PERSPECTIVES: PALEOCLIMATE

Mid-Holocene Climate Change

Eric J. Steig

Large-magnitude, rapid climate change events—some taking place within just a few decades, less than the span of a single human lifetime (*1*)—characterized the last glacial period, between about 50,000 and 10,000 years ago (*2*). Such events result in a big signal in the geologic record through the modification of the landscape by glaciers, changes in atmospheric and ocean chemistry, and altered distributions of marine and terrestrial biota. By comparison, the "signal" of climate change in our current interglacial period, the Holocene, is relatively muted. Nevertheless, many paleoclimatologists, armed with techniques that permit the examination of past climate at unprecedented temporal and spatial resolution, are now turning their attention to the Holocene.

The new focus on the Holocene is motivated in part by the recognition that substantial and possibly global climate oscillations have occurred during the past 10,000 years, with pacing similar to the larger magnitude glacial events (*3*). Because these oscillations occurred under conditions similar to those of today—that is, in a time of overall warmth and in the absence of large Northern Hemisphere ice sheets—they bear more directly on our understanding of contemporary climate change than do the events of the last glacial period. Moreover, the relatively subtle changes of the Holocene provide a challenging benchmark against which to test the numerical climate models that guide our understanding of how the climate system functions.

Several recent studies highlight the mid-Holocene (7000 to 5000 years ago) as a period of particularly profound change. During this interval, land air temperatures appear to have declined across much of the globe. This can be seen most clearly in the polar regions, as documented by data from Antarctica, Greenland, and the eastern Canadian Arctic (*4*, *5*). The evidence at lower latitudes is more ambiguous, but paleobotanical data show that most tropical and subtropical land areas either cooled or became more arid, or both; at temperate latitudes, some areas experienced a mid-Holocene dry period followed by increasingly cool and wet conditions (*6*). In some cases, the mid-Holocene shift in climate appears to have been quite abrupt (see the figure).

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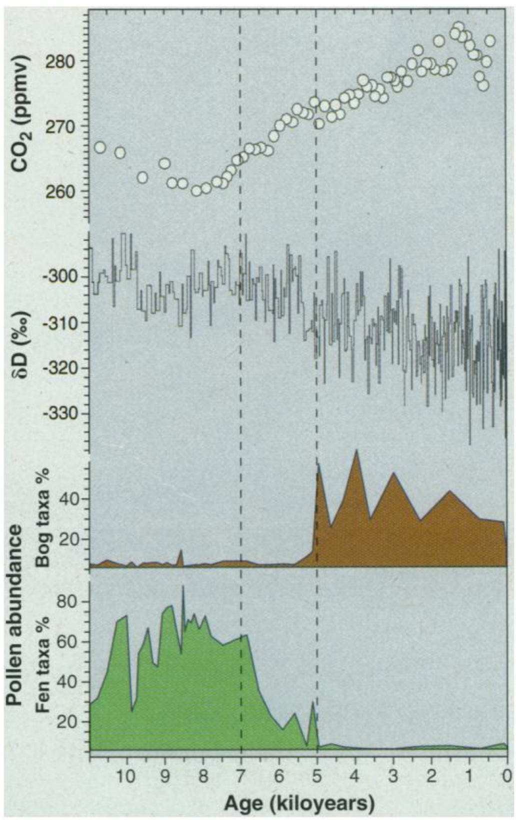
In addition to these changes in land air temperatures and precipitation, the mid-Holocene also saw substantial change in atmospheric and ocean circulation patterns. In the North Atlantic, a prominent increase in abundances of warm-water planktonic foraminifera in some marine sediment cores suggests that sea surface temperatures warmed between 8000 and 5000 years ago (*3*). This warming trend is significant, comparable in amplitude to the periodic ~1500-year cycles, which are documented in the same cores and attributed to major changes in the North Atlantic thermohaline circulation (3). Other studies show cooling of tropical Pacific (*7*) and Antarctic (*4*) surface waters between 7000 and 5000 years ago, weakening of the Australian monsoon (*8*), and an increase in the frequency of storms events in the tropical Andes (*9*). The storm-frequency data—although controversial—are especially intriguing because they suggest a relation between mid-Holocene climate change and the modern El Niño–Southern Oscillation periodicity. This may have implications for the frequency of El Niño–type events under possible future global warming scenarios.



Records of Holocene climate change. Global atmospheric CO_2 concentrations (*10*) and stable isotope (δD) ratios (*4*) are from the Taylor Dome ice core, Antarctica. Stable isotopes are a proxy for local temperature. Pollen percentage data are from Rio Rubens Bog, southern Patagonia, and show an abrupt change attributed to increasing moisture (*6*).

The mid-Holocene changes in temperature and circulation patterns were accompanied by increasing greenhouse gas concentrations. Atmospheric CO_2 increased by just over 10 parts per million (ppm) between 7000 and 5000 years ago, a rate of ~0.5 ppm per century (*10*). This pales in comparison with modern anthropogenic CO_2 increases (which amount to more than 60 ppm in the last century), but it does not differ greatly from the rate of CO_2 change during the last deglaciation and implies a major redistribution among the terrestrial, marine, and atmospheric carbon pools. According to one plausible scenario (*11*), total terrestrial biomass decreased at low latitudes as aridity increased and temperatures cooled, resulting in a net release of carbon into the atmosphere. Limited carbon isotopic evidence (*10*) does indeed suggest that the observed CO_2 increase can be attributed to terrestrial sources, rather than the oceans, but the details remain to be investigated with higher resolution data.

Understanding mid-Holocene climate change will not be straightforward. As in the case of glacial-age climate, changes in Earth's orbital parameters and in the ocean thermohaline circulation are probably important. Northern Hemisphere insolation has been decreasing since the early Holocene, with the steepest decline about 6000 years ago, while deep ocean nutrient and isotope data suggest a concomitant decline in North Atlantic deep water formation (*12*). But whereas conventional wisdom holds that Atlantic thermohaline variations tend to promote opposing climate changes at high northern and southern latitudes (*13*), the evidence from ice cores suggests that both hemispheres cooled during the mid-Holocene. A possible solution is suggested by numerical modeling efforts. In one set of simulations (*14*), a reasonable match with the available data is obtained only when ocean thermohaline changes and insolation changes are combined with the influence of the terrestrial biosphere, which produces strong feedbacks on temperature and precipitation patterns. Evidently, the terrestrial biosphere, which is often ignored in climate models, plays a more active role in the climate system when large, Northern Hemisphere ice sheets are absent.

Although the mid-Holocene represents a period of change in the climate system under conditions not all that different from today, two temptations must be resisted. The first is to use the mid-Holocene as a direct analog for contemporary climate change. Although, like today, CO_2 concentrations increased during this time, it must be reiterated that the rate of CO_2 increase was more than two orders of magnitude smaller and was very likely a response to, rather than a forcing of, climate change. The second is to assume that we have sufficient data to confidently characterize mid-Holocene climate. Because the signal of Holocene climate change is small, the noise is correspondingly large, and in consequence Holocene climate is effectively more complex than glacial climate (*15*). The "complexity" in this case is spatial variability, which can be addressed only by obtaining high-quality, high-resolution paleoclimate data from many, widely distributed locations.

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PERSPECTIVES: PLANETARY SCIENCE

On the Edge of the Solar System

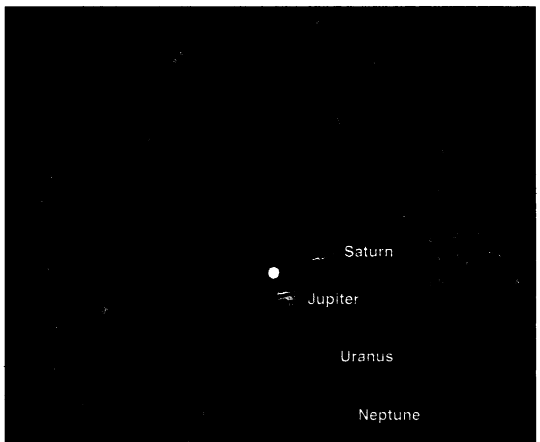
Rodney Gomes

Beyond the orbit of Neptune, the solar system does not contain any large objects. According to solar system models (*1*, *2*), a large number of smaller objects should orbit the sun in these distant regions, but with the exception of Pluto, these objects were long beyond the limits of detectability. New imaging has overcome this problem. Since the discovery of the first member of the Edgeworth-Kuiper Belt (EKB) in 1992 (*3*) confirmed the early predictions, nearly 200 objects have been observed at distances between 30 and 50 astronomical units (AU) from the sun (*4*). The wealth of new data has led to consensus on some and controversy on other central issues regarding the evolution and structure of the outer regions of the solar system.

According to Edgeworth (*1*) and Kuiper (*2*), the region now referred to as the Edgeworth-Kuiper Belt should be inhabited by a large number of small objects. The most probable scenario is that the primordial EKB was much more massive—a total mass of about 30 Earth masses is necessary to form its biggest members known today, including Pluto, two orders of magnitude larger than the mass indicated by observations. Subsequently, mass was lost, because the proximity to Neptune and Uranus created a dynamic orbital environment and led to collision of objects with these large planets, ejection from the solar system, or the breakup of larger objects (*5*, *6*). Beyond 50 AU, the planets are too distant to perturb orbits, and thus a larger amount of mass is theoretically expected to be found there. Unfortunately, there are no observations yet of any Edgeworth-Kuiper Belt objects (EKBOs) that remain outside the 50 AU boundary during their entire orbit, and this aspect of the theory cannot be confirmed or disproved without further data.

Three different groups of EKBOs are currently known. Most members of the resonant group are located in the 2:3 resonance with Neptune; that is, they complete two orbits around the sun in the time it takes Neptune to complete three orbits. The 2:3 resonance probably stabilizes these "plutinos" (see the figure) against disruptive gravitational perturbations by Neptune. A few resonant objects are in the 3:4, 5:7, and 3:5 resonances, and two are in the 1:2 resonance. Eccentricities and inclinations for plutinos can reach 0.34 and 40 symbol 176°, respectively. Members of the nonresonant group (see the figure) have been found mostly between the 2:3 and 1:2 resonances. They have average eccentricities and inclinations around 0.07 and 9.5 symbol 176 °, respectively. The scattered group consists of objects with very eccentric orbits. So far, only five members of this group have been identified, but their origin is the least controversial of all the objects. They are believed to be remnants of a collection of barely stable orbits with a perihelion (closest approach to the sun) a little beyond that of Neptune. These orbits were attained after close encounters with Neptune, either from a region of slow diffusion in the Kuiper Belt (*7*) at distances between 35 and 42 AU or from a more unstable region between the orbit of Uranus and just beyond that of Neptune in a primordial EKB (*8*). They are believed to be the source of the Jupiter family of comets (*8*).

There are two main theories regarding the origin of the first two groups: the planetary migration theory (*9*) and the large scattered planetesimals theory (*10*). Both theories assume a primordial configuration in which Neptune orbits in a planetesimal-rich environment. If the planetesimals are numerous and small, angular momentum and energy exchange of the swarm of objects with the precursors to the four major planets (or protoplanets) induce the planets to migrate radially. Neptune suffers an outward migration of about 7 to 8 AU and traps many planetesimals in resonance, whose eccentricities and inclinations are thus excited. This theory can explain the EKBOs at the 2:3 resonance with Neptune, including Pluto (*9*). However, the 1:2 resonance region seems far less populated than would be expected from numerical simulations. The theory also cannot explain the moderately high eccentricities and inclinations for the nonresonant group. The second theory assumes a few large (order of an Earth mass) planetesimals orbiting near



Position of Edgeworth-Kuiper Belt objects on 1 January 1998. The orbits of the giant planets (outward from the sun: Jupiter, Saturn, Uranus, and Neptune) are also shown. Blue circles, plutinos; red triangles, other Edgeworth Kuiper Belt objects; filled symbols, relatively reliable orbits, open symbols, less reliable orbits. Data from (*16*).

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