Solar History and Human Affairs
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# Solar History and Human Affairs

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*Historical research at different time scales from 10s to 1000s of years suggests that solar variation may have influences on global climate. Climate change has had significant impacts on cultures during these periods. Very high solar output during the Medieval Optimum would be expected to have particularly large impacts on peoples of that time as sunspot numbers are thought to have reached one third again any values observed in the current century. Certain other impacts can be inferred from modern populations. For example, the higher parts of the solar cycle are associated with greater incidence of skin melanoma.*

**KEY WORDS:** solar variation; climate change; global climate.

## INTRODUCTION

The sun is a likely initiator of climatic change — and, through the lever of climate, of cultural change as well. One need not look for examples. The different climatic regimes of the earth are fundamentally determined by differences in insolation; anyone who recognizes day and night, the march of the seasons, or the existence of the major ice ages must acknowledge that the sun has the power to alter climate and thus to affect the course of human affairs.

Climate is continuously changing. Whether the sun is responsible for any of these changes is another matter, since solar forcing is but one of many plausible mechanisms of climatic change. It is a fact that beyond the trivial examples given above (day and night, the seasons, and through the Milankovitch effect, the pacing of the major glaciations (Hays et al., 1976)) there is as yet no other well-established case of any significant effect of solar variations on the climate of the earth (National Research Council,

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1982). As always, there are several cases yet in court, including the possible correlation of the Little Ice Age with the coincident Maunder Minimum of solar behavior (Eddy, 1977a) and most recently the perplexing case of the Australian varves, where sedimentary deposits, laid down by glacial run-off nearly 700 million years ago, mimic all the features of the 11-year sunspot cycle of today (Williams, 1986). These and other cases rest, as often in science, on circumstantial evidence: still missing is the incriminating motive of an established, physical connection.

The problem is that we do not know enough about the limits of variability of solar inputs to the earth (Eddy, 1983a). We have watched the sun's surface with telescopes for almost 400 years and have found it spotted and variable and often violent. But how these superficial changes, 93 million miles away, might affect the earth or life upon it is still a matter of debate. As is the deeper question of solar uniformitarianism: whether what we see on the sun today, or in the last 100 years, which is but a wink of an eye in the life of a star, is representative of the full range of its behavior (Eddy, 1988).

To answer these questions we need to know the ancient history of the sun. Its not an easy matter to recover the true history of anything, and it grows more difficult and more ambiguous as one gropes further back in time (Eddy, 1980). Solar history, if by that we mean the coming and going of sunspots, is quite well known back to about AD 1750, the time of Benjamin Franklin. It is known, but more poorly, for the century and a half before that, to the time of Galileo and Milton. Before 1610, when the telescope first came upon the scene, the available records change character dramatically. There are a few reports of sunspots seen without the aid of a telescope in dynastic and local annals from the Orient (Stephenson and Clark, 1978; Xu and Jiang, 1982); all else that we can learn of the sun from written accounts comes from indirect accounts, such as records of the Aurora Borealis or scattered descriptions, often allegorical, of a weakened sun or of the ghostly corona that was sometimes seen at times of total solar eclipses. For the most part these dim and discontinuous records fade beyond utility at about the time of Christ.

The next layer of solar history comes from trees, through the painstaking, ring-by-ring analysis of radiocarbon that remains in the cellulose of once-living wood (Stuiver and Quay, 1980). By such methods we can now give a confident picture of the most solar variations of the last 1000 years, with the buttress of direct historical data in the more modern period of overlap. We can also give a more sketchy history of the sun to the time of the late stone age, some 7500 years into the past, based on Carbon-14 measurements in dated tree-rings of the bristlecone pine (Eddy, 1977b).

What follows is a brief review of what is known of solar history, first in the last 20, and then the last 100 years of direct observation, and finally in the last 1000 years for which direct and proxy data are combined. In each case I interpret known solar changes in terms of probable terrestrial effects, leaning often on theory and extrapolation, for as noted above, the physical connections between solar changes and terrestrial effects are ill-defined. In the final sections I review the evidence for unusually high solar activity in the 12th and 13th centuries and speculate on how enhanced solar radiation at the time may have affected the course of civilization.

## A REVIEW OF SOLAR HISTORY

### The Last 20 Years

Shown in Fig. 1 are annual averages of the measured spottedness of the sun over the 115 years between 1870 and 1985. Immediately apparent in the last two decades is the familiar rise and fall of the 11-year sunspot cycle, with maxima in 1969 and 1979, minima in 1964 and 1976.

These cycles of solar activity have little effect on the earth in terms of direct changes in solar light and heat. Far and away the most important are any changes in the total integral of light and heat from the sun: the so-called "solar constant" (Eddy et al., 1982), which is the integral under the curve of solar flux that is shown in Fig. 2. Continuous measurements of the solar constant have been made only since 1978, from spacecraft.

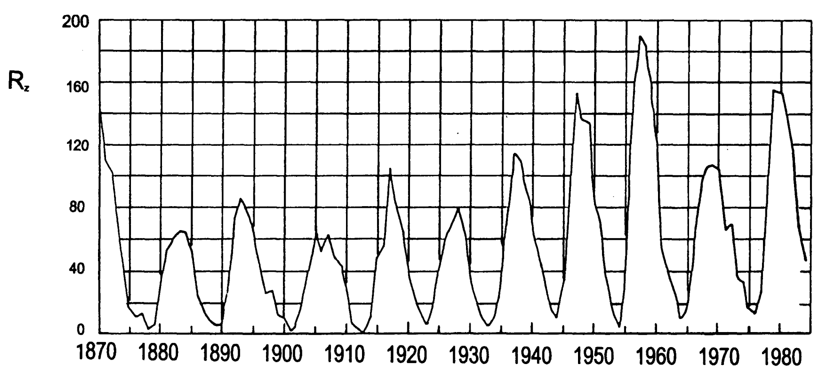


**Fig. 1.** Sunspot numbers, $R_z$, AD 1870–1985, expressed as annual averages of daily, observed values. The sunspot number is an arbitrary index of the number of dark spots on the sun, and hence of solar activity.

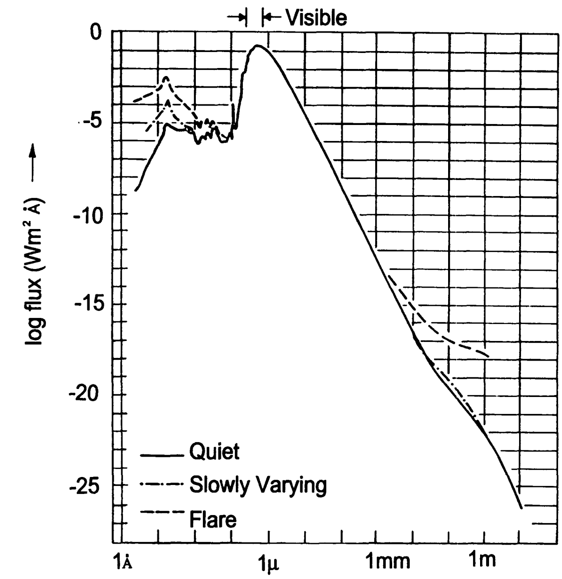


**Fig. 2.** Solar radiative flux received at the earth as a function of wavelength, logarithmic scale at bottom. Solar radiation peaks in the visible spectrum and falls off rapidly at shorter and longer wavelengths. Shown as dashed lines are typical increases over the "quiet" or unspotted sun values, corresponding to peaks of the 11-year sunspot cycle ("slowly varying" component), and during short bursts, lasting a few minutes, called "solar flares." The ultraviolet extends from about 100–3000 Angstroms wavelength. Greatest activity-related increases are in the X-ray (1–100 Angstrom) and meter wavelength radio region.

Noted from the start were day-to-day fluctuations of a few tenths of 1% that are obviously related to sunspots and associated bright features on the solar disk. The atmosphere of the earth is an effective integrator of such changes, however, and their climatic effect is certain to be small. More important in terms of terrestrial effects is a monotonic, downward drift in the solar constant that is a distinctive feature of the spaceborne measurements (Willson and Hudson, 1991). In the nine years of the Solar Maximum mission, continuous spaceborne measurements show the solar constant has monotonically decreased at the rate of about 0.18% per year. Climate responds best to persistent forcing, and the trend, if continued, could prove climatically significant. We now presume that this downward trend is periodic, though the proof of that, and the critical question of the period of oscillation, *await continued measurements.* The drift in the solar constant is possibly a reflection of the *11-year cycle,* though more likely a longer one, in which case the effects on climate would be more pronounced.

Far less energetic, though potentially as important terrestrially, are the changes in the short-wave, ultraviolet, and X-ray radiation from the sun that are known to follow the ups and downs of solar (sunspot) activity (White, 1977). The magnitude of these activity-related variations is shown in Fig. 2 as broken lines. We note that relative changes in the solar output are greatest at the shortest and most energetic wavelengths (and in the radio spectrum, where the total energy is minuscule). The radiation intercepted at the earth from the sun in the far ultraviolet can change by several percent from day to day and year to year (Smith and Gottlieb, 1974) with important effects on the chemistry of the upper atmosphere where far ultraviolet radiation from the sun is completely absorbed. Changes in the near ultraviolet are smaller, but their ground-level effects can be greater since radiation from the sun in this spectral region controls the production of atmospheric ozone and thus affects the transmission of solar ultraviolet radiation to the surface of the earth. As a result, in years of high solar activity we expect an increased flux of solar ultraviolet radiation at the surface of the earth, and particularly in the tropics where the atmospheric ozone shield is thinnest (London and Angell, 1982). There is some evidence (Fig. 3) that the incidence of malignant melanoma in humans follows the 11-year cycle of solar activity (Houghton et al., 1978; Viola et al., 1979; Houghton and Viola, 1981). This is at first surprising, considering how little of the damaging ultraviolet radiation from the sun reaches the surface of the earth. If the connection is real, we must conclude that the human skin is a very sensitive detector of the radiation in the band that is called ultraviolet "A" (Freeman, 1975).

In addition to radiation, the sun emits a continuous flux of atomic particles and magnetic fields that constitute the "solar wind." This also varies, but the direct effects are on the outermost regions of the earth's atmosphere and the energy that is involved is less than $10^{-6}$ that of the solar constant.

## The Last 100 Years

A second look at the annual sunspot numbers in Fig. 2 reveals another, longer-term feature of solar change: a slow rise and possible fall in what has been called the "envelope" of the 11-year sunspot cycle. The peak amplitudes of the 11-year sunspot cycle at the turn of the century were

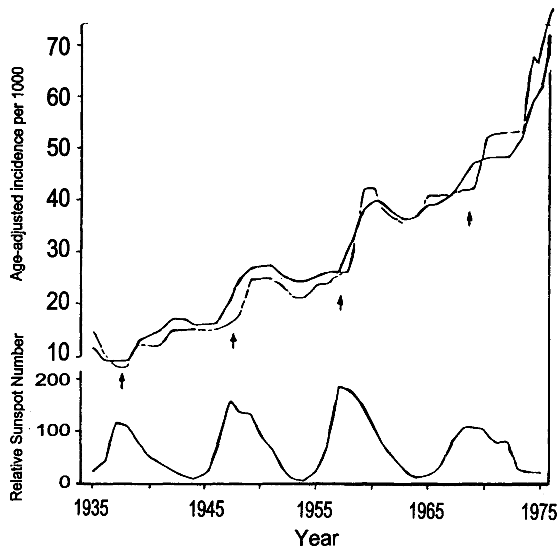


**Fig. 3.** Age-adjusted incidence of malignant melanoma in Connecticut, in number of cases per 100,000 inhabitants, for the 40-year period from 1935 through 1975 (Houghton et al., 1978), compared with annual values of sunspot number (as in Fig. 1). Malignant melanoma is induced by solar ultraviolet radiation; the rising trend is generally attributed to changes in dress and outdoor activities.

weaker by about a factor of three than the highest cycles that followed at mid-century: solar activity (expressed in annual mean sunspot numbers) rose to a broad maximum in about 1960 and has since, we think, begun to fall. Were we to look at the longer record of recorded sunspot numbers we would find evidence of earlier, similar behavior with a suggestion of a long-term cycle of about 80 to 90 years (Eddy, 1977a).

What effects might we expect at the earth from these longer, secular changes in solar activity? Continuous measurements of the solar constant and of the ultraviolet flux from the sun cover less than 10% of the span of sunspot numbers shown in Fig. 1. We can extrapolate from what we know of shorter-term changes, however, to conclude that during the last 100 years the solar ultraviolet flux at the surface of the earth followed a pattern of change that was like the envelope of sunspot numbers: increasing by a factor of two or three at maxima of the 11-year cycle from 1880 to 1960. This twofold increase in ultraviolet "A" radiation received at the earth is, for comparison, much greater than the increase anticipated from depletion of the ozone layer induced by the release of man-made fluorocarbons (National Research Council, 1984). The secular increase in solar ultraviolet radiation may explain, in part, the continuous rise in the incidence of malignant melanoma that is a striking feature in the data shown in Fig. 3, although cultural changes of dress and leisure time may be a bigger factor.

It is tempting to ascribe a more direct climatic effect to the secular, 20th century rise in solar activity. The average surface temperature of the earth has since 1880 followed a curve not unlike that of the envelope of the annual sunspot number curve that is shown in Fig. 1 — rising by about 1°C to a maximum near mid-century, halting slightly, then rising again (Jones et al., 1986). Were the global warming in the first half of the present century a direct effect of the sun it would imply a slow increase of about 1% in the solar constant between 1880 and 1950. We could explain this apparent coincidence between surface temperature and the envelope of the 11-year cycle of solar activity were the sunspot number modulation by changes in the outward flow of heat from the interior of the sun. A slow increase in the flow of heat from beneath the solar surface could amplify the long-term level of solar activity and at the same time raise the surface temperature of the earth. This speculation (Eddy, 1977b) is strengthened somewhat by the downward drift now noted in modern, spaceborne measurements of the solar constant (Willson and Hudson, 1991); it is further corroborated when one compares the climate and radiocarbon histories since the time of the Little Ice Ages: the level of solar activity has risen gradually since the late 1600s, as has the surface temperature (Eddy, 1976). The same is true on the scale of decades. Throughout the last 400 years surface temperatures were consistently higher during decades when the envelope of solar activity was higher and consistently lower when the long-term envelope of solar activity was depressed, as in the latter half of the 17th century, and in the first two decades of the 19th century.

## The Last 1000 Years

Figure 4 is a composite of direct and proxy records of solar activity during the last 1000 years. Shown as a solid line is the level of solar activity derived by Stuiver and Quay (1980) from tree-ring radiocarbon analyses. In the most recent period (far right) it is compared with measured annual sunspot numbers. The good fit in this period of overlap (AD 1650 onward) between the envelope of the sunspot number curve and the level of solar activity derived from tree-ring radiocarbon demonstrates that we can read the latter as a reliable proxy of the overall envelope of solar activity. This assumption is strengthened by a solid mechanism: we know the process by which radiocarbon is formed in the upper atmosphere (through the impact of high-energy galactic cosmic rays) and how radiocarbon production is modulated by solar activity (by scattering in the solar wind.) The reliability of Carbon-14 as a proxy of solar behavior is bolstered further by comparison with historical observations of the Aurora Borealis (open circles in Fig. 4, from the catalog of Link, 1962). Auroral displays are triggered by the impact of solar atomic particles from solar flares that occur at times of high sunspot activity. Periods of high or low solar activity identified in the record of tree-ring radiocarbon coincide with similar events in the historical record of auroral occurrence.

We note in Fig. 4 the repeated (though irregular) occurrence of prolonged periods of low solar activity when very few sunspots were noted, and when there are few auroral reports. The most recent of these secular solar minima, labeled "Maunder Minimum," falls during the period of telescopic observations of the sun when the number of sunspots reported dropped dramatically (Eddy, 1976, 1983b).

What were the effects of these long lapses in solar activity on the earth? We can be sure that solar ultraviolet radiation, tracking as it does the general level of solar activity, fell to low levels and remained there during the Maunder, Spoerer, and Wolf minima that are shown in Fig. 4. If we accept the postulated association between the solar constant and the

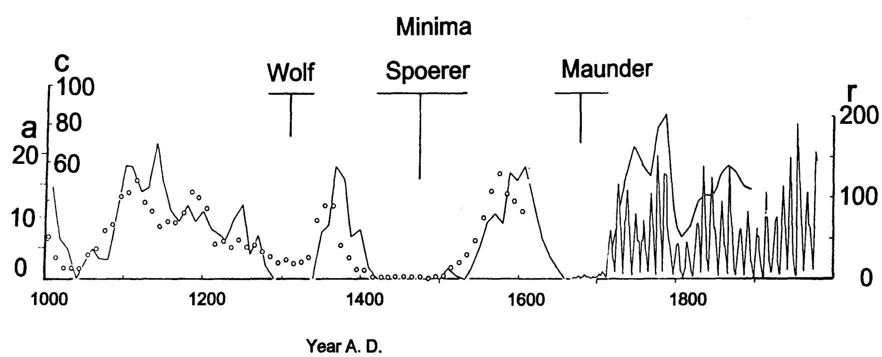


**Fig. 4.** A comparison of annual sunspot number (fine-line, 1645–1980, scale at right) with sunspot numbers derived analytically from measurements of tree-ring radiocarbon (Stuiver and Quay, 1980; scale "c" at left), and historical observations of the Aurora Borealis (from Link, 1962; scale "a" at left.) Three periods labeled "Wolf," "Spoerer," and "Maunder Minimum" are periods of suppressed solar activity identified in the radiocarbon record and confirmed in sunspot and auroral data.

envelope of solar activity we should expect the solar constant to fall by 1–2% during these periods of suppressed solar activity, inducing colder climate. As it happens, the Spoerer and Maunder minima mark the coldest extremes of the Little Ice Ages (Eddy, 1976, 1977a).

This hypothesis seems to hold when we compare the longer history of radiocarbon variations with what is known of the advance and retreat of mid-latitude glaciers for the last 7500 years (Eddy, 1977b). Throughout that time, in centuries when the sun was inactive, glaciers systematically advanced; when the sun was more active, glaciers retreated.

## THE MEDIEVAL MAXIMUM OF SOLAR ACTIVITY

It is tempting to stretch the secular solar-climate hypothesis further by examining another feature in the Stuiver and Quay record of tree-ring radiocarbon. Their original data (Fig. 5; corrected for long-term trend in the strength of the geomagnetic moment; Stuiver and Quay, 1980) show the Maunder, Spoerer, and Wolf minima of solar activity as peaks of prolonged increase in the production of tree-ring radiocarbon. In the same record is a similar, secular drop in radiocarbon production, spanning the period from about AD 1100 to 1300: a departure from the mean that is roughly equivalent, but opposite in sign to the increases in radiocarbon production that characterize the Maunder, Spoerer, and Wolf minima. A prolonged decrease in radiocarbon production may be attributed to enhanced solar activity, and this period has been called the solar "Medieval Maximum" (Eddy, 1977a). The carbon reservoir model employed by Stuiver and Quay (1980) (and employed in Fig. 4) suppressed the significance of this event. If however, we take the Medieval Maximum as defined in the raw data (Fig. 5), and scale its magnitude relative to the historically-observed peak of solar activity in about 1780 we find that solar activity between AD 1100 and 1300 was about twice as high as that experienced in modern time, including the high cycles of the middle of the present century.

There are other reasons to believe that the period between about AD 1100 and 1300 was a time of higher than normal solar activity. Large sunspots can be seen without the aid of a telescope, under favorable observing conditions. The astrologer/astronomers of the Eastern World were assiduous observers of the sky, and reports of dark spots on the sun, seen with naked eye, found their way into the dynastic histories of China, going back to the time of the Han Dynasty — the earliest from a report in 26 BC (Stephenson and Clark, 1978). The total number recorded in the Orient is not large; before the advent of the telescope only about 150 were noted, or an average of about one per decade. The reports are far from uniform

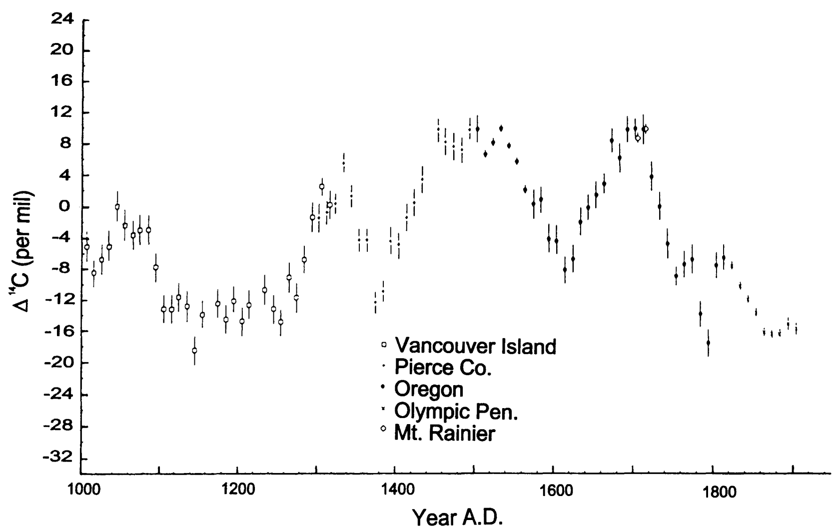


**Fig. 5.** Measured, residual $C^{14}$ variations from tree-ring measurements, after removal of long-term trend caused by changes in geomagnetic field intensity (from Stuiver and Quay, 1980), as a function of time, expressed as a deviation, in parts per 1000, from the arbitrary, AD 1890 value of the measured ratio of $C^{14}$:$C^{12}$. Radiocarbon production is inversely related to solar activity: the Wolf, Spoerer, and Maunder minima of solar activity appear as increases of 1–2% in delta C-14. The drop in radiocarbon production between about AD 1100 and AD 1300 is treated in this paper as an increase in the level of solar activity ("Medieval Maximum").

in time, however, and applied historians of astronomy have used these ancient records to verify periods of unusually high or unusually low solar activity. Specifically, the Maunder, Spoerer, and Wolf minima appear as prolonged periods when few if any naked-eye sunspots were reported (Stephenson and Clark, 1978). Naked-eye sunspots were reported much more frequently in the 12th and early 13th centuries, when the frequency of reports (in records of the Southern Sung Dynasty in China) exceeded the long-term average by more than a factor of two. Far Eastern reports of the Aurora Borealis unusual at the low geomagnetic latitude of China, increased even more dramatically (Siscoe, 1980). The only period in the 17 centuries of Chinese records for which sunspot reports are sufficiently frequent to identify the 11-year solar cycle is during the 12th century (Stephenson and Clark, 1978) — during the span of the Medieval Maximum found in tree-ring radiocarbon. All available evidence suggests that solar activity was unusually high during the 12th and early 13th centuries, and perhaps twice as high as what we have known in the more modern era.

What terrestrial effects might we expect from a twofold increase in the overall level of solar activity, lasting almost 200 years? If we accept the hypothesis of a simple connection between the envelope of sunspot numbers and the total radiative output of the sun we should expect a sustained increase of perhaps 1% in the solar constant. Such an increase would raise the average surface temperature of the earth by about 1–2°C: equal in magnitude (but opposite in sign) to the decrease in temperature that characterized the Little Ice Ages. Climate records support this notion; the period between about AD 1000 and 1300 is identified as the "Medieval Climatic Optimum," or "Early Middle Ages Warm Epoch" (Lamb, 1977). Temperature reconstructions for England suggest a gradual increase of about 1°C between the start of the 12th and the end of the 13th centuries, which is a significant climatic change.

The effect of this global warming on the affairs of man is well known to the historians of the European Medieval period, who have called the 13th century "the greatest of all centuries." The unusually benign mid-latitude climate of the 12th and 13th centuries allowed a dramatic expansion in the colonization of new land, the spread of agriculture, the advance of commerce and art, and a doubling of the population of Europe (Pounds, 1973). The Gothic cathedrals that arose in northern Europe at that time speak of an unusual burst of creative effort and of favorable economic times. The connection of this flowering of culture with a coincident change in world climate is, I think, beyond doubt. Less certain is whether the coincident anomaly in solar activity was a cause of the Medieval Climatic Optimum, through the lever of increased radiation from the sun.

## CONJECTURE

We can walk a step farther into conjecture by considering the effects of the increased ultraviolet radiation that must have accompanied the Medieval Maximum of solar activity. If the level of solar activity rose by a factor of two during the 12th and 13th centuries, we can be sure that the ultraviolet radiation would have also increased — to levels that have probably not been experienced since. This major increase in ultraviolet solar flux would have perturbed the terrestrial ozone layer, though in ways that are complicated by natural feedback between the two.

The ozone layer shields the surface of the earth from damaging ultraviolet radiation. The thickness of that shield varies from month to month but it is always thinnest in the tropics (London and Angell, 1982). It follows that an increase in damaging radiation from the sun would have been felt most severely by those who lived in the Tropics, between about 20° N and 20° S latitude. For these people, unseen and unfelt change would have made sunlight more hostile, bringing about a slow plague. The change would have been incomprehensible to those who lived there at that time, but the malignant effects were cumulative, debilitating, and potentially deadly.

Cultures of Mesoamerica that had come to full flower under centuries of a more benign sun might have been led to abandon what they had built and to move to other lands: as did, perhaps, the Zapotecs, Toltecs, and Maya, whose history, throughout the European Medieval period, was characterized by shift and change. Nor should we be surprised to find the subsequent emergence of a new culture, as in Aztec Mexico, whose principal deity was an angry and vengeful sun. The Anasazi abandonments of about this same era might also bear re-examination in this light, as would the people of other cultures who lived at low latitudes in bright-sun climates.

I should acknowledge that the magnitude of the Medieval Maximum of solar activity is as yet not well established in the available radiocarbon record, that the net effect of a doubling of solar activity on the ultraviolet "A" and ultraviolet "B" radiation received at the surface of the earth has not been calculated analytically, and that the cultural shifts that I have invoked were defined loosely and more to fit my thesis than from any systematic study. It is all too easy, when one walks into the camp of another discipline, to say more than he knows. But I think that was the intended spirit of this symposium.

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