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15. For example, if one atom of the exposed surface were removed for each incident solar wind ion, it would give the observed erosion rate.
16. A recent flaking off of a 100-μm chip would leave a surface with a lower track density characteristic of a greater (that is, 100 μm) depth. Thus, for example, the large discrepancy between the track density profiles of rock 10058 and of rock 10017 or 10003 would be resolved if a 75- to 300-μm chip had rather recently been removed from rock 10058, either by a natural process or in handling during recovery.
17. However, one test of this assumption will come from repeated evaluation of t from the place of break in the curve from $R^{-1.6}$ to $R^{-2.6}$. If this age consistently agrees with values that are independently derived from the galactic cosmic rays (*10, 13*), it will constitute strong support for the long time applicability of an E^{-3} relation.
18. We thank E. L. Haines for bringing to our attention the fact that Surveyor 3 parts were to be returned to earth, W. R. Giard and E. Stella for experimental assistance, E. W. Balis, L. B. Bronk, and D. H. Wilkins for prompt chemical analysis of the glass, R. C. DeVries for measuring the index of refraction, and N. Nickle for numerous communications relative to the exposure of the glass. We are indebted to the National Aeronautics and Space Administration for supplying the Surveyor glass.

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Solar-Climate Relationships in the Post-Pleistocene

Abstract. *The most conspicuous climatic aberration of the past two millennia was the temperature decline and glacial advance of the A.D. 1550 to 1900 period. This temperature decline has been correlated with an interval of lower solar activity and there is evidence from both the post-Pleistocene glacial record and from oxygen-18 analysis that such an interval has recurred at cyclic periods of around 2400 to 2600 years.*

During the past several millennia, temperature changes have occurred which have been correlated with variation in solar output, both for the period of European solar observations and for the longer interval of the less exact Oriental observations (*1*). These correlations have been demonstrated mainly on time intervals of a century or more and are in contrast to the lack of agreement in studies of solar-climate relationships on the scale of a year or less. The greater agreement in solar-climate correlations on a broader time scale is possibly the result of oceanic thermal inertia, but whatever the reason, the correlations reached a higher statistical significance when a cumulative index of solar activity was used (*1*).

The likelihood of some sort of solar control over climate has been greatly enhanced in the last 2 years by the discovery of cycles of around 2400 to 2600 years in the periodicity of glacial advance (*2, 3*) and in the temperature-related $\delta^{18}O$ data from the Greenland Camp Century ice core (*4*). There is evidence that these cycles are based on variation in solar activity and they have been used for extrapolation into the recent past and near future. Whether solar cycles of larger temporal amplitude have a climatic influence is still unknown; their potential discovery will be implemented if the nature of solar-climate relationships on smaller scales is better understood.

European measurements of sunspot activity have been summarized (*5*) from 1610 to 1960 and continued to the present. Of less reliability are the more extensive Oriental observations of sunspot and auroral activity (*6, 7*) which were erratically recorded by numerous observers over the period 522 B.C. to the present. These data were combined into a single solar index (*8*), which, by using both sunspot and auroral observations, or either of these if the other were missing, was able to present an index for 206 of the 227 single sunspot cycles since 522 B.C.

The reliability of this solar index has been shown by both internal evidence and by indirect methods. The index was negatively correlated ($r = -.70$, $P < .001$) with sunspot cycle length over the period 527 B.C. to A.D. 1964 (*8*). The significance of this correlation is that there was a strong relationship ($r = -.64$, $P < .001$) between sunspot cycle length (measured from cycle maximums) and mean yearly sunspot number per cycle for the European data over the interval A.D. 1699 to 1964 (*9*). The correlation between the solar index and sunspot cycle length is important because of the statements of Schove (*6*, pp. 127–128) which indicate that he was not using sunspot cycle length as a possible guide to his assessment of sunspot (or auroral) activity. Indirect evidence for the validity of the index is: (i) a correlation ($r = -.51$, $P < .01$) of 31 outlined solar activity periods from 527 B.C. to A.D. 1964 with ^{14}C variation (*8*); (ii) a change in ^{14}C activity inverse to the change in solar activity in 22 of 24 instances for a $X^2 = 20.2$, $P < .001$ (*8*); and (iii) a negative correlation ($r = -.55$, $P < .05$) of the solar index with ^{18}O variation for the 17 centuries since A.D. 300 (*10*).

The period of sunspot dearth from around A.D. 1645 to 1715 was noted to have preceded a period of maximum glacial advance in Alaska, British Columbia, and Oregon (*11*). Subsequent study (*12*) found that for the Pacific Northwest, British Columbia, and Alberta, two intervals, 1711 to 1724 and 1835 to 1849, contained over one-half the glacial advances from 1580 to 1900. These intervals followed the two lowest periods of European solar activity measurements (1645 to 1715 and 1798 to 1833). A further analysis (*9*) found that given a lag period of 18 years to allow for ice accumulation and flow to the terminus, there was a X^2 of 7.7 ($P < .006$) for the hypothesis that an equal number of glacial advances should occur after the four highest and the four lowest sunspot activity periods since 1611.

A summary of worldwide glaciation patterns since the 5th century B.C. (*2*) found that this activity was historically synchronous throughout the world and that glaciation was associated with periods of lower solar activity if these periods were of sufficient length and were not preceded by long intervals of higher solar activity. The tendency of solar periods of sufficient length to have a climatic impress was demonstrated in a rank correlation ($r =$

$-.45$, $P < .05$) over the past two millennia between worldwide glaciation and a 200-year cumulative solar index (*1*).

A graph of severe winters based on historical records (*13*) showed that their greatest frequency from A.D. 300 to the present occurred in the 17th century, the period of lowest solar activity. A general correspondence was found (*14*) between warm periods and high sunspot activity and cooler periods and lower activity from 1750 to 1950. This correspondence was supported by a summary of climatic patterns from 1580 to 1960 (*12*) which used absolute forest growth to extrapolate world temperature data to the 1580 to 1750 period. Solar activity data were extrapolated by the same method, and the results were later confirmed by the solar activity index based on Oriental data (*8*).

More recently an analysis on a century basis over the past two millennia found that of eight indexes directly or indirectly related to temperature, three had a significant rank correlation with the solar index and seven of the eight were significantly correlated with the 200-year cumulative solar index (*1*).

The three most recent post-Pleistocene glacial phases were found to be separated by around 2300 to 2500 years (*2*). Projection of such a cycle back into the Pleistocene suggested that an interval of around 2600 years gave the best fit with the climatic data which were based, however, on uncorrected ^{14}C time. With this projection, 50 of 66 events indicating temperature decline occurred in periods of lower than average predicted solar activity and 29 of 37 events indicating temperature increase occurred with predicted higher than average solar activity ($X^2 = 28.6$, $P < .001$). A later attempt to convert from ^{14}C to true time (*3*) suggested that the intervals between the four most recent glacial phases were around 2900, 2570, and 2555 years, of which the first was not very reliable. The relationship of this cycle to a possible solar cycle was shown (i) by the correlation of the most recent glacial phase (the Little Ice Age of A.D. 1550 to 1900) with an extended period of decreased solar activity and (ii) by the regular occurrence and short duration of the preceding two and probably three glacial phases.

Spectral analysis based on the Fourier integral of the $\delta^{18}O$ record at Camp Century, Greenland, indicated long-term oscillations of the climate with periods of 400 and 2400 years (*4*). These oscillations were suggested to be the result of varying solar activity on the basis of similar variation in the ^{14}C concentration in tree rings over the past 7000 years. Oscillations of 78 and 181 years were also determined, and the relationship between the 78-year period and the sunspot cycle was noted. The correlation between ^{18}O variation and the solar index (*10*) is additional evidence that these ^{18}O cycles may be related to solar activity.

What is important about the discovery of a potential 2400- to 2600-year solar cycle by two independent analyses is its noted close correspondence to the climatic history of the past several millennia. The slight variation in the estimate of the length of the cycle could be expected, given the difficulties in the glacial phase study of exactly dating the periods of glacial culmination and of converting from ^{14}C to true time, and, in the study of the Greenland Ice Core, the difficulty of basing age on a simple ice flow model calibrated against known climatic events.

As the dating of the late- and post-Pleistocene becomes more exact, it should be possible to precisely determine the length of the presumed solar cycle. Or, if we understand more about the shorter-term solar cycles, it may be possible to determine the length of the 2400- to 2600-year cycle by simple calculation.

The significance of climatic predictions based on solar activity cycles would be enhanced if a solar-climate mechanism could be verified. The conflict and confusion in the studies of such a mechanism have resulted in a suspicion of the whole field of solar-climate relationships (*15*). The recent work on the presumed 2400- to 2600-year solar cycle and the demonstrated long-term solar-climate correlations may dispel some of this suspicion and stimulate additional geophysical study. In such study, it is possible that the influence of solar flare activity will be relevant judging by some of the solar-climate correlations noted above. For western Europe, there was a positive relationship between the prevalence of southwesterlies and solar flare activity (*16*). That this relationship may have occurred in earlier times is indicated by the observation of a great dominance of southwesterly winds around A.D. 1350, 1530, 1730, and 1920 (*17*), four dates which are at the beginning of four of five outlined periods (*8*) of higher solar activity over the same interval. In a later study (*15*) an increase in solar flares was found to have resulted in the development of warm and dry summers and less severe winters in western Europe.

A future decline in solar activity accompanied by falling temperature was predicted in 1951, with a first temperature minimum predicted for around 1960 to 1965, and another quarter as warm as 1925 to 1950 unlikely before the beginning of the next century (*14*). A reversal of the worldwide glacial recession was also predicted, with ice advance predominating over recession for the next 50 years. Judging by the summary of Lamb (*18*), these predictions have been, mainly, correct. Another glacial phase of the magnitude of the A.D. 1550 to 1900 "Little Ice Age" was predicted for around A.D. 4300 on the basis of the 2600-year solar cycle (*3*). This era could be sufficiently cool for the development of mid-latitude continental glaciation if the rapid cooling predicted on the basis of the Milankovitch hypothesis to occur after A.D. 2450 (*19*) eventuates.

Further study of the timing and mechanism of the 2400- to 2600-year cycles may reveal whether larger scale climatic events, such as the shift from glacial to inter-glacial, have a solar basis.

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