Reports

Multiple Thermal Maxima During the Holocene

Abstract. *The astronomical theory of climatic change provides an alternative to the traditional chronology for Holocene climatic change, which calls for one thermal maximum about 6000 years ago. The theory predicts a series of maxima during the Holocene, one for each season. Because the relation of the perihelion to the spring equinox changes with a 22,000-year period, late summer insolation would have been greatest 5000 years ago, whereas early summer insolation would have been greatest 13,000 years ago. Climatic reconstructions based on the response of ecosystems to late summer climate indicate a later Holocene thermal maximum than paleoclimatic data sensitive to early summer climate. In southern Idaho, three different vegetation types indicate thermal maxima at different times during the Holocene, depending on the climatic variable controlling each type.*

The astronomical theory of climatic change is fast becoming the conceptual and operational paradigm of Quaternary paleoecology. This theory permits the calculation of incident solar radiation (insolation) at all latitudes for each day of the year based on changes in the eccentricity, precession, and obliquity of the ecliptic for the earth's orbit through time (*1*). The high correlation between insolation and the global ice volume (*1*) has convinced all but the most skeptical of the causal relation between the earth's orbital parameters and climatic change. Research interests have now focused on atmospheric links between climate and the orbital forcing mechanism (*2*) and on the development of a time scale based on the theory (*3*).

The theory also explains details of Holocene climatic change. Kutzbach (*4*) has shown that maximum summer insolation 11,000 years ago is associated with maximum monsoonal precipitation in Africa and Asia. Ritchie *et al.* (*5*) have demonstrated that the northernmost advance of the tree line in Canada during the Holocene coincides with the maximum of summer insolation predicted by the astronomical theory.

The timing of maximum insolation 11,000 years ago seemingly conflicts with traditional chronologies of climatic change for North America that call for a thermal maximum, variously termed the "Hypsithermal" or "Altithermal" (*6*), centering around 5000 or 6000 years ago. Modeling of the global climatic response to insolation requires incorporation of many climatic variables, including atmospheric carbon dioxide (*7*), the effects of continental ice sheets (*8*), and changes in oceanic circulation (*9*). But a simple and powerful explanation for the seeming conflict is contained within the theory itself.

The astronomical theory predicts a series of maxima during the Holocene, one for each season. Precession varies with a pseudoperiod of about 22,000 years (*10*), producing insolation maxima at different times for different seasons on a relatively short time scale. The other elements of the astronomical theory, eccentricity and obliquity, become important on larger time (and area) scales. However, precession is most important in determining the seasonal distribution of insolation on the scale of interest to the present discussion.

Seasonal insolation values for early, middle, and late summer are shown in Fig. 1a (*11*). The Holocene maximum for early summer (May through June) was reached 13,000 years ago, the midsummer (July through August) maximum occurred closer to 10,000 years ago, and the late summer (September through October) maximum occurred about 5000 years ago.

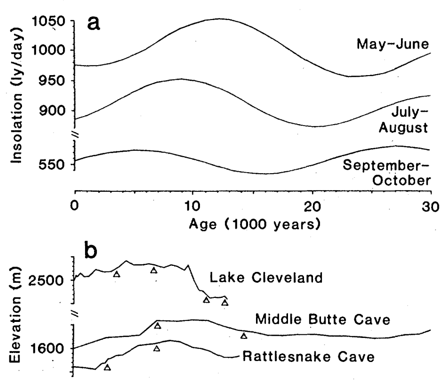

Fig. 1. (a) Average insolation for early, middle, and late summer months (*11*) over the last 30,000 years; (b) the elevations of vegetation boundaries (*17*) at three sites in southern Idaho. The scale interval is 10 m for the vegetation boundaries. Symbols on the curves in (b) indicate the positions of radiocarbon dates (*13, 14*).

For paleoecological studies, the timing of the Holocene thermal maximum depends on the type of paleoclimatic data used. Ecological phenomena depending primarily on summer temperature, such as arctic tree line (*12*), should indicate maximum Holocene temperature about 10,000 years ago (Fig. 1a). Other indicators of climate may respond to warmth in other seasons or may be relatively insensitive to temperature.

The effects of the different timing of seasonal maxima may be seen in the histories of three ecosystems on the Snake River Plain (*13–15*). The site with the lowest elevation, Rattlesnake Cave (Fig. 2), is near the ecotone between shadscale and sagebrush steppe. The position of this ecotone is primarily controlled by summer drought (*16*). The modern seasonal precipitation minimum coincides with maximum temperature in August. Elevated temperatures during this season should increase the severity of midsummer drought and produce upward migration of the ecotone.

Figure 1b shows the Holocene history of this ecotone as reconstructed from pollen indices (*17*). The ecotone reached maximum elevation approximately 8000 years ago, coinciding with the August insolation maximum. In this discussion, I am interested in the relative timing of the maximum rather than in its shape. The shape (for example, flatness, symmetry) and amplitude may provide information on ecologic and climatic factors; but, for comparison with the insolation curves, the timing of the beginning and end of the elevational maximum is of greatest interest.

Middle Butte Cave (Fig. 2) is near the lower ecotone of juniper woodland. Ecological factors controlling this ecotone are the topic of inconclusive debate (*18*), but summer drought may also be important (*19*). The elevational increase for the ecotone centers around 10,000 years ago, 2000 years earlier than for Rattlesnake Cave (*20*).

Lake Cleveland, the high elevation site, is near the ecotone between fir forest and subalpine meadow in the area. Summer temperature is undoubtedly important at this elevation (*12*); however, true tree line does not exist in the area and the ecotone between fir forest and subalpine meadow is controlled primarily by the length of the growing season (*21*). Both early and late summer insolation may influence the length of the growing season, but the maximum eleva-

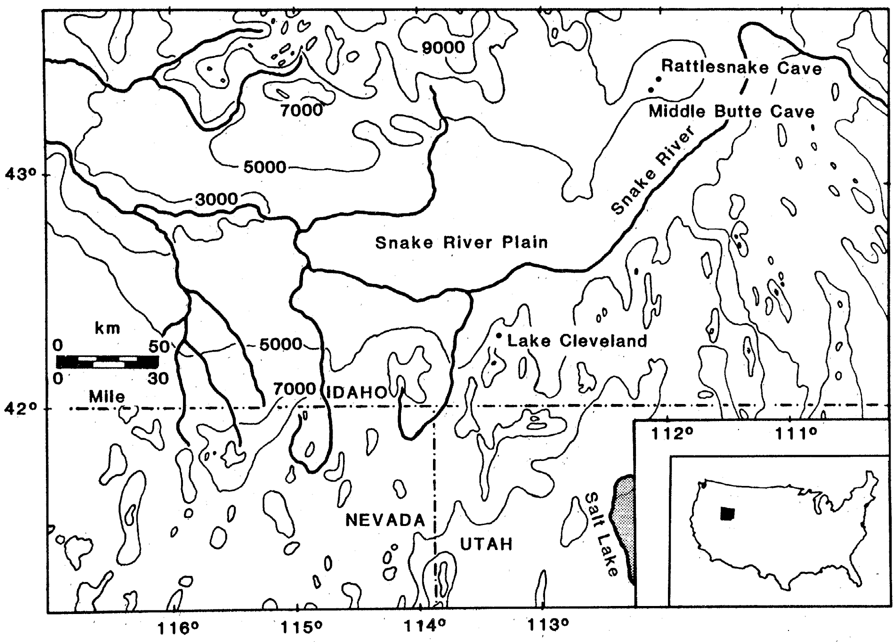

Fig. 2. Location of three fossil pollen sites near the Snake River Plain. Lake Cleveland is at an elevation of 2519 m, Middle Butte Cave, 1593 m; and Rattlesnake Cave, 1596 m (*13*, *14*).

tion of the ecotone centering around 5000 years ago best matches the curve for late summer insolation.

If the elevations of the ecotones are used as proxy indicators of climate (*22*), the traditional timing of the Holocene thermal maximum can only be seen at Lake Cleveland, whereas the maxima for the low elevation sites are substantially earlier. The timing for all three sites is attributable to the differential response to seasonal insolation at the latitude of the sites (43°N). Low elevation vegetation responded primarily to summer drought (that is, early and midsummer insolation), whereas high elevation vegetation responded to fall temperatures (late summer insolation).

The maximum aridity in southern Idaho at about 10,000 years ago is an intriguing contrast to the minimum aridity at that time in monsoonal Africa and Asia (*4*). The pluvial lakes of the northern Great Basin had dried by 11,000 years ago (*23, 24*). If the southwestern United States experienced a precipitation maximum at that time (*25*), climatic gradients across the Great Basin must have been much stronger than at present.

The traditional Holocene climatic sequence (*6*) is based on the history of European vegetation, which is strongly influenced by atmospheric and oceanic circulation in the North Atlantic (*9*). However, many of the details of European climate may actually be the result of multiple seasonal maxima. For example, ivy, mistletoe, and water chestnut were present in Denmark from 10,300 to 2500 years ago (*26*). These are frost-sensitive species, and Iversen (*26*) has interpreted their maximum abundance from 8000 to 5000 years ago as indicative of the Holocene thermal maximum. Their presence north of current ranges may reflect the maximum of late summer insolation.

Other paleoclimatic indicators may have responded to early summer insolation. Climatic reconstructions based on fossil beetle assemblages in England (*27*) indicate high temperatures 13,000 years ago while the vegetation remained tundra. Migration lag for plants has been implicated in this discrepancy, but thermophilous beetles may have been favored by maximum early summer insolation 13,000 years ago while other aspects of the growing season were unfavorable for thermophilous plants.

The pattern of global climatic change during the Holocene has been accompanied by changes in atmospheric circulation. However, some patterns of Holocene climatic change may be due to multiple seasonal maxima. The Holocene maxima for low elevation ecotones in southern Idaho coincide with the northernmost extension of the Canadian tree line. For Lake Cleveland the timing is similar to that of sites in eastern North America. The difference in timing is among ecosystems rather than among latitudes.

Holocene changes in atmospheric circulation certainly cannot have produced differences in the timing of the Holocene maximum among the three sites in southern Idaho since all three are within one macroclimatic region. Differential lag after the early Holocene maximum is also unlikely because the ecotone migrations involve less than a hundred meters, and the response rate of these ecotones to historic environmental change (*18, 28*) has been very rapid.

The traditional chronology of Holocene climatic change (*6*) was based primarily on the European chronology. Subsequent research has disputed this chronology for some regions and for some ecosystems (*4, 5, 27*). However, the sequence has remained a standard against which others are compared.

The astronomical theory of climatic change offers an alternative chronology for climate that resolves apparent conflicts among the different indicators of past climate. Rather than one thermal maximum forcing simultaneous responses in all ecosystems, the theory calls for a series of maxima depending on the season and climatic variable most important for each ecosystem.

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11. The values are averages for the insolation [in langleys (ly) per day] for the first day of each month of the 2-month interval. The values were produced by a version written in BASIC of a program written by N. G. Pisias, Oregon State University, which is based on a program that appears in A. L. Berger, *Contrib. Inst. Astron. Geophys. Univ. Cathol. Louvain* **18**, 1 (1978).
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17. The calculation of the ecotone elevation through time is described in (*13*). For each fossil sample, (i) the similarity to low elevation vegetation is subtracted from the similarity to high elevation vegetation near each fossil site; (ii) the difference is divided by the ratio of the elevation

difference between the site and the ecotone to the ordination value at the site; and (iii) a five-level moving average is plotted at the middle age. The measure of similarity is a correlation coefficient based on indicator pollen types. A description of this coefficient, and a list of the indicator pollen types, appears in O. K. Davis, *Rev. Palaeobot. Palynol.* **40**, 295 (1983).
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20. The age of Rattlesnake Cave sediments is not known prior to 6760 years ago, because samples below a depth of 60 cm did not contain enough carbon to provide a reliable date (*15*). The age of the lower sediments is interpolated between 6760 years ago at 60 cm and 14,320 years ago at 175 cm. The later date is a minimum date based on the absence of Mount Mazama "S," which is present in sites of appropriate age in the area.
21. Subalpine meadow vegetation occurs where snowbanks last late (July) into the summer. In years when snow comes early or the snowbanks last until late, perennial vegetation surrounding the meadows is killed (*13*).
22. The shapes of the three curves are not crucial for the present discussion but may be of paleoclimatological interest. The low elevation ecotones were higher during the late glacial than today (Fig. 1). There are two possible explanations for this: (i) the late glacial steppe vegetation was qualitatively different from that of today or (ii) the late glacial climate may have been drier than today. On the basis of modern lapse rates in precipitation (*13*), the difference in elevation is equivalent to at least 10 to 20 mm less annual precipitation during the full glacial.
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Uranus: Microwave Images

Abstract. *Observations of Uranus at wavelengths of 2 and 6 centimeters with the Very Large Array were made in 1980 and 1981. The resulting maps of brightness temperature show a subsolar symmetry at 2 centimeters but a near-polar symmetry at 6 centimeters. The 6-centimeter maps show an increase in temperature from equator to pole with some evidence for a warm "ring" surrounding the north pole. The disk-average temperatures (147 ± 5 K and 230 ± 6 K at 2 and 6 centimeters, respectively) are distinctly lower than recently reported values; these results suggest that the secular increase in temperature reported during the last 15 years has been reversed. The variations in brightness temperature probably reflect variations in ammonia abundance in the planet's atmosphere, but the mechanism driving these variations is still unclear.*

The microwave spectrum of Uranus is distinguished by two anomalies: a secular increase in brightness temperature during recent years and an apparent deficiency in ammonia opacity. Both of these features have been reviewed by Gulkis *et al.* (*1*), who have summarized observations from the last two decades, interpreted these results in terms of models for the atmosphere of Uranus, and predicted future trends in the planet's microwave brightness on the basis of these models. We present here the first fully resolved microwave images of Uranus, made with the Very Large Array (VLA) at wavelengths of 2 and 6 cm in 1980 and 1981. These images improve on the earlier VLA results of Briggs and Andrew (*2*), because more telescopes were available and we have observed at two frequencies. Our observations indicate that in contradiction to the prediction of Gulkis *et al.* (*1*)—that the brightness temperature of Uranus will continue to rise as the north pole becomes more visible—the maximum in the planet's microwave radiation has already occurred, before the pole reaches its closest sunward alignment in 1985. From our images we can directly assess the contribution of the pole to the measured average temperatures. We also find that there was a marked difference in the atmospheric opacity at 2 and 6 cm, as manifested by the differing symmetries of the brightness contours in the two images.

We observed Uranus at 6.1 and 2.0 cm during the May 1980 opposition and again at 6.1 cm during March 1981 (Table 1). We used the radio sources 1510-089 and 3C 286 to calibrate phase and flux, respectively. The assumed fluxes of 3C 286 were 7.41 Jy at 4.885 GHz and 3.44 Jy at 15.035 GHz (*3*).

After calibration, we constructed preliminary maps of the three fields, using standard National Radio Astronomy Observatory (NRAO) Fourier-transform programs. We then adjusted the phases of the 15-GHz data, which were in some cases affected by "seeing," to improve internal consistency, that is, we "self-calibrated" them, using an approximation of the preliminary map as a model of the true brightness distribution. A map of the second run was then made.

We "regularized" the three maps, using an algorithm implemented by F. Schwab of NRAO and W. Jaffe. This process reduces side lobes and other map artifacts and is thus similar to the more commonly used CLEAN and Maximum Entropy algorithms. It differs from these by implementing the specific constraint that the true sky emission is limited in extent. We assumed that no emission originates more than 1.5 planetary radii from the planet's center. This a priori assumption is consistent with the conclusion of Briggs and Andrew (*2*) regarding the absence of synchrotron emission at 6 cm beyond the limb of the planet. For display, the output maps were convolved with a Gaussian-function full width at half power of 0".75 in order to improve the temperature sensitivity of the results (at some loss of resolution) and to ensure a well-defined point spread function for later analysis.

The resulting maps are shown in Figs. 1 and 2. The 1981 map is not shown, since it essentially duplicates the 1980 map. Inspection of these figures reveals a distinctly different symmetry for brightness temperature (T_B) contours at the two wavelengths: at 2 cm the warmest spot on the planet is near the subsolar point, whereas at 6 cm the contours are symmetric about a point near the pole of the axis of rotation. This indicates that the temperature variations at 2 cm are caused by limb darkening only (*4*), whereas the 6-cm results reflect latitude changes in the radiation characteristics of the atmosphere. In Fig. 3 we plot the 6-cm T_B as a function of latitude, collected in bins of 15° of latitude near the pole and 30° near the equator.

A curious feature of Fig. 3 is the apparent T_B maximum some 30° off the north pole, representing a warm "ring" around the pole. Although the excess over the pole temperature is not extremely large, it also appears in the 1981 data. This feature may reflect a peculiar distribution of atmospheric opacity or it

Table 1. Observation log; IAT, International Atomic Time.

IAT date	IAT start time	Duration (hours)	Frequency (GHz)	Bandwidth (MHz)	Operating telescopes (No.)	Distance to Uranus (AU)
17 May 1980	$03^h\ 07^m$	10	15.035	50	20	17.74
18 May 1980	$03^h\ 03^m$	10	4.885	50	22	17.74
7 March 1981	$08^h\ 31^m$	10	4.885	50	26	18.50