Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

Clearing the Air:

Explaining the Science and Uncertainty of the Paleoclimatic Record

Jason E. Smerdon

Lamont-Doherty Earth Observatory of Columbia University

Thanks to:

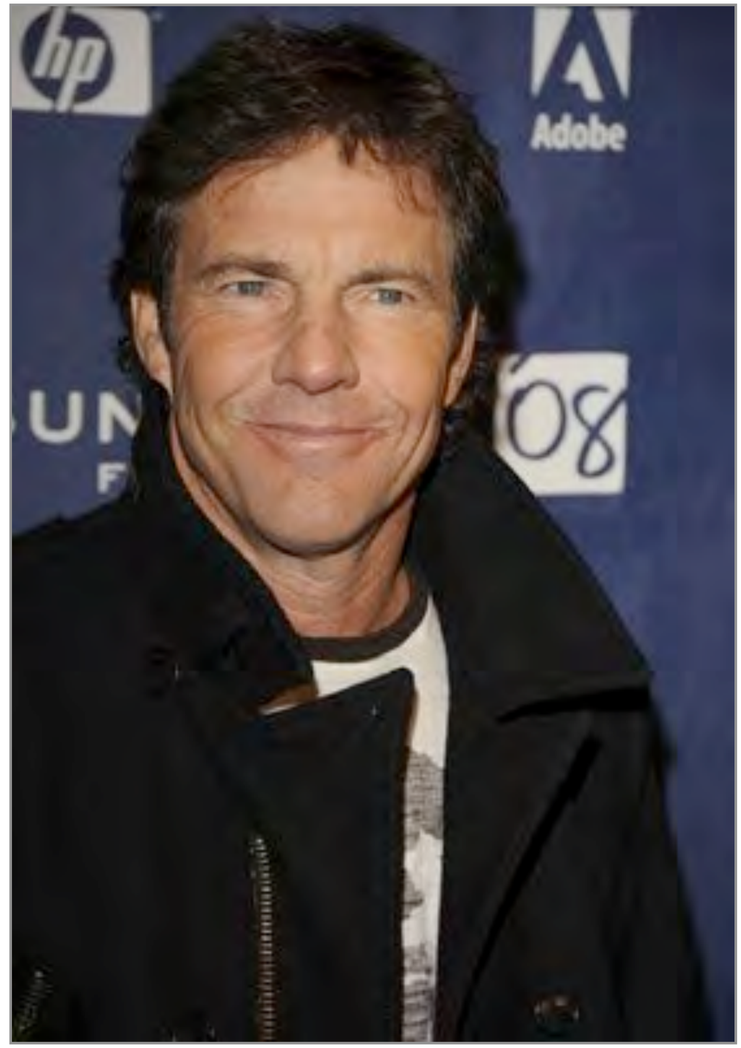
Brad Schallert (*Columbia University SIPA '10*) & Irene Boland (*EPA Region 2*)

Talk Goals

- Lead by example (science communication)
  - URLs
- Outline the paleoclimatology enterprise
  - This stuff is interesting, not just useful
  - A scientific cage match
- Highlight some important periods of Earth History
  - As an example of what we know and what we debate (scientific uncertainties)
  - Explain the relevance of these periods for the present
- Explain why paleoclimatology matters for our understanding of contemporary climate change and future challenges

A Remarkable Story

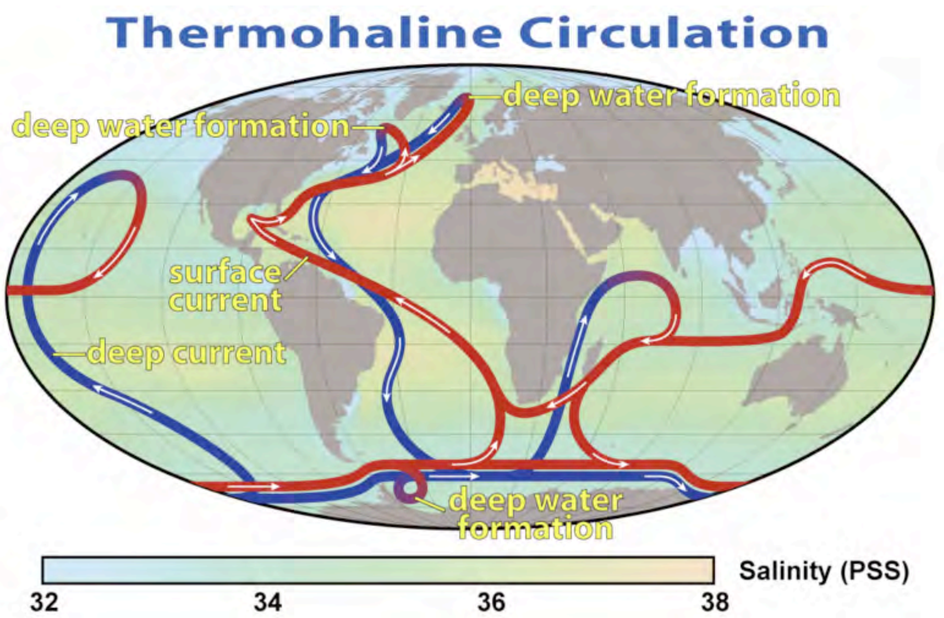
Wally Broecker (Scientist)



Dennis Quaid (Actor)

A Remarkable Story

Wally Broecker (Scientist)



The Founding of The Lamont Geological Observatory

In 1929, Thomas W. Lamont (1870-1948), a Wall Street banker, constructed a weekend residence overlooking the Hudson River in Palisades, New York. In 1948, Lamont's widow, Florence Corliss Lamont (1873-1952), donated the estate to Columbia University.

J. Lamar Worzel with Lamont cofounder Maurice Ewing (right) and sediment core, on deck of the deep-sea drilling ship Glomar Challenger, 1968

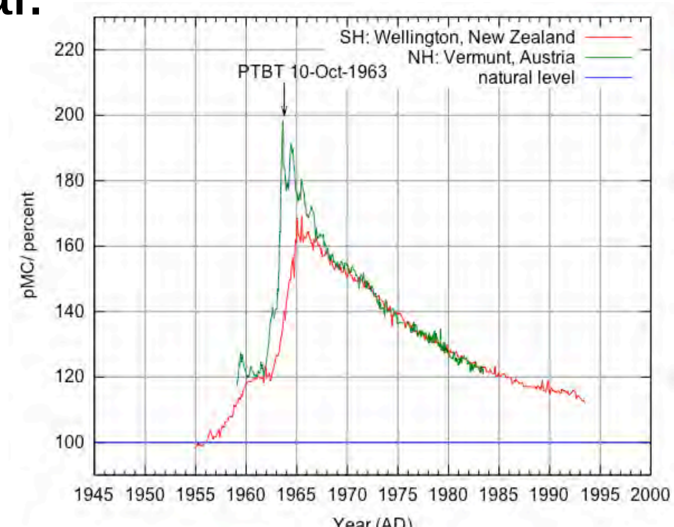
http://www.ldeo.columbia.edu/about-ldeo/history-lamont-0

Development of Radiocarbon Dating

Willard F. Libby (Nobel Laureate 1960) worked on Manhattan (District) Project at Columbia University before taking a Professorship in 1945 at the University of Chicago. Libby first developed radiocarbon dating in 1949.

Radiocarbon dating uses the naturally occurring carbon isotope C^{14} to date organic material.

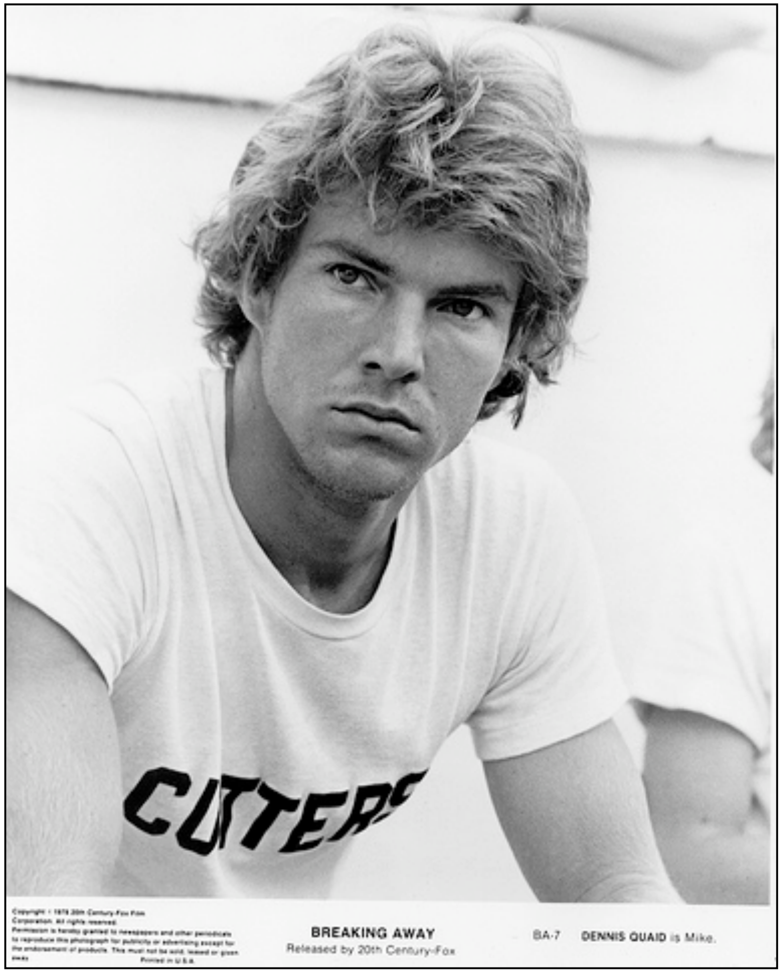
Organisims take up C^{14} while living. This C^{14} decays after death with a constant half-life. The ratio of C^{14} to C^{12} in organic material can therefore be used as an age metric for up to about 50-60K years into the past.



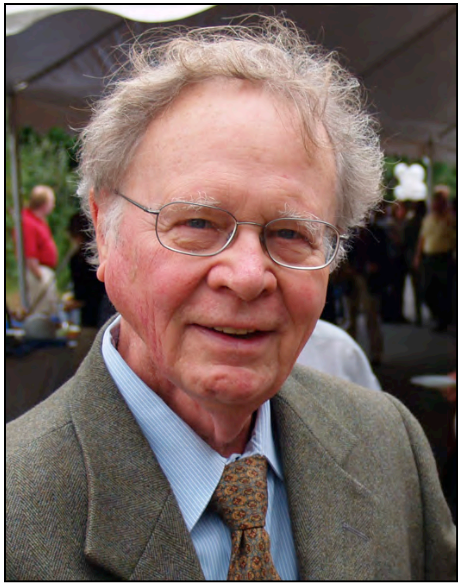
http://en.wikipedia.org/wiki/Radiocarbon_dating#History

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

Enter a young Wallace Broecker (1952)



Enter a young Wallace Broecker (1952)



Wally arrived at Columbia in 1952 to work with J. Lawrence Kulp, who in 1950 had established the Carbon 14 Research Center - the second of only two in the United States at the time.

The Carbon 14 Lab was housed at the time in Lamont Hall, the original residence of Thomas W. Lamont.

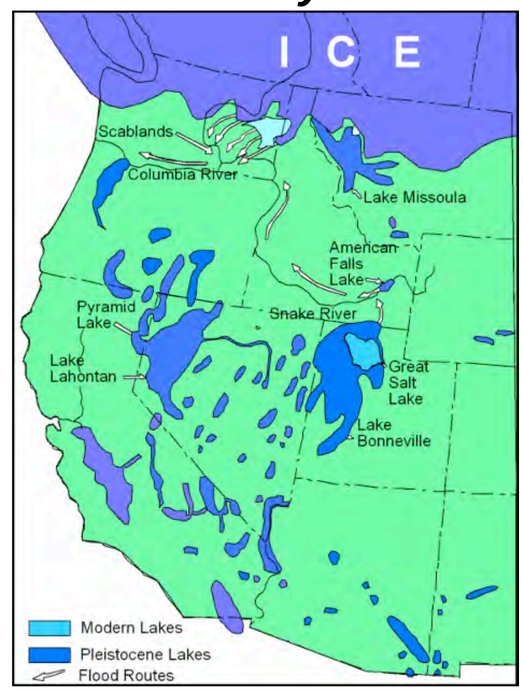
http://www.ldeo.columbia.edu/about-ldeo/history-lamont-0
http://spectrum.ieee.org/energywise/energy/environment/columbia-university-honors-one-of-its-top-geoscientists
http://eesc.columbia.edu/news-events/news/celebrating-wally-broeckers-50th-anniversary-columbia-professor

Pyramid (Lahontan) Lake

After [Broecker's talk] the man who had helped organize the conference strode up the center aisle and stood facing [Broecker]. Phil Orr, archaeology curator at the Santa Barbara Museum, was clearly more of a digger than a scholar; although he smoked a pipe, it had a cigar butt in it. He was a short man with a potbelly stuffed into jeans and cowboy boots. His face was shaped like an interstate-highway shield - a wide forehead, uncluttered by hair, narrowing to a pointy, straggly bearded chin. That forehead overhung deep-set eyes that seemed made to squint. Orr eyeballed Broecker. "***Kid***," he said…"***I can see that you know a lot about physics and math. But I also see that you don't know a goddamned thing about the earth.***"

-Broecker and Kunzig, *Fixing Climate*, 2008

http://en.wikipedia.org/wiki/Pyramid_Lake_(Nevada)



http://geology.isu.edu/Digital_Geology_Idaho/Module14/mod14.htm

The Early Theory of Ice Ages

Theories about local 'ice ages' in Europe began in the mid 1700s. The theories grew out of observations of glacial erratics found throughout the valleys of the Alps.

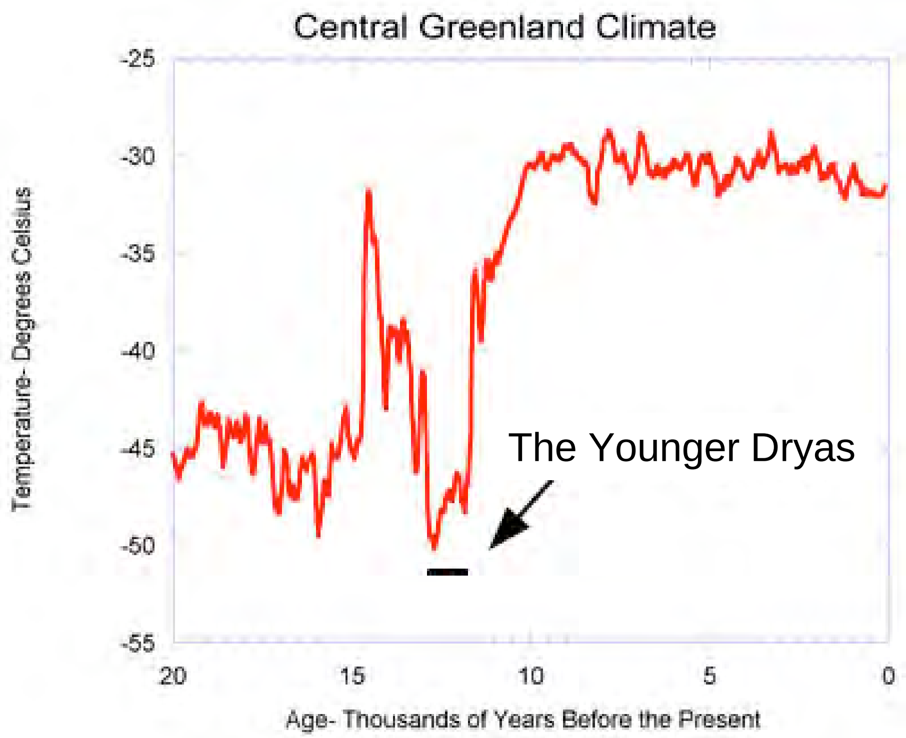
Louis Agassiz is widely credited for establishing the theory when he published his *Study on Glaciers* (1840), based on his and others study of mountain glaciers in the Alps in the late 1830s.

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

The Dawn of Modern Geochemistry

Broecker and others were embarking on the early science of isotopic geochemistry and geochemical dating.

This science, and the techniques that it developed, allowed researchers to quantify the magnitude of climatic changes in earth history and to constrain the timing of events.



http://oceanworld.tamu.edu/resources/oceanography-book/Images/younger.jpg

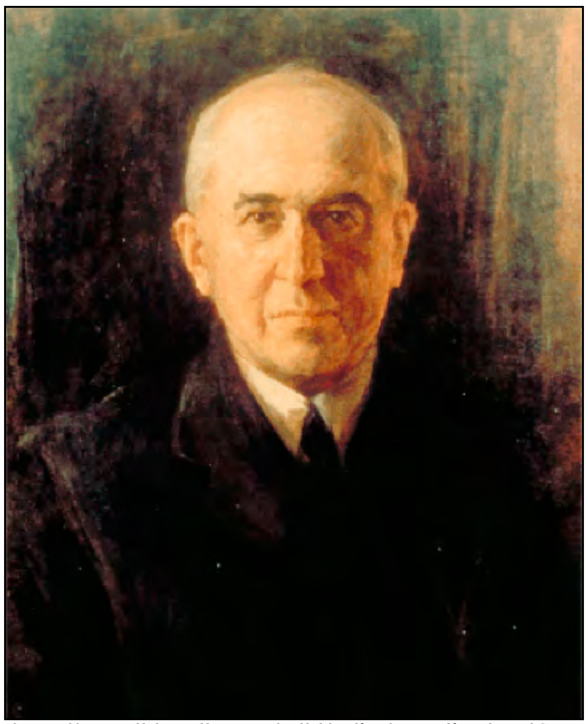
http://en.wikipedia.org/wiki/Pyramid_Lake_(Nevada)

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

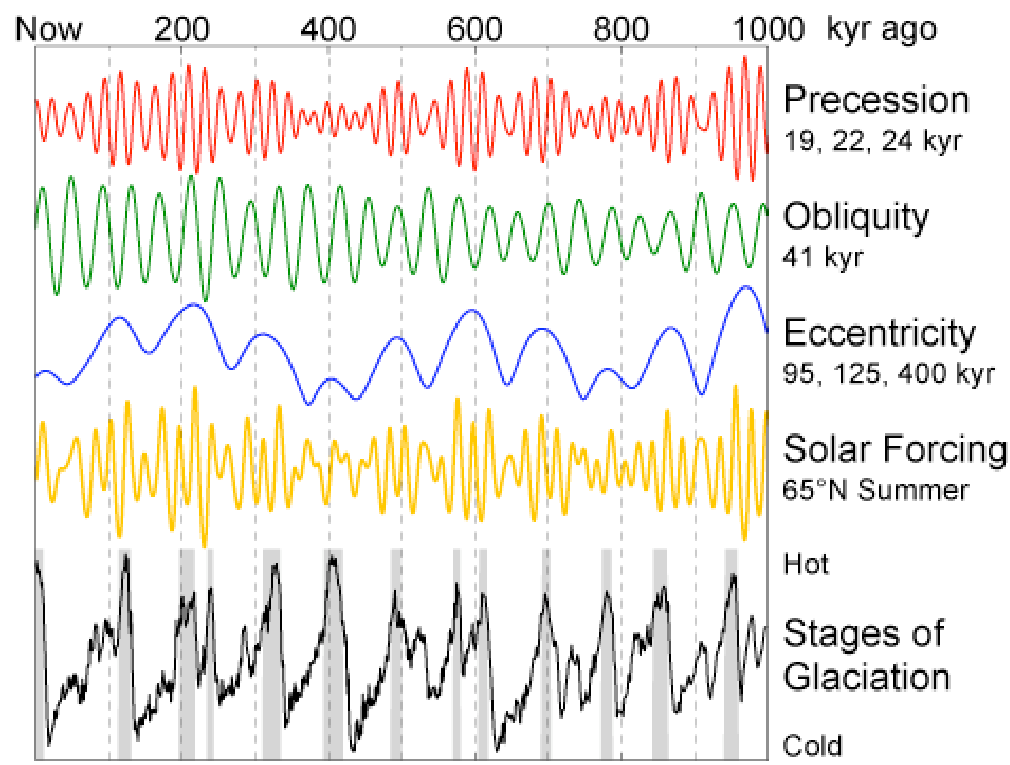
The Modern Theory of Ice Ages

After Agassiz published his *Study on Glaciers*, scientists began proposing that astronomical variations in the Earth Orbit were responsible for changes in climate.

In 1920 Milutin Milankovitch published the first comprehensive theory for the Ice Ages. He proposed that the amount of summer insolation in the high latitudes of the Northern Hemisphere regulates the growth of glaciers and showed that three major patterns of variation in the earth orbit govern that amount.



http://en.wikipedia.org/wiki/Milutin_Milanković



A Few Key Points from this Story

- Ice age theory was born out of multiple lines of evidence
- The theory was the product of both observation and theoretical calculations
- The history of the theory reflects a multifaceted effort involving many researchers and fields of study
- The surprising and not immediately obvious theory is built upon irrefutable building blocks that can be verified by anyone who cares to do so.

Paleoclimatology

- Paleoclimatology is the study of past climates using natural records of environmental change known as climate proxies, other geological or ecological evidence, and mathematical models.

- Generally speaking, the further back in time we investigate, our estimates of climate change are derived from less information and are associated with more uncertainty.

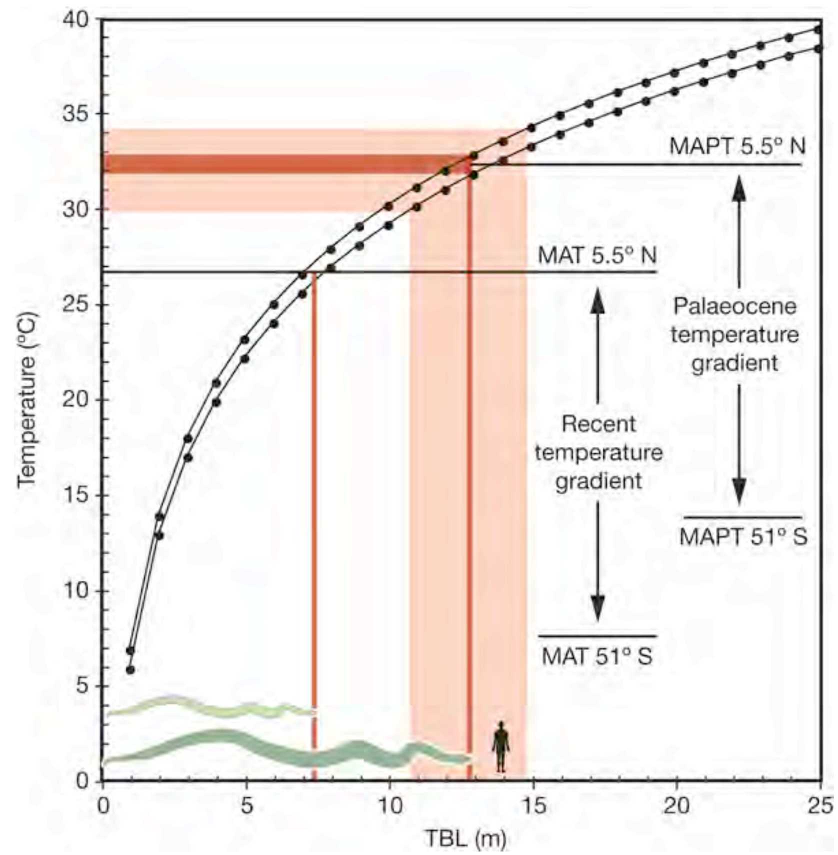
- Reduced resolution is a consequence of the loss of information back in time. Resolution is lost both in time (less data per time interval) and space (fewer measurement locations).

- Paleoclimatology has provided important insights into how our climate changes, as well as an historical context for contemporary climate change.

What is a climate proxy?

Climate proxies *can be anything* that naturally responds to climatic conditions and is preserved long enough for scientists to find it today.

Head et al., Nature, 457, 715-717 (5 February 2009)



http://climateprogress.org/2009/02/08/big-snake-titanoboa-nature-garden-of-eden-lindzen-thermostat-hypothesis/

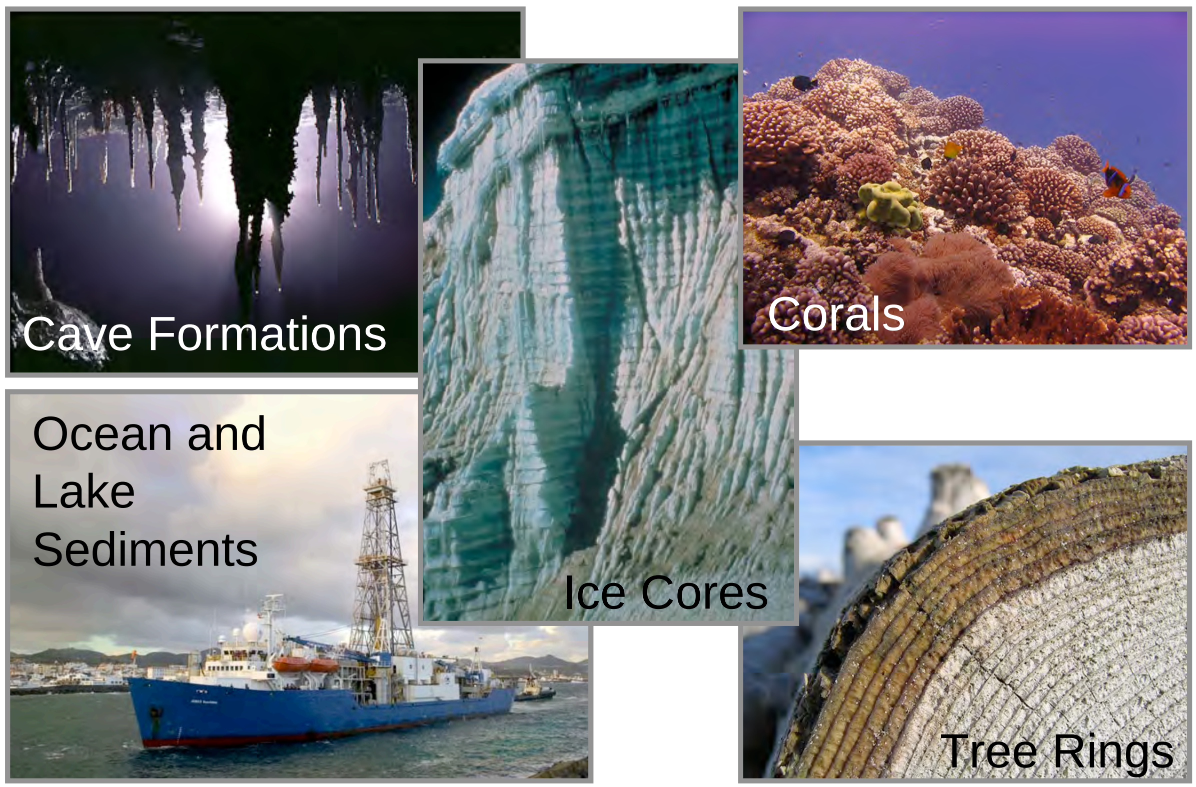
Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

What is a climate proxy?

The science of paleoclimatology focuses on the gathering, analysis, and interpretation of proxy data from natural recorders of climate variability such as: tree rings, ice cores, fossil pollen, ocean sediments, corals, and historical data.

These climate proxies are natural recorders of past climate variability. One of the key aspects of paleoclimatology is understanding the connection between climate and the response of a given proxy archive.

Proxies are collected all over the world in many different forms. Each proxy record has its own advantages and disadvantages. Attempts to synthesize the collective information in the proxy record are an important area of paleoclimatic research.



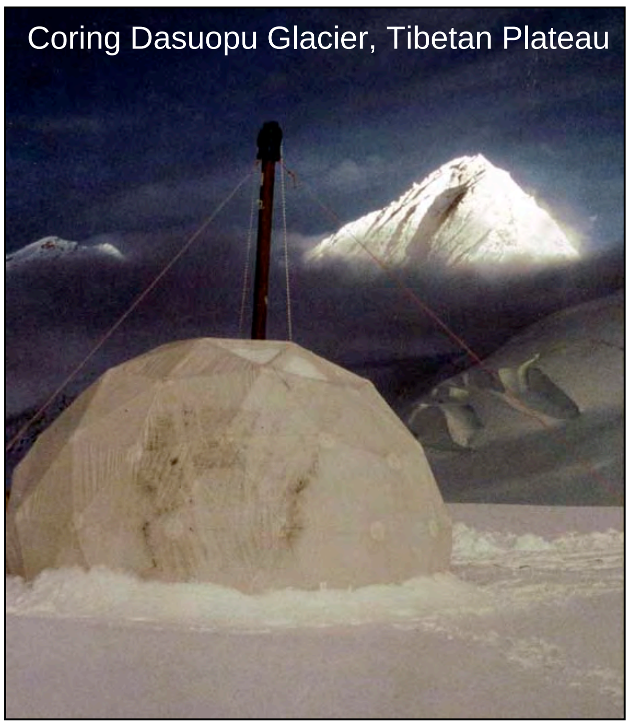
Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

Collecting Paleoclimatic Records is Hard Work

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

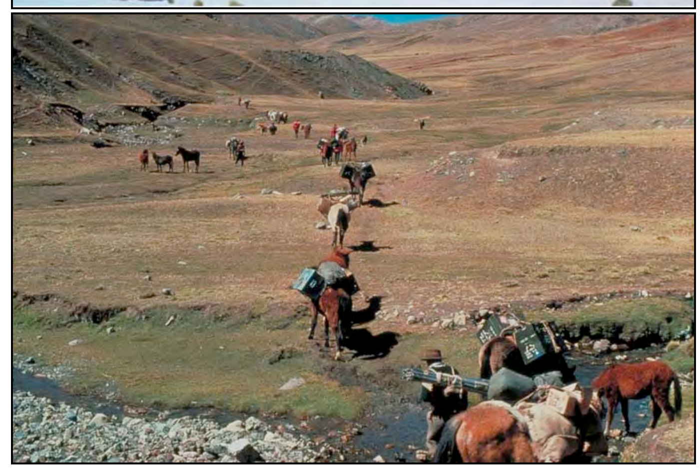
Collecting Paleoclimatic Records is Hard Work

http://researchnews.osu.edu/archive/dasuopupics.htm



Coring Dasuopu Glacier, Tibetan Plateau

Coring on Taylor Glacier



http://www.ncdc.noaa.gov/paleo/slides/slideset/index.html

http://hubpages.com/hub/Climate-change-resources--Fixing-Climate--A-review

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

Collecting Paleoclimatic Records is Hard Work

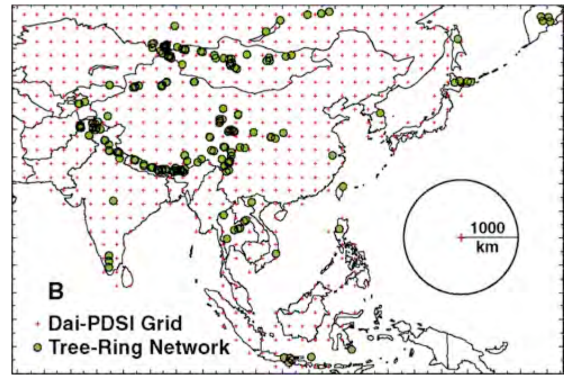
Tibet

http://www.ldeo.columbia.edu/res/fac/trl/staff/stafferc/erchome.html


Vietnam

http://www.ldeo.columbia.edu/~kja/photos.html

MADA: A 25-Country Effort



http://www.sciencemag.org/cgi/content/full/328/5977/486


1,000-year old Hemlock, Himalayas, Nepal

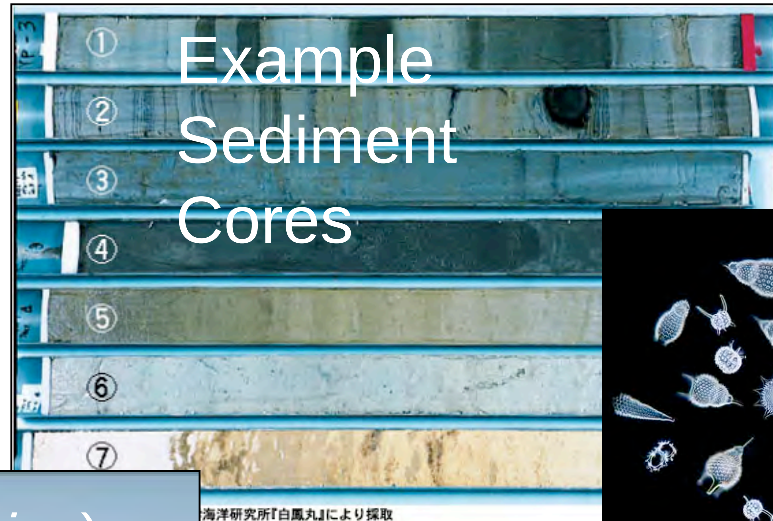
http://earth.columbia.edu/articles/view/2674


Coring a Spruce Tree in Japan

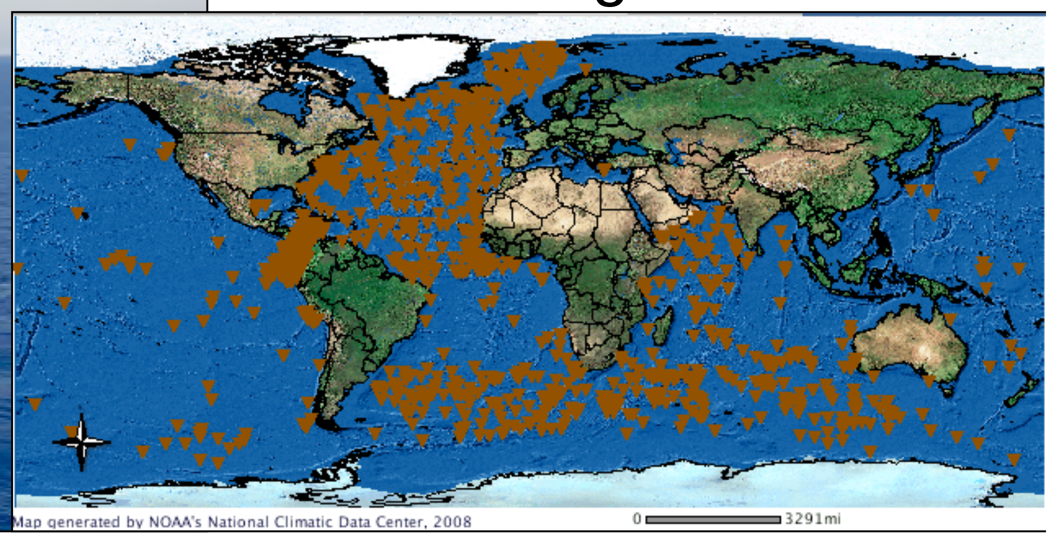
Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

Ocean Sediment Cores

- •Wide marine coverage
- •Extended temporal coverage (tens of millions of years)
- •Resolution: hundreds to thousands of years

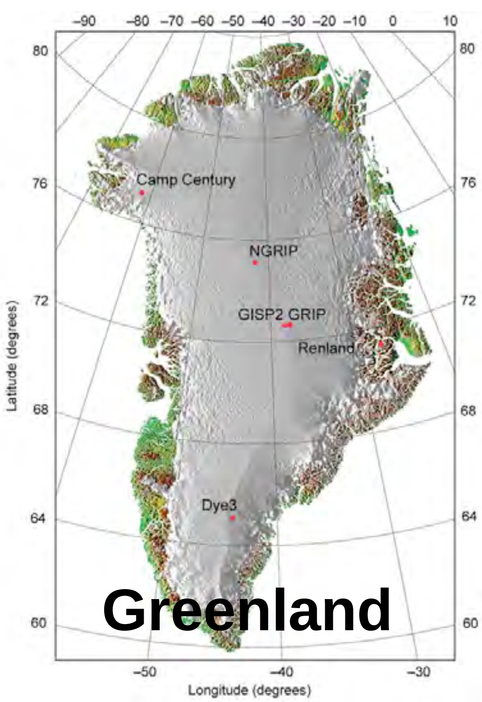


Ocean Drilling Locations



Ice Core Records

- Spatial coverage limited to regions with ice
- High resolution (years to decades) with hundreds of thousands of years of coverage
- Provide measurements of atmospheric constituents



Ice core storage at the National Ice Core Laboratory in Denver, Colorado.

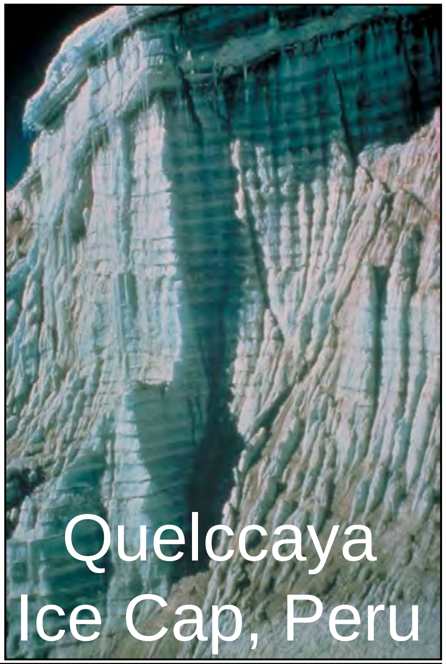
Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

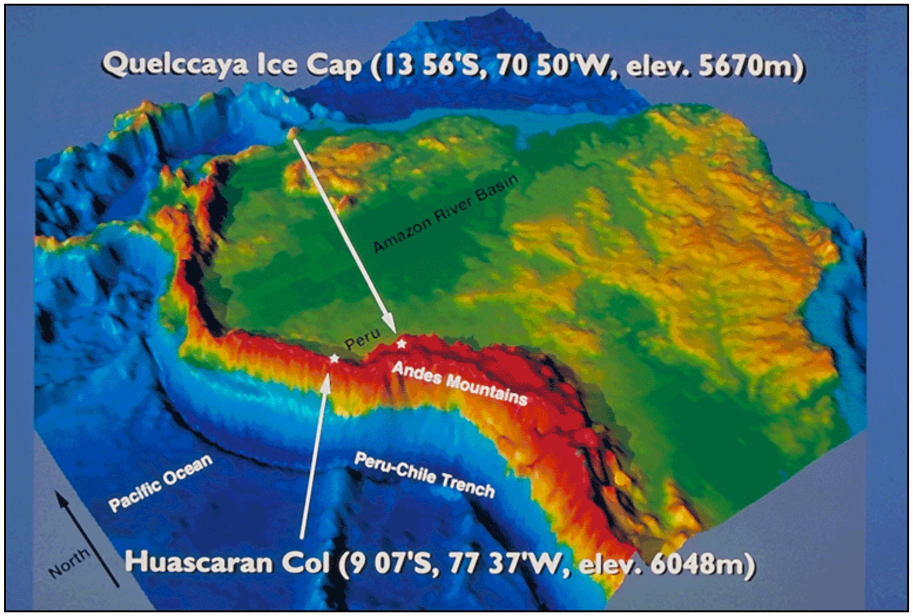
Continental Glaciers or Low-Latitude Ice Caps

•Provide the strength of the ice core method at low latitudes

•Data are difficult to retrieve

•Records are quickly melting

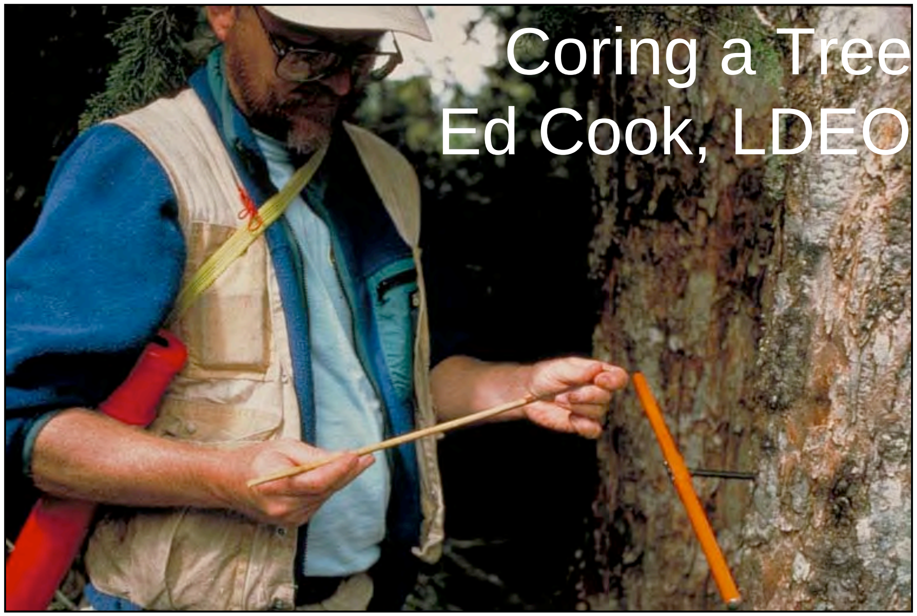


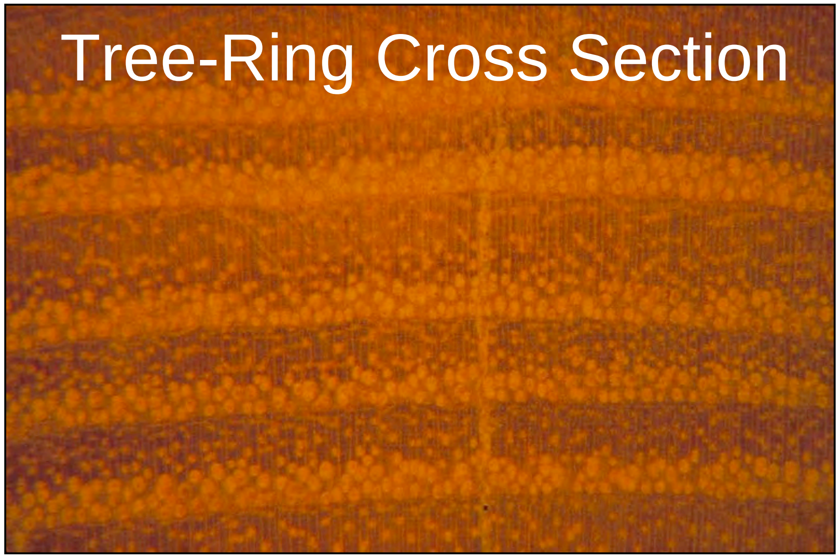


Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

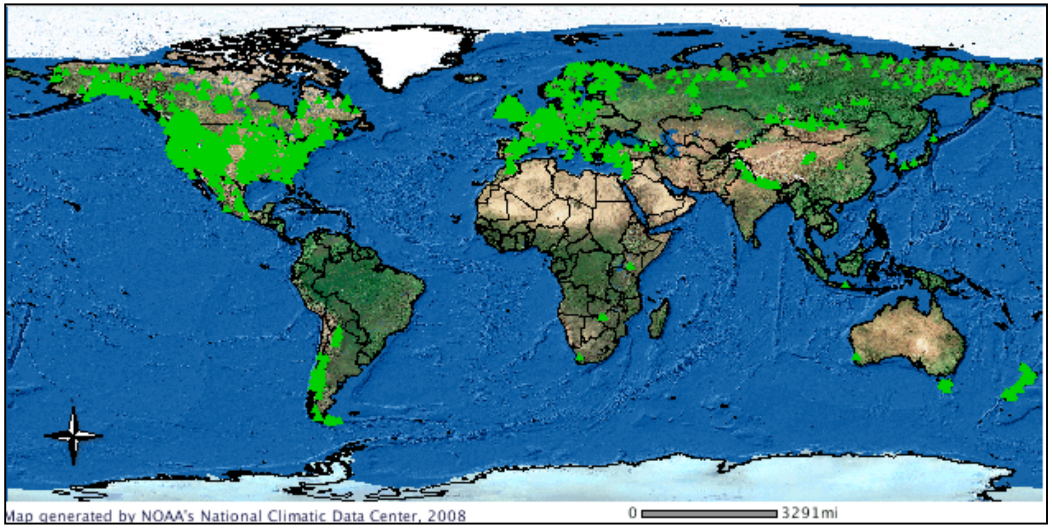
Tree Ring Records

- Wide spatial coverage on land
- Very high resolution (seasons to years) with thousands of years of coverage
- Used as both temperature, and hydrological indicators



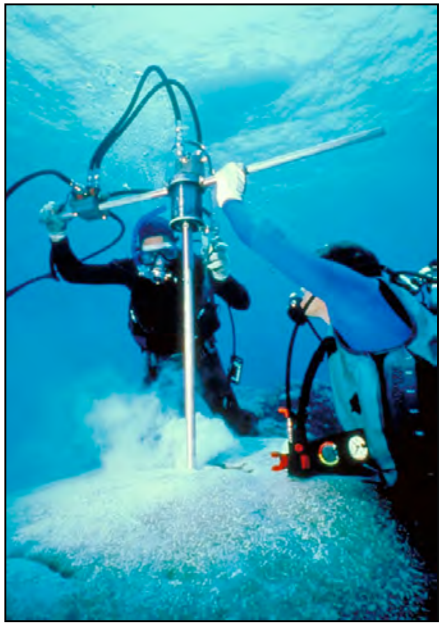


Tree-Ring Sampling Locations



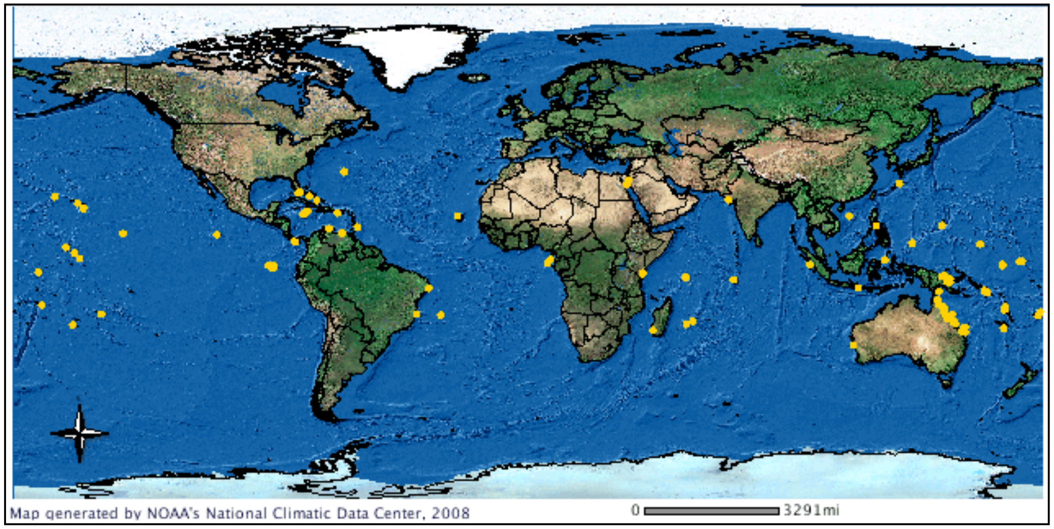
http://www.ncdc.noaa.gov/paleo/slides/slideset/index.html

Coral Records



- Provide important high-resolution coverage in the tropics
- Very high resolution (seasons to years) with thousands of years of coverage
- Used as both temperature and salinity (precipitation) indicators
- Interpretation can be complicated by combined temperature and salinity response

Coral Record Locations



http://www.ncdc.noaa.gov/paleo/slides/slideset/index.html

Paleoclimatic Uncertainties

http://climateprogress.org/2009/02/08/big-snake-titanoboa-nature-garden-of-eden-lindzen-thermostat-hypothesis/

Giant boid snake from the Palaeocene neotropics reveals hotter past equatorial temperatures
Head et al., *Nature*, 457, 715-717
5 February 2009

Biased reptilian palaeothermometer?
Sniderman, *Nature*, 460, E1-E2
30 July 2009

Re-calibrating the snake palaeothermometer
Makarieva et al., *Nature*, 460, E2-E3
30 July 2009

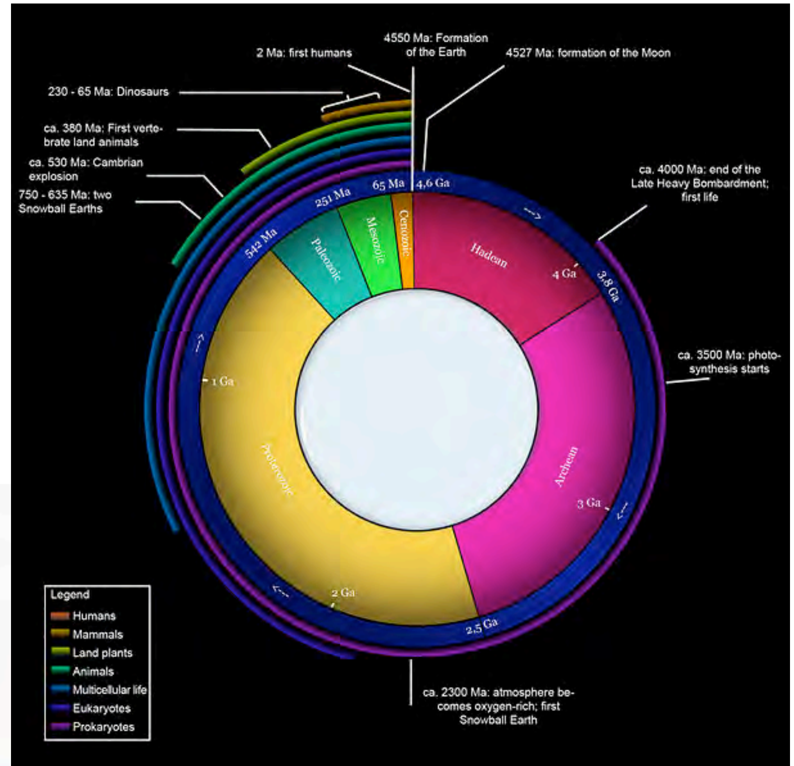
Can the giant snake predict palaeoclimate?
Denny et al., *Nature*, 460, E3-E4.
30 July 2009

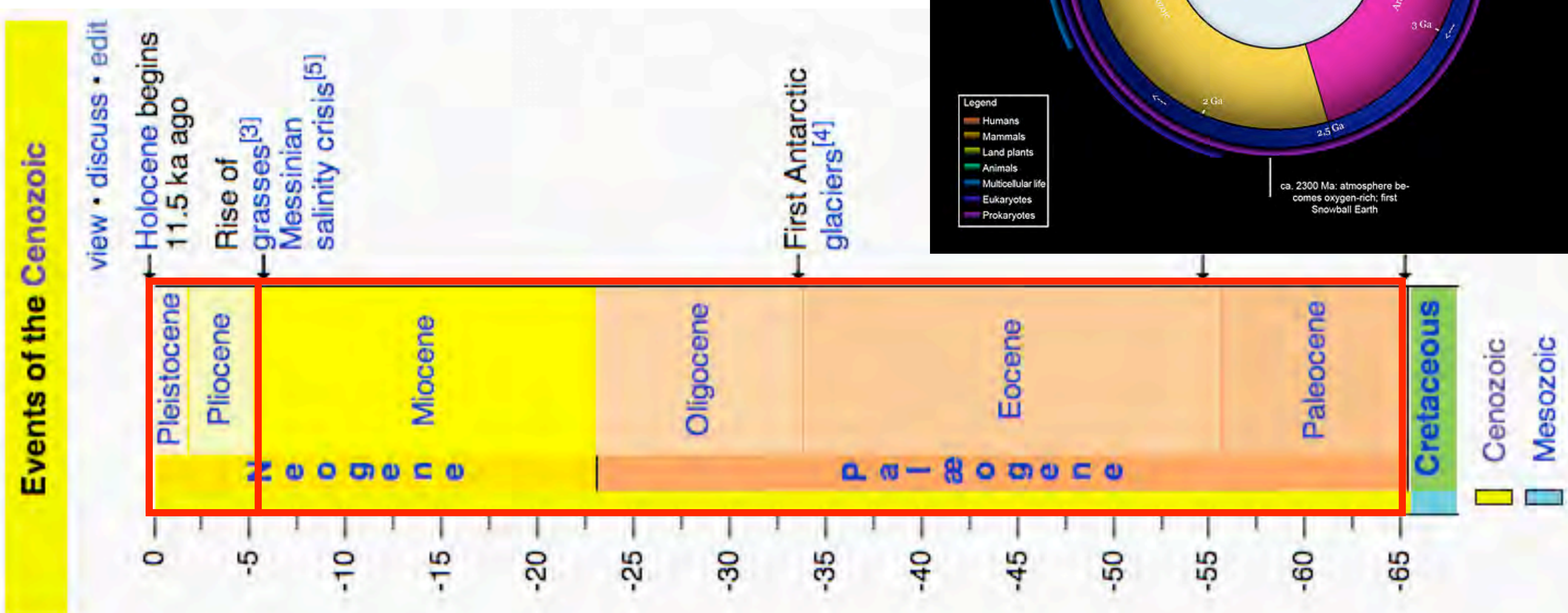
Paleoclimatic Uncertainties and Debates

- Paleoclimatic data are not direct measures of climatic variables. Calibration methods are therefore a principal area of research and debate (the proxy-climate connection).
- Agreement between multiple proxy estimates (your data say that, but my data say this).
- Agreement between proxy estimates and physical constraints (really? it was THAT cold in Walla Walla, Whichimacallit?)
- What were the mechanisms that caused the changes suggested by proxy evidence (often a modeler vs. data person fight)

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

Some Earth History Snap Shots

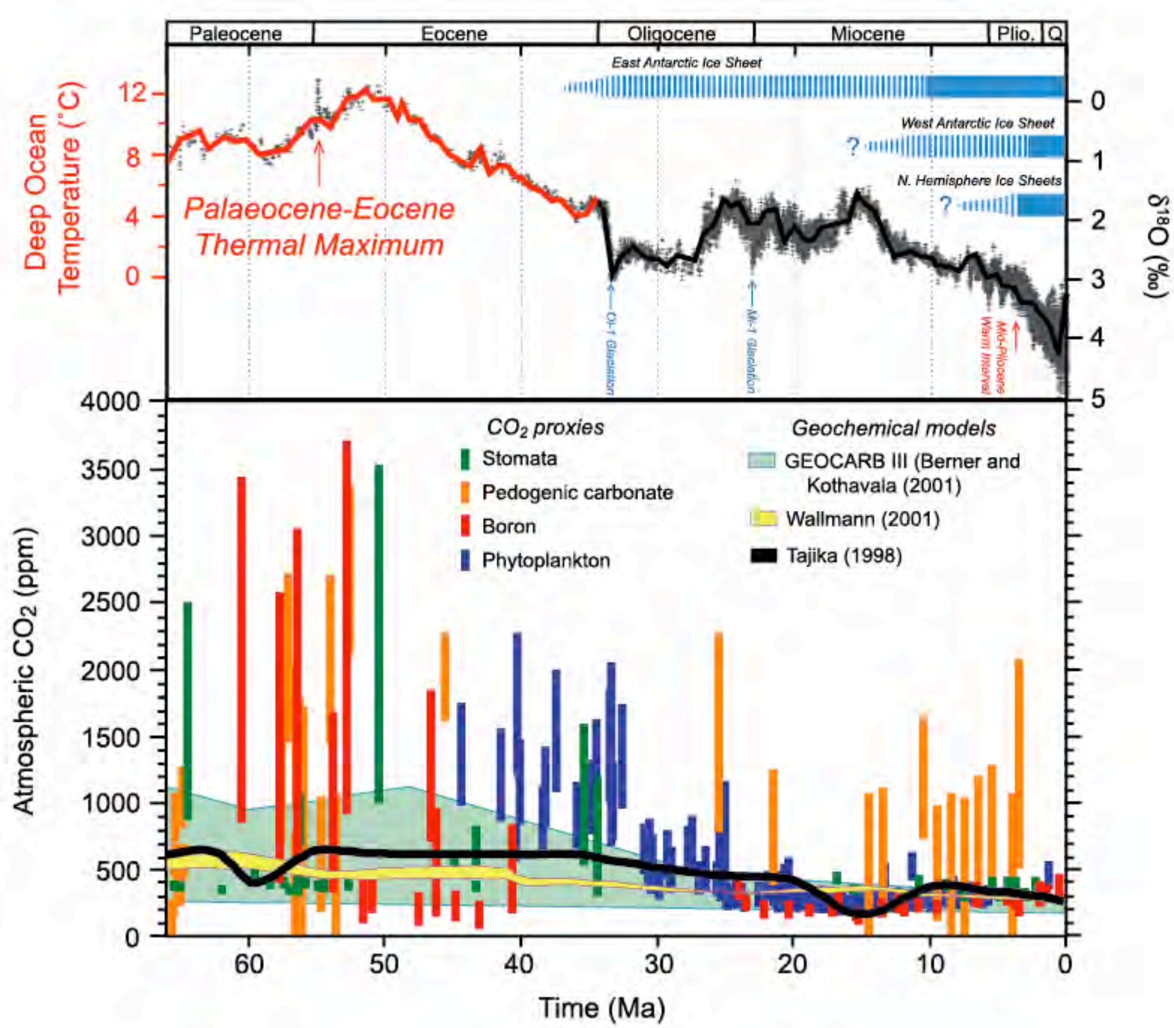




Millions of Years Before Present

http://en.wikipedia.org/wiki/Geologic_time_scale

Pre-Quaternary Climates



IPCC, AR4, Ch. 6, Figure 6.1

Past CO_2 levels have been much higher than the present day value (~390 ppm).

Temperature records also confirm much warmer periods of time, as well as periods of rapid temperature change.

Estimates of pre-ice core (later than about 1 million years ago) CO_2 levels are determined from three general methods that are more uncertain than ice-core derived estimates.

Pre-Quaternary Climates

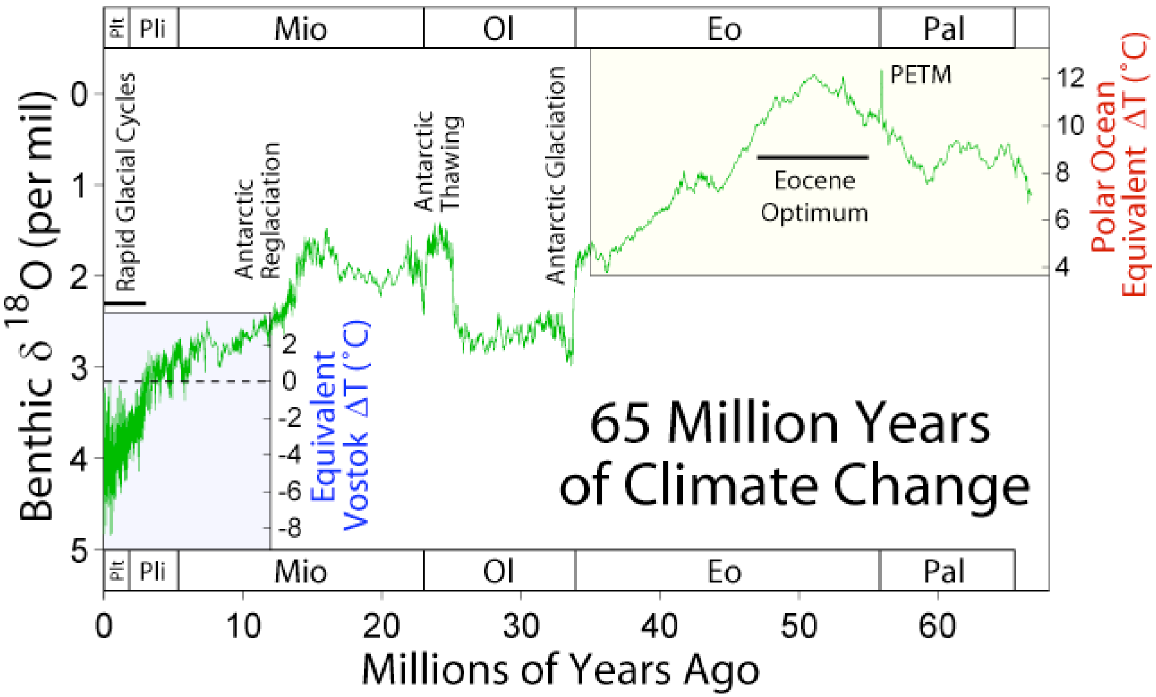
http://www.cbs.dtu.dk/staff/dave/roanoke/bio101ch19_c.htm

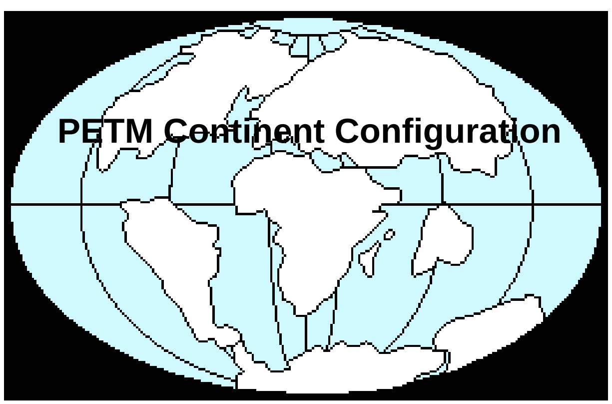
Past CO_2 levels have been much higher than the present day value (~390 ppm).

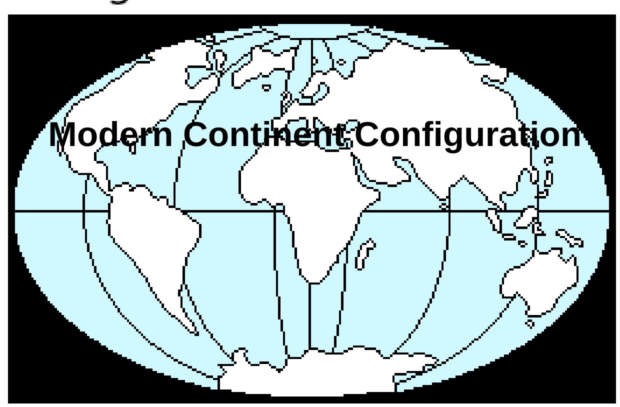
Temperature records also confirm much warmer periods of time, as well as periods of rapid temperature change.

Estimates of pre-ice core (later than about 1 million years ago) CO_2 levels are determined from three general methods that are more uncertain than ice-core derived estimates.

Paleocene-Eocene Thermal Maximum

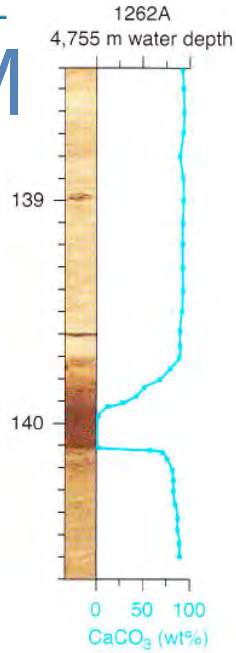






Paleocene-Eocene Thermal Maximum: A 6 ℃ rise in temperature over 20,000 years, with a corresponding rise in sea level as the whole of the oceans warmed. Around 1,500 to 2,000 gigatons of carbon were released into the ocean/atmosphere system over about 1,000 years. This rate of carbon addition is similar to the rate at which anthropogenic carbon is being released into the atmosphere today.

Some Consequences of the PETM



The climate was wetter, with more precipitation reaching the poles

Sea level rose

- No ice, but thermal expansion increased sea levels

Ocean Acidification

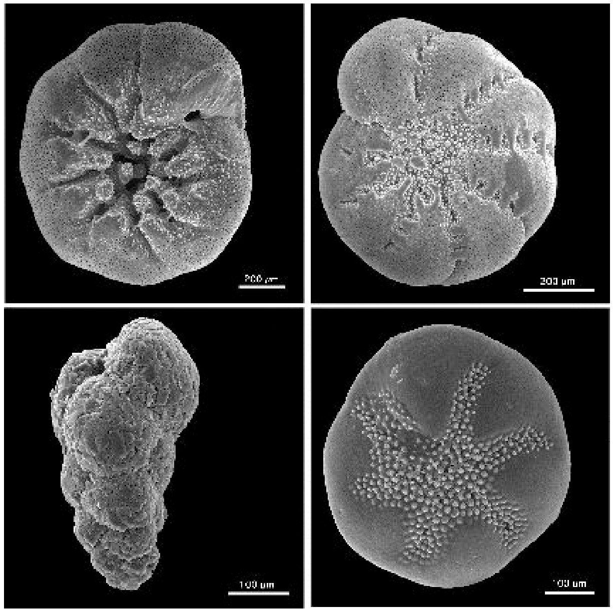
- Dissolution of deep water carbonates (cores reveal change from grey carbonated to red clays)

Mass Extinctions

- 35-50% of seafloor (benthic) forams disappeared over 1000 years

Some species benefited

- Mammals and planktonic forams



What Caused the PETM?

Total Carbon Release over 1000 years:

1500-4500 Gt(C)

✖ Comet-rich Impact

No strong evidence of such an event

✖ Volcanic Activity

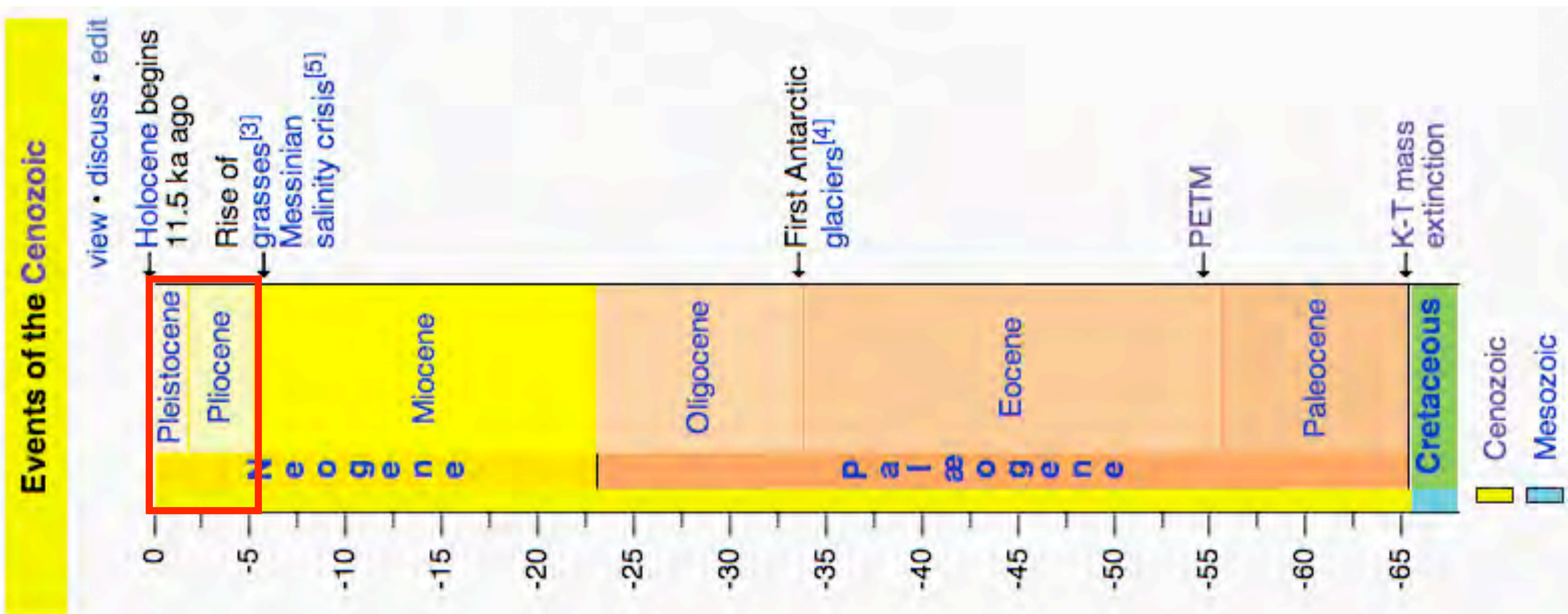
Would require 200 times the level of background activity

✖ Peat Burning

But more than 90% of the biomass on Earth would have to burn

✔ Methane Release

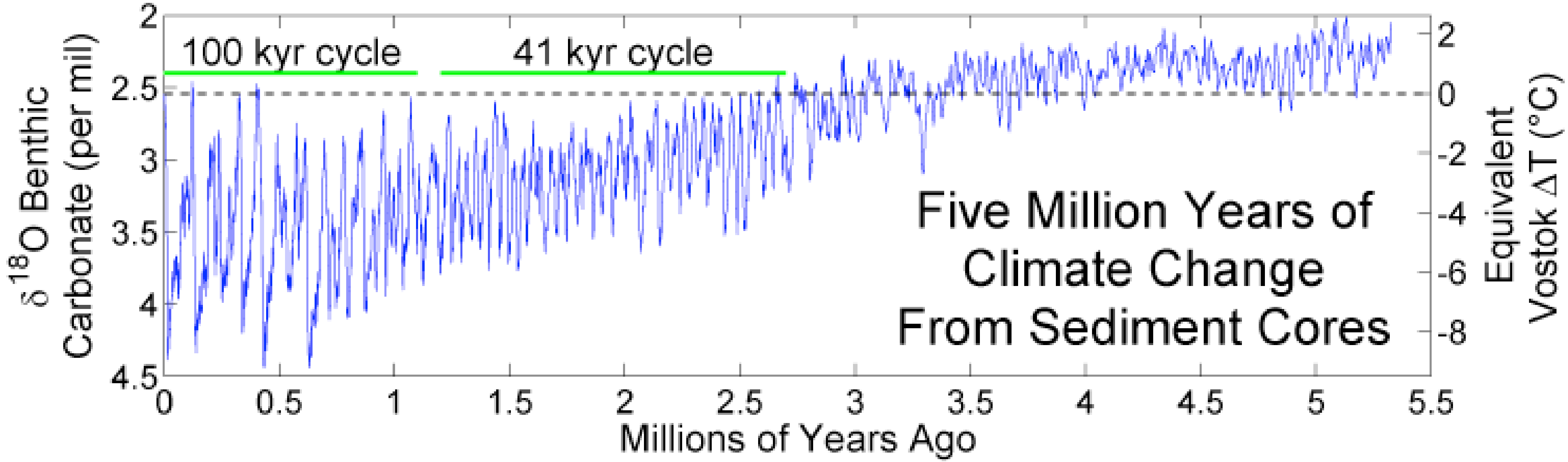
The Geologic Time Scale



Millions of Years Before Present

http://en.wikipedia.org/wiki/Geologic_time_scale

The Beginning of the Ice Age

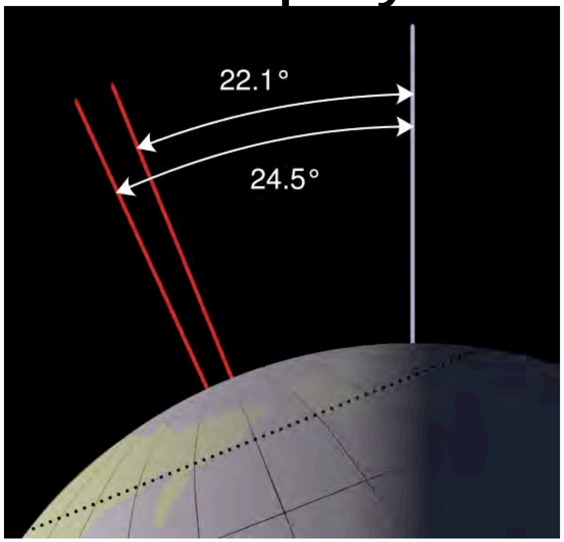


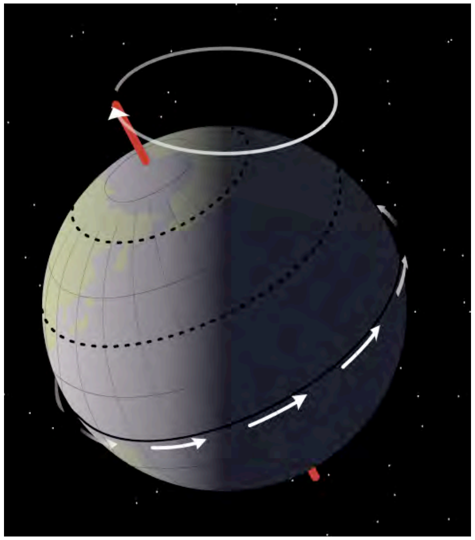
http://en.wikipedia.org/wiki/Ice_age

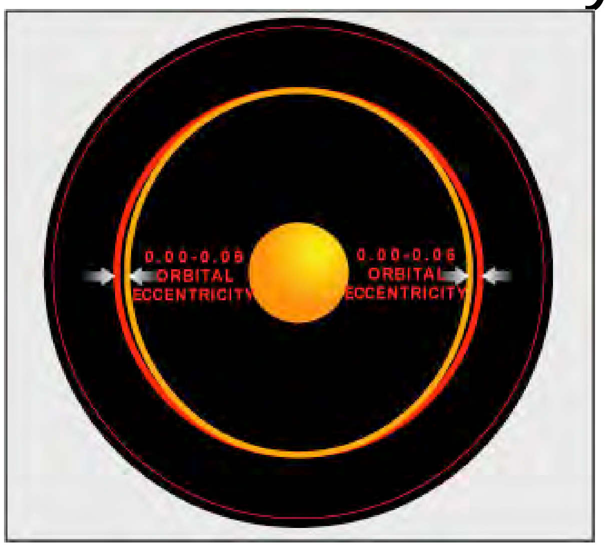
Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

Changes in Earth's Orientation and Orbit

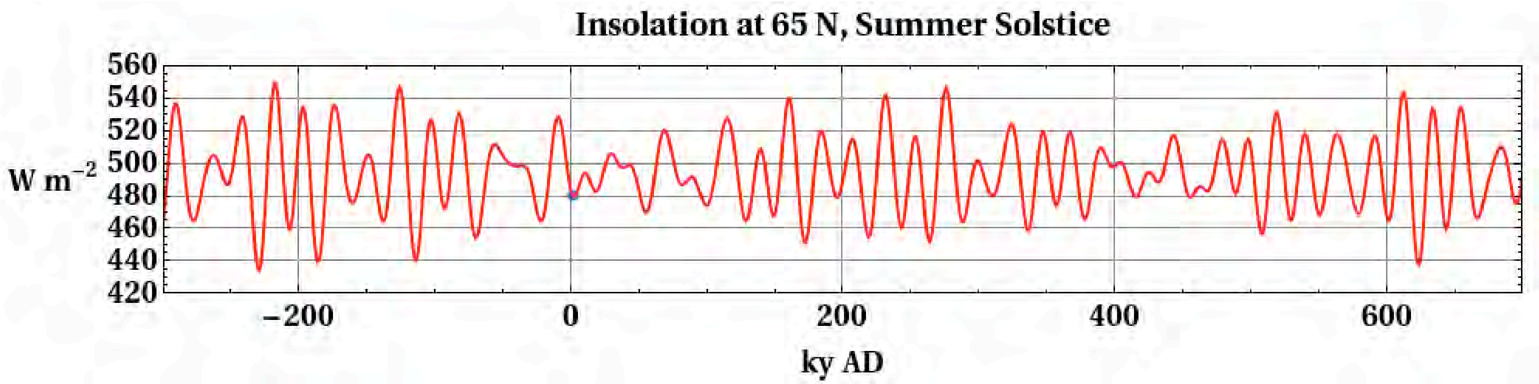
Obliquity Precession Orbital Eccentricity







http://en.wikipedia.org/wiki/Milankovitch_cycles http://www.koshland-science-museum.org/exhibitgcc/causes08.jsp

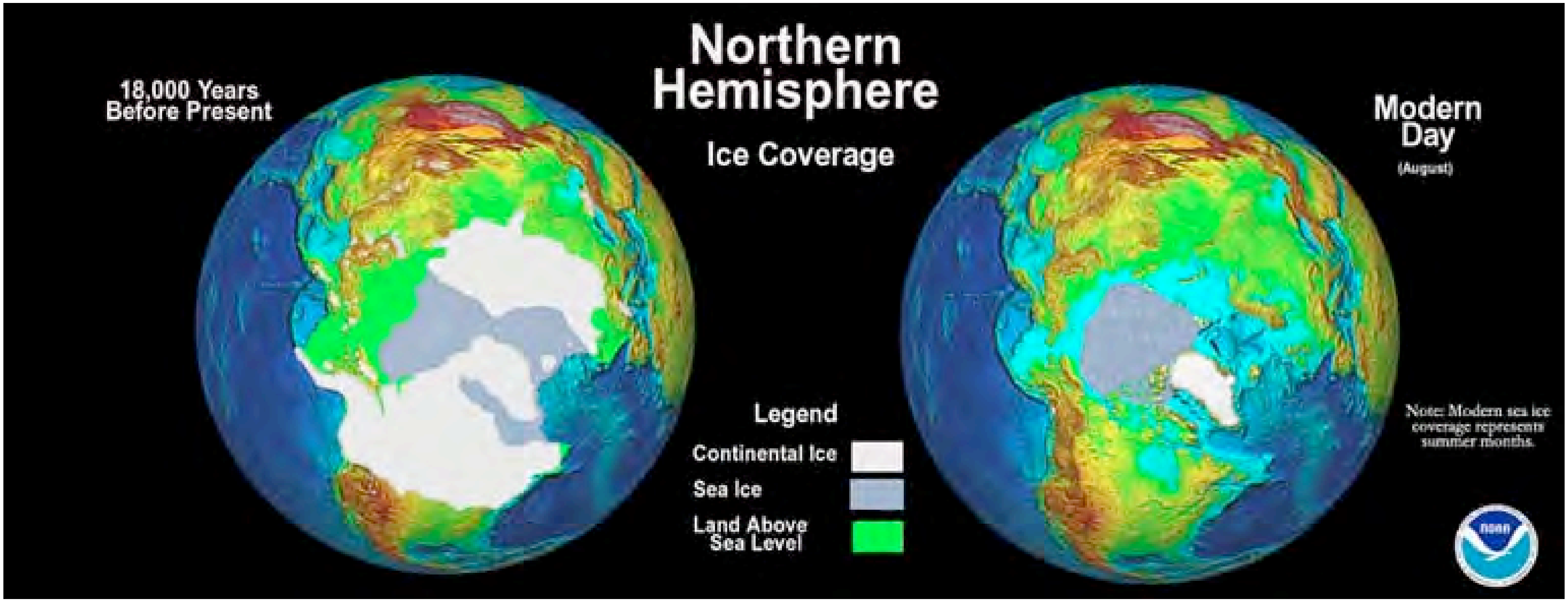


Glacial Cycles

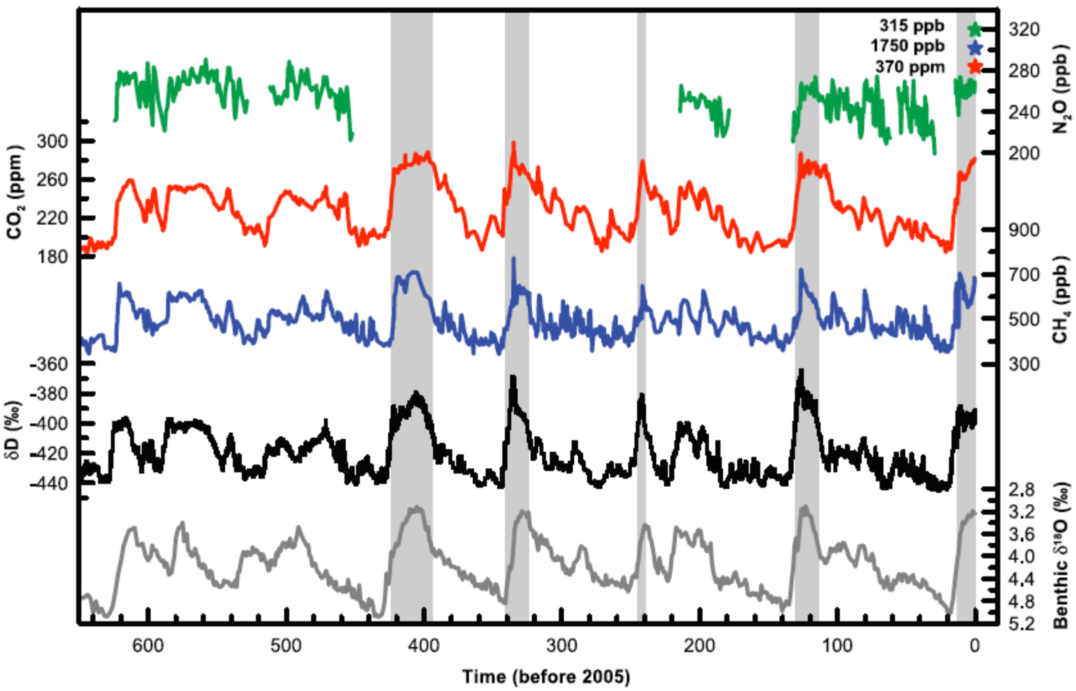
The *last glacial maximum* was about 20 thousand years ago, with a global mean temperature of about 4°C lower than today.

Land areas surrounding the North Pole were covered with thick *ice sheets* that in some regions reached a height of about 2.5 km above sea level. In North America, ice sheets covered the Great Lakes and reached the latitude of NYC.

The combined effect of NH and SH glaciation on sea level was about a 130 m lowering, relative to present day.



Antarctic Ice Cores



IPCC, AR4, 2007

In general, rates of temperature and CO_2 increases likely exceed those seen during the last 600 ky.

Ice cores reveal cycles of cold and warm climate. The warm (interglacial) intervals are separated by about 100,000 years. Other proxies taken in other locations show that these cycles were of global extent.

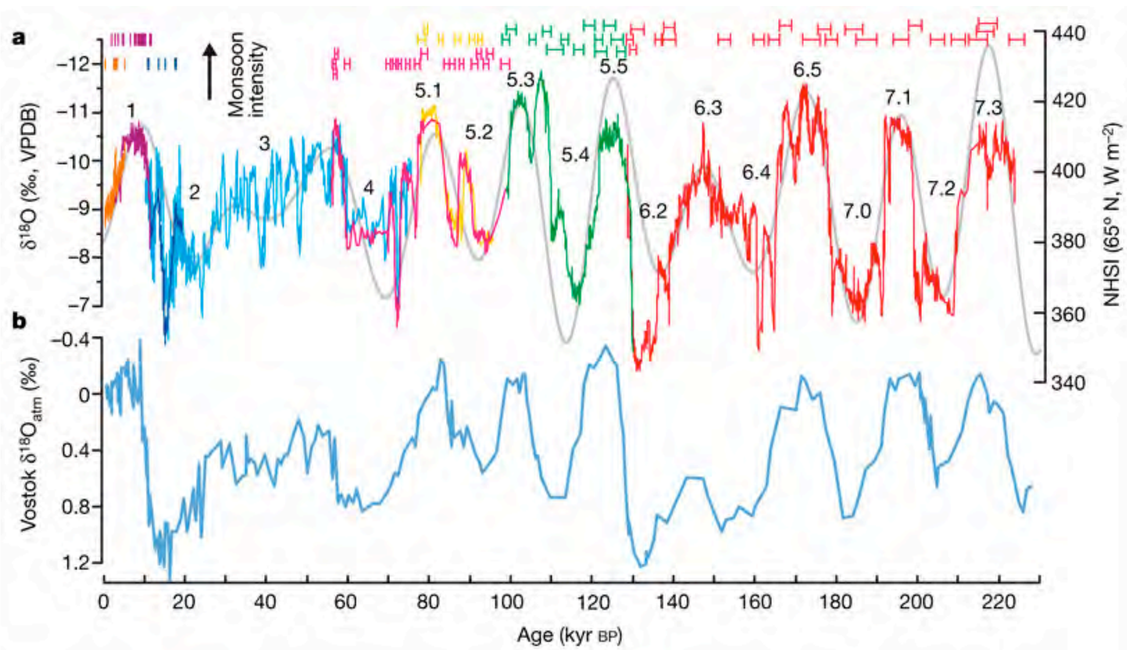
Temperature and CO_2 march in lock step, but it is difficult to tell from most records which one leads or lags.

Temperatures in the past have exceeded present day temperatures at Vostok, but not by much.

Present-day CO_2 concentrations exceed concentrations any time during the last approximately 600,000 years.

Ice Cores and Speleothems:
A Love Story

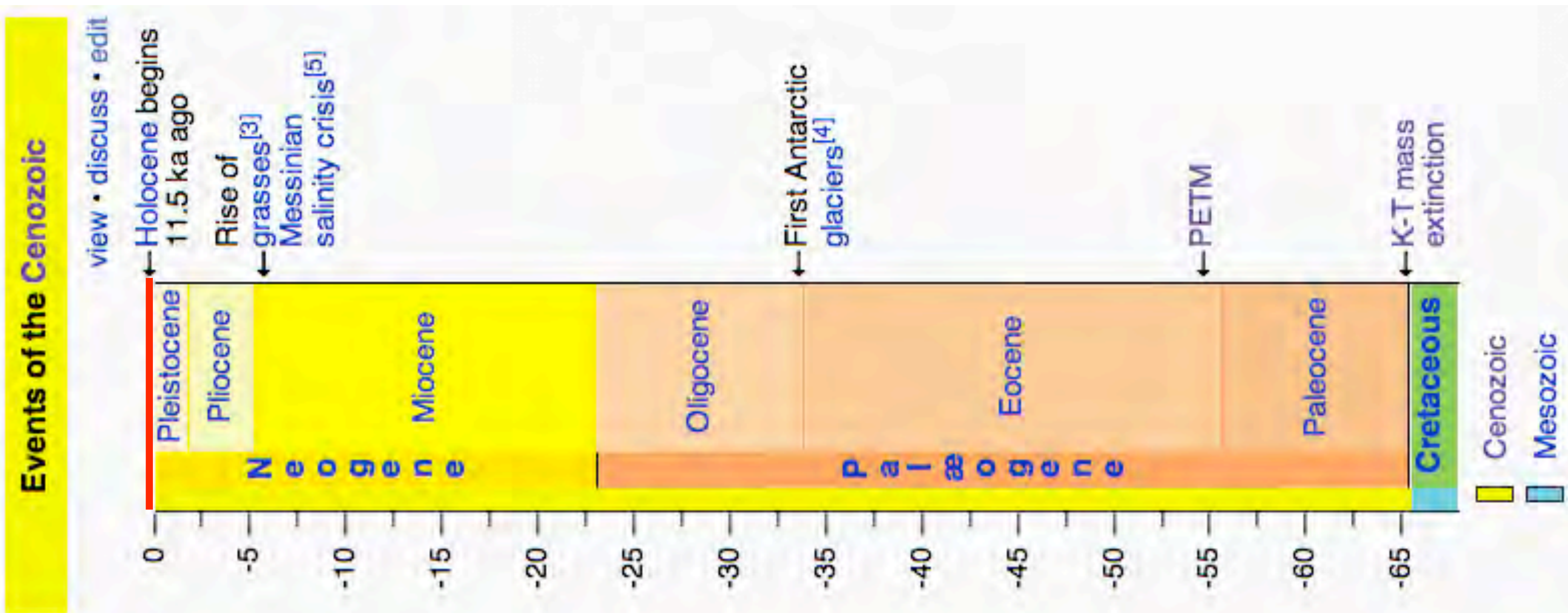
Wang et al., *Nature*, 451, 1090-1093 (28 February 2008)



http://www.nature.com/nature/journal/v451/n7182/full/nature06692.html

http://www.bgs.ac.uk/nigl/Climate_RatesChange.html

The Geologic Time Scale



Millions of Years Before Present

http://en.wikipedia.org/wiki/Geologic_time_scale

What is Important about the Climate of the Common Era

- Proxies are abundant enough during the last few millennia to provide information about spatial variability of climate
- Climate dynamics can be studied with millennial climate reconstructions
- Climate reconstructions provide estimates of climate sensitivity and validation fields for General Circulation Models
- Many human civilizations evolved during the last several millennia and responded to climatic changes during this time

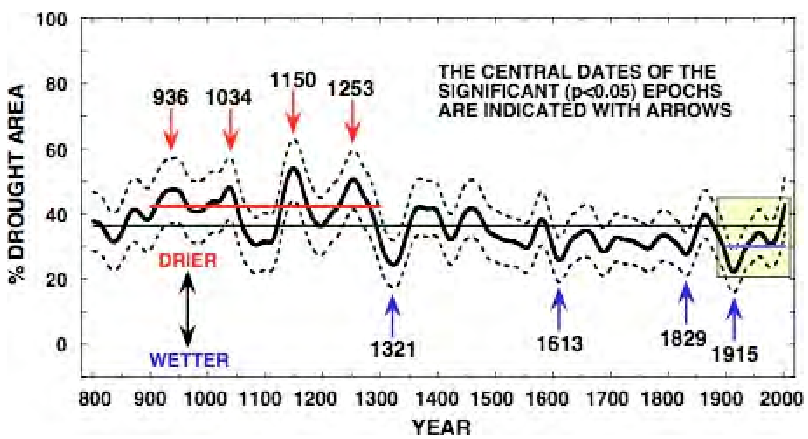
Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

Climate Transitions During the Common Era: The MCA and LIA

Medieval Climate Anomaly

Pueblo Bonito, Chaco Canyon

Temple of the Jaguar, Tikal



Long-Term Aridity Changes in the Western United States, Cook, E.R. et al., *Science, 306,* 1015, (2004)

Little Ice Age

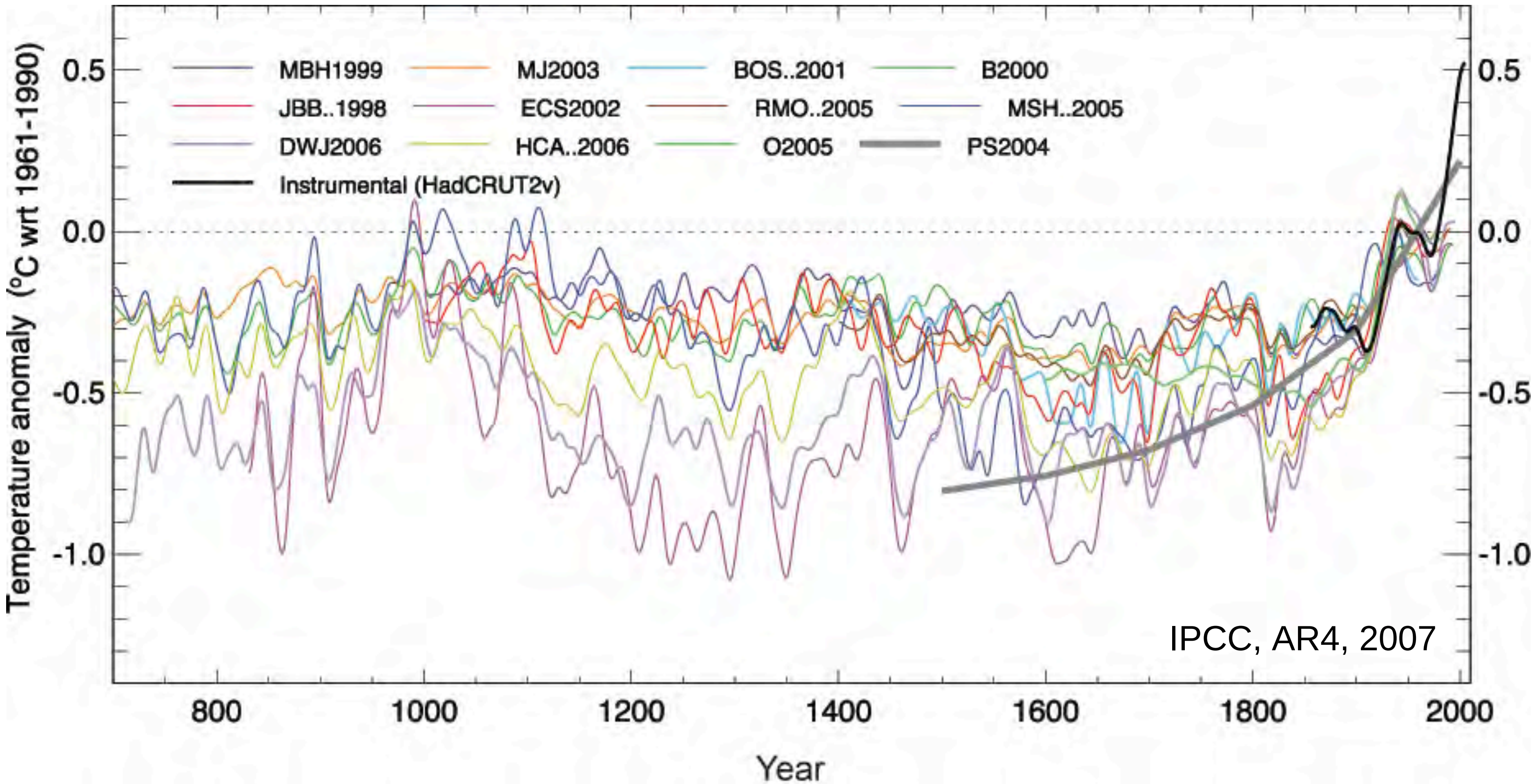
Norse Collapse during the LIA

Hvalsey Church Ruins, Greenland

A Frost Fair on the Thames at Temple Stairs,
by Abraham Hondius, 1684

During the Little Ice Age, average temperatures in Europe were 1-2 ℃ colder than they are today. The period was marked by advancing glaciers that literally invaded many mountain villages. This period was also marked by many livestock deaths, failed harvests, famine and disease.

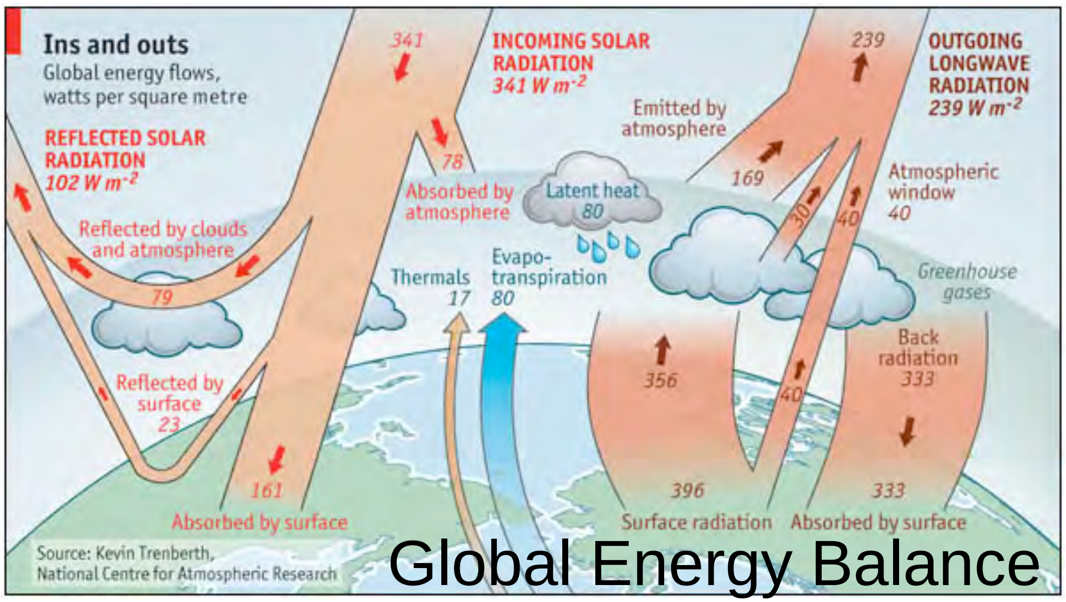
Evolving Estimates of Climate Change During the Common Era (N. Hem.)



How do you change climate?

In equilibrium, the amount of energy the Earth receives from the Sun must be equal to the amount it returns to space.

When one of the components that govern this energy balance changes, the planet must either heat up or cool down to reestablish a balanced energy budget.



Global Energy Balance

The clouds of unknowing, *The Economist*, Mar 18th 2010
http://www.economist.com/displaystory.cfm?story_id=15719298

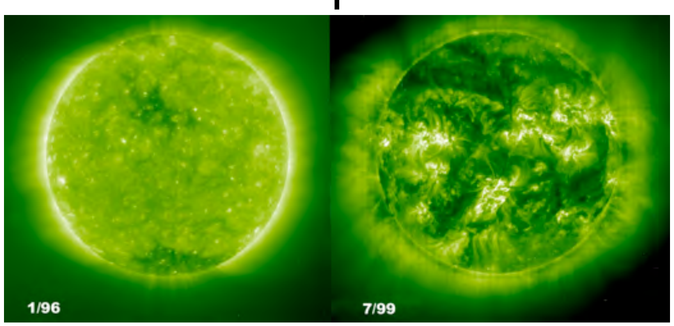
Solar Luminosity Variations

The most notable variability is the 11-year sunspot cycle that has a peak-to-peak variability of about 2 W m^{-2}, or about 0.1-0.2% of the Sun's irradiance

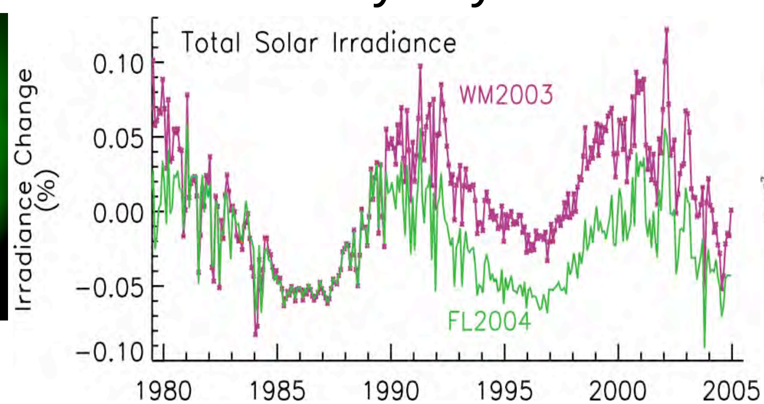
Sunspots are dark but are surrounded by bright faculae that cover a large area. The sun is brightest at the peak of a sunspot cycle

Solar luminosity variations that are longer than the 11-yr cycle are known to exist, but are not well understood. The magnitude of these variations are also hotly debated, but are known to impact climate on secular time scales.

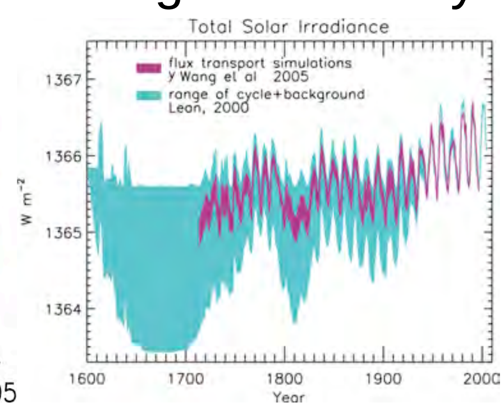
Sunspots



11-yr Cylce

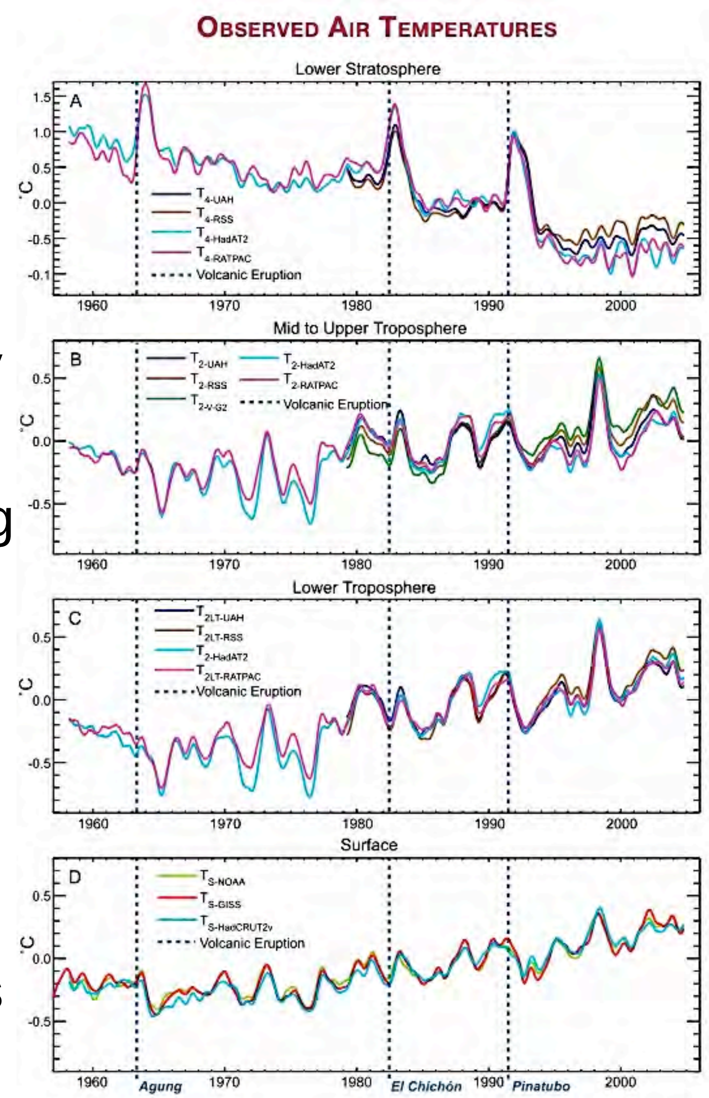


Longer Variability



Volcanic Eruptions

- Large volcanic eruptions introduce sulfate aerosols into the stratosphere where they stay for months to years.
- Small particles are formed when sulfur-bearing gases (e.g. SO_2) are injected into stratosphere, photochemical reactions form small sulfuric acid (H_2SO_4) droplets that then condense to form sulphate particles that reflect/scatter light.
- Under these conditions, volcanic aerosols reflect sunlight for several years. The aerosols raise temperatures in the stratosphere and reduce them in the troposphere.



IPCC, AR4, 2007.

Changes in Atmospheric Carbon

Carbon resides in different reservoirs within the Earth System

The vast majority (more than 99.9%) of the carbon near the Earth surface is in rocks.

The rock reservoir amounts to approximately 50 million Gt(C)

CO_2 and methane in the atmosphere have changed throughout Earth history. Principal natural causes of changes in these gases include:

Ocean uptake and release

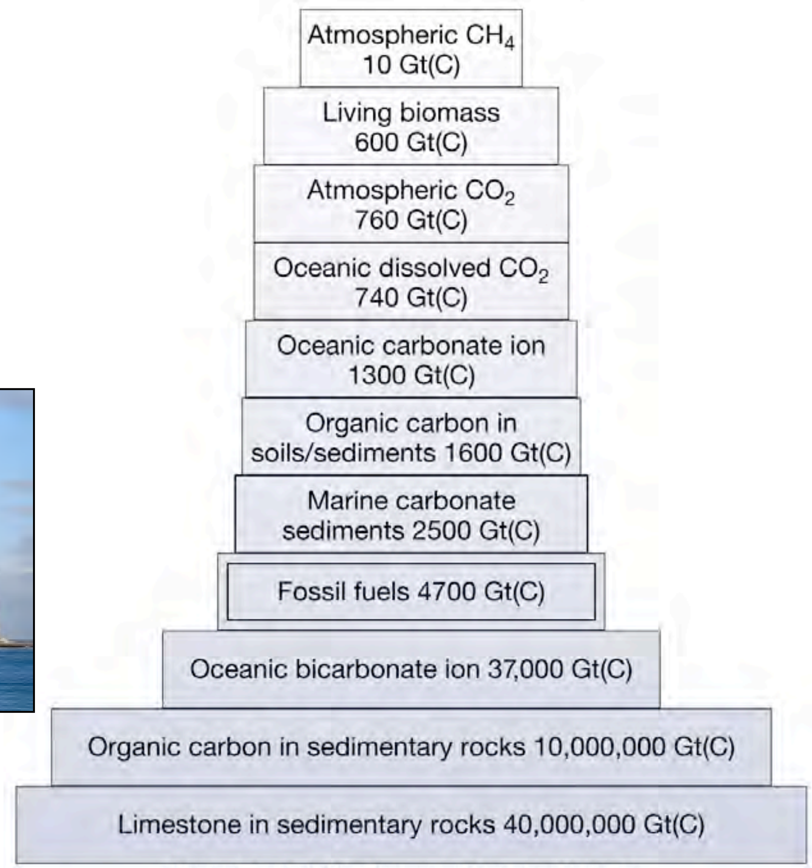
Geologic weathering

Volcanic activity

Methane hydrate storage and release

Biological activity

Total Anthropogenic Emissions from Fossil Fuel Burning in 2005:
~29 Gt(C)



Climate Feedbacks and Climate Sensitivity

Characterizing climate feedbacks are an important function of paleoclimatic studies. Some feedbacks are as follows:

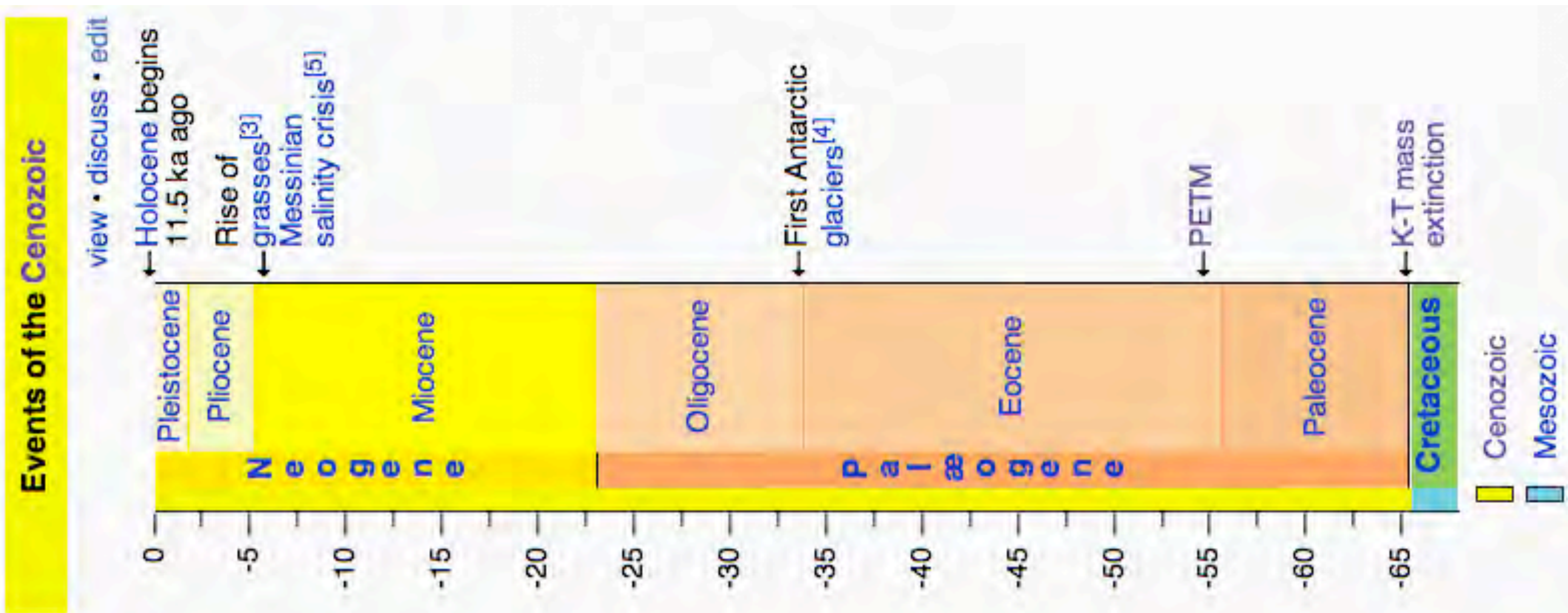
Ice-Albedo Feedback: as ice grows in the high latitudes, local and global albedo increases, more solar radiation is reflected to space and the Earth cools further.

Greenhouse Gas Feedback: Ice core records indicate that cooling and warming of the climate have been enhanced by the greenhouse effect. Possible causes for this feedback are changes in ocean uptake of CO_2 in colder climate and release of Methane and CO_2 from land surfaces exposed during glacier retreat.

Cloud Feedbacks: clouds can warm or cool the climate by either trapping more heat near the surface or reflecting more radiation back to space.

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

The Geologic Time Scale



Millions of Years Before Present

The End of an Epoch

The Anthropocene

An•thro•po•cene |ˈan θ rəpəˌsen|:

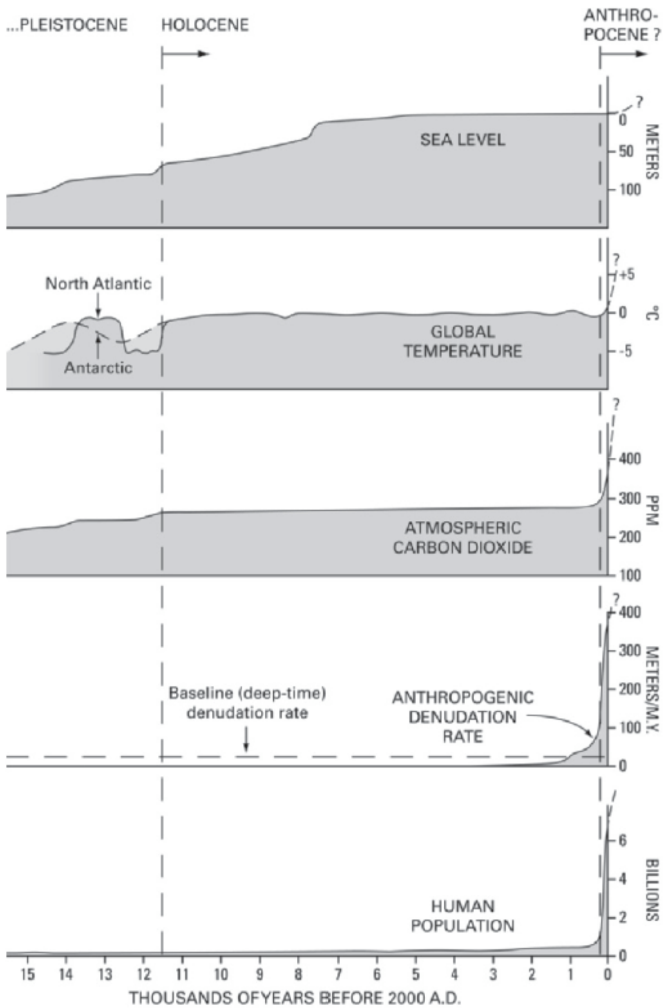
noun

The current geologic age, viewed as having begun 200 years ago with the significant impact of human activity on the ecosphere

Etymology: 2000 by chemist Paul Crutzen; Gk *anthropos* 'human' and *kainos* 'recent'

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

Stratigraphy Commission of the Geological Society of London (2008):



Sea-level changes are subject to uncertainty, but may ultimately be on the order of several tens of meters per 1 ℃ of temperature rise.

Carbon dioxide levels are a third higher than in pre-industrial times and at any time in the past 900,000 years.

Global temperature is predicted to rise by 1.1-6.4 ℃ by the end of the 21st century, leading to global temperatures not encountered since the Tertiary.

In the last 150 years humankind has exhausted 40% of the known oil reserves that took several hundred million years to generate.

Nearly 50% of the land surface has been transformed by direct human action.

Zalasiewicz, J. et al., 2008: Are we now living in the Anthropocene?, *GSA Today*, 18(2), doi:10.1130/GSAT01802A.1.

Stratigraphy Commission of the Geological Society of London (2008):

"Sufficient evidence has emerged of stratigraphically significant change (both elapsed and imminent) for recognition of the Anthropocene - currently a vivid yet informal metaphor of global environmental change - as a new geological epoch to be considered for formalization by international discussion."

Zalasiewicz, J. et al., 2008: Are we now living in the Anthropocene?, *GSA Today*, 18(2), doi:10.1130/GSAT01802A.1.

Summary

Paleoclimatology provides important insights into the dynamics of climate variability and the magnitude of past changes.

Temperature and greenhouse gas concentrations have been much larger in the past than they are during the present day. The world was much different during these times.

Rates of present-day temperature and CO_2 changes likely rival most rates of previous change.

While it is difficult to assign a “lead or lag” relationship between temperature and CO_2, the paleoclimatic record shows an unambiguous association between them over many different time scales.