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Changes in Atmospheric Carbon-14 Attributed to a Variable Sun

Minze Stuiver and Paul D. Quay

Summary. The ^{14}C production rate in the upper atmosphere changes with time because the galactic cosmic-ray flux responsible for ^{14}C production is modulated by the changes in solar wind magnetic properties. The resulting changes in the atmospheric ^{14}C level are recorded in tree rings and are used to calculate past ^{14}C production rates from a carbon reservoir model that describes terrestrial carbon exchange between the atmosphere, ocean, and biosphere. These past ^{14}C production rate changes are compared with ^{14}C production rates determined from 20th-century neutron flux measurements, and a theory relating ^{14}C production and solar variability, as given by geomagnetic *Aa* indices and sunspot numbers, is developed. This theory takes into account long-term solar changes that were previously neglected. The 860-year ^{14}C record indicates three episodes when sunspots apparently were absent: A.D. 1654 to 1714 (Maunder minimum), 1416 to 1534 (Spörer minimum), and 1282 to 1342 (Wolf minimum). A less precisely defined minimum occurred near A.D. 1040. The part of this record after A.D. 1645 correlates well with the basic features of the historical record of sunspot numbers. The magnitude of the calculated ^{14}C production rates points to a further increase in cosmic-ray flux when sunspots are absent. This flux was greatest during the Spörer minimum. A record of approximate sunspot numbers and *Aa* indices for the current millennium is also presented.

Recent research on possible causes of climate changes has focused on several aspects of solar-terrestrial relationships (*1*, *2*). The reality of such relationships is still a matter of controversy, mainly because a physical basis for a demonstrable effect on climate has not yet been established. Studies are further hampered by the lack of knowledge of solar behavior for periods beyond the last few centuries. Only with a longer record of solar activity will it be possible to search for possible correlations between climatic changes during the last millennia and changes of the sun.

The most obvious feature of solar variability is the change over time in the number of sunspots seen on the visible half of the sun. The record of observed sunspot numbers shows a regular cycle of solar activity of about 11 years. Sunspots have been observed for centuries, and past counts of sunspot numbers are available for at least a 300-year interval. The very early part of the historical sunspot record includes the Maunder minimum in solar activity, which lasted from about A.D. 1645 to about 1715 (*3*). During this minimum, very few sunspots were observed.

Another manifestation of solar variability is the change in magnetic field strength of the solar wind, reflecting velocity and intensity changes. The solar wind plasma near the earth can be considered an extension of the solar corona, and changes in solar wind properties reflect coronal changes. The magnetic changes of solar plasma in our planetary system cause changes in the magnitude of deflection of galactic cosmic rays traveling toward the earth. Thus the cosmic-ray flux, as observed in the upper atmosphere, varies with changes in solar activity, as shown by a significant correlation between the cosmic-ray flux modulation and the 11-year sunspot cycle (*4*). During intervals of low sunspot activity the magnetic shielding properties of the solar wind are such that a larger galactic cosmic-ray flux arrives in the upper atmosphere, whereas cosmic-ray fluxes are lower during periods when sunspot numbers are higher.

The changes in cosmic-ray flux cause variations in atmospheric neutron production. Because the production rate of ^{14}C is dependent on the interaction of neutrons with atmospheric nitrogen, the $^{14}CO_2$ activity levels in the atmosphere reflect the changes in cosmic-ray intensity, which in turn reflect solar variability. Thus the record of atmospheric ^{14}C activity, as given by the decay-corrected ^{14}C activity in tree rings, can provide important information on prehistoric solar changes.

Part of the incoming galactic radiation is deflected by the earth's geomagnetic field. Changes in geomagnetic field intensity modulate the incoming cosmic-ray flux, and thus ^{14}C production. The known variations in the earth's magnetic dipole moment (*5*, *6*) indicate that perhaps a major portion of the long-term trend in atmospheric ^{14}C [about 8 percent over 6000 years (*7*–*11*)] is caused by geomagnetic field intensity changes.

As first suggested in 1961 (*12*), the atmospheric ^{14}C variations lasting a few hundred years or less that are superimposed on the long-term trend may be caused by solar (heliomagnetic) modulation of the ^{14}C production in the upper atmosphere. These atmospheric ^{14}C changes are relatively small and amount to deviations of a few percent from the long-term trend. Carbon reservoir models of varying complexity were used in the studies that relate the observed at-

Minze Stuiver is a professor in the Departments of Geological Sciences and Zoology and the Quaternary Research Center, University of Washington, Seattle 98195. Paul Quay is a research associate in the Department of Geological Sciences and a member of the Quaternary Research Center at the University of Washington.

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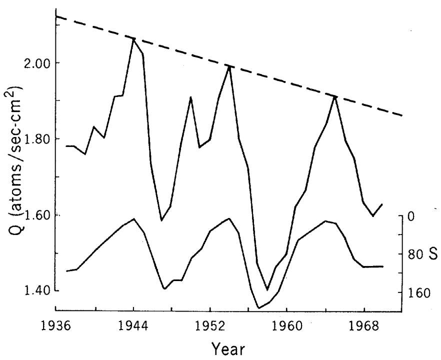


Fig. 1. Global ^{14}C production rates derived from neutron fluxes for the years 1937 to 1970. The data are from O'Brien (22). The dashed line gives the long-term change in ^{14}C production during solar minima. The lower curve gives the inverse sunspot number record.

mospheric ^{14}C variations to heliomagnetic modulation and sunspot numbers (*9, 12–16*). These studies do not always provide positive evidence for solar modulation of atmospheric ^{14}C levels. For instance, after detailed work with a six-reservoir model, Ekdahl and Keeling (*14*) concluded that "tree-ring data for the period AD 1700–1900 are not consistent enough to accept Stuiver's correlation [between ^{14}C and sunspots (*12*)] as thoroughly proven." The model also predicted solar-induced ^{14}C changes that were too small to account for the observed atmospheric ^{14}C variations after A.D. 1700. These questions will be discussed in this article.

A major complication in previous studies of solar-related atmospheric ^{14}C changes has been lack of precision in the available ^{14}C determinations. The residual ^{14}C changes of a few percent hardly exceeded three times the standard deviation in most tree-ring ^{14}C measurements. For the study reported here, large counters were constructed so that tree-ring ^{14}C activity could be measured with a precision of 1.5 to 2 per mil (*17*). The higher measuring precision enables us to compare a precise record of atmospheric ^{14}C variations derived from the decay-corrected ^{14}C activity of tree rings with existing evidence of solar variability. The ^{14}C record is used in conjunction with a carbon reservoir model (*18*) to calculate ^{14}C production rates (Q_M) over the past millennium. The variability of Q_M will be compared with the solar activity record. A new theory of ^{14}C modulation, based on geomagnetic *Aa* indices, will be discussed, and the 860-year record of ^{14}C variations obtained from tree rings will be used to estimate solar activity.

Solar Modulation of Carbon-14 Production

Global average ^{14}C production rates, calculated from observed cosmic-ray fluxes, have been given by Lingenfelter (*19*), Lingenfelter and Ramaty (*20*), Light *et al.* (*21*), and more recently O'Brien (*22*). O'Brien calculated ^{14}C production rates from a 34-year-long record of observed cosmic-ray neutron fluxes, and his work is used here as a basis for discussion of solar modulation of the ^{14}C production in the atmosphere.

O'Brien's calculated ^{14}C production rates Q, in atoms of ^{14}C per second per square centimeter of the earth's surface, are given in Fig. 1 for the years 1937 to 1970. The production rate is an inverse function of sunspot number S. A least-squares fit to sunspot number (*22*) yields

$$Q = 1.937 - 0.00242\ S \qquad (1)$$

Although the most obvious manifestation of solar change is the variability in the number of sunspots, it should be noted that sunspot changes do not directly cause the changes in the solar wind magnetic properties that result in cosmic-ray modulation. Main regions of solar wind propagation are near the sun's poles, and coronal holes are important for the generation of solar wind "streamers" (*23*). Sunspots, on the other hand, are located near the solar equator. Evidently sunspots as well as solar wind magnetic properties provide, in a complex manner, information on solar conditions. When cosmic-ray flux depression changes, sunspot numbers appear to change also.

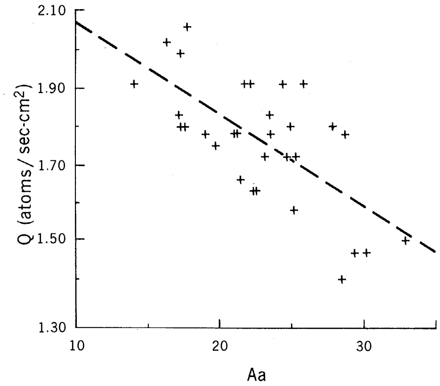


Fig. 3. Global ^{14}C production rates plotted against geomagnetic *Aa* indices for 1937 to 1967. The ^{14}C production data are from O'Brien (*22*).

The linear relationship between ^{14}C production rate and sunspot number is an empirical one established from data that cover slightly more than two complete 11-year cycles. Expressions similar to Eq. 1 have been used to predict past ^{14}C production changes from the historical sunspot record (*9, 12–16*). The basic assumption is that the sunspot-^{14}C production relationship demonstrated for the past few 11-year cycles can be extrapolated back in time. In our opinion, such a simple extrapolation is not justified. To explore the possibility that sunspots alone do not provide a complete history of ^{14}C production rates, the past changes in geomagnetic indices will be discussed.

The interaction of the solar wind and the earth's magnetosphere results in ionospheric and magnetospheric currents. These variable currents produce magnetic variations at ground surface from which geomagnetic indices are derived as a measure of magnetic disturbance. The geomagnetic data, therefore, also provide information on properties of the solar wind.

Geomagnetic variations at frequencies below about 1 cycle per minute have been recorded continuously for many decades. International indices describing the time variations of the field components are obtained from magnetometer records. Several geomagnetic indices

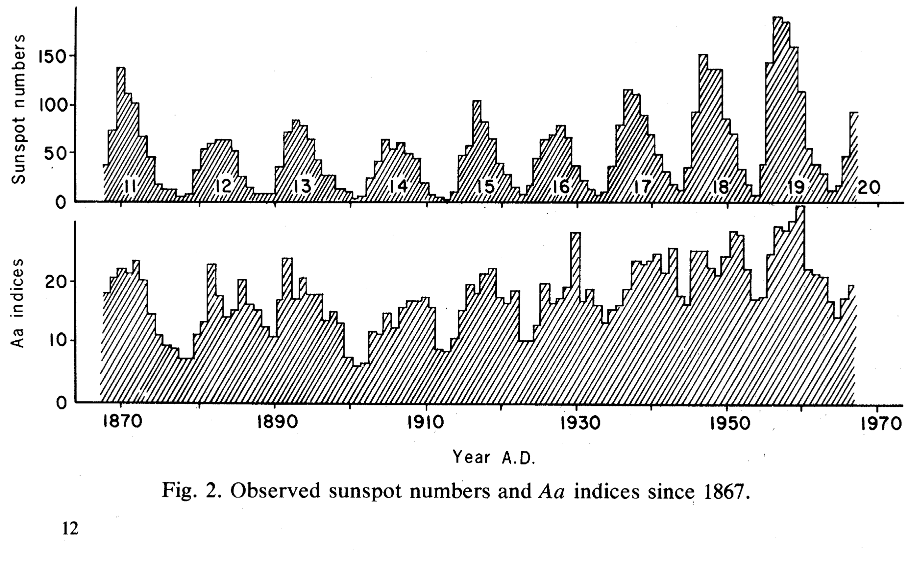


Fig. 2. Observed sunspot numbers and *Aa* indices since 1867.

are available, but unfortunately they are not related in a simple manner to any of the physical processes that are important in the solar wind–magnetosphere–ionosphere system (*24*).

The appearance of an 11-year cycle in certain indices implies that these indices reflect at least some solar wind parameter that has a solar cycle dependence. Such dependence is evident for *Aa* indices (*25*). The *Aa* indices reflect the magnitude of short-term (up to 3 hours) random occurrence of magnetic activity, obtained by using two antipodal observatories. They have been tied to solar wind properties such as solar wind speed and the southward component of the interplanetary magnetic field (*26*). Feynman and Crooker (*27*) used the trend in *Aa* indices (Fig. 2) to demonstrate changes in solar wind magnetic field strength or velocity, or both, over the past century. Changes in these parameters should also influence the modulation of the incoming cosmic-ray flux.

Figure 2 shows *Aa* indices (*25*) plotted together with sunspot numbers. Whereas the 11-year sunspot cycle shows only amplitude variability, the *Aa* record shows the 11-year variability superimposed on a long-term trend. During sunspot minima ($S = 0$) the *Aa* index is still changing, showing a long-term change in solar wind properties that is not reflected in the sunspot record. Thus a ^{14}C production–sunspot number relationship (such as Eq. 1) is not necessarily constant with time. In fact, a long-term change is already indicated in the calculated ^{14}C production rates during solar minima (dashed line in Fig. 1).

In the following discussion an attempt is made to relate the long-term change represented by the change in *Aa* index to ^{14}C production rates. The *Aa* indices and ^{14}C production rates are given in Fig. 3 for the years 1937 to 1967. They yield the following relationship ($r = .67$):

$$Q = 2.310 - 0.024\ Aa \qquad (2)$$

Changes in ^{14}C production rate, prior to 1937, can be calculated from Eq. 2 if one assumes that this relationship holds over extended periods.

It is useful to discuss production rate changes relative to an average production rate over the duration of the available *Aa* record, such as the production over the 100-year interval between 1868 and 1967 when the average *Aa* number is 17.9. For $\bar{A}a = 17.9$, $Q = 1.88$ ^{14}C atom/sec-cm^2 (Eq. 2). We define $\Delta Q = [(Q - 1.88)/1.11] \times 100$ percent, which transforms Eq. 2 into

$$\Delta Q = 22.9 - 1.28\ Aa \text{ percent} \qquad (2a)$$

Thus, in the absence of solar wind interaction with the magnetosphere, as measured by the *Aa* index ($Aa = 0$), the ^{14}C production rate would be 22.9 percent above average. This percent change in ^{14}C production rate is much greater than the value that would be obtained by extrapolating back in time the relationship between sunspots and ^{14}C production rates (Eq. 1). Substitution of $S = 0$ into this equation gives a ^{14}C production rate 7 percent above the 1868–1967 baseline (obtained by using an average sunspot number of 51.7 in Eq. 1).

As will be shown, the maximum increases in ^{14}C production rate calculated from the 860-year atmospheric ^{14}C record presented in this article are much more compatible with the maximum increase derived from the *Q-Aa* relationship than the *Q-S* relationships used so far. The atmospheric ^{14}C record also indicates a different dependence of Q on S, suggesting that extrapolation of Eq. 1 does not take into account long-term changes in solar modulation of the cosmic-ray flux.

One must realize that the assumptions inherent in extrapolating the empirical relationship between Q and *Aa* (Eq. 2) suffer the same problems as the assumptions involved in the relationship between Q and S (Eq. 1), only to a lesser degree because over the interval of the measurements the *Aa* index does not appear to have a threshold. The relationships obtained over a short time period will be compared in the following sections with the 860-year record of ^{14}C production rate changes. It will be shown

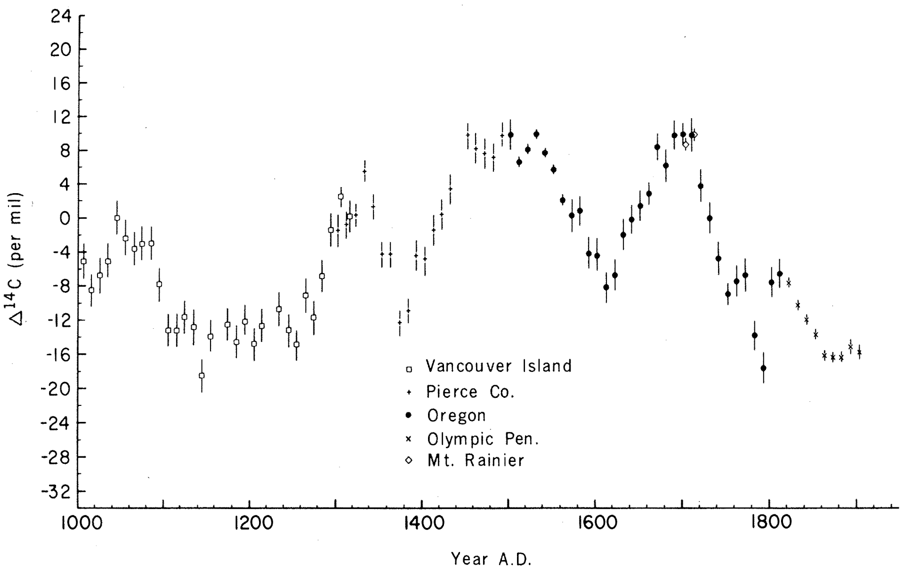


Fig. 4. Atmospheric $\Delta^{14}C$ values, relative to the NBS oxalic acid standard, observed in Douglas fir wood from the Pacific Northwest. The counting errors (1 standard deviation) are given by the vertical bars.

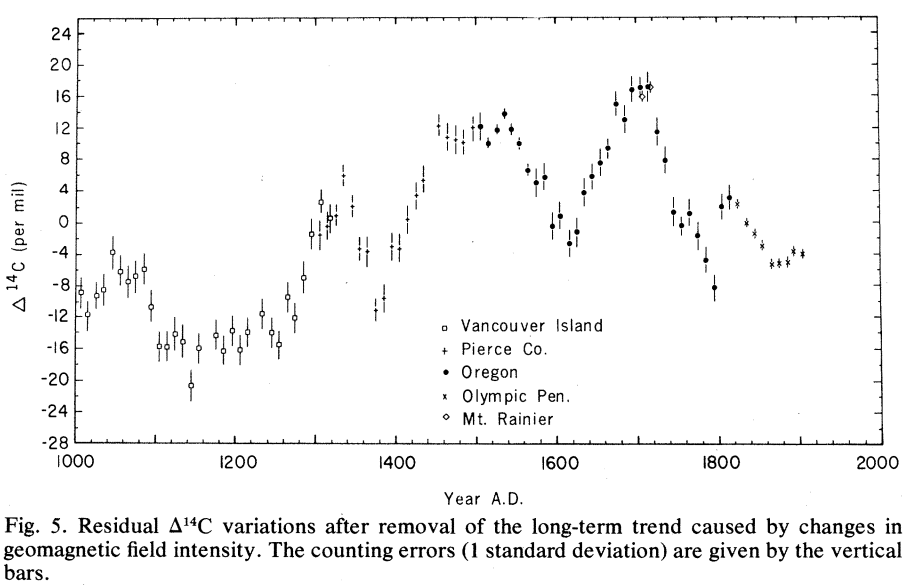


Fig. 5. Residual $\Delta^{14}C$ variations after removal of the long-term trend caused by changes in geomagnetic field intensity. The counting errors (1 standard deviation) are given by the vertical bars.

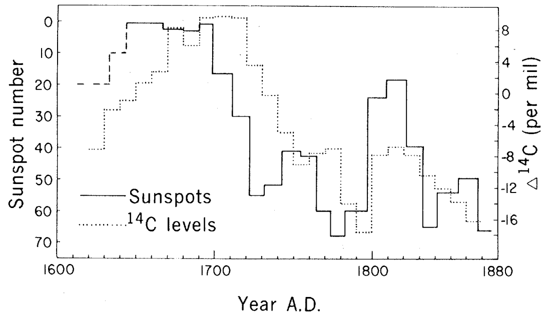


Fig. 6. Comparison of the inverse sunspot number curve (solid line) obtained by averaging observed sunspot numbers over each 11-year cycle and the Δ^{14}C curve (dotted line).

that the *Aa* theory, although probably not the final answer, is an alternative explanation that increases the compatibility of the ^{14}C production rate record of the current millennium with the independently calculated *Q* values for the 20th century.

Methods and Materials

The Δ^{14}C values given in this article are the relative deviations of the measured ^{14}C activities, after correction for age and isotope fractionation, from National Bureau of Standards (NBS) oxalic acid activity (*28*).

All samples were obtained from Douglas fir trees collected in Washington, Oregon, and Vancouver Island, Canada. Tree-ring growth for most of these trees was very complacent, and the wide rings for the Oregon and Washington firs facilitated tree-ring counting. Wood of the same age has identical ^{14}C activities, as shown by the agreement in ^{14}C activities of overlapping portions of different trees (see Fig. 4).

Although for this study we mainly report results for 10-year tree-ring sections, we are also studying in detail the annual changes in ^{14}C level. Wide rings are needed for the average 31 grams of wood used for measurements with an accuracy of 2 per mil. This is the main reason for the use of appropriate sections of wood from as many as five trees covering a total time span of about 900 years. The studied Douglas firs were from the Olympic Peninsula (47°46′N, 124°06′W); Mount Rainier National Park, Washington (46°45′N, 121°45′W); Coos Bay, Oregon (43°7′N, 123°40′W); Pierce County, Washington (~ 47°N, 122°W); and Shawnigan Lake, Vancouver Island (48°40′N, 123°40′W). The ages of the trees were, respectively, 152, 316, 491, 660, and 1268 years.

The wood samples were all treated at 60°C with 2 percent NaOH and HCl solutions to remove resins, sugars, and a portion of the lignin (the so-called De Vries method). This treatment does not remove all components added after the year of growth (*29*). The influence of incomplete removal on the ^{14}C level was studied by comparing the ^{14}C activities of wood treated by the De Vries method with the ^{14}C activities of alpha-cellulose derived from the same wood. The largest sample pair differences were found for tree rings that became heartwood after 1952, when nuclear bomb ^{14}C was added to the atmosphere. Atmospheric ^{14}C levels rose to a maximum 80 percent above normal in 1963 and 1964. The "feedback" of this ^{14}C peak to rings formed earlier resulted in an average 8 per mil increase for the wood treated by the De Vries method over cellulose. Natural ^{14}C variations are only a few percent, whereas variations due to nuclear bomb ^{14}C addition average about + 50 percent. For natural variations the calculated feedback is (2/50) × 8 or 0.3 per mil. Eight pairs of wood samples that were not yet influenced by nuclear bomb ^{14}C additions were also measured. The De Vries–treated wood and cellulose appeared to differ slightly in ^{14}C activity, but the measured average difference of 0.5 ± 0.8 per mil is statistically not significant.

Thus the error introduced by using De Vries–treated wood is only a few tenths of a per mil for Douglas fir. This error is so small compared to the counting error that we elected to keep the De Vries treatment method. This method is, at least for Douglas fir, less time-consuming than others.

Atmospheric Carbon-14 Changes Since A.D. 1000

Tree ring–derived atmospheric Δ^{14}C values are given in Fig. 4 for the period A.D. 1000 to 1900. All data points represent the average Δ^{14}C activity for a single decade, obtained either by measuring the ^{14}C activity of a 10-year-thick wood sample or by using the average of ten determinations of single-year tree rings. Single determinations have a standard error of 1.5 to 2 per mil. The counting error in the decade average is about 0.6 per mil when single years are being used.

On the basis of three points per century, De Vries (*30*) identified the ^{14}C maxima near 1500 and 1700. A third maximum is identified near 1340 and a fourth, smaller one near 1050 in Fig. 4.

Part of the Δ^{14}C change is tied to the long-term ^{14}C trend caused, at least for the last few thousand years, by changes in the earth's geomagnetic field intensity. This long-term change has been approximated with a sinusoidal function. Houtermans (*31*) derived the expression

$$C(t) = 42.71 + 49.69 \sin\left[\frac{2\pi}{10{,}402}(t + 7388)\right] \text{per mil}$$

where $C(t)$ is Δ^{14}C level and t is time in years A.D. (negative for years B.C.). The residual Δ^{14}C variation around the long-term trend is plotted in Fig. 5.

Because sunspot numbers give a record of solar changes over at least three centuries, we compare atmospheric ^{14}C levels and solar activity in Fig. 6. The Δ^{14}C values have been corrected for the long-term geomagnetic field-induced Δ^{14}C changes (*31*) in order to depict the residual change in Δ^{14}C over the time interval of sunspot measurements. The sunspot numbers in Fig. 6 are the means over solar cycles. The sunspot numbers used for the 1700–1900 period are those of Waldmeier (*32*), using the numbers of R. Wolf.

The reliability of these mean annual sunspot numbers obtained through direct observation is considered by Eddy (*3*) to be good from 1818 to the present, questionable from 1749 through 1817, and poor from 1700 through 1748. Data tabulated by Eddy were used for sunspot numbers in the 17th century. The early part of the sunspot record includes the Maunder minimum in solar activity.

Calculation of Carbon-14 Production Rates from a Carbon Reservoir Model

The atmospheric ^{14}C level is dependent not only on the ^{14}C produced by neutrons but also on ^{14}C exchange with terrestrial carbon reservoirs. Thus, although Fig. 6 suggests that a correlation exists between atmospheric ^{14}C levels and sunspot records, a better correlation should exist between ^{14}C production rates and solar activity as an indication of neutron flux.

To calculate ^{14}C production rates from the record of atmospheric ^{14}C levels, the fluxes of ^{14}C between the atmosphere, oceans, and biosphere must be determined. Several carbon reservoir models have been developed to simulate terrestrial carbon exchange (*16, 18*). We chose the four-reservoir, box-diffusion model of Oeschger *et al.* (*18*), as this model has accurately described both the long- and short-term carbon and ^{14}C variations in the atmosphere. The carbon reservoirs in the model are the atmosphere, oceanic mixed layer, deep sea, and biosphere. The reservoir sizes and carbon exchange rates used for our ^{14}C production rate calculations (Q_M) are essentially those listed in table 3 of Oeschger *et al.* (*18*). For example, the preindustrial atmospheric CO_2 concentration is assumed to be 292 parts per million, the CO_2 exchange rate between the atmosphere and ocean is 19 moles per square meter per year, the vertical eddy diffusion rate in the deep sea is 3987 m^2 per year, and the carbon residence time in the biosphere is 60 years.

Carbon and ^{14}C exchange between reservoirs is described by a finite-difference approximation of the differential equations governing the time rate of change of carbon and ^{14}C activities in the reservoirs. The transfer of carbon and ^{14}C between reservoirs is calculated over the time step of the iteration (0.04 year). The ^{14}C production rate is calculated from a mass balance of atmospheric ^{14}C over each time step. This requires a linear interpolation of the decade-averaged $\Delta^{14}C$ measurements, corrected for geomagnetic variation, to obtain a yearly ^{14}C record. Over each time step the ^{14}C production rate is calculated to balance the change in the atmospheric ^{14}C level interpolated from the $\Delta^{14}C$ record, plus the gain or loss of ^{14}C between the atmosphere and the other reservoirs. The Q_M values are averaged over a decade to represent the same time interval as the $\Delta^{14}C$ measurements. The model Q_M calculations use the A.D. 1000–1860 geomagnetically corrected average atmospheric $\Delta^{14}C$ value of -5.4 per mil as an initial condition. This corresponds to a ^{14}C decay rate of 1.57 atom/sec-cm^2 (earth). Although the Q_M calculations begin for the year 1005, the first 100 to 200 years are sensitive to the initial conditions and thus these calculated Q_M values will change as the $\Delta^{14}C$ record is extended back in time.

Observed Solar Changes and the Carbon-14 Production Record

Because the ^{14}C production rate is dependent on neutron flux rates, which in turn are related to solar activity, the computed Q_M changes for the period after A.D. 1650 should be compatible with the historical observation of changes in solar activity.

The only available fairly precise long-term record of solar changes is the record of sunspot numbers. Therefore a direct comparison between the ^{14}C production rate and the sunspot record is made in Figs. 7 and 8. The model-dependent ^{14}C production rate Q_M is plotted as the percentage deviation (ΔQ_M) from the average production rate Q_M for the interval A.D. 1000 to 1860. Clearly, the model-derived production changes are substantial and can exceed a 25 percent difference from the mean.

Sunspot numbers, averaged over each sunspot cycle, are also given in Fig. 7. The ^{14}C production rate during the Maunder minimum (in ^{14}C terms, around 1660 to 1710) is 20.7 percent above the average for A.D. 1000 to 1860. Agreement appears to exist between the trends of the sunspot and ^{14}C production curves. There is a lag of only 10 years between the earlier part of the curves. The lag decreases when ^{14}C production rates are calculated from the box-diffusion model, incorporating a 20-year biospheric residence time (dashed line in Fig. 7).

The Maunder minimum, with near-zero annual sunspot numbers, lasted from about 1645 to 1715 (*3*). It corresponds to the interval between 1654 and 1714 during which the ^{14}C production rate increases (ΔQ_M) exceeded 10 percent of the 1000–1860 production baseline. In the following discussion ΔQ_M values

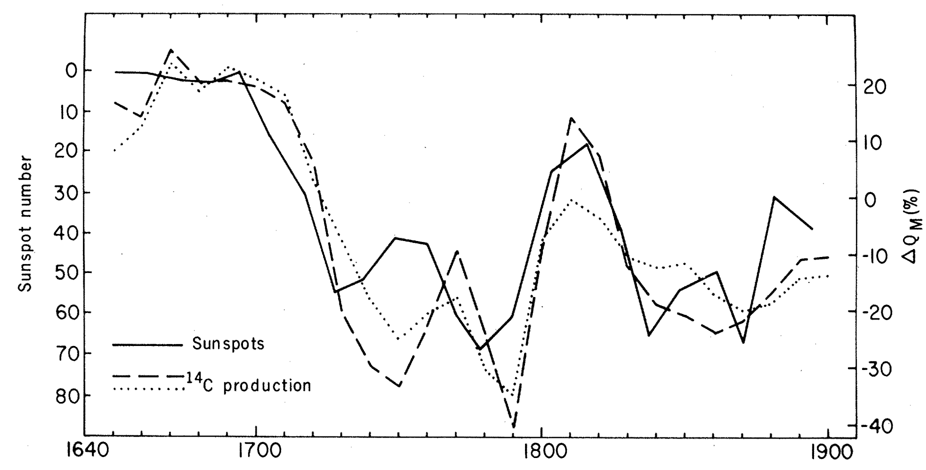


Fig. 7. Changes in ^{14}C production rate (ΔQ_M) calculated from the reservoir model, relative to the average 1000–1860 production rate, and inverse sunspot number record. The calculated ΔQ_M curves are for biospheric residence times of 20 years (dashed line) and 60 years (dotted line).

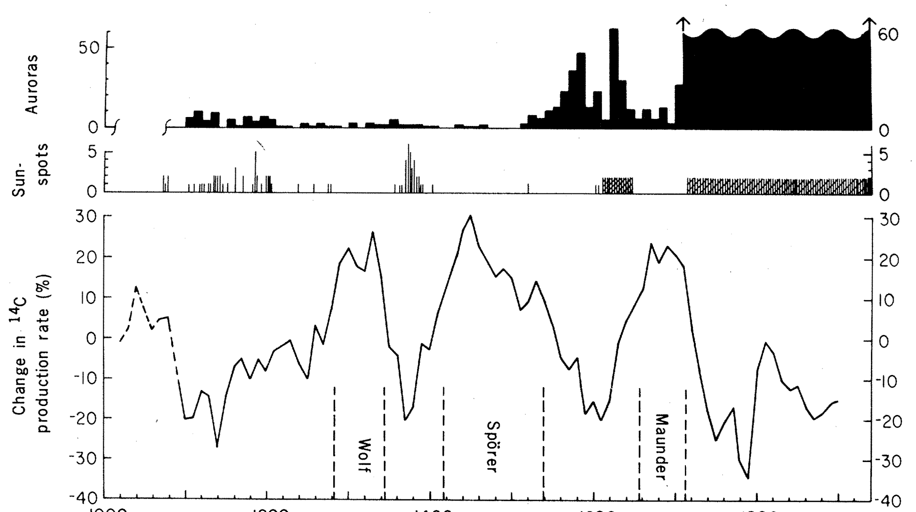
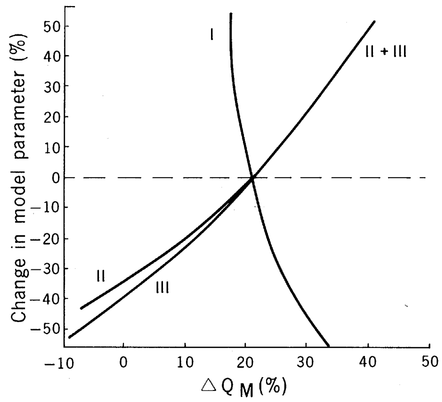


Fig. 8. Frequency of auroral observations (*3*) and sunspots (*3, 32*) and changes in ^{14}C production rate (ΔQ_M) calculated from the reservoir model, relative to the average 1000–1860 production level. The calculated ΔQ_M values are for a 60-year biospheric residence time. The number of naked-eye sunspot observations per decade before 1610 is given by the vertical bars. The cross-hatched area denotes the existence of sunspots, as observed by telescope.



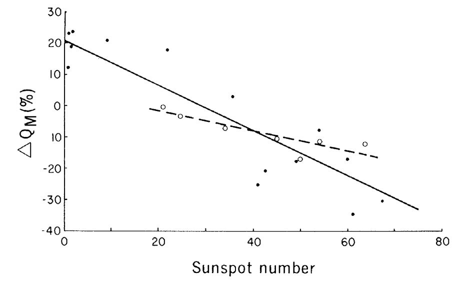


Fig. 9 (left). Analysis of the sensitivity of the Q_M calculation to the magnitudes of the carbon exchange rates used in the carbon reservoir model: (I) biospheric residence time, (II) CO_2 exchange rate, and (III) vertical eddy diffusivity in the ocean. The Q_M values over the interval A.D. 1675 to 1715 were calculated for a step change in these rates between 1615 and 1715. A 0 percent change represents the values for the carbon exchange rates used for our Q_M calculations, taken from Oeschger *et al.* (*18*). Fig. 10 (right). Carbon-14 production rate changes between A.D. 1660 and 1860 plotted against sunspot numbers averaged over the 11-year solar cycle. The dashed line gives the trend for the 19th century (A.D. 1800 to 1860).

above 10 percent are therefore tentatively equated with quiet-sun episodes during which sunspots are entirely, or nearly entirely, absent.

Other episodes of high ^{14}C production rates ($\Delta Q_M \geq 10$ percent) in the last millennium were from 1282 to 1342 and from 1416 to 1534 (with a dip in ^{14}C production to somewhat lower values near 1510). These periods of high ^{14}C production should also be periods of low auroral activity and low sunspot activity. In Fig. 8 the ^{14}C production rate changes are compared with the number of reports of auroral observations per decade between 0° 66°N (*3*) and also with sunspot observations. The sunspot data since 1610 are based on telescope observations and are divided into two groups according to whether (i) an 11-year cycle existed (crosshatched region in Fig. 8) or (ii) the cycle was not detectable.

For the pre-1610 era, only a limited number of naked-eye sunspot observations are available. A catalog of pretelescope sunspot records from the Orient was recently prepared by Clark and Stephenson (*33*). In Fig. 8 these data are depicted graphically, with each bar representing a single sighting. Clark and Stephenson conclude that the naked-eye sightings provide evidence of at least two quiet-sun intervals, near 1280 to 1350 and 1400 to 1600. The latter episode of low sunspot activity is the so-called Spörer minimum.

The interval of low sunspot activity in the early part of the 14th century is here named the Wolf minimum. The high ^{14}C production rate places the Wolf minimum at about 1282 to 1342, in good agreement with the independent analysis of frequency of sunspot observations, which places this minimum at 1280 to 1350. The Spörer minimum occurred from about 1416 to 1534 in ^{14}C terms.

The peak in ^{14}C production during the 11th century, which may be partially an artifact of the initial conditions required for the model calculation of Q_M, would indicate fairly low sunspot activity near A.D. 1040. This is in agreement with compilations of reported auroral observations for the 11th and 12th centuries, in which only the decade A.D. 1040 to 1050 is lacking in reports of auroral displays (*34*). A high sunspot sighting frequency is found between 1370 and 1390 (Fig. 8), which coincides with the minimum in ^{14}C production (active sun) from 1370 to 1380. An active sun during the 12th century is also evident from both sunspot and ^{14}C records.

The overall qualitative agreement between ^{14}C and the historical sunspot record supports the soundness of the basic premise that atmospheric ^{14}C perturbations around the main trend reflect changes in solar activity. An important remaining question is whether the magnitude of the ^{14}C production changes calculated from the model agrees quantitatively with the ^{14}C production changes derived from atmospheric neutron flux measurements.

Magnitude of Carbon-14 Production Rates

We have calculated ^{14}C production rates Q_M from an 860-year record of atmospheric ^{14}C levels, using a carbon reservoir model. Carbon-14 production rates Q have also been calculated from neutron flux measurements made over the past 30 years (*19-22*). Unfortunately, these independent estimates cannot be directly compared because during the years of neutron flux measurements the atmospheric ^{14}C levels were reduced by the addition of CO_2 from fossil fuels. As a result, we will compare our Q_M values to Q values calculated from the empirically derived relationship represented by Eq. 2. As mentioned above, for the time interval of our ^{14}C measurements (A.D. 1000 to 1860), the average $\Delta^{14}C$ is -5.4 per mil, which corresponds to a decay rate of 1.57 atom/sec-cm^2 (earth). The magnitude of the changes about this mean decay rate (ΔQ_M) peak at 21 percent during the Maunder minimum (A.D. 1665 to 1705) and at 29 percent during the Spörer minimum (A.D. 1435 to 1455).

During the time interval of the *Aa* measurements (A.D. 1868 to 1967) the mean production rate resulting from Eq. 2 for an average *Aa* of 17.9 is 1.88 atom/sec-cm^2 (earth). The maximum increase in production rates over this average rate (that is, $Aa = 0$ in Eq. 2, where the 2.310 intercept has a standard error of 0.114) is 23 ± 6 percent.

The magnitude of the average ^{14}C production rates determined by these two calculations reflects the time interval of the measurements. Thus the ^{14}C production rate of 1.57 atom/sec-cm^2 calculated from the model represents 860

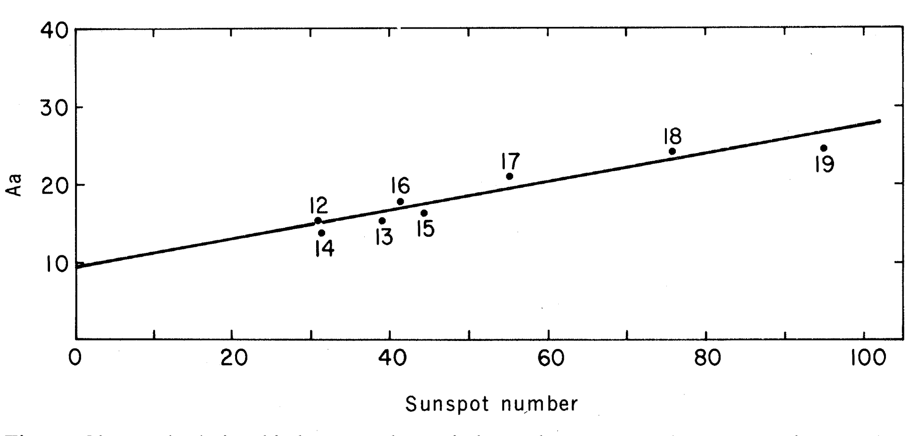


Fig. 11. Observed relationship between the *Aa* index and sunspot number, averaged over solar cycles. The numbers next to the points represent the 11-year cycles shown in Fig. 2.

years, whereas the rate of 1.88 atom/sec-cm^2 (earth) represents the 100-year duration of the *Aa* record. The discrepancy in production rates could reflect the different time intervals of the records. Also, the accuracy of the production rate calculations should be considered. The Q values calculated from neutron flux measurements have an uncertainty of about 20 percent (*19, 20*), whereas the average Q_M value is dependent on the size of the carbon reservoirs as described in the model. If the amount of terrestrial carbon (and thus ^{14}C) is underestimated by Oeschger *et al.* (*18*), then the global decay rate of ^{14}C and thus the steady-state production rate of ^{14}C will be low. A maximum estimate of carbon reservoir size (*9, 35*) would result in a ^{14}C production rate of 1.99 atom/sec-cm^2 (earth). Thus the apparent discrepancy between the neutron flux and carbon model estimates of ^{14}C production rates could be explained by the uncertainties in the respective production rate calculations.

The magnitudes of the changes in ^{14}C production rates calculated from the model and predicted by Eq. 2a are similar. If, for example, the steady-state decay rate and thus the production rate of ^{14}C in the model were increased from 1.57 to 1.88 atom/sec-cm^2 (earth), arbitrarily assigning this ^{14}C to a carbon reservoir with a 1000-year residence time, it would only result in the ΔQ_M during the Maunder minimum decreasing from 21 to 20 percent.

Because Q_M is model-dependent, changes in carbon exchange rates will also affect its magnitude. If climatic variability is parameterized as a change in carbon exchange rates (that is, a global decrease in wind speeds is represented by a decrease in the CO_2 gas exchange rate between atmosphere and ocean), we can analyze the sensitivity of the Q_M calculation to such changes. A global climatic change can be represented in the model by a change in biosphere residence time, gas exchange rate, or oceanic vertical diffusion rate. As an example we calculated Q_M values during the Maunder minimum for a step increase starting in A.D. 1615 and lasting until 1715 in these three variables. The results are shown in Fig. 9. If the model parameters of Oeschger *et al.* (*18*) are used (that is, a 0 percent change in Fig. 9) a ΔQ_M value of 21 percent is calculated for the Maunder minimum. Figure 9 shows that the magnitude of Q_M is more sensitive to changes in the gas exchange rate and vertical diffusion rate than in the biosphere residence time. The value of ΔQ_M can be reduced to 10 percent by either a 20 percent decrease in the gas exchange rate or a 25 percent decrease in the vertical diffusion rate. Likewise, if climatic changes associated with the Maunder minimum increased the gas exchange rate by 20 percent or the vertical diffusion rate by 25 percent, ΔQ_M would rise to 30 and 29 percent, respectively.

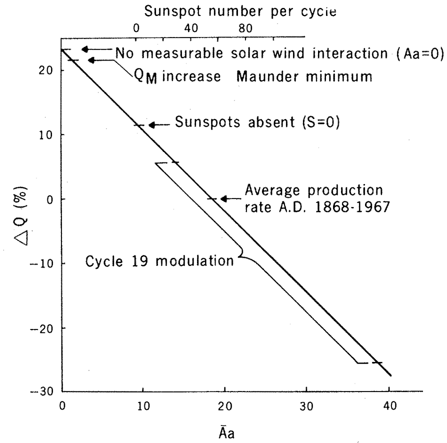


Fig. 12. Dependence of ^{14}C production rate on sunspot number and *Aa* index, according to the calculations discussed in the text. The actual production rate increase during the Maunder minimum, calculated from the tree-ring ^{14}C record, is shown for comparison. The ^{14}C production rates are expressed as percent deviations from the average ^{14}C production rate between 1868 and 1967, except for the ΔQ_M value, which is relative to the average for A.D. 1000 to 1860 (see text).

One should realize that in our ΔQ_M calculations, climatically induced changes in carbon exchange rates that would change atmospheric ^{14}C levels are interpreted as resulting from changes in ^{14}C production rates. This assumption could result in differences between the percent changes in ^{14}C production rates calculated by the model and those calculated from neutron flux measurements. There is no need, however, to assume an appreciable influence of climatic change on the Maunder minimum ^{14}C level because the ^{14}C production rates calculated from the model and those calculated from neutron fluxes agree within the inaccuracies stated earlier.

Sunspot Numbers and Carbon-14 Production Rates

The ^{14}C production rate changes ΔQ_M calculated from the model are plotted against sunspot numbers in Fig. 10. The sunspot numbers were derived from the curve given in Fig. 7 for each decade for which the ^{14}C production rate was calculated.

There is a correlation between average sunspot number per cycle, $\bar{S}$, and ^{14}C production rate (solid line in Fig. 10, $r = .89$). The slope $dQ_M/d\bar{S}$ is time-dependent. For the data given for the 19th century (1800 to 1860) a regression analysis results in

$$Q_M = 1.630 - 0.0048\,\bar{S} \quad (r = .86)$$

(dashed line in Fig. 7). If the Maunder minimum data points of 1710 and earlier, for which $\bar{S}$ is about zero, are excluded, we obtain for the 18th century (A.D. 1720 to 1800)

$$Q_M = 1.783 - 0.0099\,\bar{S} \quad (r = .59)$$

suggesting an increase in $dQ_M/d\bar{S}$ from 0.0048 ± 0.0013 to 0.0099 ± 0.0056.

These reservoir model $dQ_M/d\bar{S}$ values can be compared with 20th-century neutron flux estimates of $dQ/d\bar{S}$. Using Eq. 2 and substituting $Aa = 9.13 + 0.17\,\bar{S}$ derived from Fig. 11, where average *Aa* values observed since 1868 are plotted against $\bar{S}$, gives

$$Q = 2.091 - 0.0041\,\bar{S} \qquad (3)$$

Thus the 20th-century $dQ/d\bar{S}$ value of 0.0041, derived from production rates calculated from neutron fluxes and observed solar changes, evidently agrees quite well with the 19th-century $dQ_M/d\bar{S}$ value of 0.0048 derived from the observed ^{14}C record and carbon reservoir modeling.

The calculations above suggest good agreement between 20th- and 19th-century ^{14}C production rates and average sunspot numbers, but with a change to a greater dependence on $\bar{S}$ when approaching the Maunder minimum, when sunspots were disappearing.

Having pointed out the suggested increased dependence of Q on the sunspot number when approaching the Maunder minimum, we now neglect this effect in order to present a more simplified picture of solar modulation. The relationship between Q and *Aa* is represented by Eq. 2, whereas Eq. 3 gives the Q-$\bar{S}$ relationship for the 20th and 19th centuries. If this latter relationship is extended to the 18th century, some interesting conclusions result.

For intervals when the average sunspot number is zero, the production rate is 2.091 atom/sec-cm^2. This is 11.2 percent above the average 1868–1967 production rate of 1.88 atom/sec-cm^2. However, in the absence of solar wind interaction with the magnetosphere ($Aa = 0$), the ^{14}C production would be 2.310 atom/sec-cm^2 or 22.9 percent above the 1868–1967 average. The relevant relationships are given in Fig. 12. Evidently, even with $\bar{S} = 0$, there is some background solar wind interaction with the incoming cosmic radiation. This

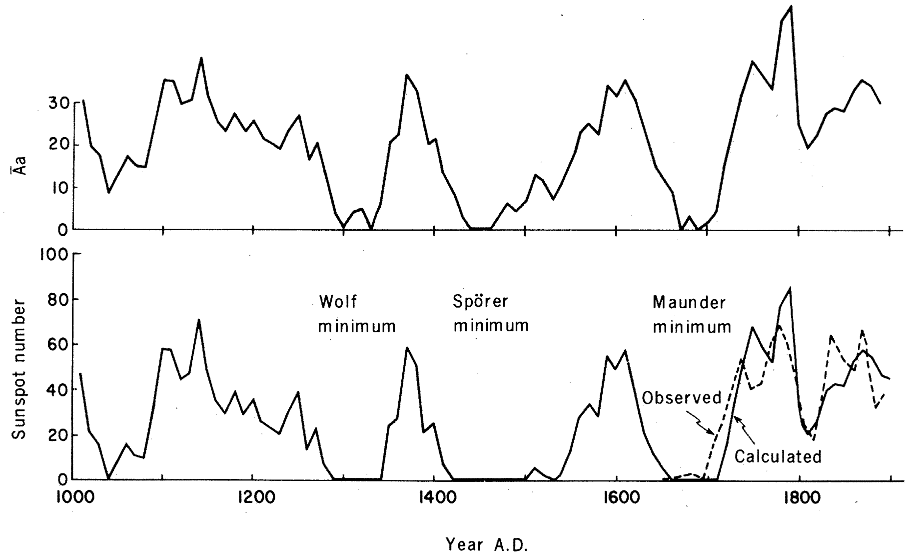


Fig. 13. Sunspot numbers and Aa indices calculated from the ^{14}C production record. The dashed line gives the actual observed averaged sunspot record. Sunspot numbers and Aa indices are averaged over the 11-year solar cycle.

residual solar wind may originate from the sun's polar regions. Forman (*36*) recently attributed the higher ^{14}C production rate for the Maunder minimum to a further modulation of the residual solar wind. However, the influence of the residual solar wind may not be as large as suggested in our simplified Fig. 12 because the Q value derived for $\bar{S} = 0$ increases when a larger $dQ/d\bar{S}$ value is used for the 18th century.

The relationship between Q and Aa suggests that during the Maunder, Spörer, and Wolf minima there was less solar wind interaction (a lower Aa index) and thus ^{14}C production rates were higher. The ΔQ_M values calculated from the atmospheric record and plotted in Fig. 8 indicate that during these periods the Aa index would have been lower than the values measured between 1868 and 1967. Our Q_M calculations suggest that during a portion of the Maunder, Spörer, and Wolf minima the Aa indices approach zero. Thus, not only did the sunspots disappear, but the interplanetary fields created by the solar wind also had little interaction with the earth's magnetosphere.

One final remark has to be made on the sunspot dependence of ^{14}C production rates. Equation 3 should be used only to approximate changes in Q over intervals of several sunspot cycles because the sunspot numbers $\bar{S}$ are averaged over each 11-year solar cycle. The long-term change in Q with $\bar{S}$ represented by Eq. 3 results in $dQ/d\bar{S} = -0.0041$. For Q modulation within a single 11-year cycle, $dQ/dS = -0.00242$ (Eq. 1). Thus the Aa theory gives a dependence of ^{14}C production rate on sunspot number for long-term changes that is nearly twice that found within a single solar cycle. This greater dependence is the result of long-term changes in solar modulation that are not accounted for by Eq. 1.

Pattern of Solar Change

The changes in Q_M calculated from the observed atmospheric ^{14}C variations are an indicator of solar wind and coronal disturbances. In our opinion, Q_M should be considered an independent parameter that provides information on solar wind conditions.

Since A.D. 1100 there were three major increases in ^{14}C production rates. Predicting the sunspot record from our Q_M calculations, according to the $Q_M \geq 10$ percent criterion discussed above, would suggest that sunspots were absent for about 60 years during the 1282–1342 Wolf minimum, for about 118 years during the 1416–1534 Spörer minimum, and for about 60 years during the 1654–1714 Maunder minimum. These episodes averaged 79 years in duration.

The switch from a quiet to an active sun differs for each episode. For the Wolf minimum the switch from high to low ^{14}C production takes about 40 years, but for the Spörer minimum it takes nearly 150 years. After the Maunder minimum, full solar activity is reached fairly rapidly in about 60 years. Each time the change from an active to a quiet sun took place in about 60 to 80 years. Our ^{14}C measurements show the time separation of ^{14}C perturbations to be quite variable. For the current millennium the intervals between quiet-sun modes may be as short as 120 and as long as 300 years.

It has been suggested that the sunspot cycle is paced by an accurate "clock" inside the sun, with transport of the magnetic field from the deep interior to the sun's surface subject to irregularities induced by turbulence in the convective layer (*37*). Accordingly, the solar clock was running while the surface indications of the cycle were predominantly switched off (*37*). The data given in this article suggest that the irregularities induced by the turbulence in the convective layer may suppress the sunspot cycle for intervals lasting 60 (Wolf and Maunder minima) to 120 years (Spörer minimum).

During the Maunder minimum switch from the active to the quiet mode, the solar rotation in the equatorial regions appears to accelerate (*38, 39*). The increased rotation rate, associated with a change in turbulence in the convective layer and inhibiting transport of magnetic field from the deep interior to the sun's surface, may also be a causal factor for the changes in solar wind properties that ultimately result in higher ^{14}C production rates.

An 860-Year Record of Sunspots and Aa Indices

Although we have given arguments that the ^{14}C production record should be considered independently from the sunspot record, there is a natural inclination to look for a paleosunspot record. Approximate sunspot numbers per cycle can be derived from the 860-year Q_M record by using the relationship $\Delta Q_M = 10.5 - 0.53\ \bar{S}$ percent empirically derived for the interval 1720 to 1860. Using this equation for the ΔQ_M data of Fig. 8 and substituting $\bar{S} = 0$ for calculated "negative" $\bar{S}$ values gives the sunspot curve in Fig. 13. The actual observed sunspot numbers since A.D. 1645 (dashed line in Fig. 13) are given for comparison. An Aa record derived from Eq. 2a is also given in Fig. 13.

The ^{14}C record and the derived Q_M, S, and Aa values can be compared with the record of past climatic changes. The understanding of the natural atmospheric ^{14}C changes gained in this article may also be used for a prediction of the natural ^{14}C levels in the 20th century. Such a prediction is of critical importance for the evaluation of anthropogenic ^{14}C changes caused by fossil fuel combustion. The $\Delta^{14}C$ data used here will be published in tabular form in a more detailed paper.

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Calmodulin Plays a Pivotal Role in Cellular Regulation

Wai Yiu Cheung

A living cell is the epitome of ingenious design; although highly complex, it functions with orderliness and efficiency. Its ability to coordinate a wide range of biological activities rests with an elaborate communications system directed toward a single goal—homeostasis and survival. Uncoordinated activities invariably lead to pathological conditions and, if not checked, to uncontrolled proliferation or cell death.

Summary. The role of calcium ions (Ca^{2+}) in cell functions is beginning to be unraveled at the molecular level as a result of recent research on calcium-binding proteins and particularly on calmodulin. These proteins interact reversibly with Ca^{2+} to form a protein · Ca^{2+} complex, whose activity is regulated by the cellular flux of Ca^{2+}. Many of the effects of Ca^{2+} appear to be exerted through calmodulin-regulated enzymes.

In a multicellular organism, communication poses an added complexity. Apart from coordinating its own activities, each cell must act in concert with neighboring cells. To meet the need for intercellular communication, each cell possesses a set of messenger molecules and cell-surface receptors that transduce the chemical messages into a recognizable signal. The signal either activates or inhibits a biochemical reaction that is controlled by a rate-limiting step, which is usually governed by a cellular regulator, defined here as a molecule that controls one or more critical processes.

The purpose of this article is to review the salient features of cellular regulators in general and Ca^{2+}-binding proteins in particular; emphasis is placed on calmodulin, a ubiquitous Ca^{2+}-binding protein that is emerging as an important mediator of Ca^{2+} functions in eukaryotes (*1*).

Cellular Regulators

Although the complexity of intercellular communication increases with the complexity of the organism, there does not appear to be a parallel increase in the number of cellular regulators. Hormones, cyclic nucleotides, and calcium ion are the three most important sets of regulators or messengers in mammalian systems, and their activities are interrelated; that is, the biochemical effect and metabolism of one invariably modify those of the others. This interrelationship is depicted schematically in Fig. 1.

The actions of hormones have long held the interest of endocrinologists. It was originally believed that the manifestation of hormonal effects required intact cells. In a series of pioneering studies on glycogenolysis, Sutherland and his

The author is a member of the Department of Biochemistry, St. Jude Children's Research Hospital, and professor of biochemistry, University of Tennessee Center for the Health Sciences, Memphis, 38101. He is currently a faculty scholar, Josiah Macy, Jr. Foundation, at the Department of Pharmacology SJ-30, University of Washington, Seattle 98195.

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