Geophysical, archaeological, and historical evidence support a solar-output model for climate change

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Although the processes of climate change are not completely understood, an important causal candidate is variation in total solar output. Reported cycles in various climate-proxy data show a tendency to emulate a fundamental harmonic sequence of a basic solar-cycle length (11 years) multiplied by 2^N (where N equals a positive or negative integer). A simple additive model for total solar-output variations was developed by superimposing a progression of fundamental harmonic cycles with slightly increasing amplitudes. The timeline of the model was calibrated to the Pleistocene/Holocene boundary at 9,000 years before present. The calibrated model was compared with geophysical, archaeological, and historical evidence of warm or cold climates during the Holocene. The evidence of periods of several centuries of cooler climates worldwide called ''little ice ages,'' similar to the period *anno Domini* (A.D.) 1280–1860 and reoccurring approximately every 1,300 years, corresponds well with fluctuations in modeled solar output. A more detailed examination of the climate sensitive history of the last 1,000 years further supports the model. Extrapolation of the model into the future suggests a gradual cooling during the next few centuries with intermittent minor warmups and a return to near little-ice-age conditions within the next 500 years. This cool period then may be followed approximately 1,500 years from now by a return to altithermal conditions similar to the previous Holocene Maximum.

The debate on the cause and the amount of global warming and its effect on global climates and economics continues. As world population continues its exponential growth, the potential for catastrophic effects from climate change increases. One previously neglected key to understanding global climate change may be found in examining events of world history and their connection to climate fluctuations.

Climate fluctuations have long been noted as being cyclical in nature, and many papers have been published on this topic (1). These fluctuations also can be quite abrupt (2) when climate displays a surprisingly fast transition from one state to another. Possible causes of the cyclic variations and abrupt transitions at different time intervals have been theorized. These theories include internal drivers such as CO_2 concentrations (3), ocean temperature and salinity properties (4), as well as volcanism and atmospheric-transmissivity variations (5). External drivers include astronomical factors such as the Milankovitch orbital parameters (6), which recently have been challenged (7), and variations in the Sun's energy output (8–10).

The most direct mechanism for climate change would be a decrease or increase in the total amount of radiant energy reaching the Earth. Because only the orbital eccentricity aspect of the Milankovitch theory can account for a change in the total global energy and this change is of the order of only a maximum of 0.1% (11), one must look to the Sun as a possible source of larger energy fluctuations. Earth-satellite measurements in the last two decades have revealed that the total energy reaching the Earth varies by at least 0.1% over the 10- to 11-year solar cycle (12). Evidence of larger and longer term variations in solar output can be deduced from geophysical data (13–17).

In an extensive search of the literature pertaining to geophysical and astronomical cycles ranging from seconds to millions of years, Perry (18) demonstrated that the reported cycles fell into a recognizable pattern when standardized according to fundamental harmonics. An analysis of the distribution of 256 reported cycles, when standardized by dividing the length of each cycle, in years, by 2^N (where N is a positive or negative integer) until the cycle length fell into a range of 7.5 to 15 years, showed a central tendency of 11.1 years. The average sunspot-cycle length for the period 1700 to 1969 is also 11.1 years (19). In fact, the distribution of the sunspot cycles is very nearly the same as the distribution of the fundamental cycles of other geophysical and astronomical cycles. Aperiodicity of the cycles was evident in two side modes of 9.9 and 12.2 years for the geophysical and astronomical cycles and 10.0 and 12.1 years for the sunspot cycle. The coincidence of these two patterns suggests that solar-activity cycles and their fundamental harmonics may be the underlying cause of many climatic cycles that are preserved in the geophysical record. Gauthier (20) noted a similar unified structure in Quaternary climate data that also followed a fundamental harmonic progression (progressive doubling of cycle length) from the 11-year sunspot data to the major 90,000-year glacial cycle.

Solar-Output Model

A simple solar-luminosity model was developed to estimate total solar-output variations throughout an entire glacial cycle of approximately 90,000 years (21). The model summed the amplitude of solar variance for each harmonic cycle from 11 to 90,000 years with the cumulative amplitude of 0.08% for the 11-year cycle and 0.62% for the 90,000-year cycle (18). The summation of the amplitudes of each of 13 individual harmonic cycles resulted in an estimate of the relative change of solar output through a full glacial cycle (full glacial through the interglacial and back to full glacial). Analysis of the ratio of oxygen 16 to oxygen 18 ($O^{16/18}$) in deep sea cores shows that the oceans have warmed and cooled in concert with the growth of continental glaciers. Emiliani (22) determined $O^{16/18}$ ratios, representing the last 720,000 years, show eight distinct glacial cycles averaging approximately 90,000 years in length. When the $O^{16/18}$ ratios for each of the eight cycles are standardized to cover a period of 90,000 years, they significantly correlate with the modeled solar-output amplitudes. Correlation coefficients between $O^{16/18}$ and modeled solar output for these eight glacial cycles averaged $r = 0.64$ (18).

Examination of the unstandardized, individual cycles in $O^{16/18}$ ratios of the deep-sea cores revealed a tendency for the shorter cycles to represent warmer conditions and the longer cycles to represent colder conditions. A relation among solar magnetic intensity, total solar-energy output, and the length of the solar cycle was speculated by Perry (23) and was later supported by Friss-Christensen and Lassen (8) with their comparison of global

Abbreviations: BP, before present; AP, after present; B.C., before Christ; A.D., *anno Domini*.

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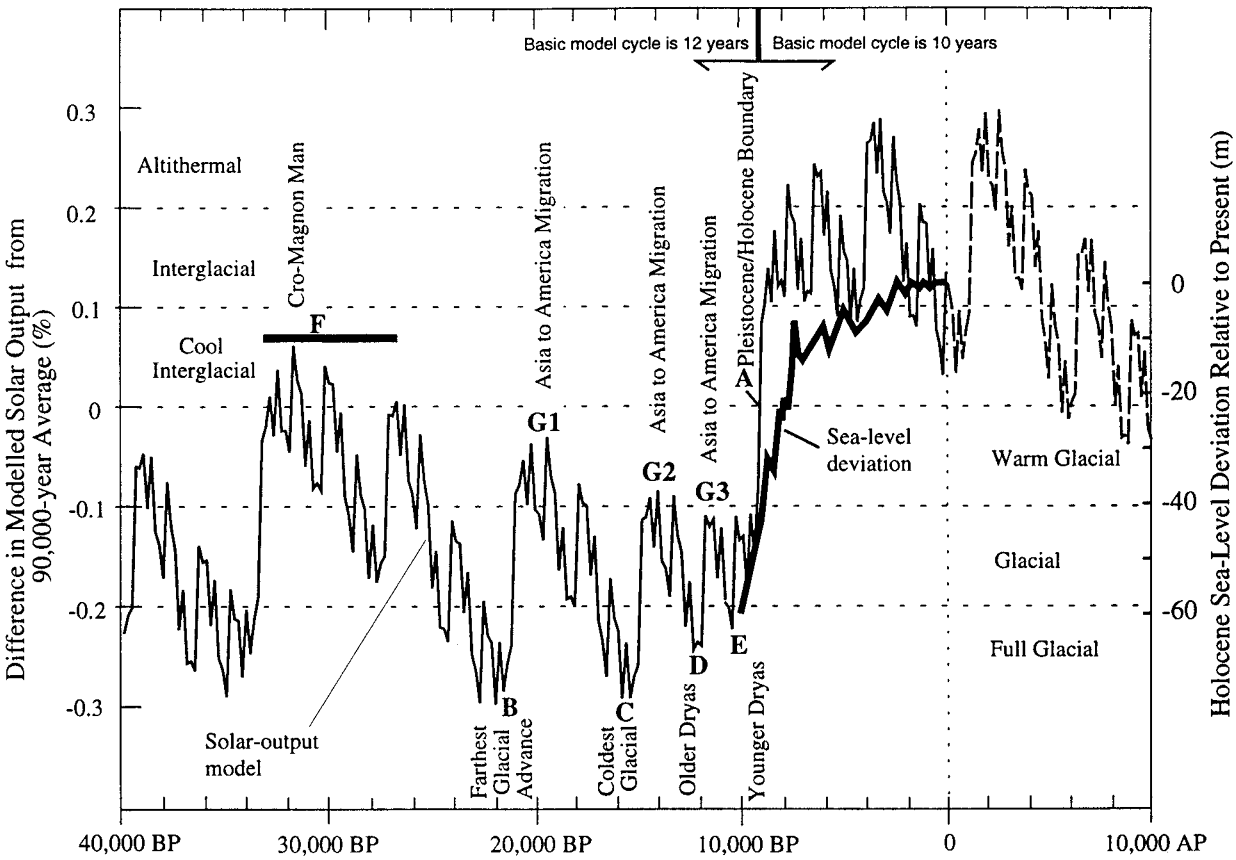

Fig. 1. Modeled solar output (luminosity) from 40,000 years BP to 10,000 years AP compared with glacial, sea-level-deviation (24), and archaeological information during the late Pleistocene and Holocene.

air temperatures and solar-cycle length. Accordingly, it may be inferred that during periods of global warmth (interglacial) the basic fundamental solar cycle would expected to be shorter, possibly averaging 10 years, whereas during global chill (glacial), the basic cycle would expected to be longer, possibly closer to 12 years. These two values correspond to the two side modes of the distribution of the basic cycles in geophysical data mentioned previously.

The solar-output model was modified to allow the basic cycle to vary from a 12-year basic cycle during the last 30,000 years of the last glacial cycle up to the Pleistocene/Holocene boundary [approximately 9,000 years before present (BP)] to a 10-year basic cycle onward for another 19,000 years [to 10,000 years after present (AP)]. This 50,000-year period includes both the full glacial and altithermal interglacial periods in the approximate 90,000-year cycle. The two modeled time periods were spliced together at the point where the change in solar output was 0% from the 90,000-year average. Fig. 1 shows the resultant solar-output model variations of luminosity compared with selected events deduced from the geophysical records and archaeological evidence during the late Pleistocene and Holocene.

Model Timeline Calibration

To initially calibrate the model, the rapid warm-up of the Pleistocene/Holocene time boundary was determined to be the most significant climatic event in the last 40,000 years. The date at the Pleistocene/Holocene boundary has been placed at approximately 10,000 years BP (6), although there is some debate on when the greatest warm-up occurred. The sea-level curve of Ters (24) shows that the oceans were rising very rapidly by 9,000 BP. It is at this point in time that the solar-output model is date calibrated (point A, Fig. 1). In further comparison of the sea-level fluctuations during the Holocene, the shape of the Ters sea-level curve (24) generally resembles that of the solar-output model. Other dated events in the very late Pleistocene can be compared with the solar-output model. Larson and Stone (25) have dated the farthest full glacial advance at 21,800 BP (point B, Fig. 1), whereas Shackleton and Hall (26) and Woillard and Mook (27) have independently dated the coldest temperatures of the last full glacial period as being 16,000 BP (point C, Fig. 1). Both periods coincide with low points in the solar-output model. Later, the warm glacial periods were interrupted by brief and sudden cold periods of the Older Dryas centered near 12,100 BP (point D, Fig. 1) and the Younger Dryas near 10,300 BP (28) (point E, Fig. 1) which also coincide with low points in the solar-output model.

Comparison of Modeled Solar Output and Archaeological and Historical Evidence

A warming period from 33,000 to 26,000 years BP (bar at F, Fig. 1) during the last continental glaciation may have allowed the Cro-Magnon Man to migrate northward and populate Europe by either acculturation (29) or eradication of the resident Neanderthals. Linguistic (9) and genetic evidence (30) suggest that the Americas were populated during the very late Pleistocene by several waves of migrations from Asia, one of which may have occurred approximately 20,000 years BP (point G1, Fig. 1). These migrations possibly could have occurred as early as 32,000 years BP, but other groups may have migrated during warm-ups near 15,000 years BP (point G2, Fig. 1) and near 11,000 years BP (point G3, Fig. 1) just before the land bridge between Asia and Alaska was finally inundated by the rapidly rising sea levels.

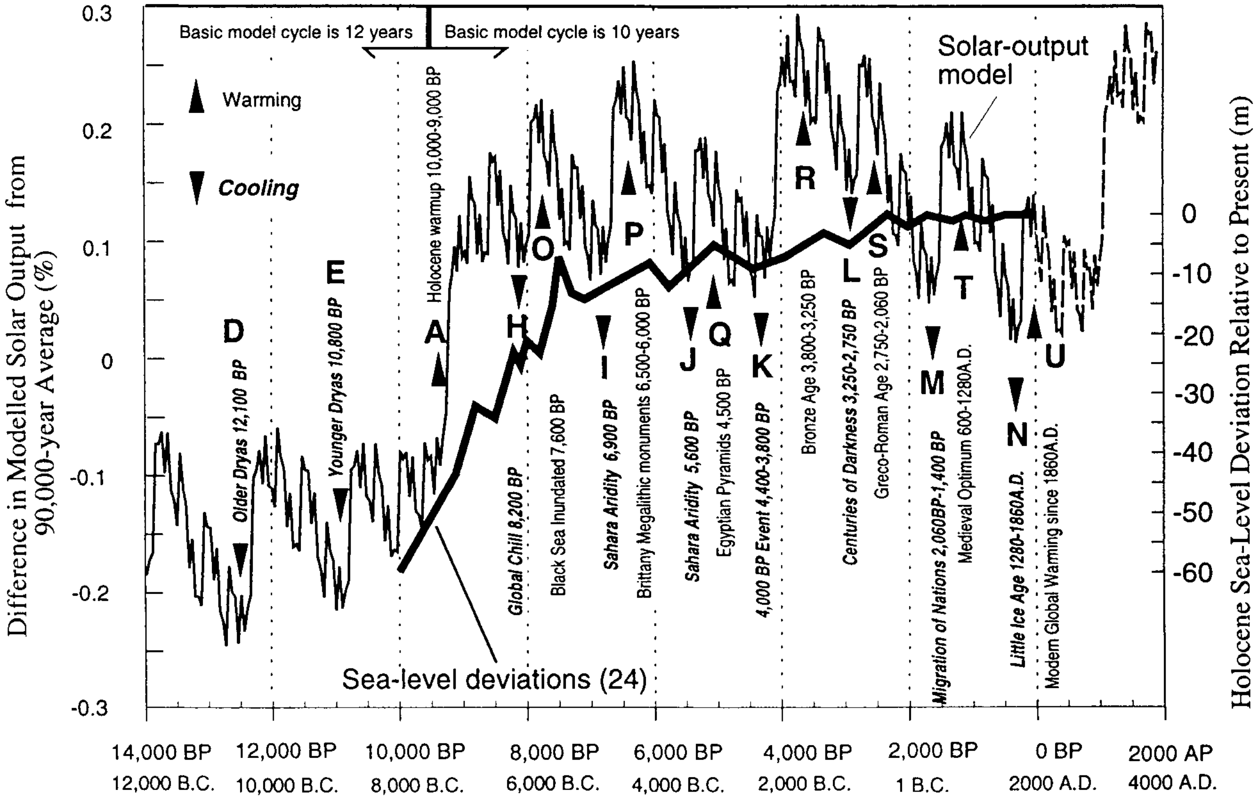

Fig. 2. Solar-output model from 14,000 years BP to 2,000 years AP compared with sea-level deviations (24) and selected events.

The solar-output model can be evaluated more accurately with dated events in the Holocene. Fig. 2 is a more detailed depiction of the solar-output model representing the period 14,000 years BP to 2,000 years AP. A notable feature is the approximate 1,300-year little-ice-age cycle that is apparent throughout the Holocene in the Ters sea-level curve and in the output model. This also coincides with historical events interpreted by Hsu (9) as being related to periodic climate changes, as evidenced by the records of history and natural science. The Older Dryas at 12,100 years BP and the early phase of the Younger Dryas at 10,800 years BP (28) correspond well with the little-ice-age cycle of approximately 1,300 years throughout the Holocene. However, there is one exception to the regular little-ice-age cycle. There is no evidence of a cold period near 9,500 years BP in the sea-level data. The solar-output model near 9,500 years BP also does not show a decrease in solar output but instead a sharp increase. During this period the positive amplitude of all of the other 12 harmonic cycles completely overwhelms the approximate 1,300-year little-ice-age cycle. After missing a little-ice-age period during the Pleistocene/Holocene transition it returned on time near 8,200 years BP in both the solar-output model and the geophysical climate record.

The "Global Chill" centered near 8,200 years BP (point H, Fig. 2) on the solar-output model is reflected in a small dip in the otherwise steady rise in the Ters sea-level curve. Later, there is evidence for two "Sahara Aridity" cold periods, one centered near 7,000 years BP (point I, Fig. 2) and another at 5,500 years BP (point J, Fig. 2), which prompted a great migration of a pastoral civilization from the now Sahara Desert to the Nile River Valley in Egypt (9). The "4,000 BP Event" that in fact prevailed from 4,400 to 3,800 BP (point K, Fig. 2) (9) may have been the coldest period since the Younger Dryas cold period. The "Centuries of Darkness" from 3,250 to 2,750 years BP (point L, Fig. 2) included the downfall of the great empires of the Bronze Age (9). Another little ice age occurred during the period from 2,060 to 1,400 years BP [60 before Christ (B.C.) to *anno Domini* (A.D.) 600] (point M, Fig. 2) called the "Migration of Nations," when at its coldest point, the Germanic tribes overran the Roman Empire and the northern Asiatic tribes overran the Chinese Empire (9). Concurrently in Central America, the cooler climate may have allowed the Mayan civilization to prosper. The cooling of this area of the tropics forced the mosquitoes that carried malaria to move farther south, allowing extensive farming and the construction of cities. When world climate warmed again, the Maya had to abandon their fields and cities and were forced to migrate northward to escape the returning malaria scourge (9).

The most recent of the climatic cooling periods was experienced during 720 to 140 years BP (A.D. 1280–1860) (point N, Fig. 2) when the climate worldwide was probably the coldest since the continental glaciers melted 10,000 years ago and is referred to as the "Little Ice Age" (31). Although the cold periods of the little ice ages vary in length and severity, they seem to track the solar-output model reasonably well. As a result of cold and drought and war, human population probably declined during each of these little ice ages.

In contrast, warmer climates were accompanied by more rain, longer growing seasons, more crops, and more land to settle on. Civilizations prospered and great human achievements were attained. A similar cycle length of approximately 1,300 years between warm periods extends through the Holocene. Rapid warming about 7,600 years BP (point O, Fig. 2) coincides with the flooding of the Black Sea basin (32) as sea levels rose from the melting of the remnants of the continental glaciers, Antarctic glaciers, and the many alpine glaciers. Nearly 1,300 years later between 6,500 and 6,000 years BP (point P, Fig. 2), Brittany megalithic monuments were built (9). The climate of the British Isles had returned to a favorable level, allowing prosperity to

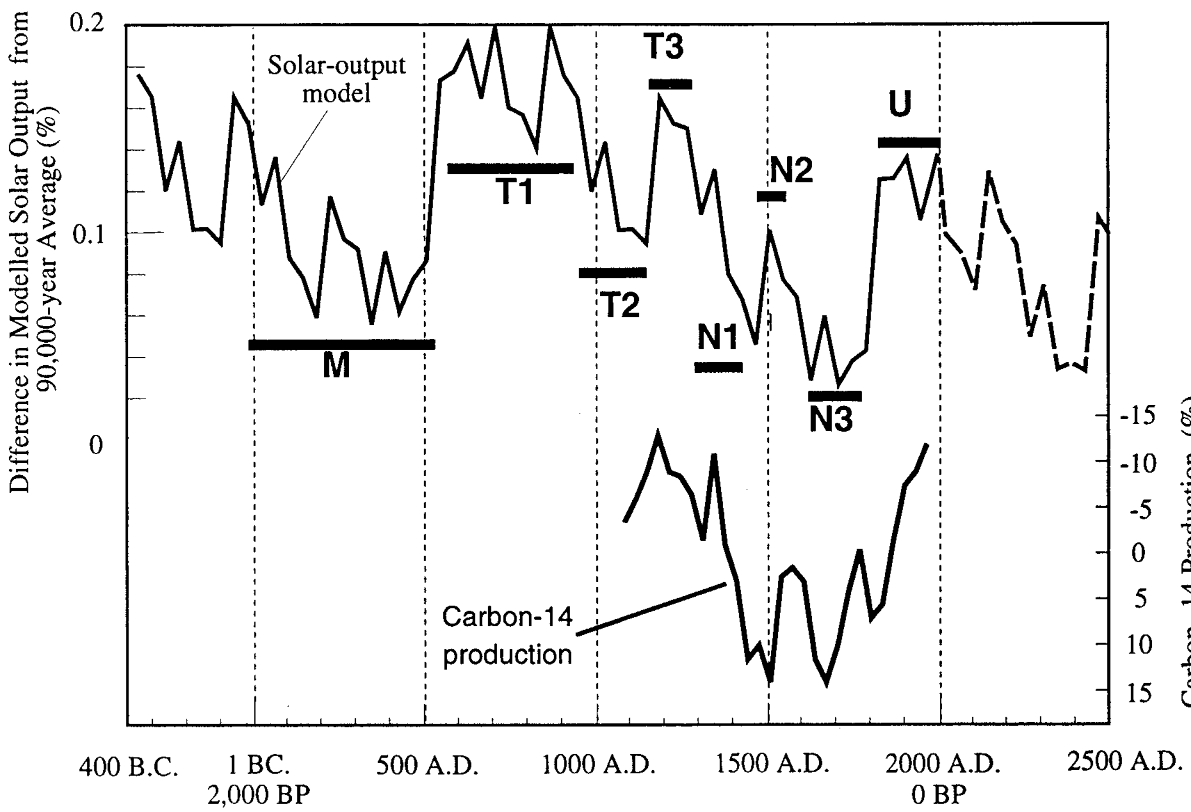

Fig. 3. Solar-output model from Gregorian calendar dates 400 B.C. to A.D. 2500 compared with carbon-14 production (36) and selected events.

return after the little ice age near 6,900 years BP. The warmer climate and prosperity allowed people time to haul huge blocks of rock many miles to construct great monuments. This civilization eventually was lost during the following little ice age during which the Man-in-Ice was buried under the first alpine glacier of the Dolomites near 5,300 years BP (9). By 5,000 years BP the warmth returned, and the first Egyptian Empire was beginning to flourish, and near 4,500 years BP (point Q, Fig. 2), the Great Pyramids were constructed (9). In India, the Harappa civilization also flourished during these warmer and wetter times only to be eradicated by conditions brought on by extreme drought during the long-lasting cold "4,000 BP Event" (9, 33).

The 4,000 BP Event was perhaps the most influential little ice age in recorded history. Global cooling started as early as 4,400 BP and ended some 600 years later. Archaeological evidence (33) indicates that the years 4,200–3,900 BP were coldest and most arid in western Asia. The cooling signifies the change from the early Holocene Climatic Optimum to late Holocene alternations of little climatic optimums and little ice ages (9). Varves from Swiss lakes indicate that the alpine glaciers became widespread during this first of the historical little ice ages. An important historical consequence of the 4,000 BP Event was the migration of the Indo-European peoples from northern Europe, to Greece, to southern Russia, to Anatolia, to Persia, to India, and to Xinjiang in northwest China (9).

The next warm period ushered in the Bronze Age, which began about 3,800 years BP (point R, Fig. 2); this probably was the most favorable climatic period of the Holocene and is also referred to as the Holocene Maximum (9). People migrated northward into Scandinavia and reclaimed farmland with growing seasons that were at that time probably the longest in more than 2 millennia. The great Assyrian Empire, the Hittite Kingdom, the Shang Dynasty in China, and the Middle Egyptian Empire flourished (9). The Bronze Age came to an end with the "Centuries of Darkness" chill, but warming returned during the "Greco-Roman Age" from 2,750 to 2,060 years BP (9) (point S, Fig. 2). During this period, philosophy made its first important advances with the thoughts of the great Aristotle. However, the climate cooled again between 2,000–1,400 years BP and the Roman Empire came to an end.

The next warm period was known as the Medieval Optimum (9) (point T, Fig. 2), which was just beginning near 1,400 years BP and lasted until the Little Ice Age began about 700 years later. Currently, the Earth is enjoying the latest warm period (point U, Fig. 2), which has been underway for almost two centuries.

The solar-output model and selected events are expanded in Fig. 3 for the period after about 2,300 years BP. The initial time calibration remains the same, only the resolution of the solar-output model and the selected events is increased. To avoid confusion of dates, the Gregorian calendar system will be used for the next section where 2,000 years BP coincides with 1 B.C.

At the time the Mayan civilization abandoned their great cities in Central America and migrated northward into the Yucatan Peninsula (A.D. 500), the Vikings were gaining power in northern Europe. By A.D. 1000 (bar T1, Fig. 3), they had discovered Greenland and had traveled on to Newfoundland. Grain was grown in Greenland, and northern Europe prospered as the first millennium (A.D.) came to an end (34). However, after A.D. 1000 the climate in the northern latitudes began to slowly deteriorate with the cooler centuries of the Medieval Optimum during the 1000s and 1100s (bar T2, Fig. 3). A brief return to a warm climate near A.D. 1200 (bar T3, Fig. 3) coincided with an increase in the building of cathedrals in Europe.

After A.D. 1200, the climate began to cool more rapidly. The frozen harbors of Greenland failed to open in the summer, and trade with Europe dwindled rapidly (34). Thirty-five hundred miles to the southwest, the Anasazi civilization in the southwestern part of North America left the tranquility of large pueblos for the protection of the cliff dwellings. Maize became more difficult to grow as the continuing lack of precipitation allowed the desert to return to the American Southwest (9). By A.D. 1400 (bar N1, Fig. 3), Europe's contact with Greenland had been lost, and the Anasazi had totally abandoned even the cliff dwellings. A slight warm-up about A.D. 1500 (bar N2, Fig. 3). allowed the return of ships to Greenland, but they found that the stranded Viking population had starved to death. Examination of their cemeteries showed that with time the graves became shallower as the permafrost returned (34). The 1500s was only a brief respite as the coldest times of the Little Ice Age were yet to come in the 1600s (bar N3, Fig. 3).

Half a world away in the tropical Pacific Ocean a similar saga unfolded. During the Greco-Roman climatic optimum, the Polynesians migrated across the Pacific from island to island, with the last outpost of Easter Island being settled around A.D. 400 (35). Between A.D. 1000 and 1350 the people moved to the ocean shores great blocks of stone carved into Moais. Moai building ceased around A.D. 1350 as famine spread across the island. Did the people of Easter Island eventually fall into cannibalism by the late 1600s (35) as a result of environmental degradation by overpopulation, or was it a major change in global climate caused by a decrease in solar output that converted their home from a wet tropical island into a desert island during the Little Ice Age?

Fluctuations of the Sun's intensity are recorded by the amount of carbon 14 in well-dated tree rings during this period (36). Carbon-14 is produced in the atmosphere by cosmic rays that are less abundant when the Sun is active and more abundant when the Sun is less active. The fluctuations of carbon-14 in dated tree rings are shown inverted in Fig. 3 for easier comparison to the solar-output model. The carbon-14 trace corresponds well with the solar-output model and selected events since the Medieval Optimum (about A.D. 1100), which further supports the hypothesis that the Sun is varying its energy production in a manner that is consistent with the superposition of harmonic cycles of solar activity.

Great civilizations appear to have prospered when the solar-output model shows an increase in the Sun's output. Increased solar output would have caused the atmosphere and oceans to warm, therefore increasing the amount of water vapor in the atmosphere and causing increased precipitation. Growing seasons in the more polar latitudes became extended. Lands marginal for human habitation became favorable to support a growing population as deserts became wetter and the subArctic became warmer. Great civilizations appear to have declined when the modeled solar output declined. Severe and long-lasting droughts came to the steppes, winters in the subArctic became fierce, and growing seasons shortened. Similar processes currently are evident on a smaller scale. In the central parts of North America, droughts occur after the Sun's output has decreased slightly over a period of several of years, and when the Sun's output increases, an abundance of moisture follows in several years (10).

Current global warming commonly is attributed to increased CO_2 concentrations in the atmosphere (3). However, geophysical, archaeological, and historical evidence is consistent with warming and cooling periods during the Holocene as indicated by the solar-output model. The current warm period is thought to have not reached the level of warmth of the previous warm period (A.D. 800-1200), when the Vikings raised wheat and livestock in Greenland. Therefore, the magnitude of the modern temperature increase being caused solely by an increase in CO_2 concentrations appears questionable. The contribution of solar-output variations to climate change may be significant.

Extrapolation of Solar Output

Because of the favorable agreement between the solar-output model fix and past climatic events, it is possible to speculate on long-range projections of global climate. Projections of future solar-luminosity variations provided by the solar-output model are shown as a dashed line in Figs. 1–3. Extrapolation of the model shows that the current warm period may be ending and that the Earth's climate may cool to conditions similar to the Little Ice Age by A.D. 2400–2900. The total decrease in solar output may be only about half the decrease experienced from A.D. 900 to 1700. The model shows a slight cooling during A.D. 2000–2100, possibly leading to more severe droughts in the African Sahel than were seen in the minor global cooling that occurred in the 1970s. The following three centuries (A.D. 2100–2400) show a gradual temperature decrease toward another little ice age. However, by the middle of the third millennium A.D. (1,500 years from now), the model shows a return to the altithermal conditions similar to the Holocene Maximum that occurred during the Bronze Age that began about 3,800 years ago. Warmer and wetter conditions may prevail on a global scale, with the warmth possibly sufficient to melt the polar icecaps and flood the world's coastlines. There is evidence that this happened during the last interglacial period, when sea levels were 3–5 m above present sea levels (37).

The solar-output model timeline also can provide an estimate of the length of the current interglacial period. Marine cores have suggested that the average length of the interglacial periods is approximately 10,000 years (38). However, there is compelling continental evidence that the average interglacial period may be twice as long. A 500,000-year-long delta oxygen-18 time series obtained from vein calcite in Devel's Hole, Nevada, shows an average of 22,000 years for the length of the interglacial periods (39). Other continental and marine evidence (40) during the previous interglacial period ($\approx$130,000 to $\approx$110,000 years BP) show fluctuations toward glacial conditions that are consistent with the solar-output model. In the model, solar output is greater than 0% of the glacial-cycle average for 15,000 years, from 9,000 BP to 6,000 years from now (Fig. 1). About 10,000 years from now, the model shows an end to the interglacial period and a gradual temperature decrease into glacial conditions punctuated by increasingly briefer warm periods and longer and more intense little ice ages.

Summary

The development and calibration of a solar-output model for climate are supported by geophysical, archaeological, and historical evidence from the last full glacial Pleistocene (30,000 years BP) through the current Holocene interglacial to the present. The solar-output model is based on a superposition of a fundamental harmonic progression of cycles beginning at 10 and 12 years and progressing to the 13th harmonic (90,000-year cycle), which is approximately equal to the average continental glacial cycle. This model was date calibrated to the Pleistocene/Holocene boundary at 9,000 years BP and compared with geophysical records of sea level, carbon-14 production, oxygen 16/18 ratios, and other geologic evidence of climate fluctuations. The approximate 1,300-year little-ice-age cycle and intervening warmer periods agree with archaeological and historical evidence of these cold and warm periods. Throughout history, global warming has brought prosperity whereas global cooling has brought adversity.

The solar-output model allows speculation on global climatic variations in the next 10,000 years. Extrapolation of the solar-output model shows a return to little-ice-age conditions by A.D. 2400–2900 followed by a rapid return to altithermal conditions during the middle of the third millennium A.D. This altithermal period may be similar to the Holocene Maximum that began nearly 3,800 years ago. The solar output model suggests that, approximately 20,000 years after it began, the current interglacial period may come to an end and another glacial period may begin.

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