TESTING THE SUN-CLIMATE CONNECTION WITH PALEOCLIMATE DATA

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ABSTRACT

If there is a significant sun-climate connection, it should be detectable in high-resolution paleoclimate records. Of particular interest is the last few thousand years, where we have both indices of solar variability (^{14}C and ^{10}Be) and climate variations (alpine glaciers, tree rings, ice cores, corals, etc.). Although there are a few exceptions, statistical analyses of solar and climate records generally indicates a "flickering" relationship between the two -- sometimes it seems to be present, sometimes not. The most repeatable solar climate periods occur at ~120 and ~56 yrs, although there is also evidence for ~420 and ~200 yr. power in some records. However, coherence between solar and climate spectra is usually low, and occurrence of solar spectra in climate records is sometimes dependent on choice of analysis program. These results suggest in general a relatively weak sun-climate link on time scales of decades to centuries. This conclusion is consistent with previous studies and with the observation that inferred climate fluctuations of 1.0-1.5°C on this time scale would require solar constant variations of approximately 0.5-1.0%. This change in forcing is almost an order of magnitude greater than observed changes over the last solar cycle and appears to be on the far-outer limit of acceptable changes for a Maunder Minimum-type event.

INTRODUCTION

The reality of a future greenhouse warming has been the topic of much heated debate. Many of the objections are based on two major points: (1) the warming is not as great as predicted by most climate models; and (2) the temperature is not uniformly increasing, in that there are significant decadal-scale fluctuations having a magnitude of about 0.4°C that significantly modify the global average temperature curve of the last century.

In order to better evaluate the significance of a greenhouse warming, it is necessary to understand the origin of decadal-scale fluctuations in global temperature that are due to "natural variability" in the climate system. At present there are three main hypotheses for decadal- to centennial-scale fluctuations due to factors other than CO_2 (see full discussion in ref. 1) -- solar variability[2], volcanism[3], and nonlinear interactions in the ocean atmosphere system[4,5].

The number of oscillations in the last century are too few to rigorously test different hypotheses as to the origin of climate fluctuation in the present century. This is where paleoclimate data come in, for there are many different realizations of such climate fluctuations over the last few thousand years (e.g., Fig. 1). These oscillations occur prior to the time of CO_2 buildup (about 1850) and therefore serve as an ideal testing ground for different mechanisms.

In this study we will examine one of the mechanisms proposed to explain decadal- to centennial-scale climate fluctuations -- solar variability. We compare an index of solar variability (^{14}C) with a number of different climate records of the last few thousand years.

METHODS

Solar Records Our sources of cosmogenic data are measurements of ^{14}C from tree rings[6]. Comparison of ^{14}C and ^{10}Be records, which have significantly different geochemical cycles, indicate that a common signal, suggestive of cosmogenic origin, can be extracted from both records[7]. A previous study of this record indicates a fundamental mode of solar response at a period of ~420 yr, with harmonics at 220, 140, 89, 67, 57, 52, and 45 years[8].

Climate Records Our terrestrial records come from a number of sources:

(1) a record of alpine glacial moraine variations for the last 5000 years developed by Röthlisberger[9]. This record, although small in number, is from a wide variety of locations (Alaska, Scandinavia, Alps, South America, Himalayas, Sierras, and New Zealand). The record was originally analyzed by Stuiver and Braziunas[8] for level of agreement with the ^{14}C record. Results suggest a possible solar-terrestrial link in the ~110 period[8]. We extend their study by compositing the record in order to remove sources of regional noise.

(2) ice core records from three widely distributed locations -- Greenland, Peru, and Antarctica[10, 11, 12].

(3) tree ring records from two locations far removed from the ice cores -- the Sierras and western China[13, 14].

Statistical procedures The data were regularly spaced in time with a cubic spline used to interpolate the data to a regular 5 year grid. In most cases this sampling interval was shorter than the average of the irregular spacing of the original data (~20-40 yr). The interpolated curves were compared to the original curves, and interpolated values were adjusted manually at those locations where the cubic spline performed poorly. The ^{14}C record contained more high frequency energy than the other records so this record was smoothed using running averages until both records appeared to have similar high frequency characteristics. Finally, all data were normalized.

A statistical analysis program based on Newton[15] was used to analyze the data pairs. The package calculates the raw periodogram, smoothed spectral and cospectral estimates, and correlation coefficients. Preprocessing removes the mean and detrends the individual data series prior to computing the spectra. Spectral estimates are obtained by the Fourier transformation of the covariance functions. Smoothed estimates are formed by applying a Parzen window to the covariance function prior to transformation. Three window widths were used, 1/5, 1/3 and 2/5 of the number of data points. The amount of smoothing is inversely proportional to the window width.

RESULTS

Figure 2 compares the ^{14}C record with various climate indices. Although in general there is not a strong visual correlation between solar and climate records, comparison of their individual spectra yields *some* indication of a solar-terrestrial connection (Table 1). In particular, the western Chinese tree ring record has quite a strong correlation with ^{14}C ($r = -0.54$). The South Pole ^{18}O record has the next strongest solar correlation (0.37). If r is relaxed to search for maximum correlation, there is a significant increase in the Greenland ^{18}O correlation.

The above discussion and Table 1 suggest that, if the solar-climate connection is real, the regional response can vary considerably, from warm periods correlating with sunspot maxima (Greenland and South Pole) to cold periods correlating with sunspot maxima (China). The large lag offsets between different regions could conceivably reflect displacements of the atmospheric circulation, a subject discussed more fully in ref. 1. Our study also suggests that western China might be the most sensitive region to respond to solar variations.

The most consistently occurring solar peaks are at periods of ~120 and ~56 years. Peaks at ~200 and ~120 yr. support previous findings[8, 16]; peaks at ~420 and ~56 yrs appear to represent new findings. Although solar spectra can be found in some of these climate records, in most cases there are a number of significant differences between the solar peaks

SOLAR SPECTRA IN CLIMATE RECORDS

PERIOD	~420	~200	~120	~87	~56	r	r_{max}
GLACIERS	x		**X**	**X**		-0.11	.15 (330)
SIERRA TR			**X**		**X***	-0.10	.22 (70)
CHINA TR		**X***	x	x	x	-0.54	-54 (0)
GRN O18	**X**		**X**		**X***	-0.01	.39 (45)
PERU O18			x	x	**X**	0.05	.08 (15)
SPOLE O18		**X***	x	x	x	0.37	.42 (-20)

Table 1. Correlations between solar spectra in climate records. A small "x" indicates that solar periods occur but not consistently (as defined by variations in the amount of record smoothing). Bold X's refer to a more consistent occurrence, and bold **X***s refers to records that have coherences >0.6. Parentheses after r_{max} refers to number of years the climate time series leads or lags at maximum correlation (minus sign indicates climate leads ^{14}C).

and peaks that, for example, occur in Pleistocene time series. In the latter, many different climate spectra have been compared to orbital forcing (the Milankovitch effect), with conclusions often being that, regardless of technique used in the analysis, orbital periods frequently occur in climate records of the Pleistocene[17]. Furthermore, coherence between climate and orbital spectra are often quite high (>0.8).

As opposed to our experience with Pleistocene records, analysis of time series covering the last few thousand years indicates that the solar spectra are not nearly so robust -- they appear in some records but not others, and often disappear with slight changes in smoothing. Furthermore, coherences are often quite low (<0.5), although in a few cases (marked by bold X* in Table 1) coherences are significantly higher (>0.6).

DISCUSSION AND CONCLUSION

The above results provide some evidence for a sun-climate link. However, the results also suggest that a sun-climate connection, if present, is relatively weak. These results are consistent with some earlier sun-climate comparisons, which suggest that <10% of the climate record can be explained by solar variability[18, 19, 20]. It is possible that other more sophisticated statistical procedures could elicit a more significant relationship, so we do not claim our results represent a final assessment of the problem. What we can say is that in general the connection certainly does not leap out at us, and that in itself suggests that even if one can find a statistically significant correlation in the future, it is unlikely to explain a great deal of the variance. This conclusion is different than an earlier study of possible sun-climate connection which suggested the correlation might be higher[21].

The above conclusion is also consistent with another line of reasoning. As summarized in Crowley and North[1], most centennial-scale climate fluctuations of the last 1000 years were on the order of 1.0-1.5°C in magnitude. If these changes were entirely due to solar variations, they would require equivalent variations in the solar constant of perhaps 0.5-1.0%, with the magnitude of solar variation depending on the sensitivity of the climate model. This estimate is approximately an order of magnitude greater than observed fluctuations over the last solar cycle[22]. Although it is not inconceivable that more extreme fluctuations such as the Maunder Minimum could be associated with larger variations in solar activity, the required numbers (assuming our climate models have the proper sensitivity) appear to be on the far-outer limit of the possible range.

Finally, we note that our results have some implications for possible future modulation of a greenhouse warming by solar activity[23]. The very low correlations in the past indicate that such a modulation is unlikely to be greatly significant (perhaps 0.1-0.2°C change in global mean temperature). Other sources of natural variability may still be important, however, in such a modulation.

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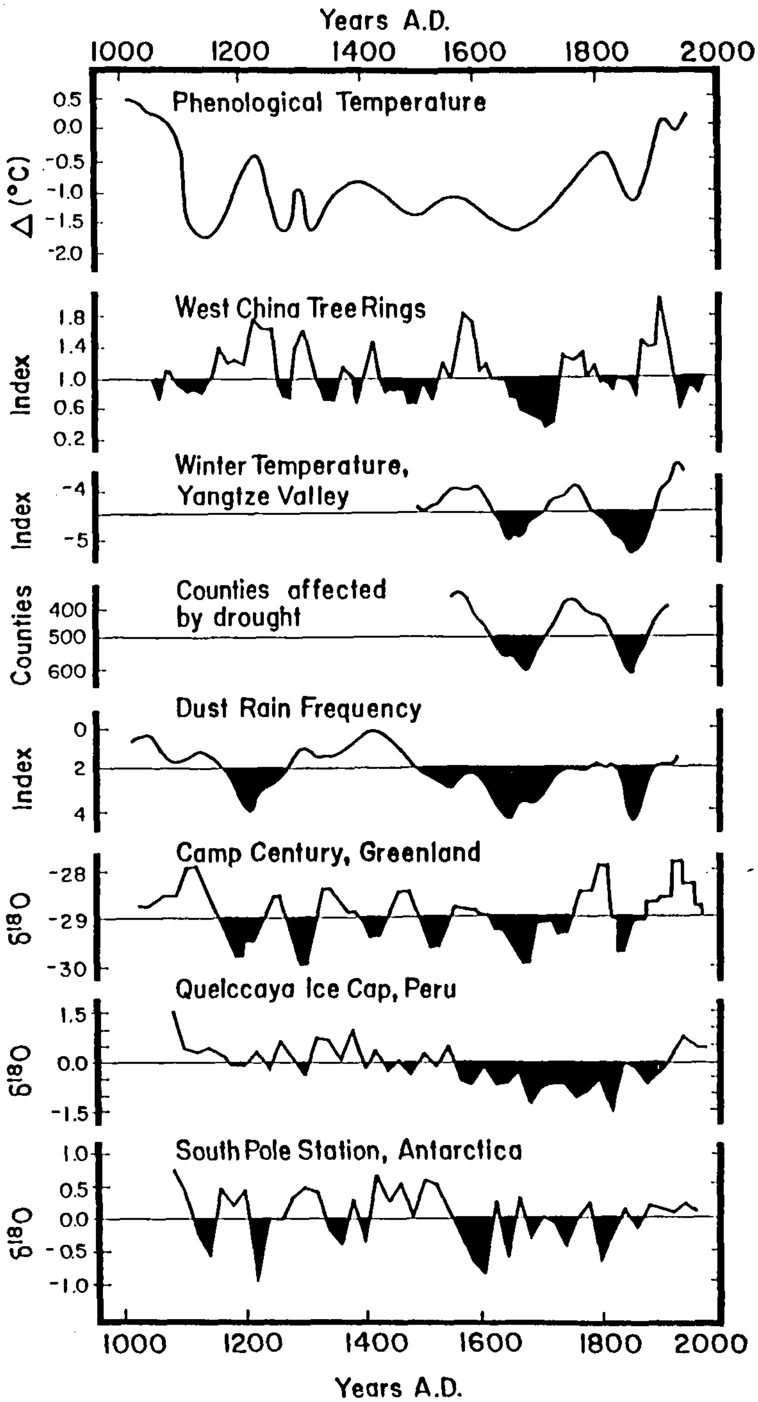
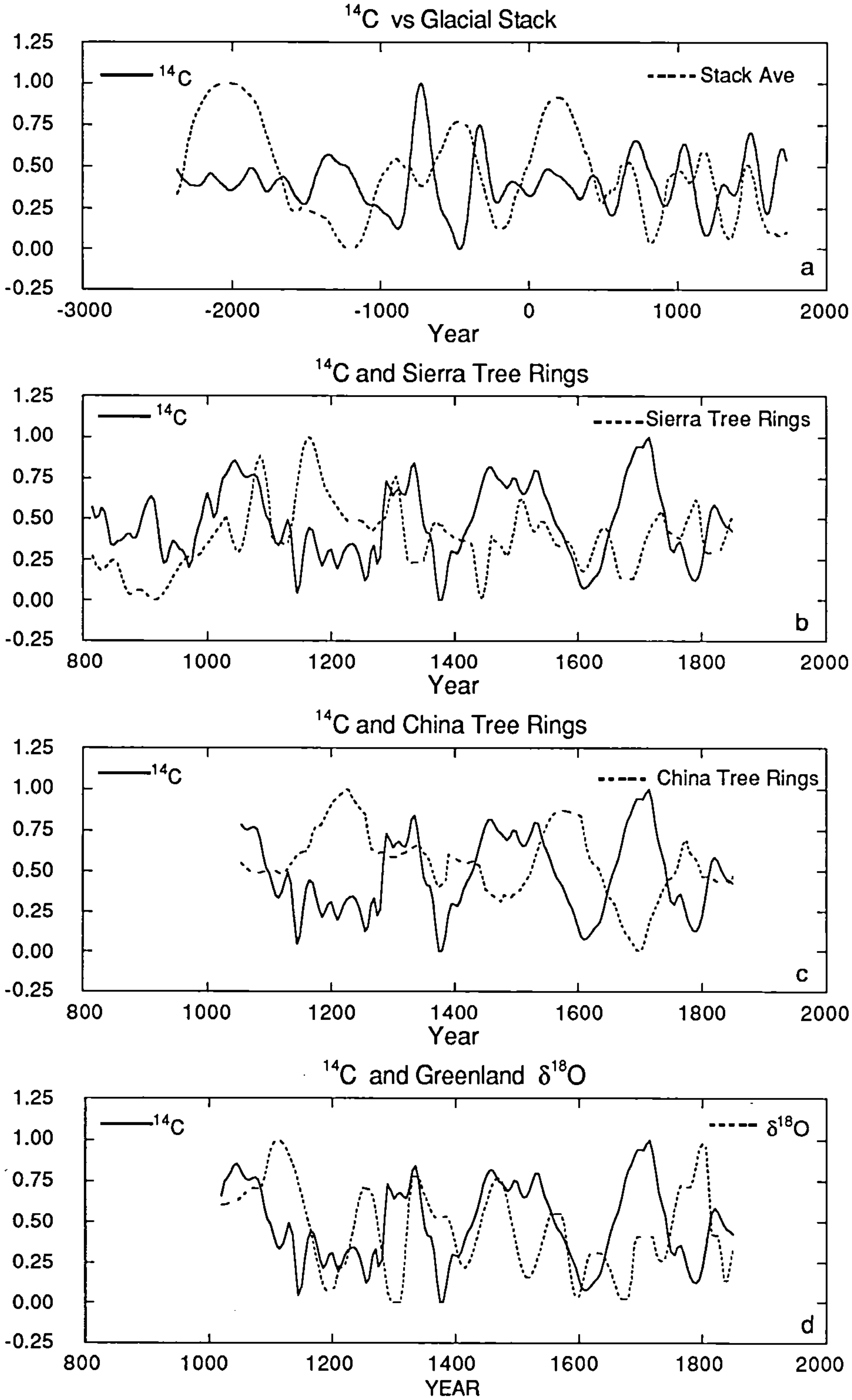


Fig. 1 Examples of decadal- and centennial-scale climate fluctuations over the last 1000 years: (a) The phenological temperature in China[24]. This index is based on timing of recurrent weather-dependent phenomena, such as dates of flowering of shrubs or arrivals of migrant birds, or distribution of climatically sensitive organisms; (b) The growth ring index of a juniper tree from western China[14]; (c) The winter temperature index in the lower reaches of the Yangtze River[25]; (d) The number of counties affected by drought in China[26]; (e) The frequency curve of dust rains in China[27]; (f) The $\delta^{18}O$ record from Camp Century, Greenland[10]; (g) The $\delta^{18}O$ record from a Peru ice core[11]; (h) The $\delta^{18}O$ record from the South Pole[12]. Shading equals cool intervals. [Courtesy E. Mosley-Thompson; modified from[28, 29]]



^{14}C vs Glacial Stack
^{14}C
Stack Ave
a
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-3000
-2000
-1000
0
1000
2000
Year
^{14}C and Sierra Tree Rings
^{14}C
Sierra Tree Rings
b
800
1000
1200
1400
1600
1800
2000
Year
^{14}C and China Tree Rings
^{14}C
China Tree Rings
c
Year
^{14}C and Greenland $\delta^{18}O$
^{14}C
$\delta^{18}O$
d
YEAR

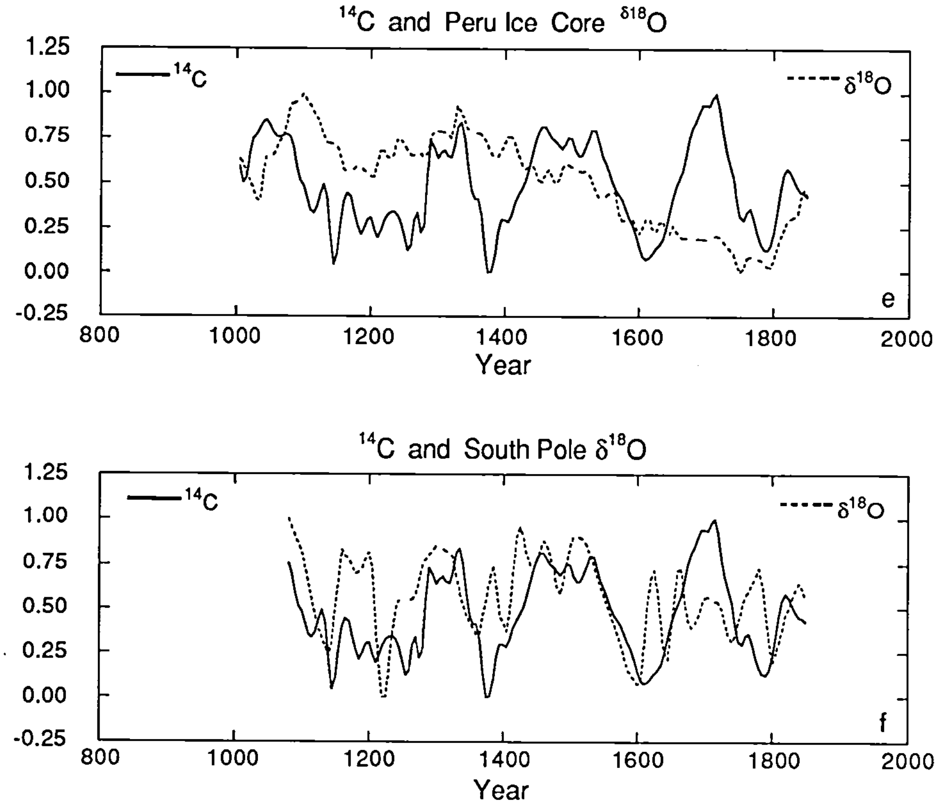


Fig. 2 Comparison of ^{14}C record of solar variability with five different indices of climate change: (a) a composite record of alpine glacial advances[9]; (b) and (c) tree rings from the Sierras and western China[13, 14]; and (d-f) $\delta^{18}O$ records from Greenland, Peru, and Antarctica[10, 11, 12].