Avoid the Unmanageable, Manage the Unavoidable

Eight Interdisciplinary Lectures on Climate Change

Charles F. Kennel

Monday Evenings, 5:30-7 pm, Martin Johnson House

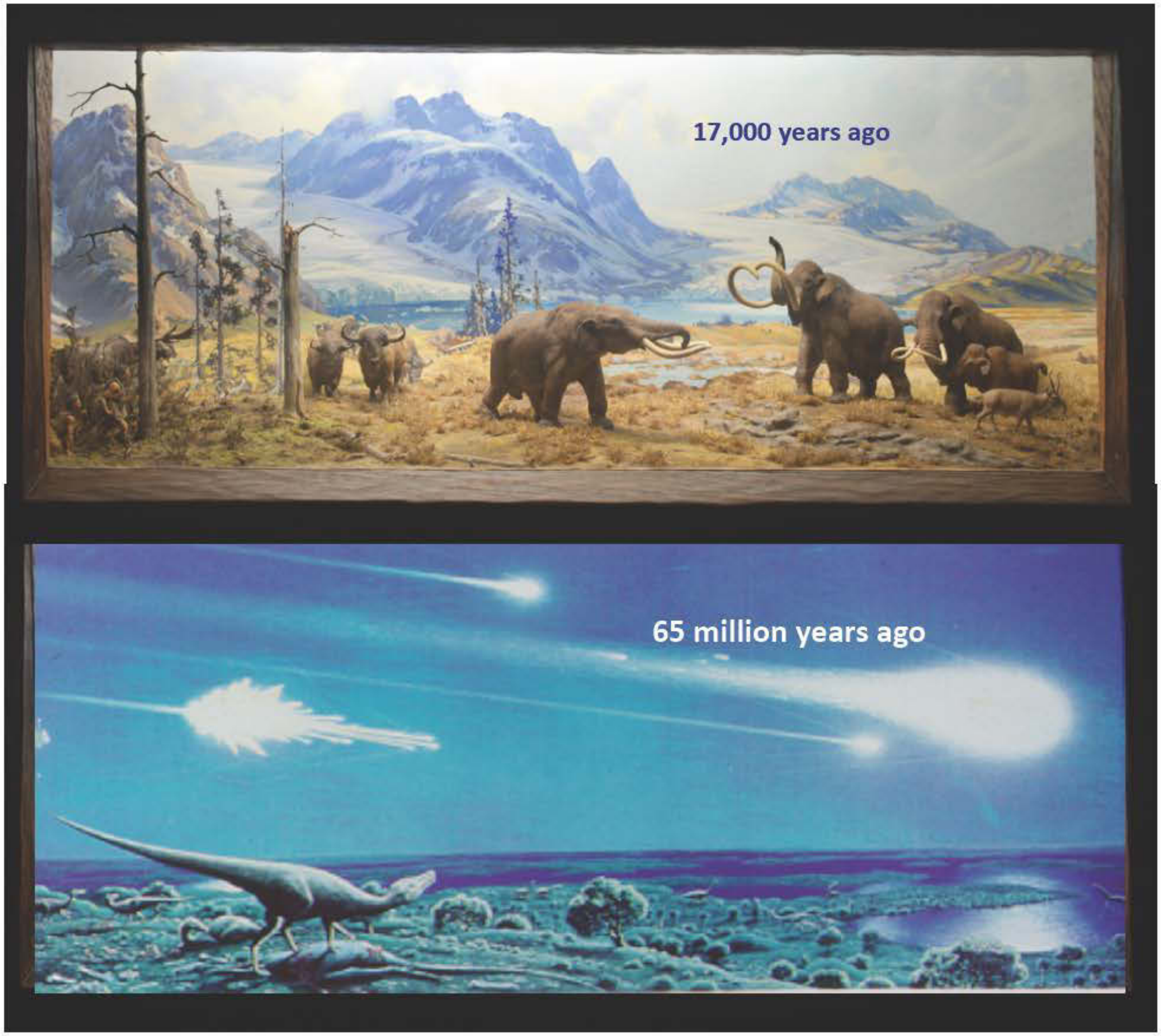
Scripps Institution of Oceanography, University of California San Diego

October 20, 2014: Paleoclimatology

Earth's climate in the past 65 million years; orbital forcing and ice ages; instability of ice age climates; abrupt events; volcanoes, ice, and ocean circulation; our benign interglacial; medieval warm period and little ice age; the Anthropocene

Paleoclimate

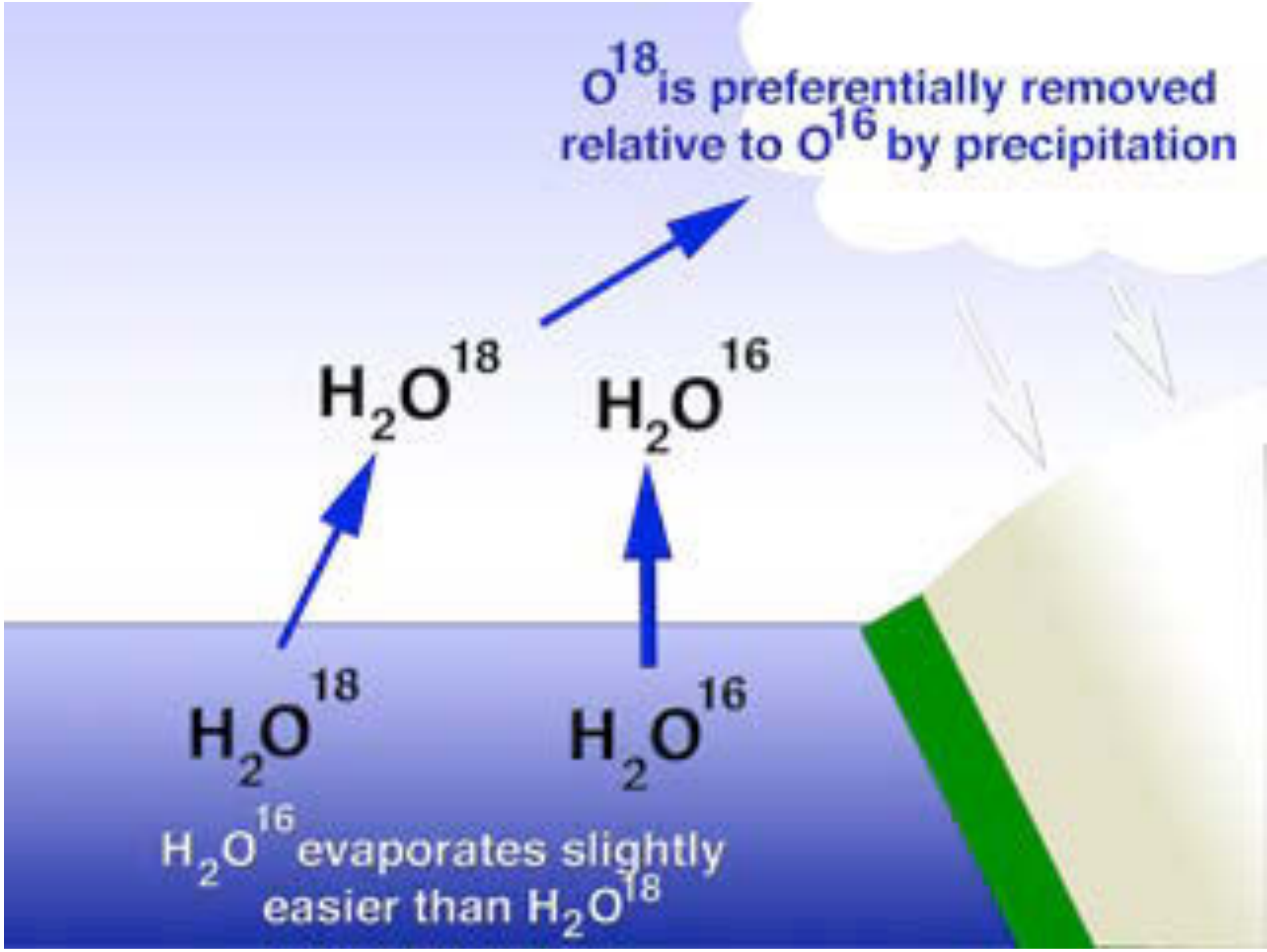
The most challenging task and the most illuminating task in climate science



If you wanted to know the temperature 65 million years ago, how would you find out?

Stable Oxygen Isotopes

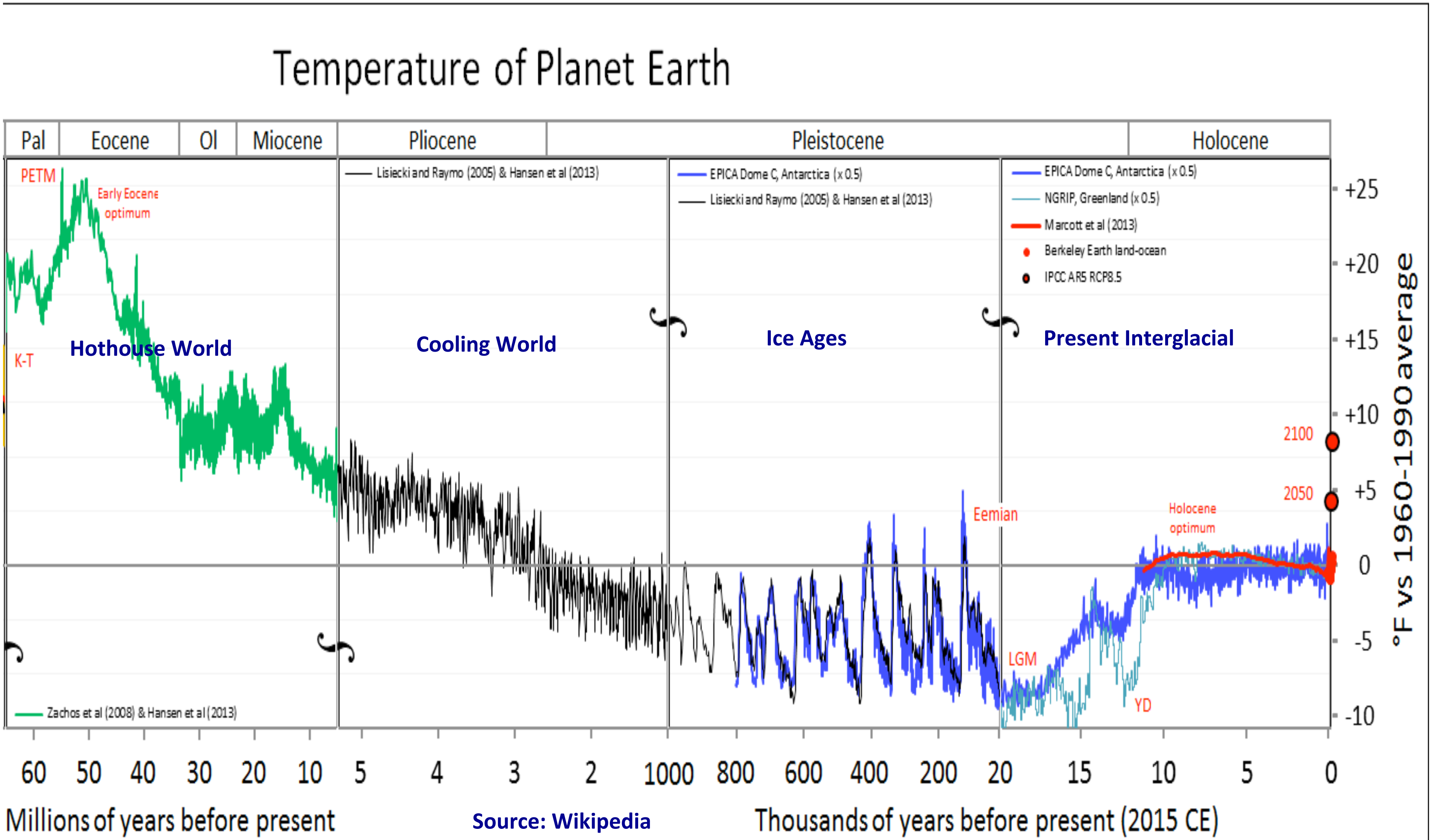
The two forms of oxygen are chemically identical, gravitationally differentiated



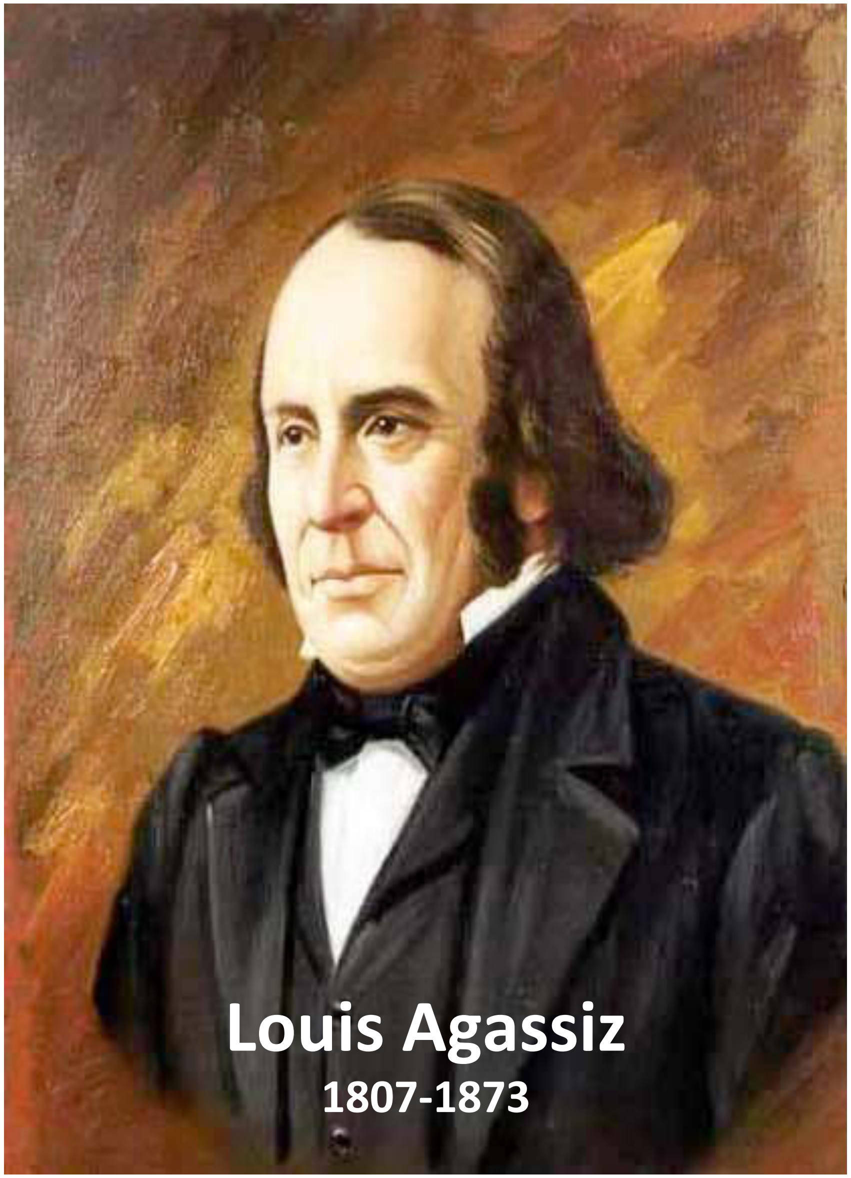
When water evaporates, heavy water is left behind. The fresh water in rainfall and eventually glaciers is lighter. The colder it is, the less O18 in the fresh water. A decrease of one ppm in the fresh water O18/O16 ratio corresponds to -1.5 degC at the time of evaporation. By the same token, sea water is heavier the lower the temperature when it last encountered the atmosphere.

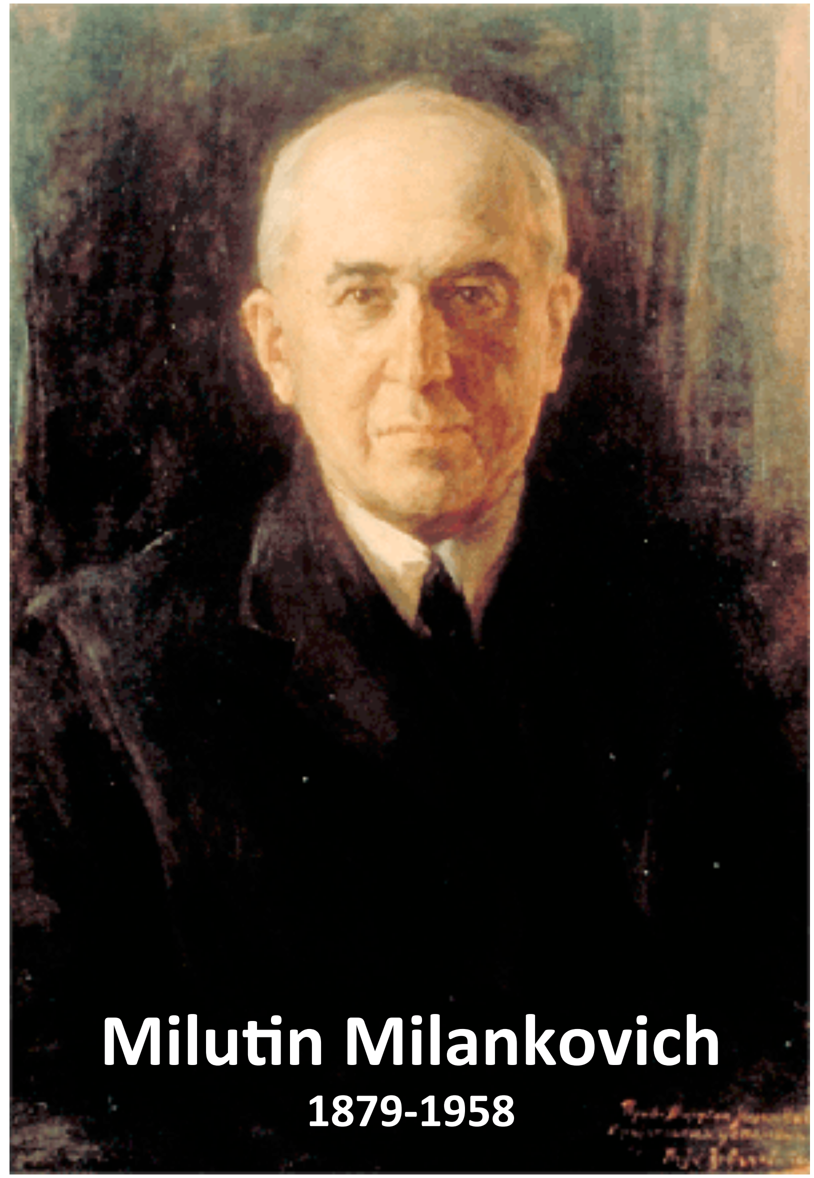
Cenozoic Climate Epochs

Increase of solar luminosity (0.4% = 1 W/m2) during Cenozoic would have led to warming but was counteracted by reductions in CO2 greenhouse warming



Pioneers of Ice Age Science

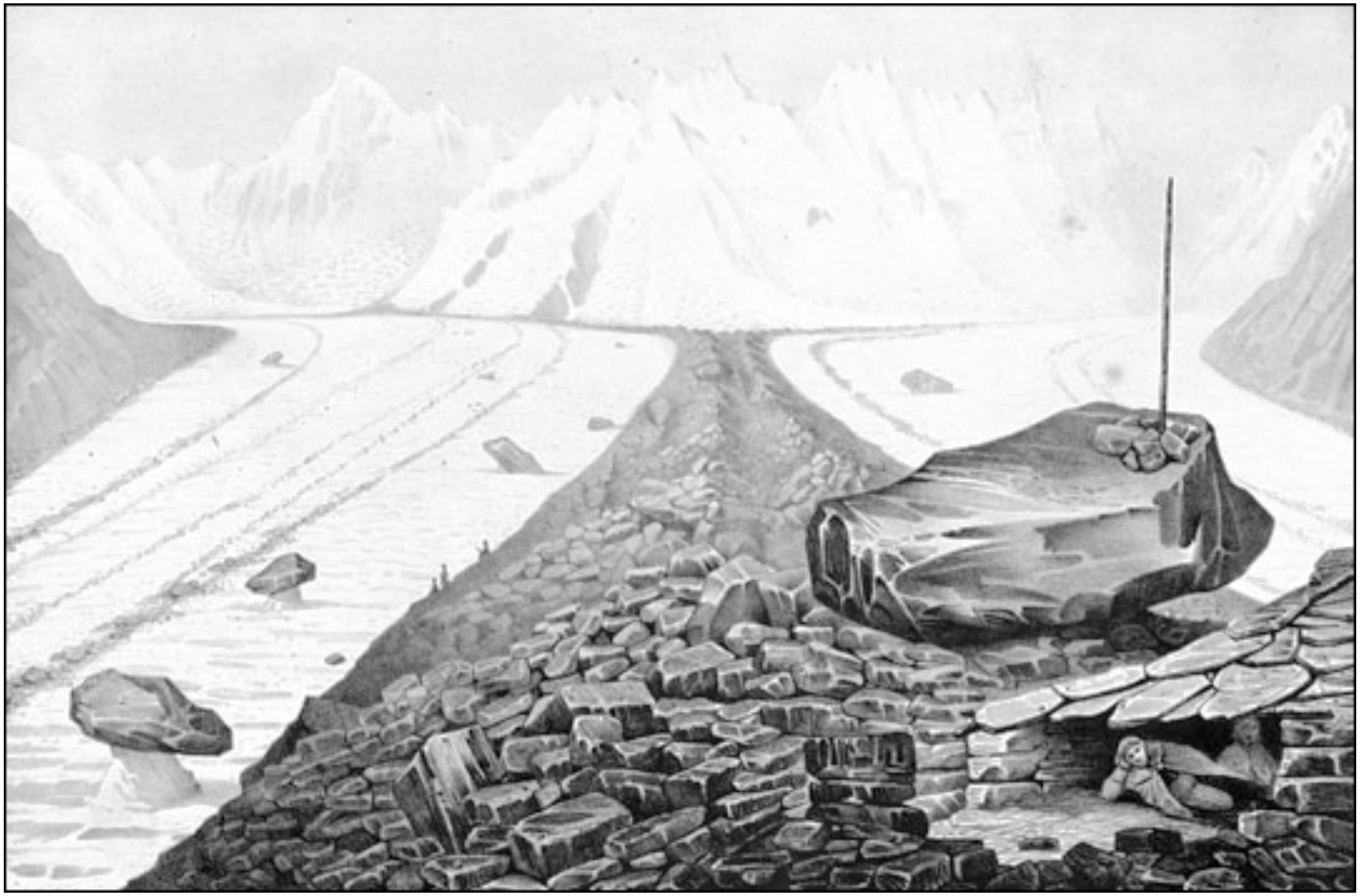




Portrait painted by Papa Jovanovic, 1943

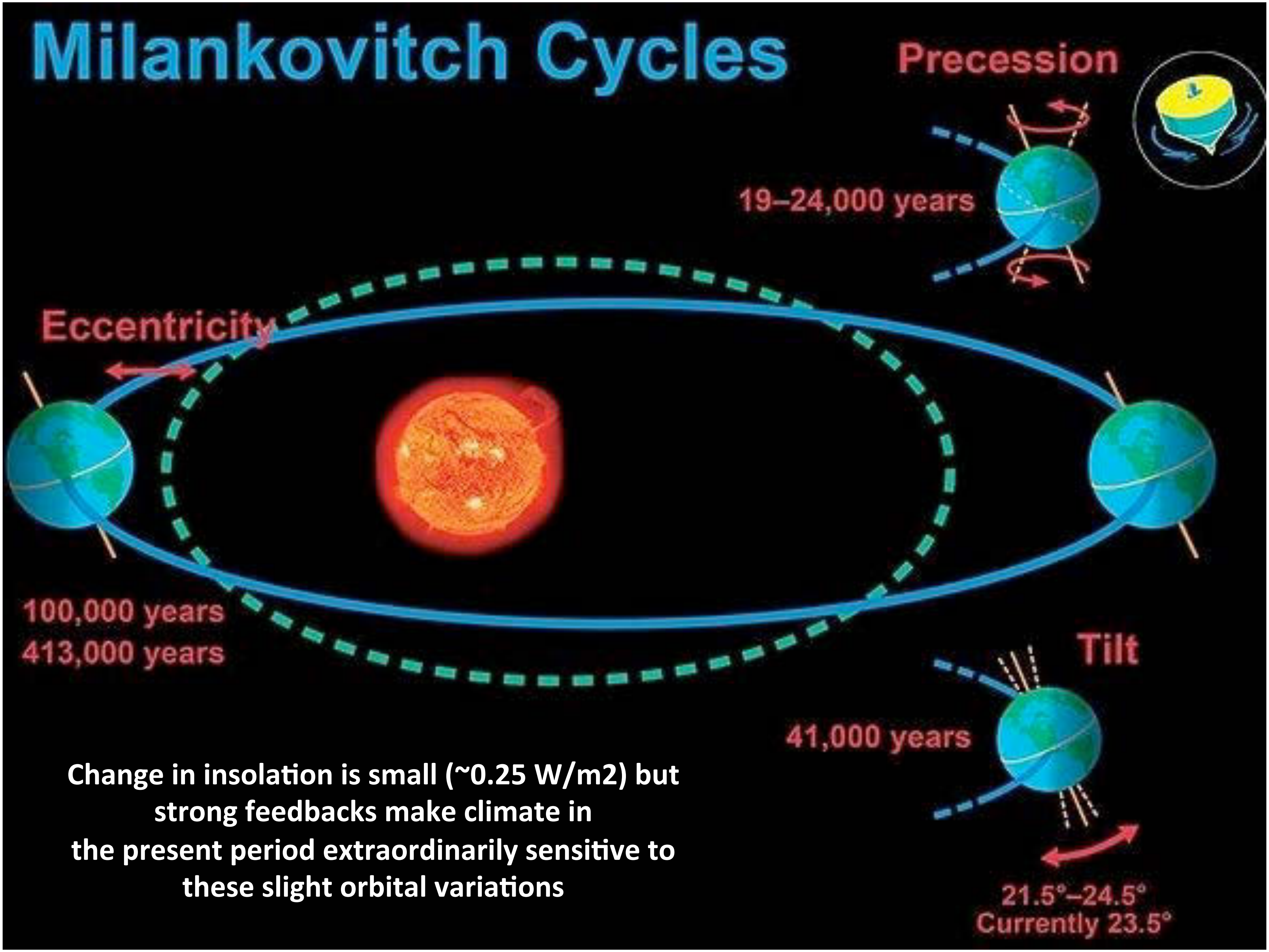
Discovery of Past Ice Ages

Jean-Pierre Perraudin: Glacial striations extended much further down Swiss mountain valleys than the glaciers
Louis Agassiz: Glacially transported "occasionals" meant that ice once covered much of Europe and North America

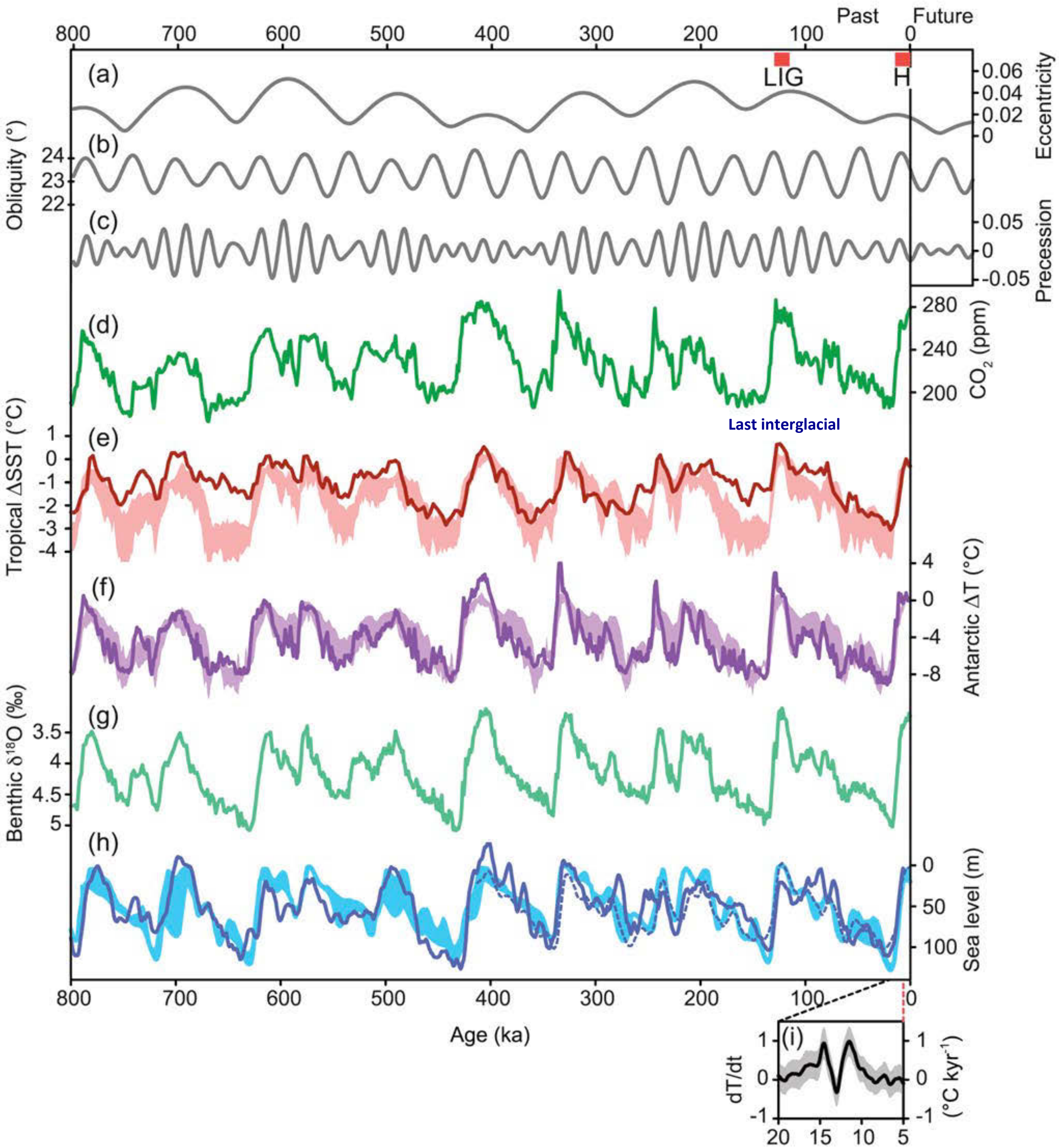


"The perched bowlders which are found in the Alpine valleys... occupy at times positions so extraordinary that they excite in a high degree the curiosity of those who see them. For instance, when one sees an angular stone perched upon the top of an isolated pyramid, or resting in some way in a very steep locality, the first inquiry of the mind is, When and how have these stones been placed in such positions, where the least shock would seem to turn them over?" Louis Agassiz, Etudes sur les Glaciers, 1840.

NASA Earth Observatory



Change in insolation is small (~0.25 W/m2) but
strong feedbacks make climate in
the present period extraordinarily sensitive to
these slight orbital variations



A World Tuned to Milankovich's Parameters

Eccentricity, Obliquity, Precession

Atmospheric CO2

Antarctic Ice Cores

Tropical SST

Antarctic Temperature

Deep Water Temperature

Sea Level

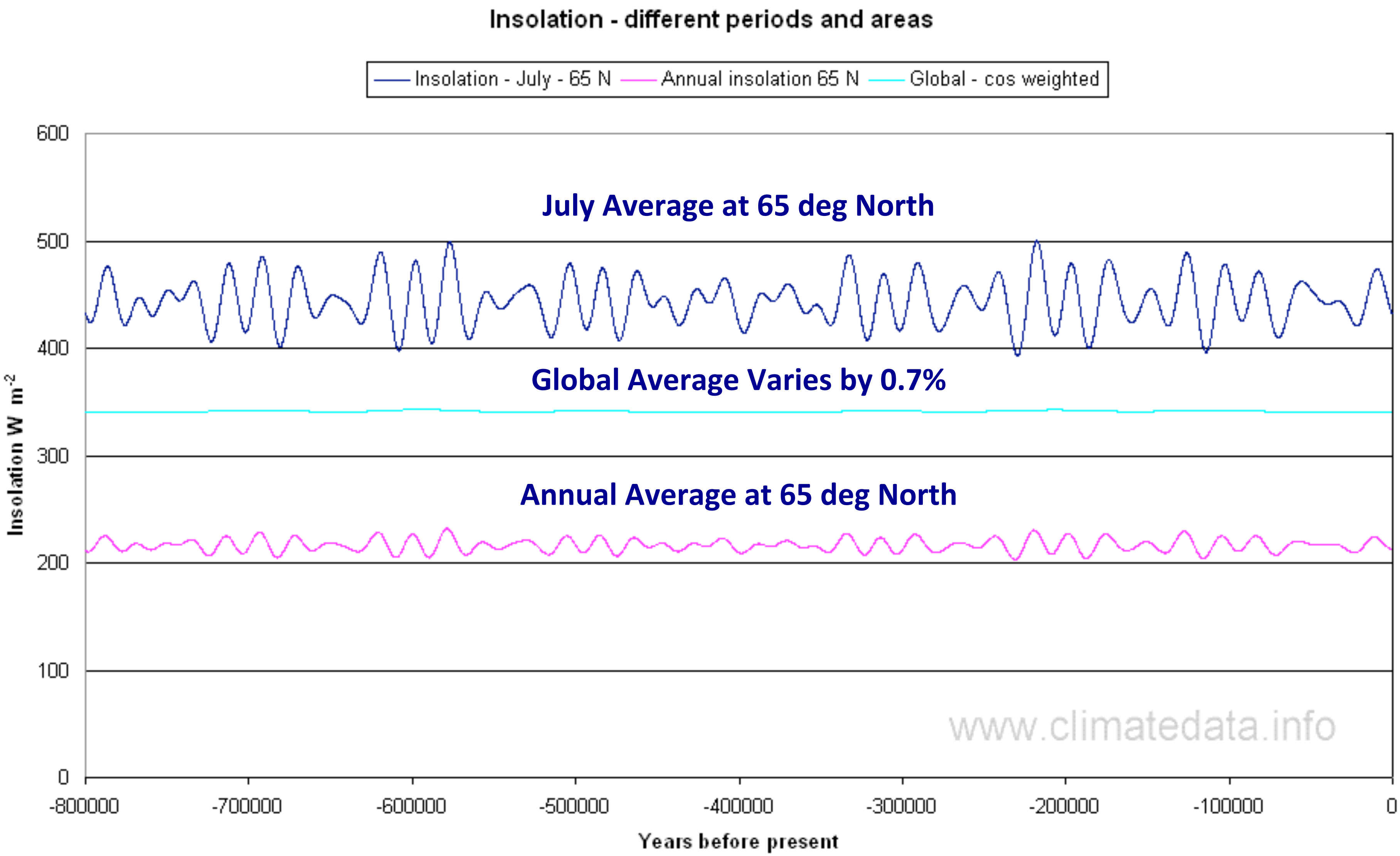
Figure 5.3, from IPCC AR5 wkgp1, ch 5

Milankovich's Inspired Guess

Arctic summer insolation is what matters in an ice age

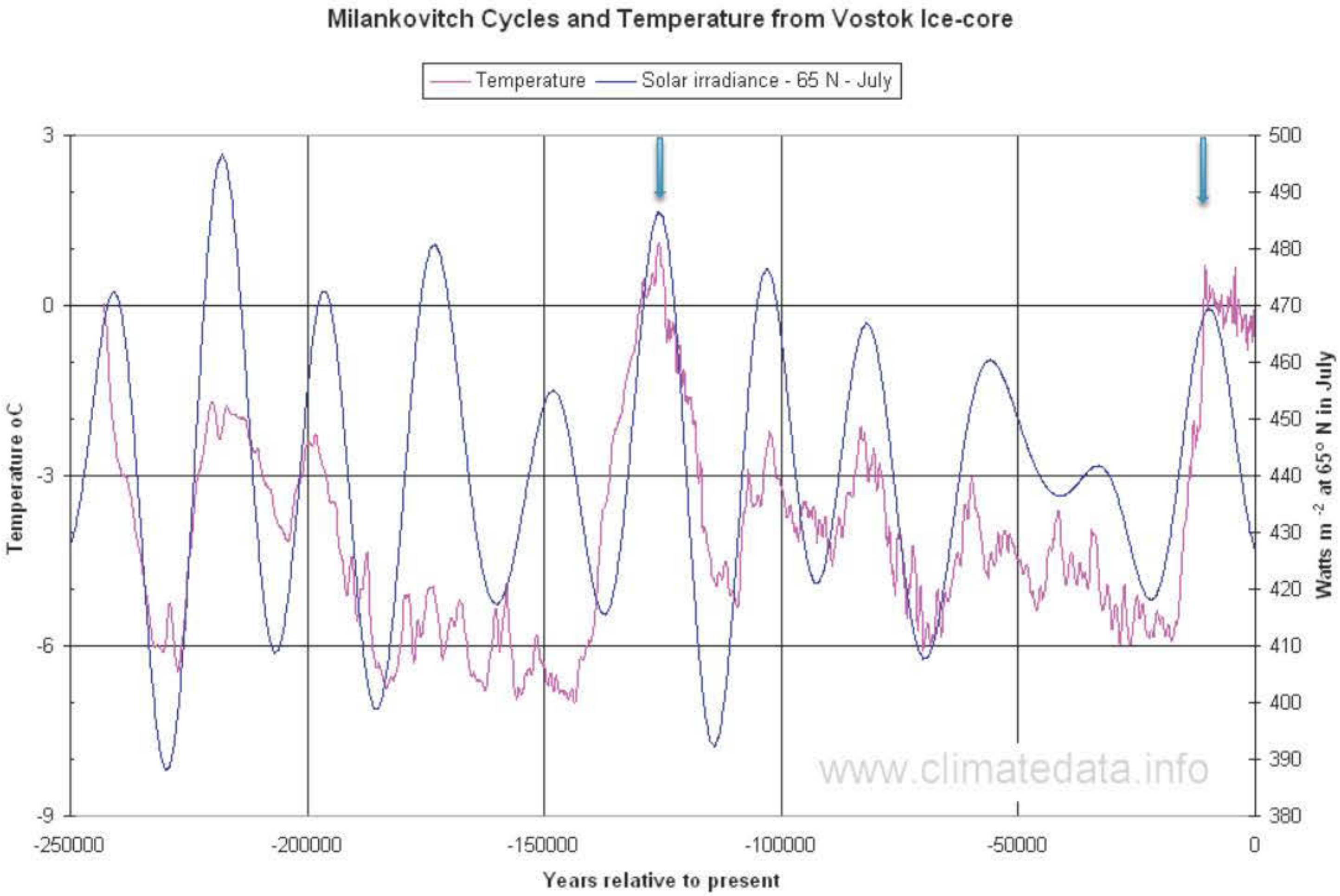
Orbital variations dramatically modify Arctic summer insolation

Global annual insolation changes by only 0.7%



Arctic Summer Forcing Matches Last Two Interglacials

Roughly accounts for variations in between



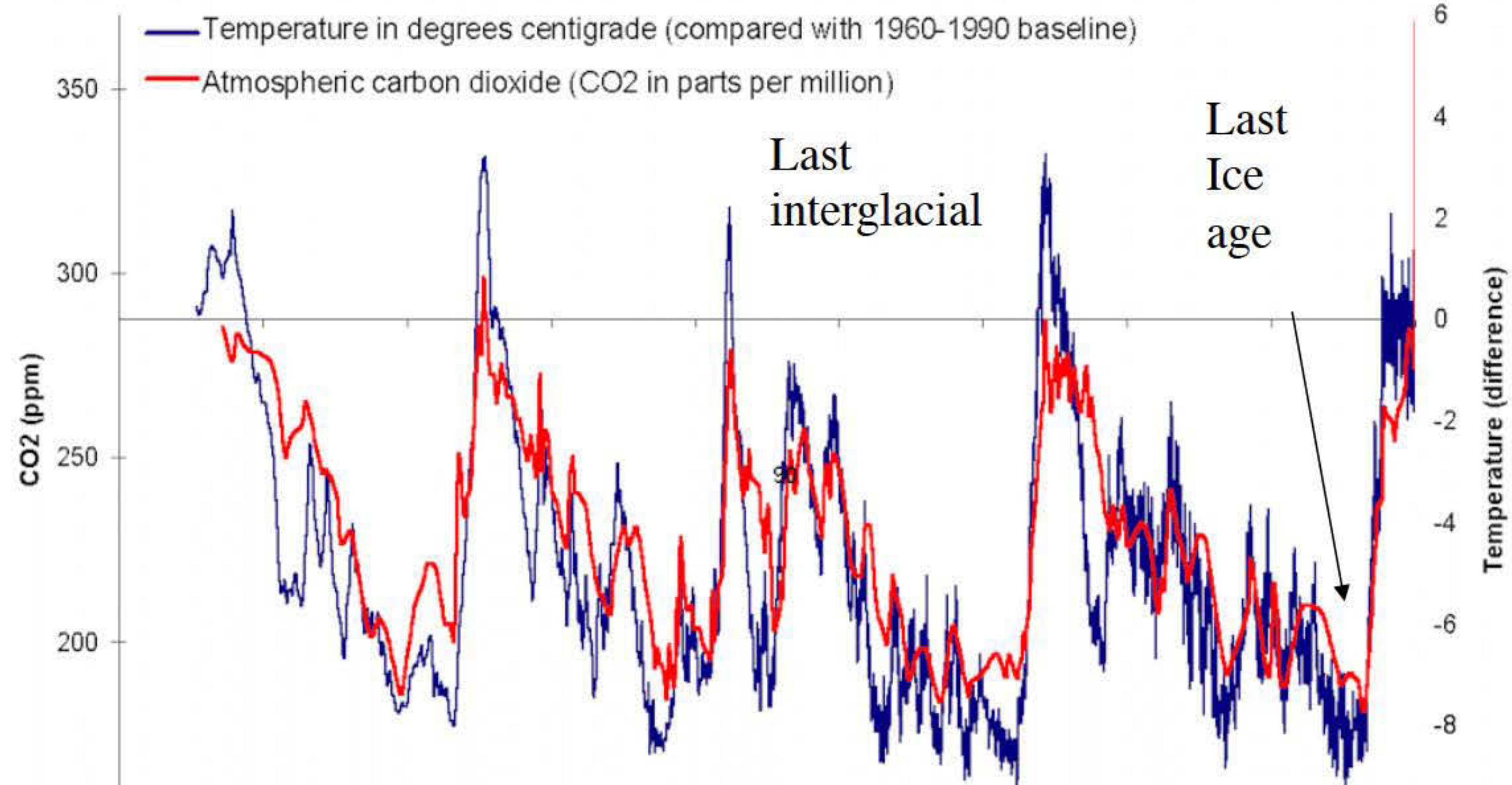
Recent modeling studies support Milankovich's inspired guess by indicating warming can be widespread when forcing is concentrated at high latitudes

Rose, B. E. J., K. C. Armour, D. S. Battisti, N. Feldl, and D. D. B. Koll, 2014: The dependence of transient climate sensitivity and radiative feedbacks on the spatial pattern of ocean heat uptake, *Geophys. Res. Lett.*, 41, doi:10.1002/2013GL058955.

Kang, S.M., and S-P. Xie, Dependence of climate response on meridional structure of external thermal forcing, Journal of Climate 2014 ; e-View doi: http://dx.doi.org/10.1175/JCLI-D-13-00622.1

Ice Age CO2 and Global Temperature

CO2 increase tends to lag Antarctic temperature increase by 600-1000 years
Warming ocean mixed layer releases dissolved CO2? CO2 from deep Southern Ocean?



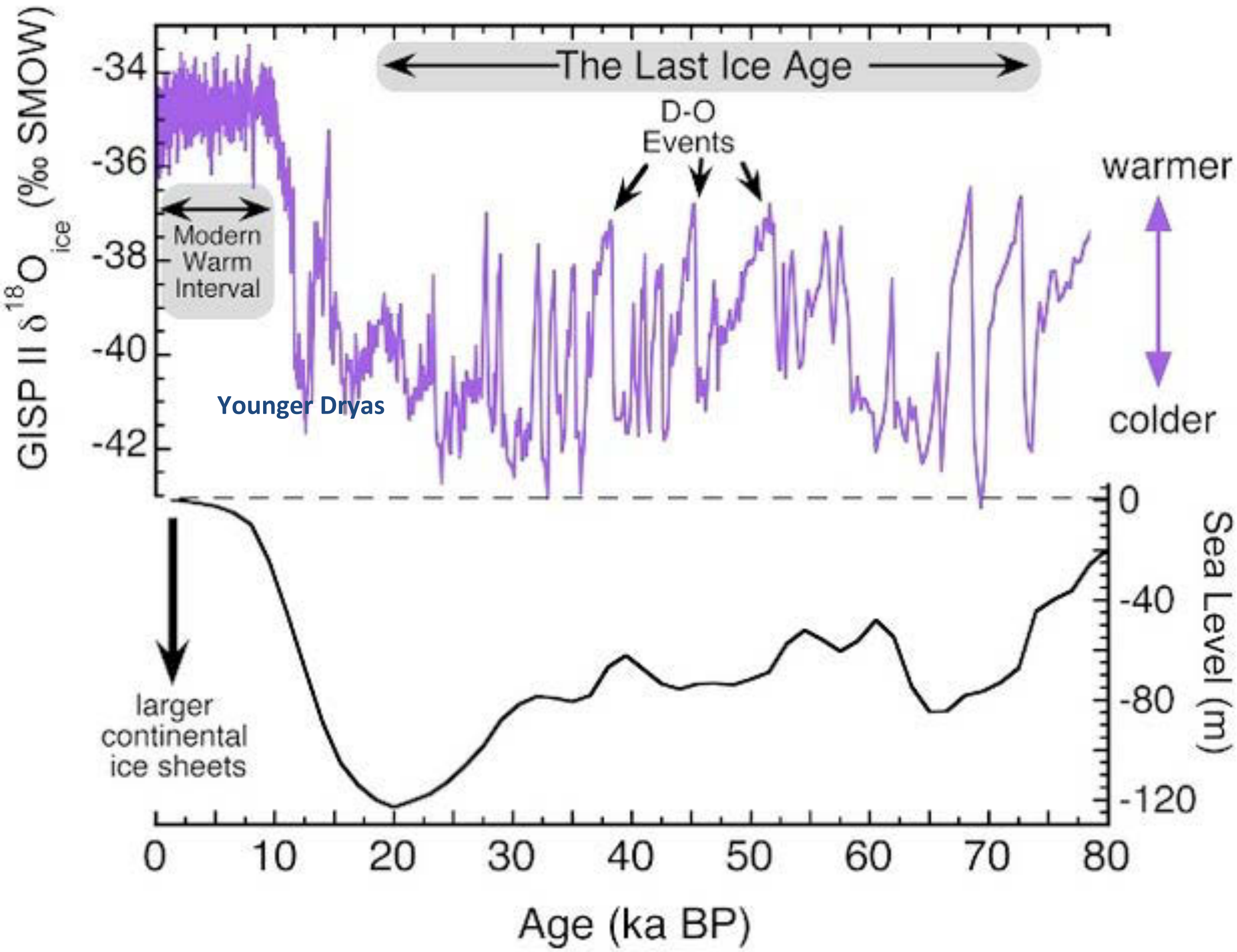
Temperature record from the Vostok ice core (dark blue), together with CO2 (red) from the Vostok ice core, the Law Dome ice core, and from the Mauna Loa monitoring station in Hawaii. IPCC AR4.

C02 never exceeded 300 ppm in any interglacial; present interglacial 270 ppm
Increase in CO2 forcing between LGM and Holocene ~3 W/m2

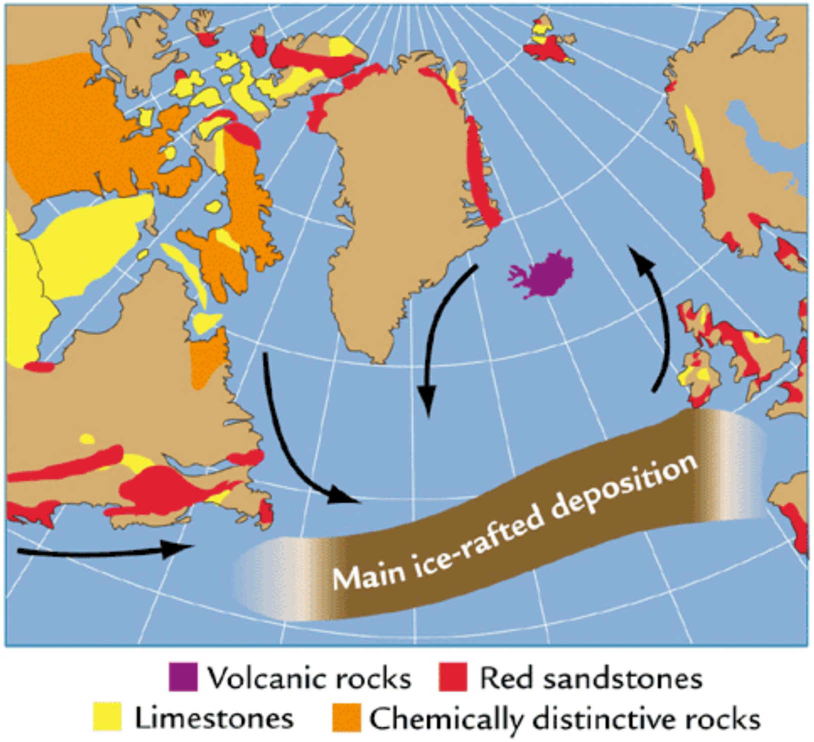
The Last Ice Age

The Greenland climate was given to abrupt warming and cooling events

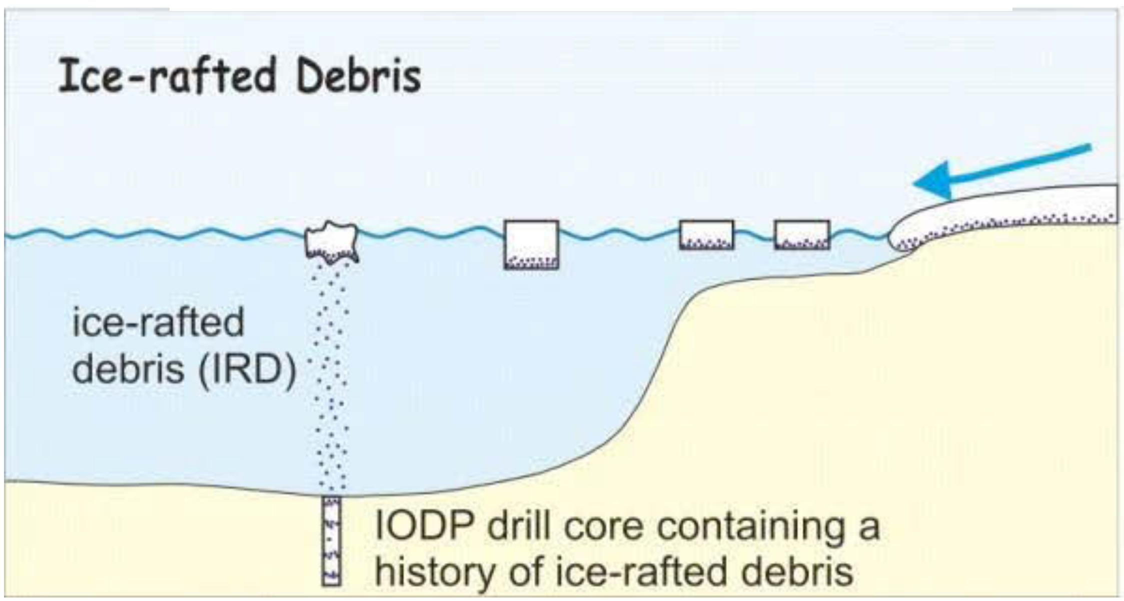
Dansgaard/Oeschger (DO) Events

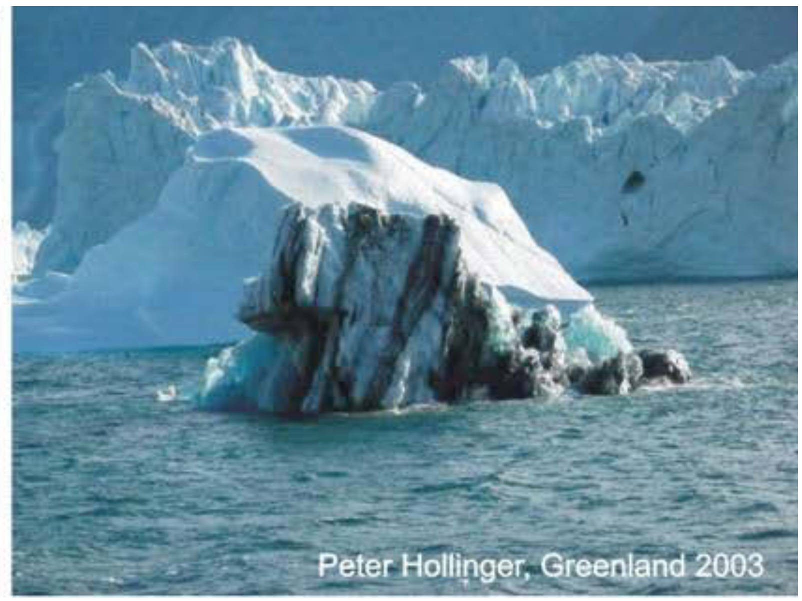


Schmidt, M. W. & Hertzberg, J. E. (2011) Abrupt Climate Change During the Last Ice Age. Nature Education Knowledge 3(10):11



Heinrich Events



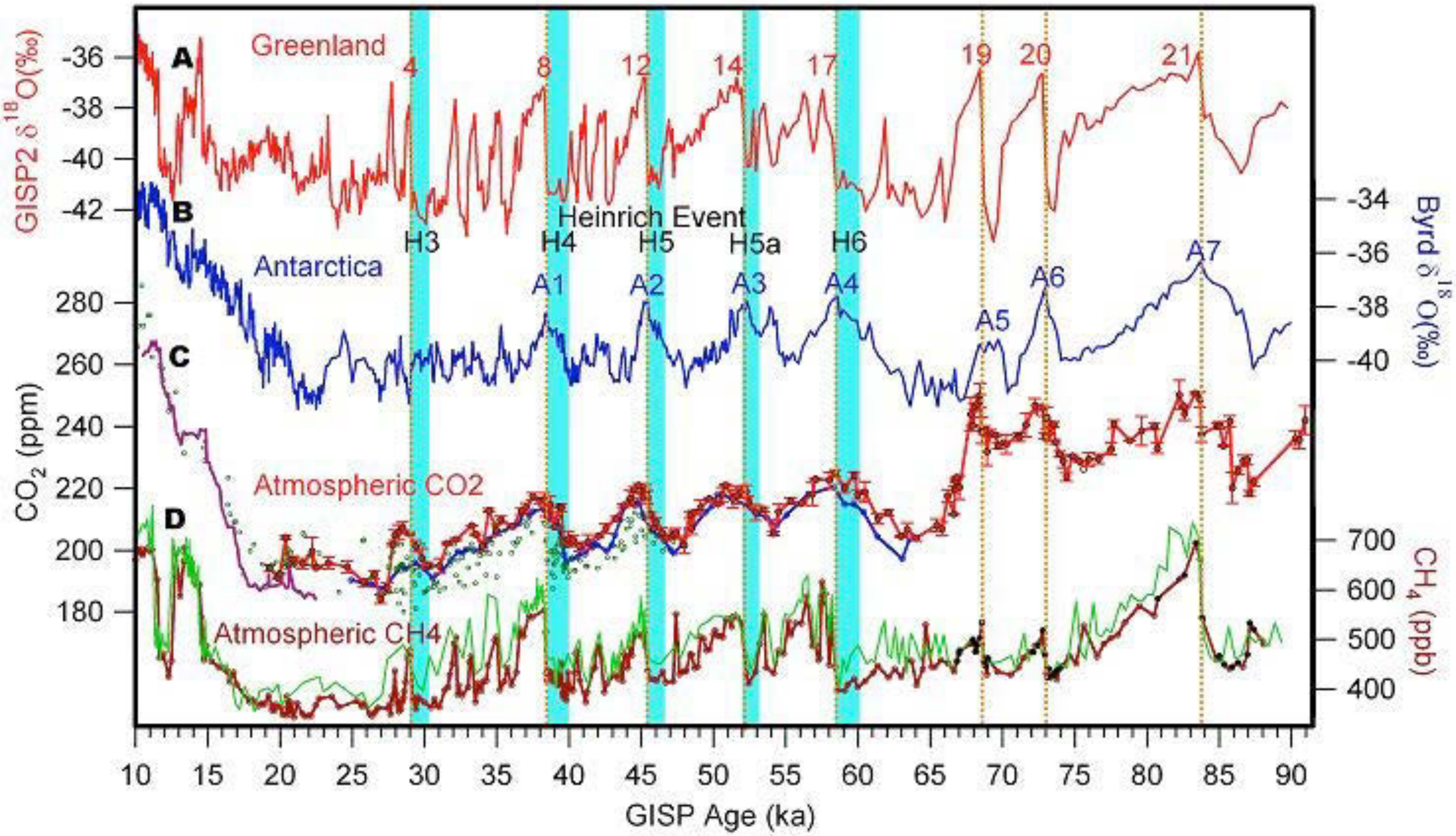


Top: NOAA National Climate data Center; Bottom: Wilkes Land IODP Expedition, Imperial College, London @wwwf.imperial.ac.uk

Climate "See-Saw"

Antarctic and Greenland Climate Events Connected on Thousand-Year Time-Scale

Antarctic warms and CO2 increases, Greenland cools and stays cold for about 1000 years
Greenland then has abrupt jump, 2-4 degC in 2-60 years; CO2 peaks after Greenland jump
Methane jumps when Greenland temperature does



Ahn, J., and E. Brook, Atmospheric CO2 and Climate from 65 to 30 ka B.P. GEOPHYSICAL RESEARCH LETTERS, VOL.34,L10703,doi:10.1029/2007GL029551,2007; Ahn, J. *et al*, Atmospheric CO2 and Climate on Millenial Times Scales During the Last Glacial period, *Science, 322,* DOI: 10.1126/science.1160832; Stefferson, J. P., *et al,* High resolution ice core data show abrupt climate change happens in few years, *Science 1 August 2008: Vol. 321 no. 5889 pp. 680-684 DOI: 10.1126/science.1157707;* Barker, S., P. Diz, M. Vautravers, J. pike, G. Knorr, I.R. Hall, &W.S. Broeker, Interhemispheric Atlantic see-saw response during the last deglaciation, *Nature* 457, 1097-1102 (26 February 2009) | doi:10.1038/nature07770

The Great Ocean Conveyor Belt

Timescale for North Atlantic deep water- half of total- to circulate is about 1000 years
1-2 kyr variability (the see-saw) has to involve N-S transport by ocean thermohaline circulation

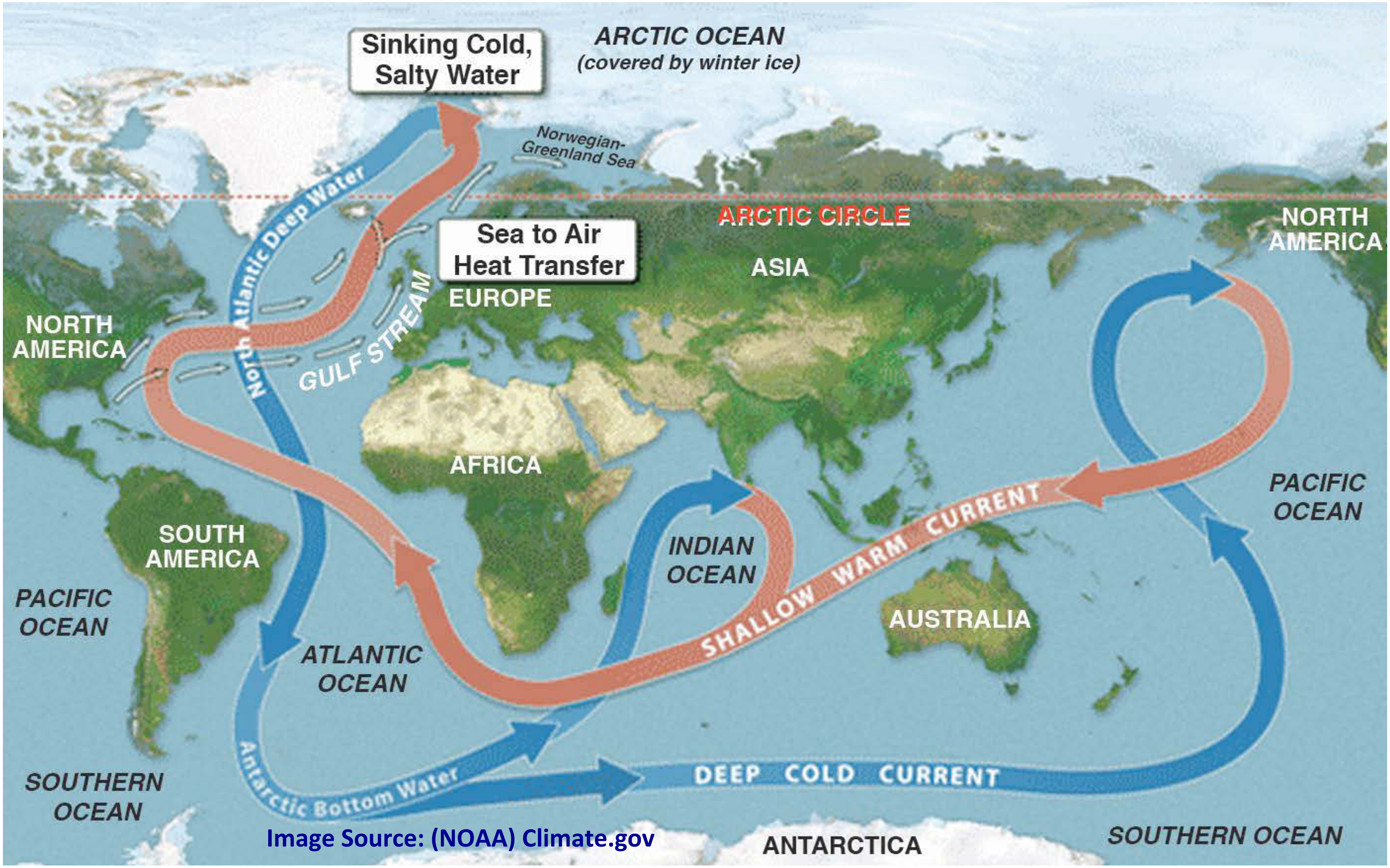
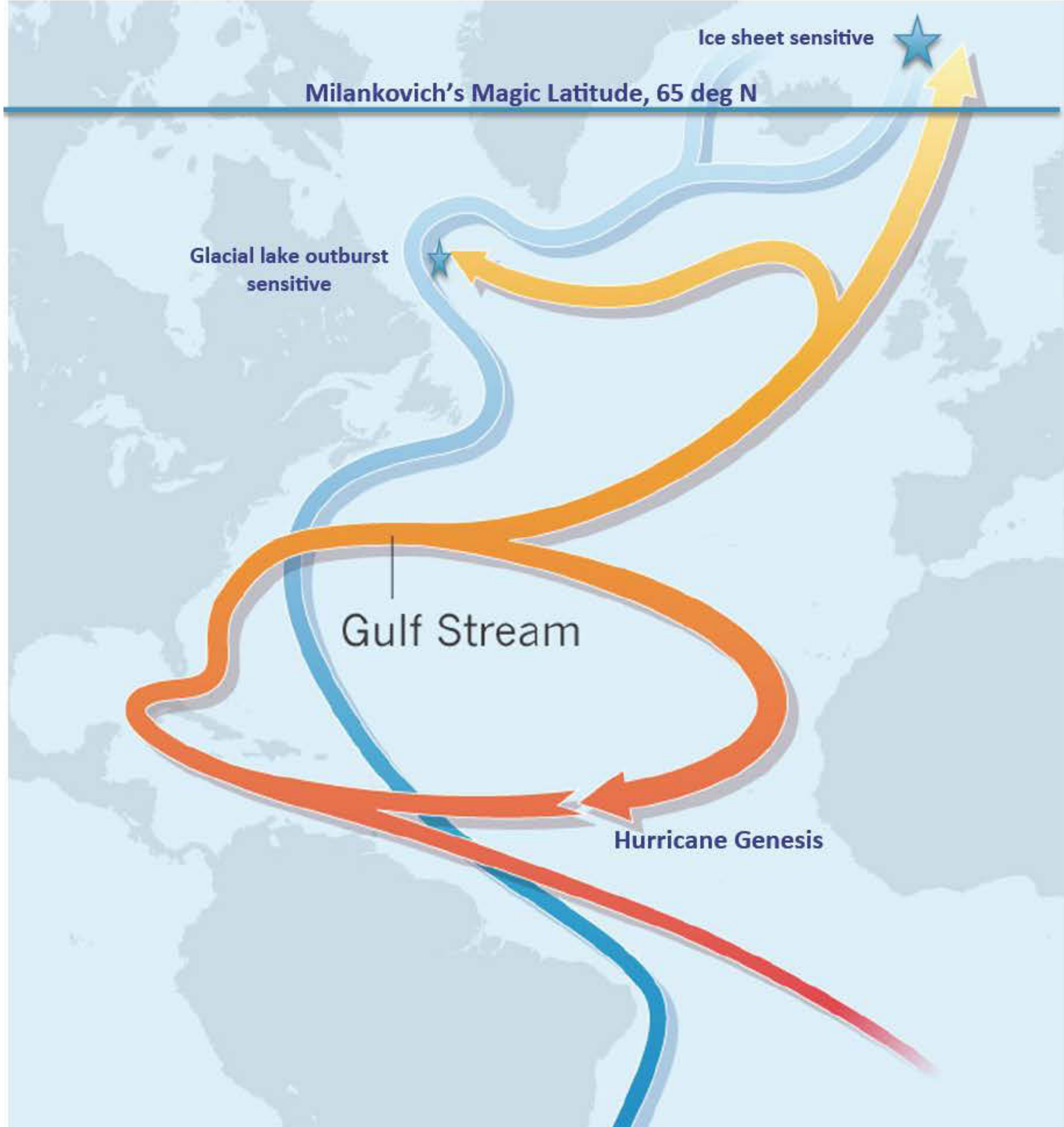


Image Source: (NOAA) Climate.gov

Sensitivity of Atlantic Meridional Overturning Circulation (AMOC) To Sea Ice and Glacial Lake Outbursts



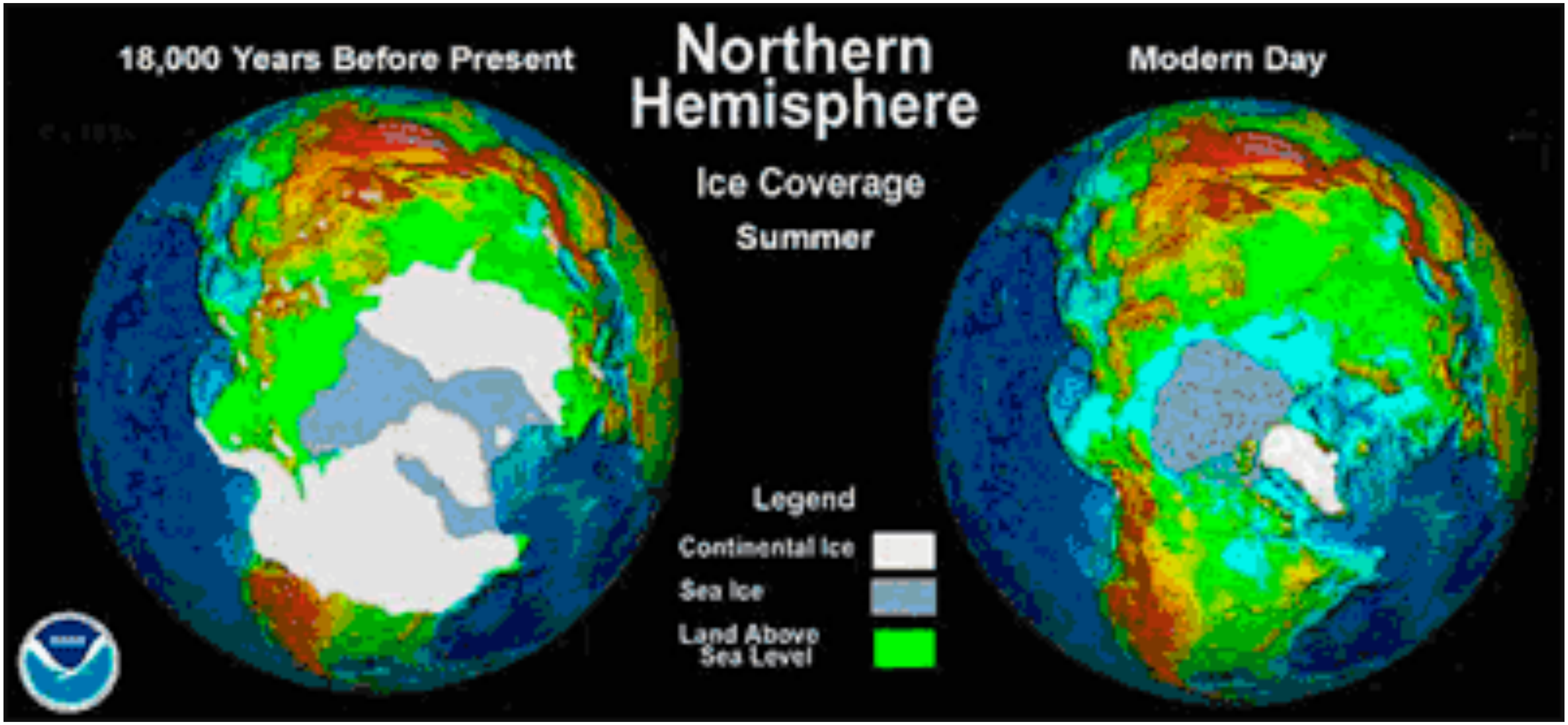
Oka, A. H. Hasumi, and A. Abe-Ouchi, The thermal threshold of the Atlantic meridional overturning circulation and its control by wind stress forcing during glacial climate, Geophysical Research Letters, 39, L09709, 2012; Jochem Marotzke, Climate science: A grip on ice-age ocean circulation, Nature 485, 180–181 (10 May 2012) doi:10.1038/485180a

AMOC heat transport (25% of the global ocean-atmosphere N-S heat flux) and the rate and locations of deep water formation has striking effects on the climate in Northern Europe and Eastern North America. There is evidence of a switch between today's strong AMOC that keeps N. Europe warm and the weaker glacial AMOC inferred from proxy data.

Enough Sea Ice or fresh water cover of the thermohaline pumps can suppress deep convection. The resulting weaker AMOC would transport less heat into Northern Europe, leave it colder than usual and encourage sea ice area to grow.

Ice sheet retreat could force the AMOC to cross a threshold and cause an abrupt Greenland warming. For example, a general warming would suddenly accelerate Greenland warming when the sea ice retreat it starts uncovers the thermohaline pumps and the stronger AMOC reasserts itself.

Last Glacial Maximum



Comparison between summer ice coverage from 18,000 years BP (based on CLIMAP) and modern day observations. Note that when more water is locked up in ice, more land is exposed due to lower sea levels. Land ice (white) and sea ice (light blue) surrounded pole year around. Ice-dominated climatic regime connected North Atlantic and North Pacific ocean basins

Last Glacial Maximum to Present

Key Events in Northern Hemisphere

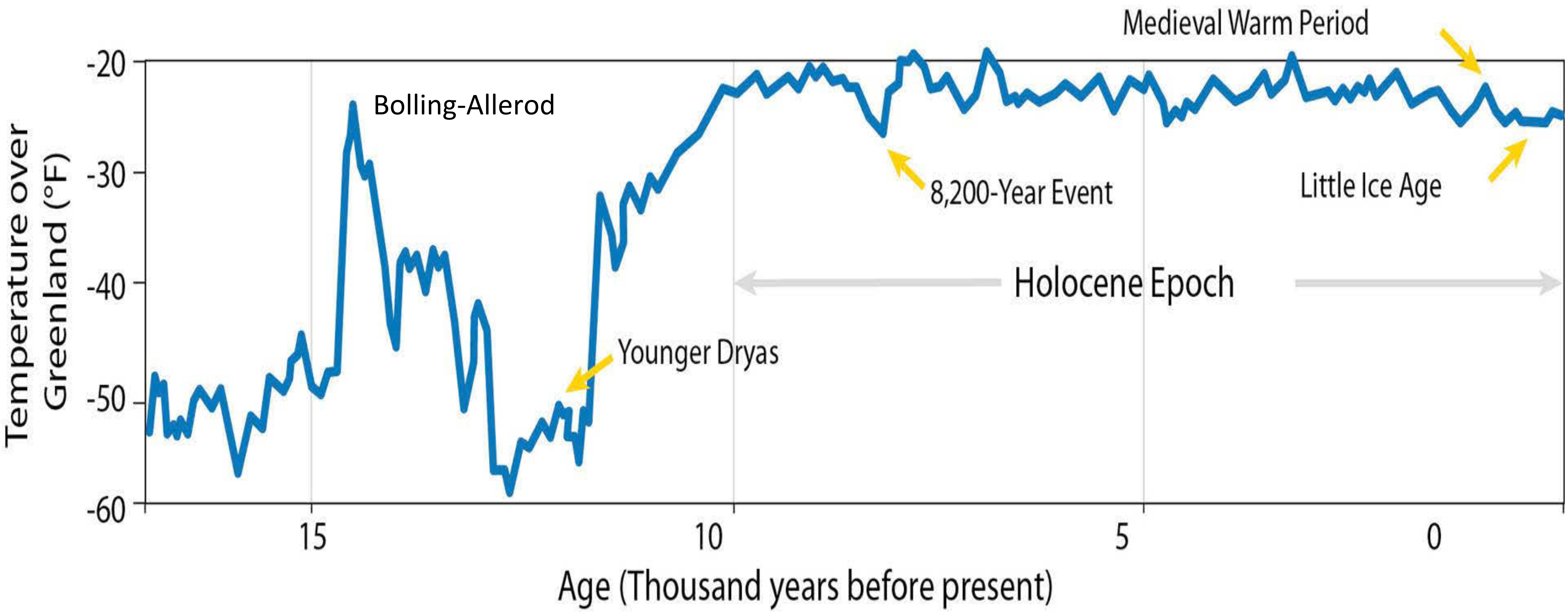


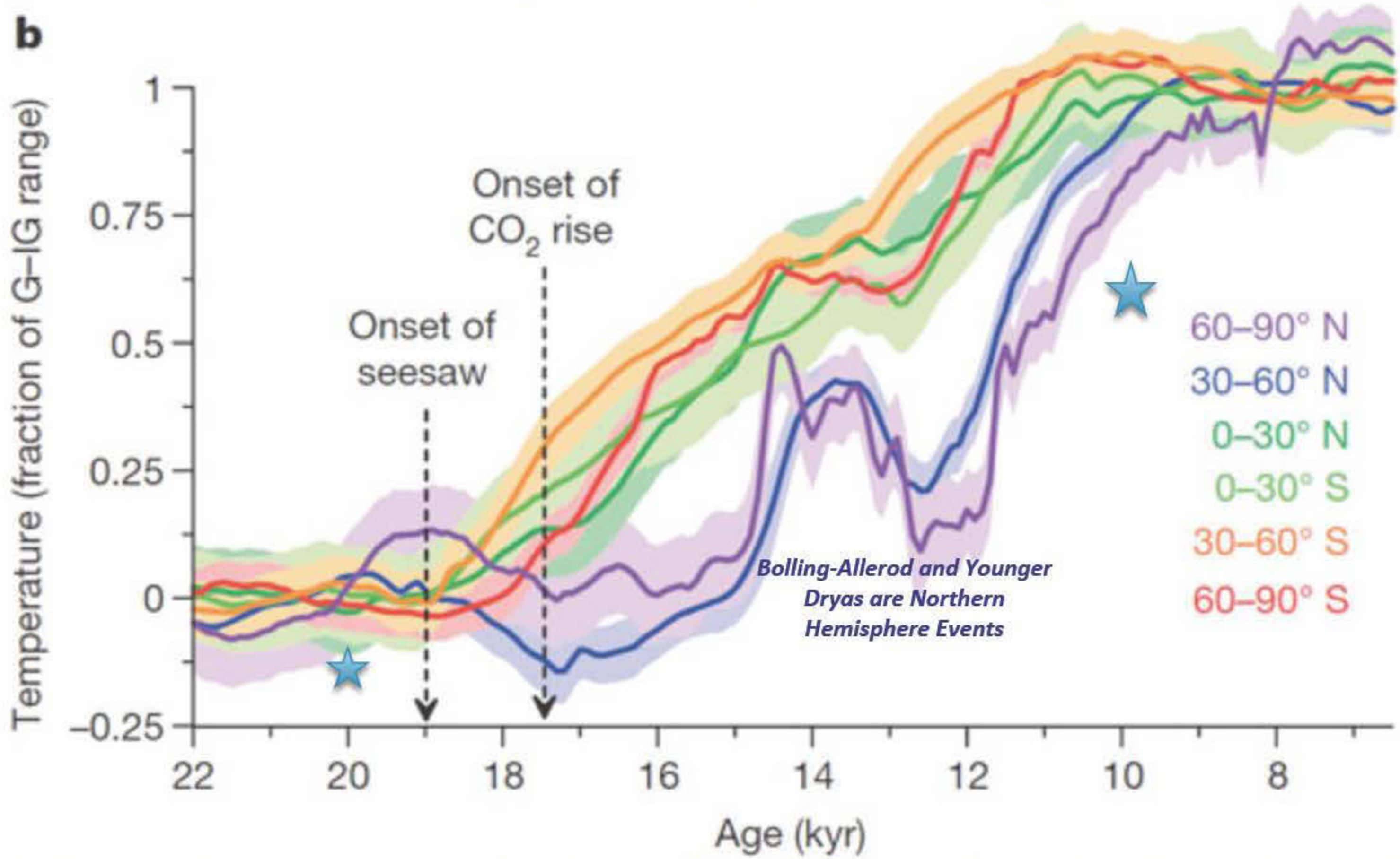
Image source: Climate.gov (NOAA)

Popular summary: Richard B. Alley, *The Two-Mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future,*

Published July 21, 2002 | ISBN-10: 0691102961 | ISBN-13: 978-0691102962

Transient Response to Milankovitch Stimulus

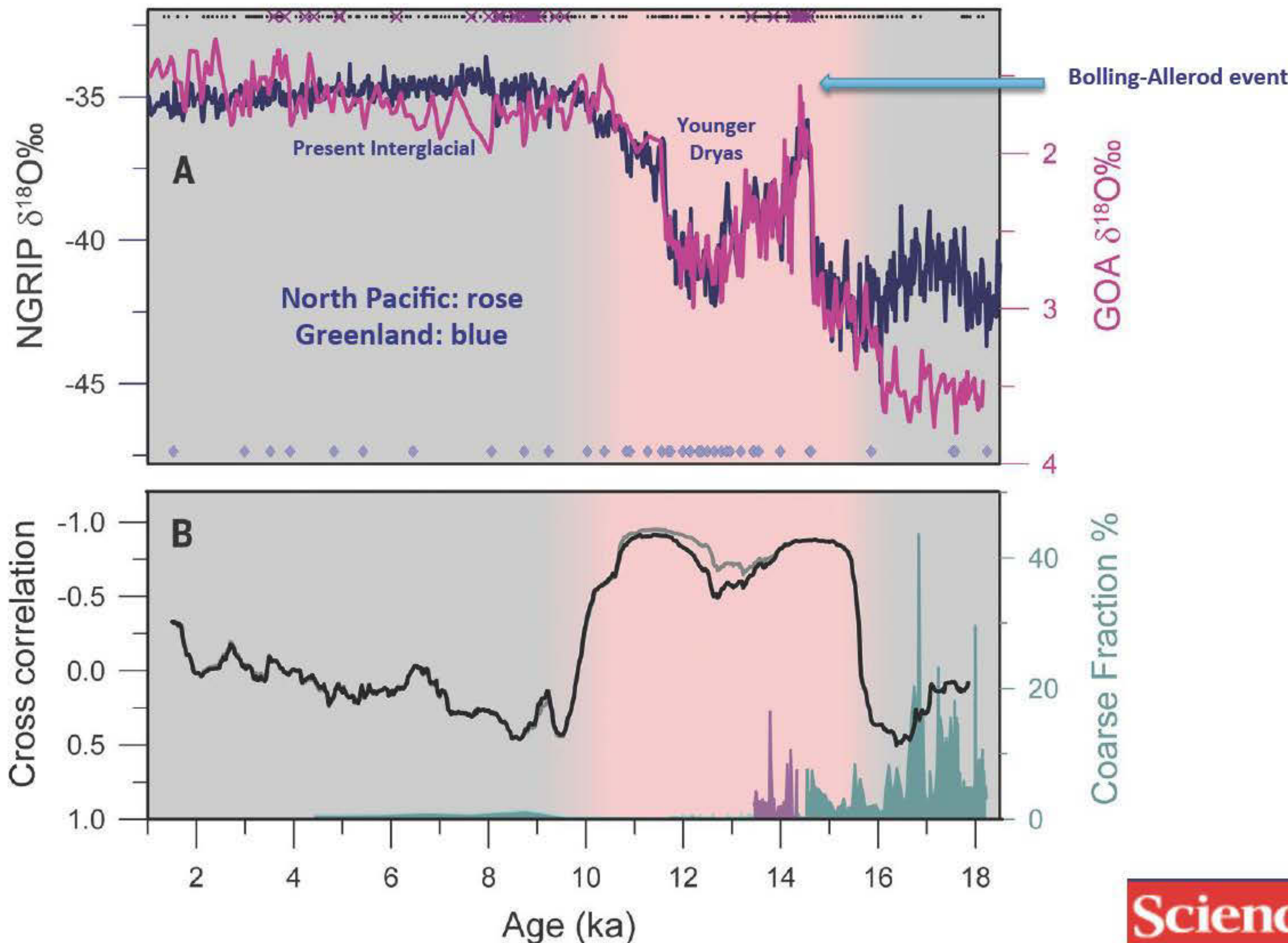
Milankovich Arctic forcing begins to increase around 20 Ka
Arctic warms until seesaw onset
AMOC slows (glacial outbursts?); Greenland and Northern Europe cool
Heat builds up in Southern Ocean which then releases dissolved CO2
Atmospheric CO2 increases world wide and drives global temperature increase
Global temperature lags Antarctic temperature and CO2
Milankovich Arctic forcing peaks at entry to Holocene and begins to decline



Shakun, J., P. Clark, Feng He, S.A. Marcott, A.C. Mix, Z. Liu, B. Otto-Bliesner, A. Schmittner, & E. Bard, Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation, *Nature 484*, 49–54 (05 April 2012) doi:10.1038/nature10915

Intermittent Coupling of N. Pacific and N. Atlantic Polar Climate

The general pattern is of alternating periods of synchronicity and asynchronicity
Synchronicity preceded Bolling-Allerud event, continued in Younger Dryas and beyond

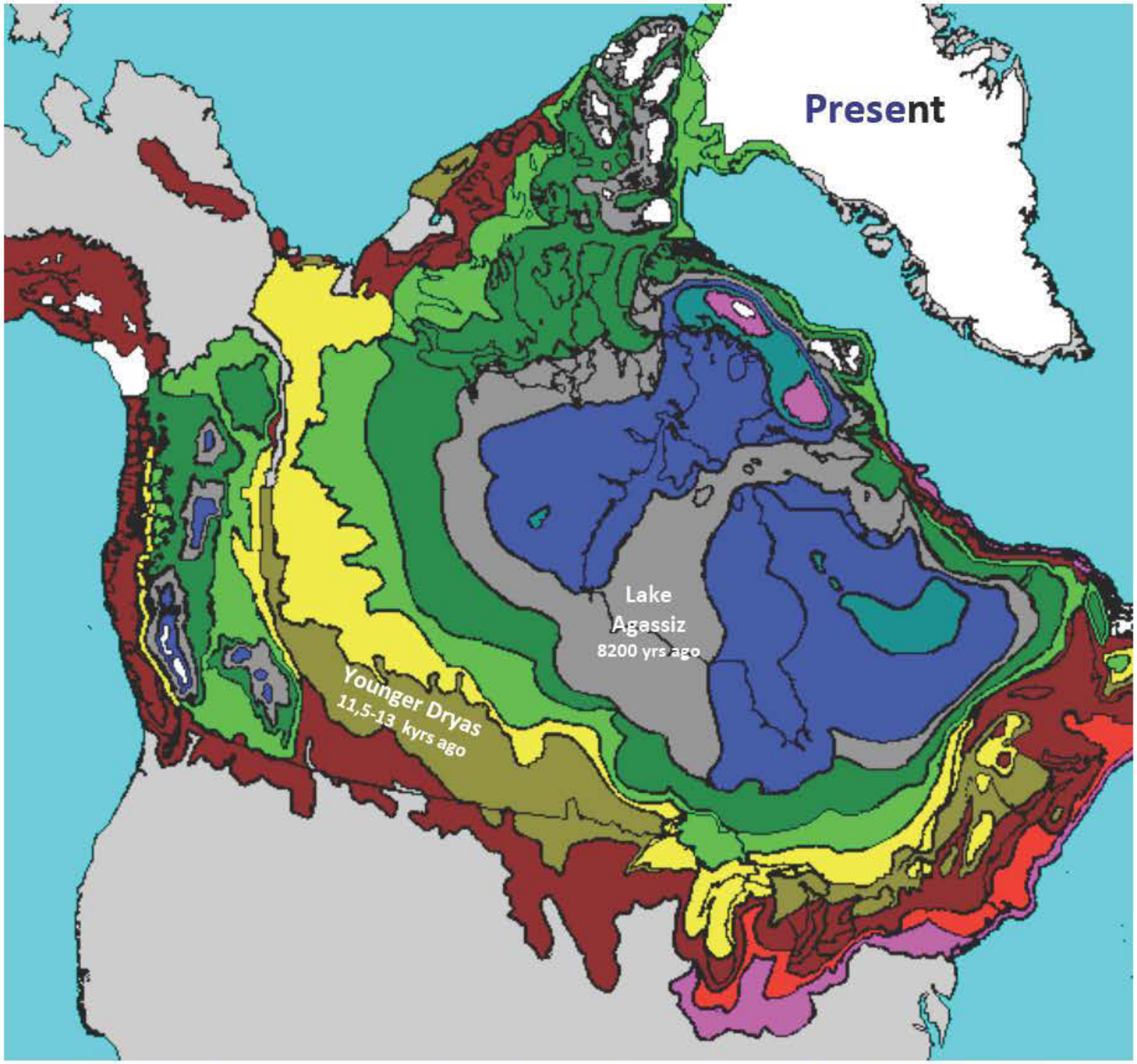


S K Praetorius, and A C Mix, Synchronization of North Pacific and Greenland Climates preceded abrupt glacial warming, Science 25 July 2014;345:444-448 *DOI: 10.1126/science.1252000*

Science
AAAS

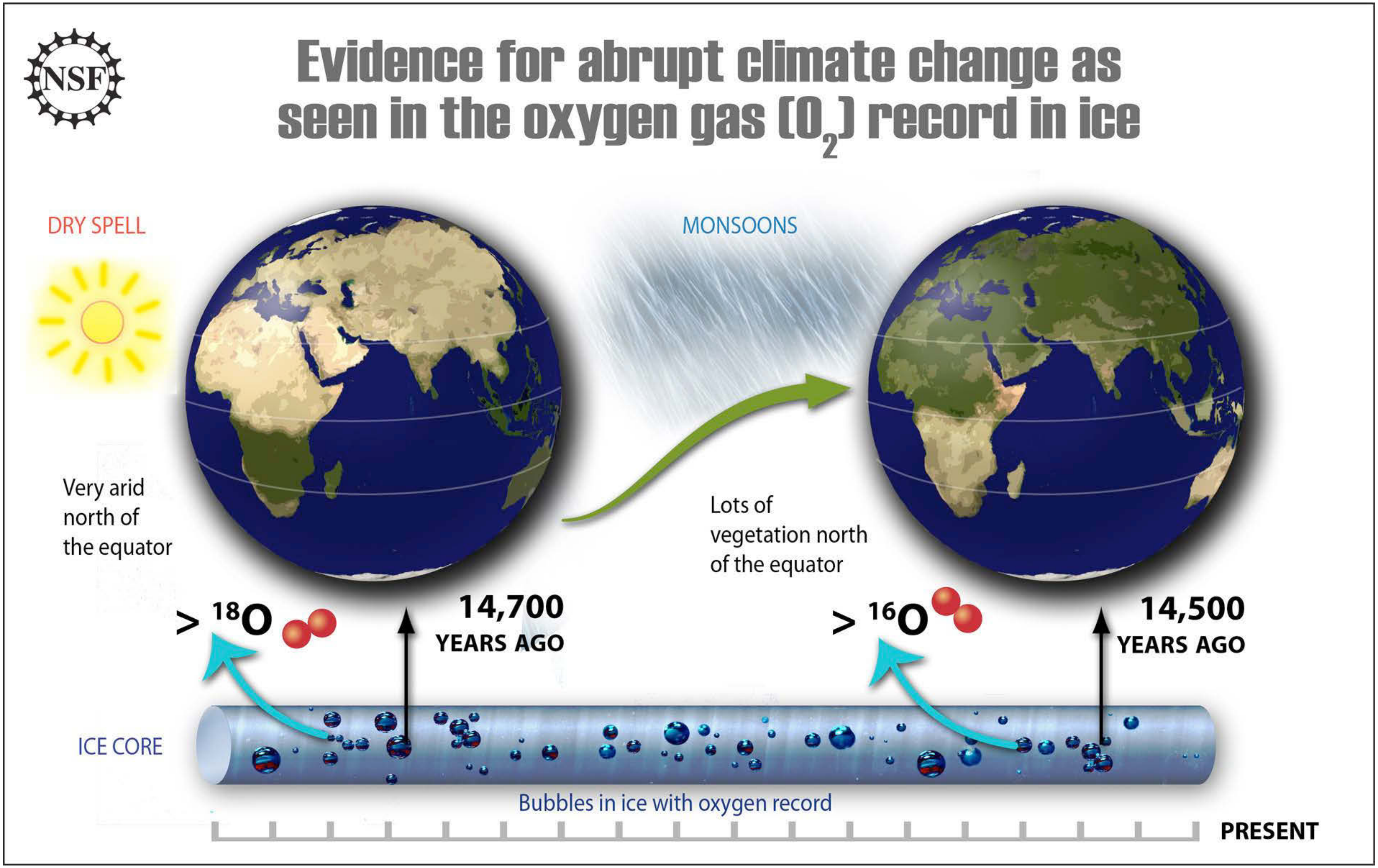
Retreat of Pleistocene Ice Sheet

Change in Albedo forcing since LGM: ~3. 5W/m2



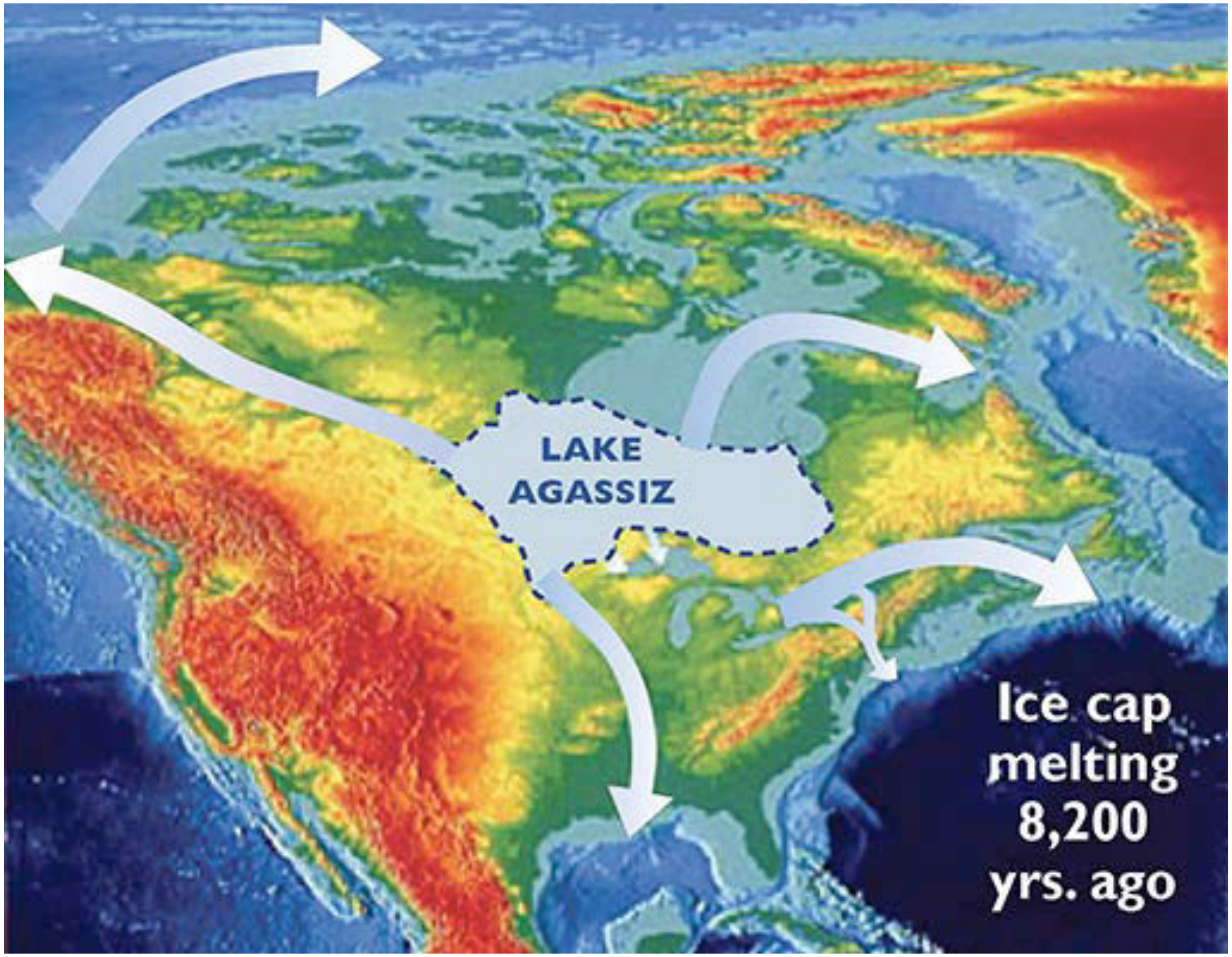
Color bands represent 1-2 Kyr intervals, starting with red, 17-15 kyr BP
Steven Dutch, University of Wisconsin Green Bay

Bolling-Allerod Event



AGU Chapman Conference: Meridional Madness, Climate Feedback. a Nature Climate Change Blog, Anna Barnett

8.2 Ka Abrupt Climate Event



AMOC circulation slowed several times in the past, as North Atlantic waters were suddenly flooded with fresh, low-salt, low-density melt-water that was too buoyant to sink. The water came from great inland glacial lakes like Lake Agassiz that probably released melt-water through Hudson Bay, the Saint Lawrence River, the Mississippi River, and the MacKenzie Straits.

8.2 Ka Abrupt Climate Event

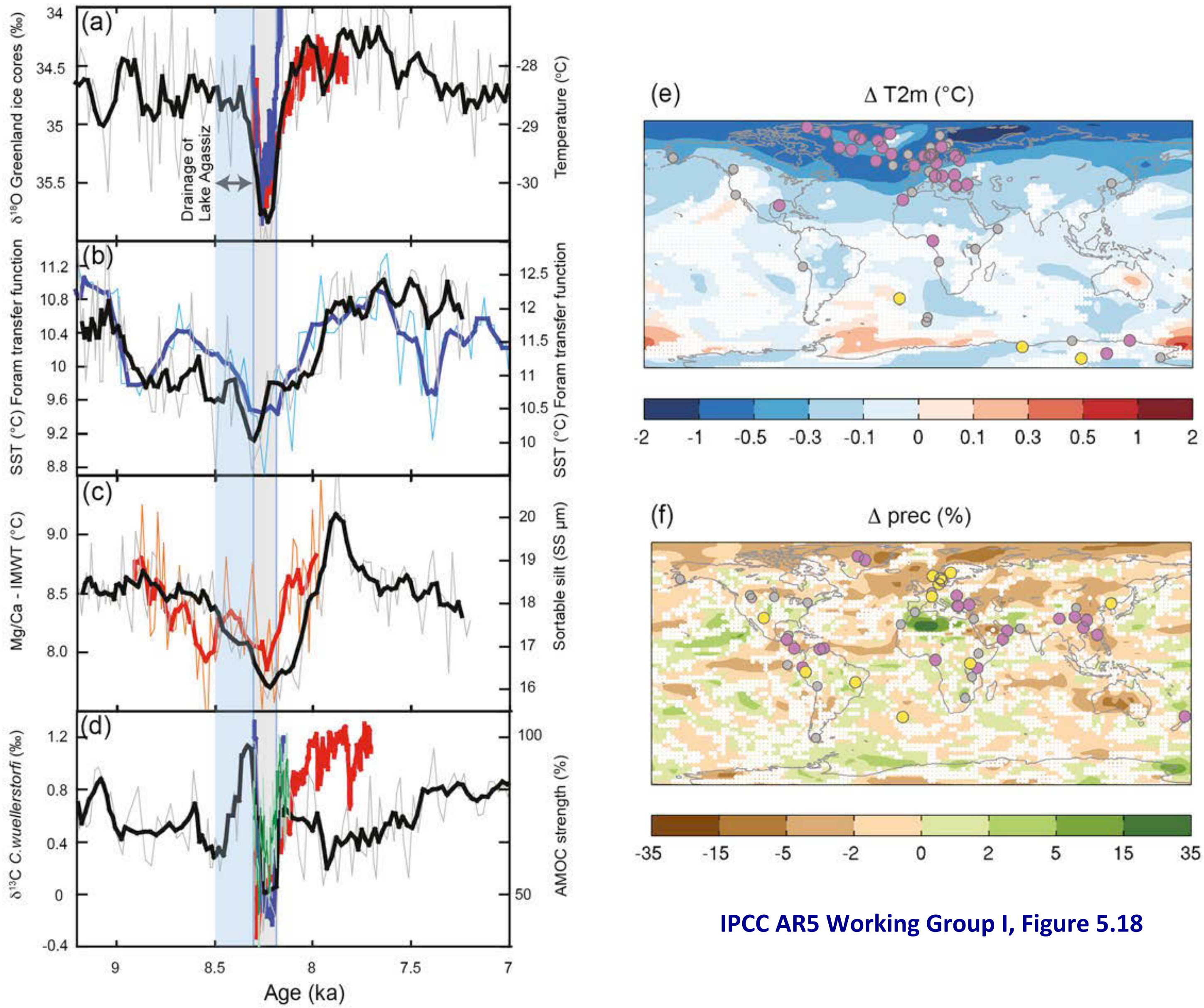
Paleoclimate Indicators (left) and Modeling Results (right)
200 year recovery time from freshwater outbreak

Greenland temperature

Sea Surface Temperature

Silt Deposition

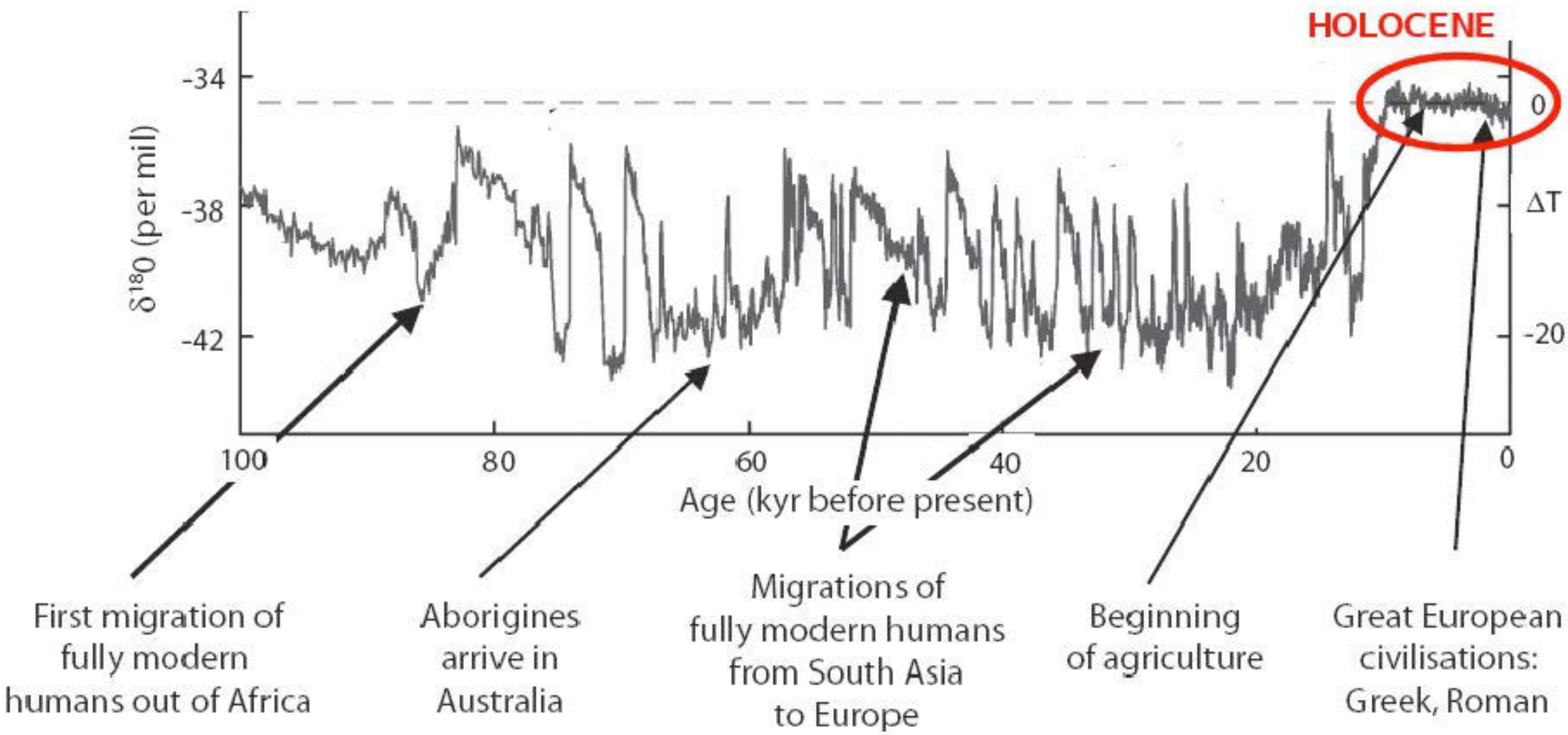
AMOC Strength



IPCC AR5 Working Group I, Figure 5.18

Humans and Climate

Last Ice Age



Adapted from O. R. Young and W. Steffen the Earth System: Sustaining Planetary Life Support Systems, in F.S. Chapin, et al, eds, Principles of Ecosystem Stewardship, DOI: 10.1007/978-0-387-73033-2_14, Springer Verlag, 2009

Humans and Climate: "Younger Dryas" Mini-Ice Age

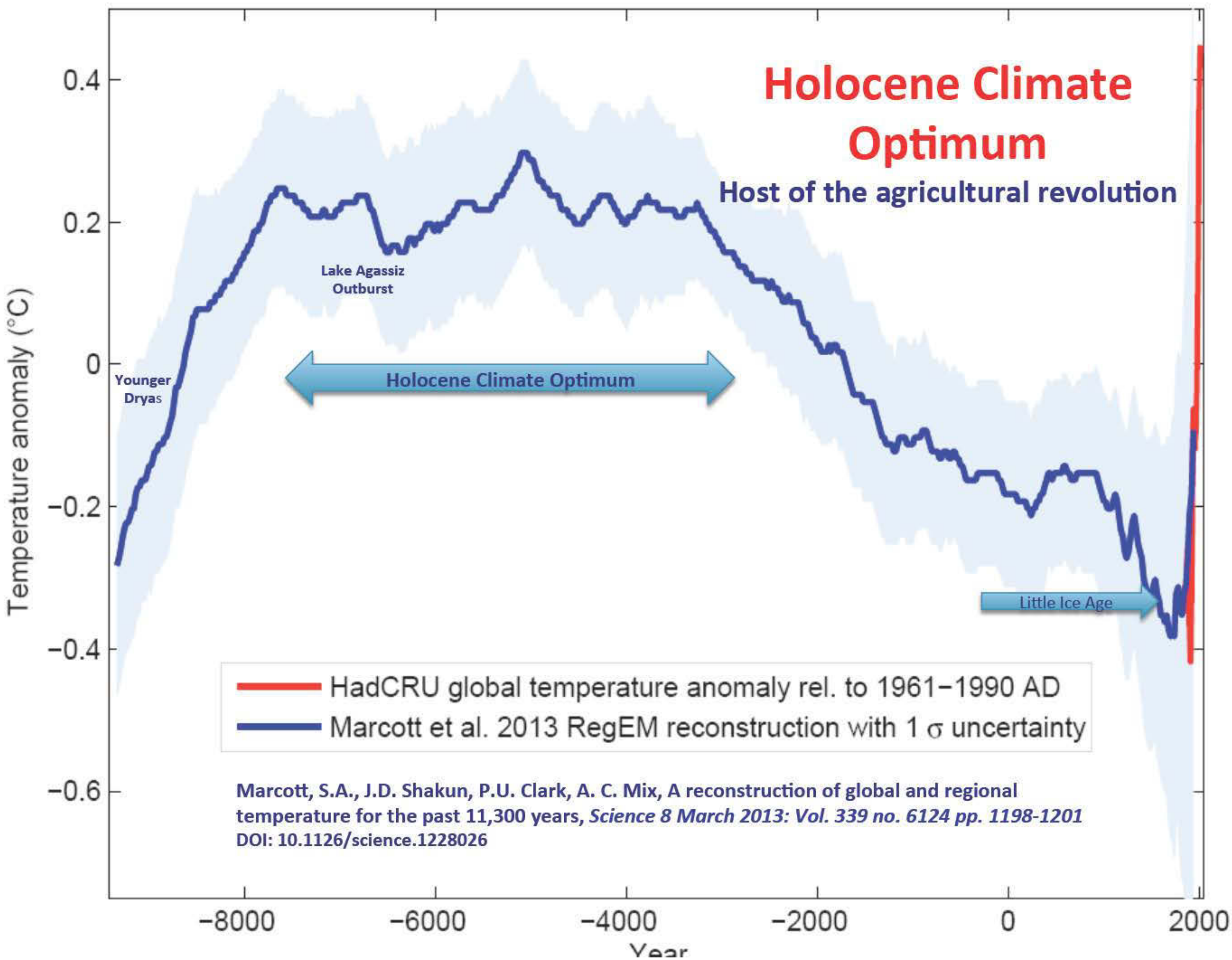
Abrupt climate fluctuations may have dispersed hunter-gatherer communities

Anderson, D.G., A.C. Goodyear, J. Kennett, and A. West, Multiple lines of evidence for possible Human population decline/settlement reorganization during the early Younger Dryas, *Quaternary International, 242*, 2, 570-583, 15 October 2011

William J. Burroughs, *Climate Change in Prehistory: The End of the Reign of Chaos,* Cambridge University Press, pp. 355, 2009

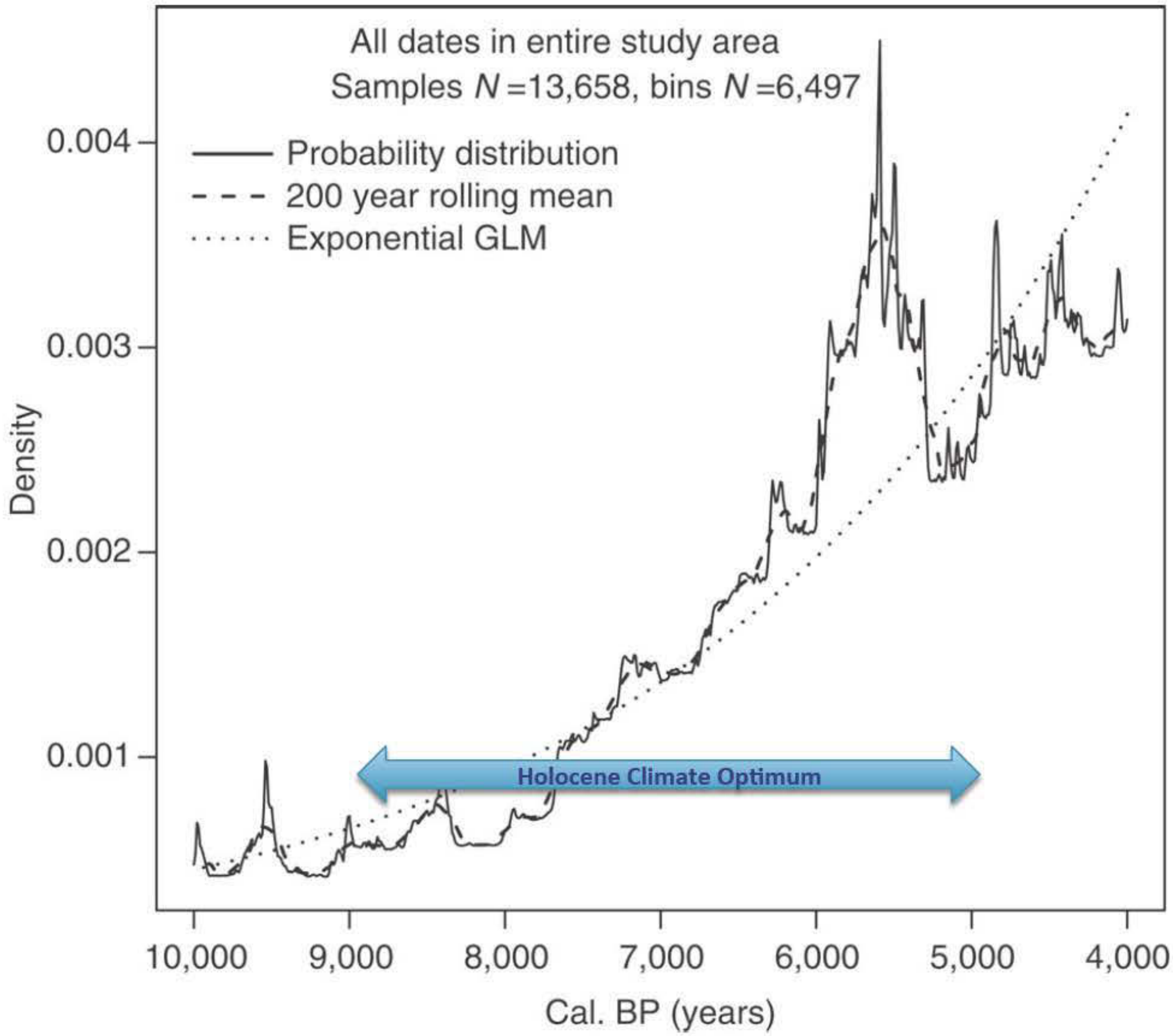
For possible relationship to origins of agriculture, see

J. Feynman and A. Ruzmaikin, Climate stability and the development of agricultural societies, Climatic Change (2007) 84:295-311


Holocene Climate Optimum
Host of the agricultural revolution
0.4
0.2
0
−0.2
−0.4
−0.6
Temperature anomaly (°C)
Younger Dryas
Lake Agassiz Outburst
Holocene Climate Optimum
Little Ice Age
HadCRU global temperature anomaly rel. to 1961−1990 AD
Marcott et al. 2013 RegEM reconstruction with 1 σ uncertainty
Marcott, S.A., J.D. Shakun, P.U. Clark, A. C. Mix, A reconstruction of global and regional temperature for the past 11,300 years, Science 8 March 2013: Vol. 339 no. 6124 pp. 1198-1201
DOI: 10.1126/science.1228026
−8000
−6000
−4000
−2000
0
2000
Year

Regional population collapse followed initial agriculture booms in mid-Holocene Europe

Shennan, S., S.S. Downey, A. Timpson, K. Edinborough, S. College, T. Kerig, K. Manning, & M.G. Thomas, *Nature*, 1 Oct 2013



Medieval Warm Period
900-1300 CE

Growth of European population from 12M to 40M
Agricultural technology improvements
Extensive land clearance
Geographical expansion of settlements
Vikings in Greenland

Transition to Little Ice Age, 1250-1450

The Great Famine of 1315

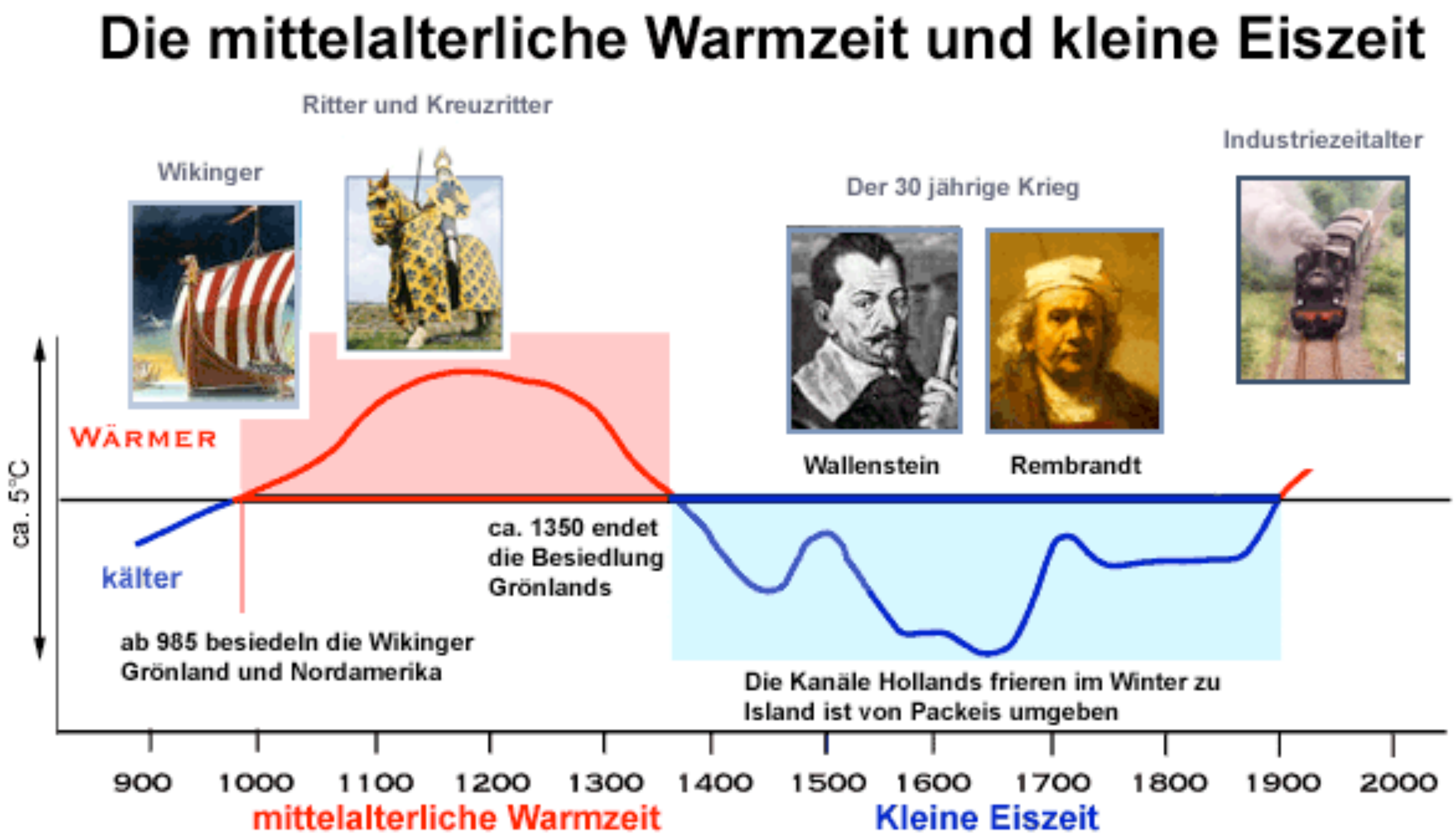
Little Ice Age
1450-1850

Winter Landscape, 1565
Pieter Brueghel, the Elder (1525-1569)

Medieval Warm Period and Little Ice Age

A saga of science, history, Euro-centrism, and contemporary politics

The temperature record of the last thousand years became the focus of the "hockey stick" controversy



Temperature schematic seems to originate from Fig. 7.1c in IPCC FAR 1990; Jones *et al* 2009 trace the diagram back to a central England series last published by the pioneering climate historian H.H. Lamb, founder of the UEA Climate Research Unit. The whole NH temperature published by Mann et al 1999 and IPCC AR3 2001 did not show a distinct MWP or LIA. This issue was revisited by IPCC 2007 and hopefully put to rest by PAGES 2K (2013).

Illustrated graphic may be found in section 4.2.5 Global Warming Fruher in www.zum.de.

The Hockey Stick Controversy

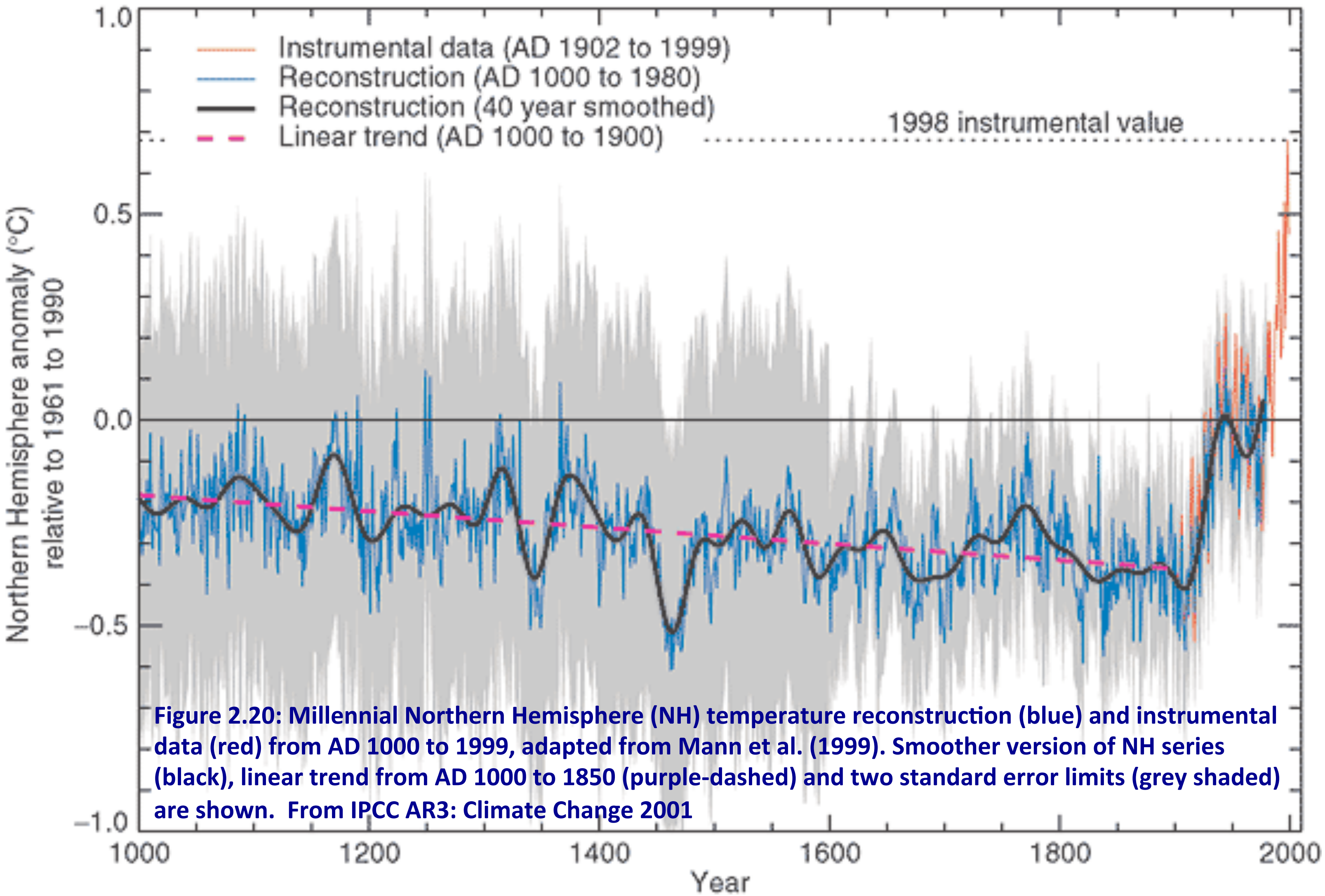


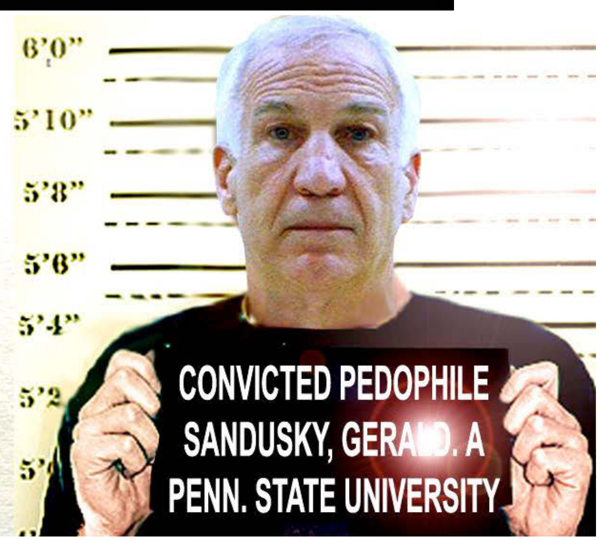
Figure 2.20: Millennial Northern Hemisphere (NH) temperature reconstruction (blue) and instrumental data (red) from AD 1000 to 1999, adapted from Mann et al. (1999). Smoother version of NH series (black), linear trend from AD 1000 to 1850 (purple-dashed) and two standard error limits (grey shaded) are shown. From IPCC AR3: Climate Change 2001

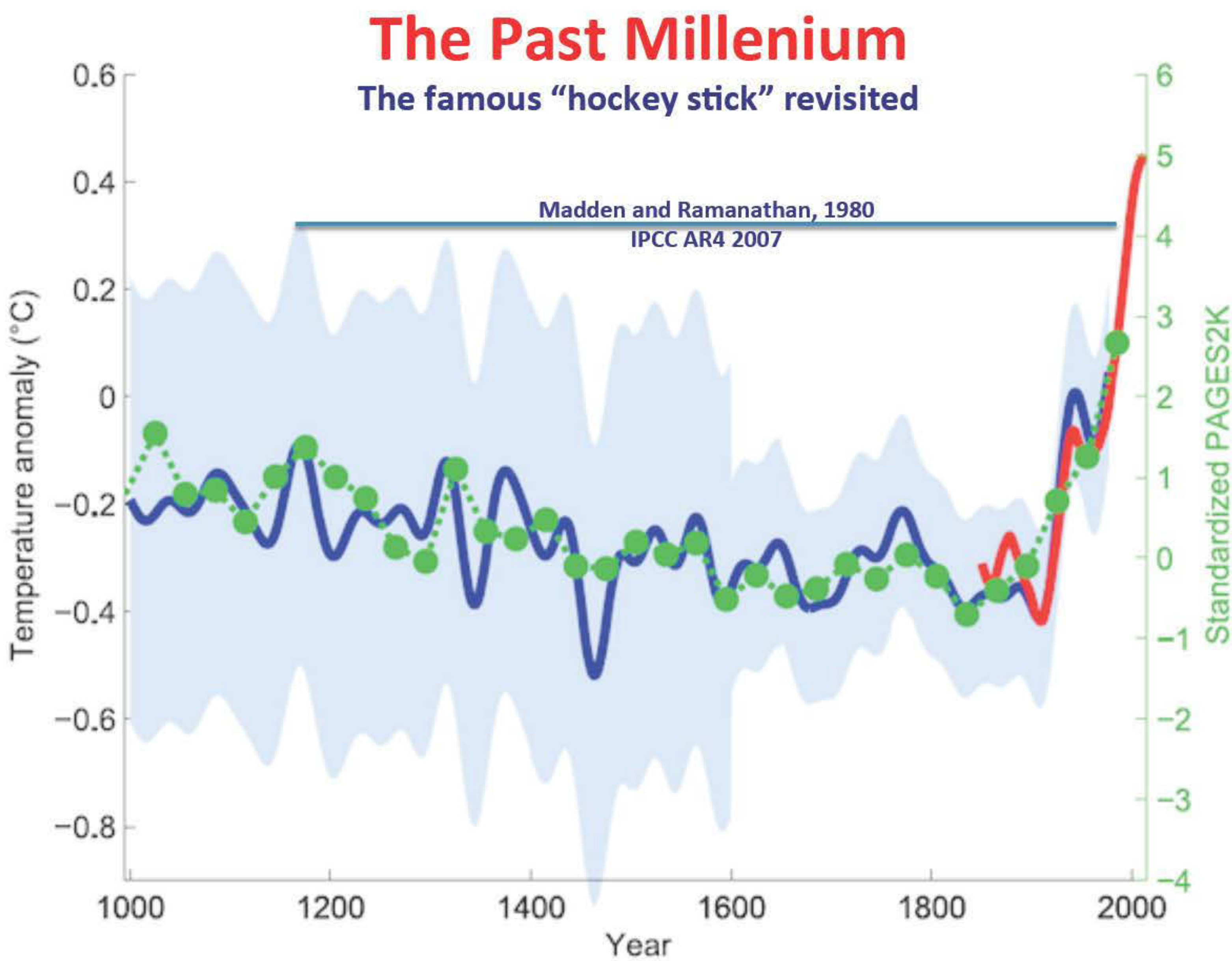
"…poor data handling, obsolete data and incorrect calculation …"

McIntyre, S., and R. McKittrick: Corrections to the Mann *et al* (1998) proxy data bases and Northern Hemispheric Average temperature series, *Energy and Environment, 14,* no 6, 751-767, 2003

Climate Gate

Hack of UEA server uploaded to Tomsk, Russia on Nov 19 2009; COP 15 Copenhagen Dec 7-18, 2009
Inter-calibration of data from different proxy sources can look like biased manipulation





Green dots show the 30-year average of the new PAGES 2K reconstruction. The red curve shows the global mean temperature, according HadCRUT4 data from 1850 onwards. In blue is the original hockey stick of Mann, Bradley, and Hughes (1999) with its uncertainty range (light blue). Stefan Rahmstorf

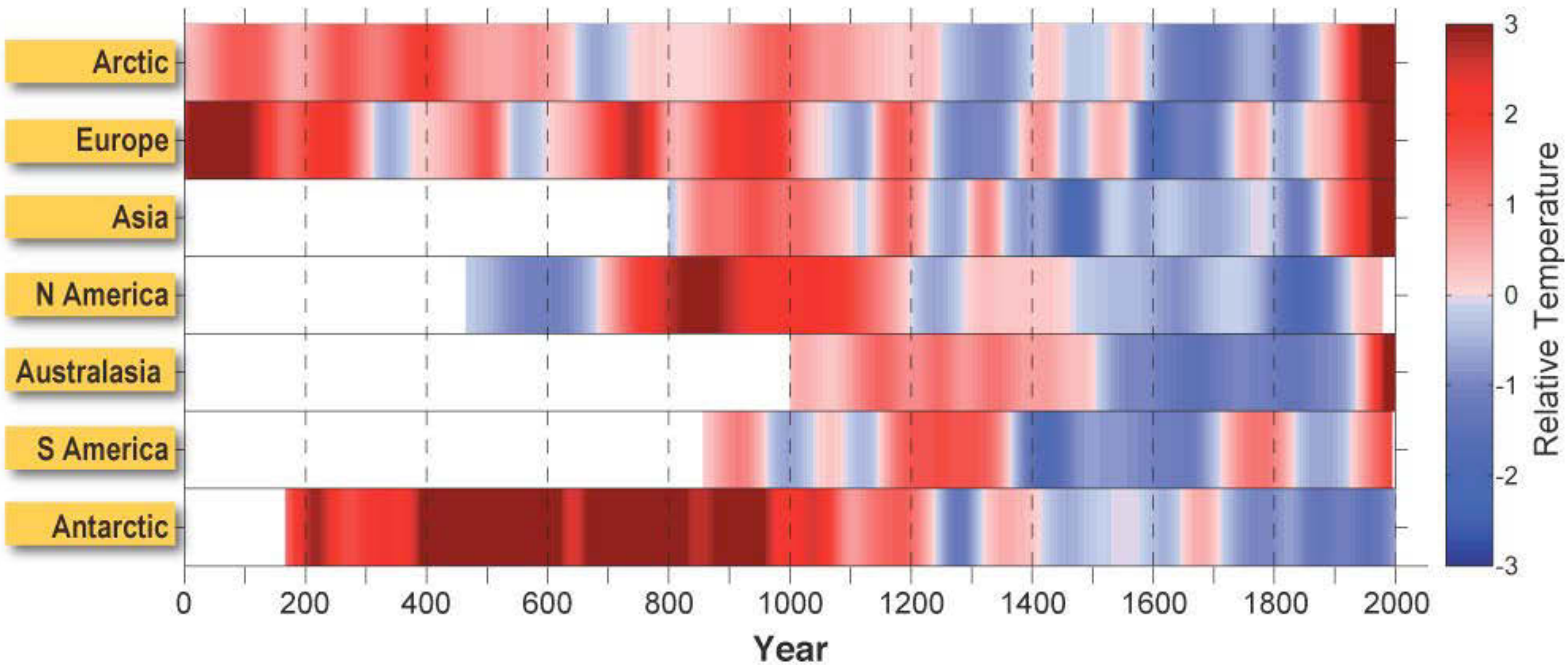
Continental Climate Change in Last 2000 Years

No pronounced MWP at global level

MWP switch to LIA in N. America and Europe

IPCC AR5 finds late-20th century Europe comparable to MWP

Long term global cooling post 1300 until industrial period

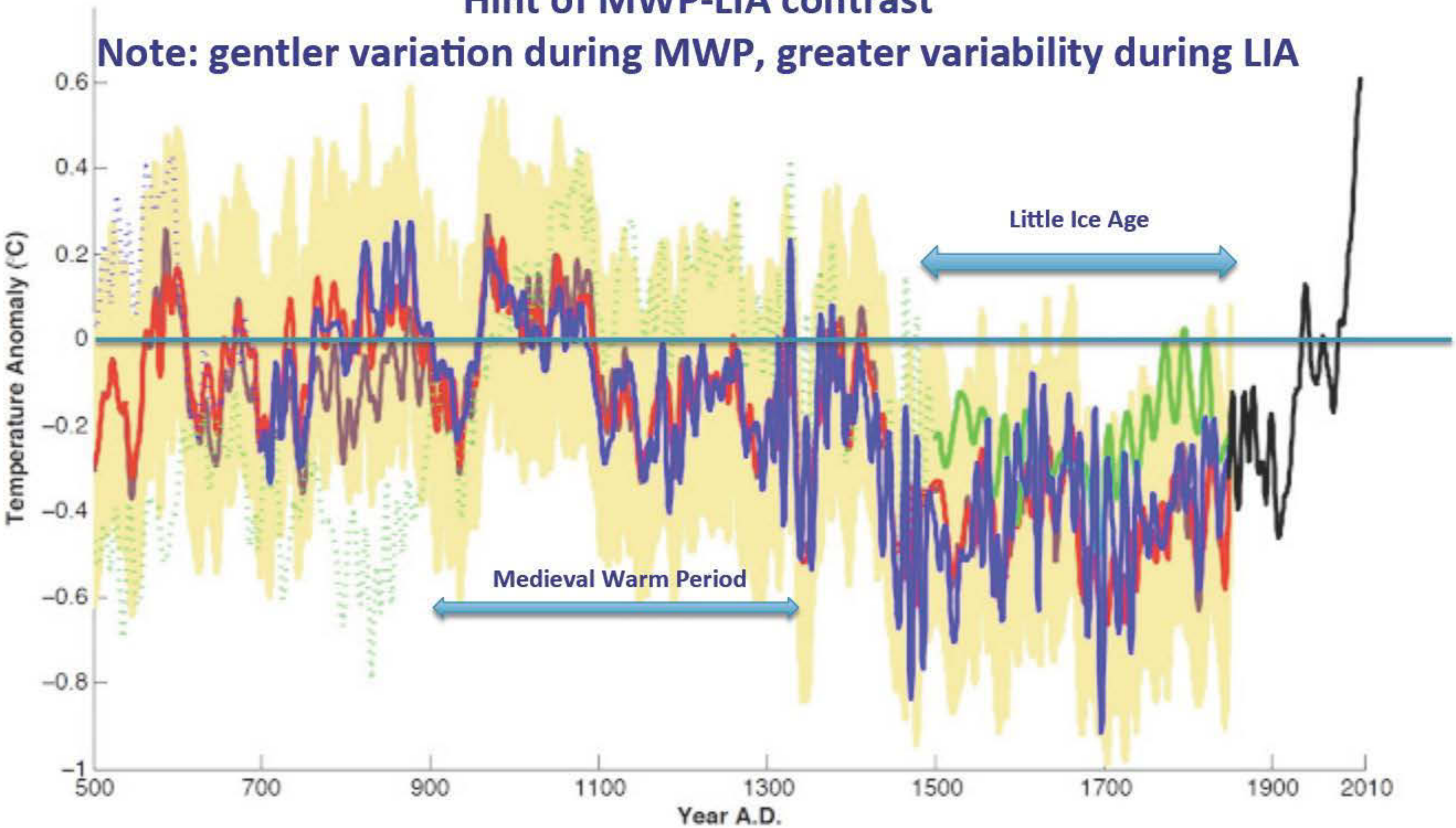


PAGES 2k Consortium (78 authors), Continental Scale temperature variability during the past 2 millennia, *Nature Geoscience, 6*, 339–346 (21 April 2013) doi:10.1038/ngeo1797

Northern Hemisphere Climate, 500-2010

Hint of MWP-LIA contrast

Note: gentler variation during MWP, greater variability during LIA

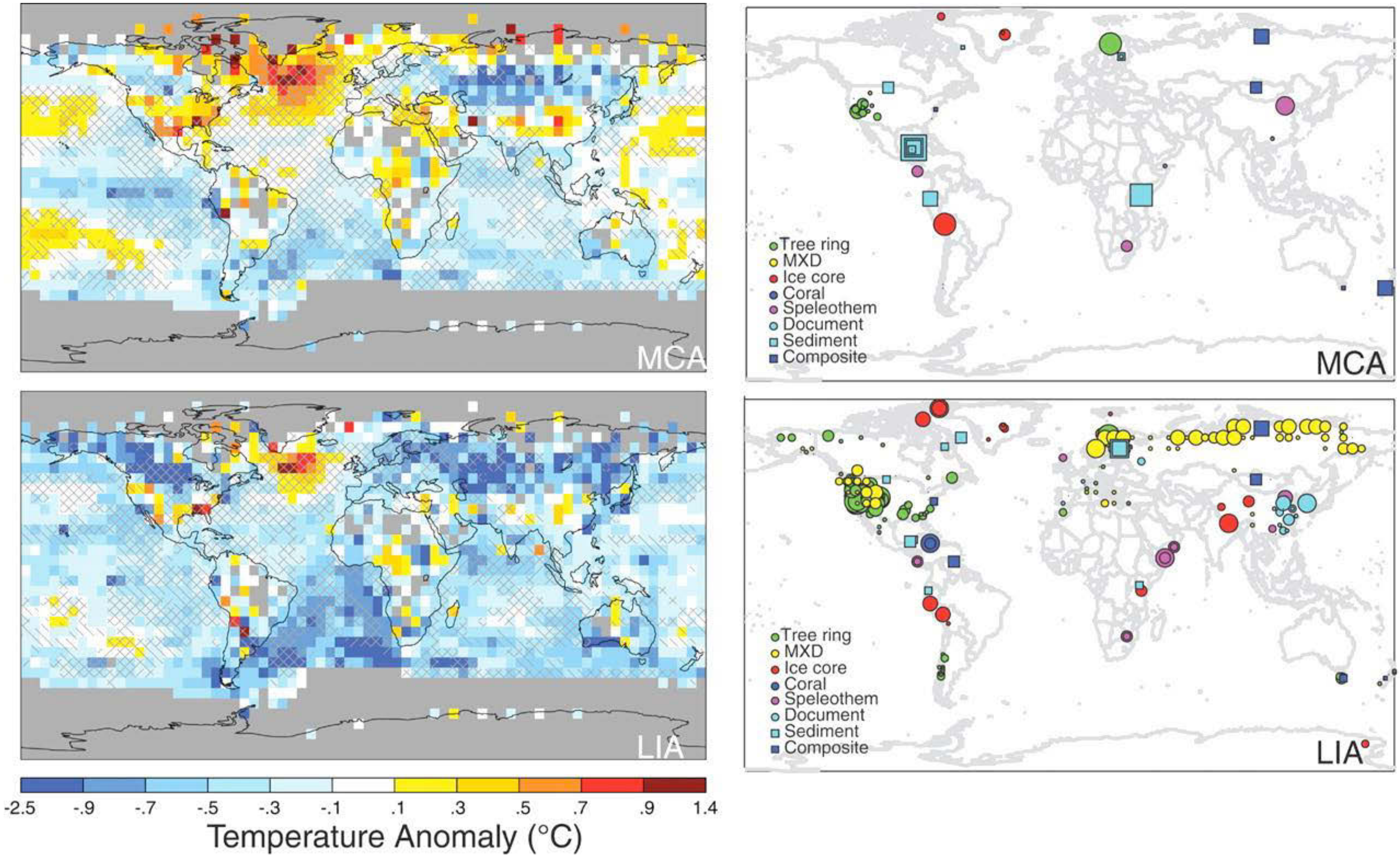


Sensitivity of NH mean reconstruction to exclusion of selected proxy record. Reconstructions are shown based on "all proxy" network (red, with two standard error region shown in yellow) proxy network with all tree-ring records removed (blue), proxy network with a group of 7 long-term proxy with greater uncertainties and/or potential biases as discussed in ref. S1 (brown) and both tree-ring data and the group of 7 records removed (green; dashed before AD 1500 indicates reconstruction no longer passes validation).

ME Mann, Z Zhang, S Rutherford, RS Bradley, MK Hughes, D Shindell, C Ammann, G Faluvegi, & F Ni, "Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly" (PDF). Science 326: 1256-1260 (Nov. 2009) (S.I. at *Science*).

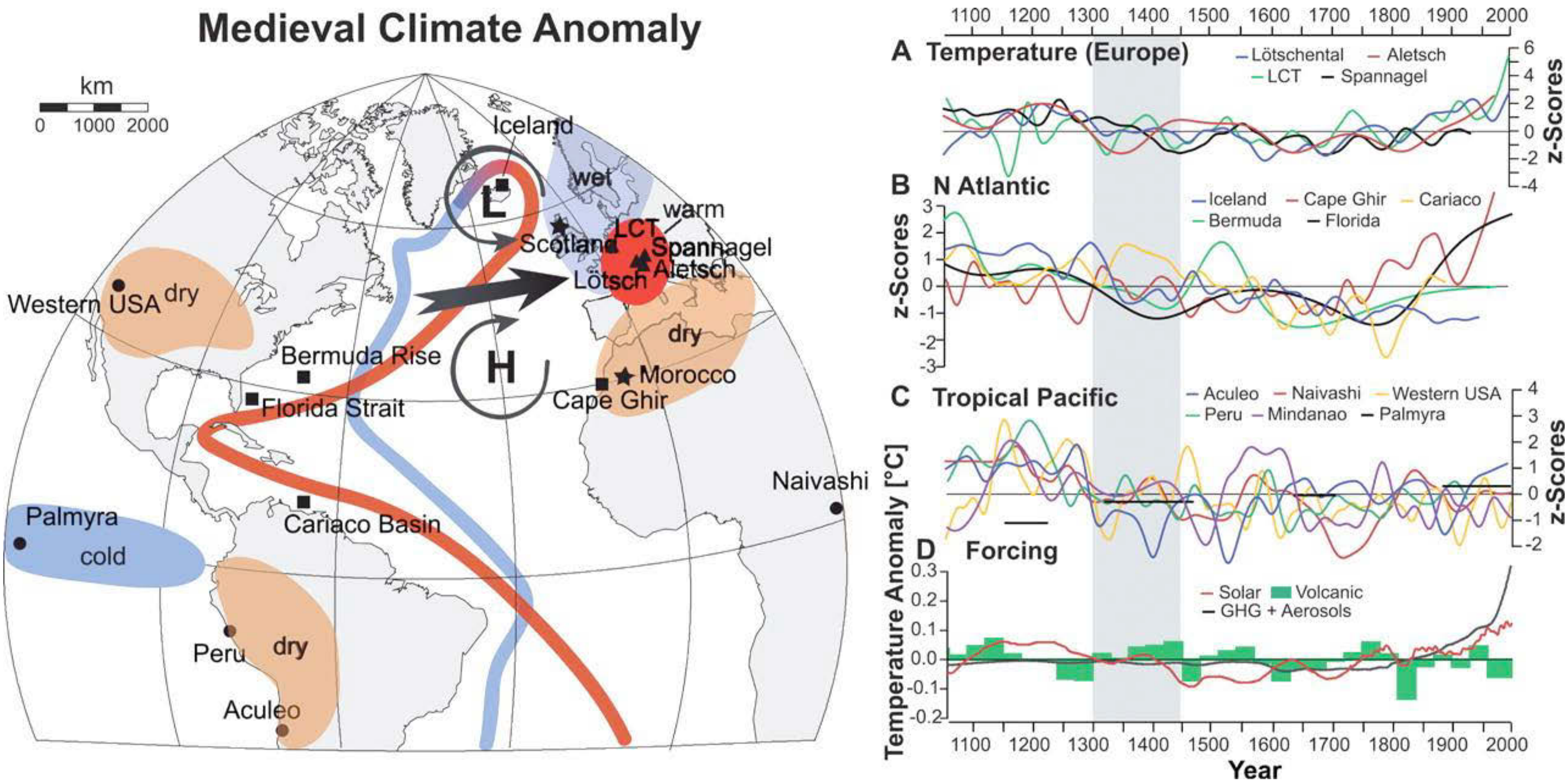
NH Warming Reconstruction Dominated by N. Atlantic Region

Medieval Climate Anomaly (MCA, top) and Little Ice Age (LIA, bottom)



Mann, M.E., *et al*, Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly, *Science, 326*, 1256-1260, 27 November, 2009

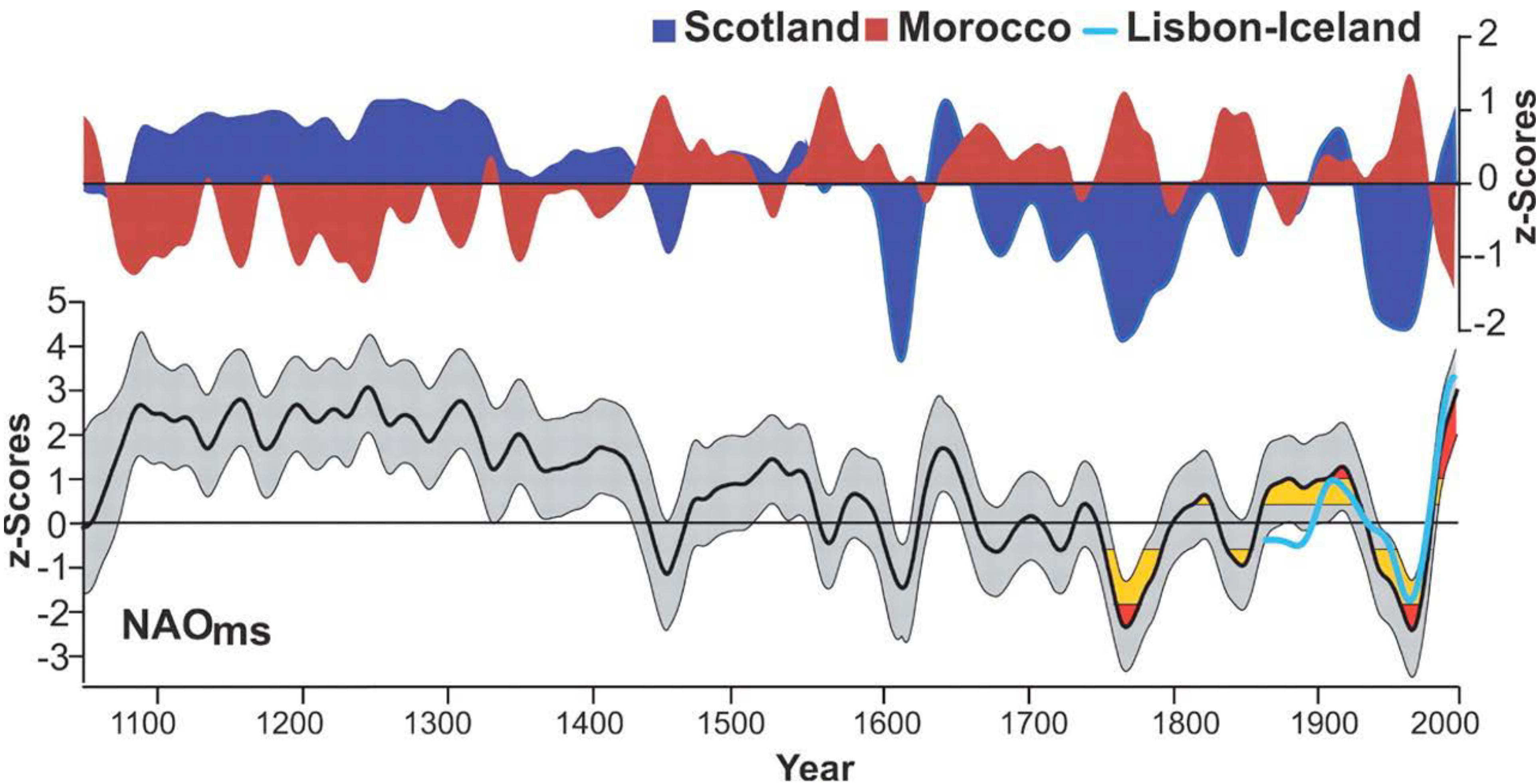
Medieval Warm Period-Little Ice Age Transition, and North Atlantic Oscillation



Trouet *et al.*, Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly, *Science, 324* (5923) 78-80, 27 March 2009

Persistent Positive North Atlantic Oscillation Mode dominated the Medieval Climate Anomaly

NAO reconstructed from proxies that correspond to pressure:
Scotland (winter precipitation) and Morocco (drought severity)



V Trouet et al., *Science 3 April 2009: Vol. 324 no. 5923 pp. 78-80 DOI: 10.1126/science.1166349*

Published by AAAS

The Great Famine of 1315-1317

Medieval Europe's Greatest Subsistence Crisis

Albrecht Durer (1471-1528)
***Four Horsemen of the Apocalypse*, ca 1497-98**

In the spring of 1315, unusually heavy rain began in much of Europe. It continued to rain throughout the spring and summer, and the temperature remained cool. These conditions caused widespread crop failures. The price of food began to rise, doubling in England between spring and midsummer.

In the spring of 1316, it continued to rain on a European population deprived of energy and reserves to sustain itself. All segments of society from nobles to peasants were affected, but especially the peasants who represented 95% of the population and who had no reserve food supplies. The height of the famine was reached in 1317 as the wet weather continued until summer.

Europe did not fully recover until 1322. The period was marked by extreme levels of crime, disease, mass death, and even cannibalism and infanticide. It is estimated that 10–25% of the population of many cities and towns died. The crisis had consequences for the Church, state, European society, and for future calamities to follow in the fourteenth century.

Abstracted from Wikipedia

LIA Transition Triggered by 4 Major Volcanoes in 50 years, Sustained by Sea Ice Interactions with AMOC

1257 Samalas, Indonesia, explosion, 3 others during 50 year period

Sea Ice rare in MWP (800-1300), expanded rapidly after volcanic explosions

Miller, G.H., *et al,* Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice ocean feedbacks, Geophysical Research Letters, 39, 02708, doi:10.1029/2011GL050168, 2012

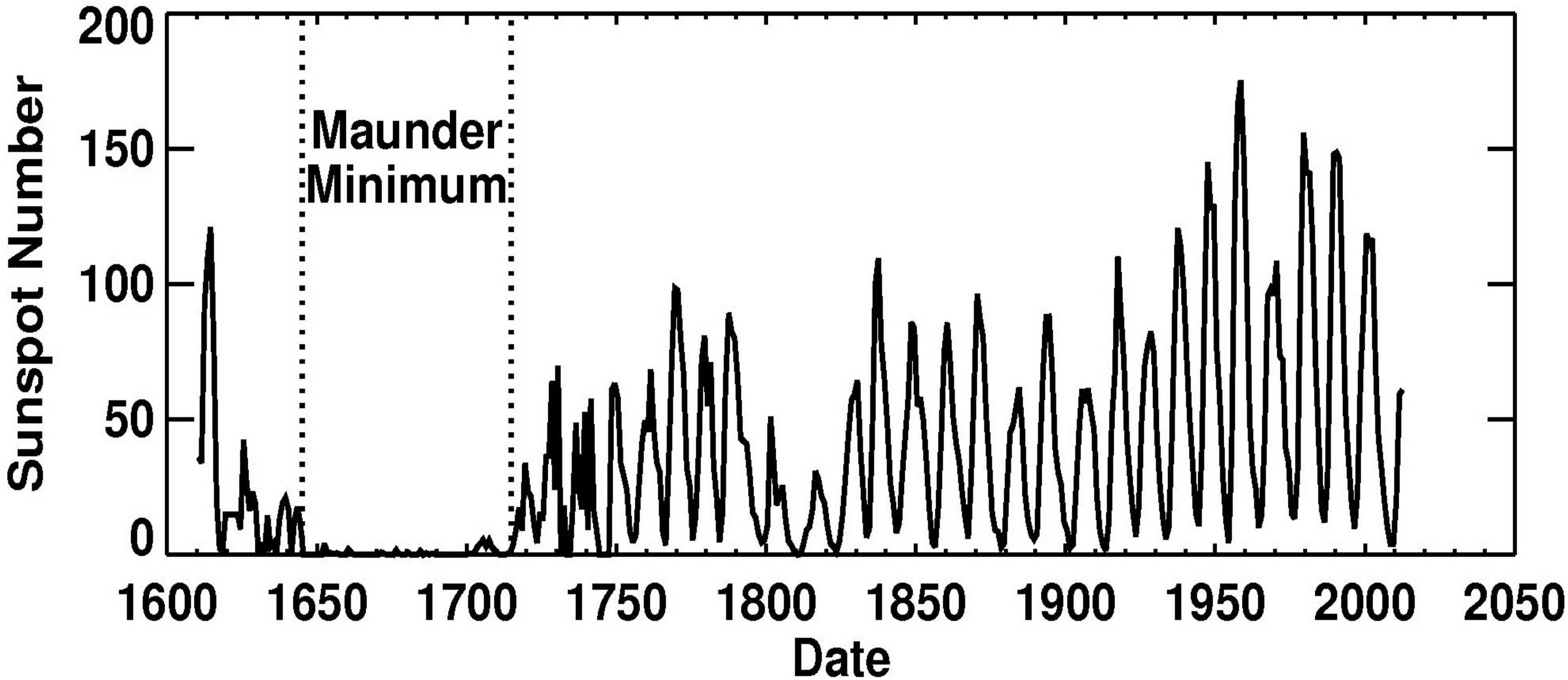
Gennaretti, F., *et al,* Volcano-induced regime shifts in millenial tree-ring chronologies form eastern North America, PNAS early edition, July 2014, doi/10.1073/pnas.132420111

The Years When Europe's Waterways Froze

The Maunder Minimum, 1645-1710?

Did Decrease in Solar Insolation Deepen the Little Ice Age?

Modern satellite measurements of total solar irradiance:
Difference of 0.25 W/m2 between solar minimum and solar maximum

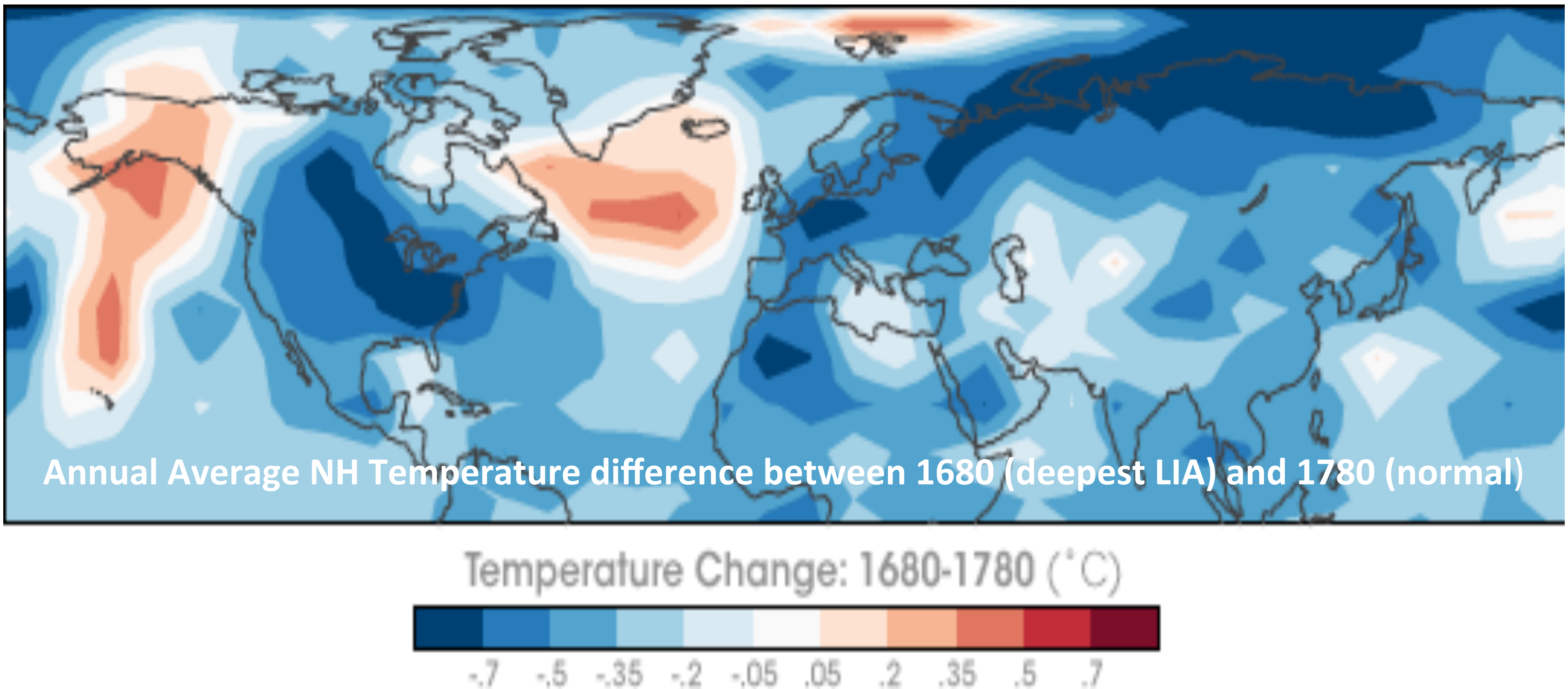


John A. Eddy, The Maunder Minimum, *Science, New Series, 192*, no. 4245, 1189-1202 (Jun 18, 1976) Stable URL: http://links.jstor.org/sici?sici=0036-8075%2819760618%293%3A192%3A4245%3C1189%3ATMM%3E2.0.CO%3B2-V

Figure: Courtesy NASA Marshall Space Flight Center

Maunder Pattern Modeled

25% decrease in solar irradiance, much at UV wavelengths that affect stratospheric O3
Forced shift to lower AO/NAO as solar irradiance decreases

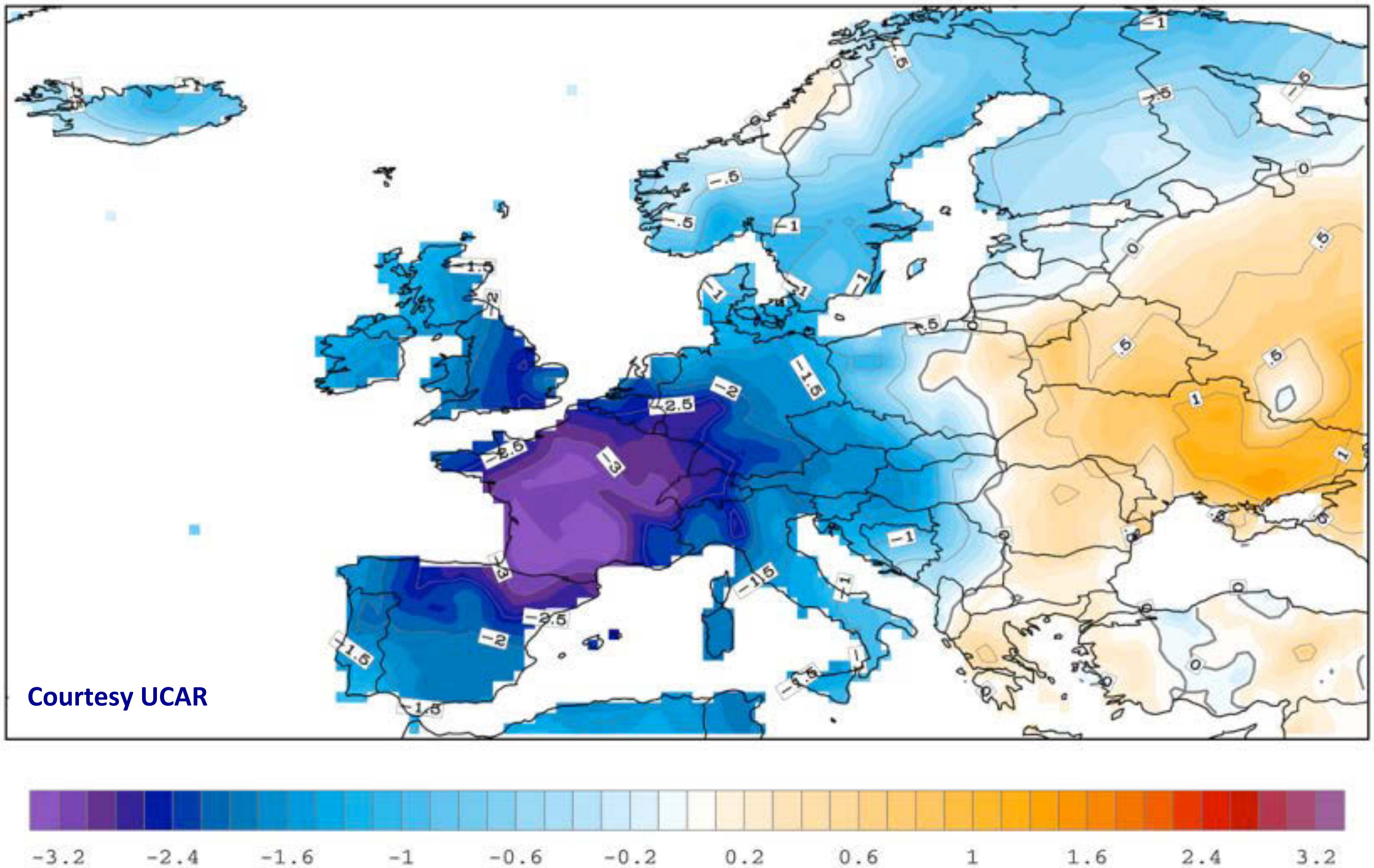


Shindell, D.T., G.A. Schmidt, M.E. Mann, D. Rind, & A. Waple, Solar Forcing of Regional Climate Change During the Maunder Minimum, *Science 294*, 2149-2152, 7 December, 2001

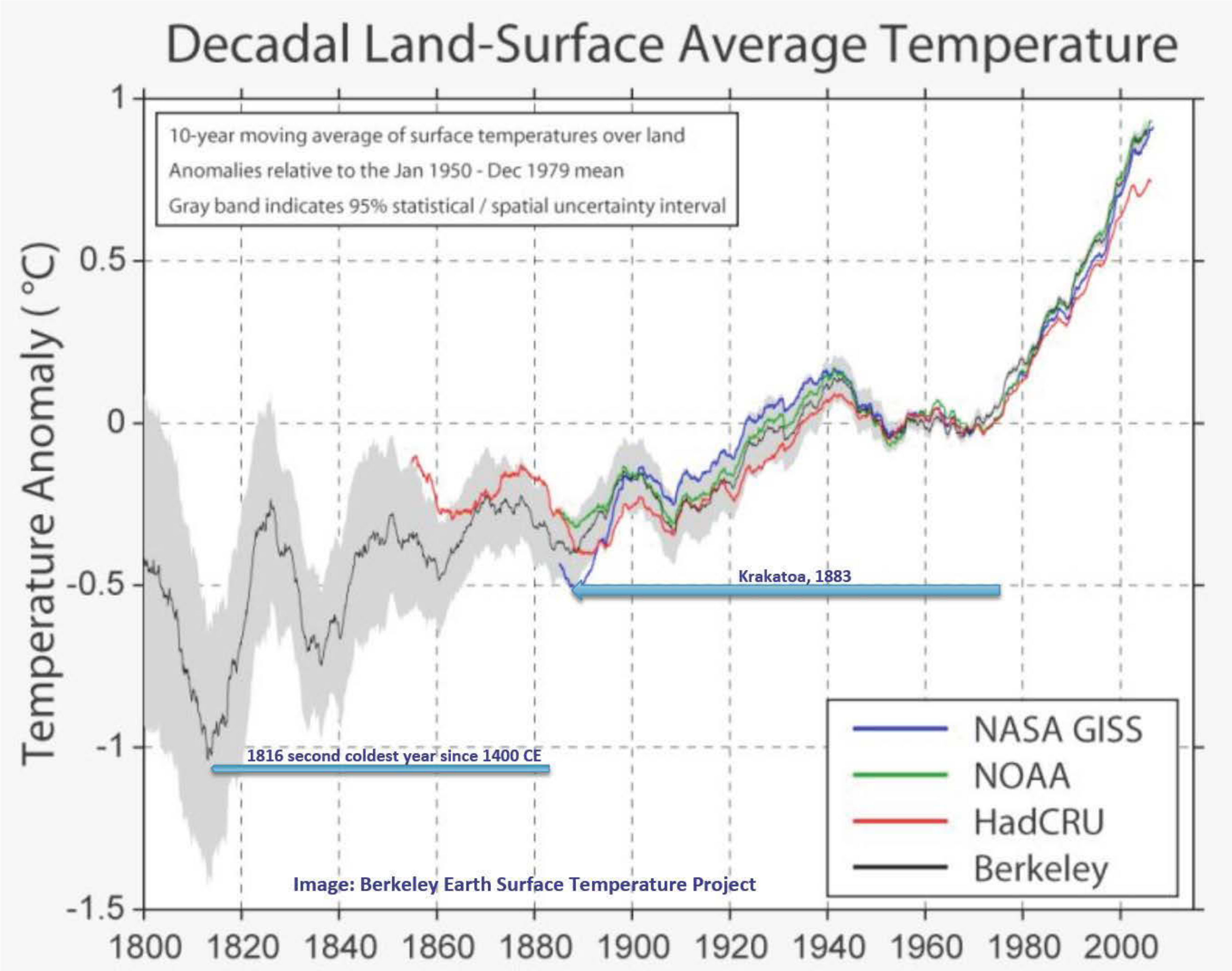
1816-The Year Without a Summer

When India had no monsoon

1816 Summer temperature anomaly



Henry and Elizabeth Stommel, *Volcano Weather: The Story of 1816 , the Year without a Summer,* Newport RI. 1983. ISBN 0-915160-71-4
Gillen D'Arcy Wood, *Tambora: the Eruption that Changed the World*, Princeton University Press, Princeton, NJ   ISBN 978-0-691-15054-3



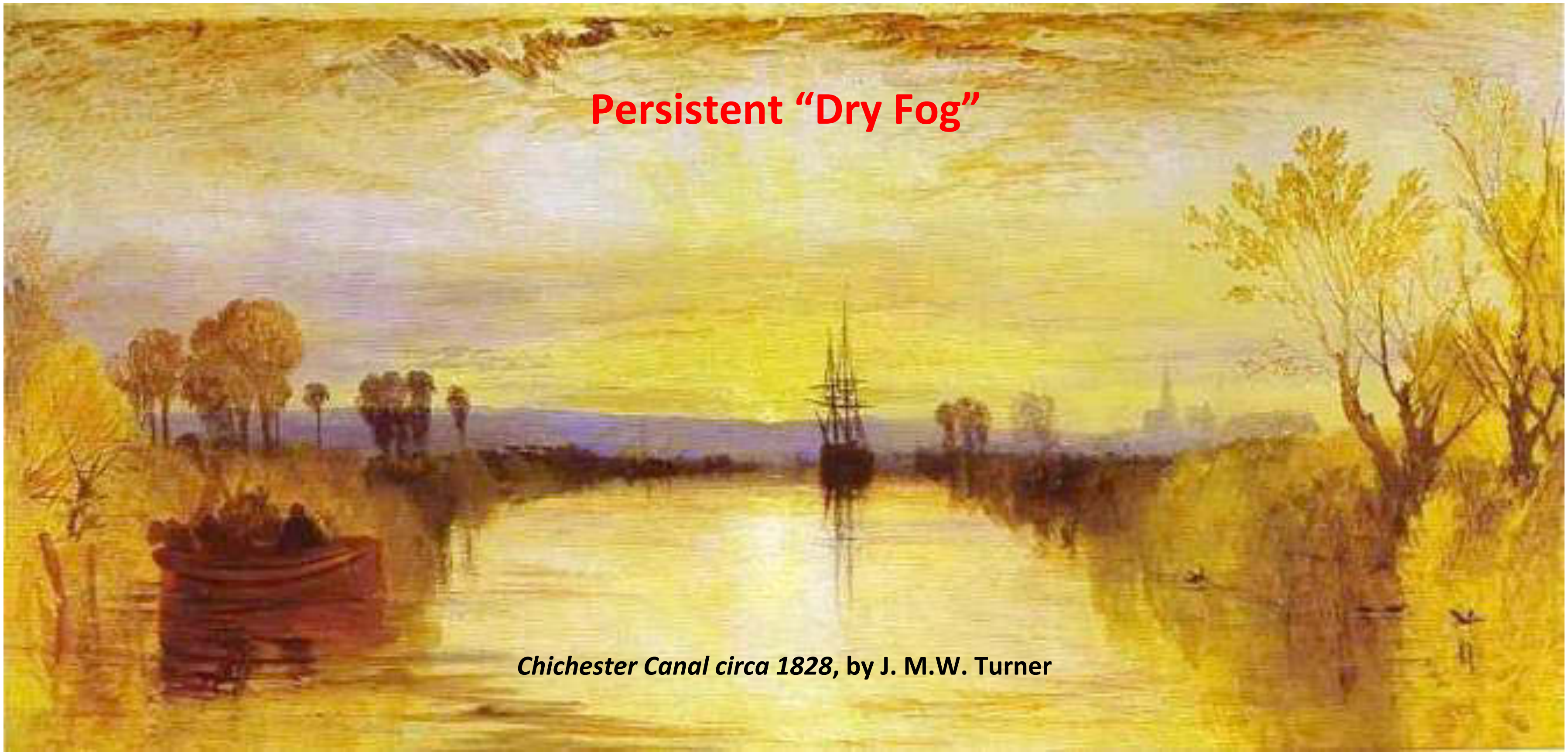
Decadal Land-Surface Average Temperature
10-year moving average of surface temperatures over land
Anomalies relative to the Jan 1950 - Dec 1979 mean
Gray band indicates 95% statistical / spatial uncertainty interval
Temperature Anomaly (°C)
1
0.5
0
-0.5
-1
-1.5
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
Krakatoa, 1883
1816 second coldest year since 1400 CE
NASA GISS
NOAA
HadCRU
Berkeley
Image: Berkeley Earth Surface Temperature Project

Tambora, April 5-15, 1815

Largest Volcanic Eruption since Lake Taupo in 180 CE

Tambora lost about 1600 meters in altitude, or about 5000 feet

Last Great Subsistence Crisis in the Western World



Chichester Canal circa 1828, by J. M.W. Turner

"Food riots broke out in the United Kingdom and France, and grain warehouses were looted. The violence was worst in landlocked Switzerland, where famine caused the government to declare a national emergency. Huge storms and abnormal rainfall with flooding of Europe's major rivers (including the Rhine) are attributed to the event, as is the August frost. A major typhus epidemic occurred in Ireland between 1816 and 1819, precipitated by the famine the Year Without a Summer caused. It is estimated that 100,000 Irish perished during this period". (Wikipedia)

What is Past Is Prologue

Is the history of the climate a guide to its future?

Janus, the Roman God of Beginnings, dagli Orta/ Cathedral Museum, Ferrara/The Art Archive

There is no climate determinism. It is foolishness to imagine that there is a single chain of causality linking changes in climate to changes in human society; it is equally foolish to claim that climate has no bearing at all on human well-being, but we do not ascribe agency to the climate. Climate operates in the background of history, while the fascinating swirl of human events occupies the forefront of our minds.

Triggers Matter

Ice Ages were triggered by tiny variations in insolation that produced reinforcing responses throughout the climate system. A persistent new climate pattern, Europe's Little Ice Age, was triggered by the volcanoes of 1257-1300; the Northern Hemisphere cooled by about 0.4 degC and stayed cool until the fossil fuel era unfolded.

Stability Matters

The last ice age in Europe was given to abrupt changes that unfolded in tens of years, triggered probably by changes in ocean heat transport and/or carbon release. Before the Holocene, hunter-gatherer communities were chased around by the unstable climate. The agricultural revolution evolved during the relatively warm and benign Holocene maximum that followed. Later, European populations prospered during the warm, relatively stable medieval warm period.

Geography Matters

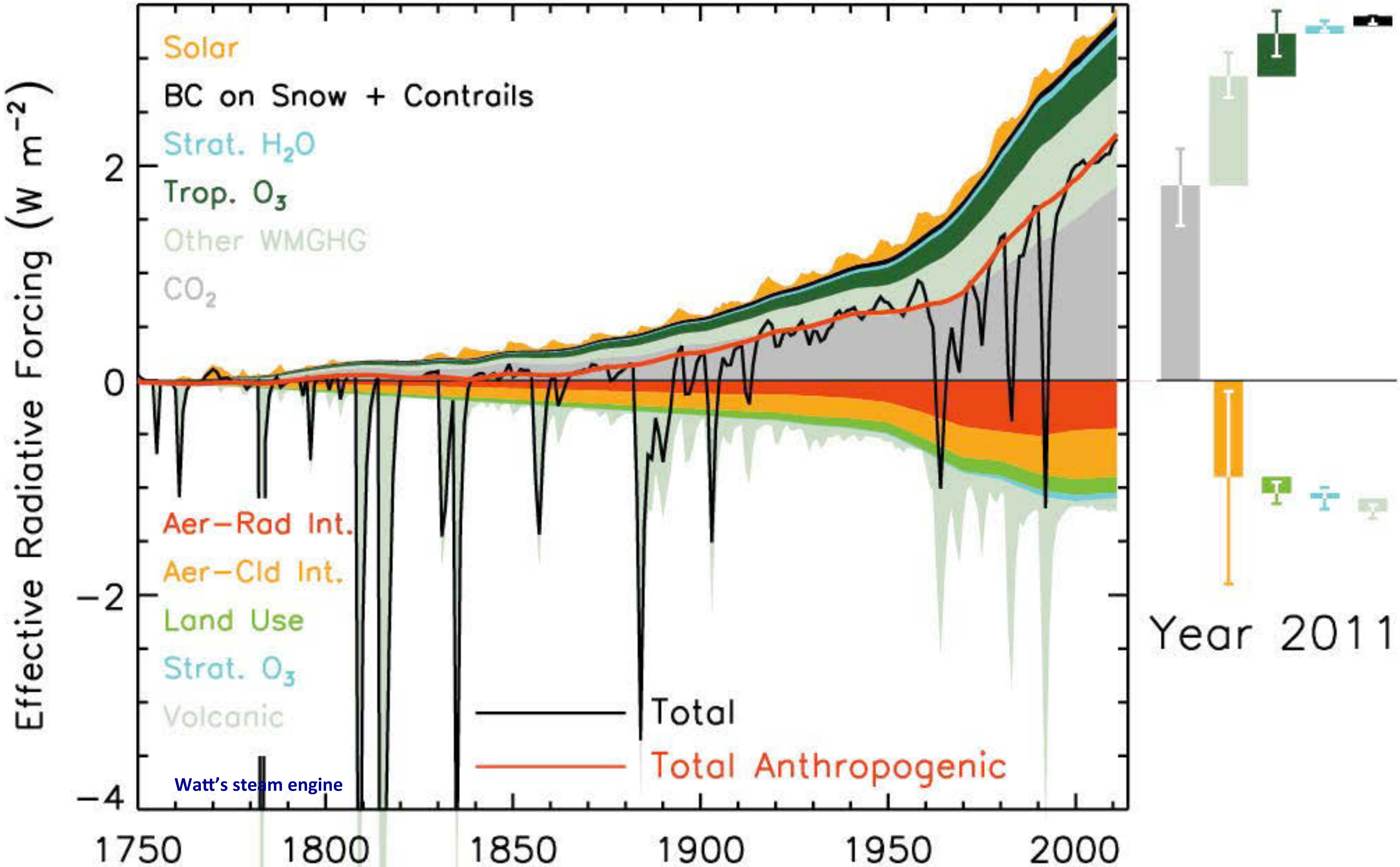
While climate change may have a global reach, its impacts are regional and local. Climate change in Europe and Eastern North America is dominated by the complex interactions between land and ocean ice, land ice melt, and ocean heat transport in the North Atlantic-the cockpit of Europe's climate. In one sense, we are fortunate to have had such an excellent bearer of climate change evidence as Greenland's ice sheet. Its proximity to the driving regions of the AMOC meant that the responses to changes in forcing were rendered all the more vivid by Europe's dependence on the Gulf Stream for warmth. But it took a long time to recognize that Europe and North America are not the world. Only now is the history of other regions' climates being unravelled. If the AMOC is central to Europe's climate past and future, so are the Monsoon to South and East Asia, and the *El Nino* to Western North and South America.

Resilience Matters

Agriculture, the basis of pre-industrial society, has always been sensitive to the vagaries of weather. Early subsistence agriculture was vulnerable to one or two bad years, but as productivity was improved by the slow accumulation of new farming technologies, and as agricultural and social resilience improved through field and crop rotation, mixed use farming, and trade, famines like that of 1315 gradually became a thing of the past in Western Society. The related vulnerabilities triggered by climate events, such as epidemics or price instability, still occurred but may be traced to weakness of social and economic organization.

Industrial Era Drivers of Climate Change

Net increase since 1750 from human and natural sources has been 2.3 W/m2



IPCC AR5 Working Group I, Figure 8-15


We humans are taking the climate places we have never seen
The atmosphere's CO_2 concentration is now 40% higher than in the past four interglacials. Anthropogenic forcing has increased by 2.3 W/m2 since 1750, on top of the natural increase between the LGM and the Holocene of 3 W/m2.
We are adding warming to warming. The global temperature has increased by 0.8 C in the industrial era. A cooling of 0.4 C in Europe had major impacts on human society at the terminations of the Holocene Climate Optimum and Medieval Warm Period.
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