CLIMATE AND THE CHANGING SUN

JOHN A. EDDY
Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory, Cambridge, Mass. 02138, U.S.A.

Abstract. Long-term changes in the level of solar activity are found in historical records and in fossil radiocarbon in tree-rings. Typical of these changes are the Maunder Minimum (A.D. 1645–1715), the Spörer Minimum (A.D. 1400–1510), and a Medieval Maximum (c. A.D. 1120–1280). Eighteen such features are identified in the tree-ring radiocarbon record of the past 7500 years and compared with a record of world climate. In every case when long-term solar activity falls, mid-latitude glaciers advance and climate cools; at times of high solar activity glaciers recede and climate warms. We propose that changes in the level of solar activity and in climate may have a common cause: slow changes in the solar constant, of about 1% amplitude.

1. The Sun and Climate

Is climate affected by changes on the sun? Since it is solar energy that drives the atmosphere of earth – creating clouds and winds and rains and ocean currents – the answer would seem obvious. Yet this question has been the subject of continuing controversy in science for more than a century. In doubt is not whether the sun is a potential source of weather and climate change (it is), or whether the sun and its measurable outputs vary (they do), but whether there is any clear-cut evidence that the sun changes enough and in ways sufficiently energetic to produce detectable changes in our lower atmosphere.

Known changes in solar output are today limited to energetically-insignificant parts of the sun's total energy output: changes in the sector structure and physical properties of the solar wind, that carries less than a billionth part of the flow of energy from the sun and reaches only the uppermost atmosphere; significant, activity-related changes in x-rays and ultraviolet wavelengths that cannot penetrate the stratosphere; and order-of-magnitude increases in radio emissions that reach the surface of the earth with no apparent meteorological effect. The bulk radiation from the sun, which through radiative heating is the real atmospheric driver, is in the near ultraviolet, visible, and near infrared, and this dominant component is known, or more truthfully, suspected, to be constant within our present ability to measure it. Moreover our physical understanding of known features of solar variability – including sunspots, flares, plages, and coronal disturbances – gives no basis for presuming that these transient events should alter the total flux of light from the sun in any appreciable way. Abbot's measurements of the integrated solar flux, or solar constant, spanning most of the first half of the present century, revealed short-term fluctuations of a few tenths of one percent [1]. These apparent

Climatic Change 1 (1977) 173–190. *All Rights Reserved.*

changes, which may have been only measurement errors [2], were uncorrelated with day-to-day changes on the sun or with the well-known 11-year solar activity cycle. And since they were made from the base of the atmosphere they probably cannot be separated from possible, concurrent changes in the turbidity and transparency of the atmosphere itself [3]. This conservative appraisal of the only extended solar constant data seems corroborated by recent measurements from above the atmosphere [4]. Recent data from the Nimbus 6 spacecraft, made during uniformly quiet solar behavior, reveal no variations greater than the measurement tolerance of about 0.1%. Prior measurements from Mariners 6 and 7, obtained during high and variable solar activity, gave the same result.

The apparent constancy of the sun's bulk radiation has fostered searches for atmospheric changes that could be triggered by short-wave or particle inputs to the top of the atmosphere. Though lacking a demonstrated physical mechanism, a statistical case has been made for perturbations in tropospheric vorticity that follow the passage of sector boundaries in the solar wind [5]. And several theoretical mechanisms have been proposed that link known changes in solar ultraviolet flux to the chemical constitution of the upper atmosphere, chiefly involving ozone [6].

2. Long-Term Solar Change

Almost all efforts to identify a sun-weather connection have concentrated on changes of short term, and have focussed on the cyclic behavior of solar activity that is most easily observed in daily changes in the numbers of spots on the sun, and the 11-year sunspot cycle. With this restriction we may have overlooked other regimes of solar change that could be more fundamental both in solar behavior and in terrestrial response. In studying climate change, in particular, we are obliged to consider the possibility of solar variation of term longer than 11 years. The existence of longer-term changes is apparent to any who examine the overall envelope of sunspot numbers (Figure 1), a record that extends for over 350 years and thus embraces periods of marked terrestrial climate change. The amplitudes achieved at 11-year maxima in the curve of annual sunspot numbers are far from uniform. Apparent is an undulation of about 80 years period, called the 'Gleissberg cycle', and other longer-term anomalies. Sunspots and related solar activity seem to have fallen to near-zero levels during a period in the late 17th and early 18th centuries known as the Maunder Minimum [7]. As we shall see, a repeated history of similar excursions in solar behavior is found in the longer record from tree-ring radiocarbon [8].

The frequency and persistence of periods of prolonged solar inactivity like the Maunder Minimum now warn us to be cautious in labelling the present, modern era of solar behavior as 'normal'. Indeed, in the longer view it now seems likely that the entire period of intensive physical study of the sun, since perhaps the middle 18th Century, has been a time of uncommonly high levels of solar activity [7,8]. And it may be significant that the same period describes as well a time of unusually benign climate – the gradual recovery from the Little Ice Age.

The existence of these major, long-term changes in the level of solar activity presents

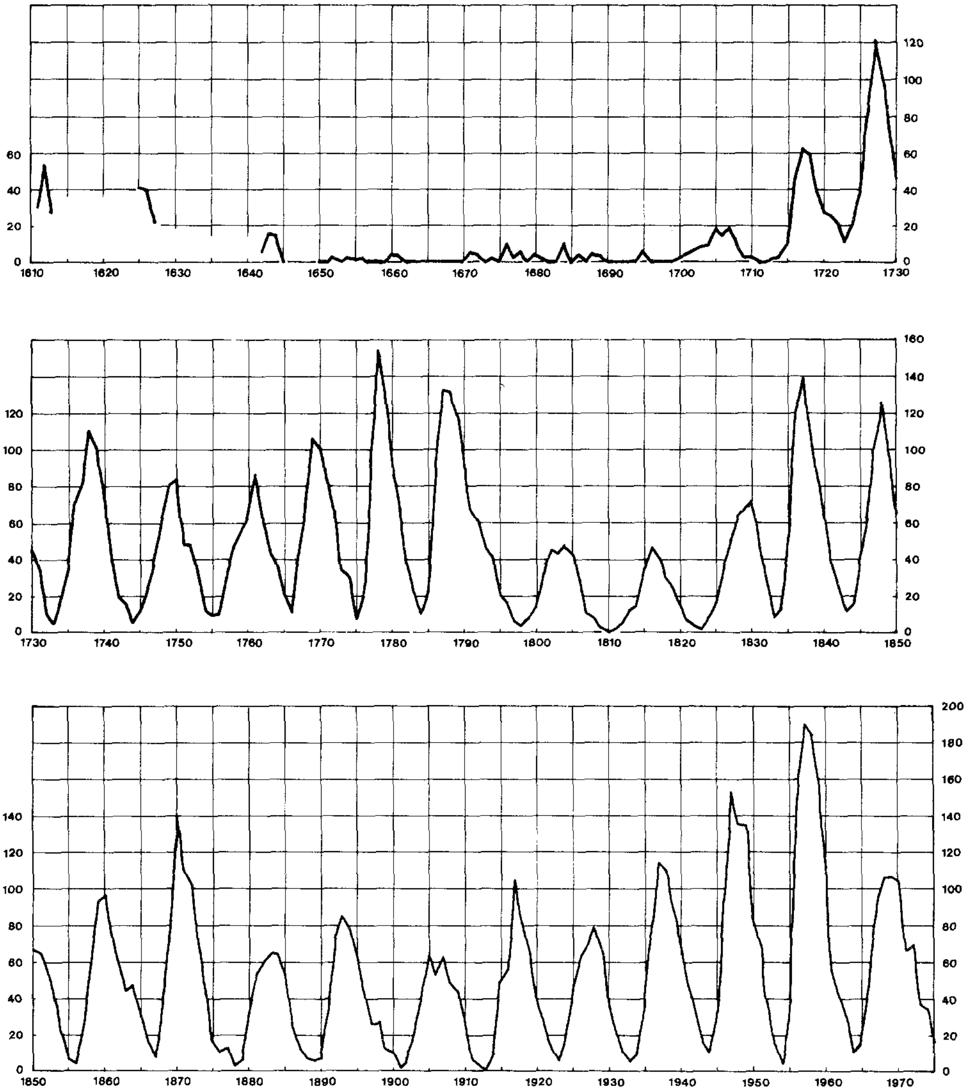

Fig. 1. Annual mean sunspot numbers, A.D. 1610 to the present, from Waldmeier [29] and Eddy [7]. Period from about 1645–1715 is the Maunder Minimum.

a new challenge to solar and terrestrial physics, for in both fields we have worked under a tacit principle of solar uniformitarianism, assuming that modern solar variability represents the full range of the sun's behavior in the past, and particularly through the Quaternary Epoch of man. There are reasons to suppose that major changes in the envelope of solar activity could have significant terrestrial effects. We may presume, for example, that terrestrially-important characteristics of the solar wind, now identified with coronal holes and sector boundaries, could be scaled upward in effect and persistence during periods of extended solar inactivity such as the Maunder Minimum. Prolonged periods of enhanced solar activity, or inactivity, could conceivably increase or diminish present-day levels of solar ultraviolet flux from the sun, with possible long-term modification of the chemical composition of the upper atmosphere. Several lines of evidence now suggest that the varying envelope of solar activity may directly record long-term excursions in the solar radiative flux, for the coincidence of peaks and valleys in the solar activity envelope with mid-latitude temperature excursions points to a possible direct thermal connection. The persistent rise in the level of solar activity in the first half of the present century (Figure 1) matches very well the established increase in world temperature averages during the same time. And the Maunder Minimum coincides in time and extent with the coldest extreme of the Little Ice Age in Western Europe and America [9,10].

3. Extended Solar History from Radiocarbon

Two developments have recently called attention to the magnitude of significant long-term solar change: a re-examination of the early historical record of solar behavior to the advent of the telescope, about 1610, and the quantitative use of fossil radiocarbon as a proxy indicator of solar behavior over a much longer time span.

The ^{14}C isotope is produced in the upper atmosphere of the earth as a result of bombardment by galactic cosmic rays [11]. The cosmic ray flux is not constant, and thus the production rate of radiocarbon varies with time. Among the established modulators is solar activity, apparently through the influence of the sun's extended magnetic field, that scatters charged, cosmic ray particles. The solar modulation of galactic nucleonic flux is well established in modern observations [12], as is its effect on ^{14}C production [13,14]. Direct measurements of high-energy cosmic ray fluxes establish an inverse relationship with solar activity: when solar activity is high, the earth is more shielded from galactic cosmic rays by the sun and ^{14}C production is diminished. When solar activity is low we receive an enhanced flux of cosmic rays and more ^{14}C is produced. Other effects are also important, the most obvious being the varying strength of the earth's magnetic moment, that changes in amplitude by about a factor of two in an apparent period of roughly 10 000 years [14,15,16].

If we had a record of how much ^{14}C was present in the atmosphere in the past, we could in principle deduce the history of solar activity. Such a record exists in carbonaceous fossil material, and most usefully in trees, where ^{14}C is assimilated as CO_2 in the process of photosynthesis. Individual tree rings preserve a record of the prevailing $^{14}C:^{12}C$ abundance ratio in the lower atmosphere at the time they were formed. The record can be read, year by year, in living trees, such as the bristlecone pine, to about 3000 B.C., and extended in well-preserved dead wood to beyond 5000 B.C.

In interpreting the tree ring record for evidence of changes in solar activity, we must allow for several important effects. Of fundamental importance is an appreciable delay in the atmospheric reservoir between instantaneous changes in ^{14}C production in the upper atmosphere and resultant ^{14}C abundance variations in the biosphere. This lag is on the order of 10 to 50 years [17]. It tends to smear and wash out short-term changes such as

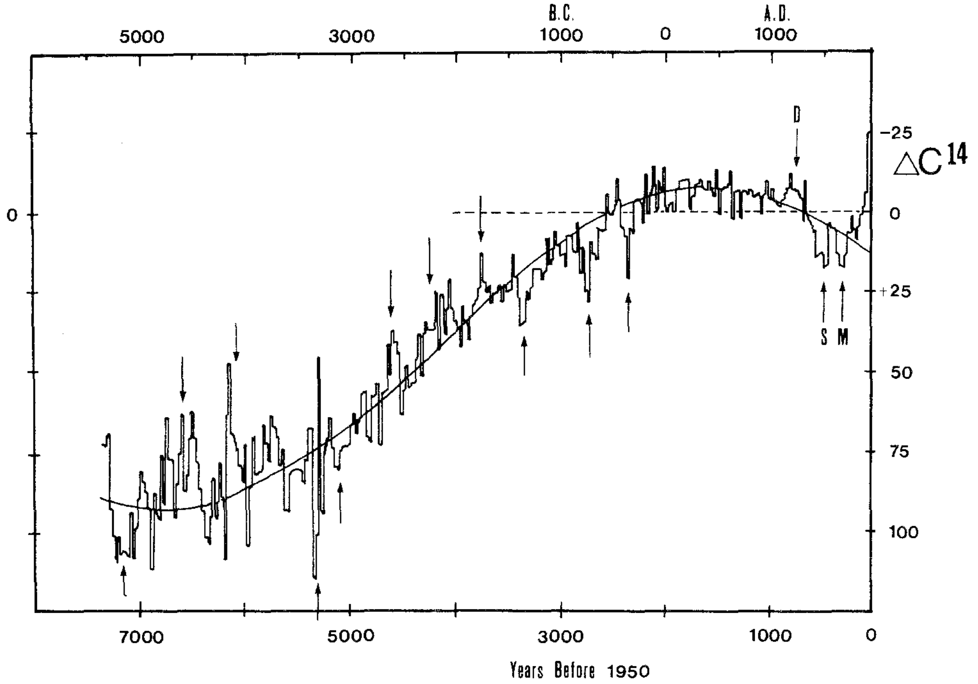

Fig. 2. Record of deviations of relative atmospheric carbon-14 concentration for tree ring analysis, in parts per mil, for about 7000 years before the present (B.P.) from Lin *et al.* [18]. Increased relative abundances (positive deviations) are plotted *downward* from the A.D. 1890 norm, which is shown as a dashed line. Solid curve (from same reference) is a sinusoidal fit which matches very closely the observed change in terrestrial magnetic field strength. Remaining significant features are of probable solar cause; some of the ones noted in Table 1 are marked with arrows. M = Maunder Minimum, S = Spörer Minimum, D = Medieval Maximum.

the 11-year solar cycle, and to displace all effects in time. In tree rings formed this year, for example, is the smeared record of nucleonic flux variations of 10 to 50 years ago. Thus we find the Maunder Minimum (A.D. 1645–1715) in tree rings formed somewhat later than the historically established time of the real drop in solar activity and aurorae.

Figure 2 is a compilation of ^{14}C data by Lin, Fan, Damon, and Wallick [18], who have assembled tree-ring derived ^{14}C results from a number of laboratories. Plotted is the $^{14}C:^{12}C$ abundance relative to the 1890 normal, expressed in parts per thousand with positive deviation (increased ^{14}C) *downward*, to agree in sense with solar activity. The 1890 norm ($\Delta^{14}C=0$) is shown as a dashed, horizontal line. The observations have been fitted with a sinusoidal curve derived by Lin, Fan, Damon and Wallick. They point out that it matches very well the smoothed curve of changing magnetic moment of the earth which is derived from paleomagnetic data. The strength of the earth's dipole moment reached a maximum in about A.D. 200, at which time we should expect ^{14}C production to minimize, as indeed the data show. Half a cycle earlier, about 5000 B.C., the earth's magnetic moment was about half as strong and at a minimum; at that time we should expect maximum galactic cosmic ray flux and a maximum in ^{14}C production, as is shown. Thus, to a first approximation, the overall envelope of the observed ^{14}C curve is explained as the result of slow and apparently cyclic changes in the strength of the terrestrial magnetic field.

Some of the remaining structure on the compiled ^{14}C curve is probably measurement error, but we can expect the significant observed deviations from the smoothed sinusoidal curve to be of likely solar origin, as has been pointed out by many authors [19,20,21, 22,23,13,16,18]. Thus the two dips (increased ^{14}C) at the recent end of the curve, labelled 'S' and 'M' are the probable signature of marked decreases in solar activity, and the opposite excursion about A.D. 1200, labelled 'D', the result of a marked and prolonged increase. Other major excursions can be readily identified. In a recent review Damon [17] has shown that the increased amplitude of excursions in the earliest part of the record (about 5000 to 7000 B.P.) is not enhanced noise but an effect of the weaker geomagnetic shielding at the time, which tends to increase the relative effect of solar modulation. Thus the excursions in this era, including marked maxima at about 6000 and 6500 B.P. and an obvious minimum at about 7200 B.P., are probably real solar effects. By the same argument we may presume that solar excursions at the modern end of the curve, when the geomagnetic moment was strongest, have been squelched in amplitude.

A more expanded plot of ^{14}C data covering only the Christian era, also from Damon [24], is shown in Figure 3. Again the sinusoidal archaeomagnetic curve is shown as a solid curve, which can be taken as an approximate baseline in identifying real,

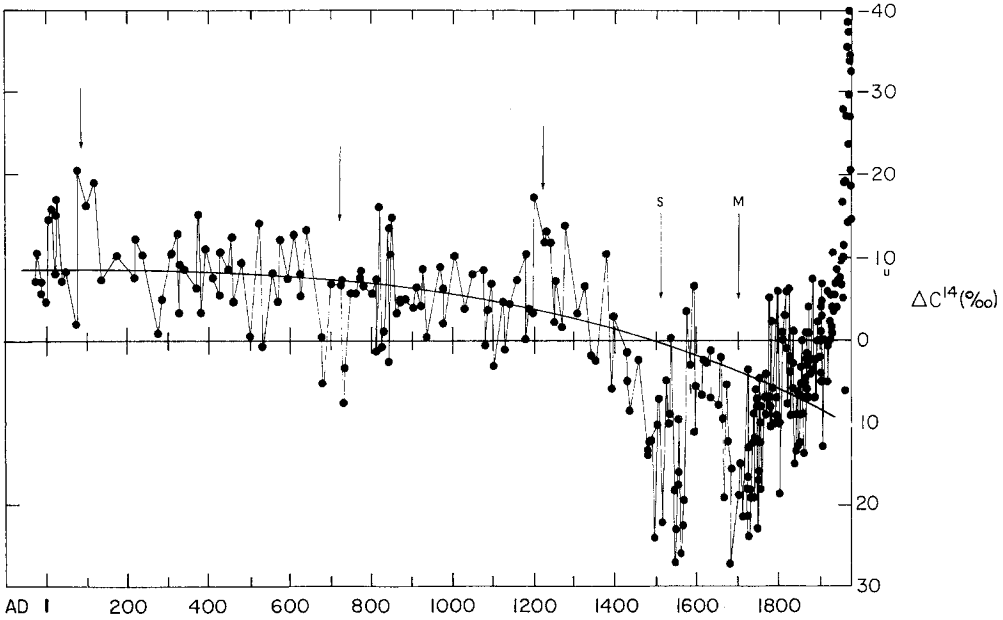

Fig. 3. An expanded version of some of the same ^{14}C data shown in Figure 2, from P. E. Damon [24]. Significant solar features in Table I are marked with arrows. M = Maunder Minimum, S = Spörer Minimum.

shorter-term excursions. We see again the same features noted in Figure 1. Also apparent are two other, less distinct features that occur near the time of maximum magnetic squelching: an apparent minimum in solar activity about A.D. 650–750 which seems confirmed in catalogs of aurorae and naked-eye sunspots [25] and a possible maximum about A.D. 100, in the Roman era.

In both figures 2 and 3 the abrupt drop in ^{14}C concentration (upward spike) at the most modern end of the curve is the well-known fossil-fuel effect: attributed to the introduction of significant levels of low-radiocarbon CO_2 in the atmosphere through the combustion of fossil fuels [22]. Hidden beneath this dramatic, anthropogenic effect may be a coincident change in the same direction, due to the sun and the modern increase in solar activity levels. This is suggested by the character of the radiocarbon record in the century preceding (ca. 1750–1850), that matches rather well the rising envelope of solar activity during the time. But the fossil-fuel, or Suess effect overwhelms and presumably destroys the solar information in the modern radiocarbon record. Thus the radiocarbon data after the middle or late 19th century cannot be unequivocally related to levels of solar activity, or at present used to provide a modern standard of solar behavior in assessing the past. This is one reason why we cannot judge with certainty whether the modern era represents normal or abnormal solar behavior.

4. Historical Verification

A yardstick useful in verifying and scaling the solar information in the radiocarbon record is the Maunder Minimum, A.D. 1645–1715, marked 'M' in Figures 2 and 3. Unlike the earlier excursions, the Maunder Minimum comes late enough – after the development of the telescope – that we have adequate historical records to describe with reasonable certainty the behavior of the sun at the time. In this sense the Maunder Minimum is the Rosetta stone which has allowed us to translate the quantitative solar information in the radiocarbon history.

It seems confirmed [7] that during the long span of the Maunder Minimum sunspots were indeed rare, as shown in Figure 1. For 70 years solar activity hovered at a level somewhat lower than conditions at the minima of the present 11-year cycle, and for periods of up to 10 years no sunspots were seen at all. None was reported on the northern hemisphere of the sun for 32 years. The possibility that the sunspot dearth was an artificiality of inadequate observers or poor technique seems untenable when one considers the advances made in other areas of astronomy and the exquisite and detailed drawings of the sun and sunspots made before and during the period. Reports of aurorae throughout Europe fell sharply during the Maunder Minimum and rose abruptly after it. The solar electron corona was either severely weakened or absent altogether; observers of the sun at total eclipses during the Maunder Minimum described a narrow ring of light around the moon, reddish in color and of uniform breadth – which fits the description of Fraunhofer corona (or zodiacal light) were the continuum corona stripped away. Spots were reported on the sun from time to time, but usually as isolated features and always at low latitudes. This pattern of appearance suggests, literally, a 'prolonged sunspot minimum', as Maunder first described the period [26], but it seems impossible to determine whether or not the 11-year cycle continued to operate at a suppressed or nearly invisible level.

Nor is it certain whether the 11-year cycle operated in the 1610–1645 period, after the introduction of the telescope and before the onset of the Maunder Minimum. In truth, 1700, or perhaps 1750, are the earliest dates for which we have unambiguous evidence of an 11-year solar cycle [25]. When Galileo first turned his telescope on the sun, in about 1611, the surface was probably more spotted than at any time in the ensuing century, and, we may assume, the sun was probably near a moderate maximum of activity. The numbers soon fell, however, as best we can determine from a far-from-continuous record. Rudolf Wolf assigned probable dates of maxima and minima of a contined 11-year cycle for the 1610-1700 period [27,28,29], but these were largely extrapolations in which he felt little confidence. He was also unsure, by the way, of the reconstructed 1700–1750 sunspot numbers that we use today. Eddy, Gilman, and Trotter [30,31] have shown that solar photospheric rotation was truly anomalous in the period just before spots disappeared in the Maunder Minimum: equatorial regions rotated about 3% faster than at present and the differential rotation was enhanced by about a factor of 3.

We may presume that the 15th century period labelled 'S' in Figures 2 and 3 was another era of solar behavior much like the Maunder Minimum, since the ^{14}C record at the time seems almost identical to that of the 1645–1715 period. Historical records are poorer for this earlier, Spörer Minimum, but its reality seems confirmed in a paucity of auroral counts, an absence of naked-eye sunspot reports, and corona-less descriptions of the eclipsed sun [7,25]. There were again probably almost no sunspots, and, we may presume, a similar dearth of other features of solar activity. By the same reasoning the marked change in Δ^{14}C between about 1100 and 1300 (an upward feature marked with an arrow in Figures 2 and 3) suggests a time of prolonged high solar activity, equal to or possibly higher than what we have seen in modern times, although a definitive comparison is made difficult by the Suess effect in the modern ^{14}C record. During this Medieval Maximum, auroral reports were higher than in preceding or succeeding centuries, and there was a marked increase in the frequency of reports of naked-eye sunspots [7,25].

5. The Sun Since Neolithic Times

Other, similar features are recognizable in the remainder of the ^{14}C record. In Table I we have selected the most obvious of these presumed solar effects and shown them in Figure 4a in a simplified, schematic manner to examine the trend of possible major solar change through the last 7000 years. The zero level in Figure 4a is the smoothed, sinusoidal curve from Figure 2, which was fitted by and represented the effect of changing strength of the earth's magnetic field. The amplitudes and durations of the selected excursions depend

TABLE 1: Major Solar Excursions in the last 7400 years.

Feature (Fig. 4)	Beginning and end in radiocarbon record		Probable extent in real time		Amplitude:	
					^{14}C	Corrected
1. Modern Maximum	AD 1800?	–	AD 1780?	–	?	?
2. Maunder Minimum	AD 1660	AD 1770	AD 1640	AD 1710	–1.0	–1.0
3. Spörer Minimum	AD 1420	AD 1570	AD 1400	AD 1510	–1.0	–1.1
4. Medieval Maximum	AD 1140	AD 1340	AD 1120	AD 1280	0.7	0.8
5. Medieval Minimum	AD 660	AD 770	AD 640	AD 710	–0.6	–0.7
6. Roman Maximum	AD 1	AD 140	20 BC	AD 80	0.6	0.7
7. Minimum	420 BC	300 BC	440 BC	360 BC	–2.0	–2.4
8. Minimum	800 BC	580 BC	820 BC	640 BC	–2.1	–2.4
9. Minimum	1400 BC	1200 BC	1420 BC	1260 BC	–1.5	–1.5
10. Maximum	1850 BC	1700 BC	1870 BC	1760 BC	1.6	1.5
11. Maximum	2350 BC	2000 BC	2370 BC	2060 BC	1.4	1.2
12. Maximum	2700 BC	2550 BC	2720 BC	2610 BC	1.7	1.3
13. Minimum	3200 BC	3050 BC	3220 BC	3110 BC	–1.1	–0.7
14. Minimum	3410 BC	3270 BC	3430 BC	3330 BC	–2.8	–1.8
15. Minimum	3670 BC	3410 BC	3690 BC	3470 BC	–0.7	–0.4
16. Maximum	4220 BC	3700 BC	4240 BC	3760 BC	1.5	0.9
17. Maximum	5050 BC	4450 BC	5070 BC	4510 BC	1.7	1.0
18. Minimum	5300 BC	5050 BC	5320 BC	5110 BC	–1.5	–0.9

directly upon the fit of the smoothed curve and on the premise of sinusoidal geomagnetic modulation. Were the smoothed curve of magnetic modulation distorted or shifted to right or left, the character of individual excursions would change. Amplitudes, relative to unit value for the Maunder Minimum, are given in Table I, with a corrected value (used in Figure 4a) which attempts to allow for the geomagnetic squelching effect that was pointed out by Damon [17]. The corrected amplitude A' for time t was obtained from the measured value $A(t)$ by the following assumed relationship:

$$A'(t) = A(t)\frac{H(t)}{H_0}$$

where H is the geomagnetic field intensity (from [17], Figure 8) and H_0 its maximum value. We should not place too much significance in the amplitudes, raw or corrected, of individual excursions, because of measurement uncertainties and the incomplete nature of the ^{14}C data. It is within the range of interpretation, and of possible physical interest, that all major excursions are of roughly equal corrected amplitude – a possibility which follows from Damon's analysis of the change in apparent amplitude of excursions with phase of the geomagnetic cycle.

The duration given for the solar features in Table I and Figure 4 have been corrected for a presumed lag of 40 years between cosmic ray flux changes and resultant ^{14}C abundance variation in tree rings. We have also arbitrarily truncated the span of each feature (by 20 years at start and end) to delineate the more likely duration of the most pronounced effect. The rationale for these rough corrections was derived from the example of the Maunder Minimum, for which the tree-ring radiocarbon excursion lagged and extended longer than the historically-observed effect on the sun. Obviously, at this

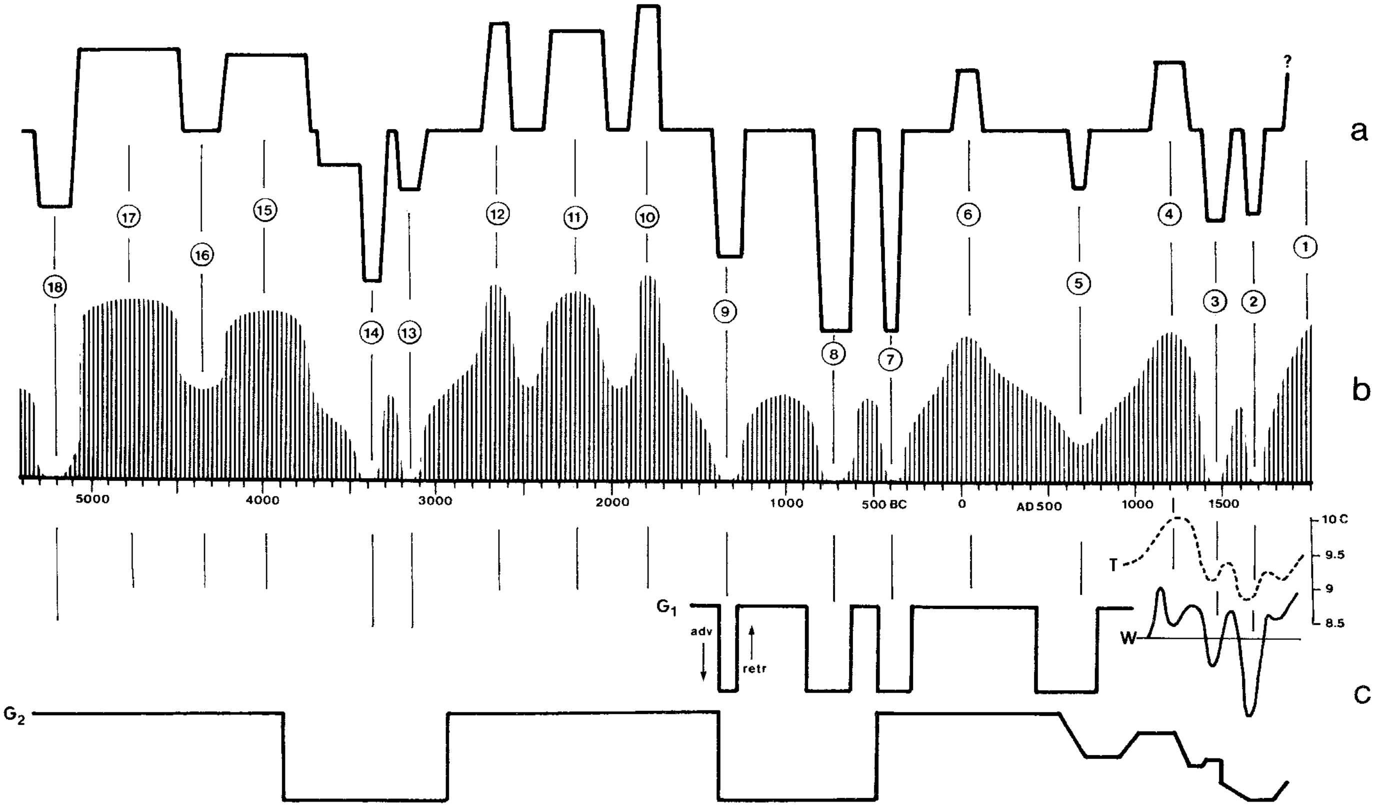

Fig. 4. Top curve (a): persistent deviations in ^{14}C from Figures 2 and 3, plotted schematically and normalized to feature 2 (Maunder Minimum); downward excursions, as in Figures 2 and 3, refer to increased relative ^{14}C and imply decreased solar activity. Circled numbers (1–18) refer to features described in Table 1. Middle curve (b): interpretation of curve (a) as a long-term envelope (of possible sunspot cycle) that minimizes in features 2, 3, etc. and maximizes at 4, 6, etc. Bottom curves (c): four estimates of past climate. Step-curve G_1 : times of advance and retreat of Alpine glaciers, after Le Roy Ladurie [38]; Curve G_2 : same for worldwide glacier fluctuations, from Denton and Karlen [39]; Curve T: estimate of mean annual temperature in England (scale at right) after Lamb [37]; Curve W: winter-severity index for Paris–London area (from Lamb [9]); downward is colder.

early stage of interpretation of an imperfect ^{14}C history all dates are uncertain to at least ±50 and possibly ±100 years.

The names assigned the most recent solar features in Table I are meant for easy, preliminary identification; for features occurring earlier than the Maunder and Spörer minima they describe the general historical period in which the apparent anomaly falls.

Is there evidence of periodicity in these representations of solar change? A clear answer is probably clouded by uncertainties in the ^{14}C record, by effects of other modulators like geomagnetic squelching, or by error in our paleomagnetic subtraction. It seems clear, nevertheless, that features like the Maunder Minimum are not negative-going half-cycles of a persisting, periodic curve: they do not alternate with equivalent maxima and more often come in groups of two or three. Taken as single features, however, these clustered minima and corresponding clustered maxima suggest a longer cycle of about 2500 years period, in which the Spörer and Maunder minima constitute parts of a single, longer excursion. Preceding minima may be found in features 7, 8, 9 and 13, 14, with clumped maxima in features 15, 17 and 10, 11, 12. A less distinct maximum in this longer cycle falls at the time of maximum geomagnetic squelching and this could suppress or distort its signature in the radiocarbon record. J. R. Bray, who has pioneered the study of long-term solar change, has noted a cycle of this length in earlier, more preliminary radiocarbon data [32,33,34], and Mitchell [35] has noted a significant peak at this same period of 2500 years in the composite spectrum of climatic change.

Recently Damon [17] has subjected the radiocarbon record in Figure 2 to power spectrum analysis to search for cyclic effects. He divided the data into 2000 year periods and found, interestingly, that statistically significant periods appeared, but of different length in different epochs, as though long-term solar activity were subject to some kind of frequency modulation. In the first 2000 years B.P., Damon found significant power at periods of 56, 69, 182, and 400 years; between 2000 and 4000 B.P. the significant periods were 286 and 500 years, and from 4000 to 6000 B.P. they were 100, 286 and 1000 years. These are preliminary findings but they suggest that the pattern of long-term solar behavior is not what purists would call well-behaved.

Figure 4b interprets the schematic ^{14}C data of Figure 4a as a direct representation of solar activity and specifically as the envelope of an *assumed* continuous, 11-year cycle, as might have been recorded in annual sunspot averages. This interpretation rests on the close correspondence between the post-1600 (A.D.) radiocarbon curve and historical observations of solar behavior from the Maunder Minimum through the onset of the Suess effect (ca. 1850). For these historically accessible periods, the ^{14}C residuum (the difference between observed radiocarbon deviations and the terrestrial magnetic curve) followed very closely the observed envelope of the annual sunspot number [7]. We have therefore assumed that the general, long-term level of solar activity can be read almost directly in the radiocarbon residuum: bottoming out in departures like the Maunder Minimum and maximizing when the radiocarbon residuum reaches the large negative levels of the A.D. 1100–1300 Medieval Maximum. Where the modern end of the curve is masked by the Suess effect, we have simply used the observed envelope of sunspot number, which indicates a continued rise in the level of solar activity from A.D. 1715 through the 1959 maximum. The rounded, connecting curve in the remainder of Figure 4b is an arbitrary and wholly artistic connection between the maxima and minima of Table I and Figure 4a.

The 'floor' imposed on the interpreted curve in Figure 4b acknowledges that solar activity has a zero level below which it cannot go and which was nearly reached during the Maunder Minimum. Deeper minima, as in the first two millenia B.C. (Figure 4a) are interpreted as the result of the longer persistence of these three, earlier events and their clumping in time, since the radiocarbon data necessarily reflect a temporal integration in the atmospheric reservoir.

In the reconstructed solar activity curve is a possible explanation for two historical enigmas of solar and solar-terrestrial history [7]: the 'auroral turn-on' in the early 18th century and the apparent absence of reports of the structured corona before the same general date. If we accept that activity-related aurorae and the solar corona are both threshold phenomena that correspond to a certain minimum long-term level of solar activity, then their absence or suppression in much of early history seems a logical result of the apparent pattern of excursions of solar activity. By this interpretation we would expect frequent aurorae and a prominent and extended electron corona only during periods like the present, which are times of maxima in Table I and Figure 4. In the past 3500 years of better recorded history these conditions seem to have applied but infrequently – only about 15% of the time: for several centuries during the Medieval Maximum and an apparently shorter interval during the Roman Maximum. When these limited opportunities are combined with sociological trends in the rise of civilization, and the difficulties of securing evidence from ever more ancient times, the enigmas of the missing aurorae and coronae largely vanish. Ironically, these spectacular displays of nature would seem to have been withheld or suppressed during some of the more vigorous times of learning on the earth, including the era of early Greek intrest in science and natural philosophy.

6. Comparison with Climate History

We must allow that these ponderous solar changes could have had pronounced effect on terrestrial climate, and through regional and global climate change, on the course of civilization itself. Nor is it physically unrealistic that day-to-day and year-to-year changes, and the 11-year cycle, could be such minor perturbations in the life of the sun that their imprint, if any, on earth and climate could be lost in more energetic and self-generated changes in the atmosphere itself. The close correspondence of what we here call the Maunder Minimum, the Spörer Minimum, and the Medieval Maximum of solar behavior with the long-term record of climate has been pointed out before [32,34,36,7,25,23]. It is particularly striking when one allows for a 40-year delay between the tree ring record of ^{14}C and the initiating changes in the upper atmosphere. Times of depressed solar activity correspond to times of global cold: the Maunder and Spörer minima match the two coldest extremes of the Little Ice Age, when European and American temperatures were depressed 0.5 to 1°C; high levels of solar activity seem to relate to periods of high global temperatures: our Medieval Maximum to the Middle Ages Warm Epoch, or Climatic Optimum [9,10,37].

The correspondence is no less striking when the earlier solar record is compared with even earlier climate history, as best as it is known. In part c of Figure 4 we show this comparison, on the same time scale as the rest of the figure. The step function G_1 depicts the advance (downward) and retreat (upward) of Alpine glaciers, taken from the climate summary of Le Roy Ladurie [38], and G_2 the same function as derived by Denton and Karlén [39] for worldwide, Holocene glacier fluctuations. Curves T and W are temperatures (scale at right) and estimates of winter severity (colder downward) for England and Paris–London, respectively, from the historically reconstructed data of H. H. Lamb [9,37]. The correspondence, feature for feature, is almost the fit of a key in a lock. Wherever a dip in solar activity occurs (as in features 2, 3, 5, 7, 8, 9, 13–15) the climate swings coldward, and mid-latitude glaciers advance. When a prolonged maximum of solar activity is indicated (as in features 4, 6, 10–12, 16–17) glaciers retreat and the earth warms. We should recognize that we deal here with very coarse data, particularly in the record of reconstructed climate, and we should also be warned that these 'climate' curves may represent only regional or longitudinal trends. Bray [40,32,33,34,41] and La Marche [10], however, have demonstrated a more global extension of many of these same climate epochs, and indeed Bray has pointed out the same long-term sun-climate correspondence shown here.

The physical connection with long-term solar changes could be through the recognized increase in ultraviolet solar flux with solar activity, and the effect of that increase on chemical processes in the upper atmosphere. Were that the case, however, we should probably expect more obvious correlation of shorter-term solar activity and weather. The connection could also come about through known changes in the particle flux from the sun, as in the sector structure or high-speed streams of the solar wind, through some triggered reaction necessary to amplify the wholly inadequate energies in these fluxes. But before we entertain these or other more complex mechanisms, we should first examine the simplest and most straightforward process: namely, that the total radiative output of the sun, or solar constant, is slowly and ponderously changing, and that these possibly meandering changes are reflected in sign and magnitude in the overall envelope of solar activity. By this notion the smoothed curves of Figure 4b could represent a record of the solar constant, with a peak-to-peak amplitude range of perhaps 1%, the amount that seems adequate in present global climate models to change the terrestrial temperature by 1° or 2°C. Long-term changes of this amount in the solar constant would be very difficult to detect directly, and would be unnoticeable in observations of other G stars.

We find some support for this hypothesis in a preliminary finding [42,36] that the average value of the measured solar constant increased steadily in the first half of the 20th century – by about 0.25%, which is about the right amount to explain the established increase in world temperature during the same span [9]. During the same half-century the envelope of sunspot number was also monotonically increasing (Figure 1).

It may be significant that while the solar constant was presumably rising, between about 1908 and 1955, its reported fluctuations did not seem to follow the 11-year cycle [1]. If the solar constant does not follow the wiggles in daily or annual sunspot number, how can it follow the envelope? A simple answer is that the solar constant may not follow the sunspot number at all; rather, *the sunspot number may follow changes in the solar constant, through a kind of amplitude modulation of an otherwise more uniform cycle* [7,36]. A mechanism for this modulation exists in the solar dynamo [43] which we now think responsible for the maintenance of the 11-year sunspot cycle. By this hypothesis, were the flow of radiation through the outer solar atmosphere perfectly constant, we might expect a sunspot cycle whose peaks were almost uniform in amplitude. If the flow of radiation were slowly increased, we would expect an overall enhancement of sunspot production, which would be most visible in *retrospect*, in the run of heights of the 11-year peaks. If the flow of radiation were slightly reduced, the peaks of the cycle would be depressed. And if the radiation fell below some critical level perhaps only a drop of 1% or less, the amplitude of the cycle might be damped so much that the cycle would shut down, or appear to shut down, as during the Maunder Minimum, and presumably the Spörer Minimum and the earlier cases we have pointed out. The connection of varying radiative flux to the action of the dynamo could come about through changes in the convective layer of the sun and as a consequence in the nature of differential rotation. Supporting this connection are recent findings [30,31,44] that the character of differential rotation is significantly altered with changes in the general level of solar activity.

An intriguing consequence of the envelope hypothesis is that individual ups and downs of the 11-year cycle, or of shorter-term solar variability, are almost wholly unrelated to the sun-weather problem: they would tell little of bulk changes in the radiative solar output and might predict almost nothing of consequence in terrestrial meteorology.

7. Conclusions and Questions

Our first quantitative look at solar history in fossil radiocarbon presents a rather compelling case for a direct connection between the sun and climatic changes of century or half-century time scales. Throughout the last seven millenia extended periods of suppressed solar activity seem to coincide with times of protracted cold and mid-latitude glacier advance. Long-term highs in the level of solar activity are coincident with times of warmer climate and glacier retreat, as during the last several hundred years, and before that, during the Medieval Climatic Optimum. We suggest as a first hypothesis that both the changes in the envelope of solar activity and the changes in climate result from long-term fluctuations of about 1% in the solar constant, that come and go in a possibly aperiodic manner in time scales of centuries. A longer cycle of about 2500 years, made up of clustered maxima and minima, also appears in the radiocarbon record, as had been pointed out by Bray [32,33,34]. A significant peak at 2500 years, and a possible feature at 100–400 years appear in Mitchell's estimate of the spectrum of climatic change [35].

The weakest link in the chain of evidence is surely the climate record, for comparisons are made, of necessity, with an incomplete climate history that is probably more poorly established than is the history of the sun. We have taken for climate reference the most commonly cited extremes. They may not represent truly global changes.

One should also question the reliability of tree-ring radiocarbon as a real indicator of solar activity. The good agreement of radiocarbon-derived solar history with climate extremes raises the question of whether it is climate itself that is modulating radiocarbon levels in the tropospheric and oceanic reservoirs, with no important influence from the sun. Ocean and atmospheric temperatures can be expected to have an effect on the radiocarbon abundance in the biosphere, and that effect is probably not well established, although present models suggest that the solar modulation should be the more dominant [17,14]. Moreover direct historical observations of sunspots and aurorae seem to establish that the three most recent radiocarbon excursions – the Maunder Minimum, and, from weaker evidence, the Spörer Minimum and Medieval Maximum, were indeed times of marked solar change, of appropriate sign to explain the radiocarbon effects.

Detailed, direct evidence of a drop in solar activity exists only for the Maunder Minimum; could it be that the remaining excursions in the radiocarbon record are not solar features but the result of small scale fluctuations in the strength of the earth's magnetic moment? The possibility is reasonable since we attribute the overwhelming feature of the radiocarbon curve – the 10 000-year undulation – to longer-term, secular change in the field. Were this the case, the Medieval Maximum would represent a 70-year *increase* in the strength of the magnetic moment, and the Spörer Minimum a time of magnetic *decrease*. Thus, were the long-term solar level constant we would expect the incidence of aurorae to *fall* during the Medieval Maximum and *rise* during the Spörer Minimum, through changes in the shielding of the charged solar particles that produce aurorae. In fact, the historical auroral record [25,45] shows in each case the opposite effect: a decrease in aurorae during the Spörer Minimum and a marked increase during the Medieval Maximum, seeming to confirm the solar hypothesis.

We can anticipate refinements in almost all of the data that have led to our new knowledge of solar history and its apparent climate connection. The climate history of the Holocene will surely be clarified and extended to more regions of the world through modern isotope study [46] and interpretations of climate-sensitive tree growth [47]. As more samples are analyzed the radiocarbon record will be clarified both in general form and in detail. Most of the radiocarbon excursions singled out in this survey have come from averages of ten or more rings, and from single, sometimes diverse laboratories. More detailed examination of periods of obvious anomaly, such as the Maunder Minimum and Medieval Maximum, has now begun. We can also hope that independent methods of reading solar history will come from other studies of dated, terrestrial isotopes, such as ice core samples, and that the re-examination of aurora data will lead to an improved, proxy history of the sun.

If the sun changes in ways that affect world climate, high scientific priority need be given to programs of monitoring solar behavior. It seems important to start such a program now, to determine once and for all whether and how the radiative flux from the sun changes, and in what time scales. As there is only one object in the sky on whom we utterly depend, there can be no astronomical question of more practical significance to mankind than that of the sun's variability. To determine whether the solar constant is varying as here implied requires long-term monitoring of both the bulk solar radiation and its terrestrially-important spectral components. This assignment is not an easy one, for it demands a capability of sensing changes of no more than 0.1% in a decade, carried out over many decades. In the real world of science the greater challenge may be that of insuring the continuance of such a program.

Acknowledgements

I am indebted to Paul Damon, Department of Geosciences, University of Arizona for radiocarbon data, and to Peter Gilman, Val La Marche, Juan Carlos Lerman, Murray Mitchell, and Minze Stuiver for help and advice. This research was sponsored in part by NASA Contract NAS5-3950 and the Environmental Research Laboratories of the National Oceanic and Atmospheric Administration.

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(Received 1 July, 1977)