Holocene Climatic Change, ^{14}C Wiggles and Variations in Solar Irradiance [and Discussion]

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Holocene climatic change, ^{14}C wiggles and variations in solar irradiance

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Evidence from the advances and retreats of alpine glaciers during the Holocene suggests that there were at least 14 century-timescale cool periods similar to the recent Little Ice Age. Here, we examine the hypothesis that these cool periods were caused by reductions in solar irradiance. A statistically significant correlation is found between the global glacial advance and retreat chronology of Röthlisberger and variations in atmospheric ^{14}C concentration. A simple energy-balance climate model is used to show that the mean reduction of solar irradiance during times of maximum ^{14}C anomaly like the Maunder Minimum would have to have been between 0.22 and 0.55% to have caused these cool periods. If a similar solar irradiance perturbation began early in the 21st century, the associated climate effects would be noticeable, but still considerably less than those expected to result from future greenhouse gas concentration increases.

INTRODUCTION

Although they have been far less spectacular than the longer, ice-age timescale changes, significant changes in climate have occurred during the Holocene. The evidence for these changes comes from a variety of forms of indirect or 'proxy' evidence: fossil pollen records (COHMAP members 1988), glacial advance and retreat chronologies (Röthlisberger 1986; Grove 1987), lake level fluctuations (Kutzbach & Street-Perrott 1985), tree line changes (LaMarche 1973; Karlén 1976), ice core data (Dansgaard *et al.* 1982; Jouzel *et al.* 1987), and so on. These data, together with information from modelling studies (Kutzbach & Guetter 1986), suggest that there are at least two main causal factors operating.

On 1000-year and longer timescales, the primary control appears to be the Milankovitch effect, changes in the seasonal and spatial character of incoming solar radiation due to variations in the Earth's orbit around the Sun. Nine thousand years ago, for example, the Northern Hemisphere received up to 17% more solar radiation in the summer and up to 12% less solar radiation in the winter compared with today. Averaged over the year, high latitudes received up to 2% more solar radiation, whereas low latitudes received less (see Mitchell *et al.* 1988, fig. 4). The zero change points were around 43° N and S. Globally, the net change was close to zero. Over subsequent millennia, these radiation differences slowly relaxed towards present-day conditions.

Because the largest changes are on the seasonal timescale, the effects are manifest mainly in variables which respond to seasonal climatic influences, with vegetation and lake levels being two of the most widely studied (COHMAP members 1988). Fossil pollen data indicate that, during the early Holocene, summer temperatures in many parts of the globe were noticeably warmer than today, by up to 2 °C (where 'today' refers to the early twentieth century), and lake level data suggest that the early Holocene was considerably wetter than today in low latitudes. These conditions have been successfully simulated by using general circulation models of the climate system forced with appropriate insolation values (see, for example, Kutzbach & Guetter 1986; Mitchell *et al.* 1988).

Because most available proxy data tend to reflect summer climate conditions (Williams & Wigley 1983), it is not known with certainty whether any noticeable changes in annual-mean temperature occurred on the 1000-year timescale. The Milankovitch effect clearly produces annual mean changes on the ice age (10000-year) timescale, but these occur through a variety of feedback effects involving ice sheets, CO_2 and CH_4 concentration changes, cloudiness changes, tropospheric aerosol changes, and so on. Most of these feedbacks would have had substantially smaller influences during the Holocene. Because winter insolation over most of the globe was much less than today during the early Holocene, one might argue that this may have compensated for the greater summer insolation. Model results, however, together with the zonal, annual-mean insolation data which show a net increase north or south of 43° N or S, suggest that annual-mean temperatures were greater in the early Holocene, at least in high latitudes (Mitchell *et al.* 1988).

On shorter timescales, it is clear that substantial global-scale annual-mean temperature changes did occur during the Holocene. The main evidence for this comes from glacial advance and retreat chronologies. Small mountain glaciers respond to both precipitation and temperature changes (Porter 1981), and their movements are controlled by the integrated effects of these parameters over the seasonal cycle. Both empirical evidence (Meier 1984) and modelling studies (Oerlemans 1988) indicate that advances and retreats reflect annual-mean temperature changes. Thus the chronologies produced by Röthlisberger (1986), which are supported by a number of other studies (see, for example, the comprehensive review by Grove (1988)), may be cautiously interpreted as indicators of annual-mean temperature changes. These data show that, during the Holocene, there were a number of globally near-synchronous cold periods lasting for centuries and interspersed by longer warmer intervals. The most recent of these cold periods was the Little Ice Age.

The resulting picture of the Holocene is therefore as follows. On the 1000-year timescale, slow changes occurred associated with Milankovitch orbital effects. Although these are manifest mainly in seasonal data, noticeable annual-mean temperature changes on this timescale are likely to have occurred in mid to high latitudes. Superimposed on this there have been a number of century-timescale Little Ice Age events, apparently occurring at random. Mainly through the work of Kutzbach and colleagues, we are reasonably certain of the cause of the slower changes. But what is the cause of the series of Little Ice Ages? Grove (1988) has reviewed the possibilities. Here we concentrate on just one of these, solar variability.

There is no direct evidence of changes in solar irradiance during the Holocene. However, we do know that some characteristics of the Sun's output did change during the Holocene on the century timescale. For example, historical evidence shows that the incidence of sunspots has varied markedly, with prolonged periods of sunspot minima occurring on a number of occasions during the past thousand years (Eddy 1976). The Maunder Minimum of the seventeenth century is the most recent and well known of these. These sunspot minima are also associated with periods of enhanced ^{14}C productivity in the upper atmosphere (Stuiver & Quay 1980; Stuiver & Braziunas 1987).

Changes in ^{14}C production rate cause changes in atmospheric ^{14}C concentration that can be measured by comparing radiocarbon and dendrochronological dates of tree-ring samples. The difference between these dates is called the ^{14}C anomaly. Over the past 10 millennia, the ^{14}C anomaly record shows both slow, 1000-year timescale fluctuations and more rapid changes. Of the latter, on the century timescale there are a number of 'wiggles' in the record. We now know that these wiggles are the result of changes in the solar wind (Stuiver & Quay 1980; supported by ^{10}Be evidence, Siegenthaler & Beer 1987) and that they are largely contemporaneous with periods of sunspot minima. What we do not know is whether these ^{14}C anomalies were associated with changes in solar irradiance.

In the following, we examine the relation between atmospheric ^{14}C changes and changes in climate during the Holocene. On the assumption that they are related, we use a simple climate model to estimate the solar irradiance changes that would be required to produce the observed climate changes (namely, the Little Ice Age events described above). Finally, we consider the implications that a future Little Ice Age might have, given that it is likely to occur against a backdrop of anthropogenic climatic change due to the greenhouse effect.

COMPARING THE ^{14}C ANOMALY AND CLIMATE RECORDS

In Wigley (1987*a*), the time histories of atmospheric ^{14}C anomaly changes and climate changes were compared both visually and statistically, and it was concluded that there was a statistically significant similarity between the two. Here we repeat this analysis, but with the following differences. First, the analysis is extended back beyond 4000 B.C. to include the earliest available data. Secondly, the dates of the major ^{14}C anomalies are determined by using an objective filtering method, rather than by visual inspection of the curve given by Stuiver *et al.* (1986*a*). Thirdly, the calendar dates for the Holocene cold intervals and temperature minima are re-estimated by using all of the most recently available calibration curves (namely Stuiver & Pearson 1986; Pearson & Stuiver 1986; Stuiver & Becker 1986; Pearson *et al.* 1986; de Jong *et al.* 1986; Linick *et al.* 1986; Kromer *et al.* 1986; Stuiver *et al.* 1986*b*). Fourthly, more statistical tests will be carried out.

For the climate data, the record we use is as in Wigley (1987*a*); namely, a composite of the regional records of glacial advance and retreat produced by Röthlisberger (1986). Röthlisberger's glacial data come from 12 regions in both the Southern and Northern Hemispheres. He has combined these into six larger-region time series for the following locations: southeastern Alaska, tropical western South America (around 10° S), southern South America (35–55° S), the European Alps, the Himalayas, and southern New Zealand. In addition, he has included data for nothern Scandinavia obtained from Wibjorn Karlén. These have been combined with rough area weights by Wigley (1987*a*) to produce hemispheric- and global-mean time series. Because all time series are highly correlated (an interesting result in itself), the mean series do not depend much on the actual values used for the weights. The series are shown in figure 1.

To identify cold intervals, an arbitrary threshold was used (see figure 1). Minima were read directly from the curve. Some minima occur as isolated values rather than within a cold period because they are at times when prevailing conditions were apparently warmer than the chosen threshold value. These occur particularly in the early Holocene, suggesting that Milankovitch effects may have caused low-frequency, annual-mean changes upon which the shorter cooling events were superimposed. The radiocarbon dates for the minima and the interval boundaries were converted to calendar dates by using the above-cited references. In some cases more than

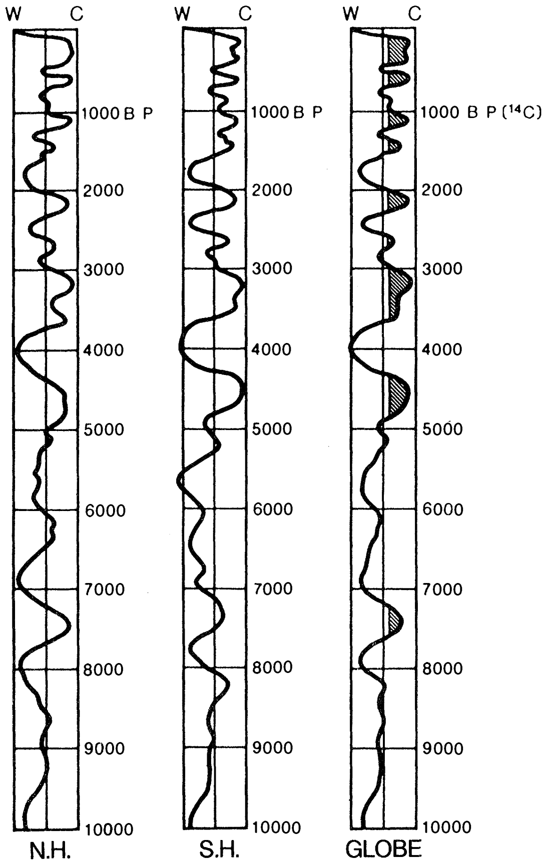

Figure 1. Alpine glacier advance and retreat chronologies for the Northern Hemisphere (N.H.), Southern Hemisphere (S.H.) and globe based on Röthlisberger (1986). W and C refer to warm (glaciers less advanced) and cold (glaciers more advanced).

one calibration curve could be used giving slightly different calendar dates. Single 'best' calendar dates were then chosen, mostly as the mean of a range of possibilities, but with greater emphasis on results derived by using the calibration curves with smaller error bars. In a few cases it was impossible to distinguish between two alternative dates. The results are shown in table 1.

The calendar dates given here are subject to considerable uncertainty for a number of reasons, not least being uncertainties in the original data and dating, the method used for averaging the data from different regions, the extraction of radiocarbon dates from the composite curve, and the conversion from radiocarbon to calendar dates. These uncertainties produce an inherent 'noise' in the climate record which would probably tend to obscure any ^{14}C–climate link, if one exists.

For the ^{14}C anomaly record we used data kindly supplied by Minze Stuiver (personal communication). These are essentially a digitized version of the information contained in figure 1 of Stuiver *et al.* (1986*a*). Major ^{14}C anomalies were identified in the following way. First, two gaussian filters were used to band-pass filter the data, retaining frequencies within the periods L_1 to L_2. These results were filtered again to produce a roughly constant base level by applying the L_2 filter to the negative values of the record (i.e. if Z is the band-pass filtered data, then Z was replaced by zero if $Z > 0$, and the results filtered by using L_2 to give Z^*). The curve finally

TABLE 1. CALENDAR DATES OF COLD INTERVALS, TEMPERATURE MINIMA AND ^{14}C MAXIMA

climate[a]		^{14}C maxima	
cold intervals	minima	this work[b]	Stuiver[c]
—	—	—	7490 B.C.
—	7110 B.C.	7010 B.C.	7030 B.C.
6430–6080 B.C.	6190 B.C.	6370 B.C.	6370 B.C.
—	—	5970 B.C.	5950 B.C.
—	5190 B.C.	5190 B.C.	5190 B.C.
—	—	4710 B.C.	—
—	—	4250 B.C.	4330 B.C.
4030–3940 B.C.	3980 B.C.	3930 B.C.	3930 B.C.
—	—	3590 B.C.	3590 B.C.
—	—	—	3490 B.C.
3550–2920 B.C.	3320 B.C.	3290 B.C.	3290 B.C.
—	—	2830 B.C.	2850 B.C.
—	—	2410 B.C.	—
2040–1250 B.C.	1430 B.C.	1350 B.C.	—
900–800 B.C.	820 B.C.	730 B.C.	740 B.C.
350 B.C.–0	150 B.C.	330 B.C.	340 B.C.
A.D. 570–660	A.D. 640	A.D. 730	—
A.D. 850–1040	A.D. 930	A.D. 1050	A.D. 1040
—	A.D. 1190	—	—
A.D. 1280–1400	A.D. 1330	—	A.D. 1340
A.D. 1450–1890	A.D. 1460	A.D. 1510	A.D. 1460–1540
—	A.D. 1680	A.D. 1690	A.D. 1720

[a] From figure 1.
[b] From figure 2*b*.
[c] From Stuiver & Braziunas (1987, figures 1–4).

considered was $Z - Z^*$. Various combinations of L_1 and L_2 were used. Examples are shown in figure 2. Dates of major ^{14}C anomaly maxima were then extracted (from figure 2*b*). These are listed in table 1.

Also shown in table 1 are dates of ^{14}C maxima identified by Stuiver & Braziunas (1987). The differences, which are generally small, arise mainly from the methods used to filter the raw data. We have identified four maxima (at 730 A.D., 1350 B.C., 2410 B.C. and 4710 B.C.) that are not identified by Stuiver & Braziunas, while these authors have identified two maxima which are not evident in figure 2 *b* (at 1340 A.D. and 3490 B.C.). These two maxima are evident in figure 2 *a*. Note, however, that figure 2*a* contains an additional maximum at 5450 B.C. not identified by Stuiver & Braziunas. Apart from these differences, the only other discrepancy occurs around 4250 B.C. This peak occurs at 4330 B.C. in Stuiver & Braziunas. In figure 2*a* it appears as a split peak with maxima at 4210 B.C. and 4310 B.C.

Is there any relation between the climate data (figure 1) and the ^{14}C data (figure 2)? We can examine this possibility visually by superimposing the two time series. This has been done in figure 2*b* where the climate timescale has been converted to calendar years. It is very difficult to judge from this figure whether or not a link exists. If one accounts for an inherent timing uncertainty of, say, ±100 years in the climate data, then most of the cold periods (taking isolated minima as cold periods of zero length) contain ^{14}C peaks (11 out of 13), and most of the ^{14}C peaks occur within cold periods (14 out of 18). In the absence of this ±100-year flexibility, however, the direct correspondences are less convincing, and some cold periods correspond better with ^{14}C minima than with maxima.

To examine the possible relation further, we consider only the climate minima. Climate

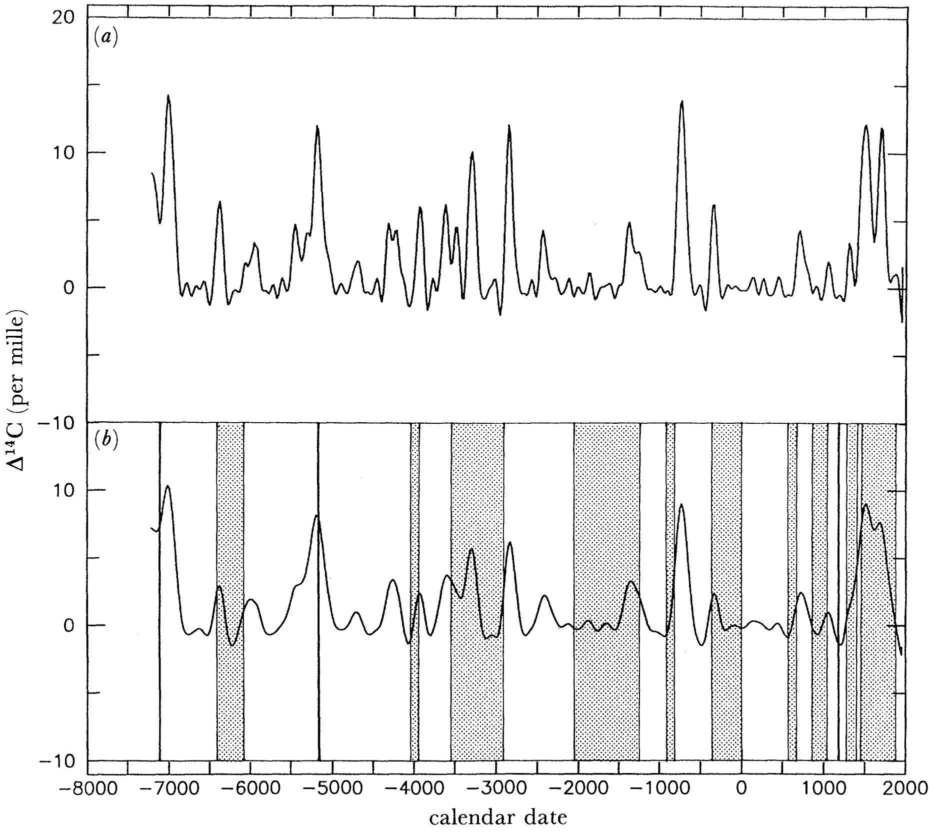

FIGURE 2. Atmospheric ^{14}C anomalies and climate. The two curves show band-pass filtered values of the atmospheric ^{14}C anomaly record using (*a*) 1000- and 100-year filters and (*b*) 1000- and 200-year filters. In (*b*), cold intervals (from figure 1, converted to calendar years) are marked by screening or as vertical lines (for the three shortest-duration events).

minima and ^{14}C maxima are highlighted and compared in figure 3. The visual agreement is better than in figure 2*b*, partly because the ±100-year uncertainty is represented. There are, nevertheless, some striking correspondences. Six out the the seven strongest ^{14}C maxima correspond closely to climate minima.

The statistical significance of the correspondence can be assessed in the following way. The ^{14}C maxima can be considered as 'bullets' that are fired at a set of 200-year wide 'targets', namely the climate minima. If the maxima were fired randomly at the whole 9160-year record, how many 'hits' would we expect to occur? As a reasonable approximation, this can be considered as a binomial problem. The total target width is 2670 years (i.e. 14 minima by 200 years, less a small amount of overlap because of closely spaced minima), so the probability of a single hit occurring by chance is $2670/9160 = 0.291$. The observed number of hits is 9 out of 18, and the probability of this occurring by chance is 0.033.

Alternatively, the roles of ^{14}C maxima and climate minima can be reversed. In this case the target area is 3580 years so the probability of a hit in any one trial is 0.391. The observed number of hits is 9 out of 14, and the probability of this occurring by chance is 0.036. Both of these results are significant at the 5% level, implying a significant ^{14}C–climate relation. This is in accord with the slightly different analysis carried out in Wigley (1987*a*).

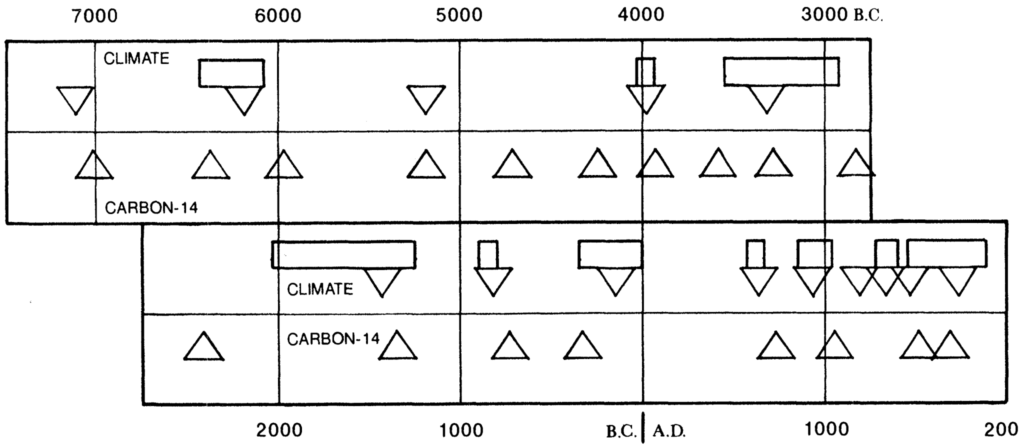

FIGURE 3. Simplified atmospheric ^{14}C and climate records. The upper halves show temperature minima (triangles) and cold periods (rectangles) based on figure 1. The lower halves show ^{14}C maxima based on figure 2*b*.

To further test this hypothesis, we considered the correspondence between ^{14}C *minima* and climate minima. By using the same filtering method as used for ^{14}C maxima, 18 ^{14}C minima were identified and located. For ^{14}C minima as 'bullets', the results were as follows: probability of a hit in a single trial, 0.291 as before; probability of the observed number of hits (7 out of 18), 0.129. For climate minima as bullets, the results were the following: probability a hit in a single trial, 0.384; probability of the observed number of hits (8 out of 14), 0.078. These results are not statistically significant, but they do indicate some sort of correspondence between ^{14}C minima and climate minima. This arises because the major ^{14}C minima identified by our filtering method tend to lie close to the identified maxima. The example exposes some of the problems in proving a relation, and should act as a warning in the interpretation of the ^{14}C maxima results.

Overall, we consider these results to be highly suggestive of a ^{14}C–climate link, but not ultimately convincing. For some ^{14}C maxima, Röthlisberger's data show no evidence of a climate minimum, although this does not preclude the existence of an unidentified cold period. Alternatively, potential cold periods may on occasion be masked by other processes, including internally generated natural climatic variability. There is also a lack of accord between the duration of ^{14}C maxima and the duration of cold periods. The former generally last from 100–200 years (see Stuiver & Braziunas 1987, figures 5–7), while the latter are generally substantially longer, by amounts much larger than can be explained by the lag effect of oceanic thermal inertia and/or the response times of alpine glaciers. A 'believer' may explain this duration difference as resulting from uncertainties in the dating of the climate events, but to the unbiased observer there must be nagging doubts. Clearly, there are complexities that remain to be resolved.

Although we have described this analysis as a test of the hypothesis that there are major solar irradiance perturbations that occur in parallel with the solar events that lead to major ^{14}C anomalies, there may be alternative explanations. For example, the ^{14}C anomalies could, themselves, be the result of the climate perturbations. We consider this to be unlikely, because the ^{14}C anomaly link with the Sun has been convincingly demonstrated (Stuiver & Quay 1980; Siegenthaler & Beer 1987). However, if major cold periods were associated with a large change in the rate of oceanic bottom water formation (as has been hypothesized for the late glacial), then parallel perturbations in the atmospheric ^{14}C content would certainly occur. This is a topic that deserves further attention.

Irradiance changes during ^{14}C maxima

We now consider the implications of a ^{14}C–climate link and estimate the change in solar irradiance that is likely to be associated with ^{14}C–anomaly-producing solar events like the Maunder Minimum. To do this, it is first necessary to estimate the global-mean temperature deviation associated with the major glacial advances documented in figure 1. This can be done (albeit with some uncertainty) by reference to the most recent period of the record. Over the past 100–150 years, the globe has warmed by approximately 0.5 °C (Jones *et al.* 1986). This interval corresponds to that part of the most recent warming trend in figure 1 that lies above the 'zero' reference line. From this it can be deduced that the glacial advance maxima correspond roughly to an annual, global-mean cooling of 0.4 °C below the reference line, or about 0.6 °C below the average level of the warm intervals. We therefore assume that the cooling associated with ^{14}C maxima is 0.4–0.6 °C.

The solar forcing required to produce such a cooling depends on a number of factors. The most important of these is the equilibrium climate sensitivity, i.e. the temperature change what would eventually occur for a forcing of 1 W m^{-2} at the top of the troposphere. The observed response to any given forcing, however, is only a fraction of the equilibrium response because of the lag or damping effect of oceanic thermal inertia. Just how much of the equilibrium response is realized depends on the timescale of the forcing, the mixed layer depth, the rate of ocean mixing below the mixed layer, and the climate sensitivity. For example, for sinusoidal forcing with a 10-year period, only 13–23 % of the potential response is observed, while for forcing with a 200-year period, 57–75 % of the potential response is observed (see Wigley 1987*a*, table 1). Finally, the observed cooling clearly depends on the precise time history of the forcing.

Stuiver & Braziunas (1987) have given details of the average shape of ^{14}C maxima events. They distinguish two types of event, similar to either the Maunder Minimum or the Spörer Minimum. For each, the ^{14}C fluctuation spans a period of 100–200 years and is roughly parabolic in shape. We have therefore assumed that the solar forcing is quadratic in time and spans 200 years. To be specific we have assumed that the mean forcing over the 200-year period is 2 W m^{-2} (i.e. with a peak value of 3 W m^{-2}). The response is directly proportional to the forcing, so the results may be scaled to any similar forcing value. Temperature changes were calculated by using the energy-balance climate model of Wigley & Raper (1987), which takes account of oceanic thermal inertia by modelling vertical ocean mixing as an upwelling-diffusion process. The results are shown in table 2.

For a mean cooling of 0.4 °C, the implied mean forcing depends critically on the climate sensitivity. Based on table 2, for a sensitivity of 0.33 °C (W m^{-2})$^{-1}$ the forcing would be 1.32 W m^{-2}, for 0.67 °C (W m^{-2})$^{-1}$ it would be 0.72 W m^{-2}, whereas for a sensitivity of 1 °C (W m^{-2})$^{-1}$ the forcing would be 0.53 W m^{-2}. These values are slightly smaller than those estimated previously, based on slightly different assumptions, by Wigley (1987*a*); namely, 1.1 W m^{-2} and 0.7 W m^{-2} for climate sensitivities of 0.5 °C (W m^{-2})$^{-1}$ and 1.0 °C (W m^{-2})$^{-1}$.

When expressed as percentages of the net incoming solar radiation at the top of the troposphere (namely 240 W m^{-2}), the implied forcing is 0.55, 0.30 or 0.22 % for sensitivities

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Table 2. Global-mean temperature changes

(Changes result from a parabolic solar irradiance fluctuation lasting 200 years with mean radiative forcing of -2 W m^{-2} ($\Delta Q = 3(0.01t-1)^2-1$) W m^{-2}). The results were obtained using the model of Wigley & Raper (1987) with a mixed layer depth of 100 m and a diffusivity of 1 cm^2 s^{-1}.)

climate sensitivity °C (W m^{-2})$^{-1}$	equilibrium response to mean forcing	mean change over forcing interval	maximum equilibrium response	maximum change	residual changes at $t = 200$	residual changes at $t = 300$	residual changes at $t = 400$
0.333	-0.667	-0.604	-1.000	-0.915	-0.180	-0.024	-0.011
0.667	-1.333	-1.106	-2.000	-1.664	-0.559	-0.107	-0.049
1.000	-2.000	-1.515	-3.000	-2.276	-0.996	-0.243	-0.117

of 0.33, 0.67 or 1.0 °C (W m^{-2})$^{-1}$. Thus to produce a cooling similar to that of the Holocene Little Ice Age events, solar irradiance would have to be reduced by an average of 0.22–0.55% over a period of order 200 years. For the parabolic time dependence assumed here, the maximum depression of solar irradiance is 1.5 times these values. These changes are up to an order of magnitude greater than the changes in irradiance that have been observed over the past decade by using satellite-based instruments (Kyle *et al.* 1985; Willson *et al.* 1986; Lean & Foukal 1988).

The only comparable estimate of possible century-timescale changes in solar irradiance is a reduction by 0.14% during the Maunder Minimum, attributed by Kerr (1987) to Lean & Foukal and based on their model relating solar irradiance changes to changes in sunspots, faculae and network radiation (Lean & Foukal 1988). There is a difference of a factor of two to four between this estimate and ours. Apart from the quantitative differences in these estimates, however, there are important qualitative differences. The Maunder Minimum (i.e. the period of near-zero sunspot activity) lasted only from around 1645–1715 (Eddy 1976), whereas the corresponding ^{14}C anomaly spanned the period 1600–1800 (Stuiver & Braziunas 1987). The required comparison, therefore, is between a 70-year-long reduction in irradiance of 0.14%, and a 200-year period with an average irradiance reduction of 0.22–0.55%.

On the basis of this comparison, it would appear that the Lean–Foukal model does not give a large enough, nor long enough, drop in irradiance to explain the observed cooling during the Little Ice Age. Thus if the Little Ice Age (and earlier, similar cold periods) were the result of solar irradiance reductions, either some currently unsuspected mechanism must operate to cause these reductions, or the form of the relation between sunspot number, sunspot area, facular area and network radiation deduced from recent data by Lean & Foukal (1988) must break down during and around periods of anomalously low sunspot activity.

Conclusions and implications for the future

The atmospheric ^{14}C evidence of solar variability on the century timescale during the Holocene is indisputable. Because major ^{14}C anomalies occur throughout the Holocene (17–21 in 9500 years), spanning the whole of the available data, this type of solar variability must be considered to be a permanent feature of the Sun's behaviour. Global-scale climate fluctuations of the Little Ice Age type appear to be associated with these ^{14}C anomalies. This implies that significant irradiance variations occur in parallel with the solar fluctuations responsible for the ^{14}C anomalies.

This link has been examined previously by a number of authors (e.g. de Vries 1958; Damon 1968; Suess 1968; Denton & Karlén 1973; Eddy 1977; Williams *et al.* 1980), but until recently the data were of insufficient quality to offer convincing evidence either for or against. Here, in expanding on a previous analysis (Wigley 1987*a*), we have shown that temperature minima and ^{14}C maxima are significantly correlated at the 5 % level. Although some measure of doubt must remain because of uncertainties in the climate record, and because there are still many inconsistencies when the two records are compared in detail, we consider these new results to be highly suggestive. Indeed, the dating uncertainties in the climate record, together with the undoubted natural variability of the climate system that must have been superimposed on and would tend to obscure any solar forcing effects, make it somewhat surprising that a significant result can be obtained at all.

On the assumption that the Little Ice Age events of the Holocene are the result of solar irradiance changes, we have used an appropriate, time-dependent climate model to estimate the magnitude of these changes. The results depend on the cooling assumed to occur during the Little Ice Ages, which we have taken to be 0.4–0.6 °C, and on the assumed climate sensitivity. For sensitivities in the range 0.33–1.0 °C $(\mathrm{W\ m^{-2}})^{-1}$ (which span the known range of uncertainty in this parameter), the implied solar irradiance changes averaged over the 200-year interval range between 0.55 and 0.22 %.

These results allow Man's potential influences on future climate to be put into perspective. In the future the dominant climate forcing mechanism is likely to be the effect of increasing concentrations of greenhouse gases, primarily carbon dioxide, methane, nitrous oxide, ozone and the chloroflurocarbons (CFCs). Over the past few centuries, the forcing due to this effect has amounted to about 2.2 $\mathrm{W\ m^{-2}}$ (Wigley 1987*b*), equivalent to increasing solar irradiance by over 0.9 %. Already, therefore, Man's activities have perturbed the Earth's radiation balance by appreciably more than the perturbations that lead to the Holocene Little Ice Ages. This result is independent of the feedback mechanisms whose uncertain magnitude leads to uncertainties in the climate sensitivity.

Future greenhouse-related forcing changes are certain to exceed those that have occurred in the past. Between now and 2030, the best estimate for future forcing is about 2.4 $\mathrm{W\ m^{-2}}$ (Wigley 1987*b*; modified to account for reduced CFC concentrations due to the Montreal Protocol, (see Wigley (1988)). If a new Little Ice Age began soon, as has been suggested by some authors (e.g. Landscheit 1983; Fairbridge & Shirley 1987), how would this influence future climate in the face of the onslaught of the greenhouse effect?

Let us suppose a Little Ice Age begins in the year 2000 A.D., and that the solar irradiance decline lasts for 200 years. As a backdrop, we use a projection for greenhouse-gas forcing that follows Wigley (1987*b*, 1988), to 2030, increases at half the 2000–30 rate of increase until 2100, and then remains unchanged. Under this scenario, the forcing between now (1988) and 2100 is 4.6 $\mathrm{W\ m^{-2}}$, a not unreasonable possibility. This amounts roughly to a further doubling of the effective CO_2 level (i.e. accounting for all other anthropogenic greenhouse gases) between now and 2100. These greenhouse projections, shown in figure 4, are given only for illustrative purposes. They should not be taken too seriously beyond 2050, because, on the 50-year timescale, Man has the ability to modify future greenhouse-gas concentration changes and significantly reduce future forcing changes.

The solar perturbation during the Little Ice Age depends on the assumed climate sensitivity. For low sensitivity the perturbation is larger, although the influence in terms of global-mean

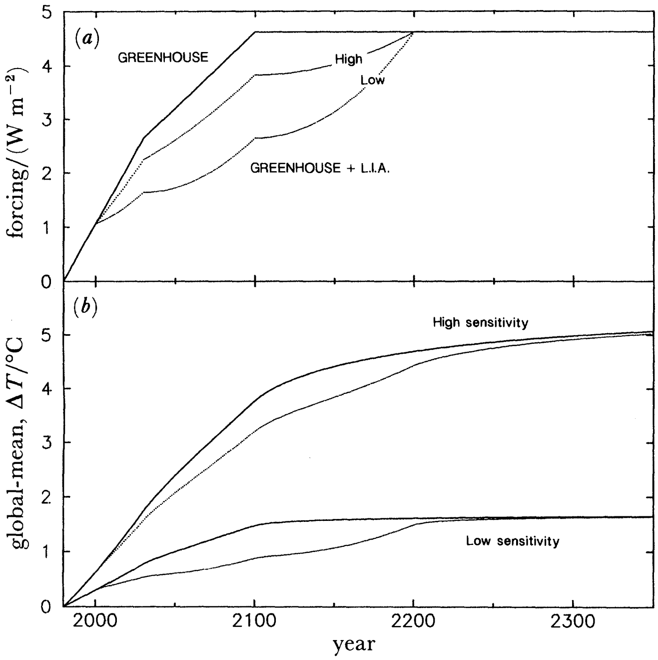

FIGURE 4. Future climatic change if greenhouse-gas-induced warming were partly offset by a Little Ice Age (L.I.A.) event. Part (*a*) shows the forcing: top curve due to greenhouse gases alone and the lower two curves for greenhouse plus L.I.A. forcing. 'High' and 'low' give the range of uncertainty for the L.I.A. perturbation, and correspond to high and low climate sensitivities, as explained in the text. Part (*b*) gives the global-mean temperature response to the assumed forcing. The upper curves of the two pairs are for greenhouse forcing alone assuming either high or low climate sensitivity (namely 1.0 °C $(\mathrm{W\,m^{-2}})^{-1}$ or 0.33 °C $(\mathrm{W\,m^{-2}})^{-1}$). The lower curves of the pairs show the relative cooling that would be induced by a Little Ice Age event. The model used was that of Wigley & Raper (1987) with a diffusivity of 1 $\mathrm{cm^2\,s^{-1}}$. The simulation was begun with the system in equilibrium in 1765 and forced by observed greenhouse gas concentration changes to 1988 and projected changes subsequently. Future greenhouse forcing is subject to considerable uncertainty; the scenario assumed here is close to the current best estimate.

temperature changes remains the same. Figure 4 shows projected temperature changes for climate sensitivites of 0.33 and 1.0 °C $(\mathrm{W\,m^{-2}})^{-1}$. In the low sensitivity case the solar perturbation is clearly appreciable relative to future greenhouse forcing, but still far from sufficient to offset it completely. In this case the rate of future warming is roughly halved. For high climate sensitivity, however, the effect is, in relative terms, much smaller.

Given the difficulty of detecting the greenhouse effect to date, detecting the onset of a future Little Ice Age in the climate record would be no easy task. The solar irradiance changes would be more easily detectable. At the low end of the estimated irradiance change, where the mean change is 0.22 %, the rate of change during the early stages (based on the parabolic forcing assumed above) is 0.044 % per decade. Over the last sunspot cycle, solar irradiance varied at about 0.07 % per decade, so it would probably require the better part of a full cycle to be sure that some new mechanism had begun to operate.

On uniformitarian grounds, another Little Ice Age must be expected. Past anomalous ^{14}C events were separated by an average of 250–350 years, with the last such event ending around 1800. In one way, therefore, the anthropogenic greenhouse effect might be considered a benefit, because it will certainly offset the next and possibly future Little Ice Ages. This would be an exceedingly optimistic viewpoint, however. Given the disruption caused to society by the cold conditions of the last Little Ice Age, and given that this was a mere 'blip' compared with expected future climatic change, the results of this paper should be seen as further reinforcement for the concerns already felt with regard to the future.

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Discussion

J. A. Eddy (*UCAR/OIES, Boulder, Colorado, U.S.A.*). Does Dr Wigley agree that the weaker link in the connection he proposes between solar irradiation and terrestrial surface temperature response is that of climate history? Is it not true that for the Holocene period we now know the solar total irradiance forcing better than we know the corresponding climate history?

T. M. L. Wigley. It is true that the climate history is a weak link in inferring that significant solar irradiance changes occurred in parallel with century-time scale atmospheric ^{14}C fluctuations. However, the irradiance history is far less certain: we simply have no direct information at all. The atmospheric ^{14}C record is now well established, but one cannot assume that this is a proxy for irradiance changes; and, even if one could, the magnitude of these changes would still be unknown. The only way we can estimate irradiance changes during the Holocene is by using climate data, as we have done.

A. Berger (*Université Catholique de Louvain, Belgium*). One fundamental hypothesis of Dr Wigley's model is to identify the sensitivity of the climate system to a doubled CO_2 forcing with its sensitivity to solar forcing. Can he comment to what extent this is allowed given the difficult physical mechanisms within the climate system that would be involved in these two experiments.

T. M. L. Wigley. In my verbal presentation, I expressed climate sensitivity in terms of the equilibrium global-mean temperature change for a CO_2-doubling merely to use a concept more familiar to non-specialists. In the written text, climate sensitivity is expressed in the conventional way. There is a close relatinship between the two. If f is the climate sensitivity (in degrees Centigrade per (watt per square metre)), ΔT_d is the equilibrium warming for $2 \times CO_2$, then

$$f = \Delta T_d / \Delta Q_d.$$

ΔQ_d is approximately 4.4 W m^{-2} (uncertainty, $\pm 10\%$ at least), while ΔT_d is usually thought to lie in the range 1.5–4.5 °C with about 90% confidence. Hence, f lies roughly in the range 0.33–1.0 °C (W $m^{-2})^{-1}$. Model studies suggest that f is similar for solar and greenhouse forcing.

A. C. Renfrew, F.B.A. (*Department of Archaeology, University of Cambridge, U.K.*). The paper deals with short-timescale (up to century-timescale) events. But it would be helpful if Dr Wigley would clarify the assumptions that he is making about the major, long-term factors that were responsible for the ice ages themselves and for the succeeding onset of the Holocene. Is it clear that these first-order factors (on the 1000-year timescale and beyond) are irrelevant to Holocene changes? To put the question another way, are these first-order variations unaccompanied by shorter-term, second-order changes? If the major effects are seen as governed by orbital variations, usually expressed by Milankovitch curves, is it appropriate to omit all considerations of these variations when surveying Holocene changes?

T. M. L. Wigley. The Milankovitch context of Little Ice Age type fluctuations during the Holocene is discussed in our written paper. The crucial differences are in the timescale and in the seasonal character of the radiative forcing perturbations. Milankovitch effects are changes in *seasonal* insolation that occur on the 1000-year timescale, while I hypothesize that the Little Ice Age climate fluctuations are caused by perturbations in *annual-mean* incoming radiation occurring on the century timescale. Even during the Holocene, there is striking evidence of Milankovitch effects, and I see these as a slowly moving backdrop against which Little Ice Age events are superimposed. Although this could be related to the difficulty of discerning evidence of global advances so far back in the past, the glacier fluctuation record (figure 1) indicates that Little Ice Age events may have been less pronounced in the early Holocene and that the prevailing background conditions were warmer then. Indeed, in the mid- to high-latitude zones that most of the glacial data come from, the annual-mean incoming solar radiation in the early Holocene was up to 2% more than today, and model results (Mitchell *et al.* 1988) suggest that the climate was warmer in these zones throughout the year.