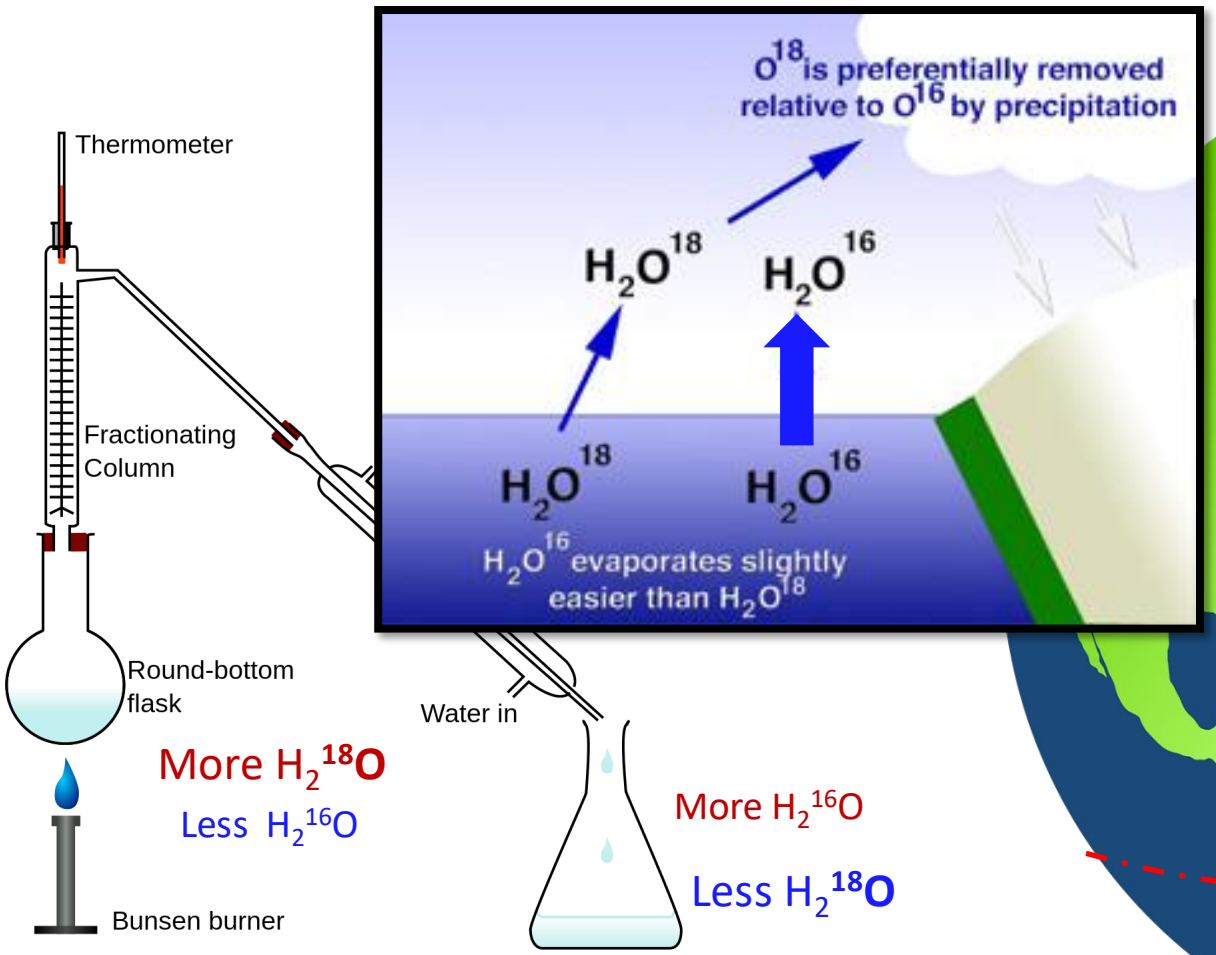
Fractionation by Distillation

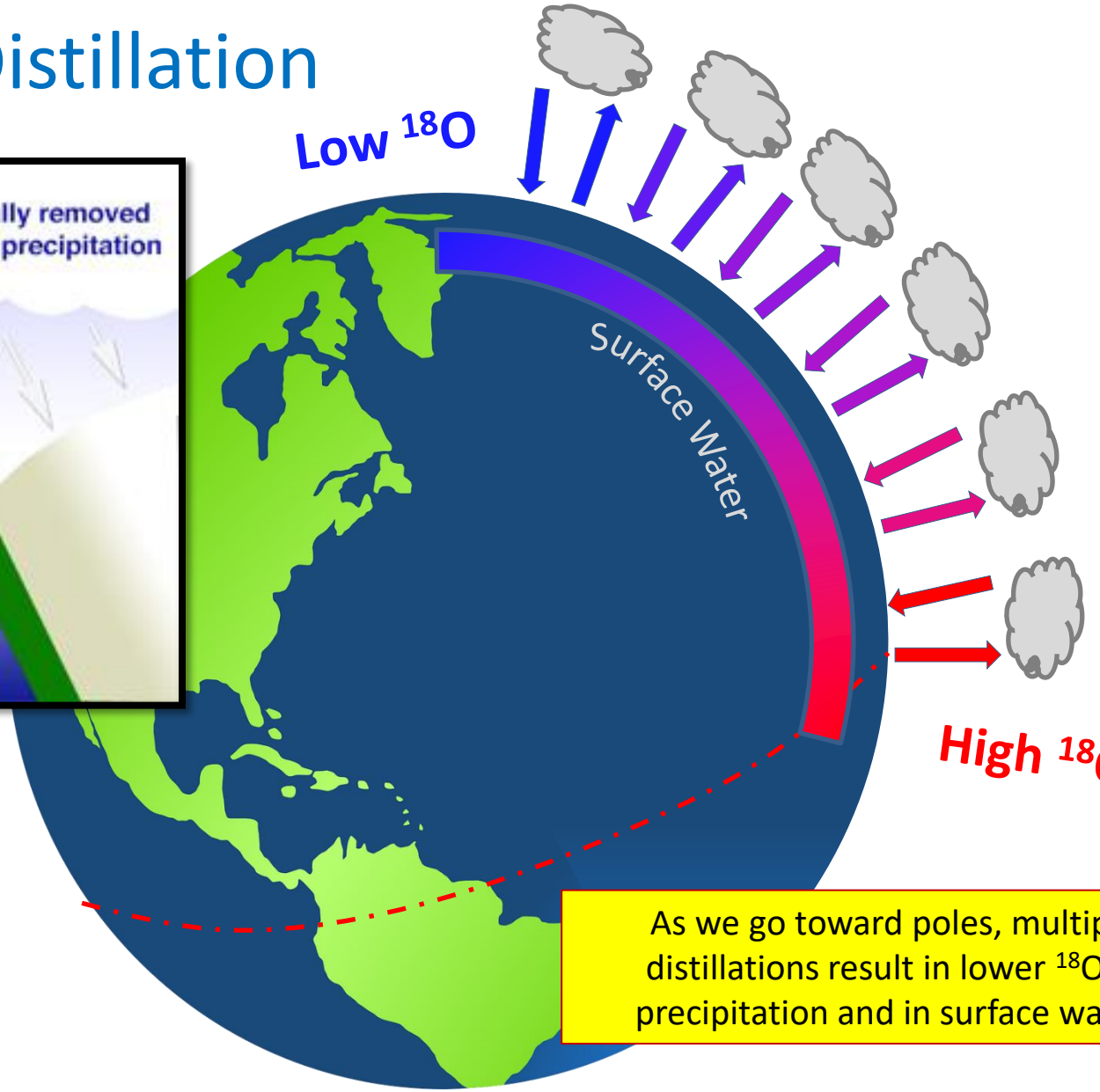


Fractionation by Distillation



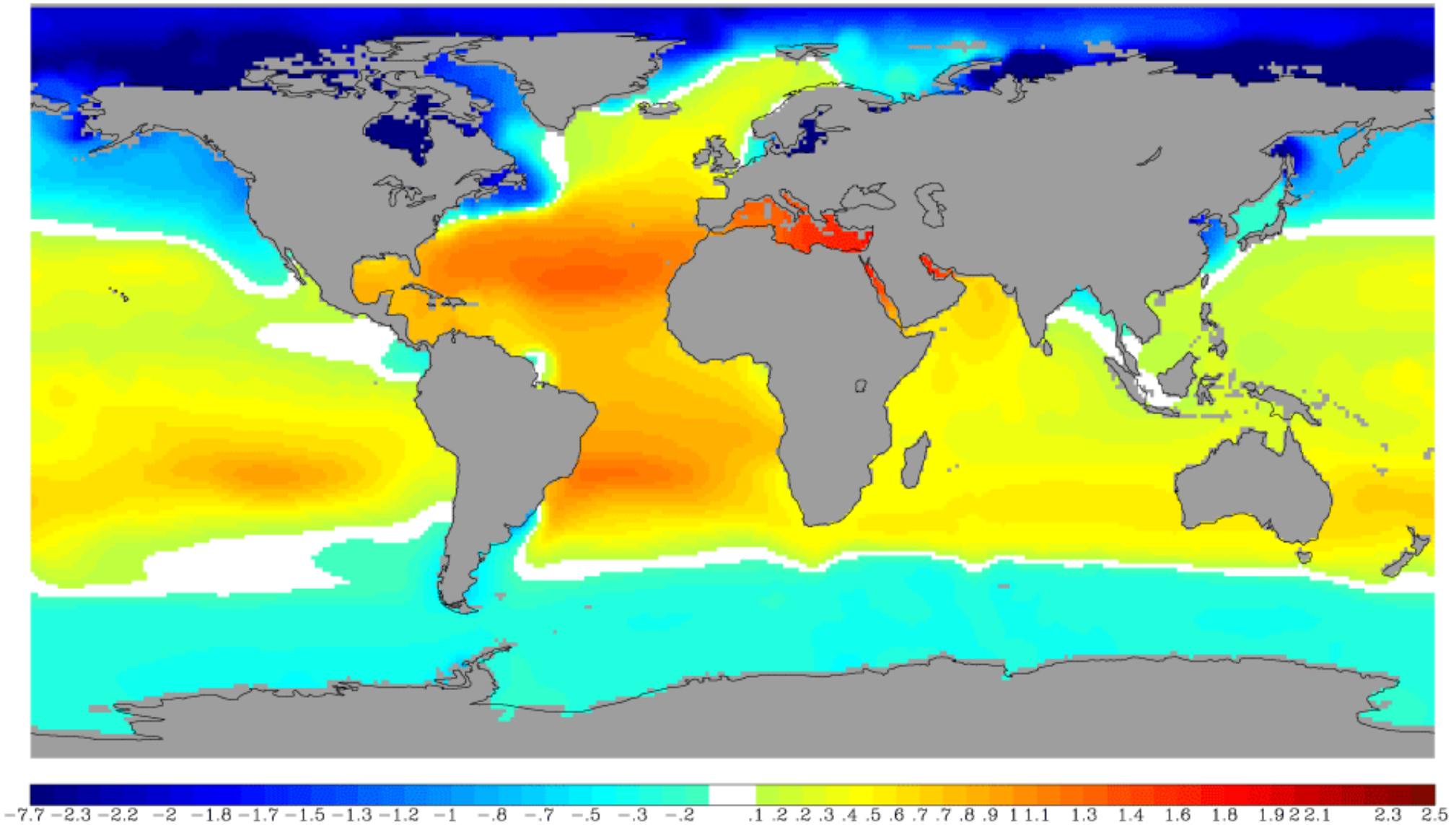
Fractionation by Distillation





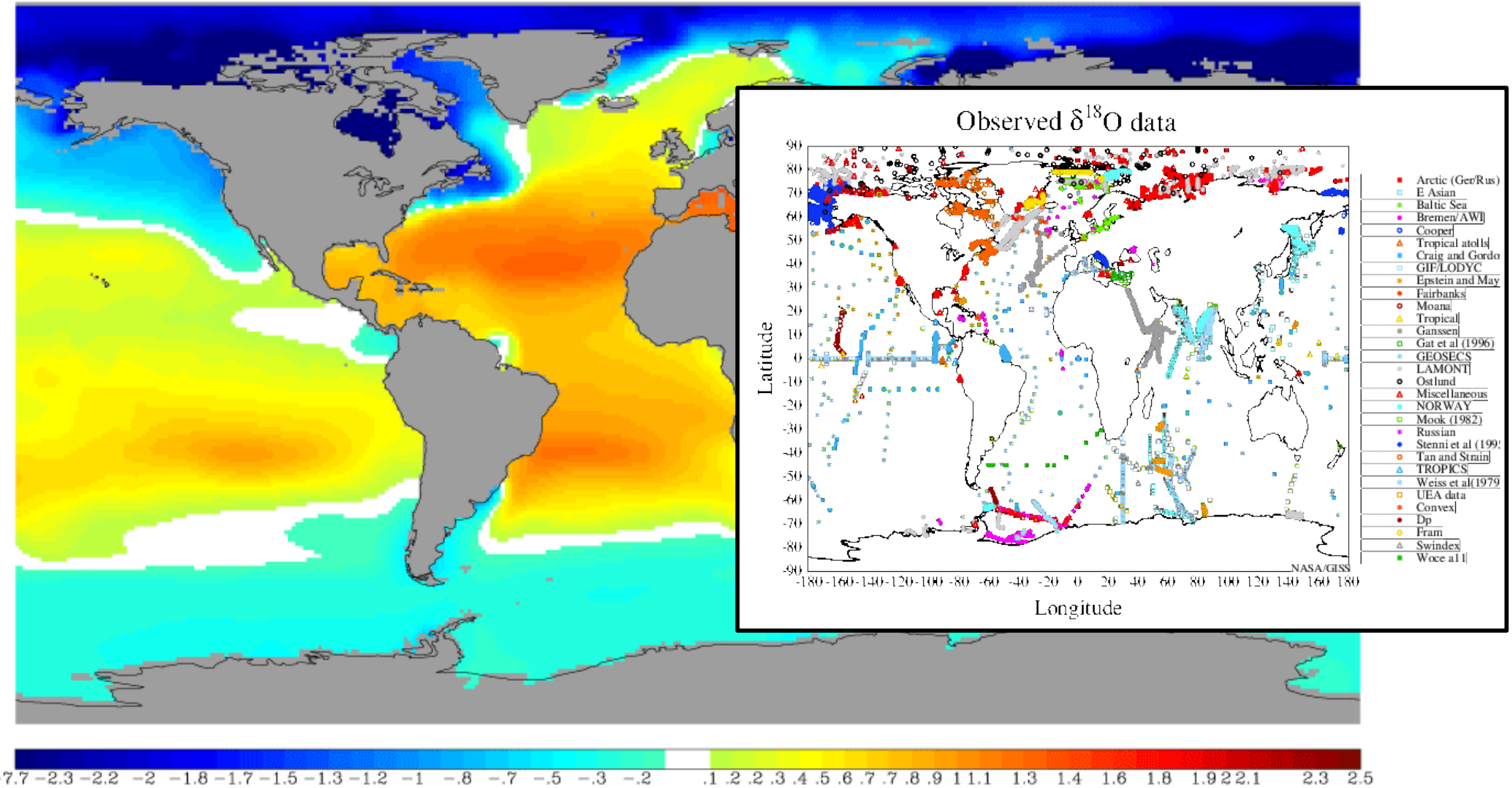
As we go toward poles, multiple distillations result in lower ^{18}O in precipitation and in surface water.

Global Map of ^{18}O in Surface Seawater



NASA Goddard ISS

Global Map of ^{18}O in Surface Seawater



NASA Goddard ISS

Global Map of ^{18}O in Surface Seawater

$\delta^{18}O$

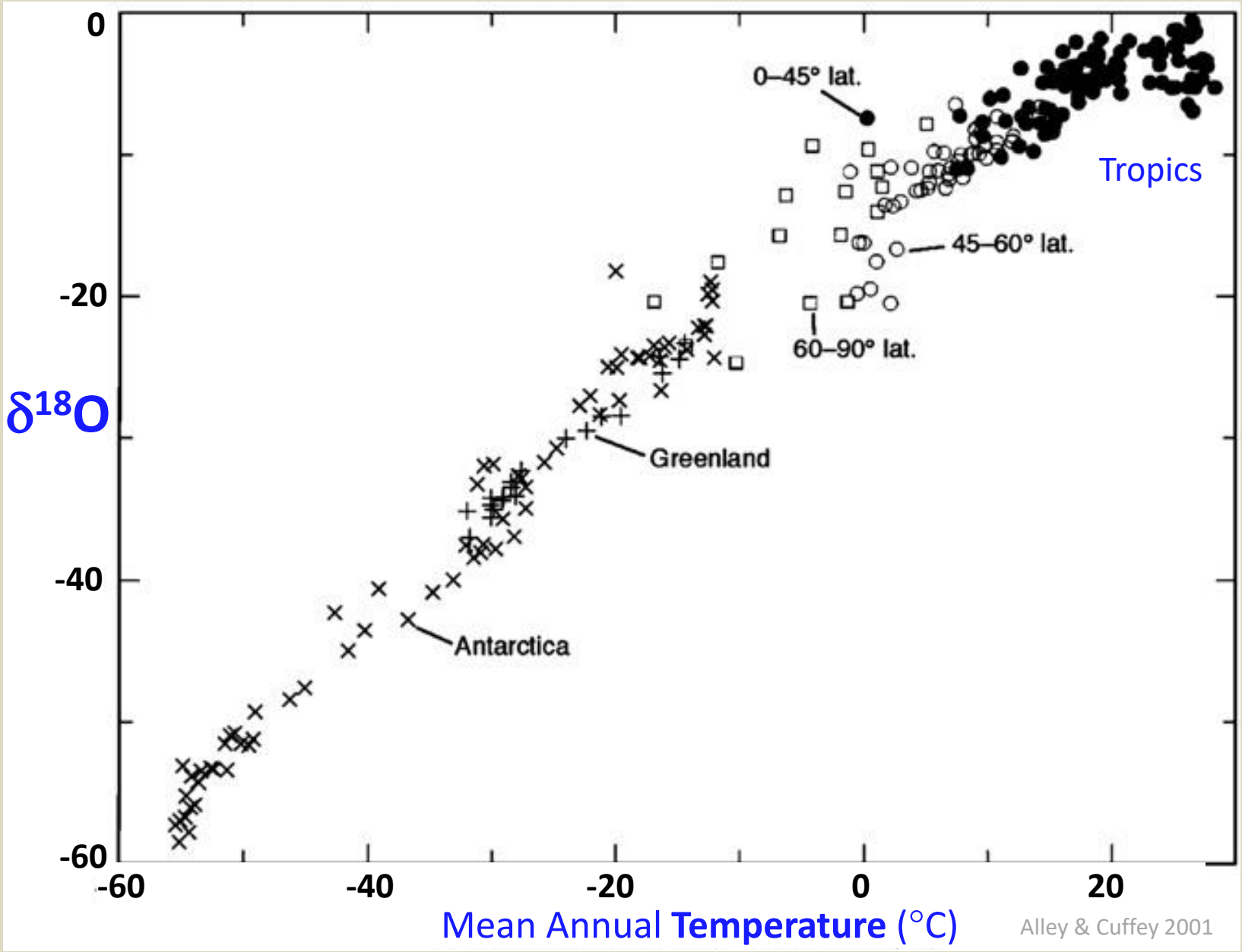
Difference in Parts per Thousand from **VSMOW** (**V**ienna **S**tandard **M**ean **O**cean **W**ater)

Wikimedia

Water samples are compared with a "standard ocean water" sample (VSMOW) to determine a $\delta^{18}O$ value in "parts per thousand"

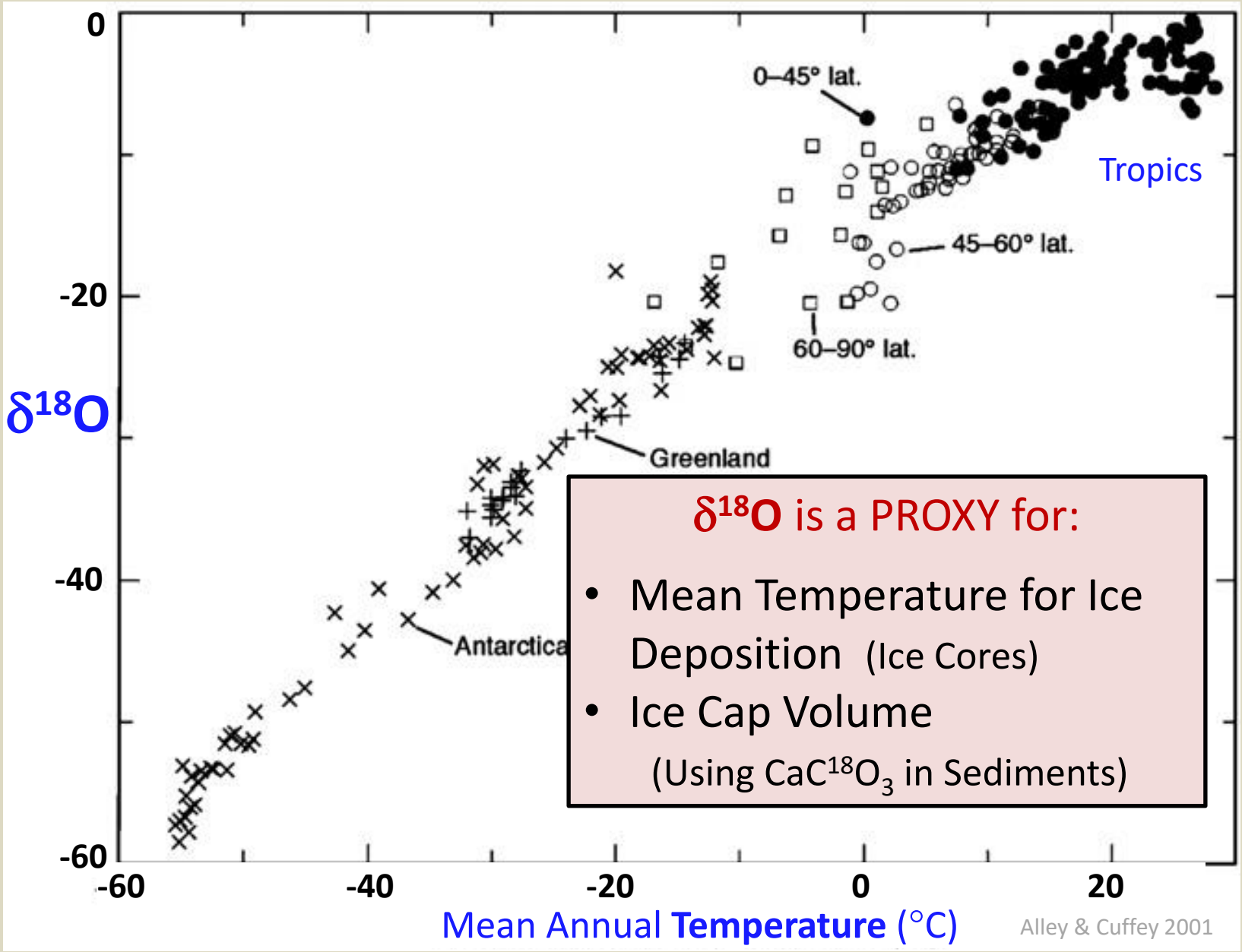
Comparison of $\delta^{18}O$ in **Precipitation** ICE and Mean Annual **Temperature** at various sites

For Cold Places, $\delta^{18}O$ makes a decent thermometer!



Comparison of $\delta^{18}O$ in **Precipitation** (ICE) and Mean Annual **Temperature** at various sites

For Cold Places, $\delta^{18}O$ makes a decent thermometer



Temperature effect on the $\delta^{18}O$ of precipitation

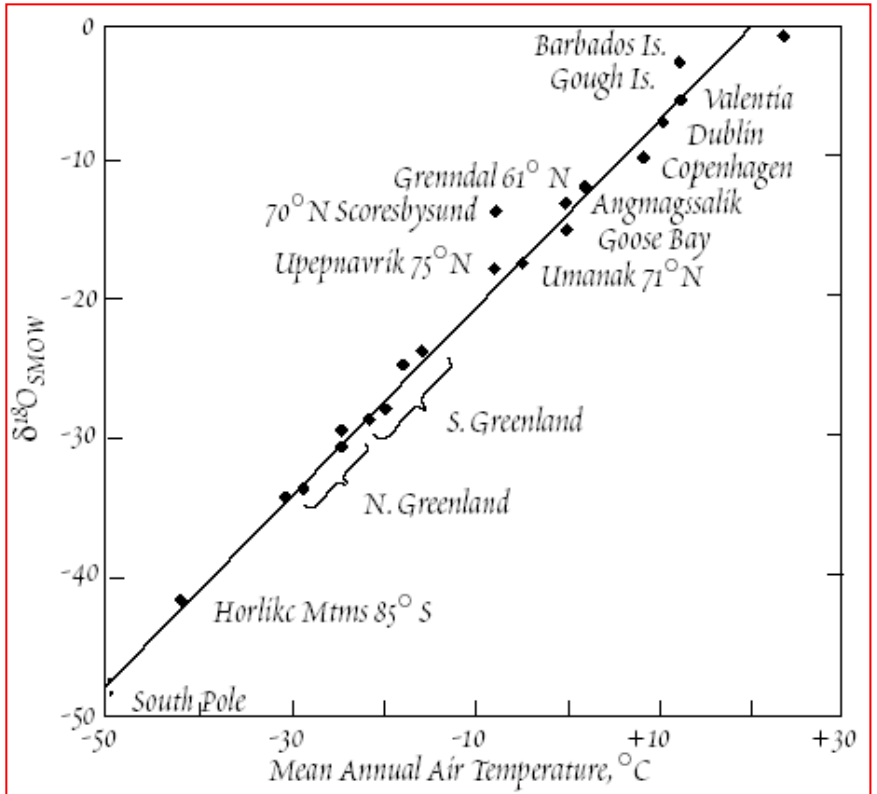


Figure 9.8. Variation of $\delta^{18}O$ in precipitation as a function of mean annual temperature.

Another data set showing how $\delta^{18}O$ correlates with mean annual temperature.

holds for both spatial T variability

and temporal variability

… and yet another data set showing how $\delta^{18}O$ at one location (Vienna) correlates with temperature over 30 years.

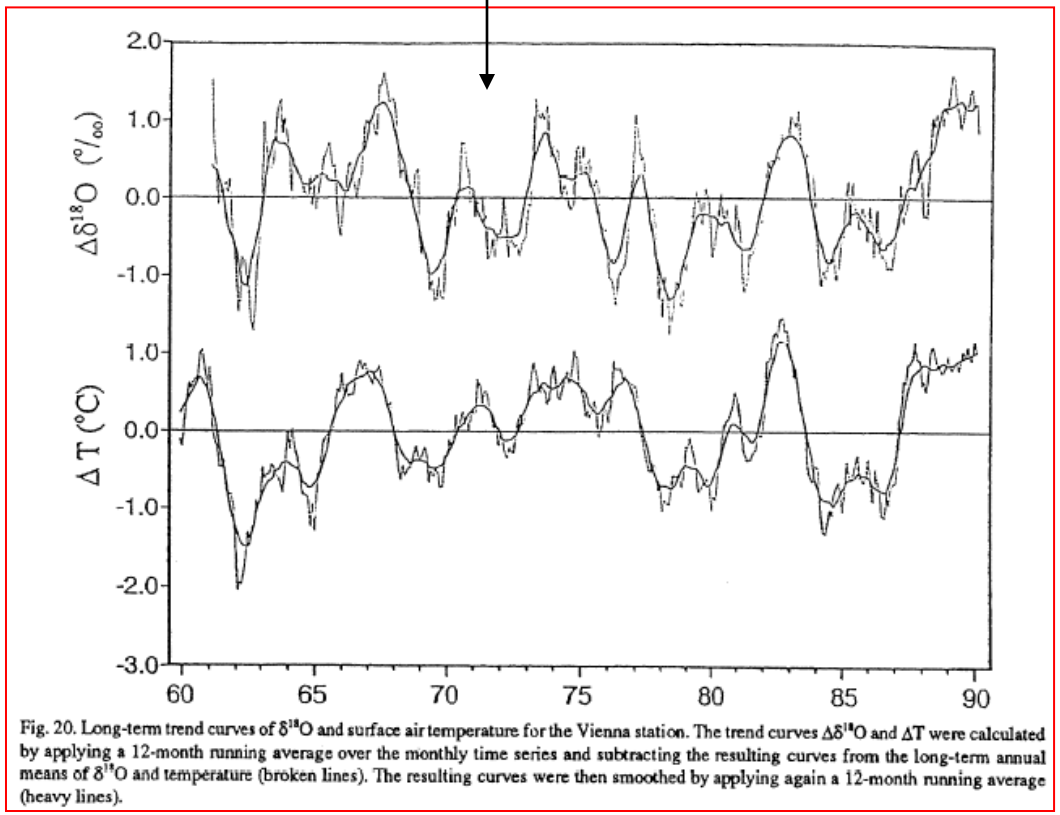
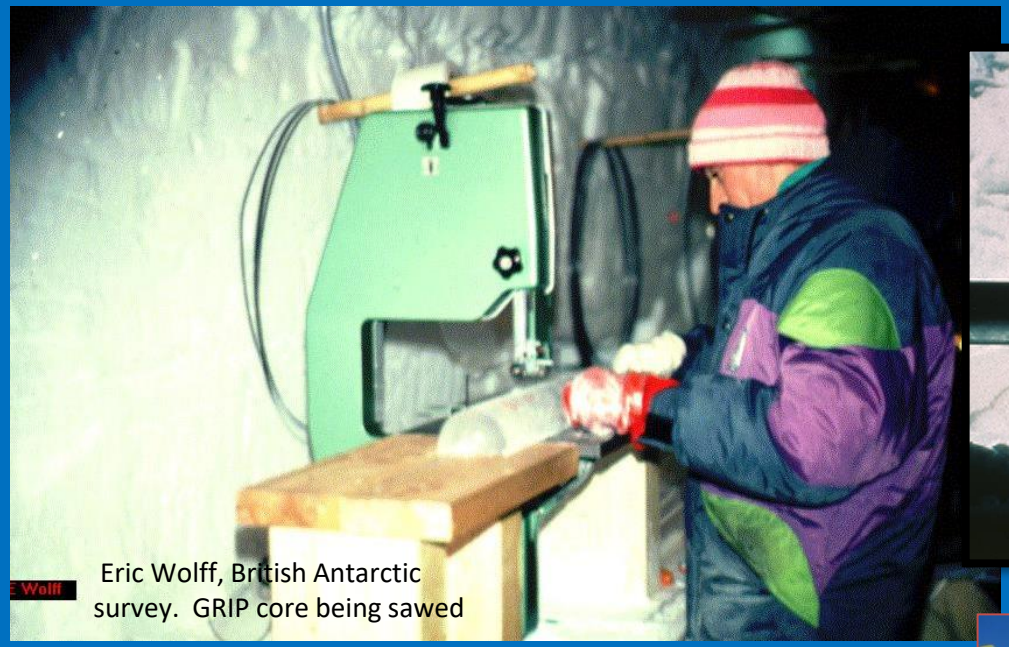
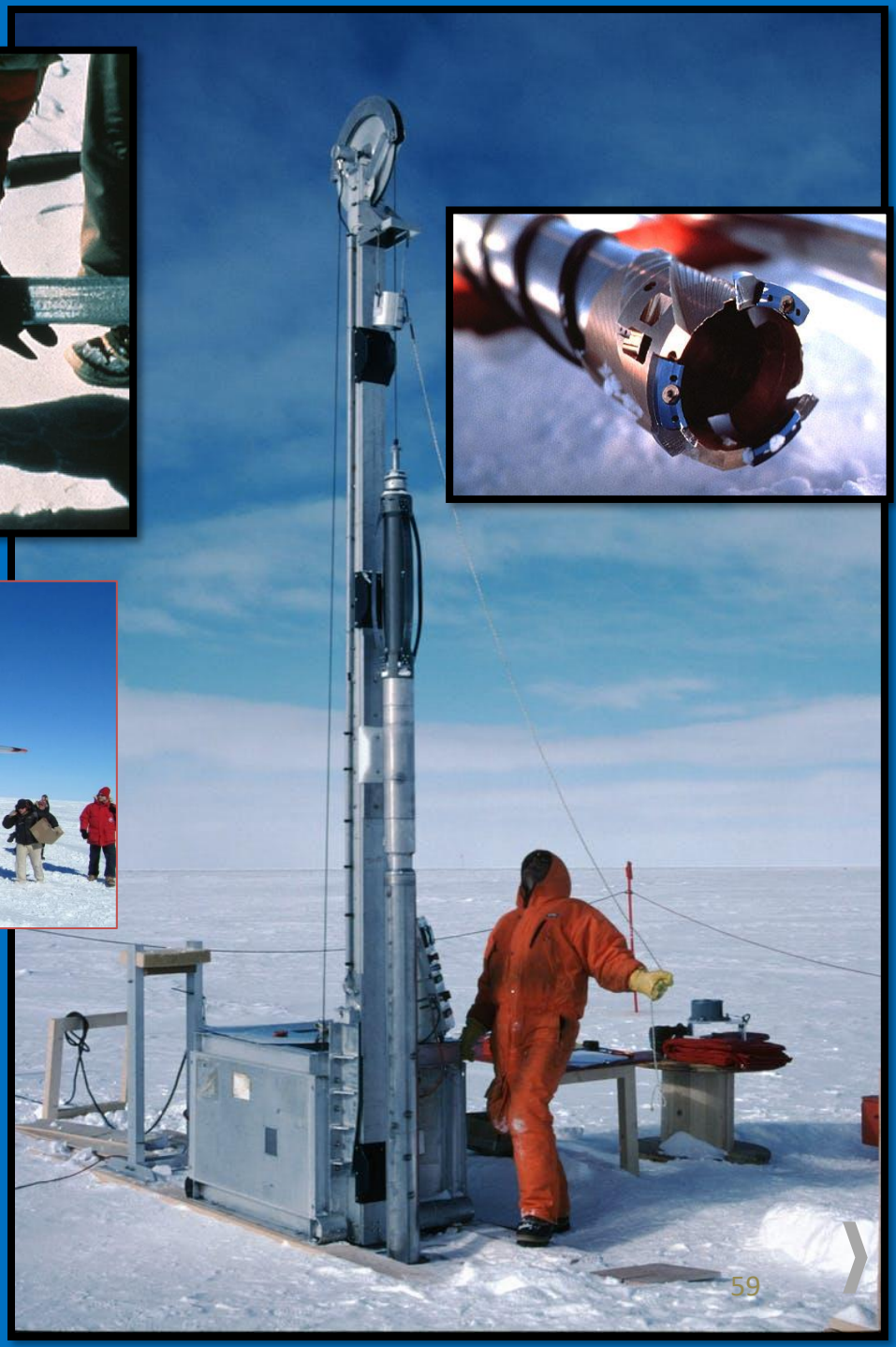


Fig. 20. Long-term trend curves of $\delta^{18}O$ and surface air temperature for the Vienna station. The trend curves $\Delta\delta^{18}O$ and ΔT were calculated by applying a 12-month running average over the monthly time series and subtracting the resulting curves from the long-term annual means of $\delta^{18}O$ and temperature (broken lines). The resulting curves were then smoothed by applying again a 12-month running average (heavy lines).

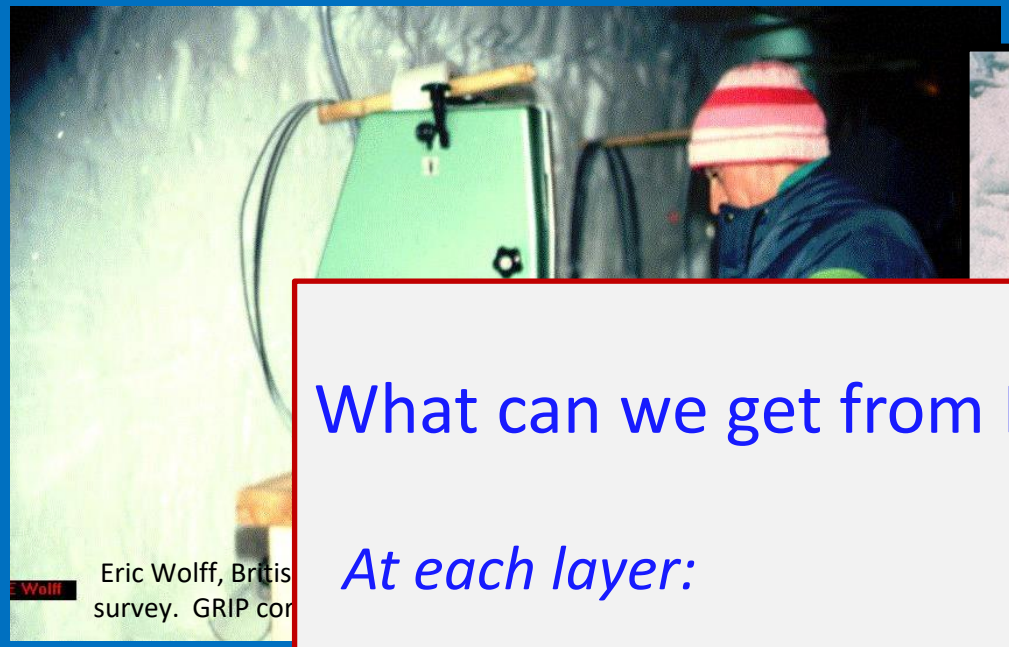
Rozanski, 1993



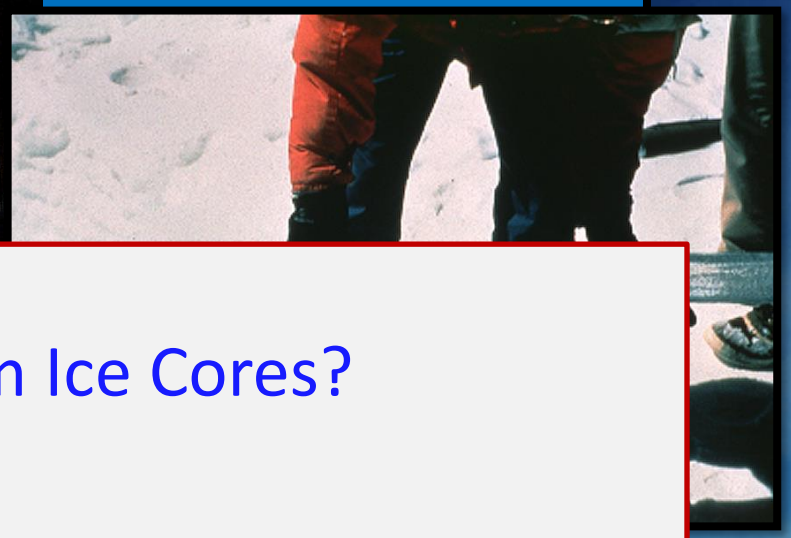
Eric Wolff, British Antarctic survey. GRIP core being sawed

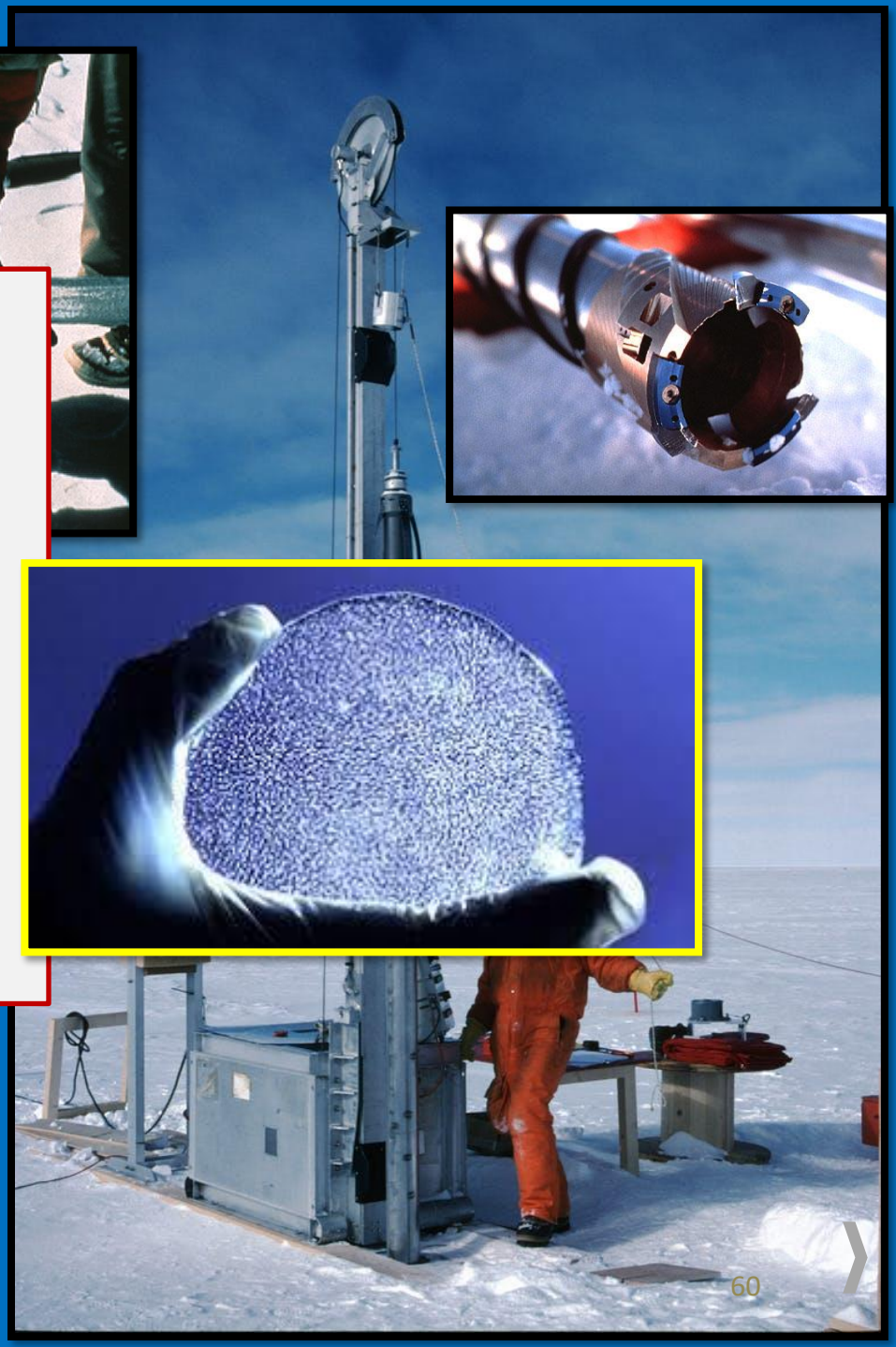


Ice Core Drilling



Eric Wolff, Britis
survey. GRIP cor





What can we get from Ice Cores?

At each layer:

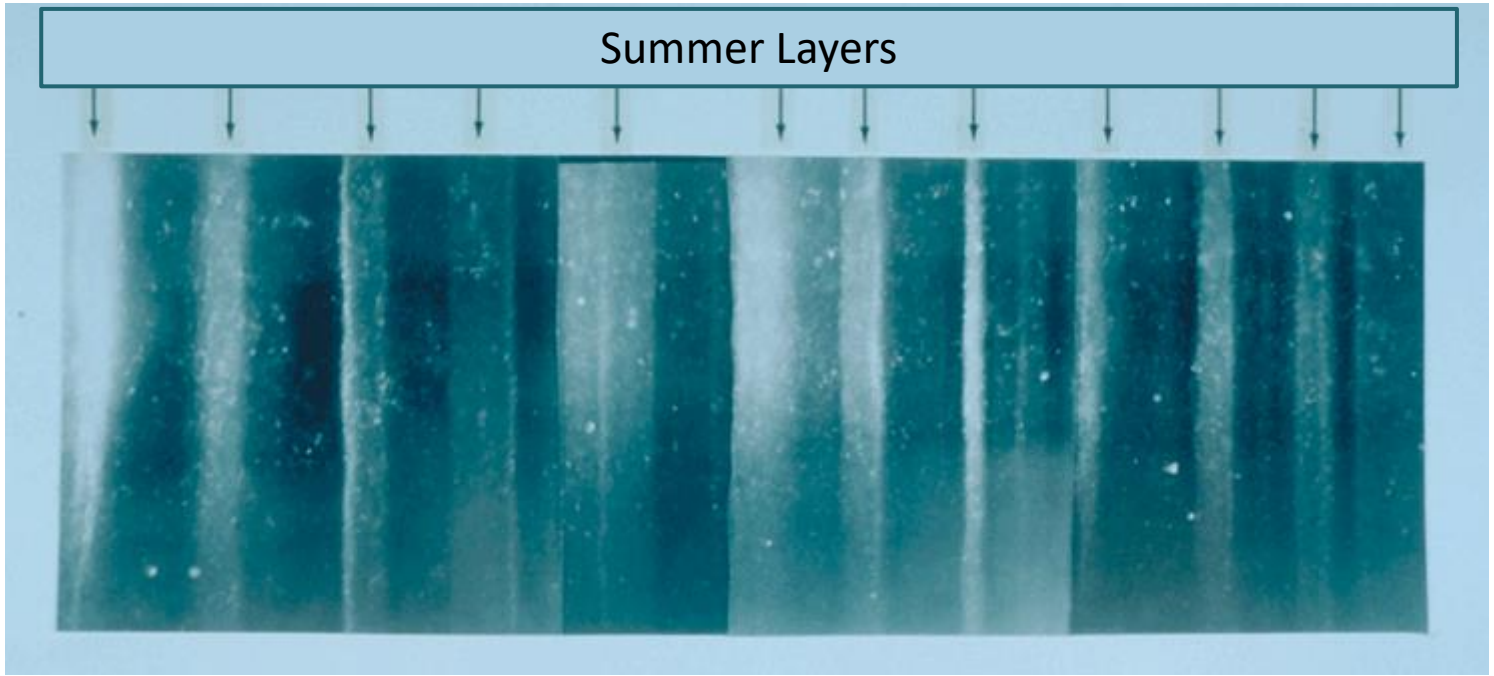
1. Precipitation Temperatures from $\delta^{18}O$
2. Atmospheric Gases from Bubbles (e.g. CO_2)
3. Dust

Ice Core Drilling

Annual Layers Visible in Vostok Core

Depth = 1855 m (6085 feet)

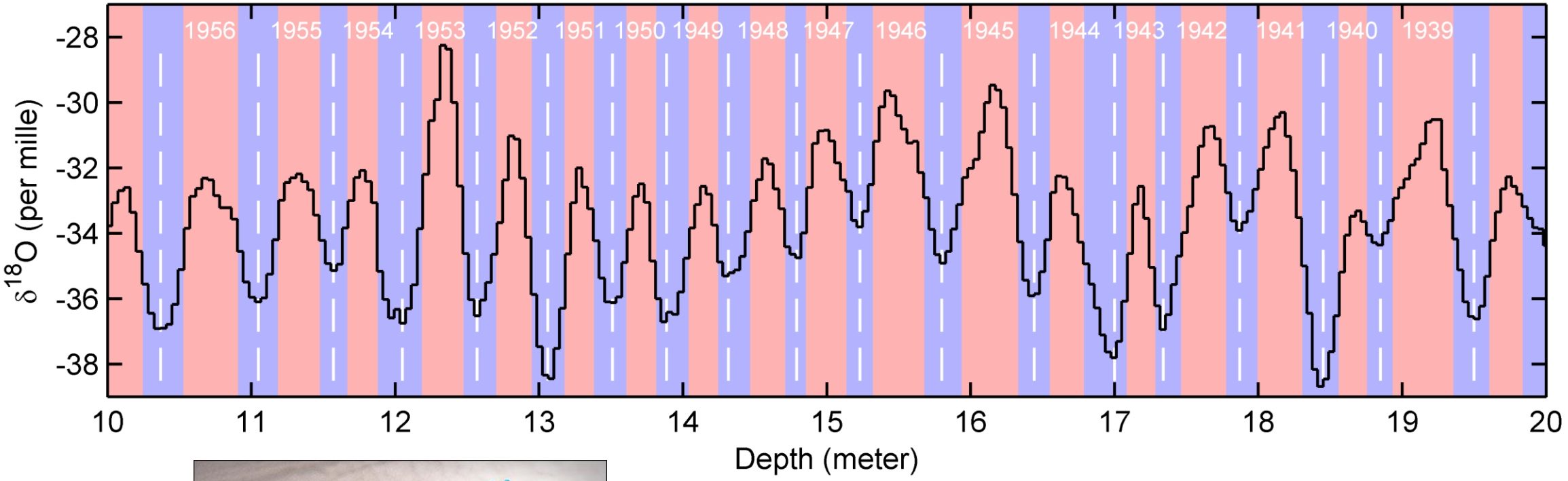
Annual layers counted down to 55,000 years before present!



11 years

~ 8 inches

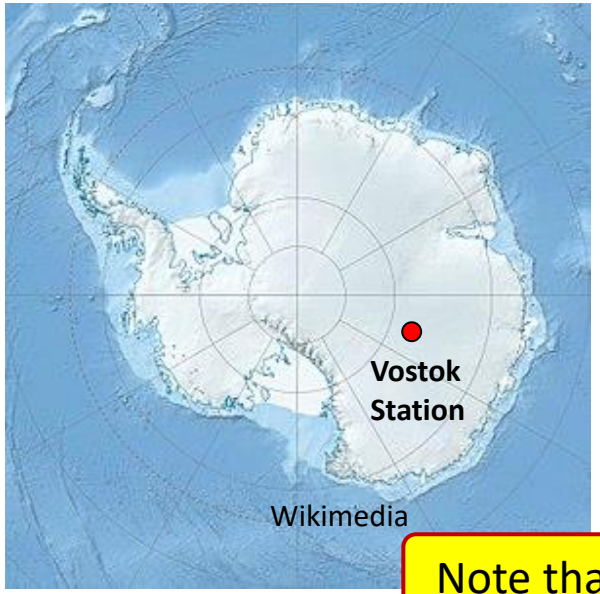
Finely Spaced Ice Core $\delta^{18}O$ Measurements Can Sometimes Trace Out Annual Deposition Layers



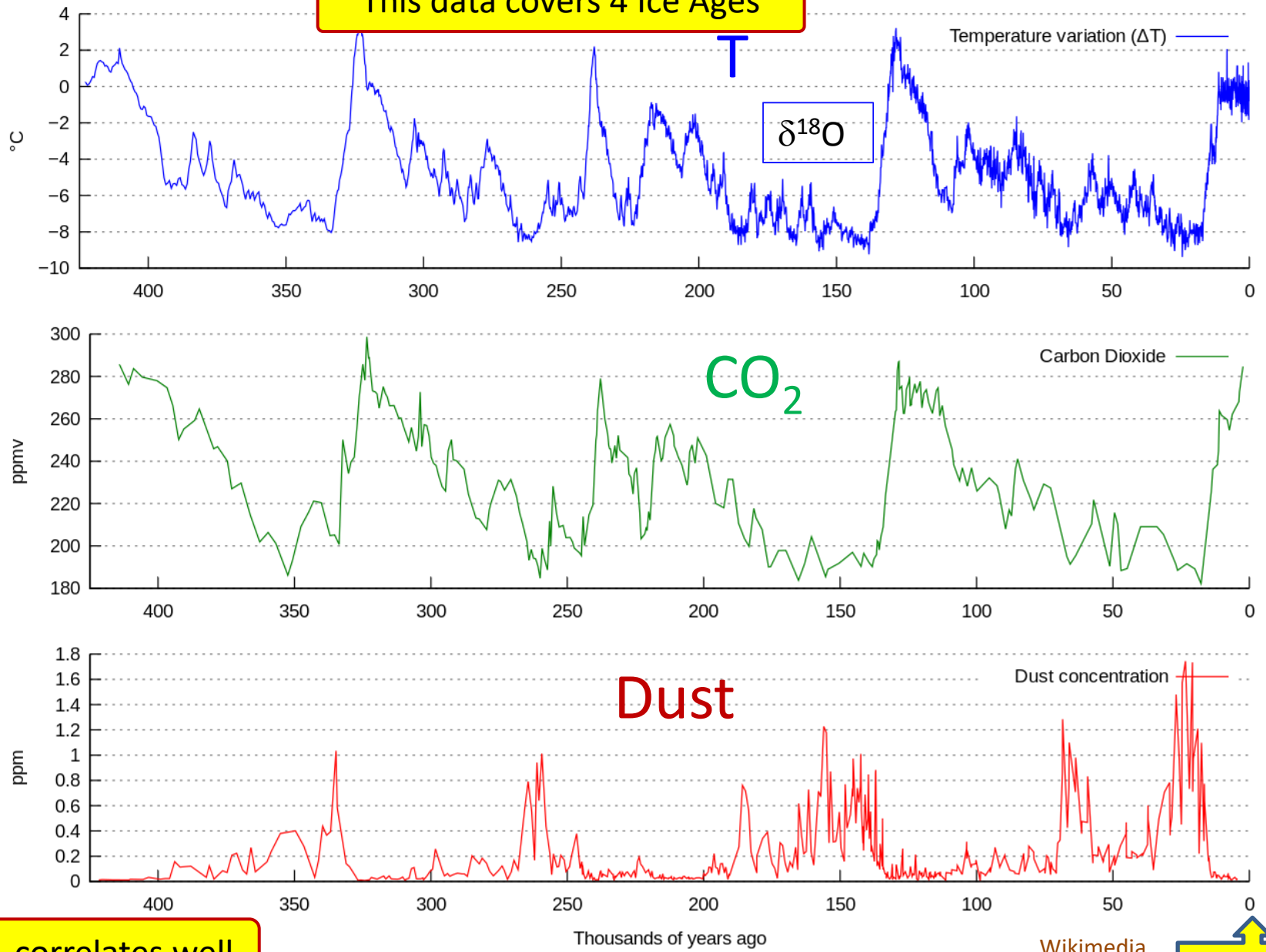
Kobenhavns University
Niels Bohr Institute
Centre for Ice and Climate

Vostok Ice Core Data
Past 420,000 years

From Drilling 1970's through 1996



This data covers 4 Ice Ages

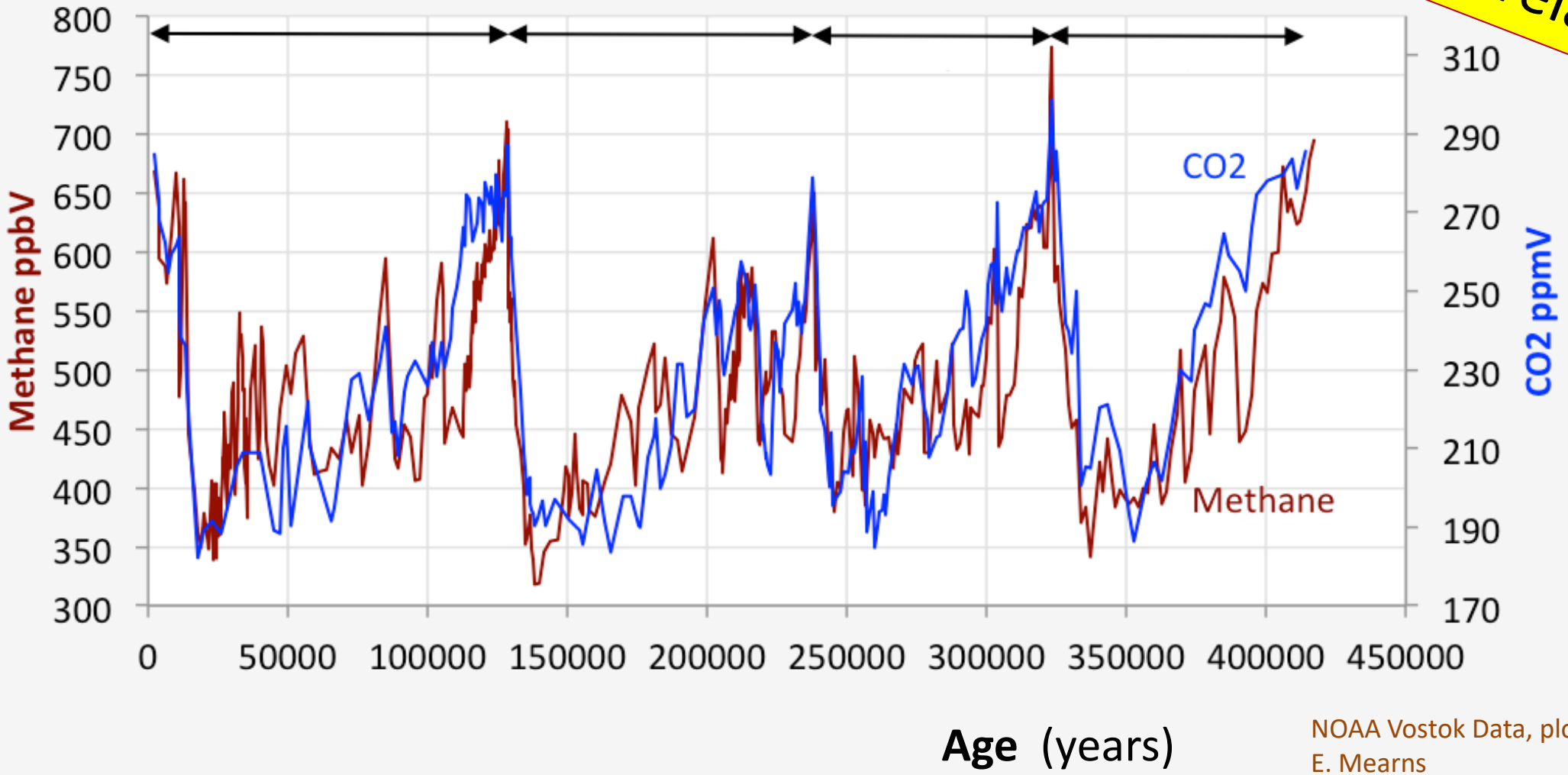


Wikimedia

Note that CO_2 correlates well with temperature (from $\delta^{18}O$)

Vostok Gas Data: CO_2 *vs.* Methane

N_2O Also Correlates

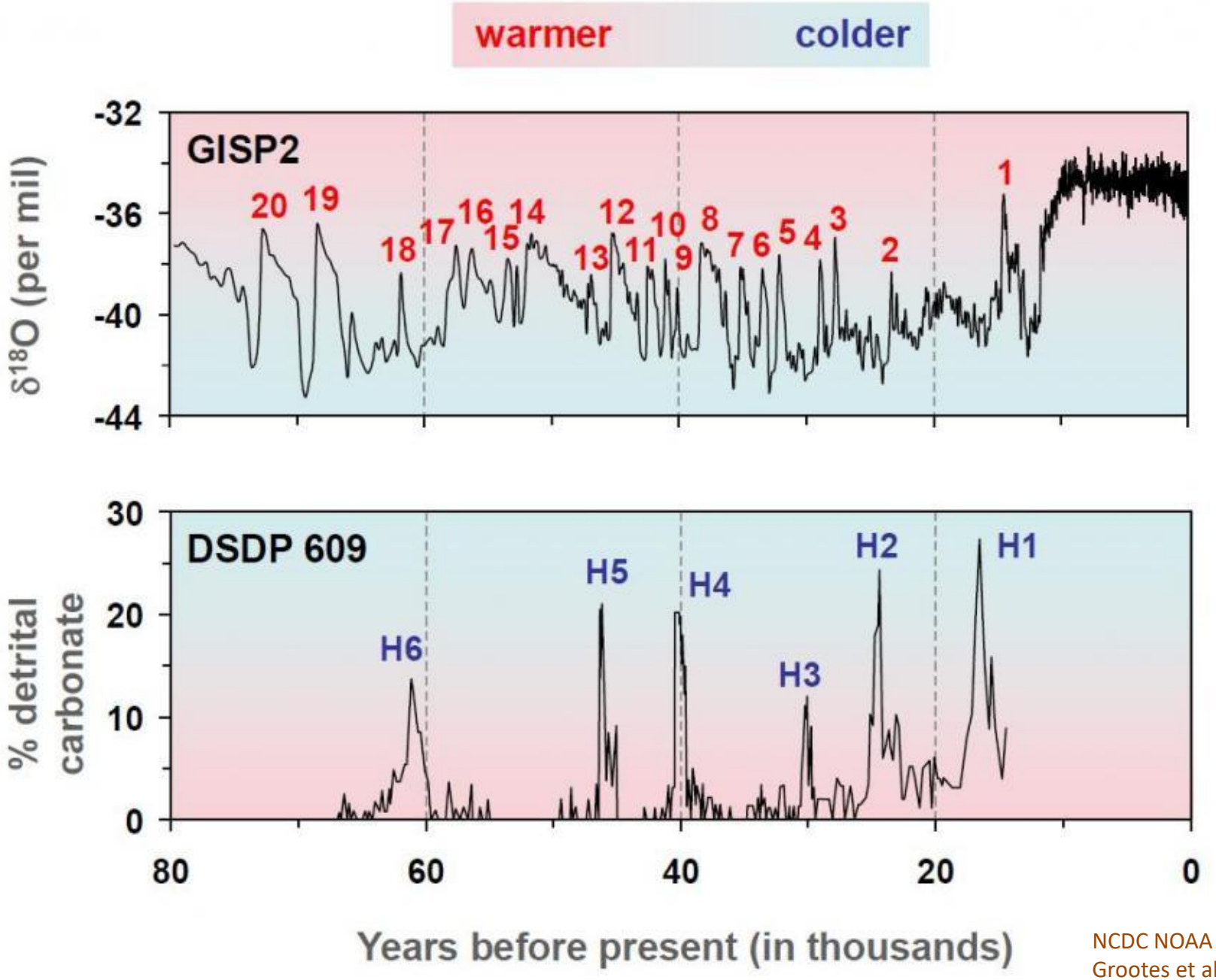


NOAA Vostok Data, plotted by E. Mearns

Ice Ages not so Simple:

D-O and Heinrich Events during last Ice Age

DO and Heinrich events only in Northern Hemisphere!



Dansgaard-Oeschger Events in Greenland during last Ice Age:

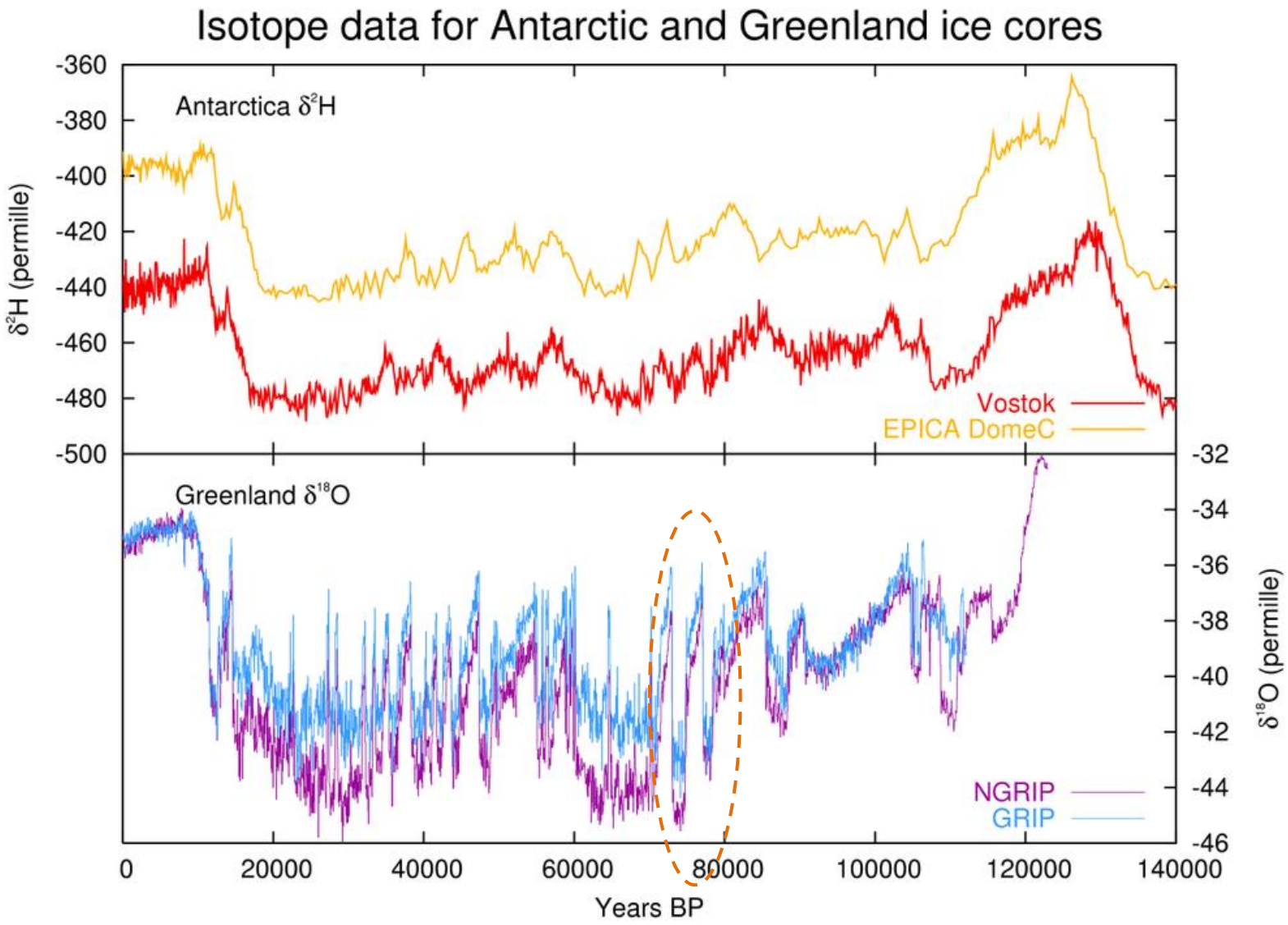
Short Warm Spells

Heinrich Events in North Atlantic during last Ice Age:

Rafted Stones Dumped in Ocean during Cold Spells

NCDC NOAA
Grootes et al 1993, Bond & Lotti 1995

Dansgaard-Oeschger Events only show up in Greenland



D-O Events:
Rapid climate fluctuations during last glacial period.

~25,
in Arctic Only

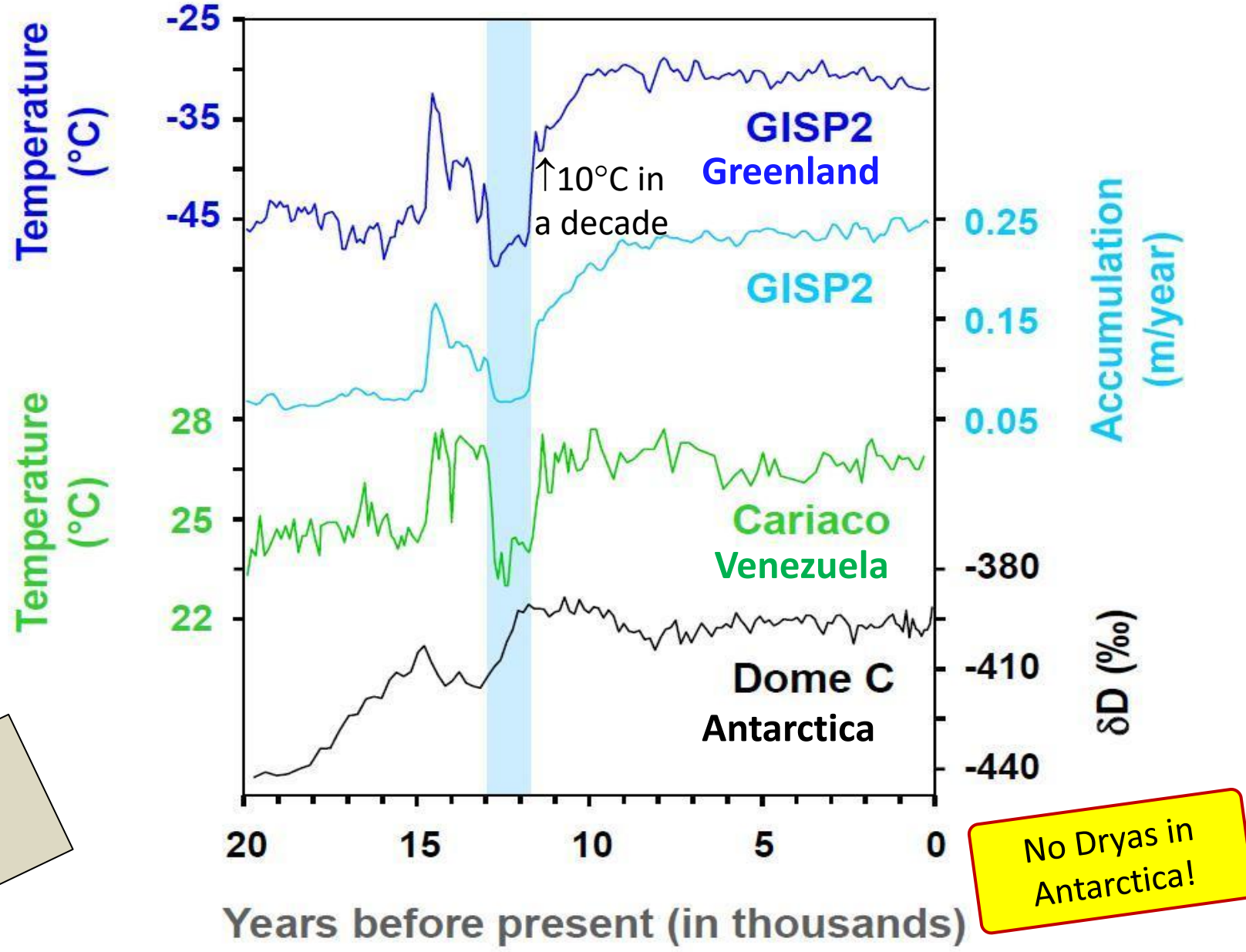
Leland McInnes
Wikimedia

Last Big Cooling Event as we emerged from the last Ice Age 13K years ago:

The Younger Dryas

Dryas octopetala

Cold loving flower flourished in Europe



No Dryas in Antarctica!

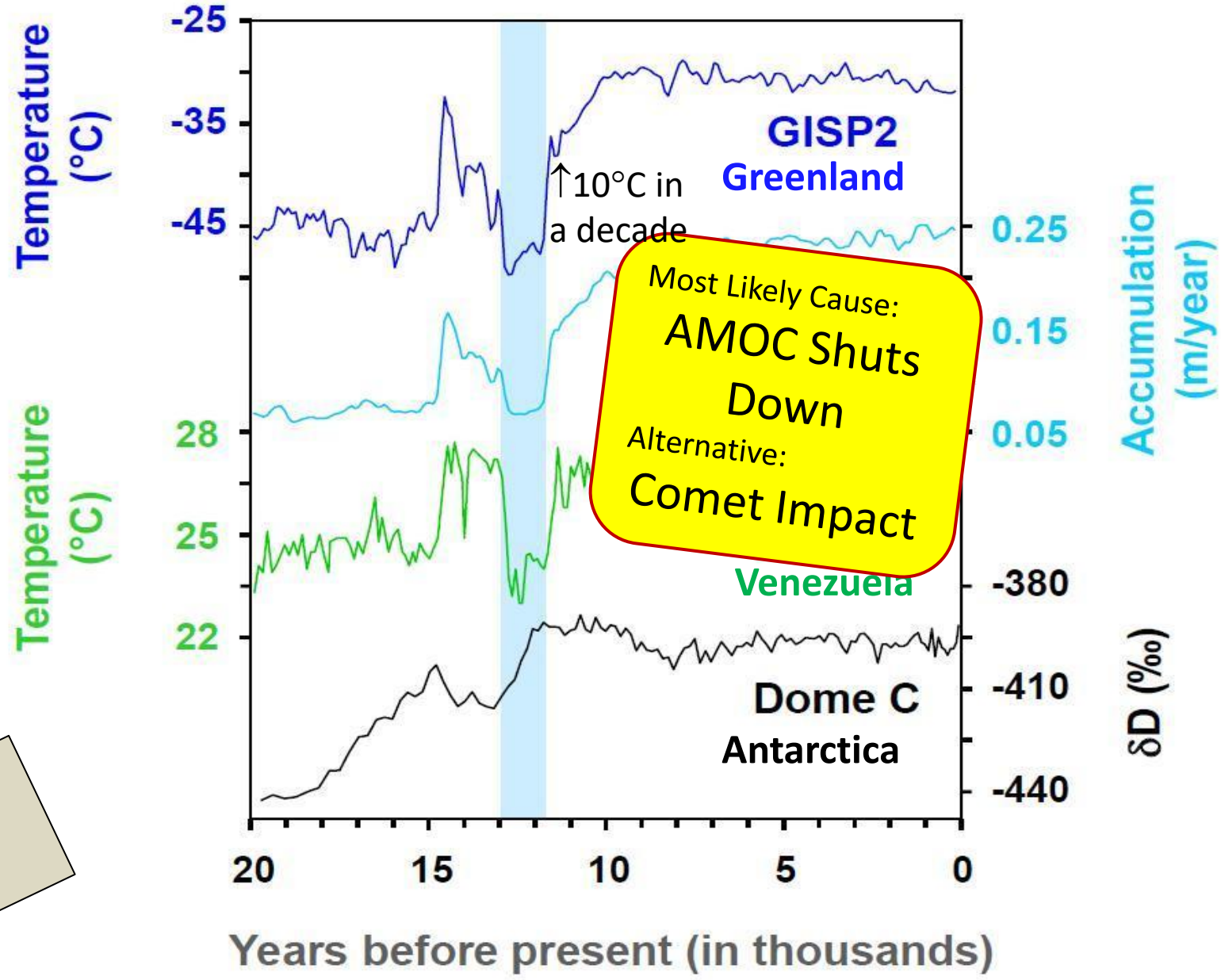
NCDC.NOAA

Last Big Cooling Event as we emerged from the last Ice Age 13K years ago:

The Younger Dryas

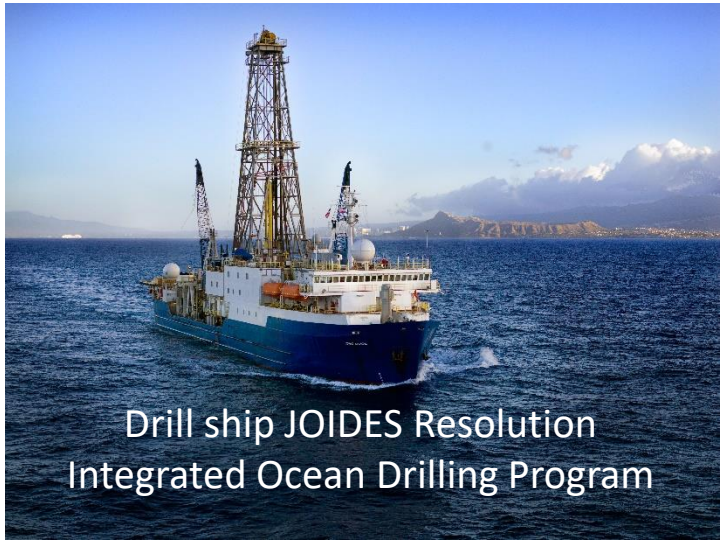
Dryas octopetala

Cold loving flower flourished in Europe



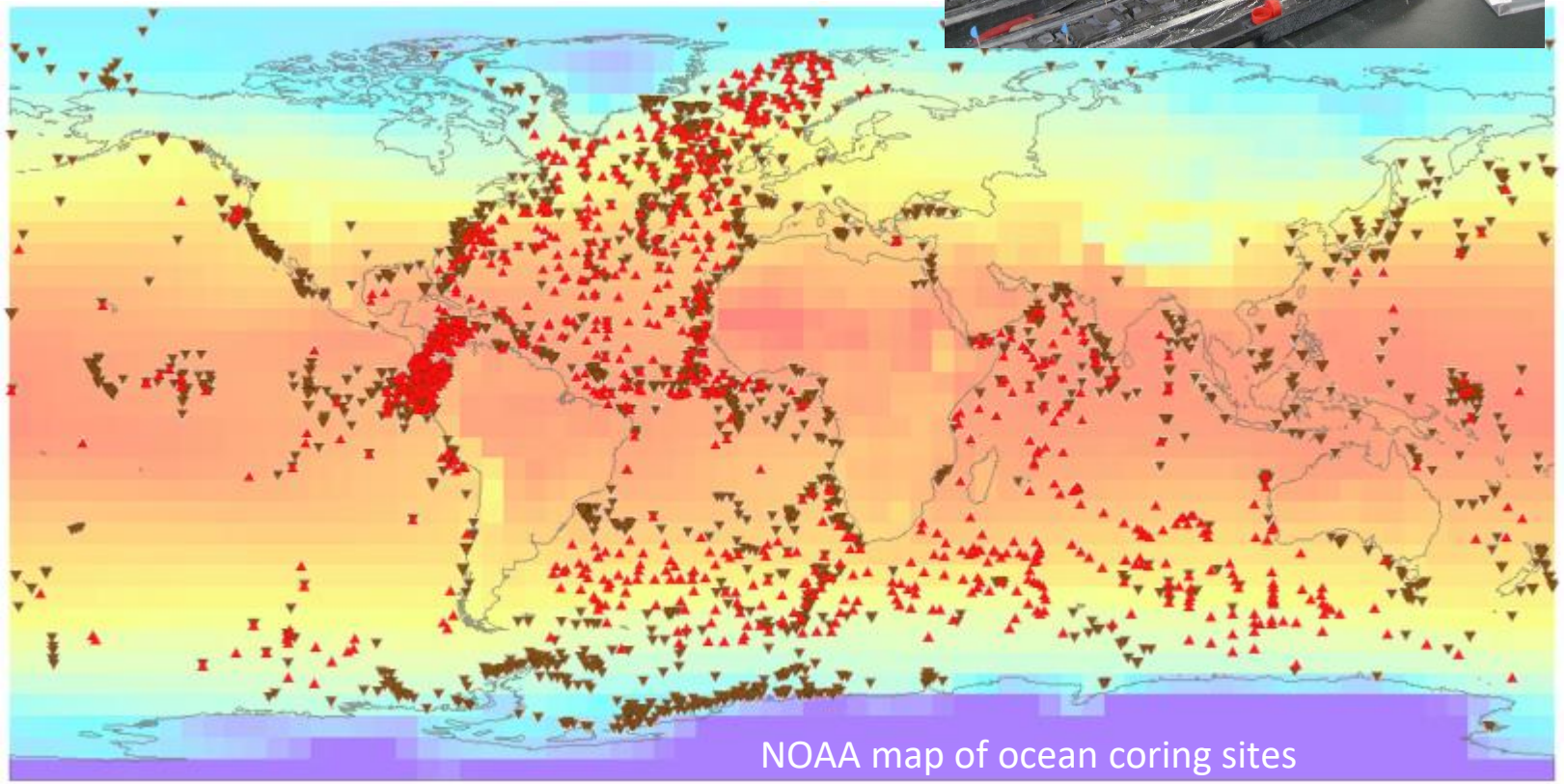
NCDC.NOAA

Deep Sea Drilling

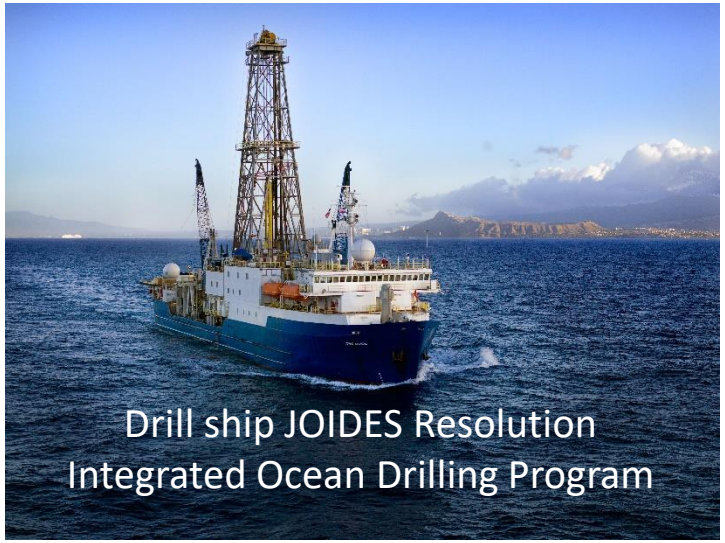

Drill ship JOIDES Resolution
Integrated Ocean Drilling Program

Sediment Layers

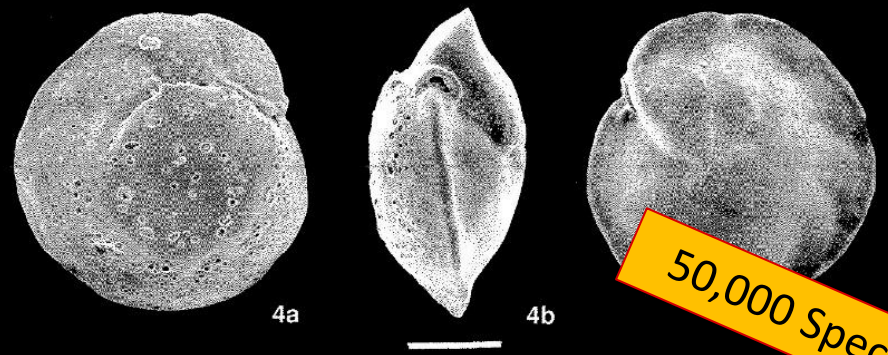
Oregon State Univ. Ocean Sediment Core Collection (2017) 35 km


NOAA map of ocean coring sites

Deep Sea Drilling



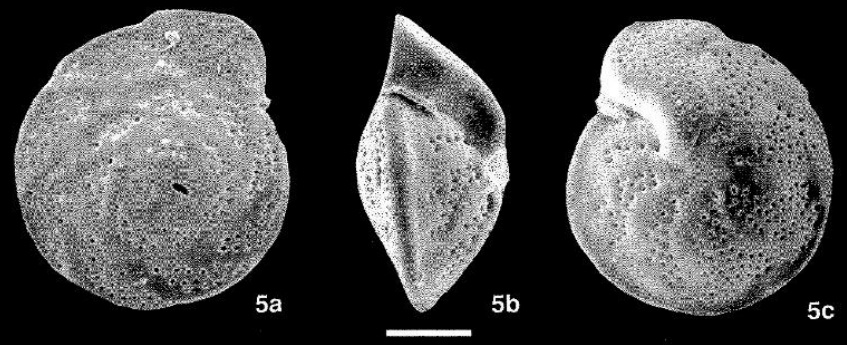
Foraminifera (forams)



50,000 Species

Typically .05-0.5mm

Planktonic or Benthic



So they measure the $\delta^{18}O$ in the Calcium Carbonate shells of the Forams…

Oregon State Univ. Ocean Sediment Core Collection (2017) 35 km

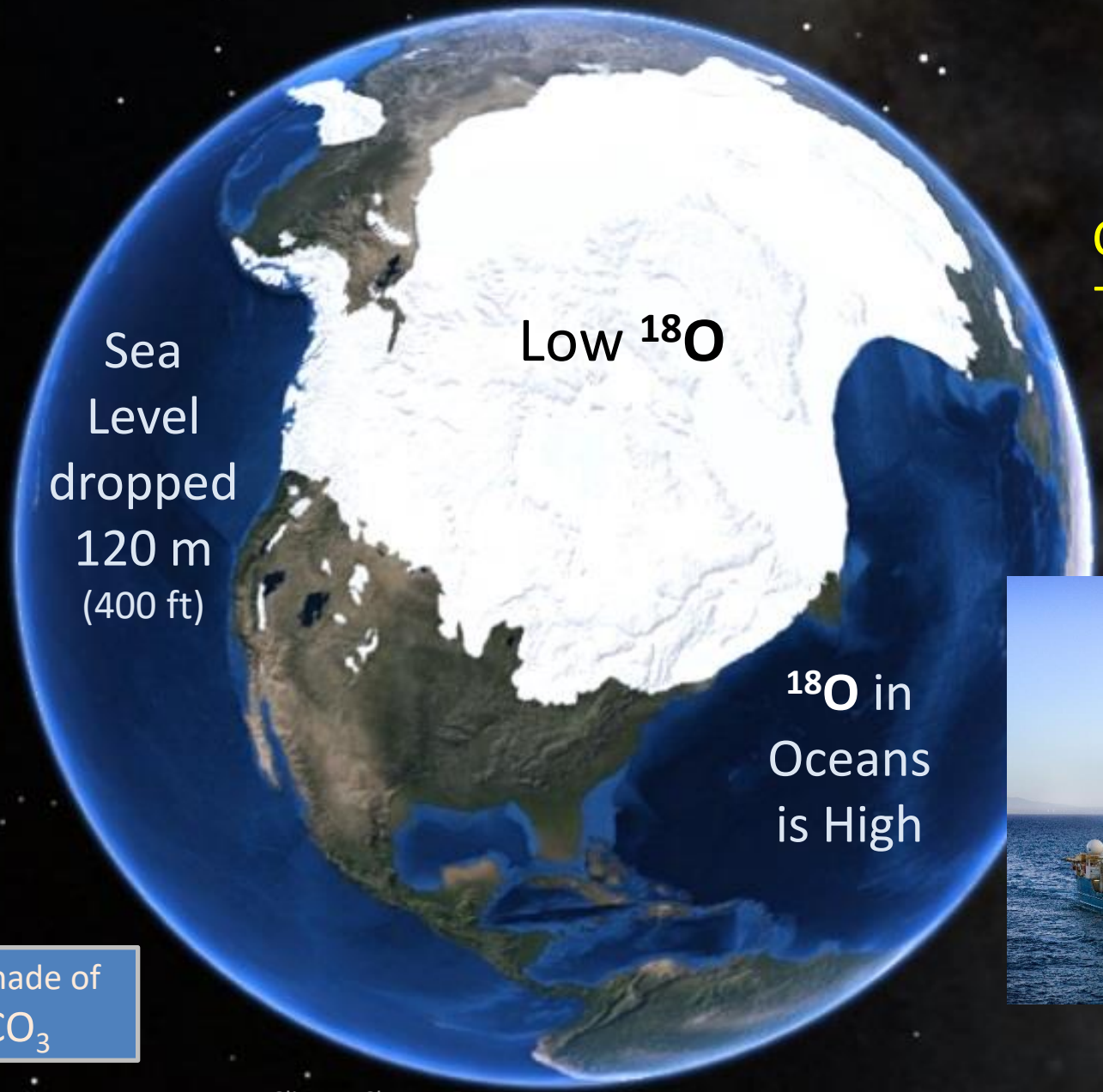
Deep Ocean $\delta^{18}O$ Tracks Ice Cap Volume

Bottom Dwelling Forams

0.5 mm

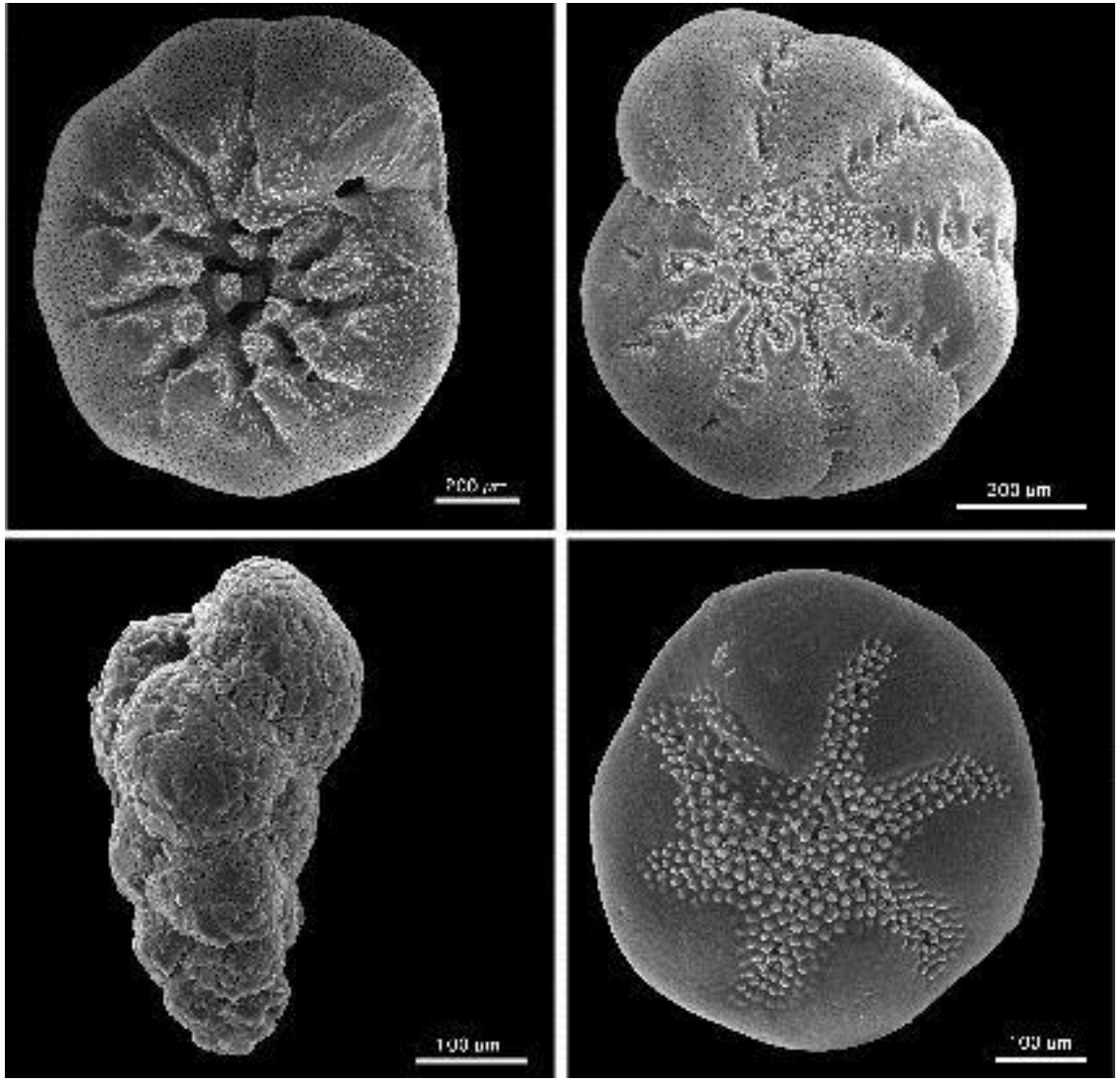
Ammonia beccarii
(Wikimedia)

Shells made of $CaCO_3$



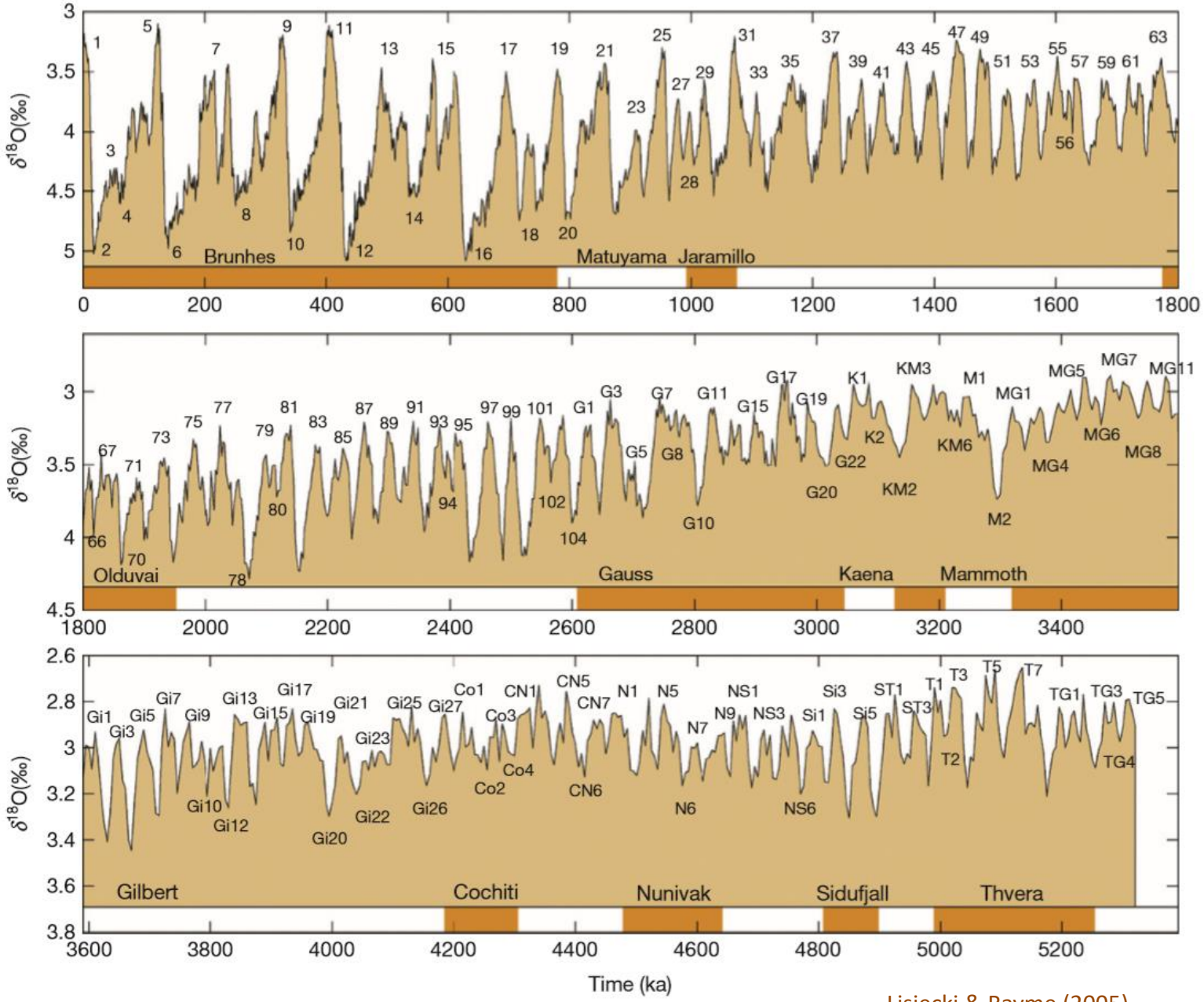
Deep Sea Sediment Cores Reveal Total Ice Cap Volume

SEM micrographs of four benthic **foraminiferans** (ventral view) from the USGS. Clockwise from top left: *Ammonia beccarii*, *Elphidium excavatum clavatum*, *Buccella frigida*, and *Eggerella advena*.



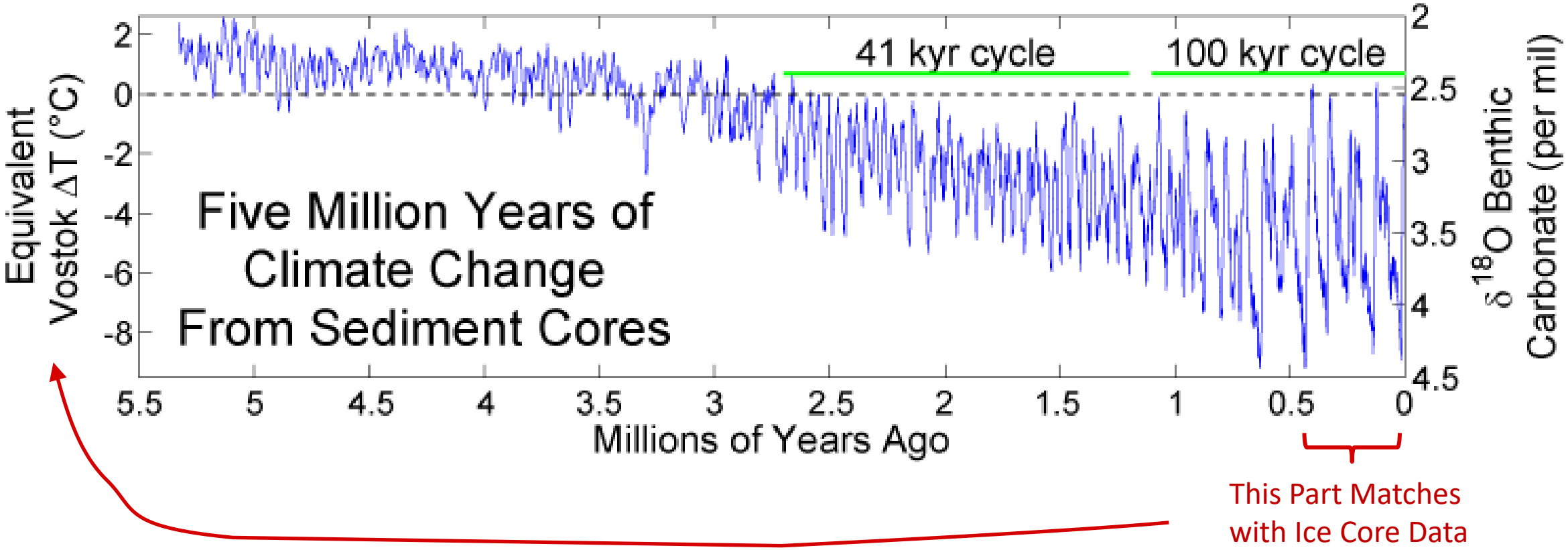
5.3 Million Year Record of $\delta^{18}O$ in Deep Sea Benthic Forams

- "Stacked" Record
  - 57 cores
- Proxy for Ice Cap Volume
  Thus indirectly
  - Climate
  - Sea Level



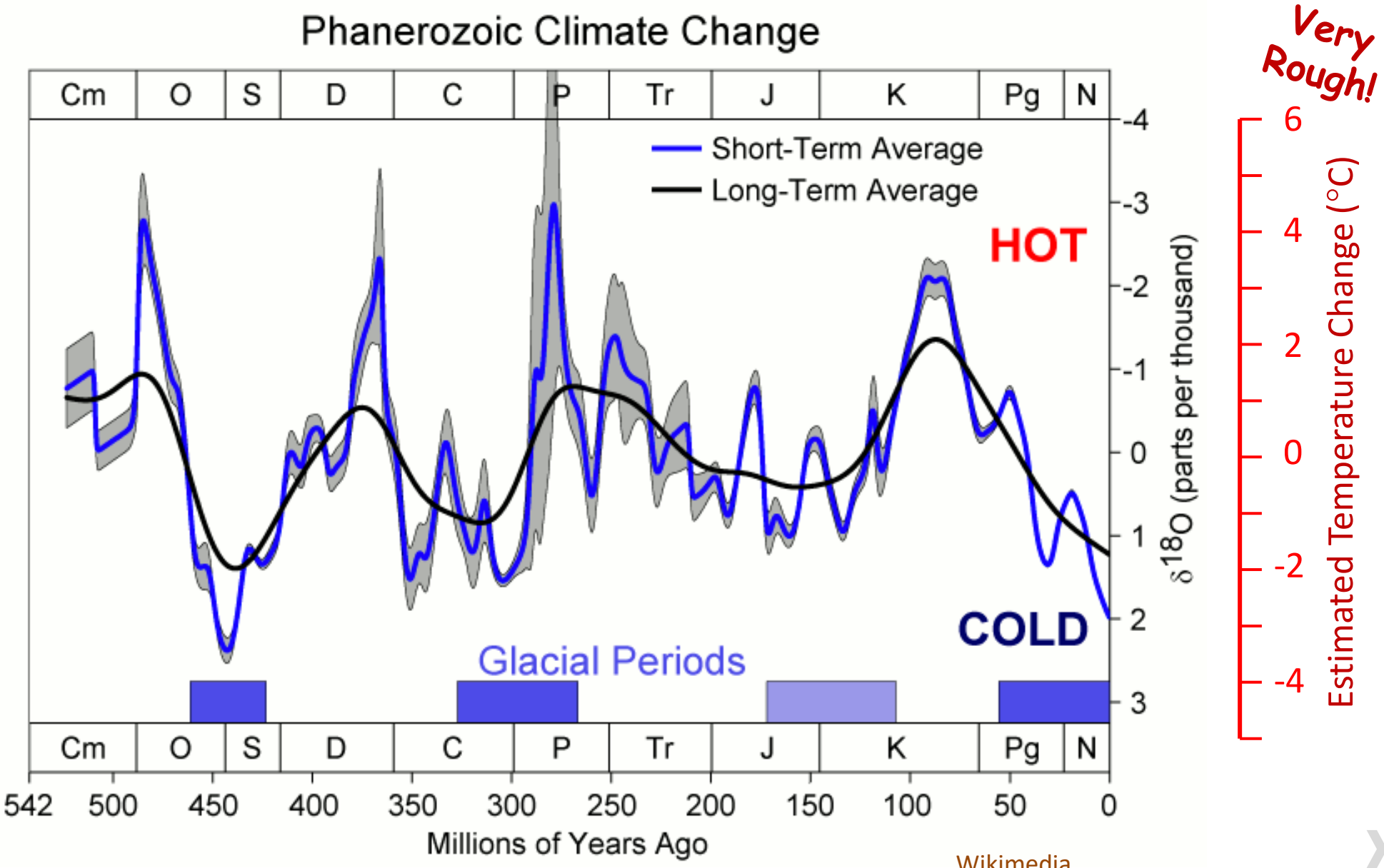
Lisiecki & Rayme (2005)

Another Plot of the Same Foram $\delta^{18}O$ Data



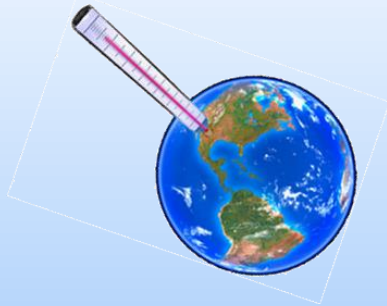
Climate Estimates from $\delta^{18}O$ in Larger Fossil Shells:

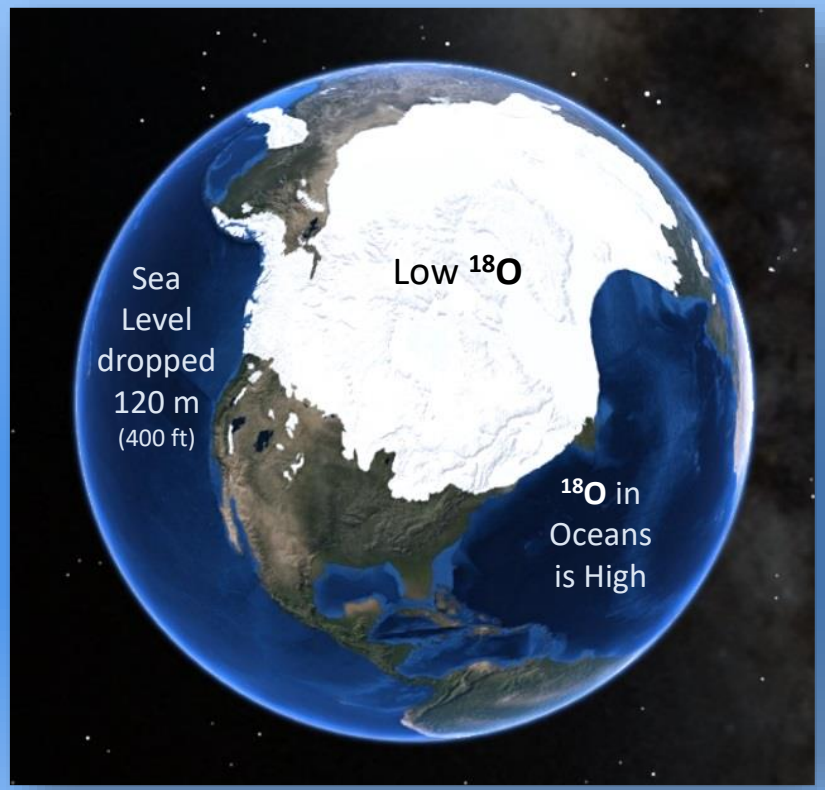
back 500 million years



Wikimedia, Veizer 1999

Questions about $\delta^{18}O$, Ice Cores, Ocean Sediments





Milanković Cycles

Milutin Milanković
(1879-1958)
Serbian Civil Engineer
and Climatologist

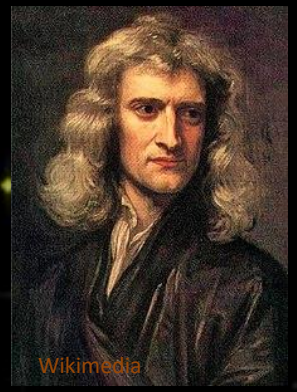
Magnum Opus:
"Canon of Insolation of the Earth and its Application to the Problem of the Ice Ages"
(1941, in German)
[English Translation 1969]

Basic Idea:

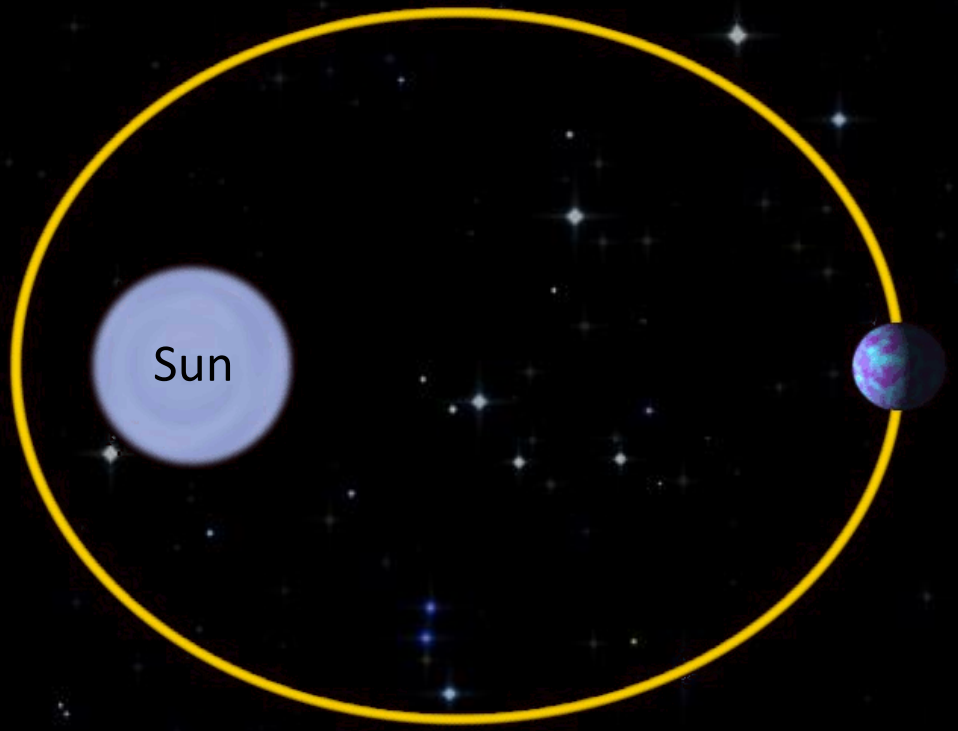
- Changes in Solar Insolation due to Earth's Orbit Changes over time can drive climate
  - Solar Radiation Forcing
- Orbital Changes Include
  - Axial Tilt and Precession
  - Elliptical Orbit Eccentricity
  - Orbital Precession

Earth's Orbit Nearly Elliptical

Johannes Kepler (1571-1630)



Isaac Newton (1643-1727)

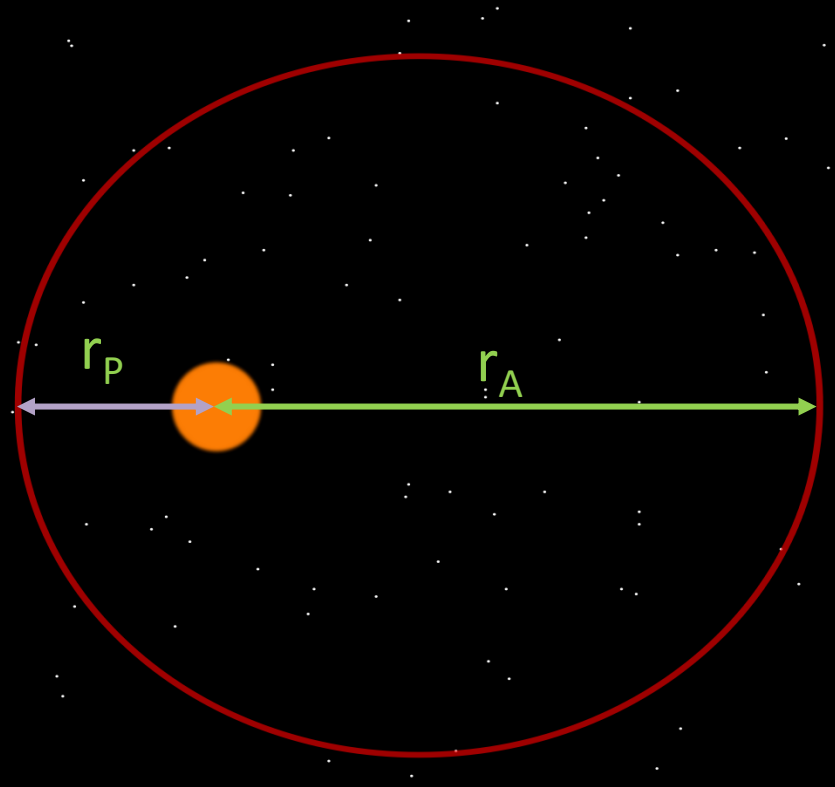


Wikimedia

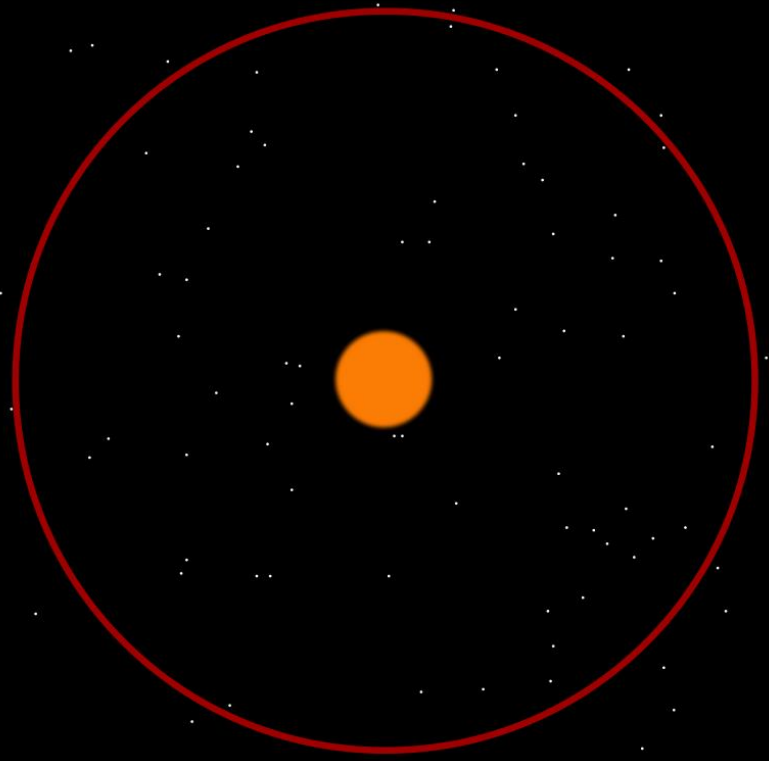
…but not nearly *this* eccentric

Plane of Orbit called the "Ecliptic Plane"

Orbital Eccentricity Varies Slowly



$$e = \frac{r_A - r_P}{r_A + r_P}$$



Seasonal solar insolation variation of 20-30%!

Eccentricity:

- varies from 0.0034 to 0.058
- Now 0.0167 (almost circular)
- Complex variation
  - Roughly 100,000 year cycle

6%

Apsidal Precession ~112,000 years

Wikimedia

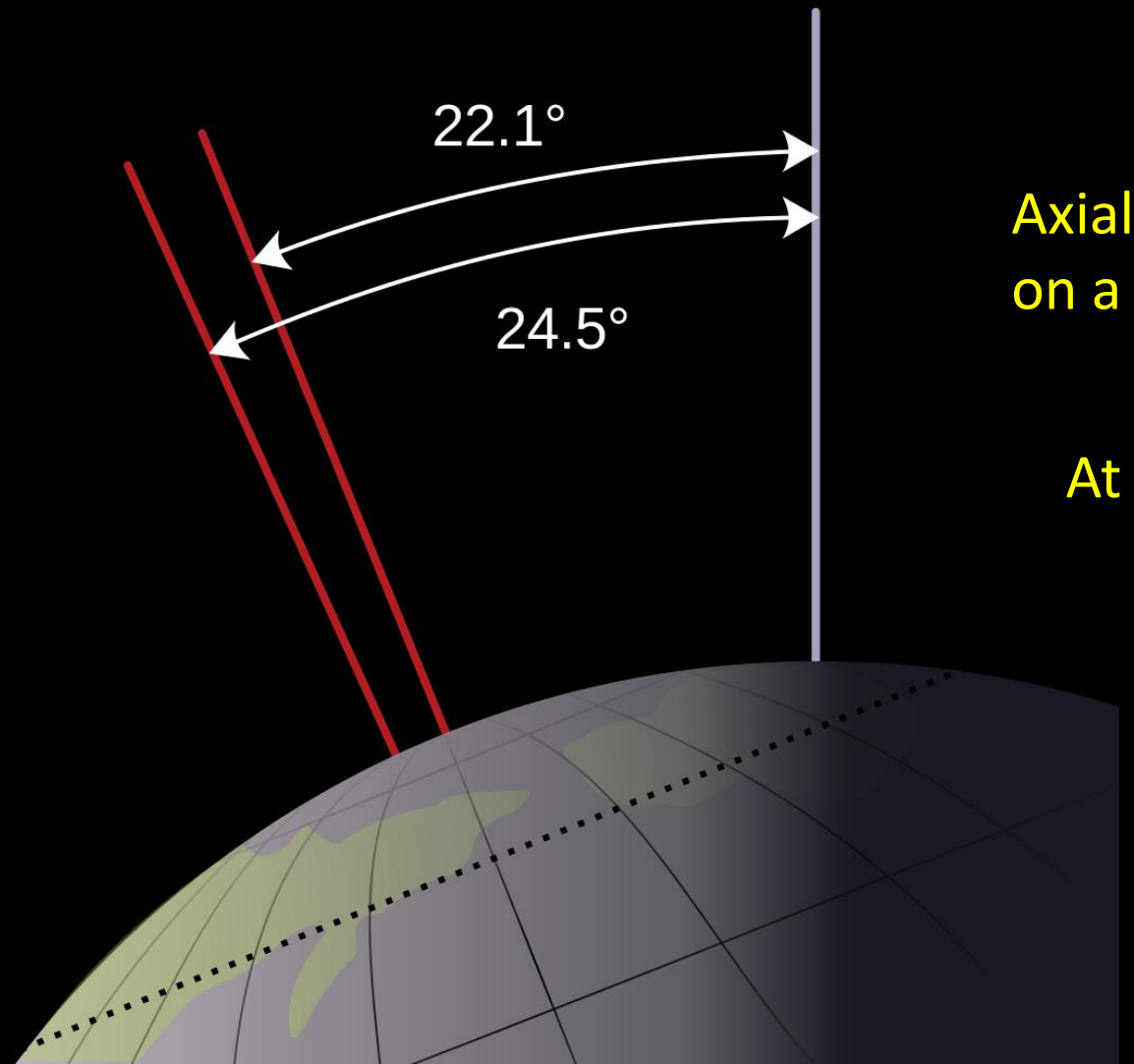
No climate effect, however

Inclination to the Invariable Plane: Procession of the Ecliptic

Not directly considered by Milanković

Again, No climate effect

Axial Obliquity (Tilt)



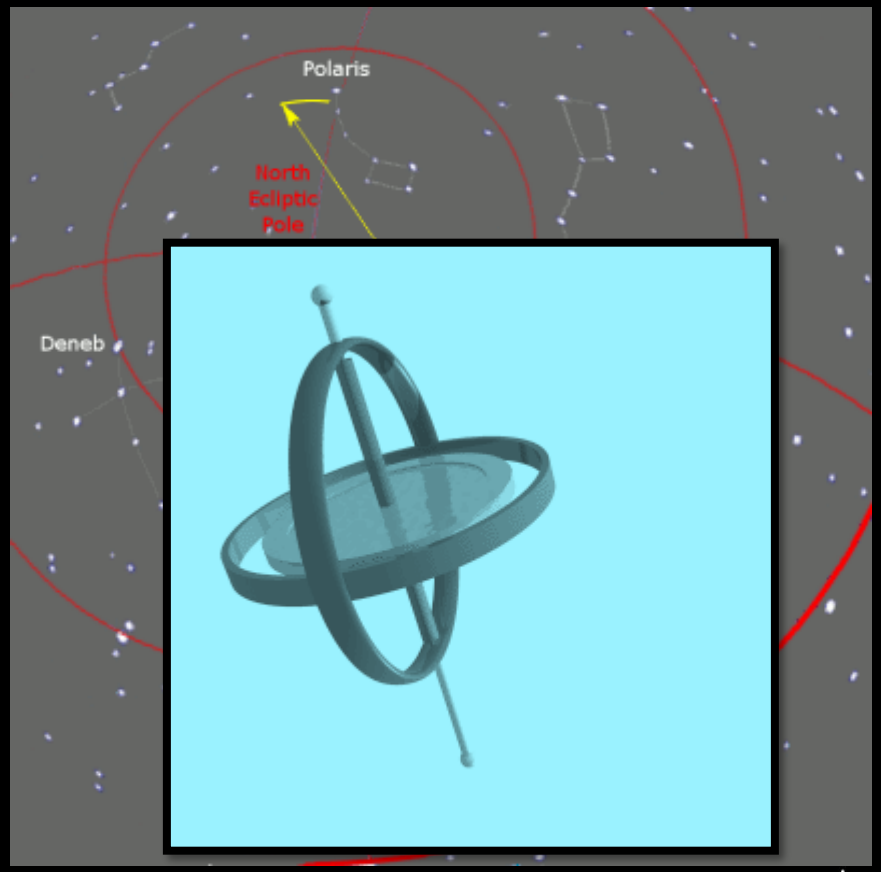
Angle referenced to Ecliptic Plane

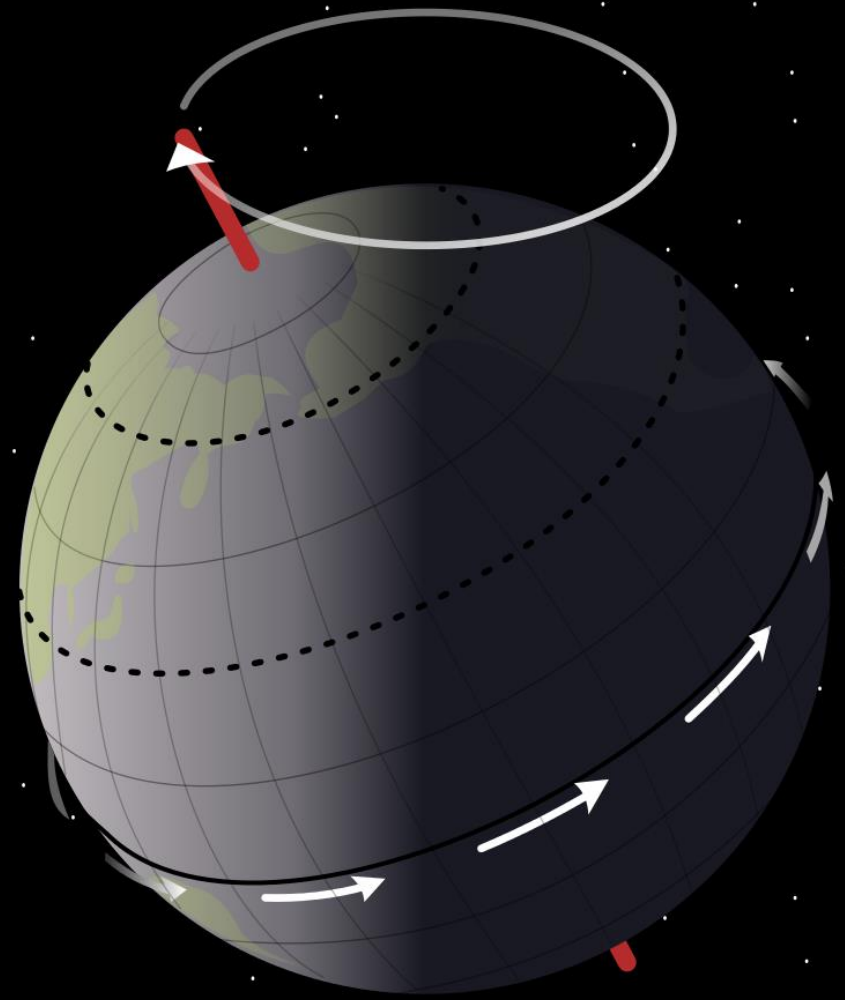
Axial Tilt *appears* to vary on a 40,000 year cycle…

At present, Tilt ≈ 23.4°

Sizable climate effect

Axial Precession

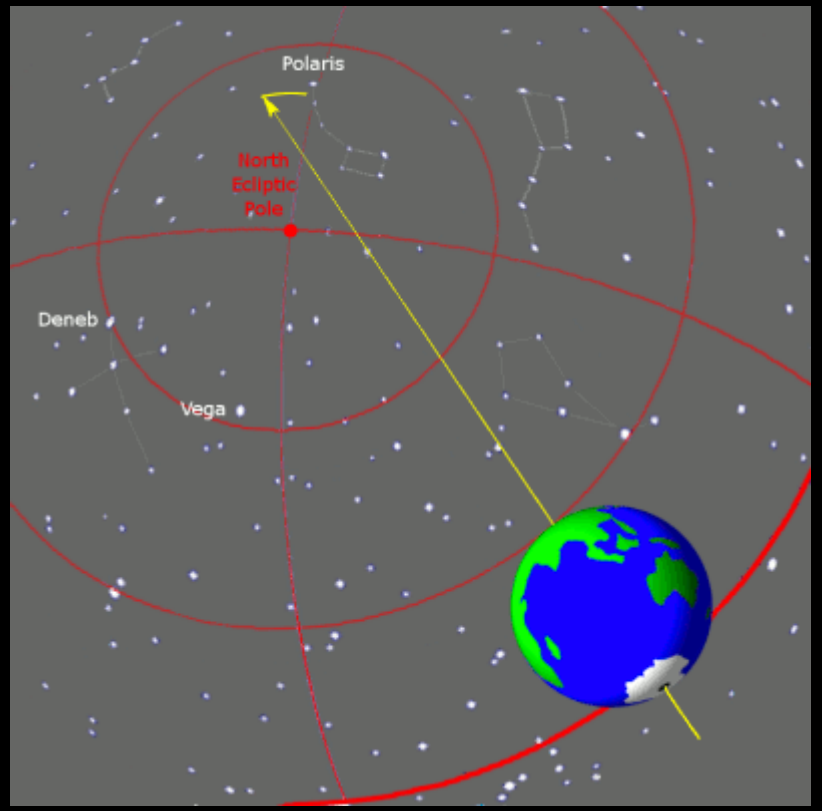


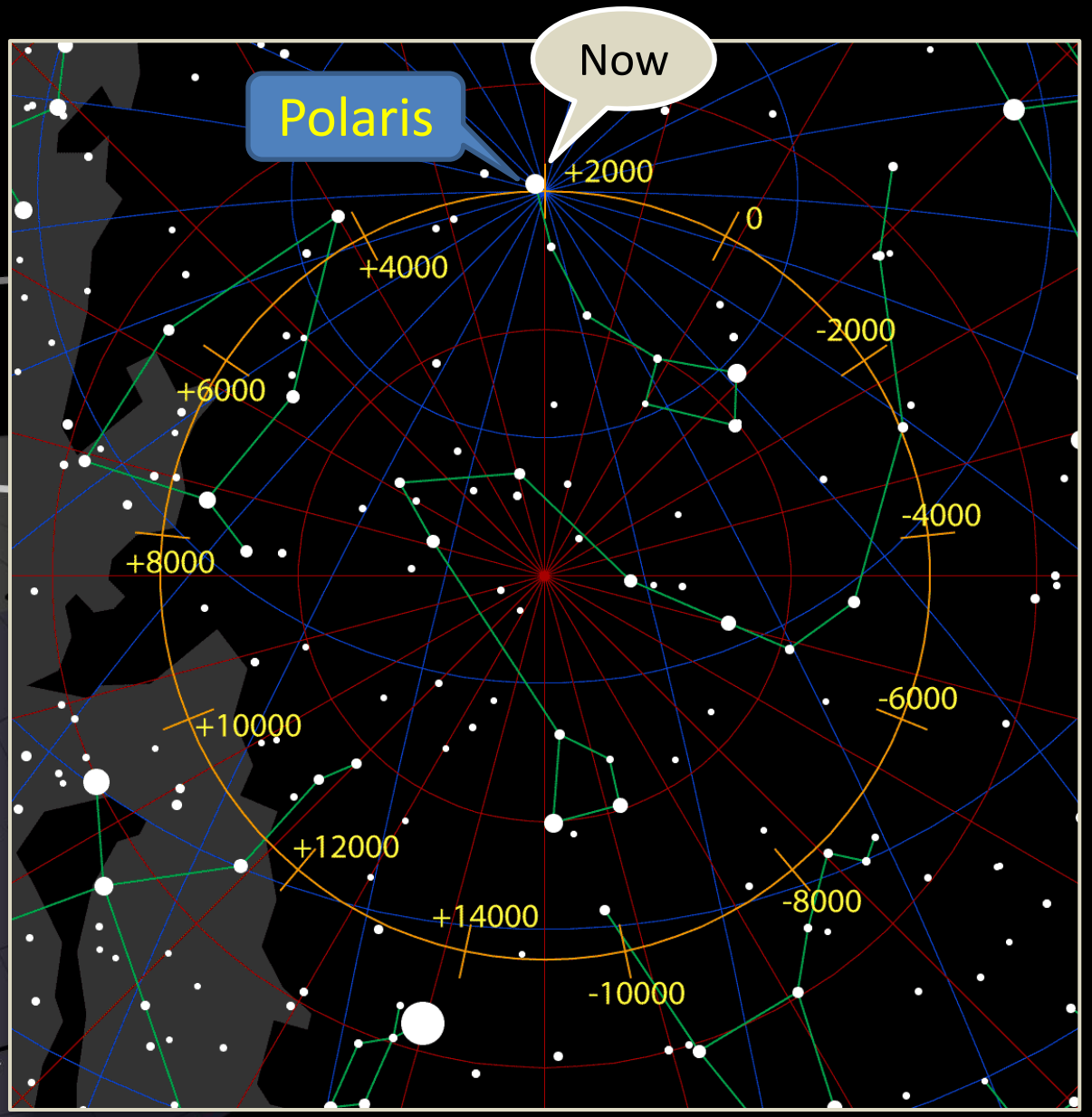


Caused by Tidal Torques from Moon & Sun

25,770 Year Period

Axial Precession



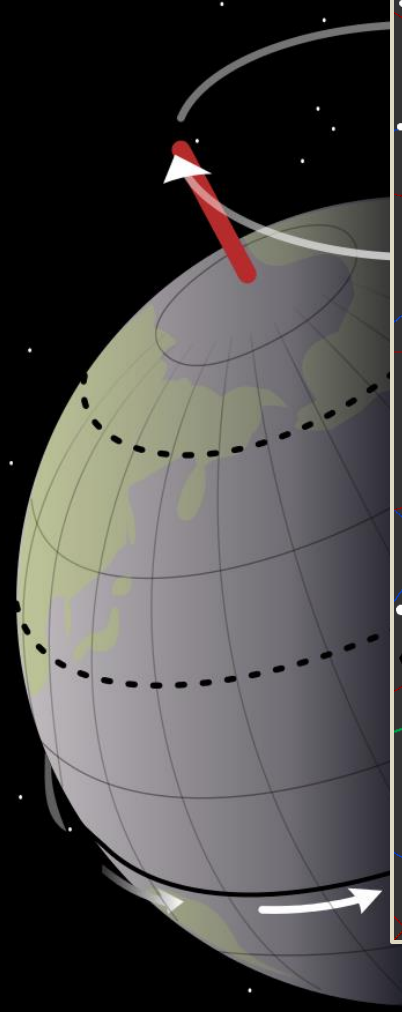


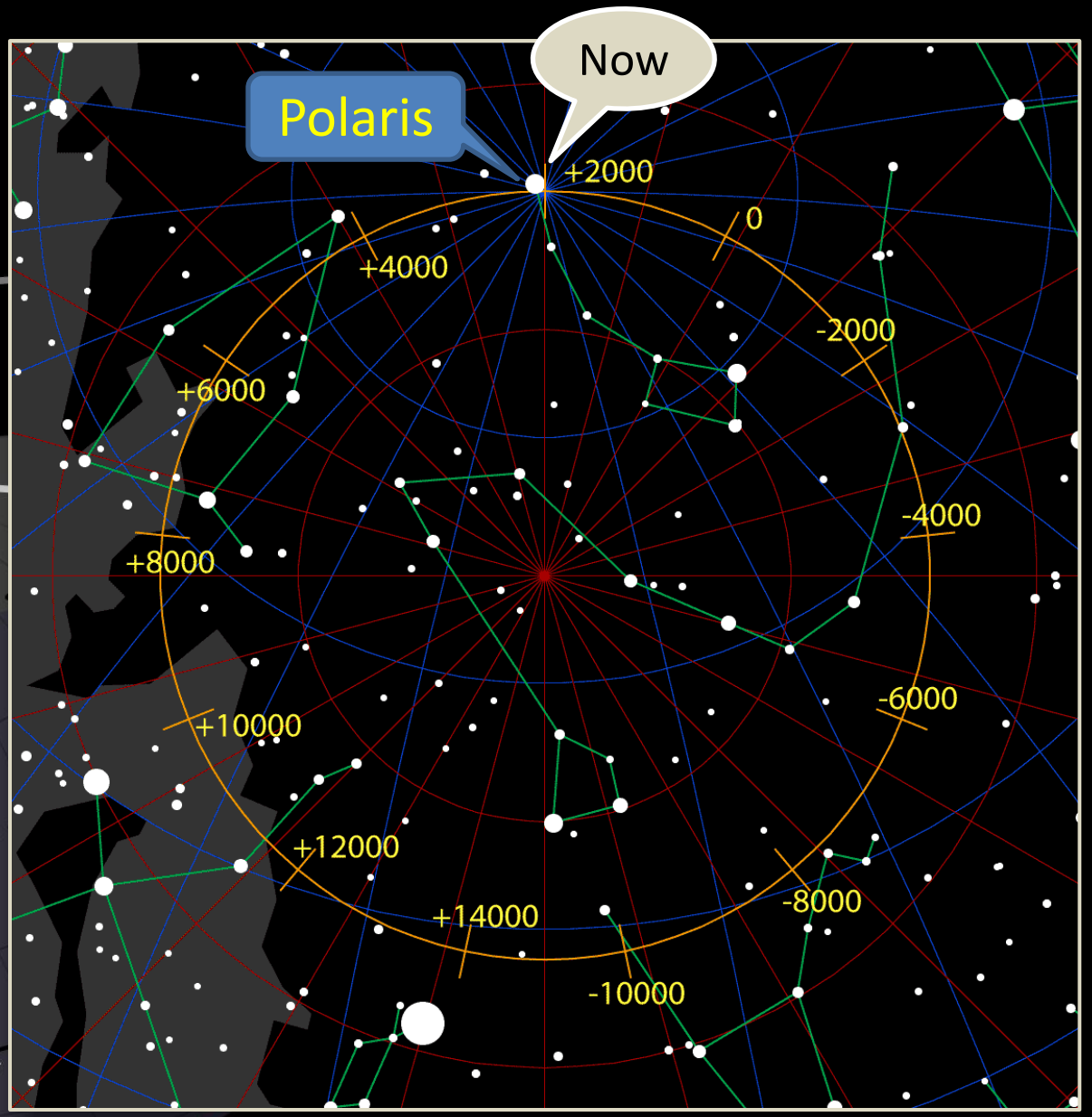
25,770 Year Period

Axial Precession

Hipparchus of NIcaea
(~190-~120 BC)
Greek Astronomer

Discovery and Measurement of the "Precession of the Equinoxes"



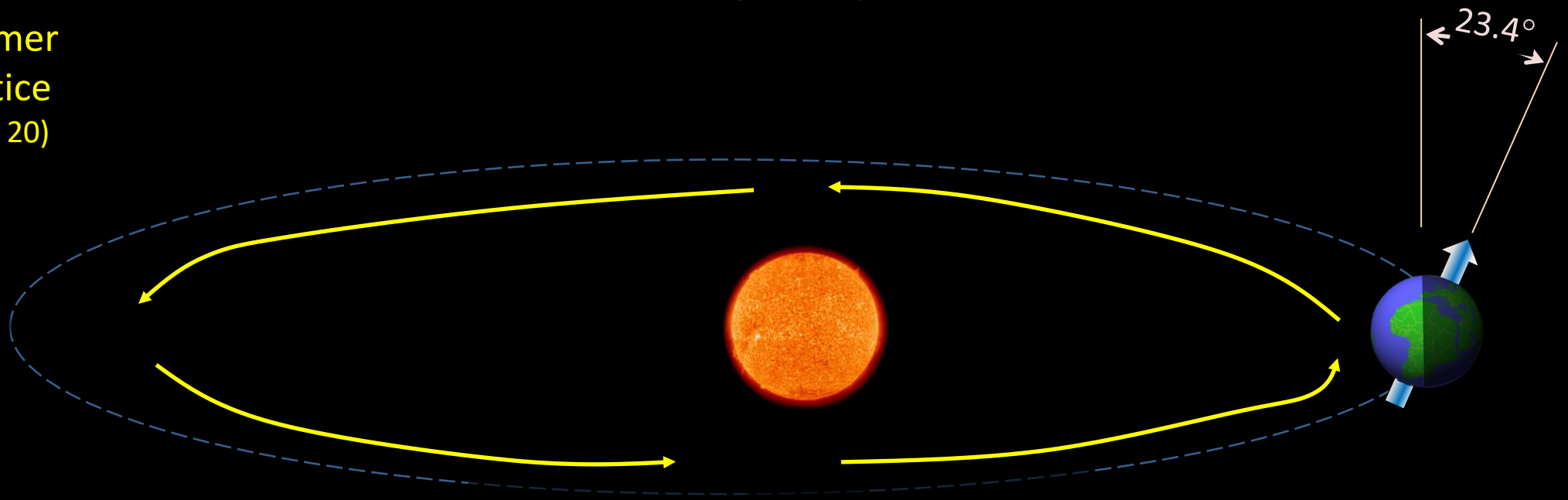


25,770 Year Period

Current Orbit

Spring Equinox (~Mar 20)

Summer Solstice (~Jun 20)



Winter Solstice (~Dec 21)

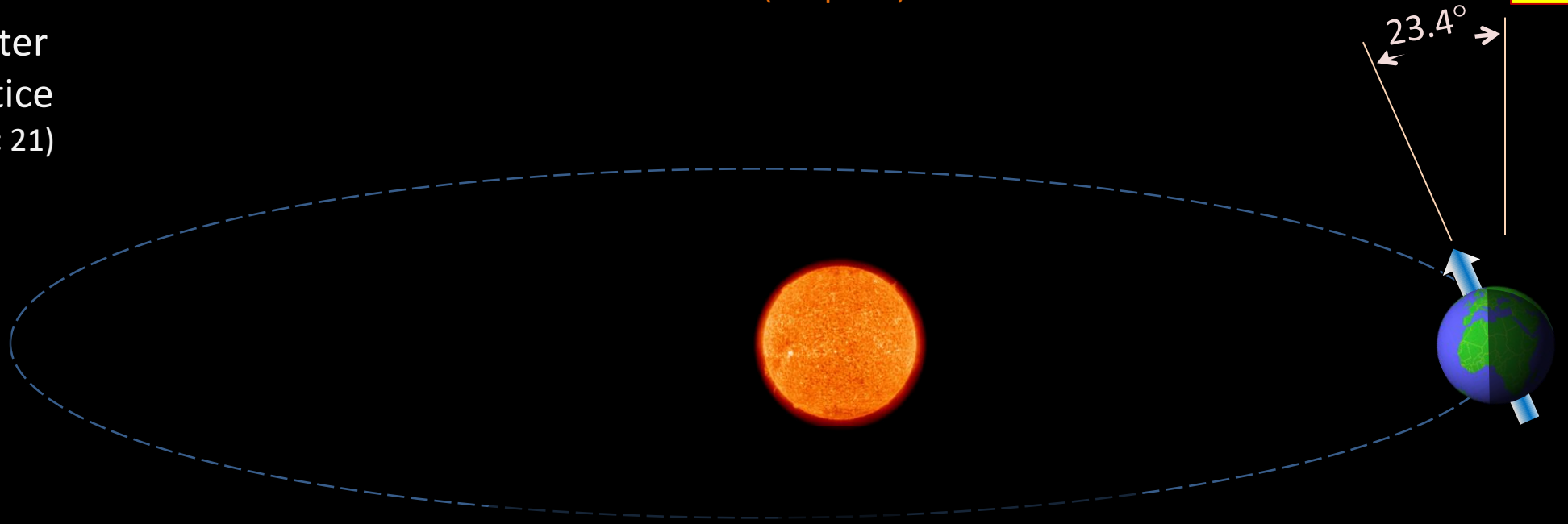
Fall Equinox (~Sept 22)

13,000 Years Ago

Fall
Equinox
(~Sept 22)

Due to axial precession, North pole now pointed toward sun

Winter
Solstice
(~Dec 21)



Winter
Solstice?

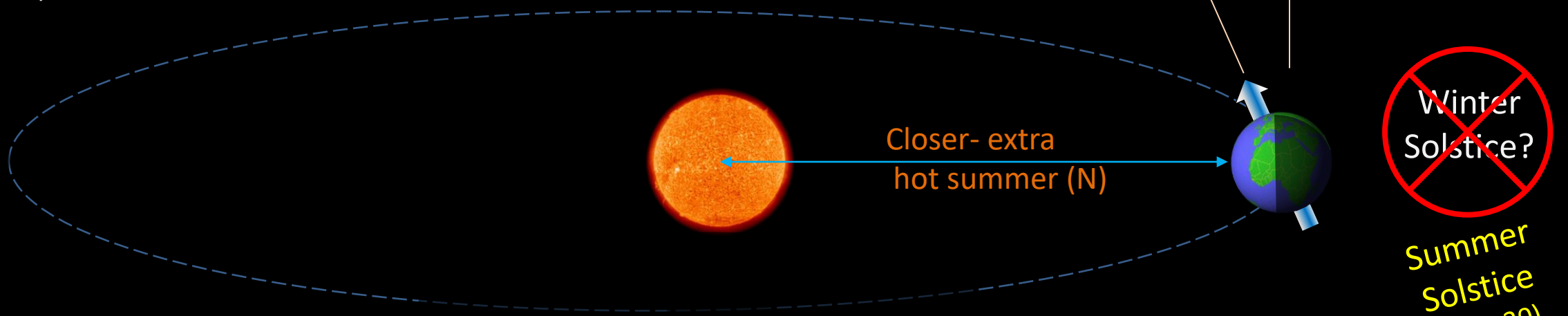
Spring
Equinox
(~Mar 20)

13,000 Years Ago

Fall
Equinox
(~Sept 22)

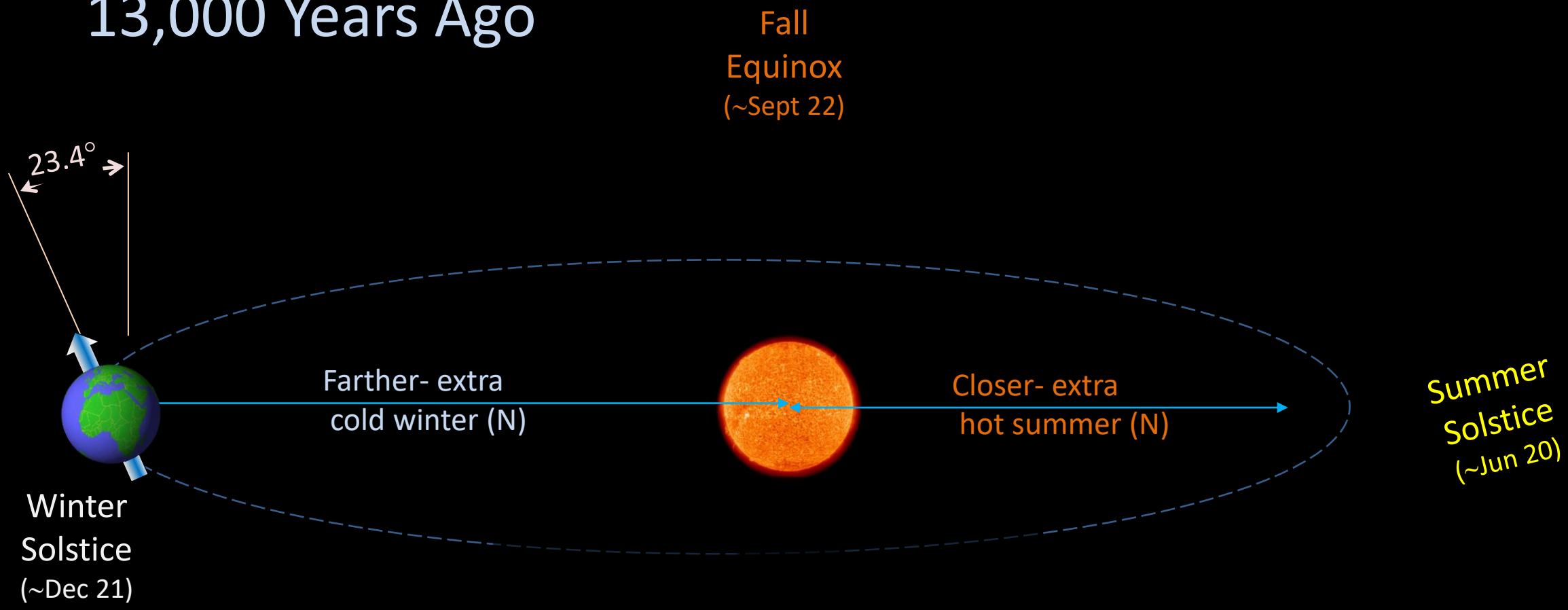
Winter
Solstice
(~Dec 21)

…so it's now actually a Summer Solstice… but a much hotter summer since we're close to sun



Spring
Equinox
(~Mar 20)

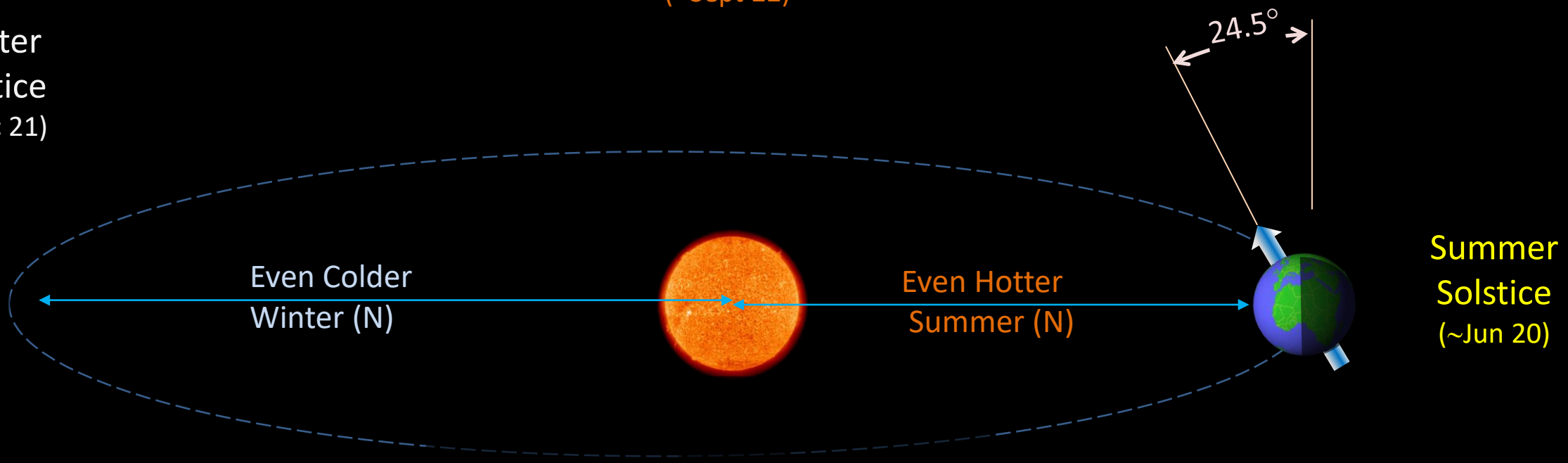
13,000 Years Ago



??? Years Ago: Max Axial Tilt

Fall Equinox (~Sept 22)

Winter Solstice (~Dec 21)

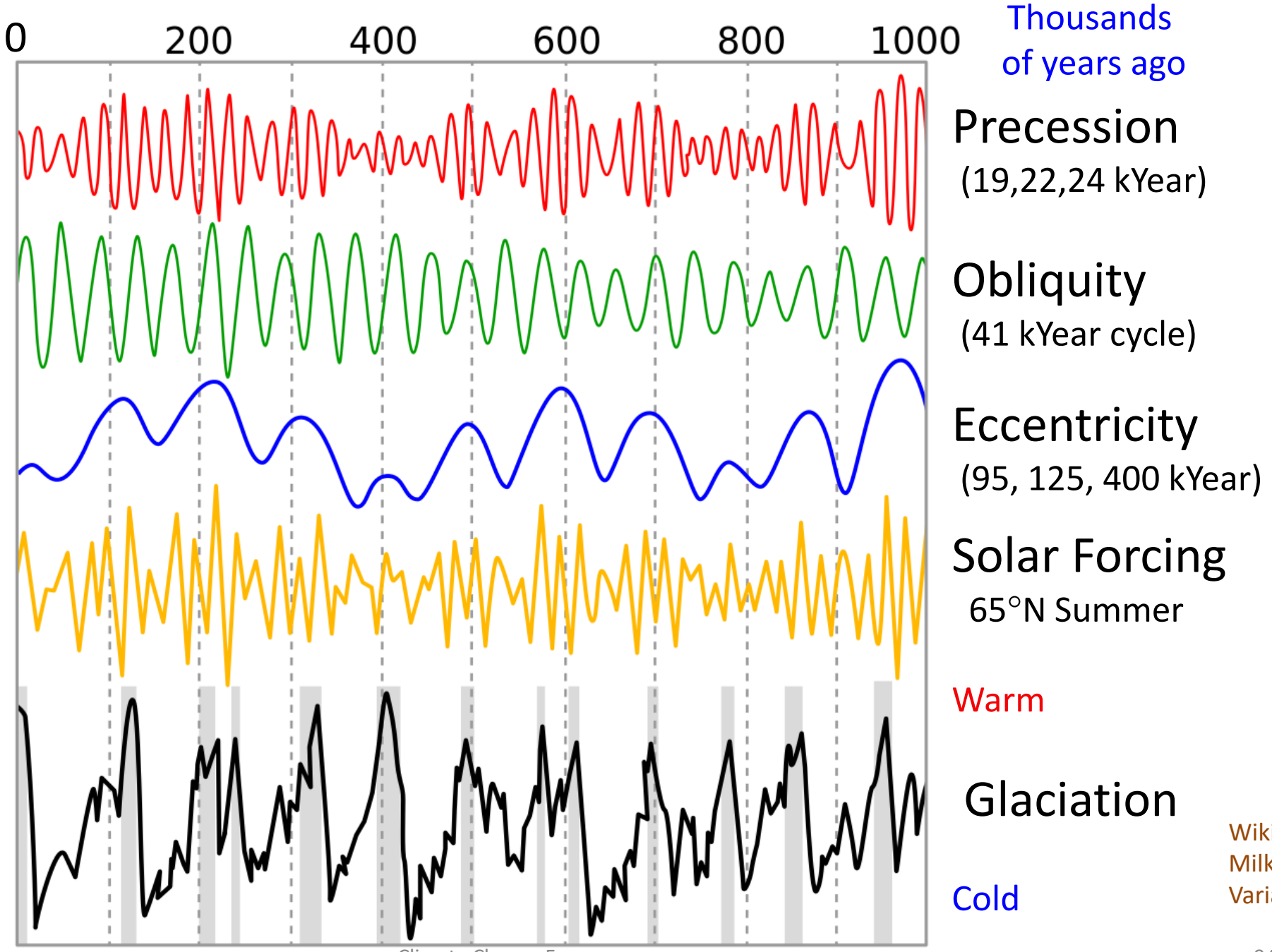


Summer Solstice (~Jun 20)

Spring Equinox (~Mar 20)

When max axial tilt coincides with maximum eccentricity and summer solstice is closest to sun… super hot summer

Milkanovic Cycles and Ice Ages

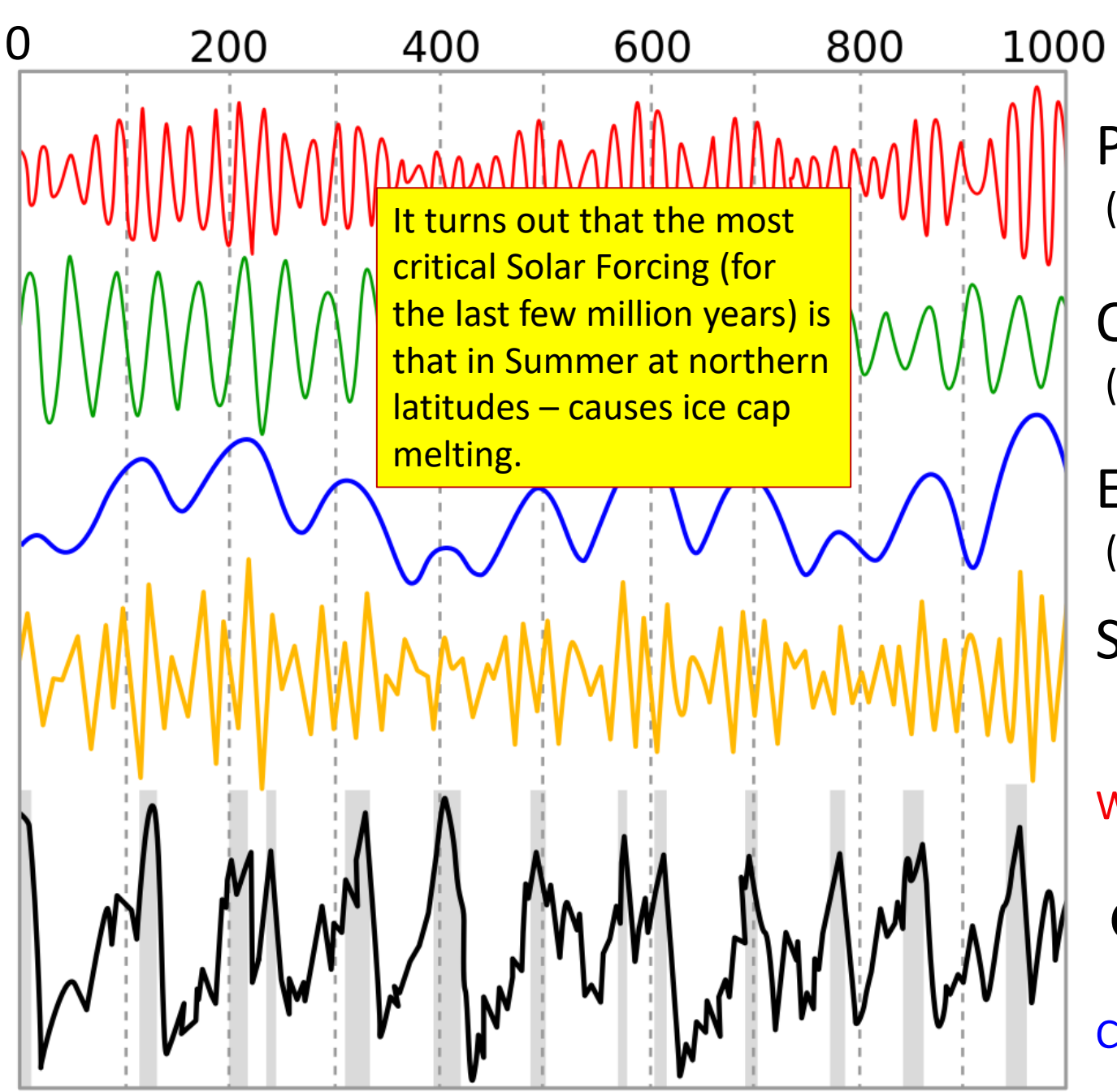


Solar Forcings are sizable, but not enough alone to explain huge temperature swings.

Probably act as triggers -- Amplified by CO_2 from Ocean and by Ice Dynamics

Wikimedia Milkanovich Variations

Milkanovic Cycles and Ice Ages

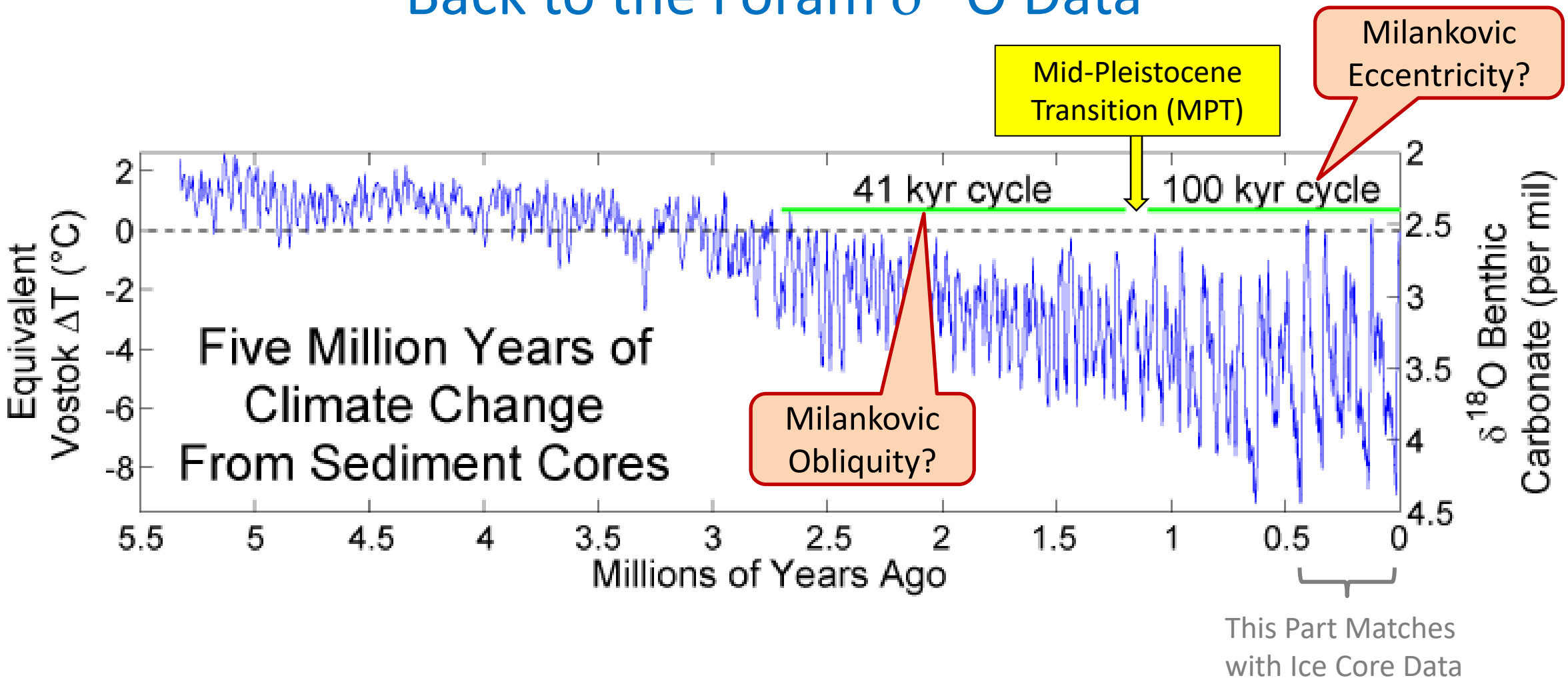


Solar Forcings are sizable, but not enough alone to explain huge temperature swings.

Probably act as triggers -- Amplified by CO_2 from Ocean and by Ice Dynamics

Wikimedia Milkanovich Variations

Back to the Foram $\delta^{18}O$ Data



Explaining the **Mid-Pleistocene Transition** 1 Million Years Ago

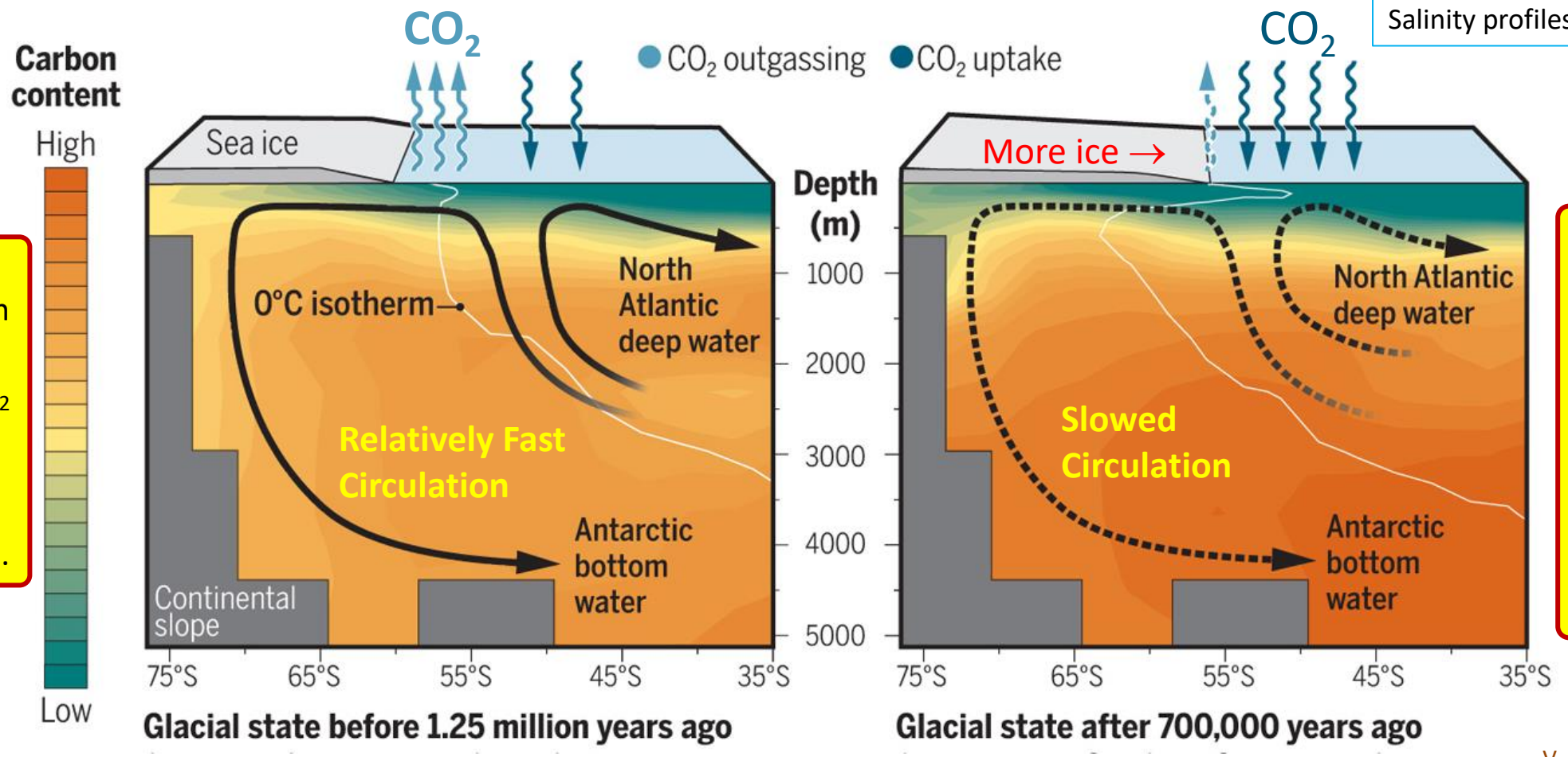
(from 41 ky to 100 ky Glacial Cycles)

Hasenfratz et. al. Science, March 2019

Ocean Cores at 53°S :
$\delta^{18}O$, Mg/Ca in both Benthic & Floating Forams used to estimate southern ocean Temperature and Salinity profiles.

Stratification of the Southern Ocean

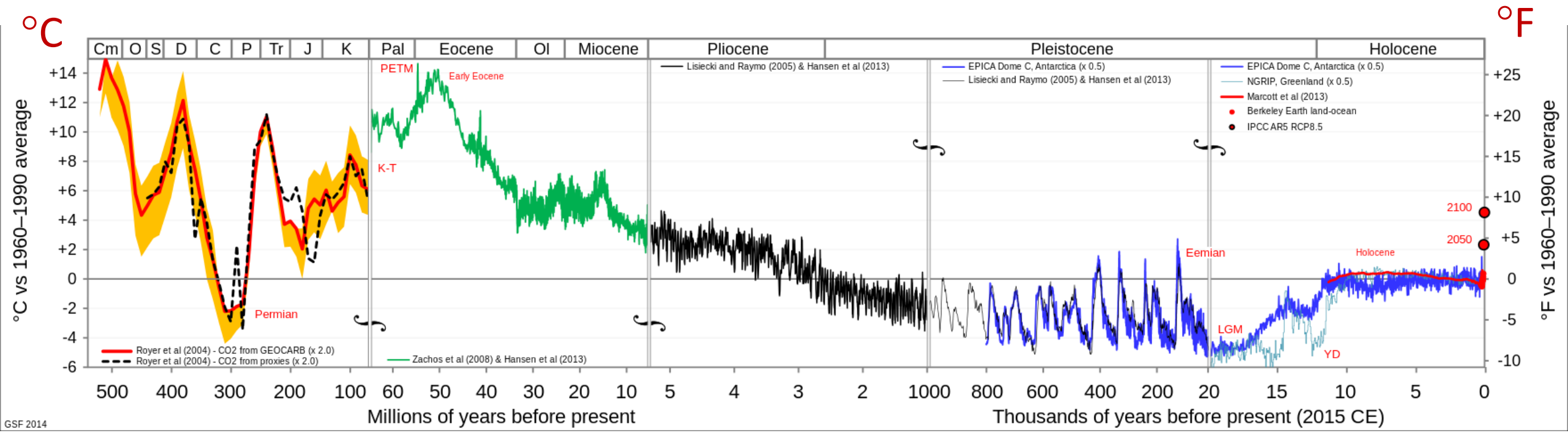
Earlier: Faster ocean circulation, stronger CO_2 transfer from deep ocean to atmosphere.



Later: Slower ocean circulation, enhanced CO_2 transfer from atmosphere to deep ocean lowers air CO_2.

V. Altounian/Science

Proxy Estimates of Earth Surface Temperature



Subtropical and Tropical Marine Shell Fossils $\delta^{18}O$

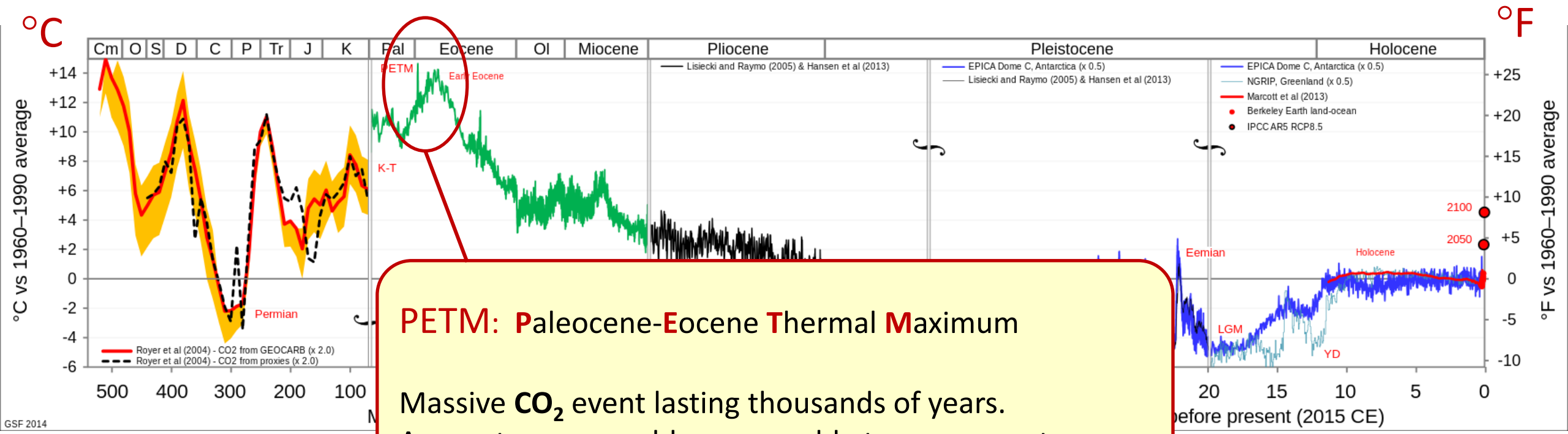
Microscopic Marine Organism Shells $\delta^{18}O$

Ice Core Polar Data ($\delta^{18}O$ & $\delta^{2}H$) [Adjusted for Global]

Multi-Proxy Data

Glen Furgus "All Palaeotemps.svg" Wikipedia "Paleoclimatology". Composite from various source data.

Proxy Estimates of Earth Surface Temperature



PETM: **P**aleocene-**E**ocene **T**hermal **M**aximum

Massive CO_2 event lasting thousands of years. Amounts very roughly comparable to our current injection, but over much longer time span.

5-8°C warming, mammals appear, mass extinctions, etc.

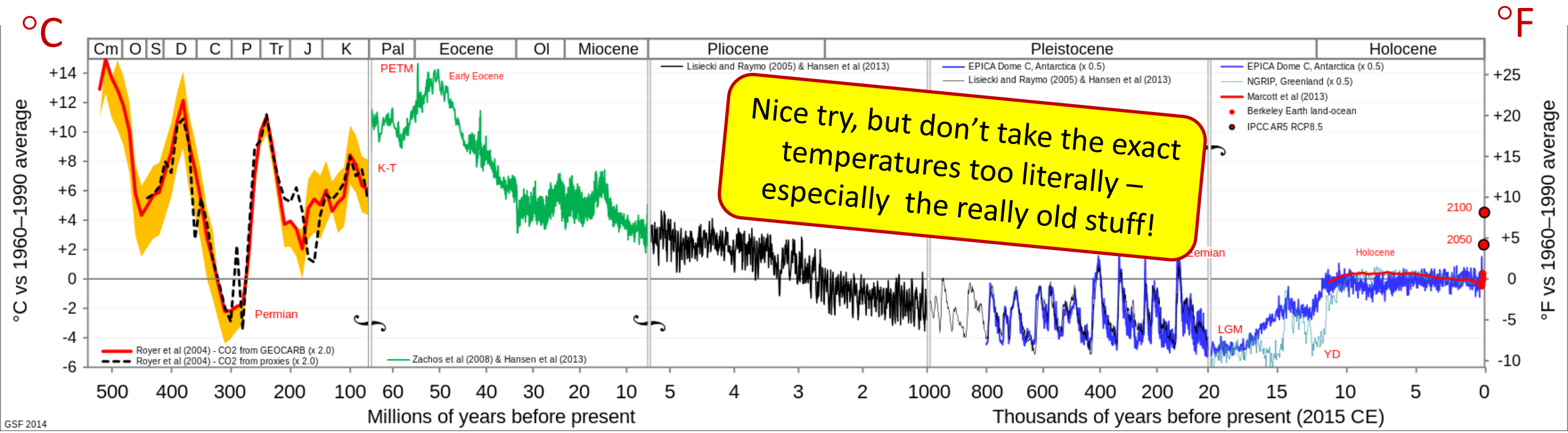
Subtropical and Tropical Marine Shell Fossils $\delta^{18}O$

e Polar Data
D & δ^2H)
ed for Global]

Multi-Proxy Data

Glen Furgus "All Palaeotemps.svg" Wikipedia "Paleoclimatology". Composite from various source data.

Proxy Estimates of Earth Surface Temperature



Nice try, but don't take the exact temperatures too literally – especially the really old stuff!

Subtropical and Tropical Marine Shell Fossils $\delta^{18}O$

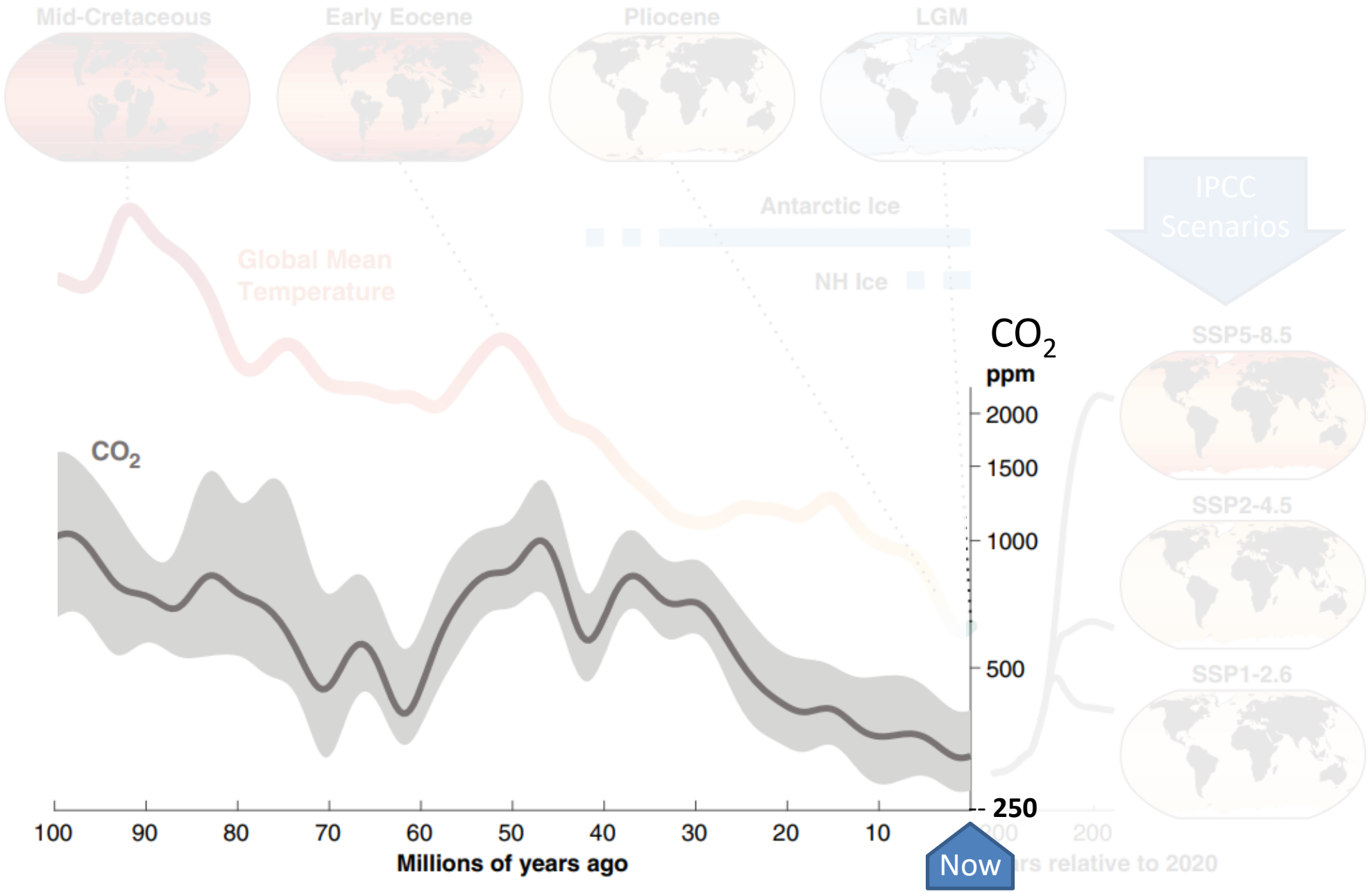
Microscopic Marine Organism Shells $\delta^{18}O$

Ice Core Polar Data ($\delta^{18}O$ & $\delta^{2}H$) [Adjusted for Global]

Multi-Proxy Data

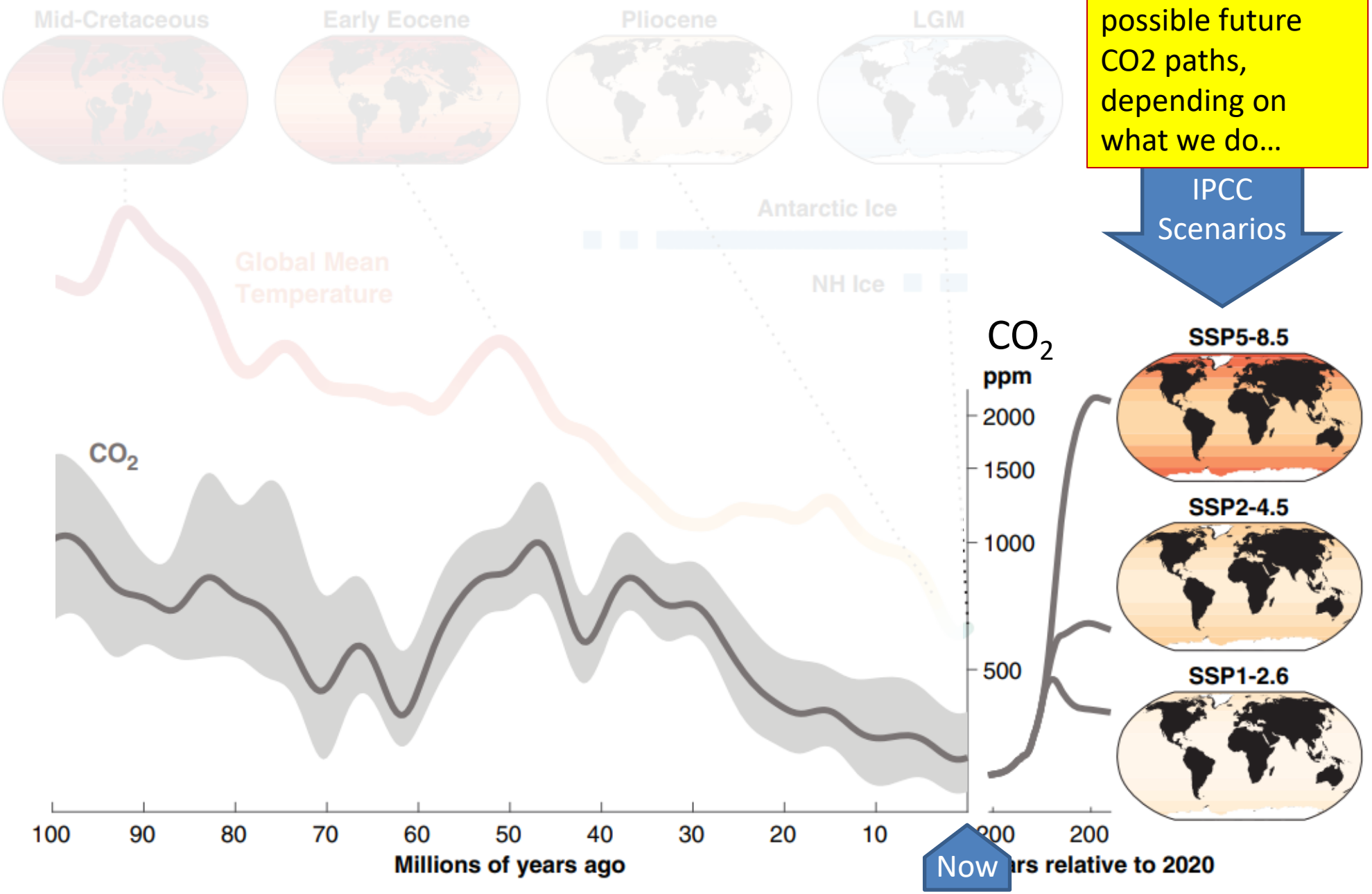
Glen Furgus "All Palaeotemps.svg" Wikipedia "Paleoclimatology". Composite from various source data.

Estimates of Past CO_2 Levels and Global Temperatures



Jessica Tierney *et. al.*, *"Past Climates Inform our Future"* Science (Nov 2020)

Estimates of Past CO_2 Levels and Global Temperatures

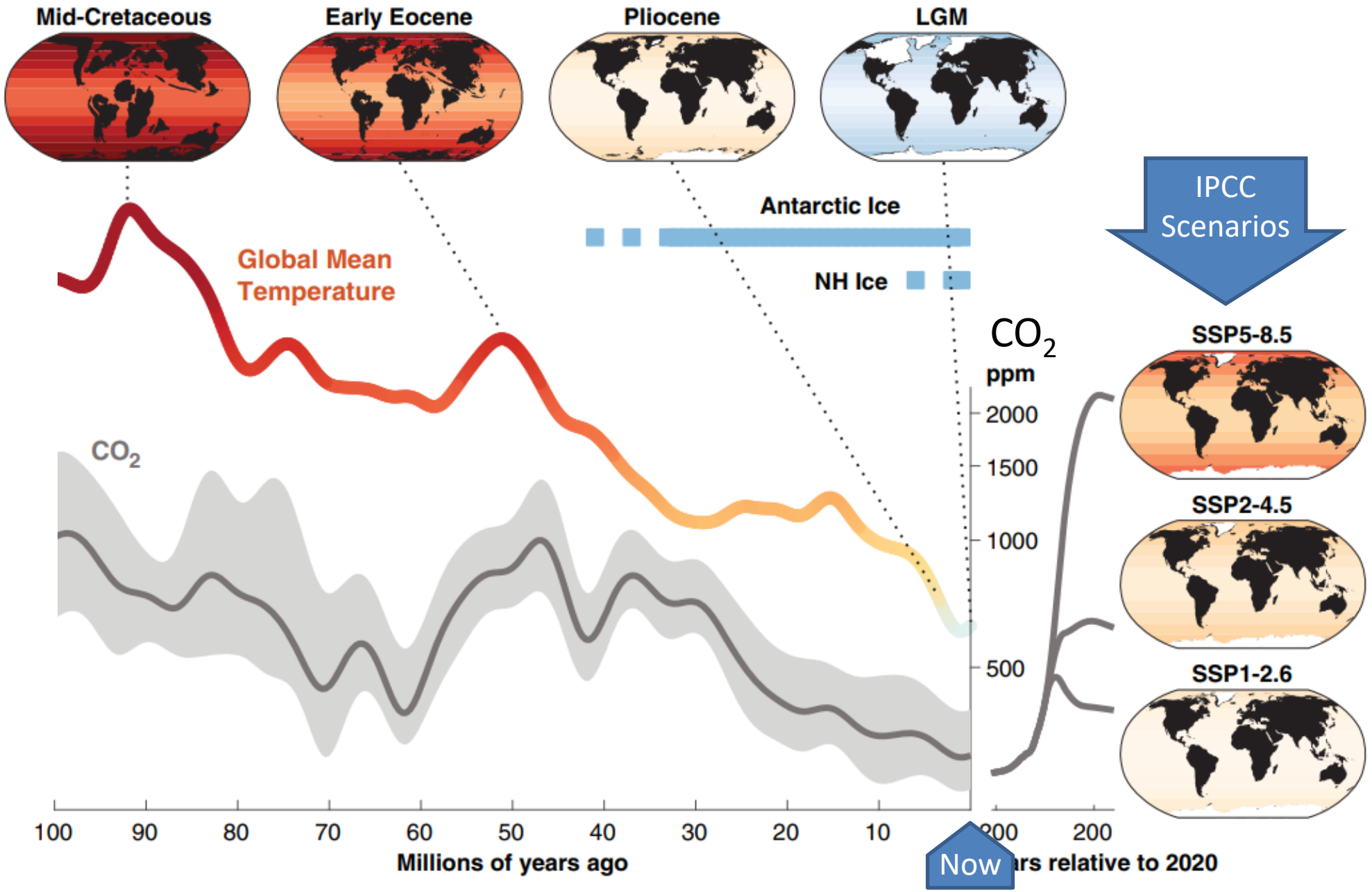


possible future CO2 paths, depending on what we do…

IPCC Scenarios

Jessica Tierney *et. al.*, *"Past Climates Inform our Future"* Science (Nov 2020)

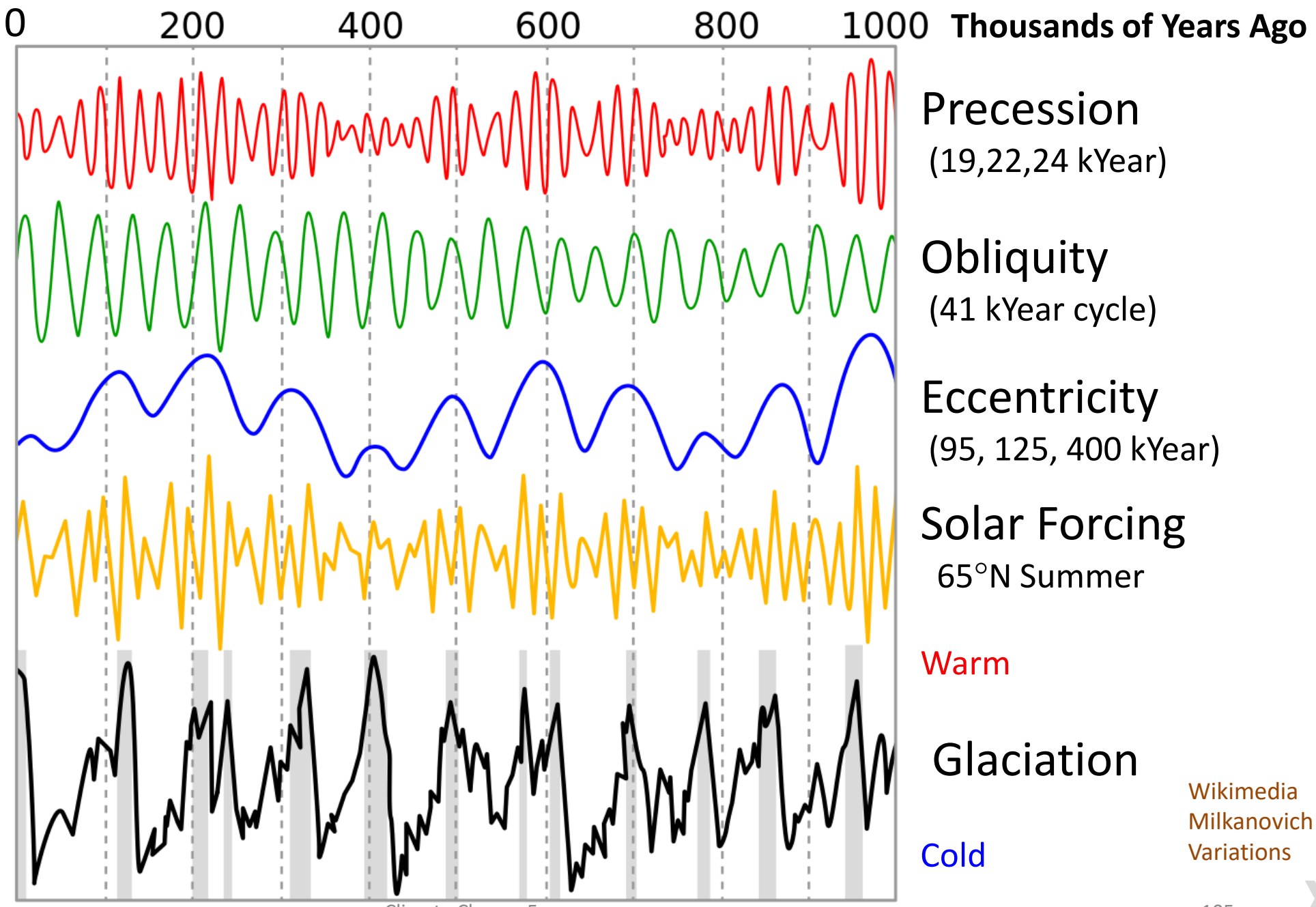
Estimates of Past CO_2 Levels and Global Temperatures



Showing roughly how possible futures line up with climates 10's of millions of years ago….

Jessica Tierney *et. al.*, *"Past Climates Inform our Future"* Science (Nov 2020)

Milkanovic Cycles and Ice Ages



Solar Forcings are sizable, but not enough alone to explain huge temperature swings.

Probably act as triggers -- Amplified by CO_2 from Ocean and by Ice Dynamics

Wikimedia Milkanovich Variations

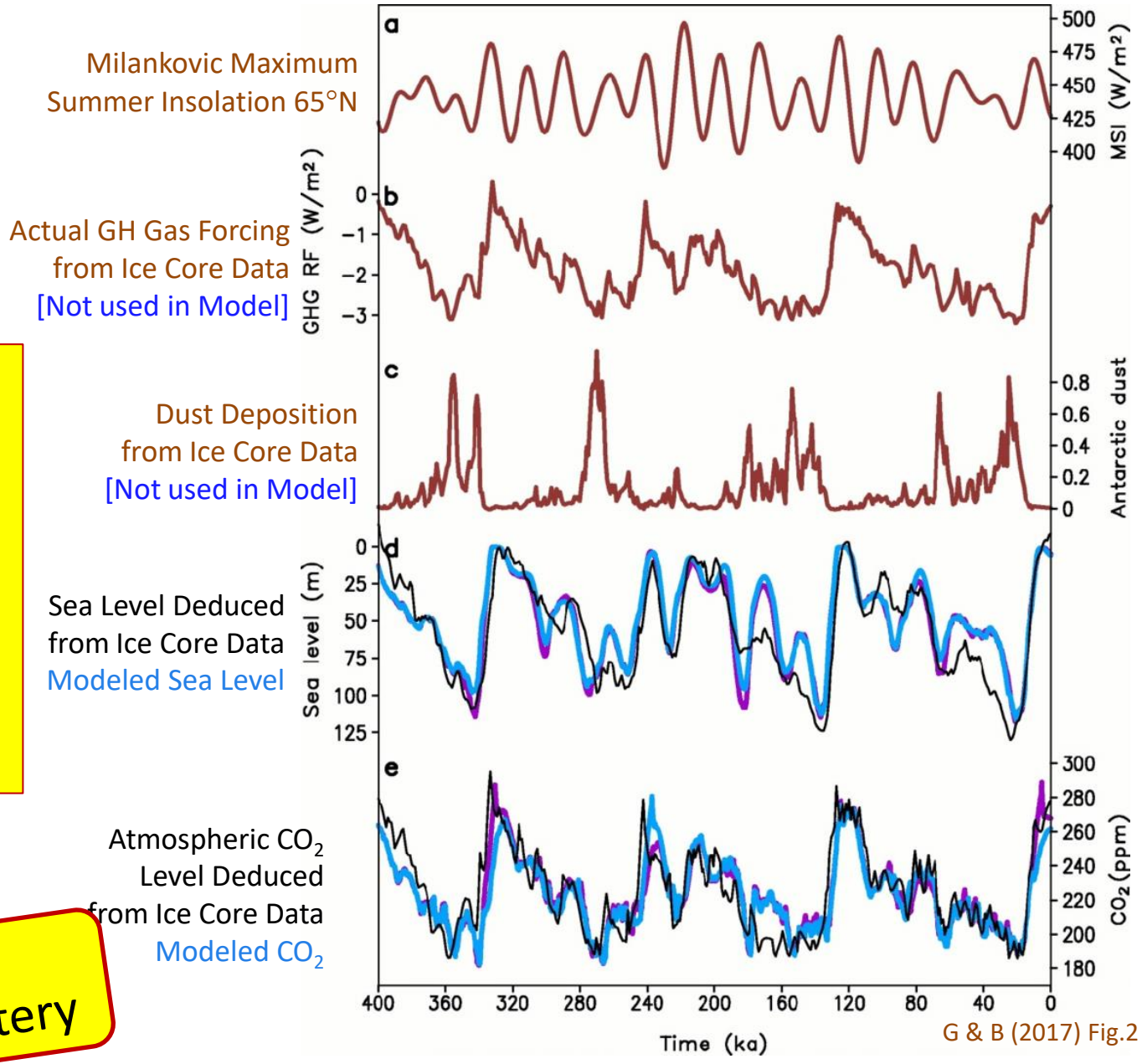
Example of Recent Ice Age Modeling:

Ganopolski & Brovkin 2017

Were able to model last 4 Ice Ages using **only Milankovic Orbital Forcing** together with reasonable feedbacks from

- Ice sheet models
- AMOC models
- CO_2 automatic feedbacks
  - Ocean dynamics
  - Plankton blooms due to dust
  - Peat and Permafrost dynamics
  - Land biota
  - Volcanic Activity

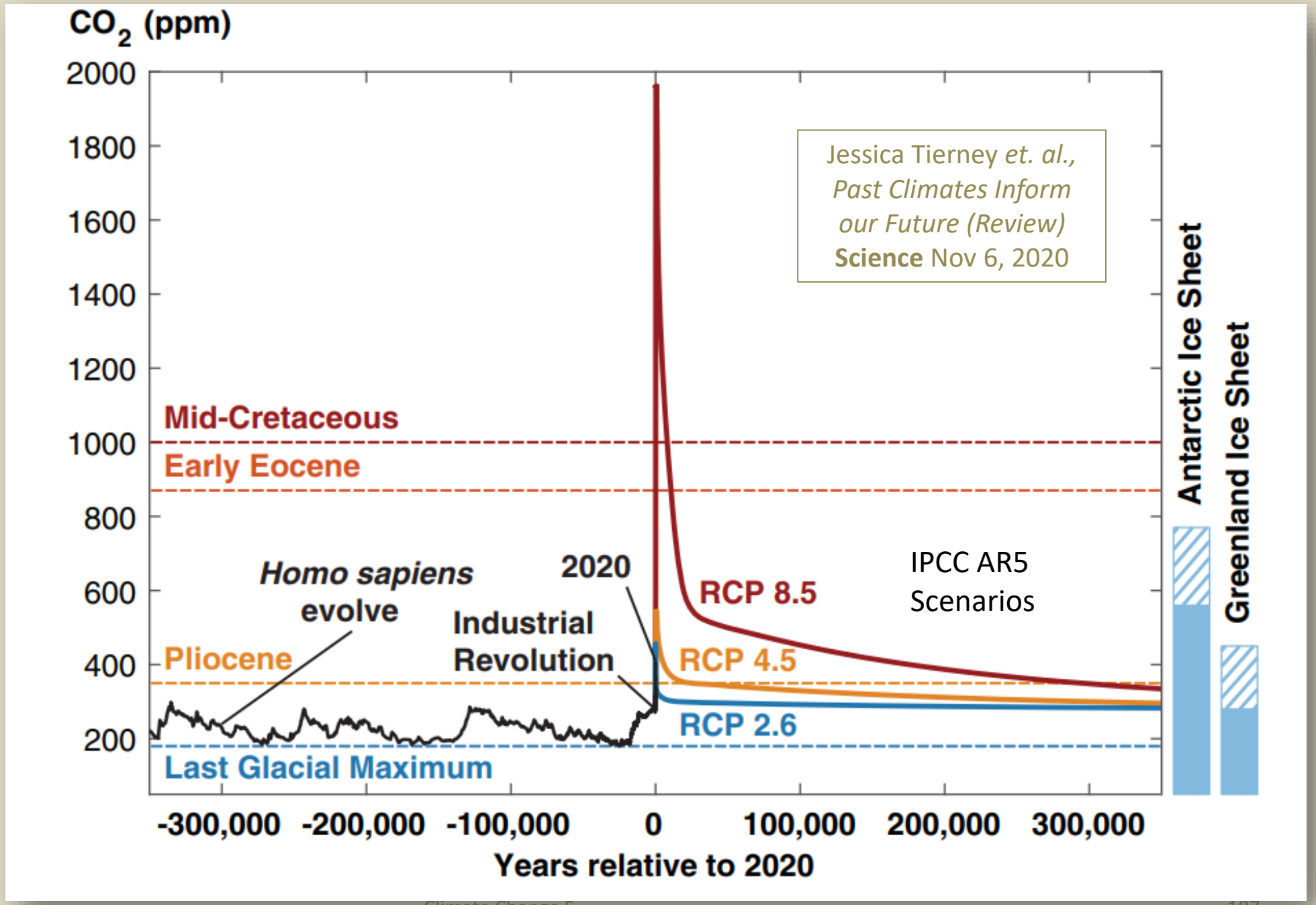
…Models can be tweaked (with reasonable parameters) to produce ice ages that look pretty close to what actually happened.



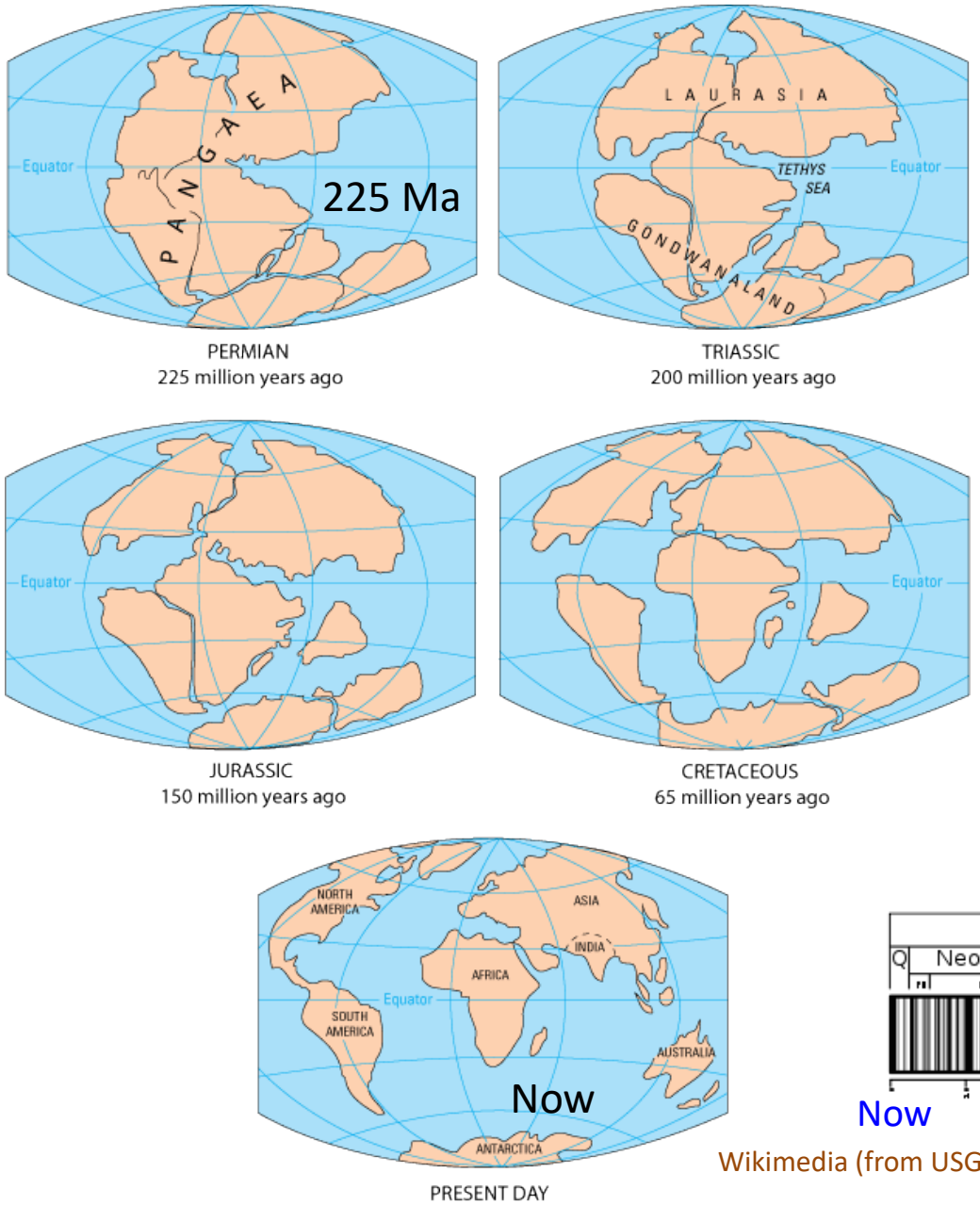
G & B (2017) Fig.2

Bottom Line:
Ice Ages are No Mystery

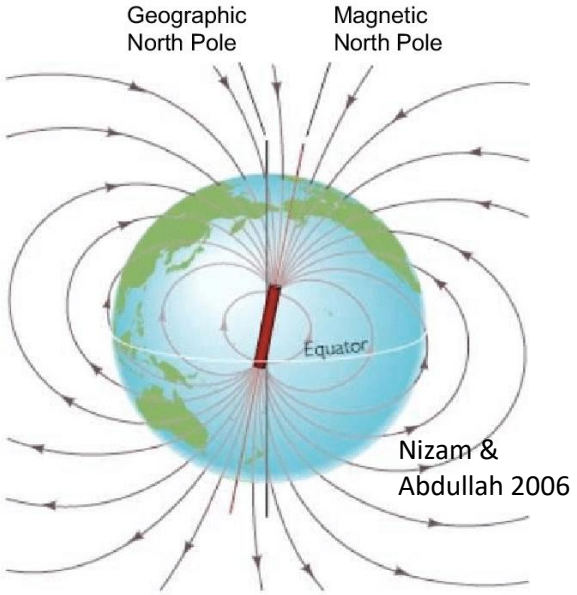
What Might the Future Hold for CO_2?



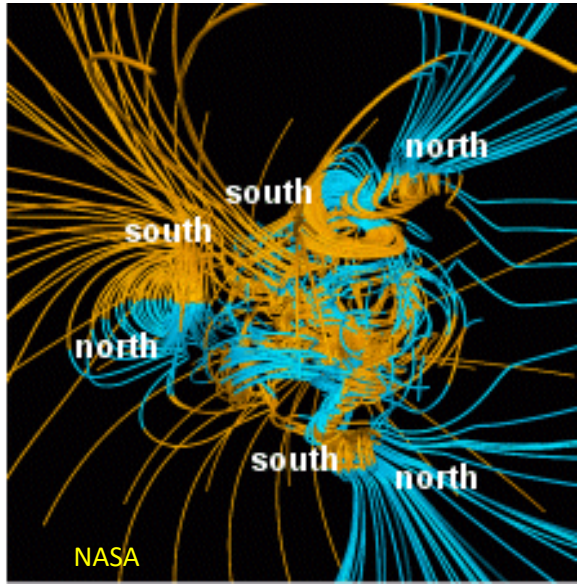
Figuring Out Where a Glaciated Rock *Was*… Way Back Then



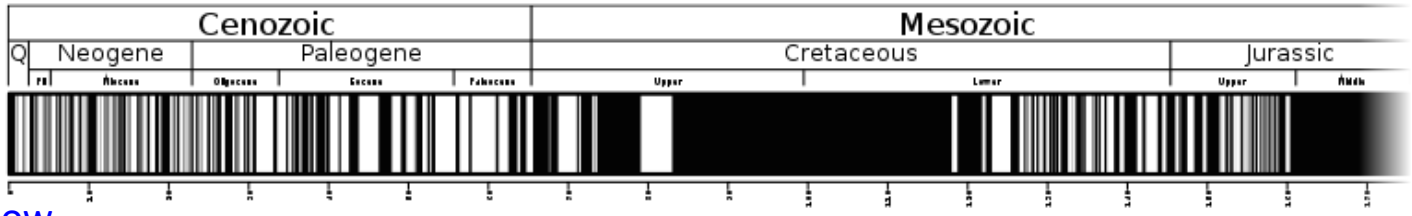
Wikimedia (from USGS)



Nizam & Abdullah 2006



Modeled Magnetic Field During a Reversal

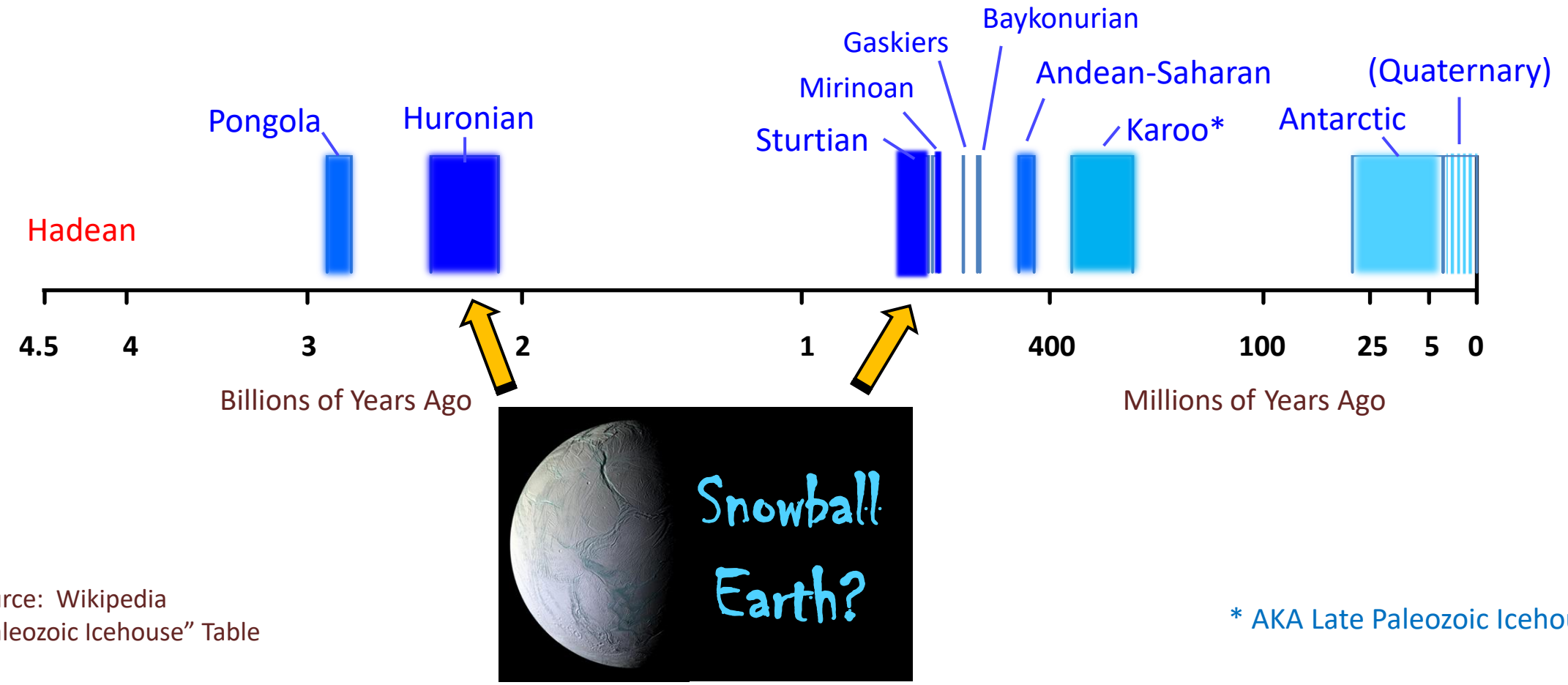


Now

Hundreds of Random Flips

170 Ma

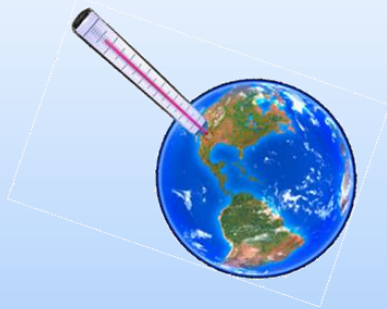
Rough Timeline of Past Glaciations

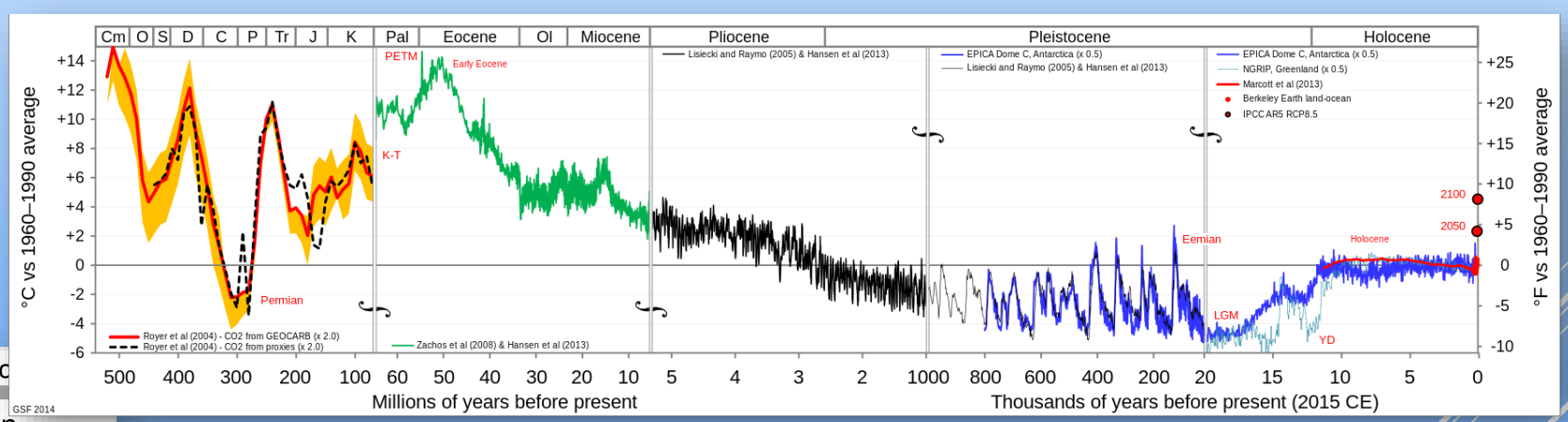


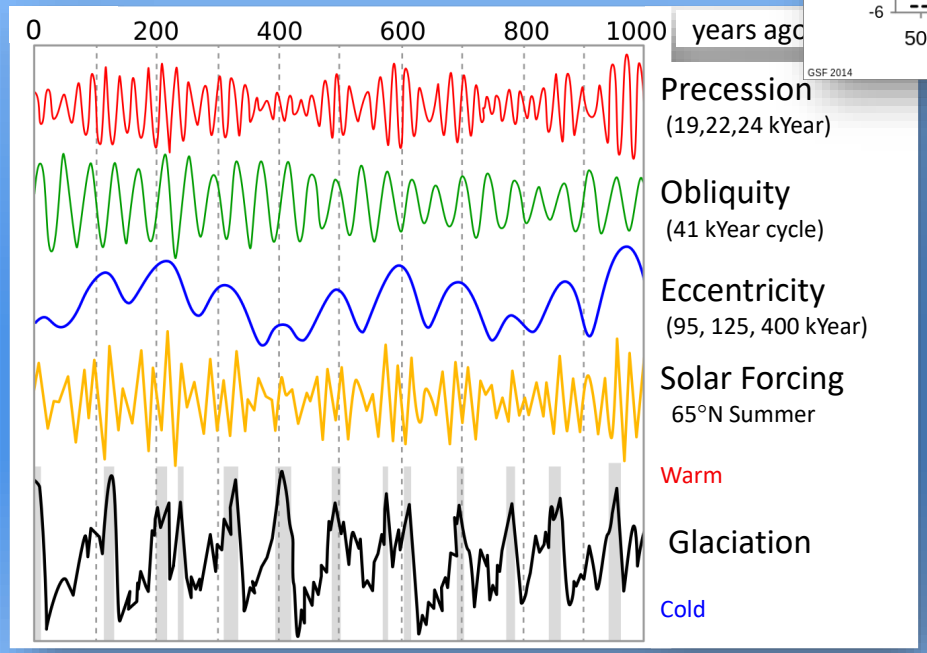
Data source: Wikipedia
"Late Paleozoic Icehouse" Table

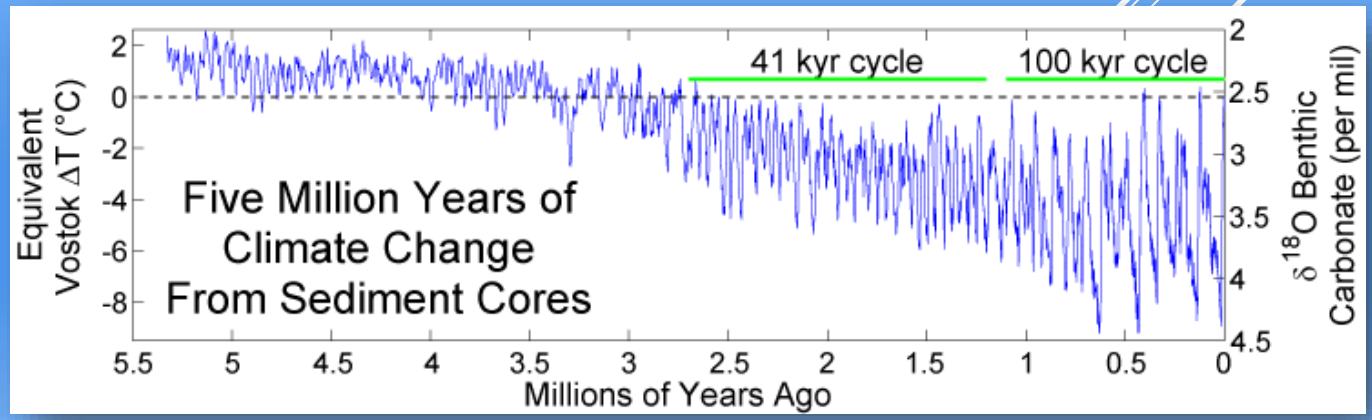
* AKA Late Paleozoic Icehouse

Questions about Milanković Cycles and the Long Term Proxy Record?









Course Outline

1. Building Blocks: Some important concepts
2. Our Goldilocks Earth: a Radiative Balancing Act
3. The Role of the Atmosphere: Greenhouse Gases & Clouds
4. Global Circulation and Dynamics of the Earth System:
   Oceans, Atmosphere, Biosphere, Cryosphere, People, Lithosphere
5. **Natural Variability of the Climate, short and long term. Ice Ages**
6. Carbon Dioxide and other Greenhouse Gases: where do they come from, where do they go, how are they regulated?
7. Impacts and Future Projections for Global Warming -- Uncertainties
8. Adaptation and Amelioration Strategies. The Climate debate. Policy options.