QUATERNARY HISTORY

E. A. Oches
Department of Natural and Applied Sciences, Bentley College, 175 Forest St., Waltham, MA, USA

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Summary

The Quaternary Period covers the last two and a half million years of Earth history and is best known as the period of the ice ages. The Quaternary is characterized by repeated cycles of cold – warm climatic oscillations as the Earth alternated between glacial and interglacial modes. Associated with the climatic fluctuations and advancing and retreating continental ice sheets was the dramatic response of biota, rivers, lakes, oceans, and other natural systems. More than 30 glacial-interglacial cycles are recorded in deep-sea sediment records spanning the last 2.6 myr. Ice-core records, extending as much as 800,000 years into the past, have been used to reconstruct past temperatures, aridity, and greenhouse gas composition of the atmosphere. During glacial periods, Earth surface temperatures were probably 10 degrees Celsius colder in middle latitudes and 5 degrees C cooler in the tropics. Atmospheric circulation intensified, driven by the

increased equator to pole temperature gradient, and arid regions of the globe expanded. The transition to warm climates was relatively rapid, with interglacial periods lasting only around 10,000 years, compared with the gradual cooling trend into full glacial conditions, occurring over approximately 90,000 years.

Glacial – interglacial climate changes during the Quaternary were largely controlled by cyclic variations in the amount of solar radiation, or insolation, received in middle to high latitudes of the northern hemisphere. The "pacemaker of the ice ages", as it has been called, is driven by variations in Earth's orbital elements, including the path around the sun, the tilt of Earth's axis, and precession of the equinoxes. Superimposed on the longer glacial-interglacial cycles were much shorter periods of rapid, extreme shifts in climate, probably due to complex interactions between the ocean and atmosphere. The exact mechanisms of Quaternary climate change continue to challenge scientists and will remain the focus of active research for many years to come.

1. Introduction

1.1. Definition of the Quaternary Period

Approximately 40 million years ago, Earth's climate began a long cooling trend, culminating in the cyclic glacial-interglacial oscillations that characterize the Quaternary Period of recent Earth History. The Tertiary – Quaternary boundary was defined by the 1948 International Geological Congress as the base of the Calabrian marine sediments at Vrica, Italy. This interval contains fossils, including the foraminifer *Hyalinea baltica*, that reflect the first distinct climatic cooling in the Mediterranean region and coincides with the top of the Olduvai paleomagnetic subchron, which is dated at about 1.8 Ma B.P. Recent proposals by the International Commission on Stratigraphy leave its formal status uncertain, although the International Union for Quaternary Research (INQUA) recommends that the Quaternary remain formally defined as a Period within the Geologic Time Scale, the base of which should be placed at 2.6 Ma.

Unique in Earth History, the Quaternary is an interval of frequent measurable and dramatic changes in climate, environment, and human physical and cultural evolution. It includes the past 2.6 million years, with repeated advances and retreats of continental ice sheets, the corresponding fall and rise in sea level, and the response of flora, fauna, rivers, and other natural systems to major climatic and environmental disturbances. Hominids initially emerged from Africa, bringing fire and tool-making technology first to Eurasia, then spreading across the globe, giving rise to the genus *Homo*, and finally to anatomically modern humans during this time period. The Quaternary also includes the present, where humans are acting as significant agents of atmospheric, geomorphic, and biological changes. It includes the future, in which predictions of the effects of our activities forecast climatic and environmental shifts and rates of change that are unprecedented in Earth history. In our efforts to foretell Earth's future climate and recognize the natural background against which possible anthropogenic disturbances are measured, the climate of the Quaternary has been the focus of extensive investigation over the past several decades.

The Quaternary Period includes the Pleistocene and Holocene Epochs, corresponding to the "period of the ice ages" and the "recent", respectively. The Pleistocene Epoch is divided into the Early Pleistocene, from 1.8 Ma to the Brunhes/Matuyama paleomagnetic reversal at 0.79 Ma B.P., the Middle Pleistocene, from 0.79 Ma B.P. to the beginning of the last interglacial period at about 130 ka B.P., and the Late Pleistocene, from the last interglacial to the beginning of the present interglacial, or Holocene Epoch at about 10 000 years ago. Recently the Pleistocene–Holocene boundary has been proposed at 11.5 ka, corresponding to an abrupt change from glacial to interglacial temperatures recorded in ice cores recovered from the Greenland Ice Sheet.

The Holocene Epoch, beginning about 11,500 years ago, is the period of the present interglaciation. Although Holocene climate has been considerably less variable than during the preceding glacial interval, it has been informally subdivided according to broad climatic shifts recognizable in different regions of the world. Based on floral, faunal, and sedimentary records, the Holocene has been traditionally divided into the Preboreal (11.5 – 10.1 ka), Boreal (10.1 – 9 ka), Atlantic (9 – 5.7 ka), Subboreal (5.7 – 2.5 ka), and Subatlantic (2.5 ka – present) zones. Other recognized intervals within the Holocene include the Climatic Optimum (ca. 9 – 5 ka), the Medieval Warm Period (ca. 800 – 1300 C.E.) and the Little Ice Age (ca. 1350 – 1850 C.E.).

Some scientists have recently suggested an additional epoch, the Anthropocene, beginning in the middle of the eighteenth century, to acknowledge the time of the most dramatic influence of humans on Earth systems.

1.2. Onset of Northern Hemisphere Glaciation

In many regions of the world, sedimentary records document widespread glaciation, major cooling, and the loss of thermophilous (warmth-loving) floral remains at about 2.5-2.7 million years ago. Major northern hemisphere ice sheet growth is indicated by increases in the oxygen-isotope composition of benthic (bottom dwelling) foraminifers around 3.1 – 2.5 Ma B.P. Ice-rafted detritus (IRD) appears abruptly in sediments of northern hemisphere high latitude oceans at about 2.7 Ma B.P. Glacial deposits on land suggest that continental glaciation became significant in the northern hemisphere by about 2.5 Ma B.P. Loess, a wind-blown sediment associated with glacial climates, began accumulating in China by at least 2.5 Ma B.P., and Pacific Ocean sediment cores record the eolian (wind-blown) transport of dust from China as early as 2.6 Ma B.P. In Alaska, loess deposited as early as 3.0 Ma B.P. has been identified, although it is unclear whether it is associated with continental glaciation or more restricted mountain glaciers in the region. Fossil pollen records of past vegetation from the western U.S. indicate warmer and wetter conditions about 4.8 – 2.5 Ma B.P., with cooler and more arid climate indicated after 2.5 Ma B.P. Similar pollen and faunal-based climatic inferences come from northwest Europe, suggesting a shift to cooler, drier climates about 2.4 Ma B.P. Given these and numerous other indications of a shift in Earth's climate at that time, many scientists consider an age of about 2.6 Ma B.P. as a more appropriate lower boundary for the Quaternary. This corresponds to the age of the Matuyama/Gauss paleomagnetic boundary, offering a recognizable independent marker in the geologic record to identify the onset of the Quaternary.

1.3. Historical recognition of the Quaternary Period

A glacial transport explanation for the origin and distribution of erratics (boulders that are found far from the bedrock where they originated) across Europe was proposed as early as 1795 by James Hutton, and later by J. Esmark (1824), A. Bernhardi (1832), and J. De Charpentier (1834). However, the "glacial theory" wasn't really born until it was presented in a lecture by Louis Agassiz in 1837 at the Naturforschende Gesellschaft in Neuchâtel, Switzerland. In Massachusetts, Edward Hitchcock first presented the glacial theory in North America to the 1841 meeting of the American Association of Geologists. L. Agassiz moved to the U.S. in 1846 and took a position at Harvard University, where he continued to advance his ideas about continental glaciation. In 1863, the glacial theory appeared for the first time in J. D. Dana's textbook, *Manual of Geology*, and the concept quickly became established in North America.

The term "Quaternary" was first used in a geological context by J. P. Desnoyers in 1829 when he was differentiating Tertiary and Quaternary strata in the Paris Basin. In 1855 A. Von Morlot introduced the term in reference to the Ice-age era. Charles Lyell is said to have been the first to use the term Pleistocene in the 1830s, although E. Forbes defined it in 1846 as the period during which ice-age deposits were formed. Some of the first comprehensive regional overviews of the Quaternary Period include those by J. Geike (1874): *The Great Ice Age and its Relationship to the Antiquity of Man*; G. F. Wright (1890): *The Ice Age in North America*; three volumes documenting glacial deposits in the Alps by A. Penck and E. Bruckner (1901/1909): *Die Alpen im Eiszeitalter*; W.B. Wright (1914): *The Quaternary Ice Age*; P. Woldsted (1929): *Das Eiszeitalter*, reviewing evidence for the ice age in Germany; and H.C. Lewis (1894): *Papers and Notes on the Glacial Geology of Great Britain and Ireland*.

1.4. General Characteristics of the Quaternary Period

The Quaternary is characterized by repeated cooling and warming of global climate and the associated advance and retreat of continental ice sheets, primarily in the northern hemisphere. Various records suggest that there were at least 30, and probably closer to 50, of these glacial – interglacial cycles during the last 2.6 million years. In general, the last several glacial – interglacial cycles are characterized by an abrupt transition from cold, arid, full glacial conditions to interglacial warmth. Following 10 – 20 kyr of interglacial climate, there is a long period of gradual cooling to full glacial conditions, interrupted several times by brief intervals of milder temperatures. During the last several cycles, glacial phases continued for about 90 kyr, followed by another abrupt shift to the next warm period. The rapid transition on either end of the glacial cycle is called a termination. Several shorter cycles of climatic change, lasting from a few centuries to several millennia, are superimposed on the complete glacial-interglacial climatic cycle.

During the first 1.6 million years of the Quaternary, the cold – warm cycles had a periodicity of about 41,000 years, corresponding to the timing of variation the angle of the tilt of Earth's axis, which ranges from 21.8 – 24.1 degrees. This change in tilt of

Earth's axis of rotation, called obliquity, alters the amount and latitudinal distribution of solar radiation (insolation, or heat energy; see: Atmosphere *and Climate*) received in the northern hemisphere, which is believed to be partly responsible for the cyclic changes in climate. During the last 0.9 Ma, the alternation between glacial and interglacial climate had a greater amplitude (larger difference between cold and warm periods) and repeated every 100,000 years. Similarly, the shape of Earth's orbit around the sun, called eccentricity, ranges from nearly circular to slightly elliptical, with a period of about 100,000 years. Eccentricity of Earth's orbit also influences the amount of solar radiation reaching the surface. A third significant factor in Earth's path around the sun, called precession, relates to the time of year during which Earth is closest (perihelion) and farthest (aphelion) from the sun on its annual orbit. Precession therefore influences seasonality (difference between winter and summer) and has periods of 19,000 and 23,000 years. Effects of these three orbital parameters are additive; i.e., when they are in phase with one another, their cumulative effect on climate is enhanced; when they are out of phase, their effects are dampened. Collectively termed Milankovitch orbital variations, they are named after the Serbian mathemetician Milutin Milankovitch, who, in the first half of the 20^{th} century, determined their periods and calculated their effects on the receipt of solar radiation at Earth's surface through time. While Milankovitch orbital variations are believed to be largely responsible for the cyclic nature of Quaternary climate change, there are many shorter term fluctuations in climate that must be attributed to some other causes, which are discussed further below.

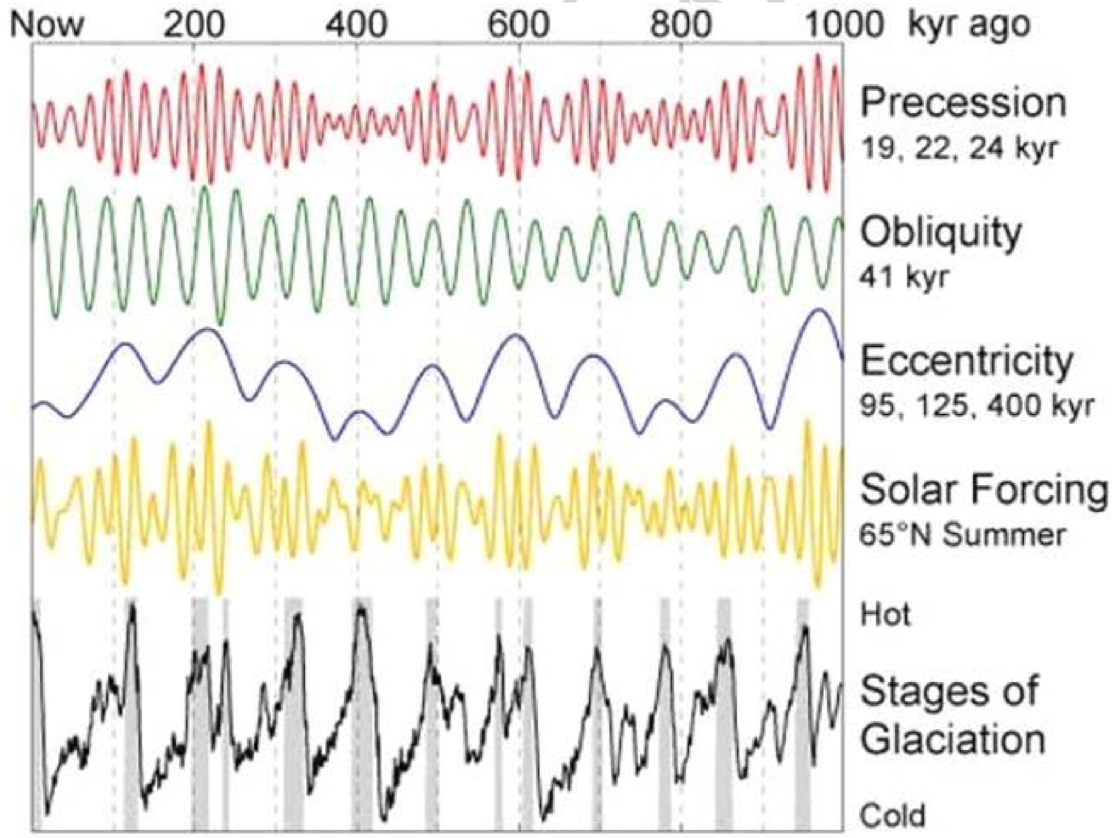

Figure 1. Data plot showing variations in Milankovich orbital parameters over the last one million years. Solar forcing is derived from the influence of the Milankovitch

variations and reflects changes in solar radiation reaching Earth's surface at 65 degrees north latitude in summer. For comparison, stages of glaciation, determined independently from marine oxygen-isotope records, are shown at the bottom of the figure.
Source: http://commons.wikimedia.org/wiki/Image:Milankovitch_Variations.png (http://en.wikipedia.org/wiki/User:Dragons_flight/Images)

As Earth's climate varied between glacial and interglacial states, ecosystems, rivers and lakes, deserts, and other natural systems adjusted to accommodate the changing climate and the advancing and retreating ice sheets. In general, it is estimated that mean annual temperature in the middle latitudes was about 10 degrees Celsius colder during glacial periods than interglacial times. Permafrost regions and tundra vegetation expanded beyond the margins of the growing ice sheets. Middle latitude forest belts contracted or were replaced by steppe vegetation, and there was a general shrinking and displacement of temperate biomes toward the equator. In the tropics, the glacial – interglacial temperature change was probably about 5 degrees C. Tropical rainforests in Brazil, Africa, and Australia were probably more restricted, and the Sahara desert expanded in area during the last glacial maximum.

Atmospheric circulation patterns are largely determined by temperature and pressure gradients between the equator and poles (see: *Atmosphere and Climate*). During glacial periods, the temperature gradient was larger, resulting in more vigorous atmospheric circulation, stronger trade winds, increased storminess, and displacement of atmospheric circulation features such as the jet stream and the intertropical convergence zone (ITCZ). During glacial maxima, an estimated 5.5% of the water on Earth was stored in ice sheets, compared with about 1.7% in the present interglacial time. As the glaciers grew, massive volumes of water evaporated from the oceans and became locked up in the ice sheets, causing sea-level to fall as much as 140 meters. With the lowered sea level, much of the continental shelf was exposed, creating large areas of newly emergent land. This altered the base level of rivers draining into the seas, causing erosion and down cutting during falling sea level and aggradation as seas were rising. New land bridges, such as the Bering Land Bridge connecting Siberia and Alaska, were exposed during sea-level low stands, which allowed faunal, floral, and later human migrations into new continental regions. The ice sheets grew to as much as 3 – 4 km in thickness, which further influenced atmospheric circulation patterns. Patterns of precipitation were reorganized, monsoon systems in Africa, Asia, India, and China were impacted, and climate was generally more arid during glaciations. Vegetation, animals, insects, and other organisms either adapted or more commonly migrated to new regions in response to the changing climate and growth of ice sheets.

Ocean circulation changes were also significant during the Quaternary and had important impacts on regional and global climates. Surface ocean currents, such as the Gulf Stream in the Atlantic, are largely due to frictional drag of winds blowing across the oceans. Deeper water movement in the oceans is driven by thermohaline circulation, which is controlled by temperature and salinity differences in the ocean waters. The thermohaline "conveyor belt" is the principle system that transfers heat and energy from low to high latitudes and, through a number of atmospheric interactions, contributes to climate. As the warm north-moving water cools and increases salinity through evaporation, it becomes denser and sinks, presently east of Greenland, in the Greenland and Norwegian seas. The sinking water mass, or North Atlantic Deep Water, moves at depth to the South Atlantic, where it joins cold, dense, deep water around Antarctica, called Antarctic Bottom Water. Flowing around Africa, the conveyor belt transfers the cold, deep water into the Indian and north Pacific Oceans, where it is warms, rises to the surface, and travels as shallow currents back to the Atlantic. The whole cycle of deep ocean circulation takes about 1000 years. The conveyor belt and the Gulf Stream both transport warm, equatorial Atlantic water to the North Atlantic, carrying heat and moisture to higher latitudes. Today the warm Gulf Stream is responsible for the moderate climate of northern and western Europe.

When oceanic thermohaline circulation is disturbed, climatic repercussions are felt on adjacent continental regions. It is believed that changes in North Atlantic Deep Water (NADW) production occurred regularly during the Quaternary. During glacial periods, sea-ice extended much farther south than present, preventing the northward penetration of warm shallow currents and limiting or shutting off NADW production. During times of rapid melting of continental ice sheets, there were significant inputs of cold, fresh water to the North Atlantic. The freshwater layer was less dense than seawater, preventing overturn of the water, which also may have interrupted formation of NADW. In either case, lack of warm, moist air enhanced cooling in continental regions adjacent to the North Atlantic. Numerous episodes of abrupt, rapid, cold-warm cycles, in which temperature changes of as much as 10ºC occurred over a few decades or less, are recorded in Greenland ice-cores. The Younger Dryas cold interval is the most recent of these events in which continental and ice-core records indicate sudden cooling accompanied by a rapid return to full glacial conditions in northwest Europe, interrupting deglacial warming around 12-11 ka B.P. These brief cyclic episodes are hypothesized to result in part from disturbances to the oceanic conveyor belt and shutting off of NADW formation (See: *Thermohaline Circulation*).

Figure 2. Map showing simplified large-scale “conveyor belt” thermohaline circulation of ocean water. Lighter blue color indicates surface water movement, while darker blue band shows deep ocean circulation.

Source: http://commons.wikimedia.org/wiki/Image:Circulacion_termohalina.jpg

2. Records of Quaternary Climate Change

Instrumental records of climate are only available for the last few hundred years. Because direct measurements of particular climatic parameters such as temperature, precipitation, and wind speed, are not possible for the time prior to instrumental recording, the climate of the Quaternary Period is reconstructed using a variety of proxy data. Proxy data are derived from ice cores, ocean sediment cores, and terrestrial sedimentary deposits. Data include geochemical measurements, such as oxygen-isotope composition of the calcareous shells of marine organisms or gas bubbles preserved in ice cores, vegetation reconstructions using preserved pollen and plant macrofossils, vertebrate and invertebrate fossil remains, geomorphological features such glacial deposits, paleo-shoreline features, or formerly active sand dunes, sedimentary archives such as loess and lake sediments, and numerous other approaches. Historical documents can also provide information regarding events or conditions from which climatic deductions can be made.

Inferences about climate of the last few thousand years can be determined using chronicles of climate-related phenomena such as the timing of grape harvests in Europe, floods and droughts in China, date of annual flowering of cherry blossoms in Japan, date of last snowfall in China, timing of river and lake freezing, extreme weather conditions, and similar events. The earliest records of climate-related occurrences come from Egyptian inscriptions documenting Nile floods as early as 5000 yr B.P. While these records can provide useful qualitative climate information, such as “warmer vs. colder” or “wetter vs. drier” periods in the past, it is difficult to translate them into quantitative estimates of temperature, precipitation, etc.

Proxy data ultimately relate features in the geological record to the climate at the time they were created. Climate reconstructions using proxy data are limited by the ability to link a measured geological or geochemical characteristic to a specific climatic value. For example, pollen preserved in lake sediments is commonly used to reconstruct the vegetation assemblage in the surrounding catchment area. However, estimating seasonal precipitation and temperature values based on the reconstructed vegetation is complicated. One approach to overcoming such limitations is to use a multi-proxy method, where several types of records offering different proxy data are examined, and best estimates of climate are determined from commonalities in the records. Finding long, continuous records with an accurate chronology is another significant constraint when using proxy data to reconstruct climatic changes in the past. The best dated, high-resolution terrestrial records come from the last 40,000 years, which is within the range of reliable radiocarbon dating. Longer series extending farther back in time are available, but accurately dating the records can be problematic. (See Appendix 1 in. *Wind Processes).*

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Biographical Sketch

Eric Oches is an Associate Professor of Natural & Applied Sciences at Bentley College, Waltham, MA, and was formerly a faculty member of Geology and Chair of Environmental Science & Policy at the University of South Florida, Tampa, FL. Trained in the glaciated northern United States at Purdue University and University of Massachusetts, he developed an early interest in glacial history and terrestrial sedimentary records of Quaternary climatic and environmental change. Following graduate school, Oches was a post-doctoral research associate at the Institute for Rock Magnetism, University of Minnesota, and a NSF-NATO postdoctoral fellow at the Geological Institute, Czech Academy of Sciences, Prague. Oches specializes in loess–paleosol archives of past climatic change and has done fieldwork in the loess regions of the Mississippi Valley and Alaska, U.S., throughout Western, Central, and Eastern Europe, in the loess region of northwest Argentina. He is also interested in paleoclimatic and environmental pressures on early human societies associated with Middle Holocene aridification in southern Arabia, and most recently in coastal records of Quaternary sea-level change in the southeastern U.S.