The Solar Engine and Its Influence on Terrestrial Atmosphere and Climate

Edited by
Elizabeth Nesme-Ribes

NATO ASI Series

Series I: Global Environmental Change, Vol. 25

PERSPECTIVES ON THE CLIMATE OF THE LAST 500 YEARS

R.S. Bradley,
University of Massachusetts,
Amherst, MA 01003-5820, U.S.A.

Abstract

High resolution proxy records of past climate can be used to extend our perspective on regional and hemispheric changes of climate back in time by several hundred years. Using historical, tree-ring and ice core data, we examine climatic variations during the period commonly called the "Little Ice Age". A reconstruction of summer temperatures reveals that, for the northern hemisphere as a whole, the coldest summer temperatures of the last 560 years were between 1570 and 1730, and in the early to mid-19th century. At other times, temperatures were relatively high, in some regions equalling or exceeding levels typical of the early to mid 20th century. Temperatures during the Maunder Minimum (1655-1714) correspond to the coldest 60 year interval of the last few centuries at many locations, but the period of the Spörer Minimum was not particularly unusual. In the context of the last 500-600 years, unusually warm conditions have prevailed since the 1920s ; this may be related to a relative absence of major explosive volcanic eruptions and higher levels of greenhouse gases.

1. Introduction

For most parts of the world, instrumentally-recorded records of climate span a period of less than a century, providing a very limited perspective on climate variability and its relationship to potentially important forcing factors. To obtain a longer perspective requires reliance on climate-dependent natural phenomena which have preserved, in some way, a climate signal (Bradley, 1985 ; Bradley and Jones, 1992). To utilize such material in paleoclimatic reconstruction, two fundamental criteria must be met : (1) the material must

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be capable of being accurately dated, and (2) the climatic signal must be clearly separable from non-climatic noise. Given that such records are difficult to find, a further attribute should be that the record represents climate variations of more than purely local significance. This encounters the difficulty of determining the "spatial representativeness" of a record, and whether this "spatial field" has remained constant over time. It is likely that the spatial field is frequency-dependent, such that lower frequency components of a record represent a wider geographic area than higher frequency components. Thus, a few widely separated records may be sufficient to represent century-scale variations (10^2-10^3 year) over a large region whereas decadal scale variations (10^1-10^2 year) may require a larger network of data. Thus, in determining the relationship between forcing factors and climate response (whether low or high frequency) the network density required to adequately detect a signal must be considered.

2. Types of Record Applicable to Paleoclimatic Reconstruction of the Last 500 Years

The period before the beginning of the 20th century is often referred to as the "Little Ice Age", largely because of the abundant evidence that alpine glaciers throughout the world were significantly larger in preceding centuries. Unfortunately, records of glacier fluctuations are insufficient to address the relationship between forcing and climate response. Geological evidence of glacier position cannot provide a continuous time series ; moraines can delimit forward ice positions but the extent of recession between advances is not determinable by geomorphological evidence. Moraines cannot be accurately dated ; usually ice advances are 'bracketed' by radiocarbon dates on organic material over-ridden by ice advance, and material subsequently growing on the stable moraine. Even if this interval was in reality very short, the uncertainties in radiocarbon dating material with a time age of 0-500 years B.P. (because of changes in ^{14}C production rate) mean that assigning a unique date range to individual samples is often impossible. The problem is only compounded when using lichonometrical dating in which the lichen growth curve is defined by ^{14}C-dated material. Some of these difficulties are

overcome when historical records provide precise documentation of glacier position (e.g. Messerli *et al.*, 1978) but such cases are rare outside of Alpine Europe and the vast majority of glaciers studied rely on geological methods to define glacier positions in the past. Even if dating of glacier position was not a problem, the value of such evidence for paleoclimatic purposes is far from clear. Glaciers may lose considerable mass by down-wasting before the terminal position changes significantly. Individual glaciers respond quite differently to climatic changes depending on their topographic situation, size and 'activity ratio' (that is the effective rate at which snowfall moves through a glacier from accumulation area to ablation zone). Finally, it is an obvious fact that glaciers are limited in their geographic extent and, hence, cannot provide widely distributed evidence for past climatic conditions. All of these factors contribute to limiting the value of glacial evidence in determining *quantitatively* former climatic conditions over a wide area. Far preferable are continuous, accurately dated, proxy records which have been calibrated with modern, instrumentally-recorded climatic data. Such records (discussed in somewhat more detail in Duplessy *et al.*, this volume) include :

a) historical data
b) tree ring data
c) ice core data
d) coral data
e) varved sediment data

Historical records can, potentially, provide seasonally-resolved quantitative estimates of past climate over wide geographic regions, though at present only European and East Asian sources have been adequately utilized.
Tree ring data includes both ring width and ring density variations. Records are available from all continental areas (except Antarctica) though most series are from extra-tropical regions. High latitude and high altitude trees generally provide paleotemperature estimates ; trees in semi-arid regions generally provide paleo-precipitation estimates though even in wetter areas, records of precipitation changes can sometimes be obtained.
Ice cores provide multi-proxy records of paleoclimate but changes in ^{18}O accumulation rate and (summer) melt conditions are of primary interest in

examining recent centuries. ^{18}O in polar regions is generally considered to be an indicator of annual temperature (Dansgaard *et al.*, 1973) and though there are innumerable problems in applying this simple interpretation to regions beyond the interior of Antarctica (Bradley, 1985 ; Jones *et al.*, 1993) it continues to be equated with mean annual temperature. Other useful climate indicators include the fraction of a core containing 'melt features' (produced by the re-freezing of percolating surface melt water) which provides a useful index of summer temperature conditions, and accumulation rate changes which indicate past precipitation amounts (assuming no net loss during the year).

Corals provide a unique high resolution record of sea-surface temperatures from changes in the (temperature dependent) oxygen isotopes in the carbonate skeleton of the corals. In some cases, salinity variation is the most important factor influencing isotopic content, in which case the changes reflect precipitation and runoff from adjacent continental regions (Dunbar and Cole, 1993).

Varved sediments, from both lacustrine and marine environments, are annually laminated records of past environmental conditions in the lake or oceanic region. There are few ocean areas where varved sediments are known to occur (generally upwelling coastal regions where anoxic bottom waters are found) but varved lake sediments are quite widespread across all continents. Providing the records are clearly annual and a strong climatic signal can be demonstrated, these records can provide useful data from many regions of the world.

In the following section, we discuss the evidence provided by such records in reconstructing the climate of the last few centuries. It should be noted, however, that most proxies are quite season-specific, and provide information only about the time of year when the proxy is in some way registering the climate signal. In comparing proxies, it is necessary to ensure that the same seasonal signals are being examined. This often limits large scale comparisons to the summer season.

3. The Climatic Record of the Last 500 years

Using a variety of proxy temperature records, an estimate of the northern hemisphere summer paleotemperatures over the last 500 years has been made (Bradley and Jones, 1993). This estimate is based on records from three regions (North America, Europe and East Asia) which are known to "track" temperature variations of the hemisphere as a whole during the period of instrumental records (i.e. they explain > 70% of the northern hemisphere temperature variation on a decadal time-scale). The limited number of similar records from the southern hemisphere precludes a similar analysis being made for this region at present.

In the northern hemisphere, temperatures were generally cooler than in the 20th century for most of the preceding 500 years, but not continuously so (Figure 1). Overall, the coldest periods were between 1570 and 1730, and in the early to mid-19th century. In some regions (e.g. Europe in the 18th century) temperatures were as high as in the early 20th century. Thus, the notion of a prolonged and uninterrupted cool interval, implied by the term "Little Ice Age", is not supported by the limited evidence available. Rather, the last 500 years experienced both cool and warm intervals, with temperatures generally increasing over the last 400 years.

It was noted earlier that most proxies are related to summer temperature and therefore the northern hemisphere reconstruction described above is based on data for this season only. In a few regions, temperature reconstructions have been made for all seasons of the year, based largely on historical data (e.g. Switzerland ; Pfister, 1992 ; eastern and northern China, Wang, 1991). In comparing these different seasonal records, it is apparent that summer temperatures are not always in phase with the other seasons. Therefore, it must be recognized that our perspective on past climate from the available proxies may be somewhat biased by the preponderance of summer temperature indicators. However, for at least the period of instrumental records (1901-1990) inter-annual summer temperature variations over the northern hemisphere are highly correlated with annual temperature variations ($r \geq 0.88$, for $n=90$; Jones and Briffa, 1992).

4. Solar Activity Variations and the Record of Past Climate over the Last 500 years

It is often argued that climatic variations of the last few centuries are largely the result of either solar or volcanic forcing (e.g. Wigley, 1991 ; Porter, 1986). Here we examine the relationship between estimates of long-term summer temperature variations and solar irradiance changes. Recent studies have shown a strong correlation between temperature changes over the last 100 years and solar cycle length, which is considered to be an index of solar irradiance variations (Friis-Christensen and Lassen, 1991). However, the change in solar cycle length has occurred at a time when greenhouse gas concentrations have also been rising, so separating the influence of each forcing factor is problematical. Theoretical considerations suggest that the magnitude of irradiance change (indicated by the change in solar cycle length) is too small to have been of great climatic significance, and that forcing by greenhouse gases is of more importance (Kelly and Wigley, 1992 ; Schlesinger and Ramankutty, 1992). Another way of examining this issue is to compare irradiance variations with temperature changes prior to the 20th century, since the influence of anthropogenic greenhouse gases was small before 1900. Figure 2 shows estimated solar irradiance (based on several measures of solar variability calibrated against recent satellite-based irradiance measurements ; Hoyt and Schatten, 1993) compared with the reconstructed summer temperature record for the northern hemisphere, discussed above. The correspondence is poor ($r = 0.49$, for decadal averages, $n=29$) especially between 1770 and 1880. However, ^{10}Be measurements in polar ice cores, which serve as an index of short-term solar variability, do show a very good correlation with the long-term record of temperature in central England (Beer *et al.*, this volume). Given the uncertainties in both the reconstruction of past solar irradiance, and of paleotemperatures, there is a real need to undertake further analysis of these data, especially using ^{10}Be from many sites as a proxy of solar irradiance changes.

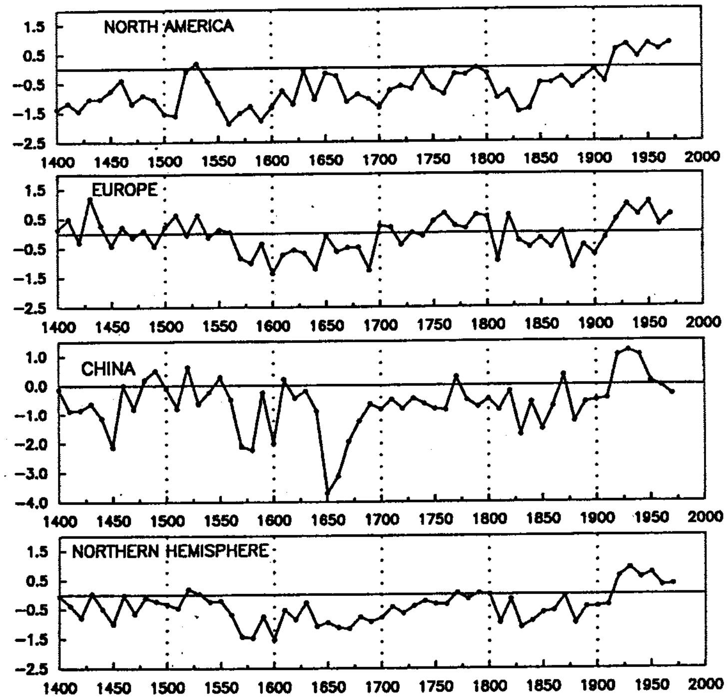

Figure 1. Composite northern hemisphere summer temperature anomalies (with reference to the 1860-1959 mean) for three regions (North America, Europe and China) and for the northern hemisphere. Y-axis is in standard deviation units ; each series is the average of a set of normalized, decadal anomalies, derived from different proxy records. The largest decadal temperature anomaly (1600-1609) is estimated to be 0.43°C below the 1950-79 average for the northern hemisphere [from Bradley and Jones, 1993].

5. The Maunder Minimum

The period of reduced sunspot activity from A.D.1655-1714, known as the Maunder Minimum (Eddy, 1976) is often cited as a period of reduced solar

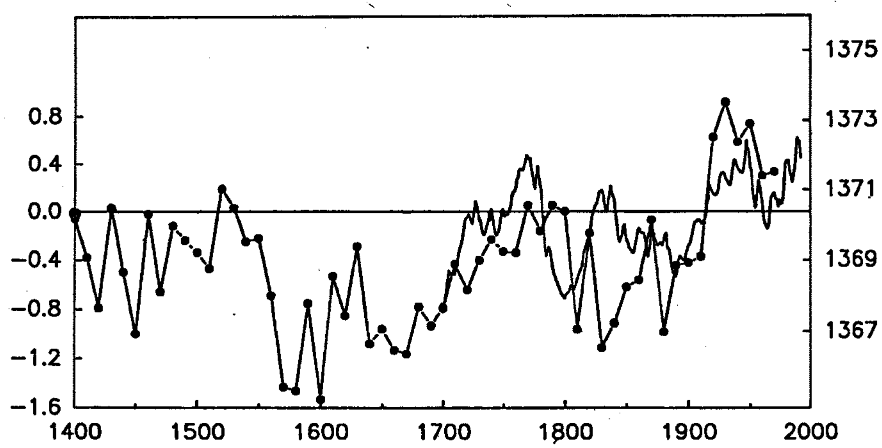

Figure 2. Mean normalised northern hemisphere summer temperature anomalies (with reference to the 1860-1959 mean) [same as lowest panel of Figure 1, shown as the line with circles ; from Bradley and Jones, 1993] and solar irradiance changes (Watts per square meter) (from Hoyt and Schatten, 1993).

irradiance. Recent studies indicate that other indices of solar activity may not have changed at that time, so it is not clear if solar irradiance was, in fact, lower (cf. Silverman, 1993). Without entering that debate, we simply note here that many proxy records (especially those from high latitudes) did record the most extreme conditions of the last few centuries at the time of the Maunder Minimum (i.e. in comparing 50-60 year means for periods before, during and after the Maunder Minimum, the Maunder Minimum is frequently the coldest interval of record).

For example, records of melting conditions on polar ice caps in Spitsbergen, Ellesmere Island and Greenland all show the lowest levels of melting over the past 600-700 years (indicating low summer temperatures and/or low net radiation) occurred during the Maunder Minimum. Oxygen isotope values

(^{18}O) were also lowest at this time, suggesting low temperatures during periods of precipitation on the ice caps. Similarly, many historical records from Korea, and from northern and eastern China indicate that the coldest summers of the last 500 years were during this interval ; winters were also exceptionally cold, in many regions. Tree ring records from northern Patagonia also indicate low summer temperatures at the time of the Maunder Minimum. Of course, there are also proxy records which show nothing unusual about the Maunder Minimum, and to obtain a complete perspective, as dense a network as possible must be examined, and the anomalies mapped, to determine the spatial distribution of the extremes. These maps may then be compared with general circulation model simulations of circulation changes associated with a reduction in solar irradiance (e.g. Lean and Rind, 1994). By combining proxy records and model simulations, it should eventually be possible to understand the significance of small changes in solar forcing on the general atmospheric circulation.

6. Summary and Conclusions

A set of proxy records are available which provide a representative estimate of northern hemisphere summer temperature changes, on a decadal scale for the last 500 years. Although generally lower temperatures prevailed before the 20th century, there were relatively warm intervals in the 18th and 16th centuries, and in some regions these approached 20th century levels. Estimates of solar irradiance changes do not correspond well with the paleotemperature record before 1900, though there are clearly limitations in both reconstructions. The Maunder Minimum period was one of the coldest 60 year periods of the last few centuries at many, but not all, sites around the world. A comprehensive study of long-term temperature proxies, focusing on this interval, is needed to establish the pattern of large-scale circulation anomalies.

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