Introduction

The study of Earth’s history has revealed major and minor climatic changes. The Pleistocene ice ages of the past 2 Ma exhibit a periodicity (Jouzel et al. 2007) that has been attributed to orbital influences (Paillard 1998; Berger and von Rad 2002). Spectral analysis methods have produced evidence for various other periodicities in long-term data, such as from ice cores. One particular climate cycle has received an extra degree of attention: an approximate 1500-year cycle. An understanding of this cycle, if it is real, would help clarify some of the processes operating in the Earth’s climate system.

The ~1500-year cycle was initially observed in the timing of abrupt warming events in the Pleistocene history of Greenland; these events are called Dansgaard–Oeschger (DO) events (see review in Singer and Avery 2007). Rahmstorf (2003) showed that 14 DO events (defined objectively from δ¹⁸O data from the GISP2 (Greenland Ice Sheet Project 2) Greenland ice core) over the interval 10 000 to 50 000 years before 2000 A.D. (b2k) all follow a 1470-year period — with a small random deviation that Rahmstorf attributed to dating errors.

Not every 1470-year interval in the ice cores has a DO event; this has led to claims that the appearance of periodicity is illusory or is caused by stochasticity (e.g., Muller and MacDonald 2000; Clemens 2005; Ditteansen et al. 2007). However, if DO events result from some trigger process (e.g., Ganopolski and Rahmstorf 2002) rather than from strict periodic forcing, then a test for periodic events would not be appropriate.

It has been maintained that the DO events ended with the glacial termination ~15 000 years b2k. However, Pestiaux et al. (1988), Campbell et al. (1998), Bond et al. (2001), Vial et al. (2002), Clemens (2005), Debret et al. (2007) and Thorneley et al. (2009) all show that 1500–1600-year cycles (commonly called Bond cycles) are detectable in both Greenland ice and North Atlantic sediments, as well as in North American lake sediments, Indian Ocean sediments, and China cave deposits throughout the Holocene and a 1000-year cycle in some cases (Campbell et al. 1998; Neff et al. 2001; Clemens 2005; Debret et al. 2007). Willard et al. (2005) detected a 1429-year cycle in North American pollen records from sediments, as well as shorter cycles, but had high-resolution data only before 6000 years b2k.

Several models have recently been developed that explain transitions between climate states as a nonlinear threshold process. In such a model, small changes in forcing can lead to a large change of state once a threshold is crossed. Overland et al. (2006) studied regime-shift-type behavior in the Pacific Decadal Oscillation. Tsonis et al. (2007) developed a model for linkage between the different climate oscillations, such as the Pacific Decadal Oscillation and North Atlantic Oscillation. According to their model, interactions between these systems can lead to abrupt periodic shifts in global climate. At the scale of ice-age cycles, Paillard...
A recent reconstruction (Loehle 2007; Loehle and McCulloch 2008) is based on 18 records using several different northern hemisphere and tropical proxies (ice cores, pollen, cave deposits, etc., but not tree rings) that had been calibrated to temperature in the original studies. The individual temperature series were interpolated, normalized, smoothed with a 29-year centred running mean, and then averaged. No rescaling was done. The reconstruction spans most of the past 2000 years and has wide geographic coverage, including the Southern Hemisphere. It has data only up to 1949 A.D., so it is not influenced much, if at all, by possible anthropogenic warming. The reconstruction also has confidence intervals; this aids with comparisons. The low-temperature point of the reconstruction overlaps the Maunder Minimum, and the peak coincides with the Medieval Warm Period (MWP) (Fig. 2).

A third reconstruction (Fig. 3) is that of Moberg et al. (2005). This multiproxy reconstruction has data only up to 1925 A.D., so it also is not influenced by possible anthropogenic warming. The low-frequency component of their reconstruction (analyzed here) is based on 11 non-tree-ring proxies from the Northern Hemisphere and tropics, eight of which (those that were calibrated to temperature in the original publications) were also used in Loehle (2007) and Loehle and McCulloch (2008). In spite of the data overlap, the two studies used different methods of analysis. In the Moberg et al. (2005) study, wavelet analysis was used to reconstruct pattern and the final curve was rescaled to unit variance.

The fourth data set tested is the sea-surface temperature (SST) reconstruction off north Iceland by Sicre et al. (2008). This series, based on analysis of alkenones in sediments and using the Prahl et al. (1988) temperature calibration (Fig. 4), is from a high-deposition-rate site, thereby allowing a high-resolution reconstruction from 76 B.C. to 1949 A.D. Data are from Sicre et al. (2008, fig. 1), provided by the author. A linear cooling trend in the data was removed before analysis. Again, any 20th century warming is not included in these data. The researchers of this study suspect the top of the core is closer to 1900 A.D. than to 1950 A.D. (M.-A. Sicre, personal communication, 2008).

The fifth proxy used is the $\delta^{18}$O (%) values from speleothems in the Central Alps (Mangini et al. 2007). This data was shown by Mangini et al. to correlate well with the hematite-stained grain data from the North Atlantic (Bond et al. 2001). The data cover from 9000 years b2k through 2004 A.D. (~4 b2k).

Kitagawa and Matsumoto (1995) found that $\delta^{13}$C variations in tree rings of Japanese cedar (not the ring width) could be calibrated to temperature. We digitized data from their fig. 3 for the years 125–1955 A.D. and used their temperature conversion.

Thornalley et al. (2009) found ocean density stratification to be a good climate indicator for the subpolar North Atlantic. We used their data for the period 50–8389 years b2k.

Subpolar North Atlantic upper ocean temperatures were estimated by Came et al. (2007) for the period 554–6633 years b2k.

A 2000-year-long SST record was estimated by Oppo et
Fig. 1. Greenland data analysis. (a) Updated GICC05 ice-core chronology (Andersen et al. 2006; Rasmussen et al. 2006). (b) Best-fit model for 30,000 to 37,000 years before 2000 A.D. (b2k; year zero for b2k is 2000 A.D.) ($R^2 = 0.36$, period = 1486 years). (c) Best-fit model for 40,000 to 46,000 years b2k ($R^2 = 0.30$, period = 1598 years). For (b) and (c), the $\delta^{18}$O values are centered for better estimation of cycles.
al. (2009) for the Makassar Strait, Indonesia. Data points represent overlapping 50-year intervals and, thus, are not annual data.

Although it might seem that there are many other climate reconstructions available for this study, few go back more than 1000 years, which is inadequate for detecting a 1470-year cycle. Of these, many are based on or include tree rings, which have been severely criticized for this purpose (Stockwell 2007, chap. 9; Loehle 2009). In other cases, data are too widely spaced (e.g., every 500 years for the Antarctic data in Kawamura et al. (2007), or every 200 to 1000 years for temperatures from Lake Malawi, Africa from Powers et al. (2005)), or were not available from the authors. Repeated attempts to obtain the original Bond data from his coauthors were unsuccessful.

Analysis

The plausibility of these proxy data containing a 1470-year cycle was determined by fitting a cyclic (sine-wave) model to the reconstructions using unconstrained nonlinear least-squares estimation (per Schulz 2002a). This method and equivalent methods have been used frequently (e.g., Schlesinger and Ramankutty 1994; Campbell et al. 1998; Klyashtorin and Lyubushin 2003; Zhen-Shan and Xian 2007) and are equally able to detect periodic signals in data as are spectral methods. When data are irregularly spaced and not dense, direct estimation of a sinusoidal model is superior to spectral methods because no interpolation is necessary. In addition, when dating errors are present, spectral methods may fail to detect a signal that is in fact present or may falsely detect derived mode periodicities (Dima and Lohmann 2009). The ability to detect a 1500-year cycle in series as short as 2000 years (the shortest we used) was tested (see supplementary data2). It was found that the mean period found for 1000 replicates after noise was added was 1500.6 years with standard deviation of 20 years. In some cases, the fit with a fixed 1470-year period cycle was tested. All data were normalized (centred on 0°C) before fitting, and linear or very long-period trends removed if possible. The presence or absence of a 1500-year cycle is unaffected by this procedure, which simply makes the key question of the existence of this cycle easier to visualize.

In the statistical estimation of nonlinear models in the next section, models are only reported if the $F$ value was significant. Confidence intervals are not available for nonlinear estimation. In testing the method, it was found that if no signal was present (e.g., for white noise with the same variance), the estimation method simply fit a straight line to the data (i.e., no sinusoidal model). The possibility of spurious red-noise processes generating the pattern was considered. Generally, temperature autocorrelation owing purely to red-noise processes (internal earth-system autocorrelations) has only been assumed to apply for periods of a few years to a few decades at most, and no mechanism exists for proposing longer periods. Most of the data presented in the following section exist at sampling intervals longer than this. Thus autocorrelation caused by climate inertia or red

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2Supplementary data (information note and Fig. S1) for this article are available on the journal Web site (cjes.nrc.ca) or may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Building M-55, 1200 Montreal Road, Ottawa, ON K1A 0R6, Canada.
noise can be ignored in what follows. The $R^2$ values quantify the percent of variance explained by the model. There is no conventional fixed cutoff for “good” $R^2$ values, but $R^2 < 0.20$ is too low to report for our purposes.

**Results**

(1) The Greenland GICC05 chronology (Fig. 1a) captures the recent glacial termination at about 10,000 years b2k; thus, it could not be analyzed all at once because it is nonstationary. There are three discrete semi-stationary segments: cooling from 60,000 to 30,000 years b2k, warming from 30,000 to 10,000 years b2k and cooling from 8000 b2k to present. These were analyzed separately. The deep glacial interval 30,000 to 60,000 years b2k was analyzed first. No cycle could be fit to this interval with an $R^2 > 0.05$, perhaps because of missing peaks. This contrasts with the GISP2 chronology, in which the 1470-year cycle was more evident (Rahmstorf 2003). Portions of the record appear to have a regular pattern, and these were analyzed. For the interval 30,000 to 37,000 years b2k (Fig. 1b), the fit is much better ($R^2 = 0.48$), and the period is very close to the Braun et al. (2005, 2007, 2008) model at 1486 years. If the interval is extended to 40,000 years b2k, the fit degrades rapidly to $R^2 = 0.26$, so a longer interval was not used. For the interval 40,000 to 46,000 years b2k (Fig. 1c), the fit is again good ($R^2 = 0.35$), especially visually, and the period is 1571 years. For the interval 10,000 to 30,000 years b2k, the best-fit model (after linear detrending) is virtually overwhelmed by noise ($R^2 = 0.08$), but it still has a period of 1436 years. Owing to the low $R^2$ value, this interval is not considered further. For the Holocene (to 8000 years b2k), the data (after the linear cooling trend is removed) do not show any periodic signals ($R^2 < 0.05$). Thus, over the past 46,000 years, this cycle could be detected over two intervals covering 13,000 years. It is also noteworthy that no other periodic signals could be detected in this record except the ~1470-year cycle. Therefore, the results suggest intermittent operation (or detectability) of the ~1470-year cycle during the Pleistocene, consistent with a threshold process.

(2) The best-fit model to the Loehle reconstruction (Fig. 2) shows excellent agreement with the proxy reconstruction ($R^2 = 0.68$) and has a cycle trough that overlaps with the Little Ice Age (LIA) and Maunder Minimum, as well as a maximum at the MWP. It has a cycle length of 1681 years, which is almost precisely the same as those periods found by Clemens (2005) of 1667 years, by Viau et al. (2002) of 1650 years, and by Debre et al. (2007) of 1650 and 1660 years. The peak-to-trough amplitude is 0.59 °C. The MWP peak is at 798 A.D. Forcing the period to be 1470 years brings the $R^2$ value down only slightly (to 0.65) and gives a curve that differs only modestly from the best-fit curve. The MWP peak of this forced-fit model is at 833 A.D. We further note that both models stay almost entirely within the 95% confidence intervals of the Loehle and McCulloch (2008) reconstruction. Formally, we cannot reject either a 1470-year or a 1680-year cycle when tested against this reconstruction.

(3) We applied the same procedure to the Moberg et al. (2005) reconstruction. The best-fit model (Fig. 3) has $R^2 = 0.69$ and a slightly later peak, with a peak-to-trough amplitude of 0.39 °C and a MWP peak at 1036 A.D. The best-fit model falls within the Moberg confidence intervals 49% of the time (not shown). If the confidence intervals are expanded by merely 0.08 °C, then 93% of the fitted curve falls within the bounds. The cycle length is 1152 years, which closely matches the 1190-year cycle of Clemens (2005), the 1030-year cycle of Campbell et al. (1998), and the 1000-year cycles of Clemens (2005) and Debre et al. (2007). Forcing a 1470-year cycle gave a good fit ($R^2 = 0.54$), so it is not possible to say the 1470-year cycle is incompatible with the Moberg reconstruction. The 1470-year cycle MWP peak is at 948 A.D.

(4) The Sicre et al. (2008) north Iceland SST data were fit as before after a linear trend was removed. The best-fit model (Fig. 4) shows the MWP and LIA, with a period of 1408 years, a MWP peak at 1138 A.D., and $R^2 = 0.20$. The LIA trough was at 1842 A.D., with an upturn after that. The peak-to-trough amplitude is 0.85 °C. The alternate dating for this data would make the timing of the MWP and LIA more in line with the other results in this study (LIA at 1798 A.D., MWP at 1088 A.D.).

(5) The Mangini et al. (2007) speleothem data analysis results are shown in Fig. 5. An attempt to fit the full set of data with any periodic model failed ($R^2 = 0.053$). It was noticed that the pattern at the beginning and end of the record looked different than the middle portion, so these sections were analyzed by giving the middle segment zero weight in the fitting process. Simultaneously fitting the segments 9000–6500 years b2k and 3500 years b2k to most recent (an interval of 6000 years), a cycle length of 1479 years is found ($R^2 = 0.46$). The middle time section curve does not quite line up with the other two time segments even though the periods are quite similar; this gives the appearance of a phase shift of a few hundred years or some sort of interruption of either the cycle or the data (not shown). This intermittency is possibly compatible with the nonlinear multistate models of Braun et al. (2005, 2007, 2008) or could result from problems with the sediment core dating (missing segments, etc.). The MWP peak is at 907 A.D., LIA is at 1647 A.D.

(6) The Japanese cedar data when fit free-form (Fig. 6) gave a cycle length of 1089 years ($R^2 = 0.28$) with a peak-to-trough amplitude of 1.95 °C and MWP peak at 1047 A.D. When forced with a 1470-year cycle (Fig. 6), it also fit reasonably well ($R^2 = 0.22$), with a peak-to-trough amplitude of 1.5 °C, and a MWP peak at 954 A.D. In both cases, the MWP and LIA timings are clearly shown and match those seen in other studies. As well, there is an upturn following the LIA. Because the data do not extend past 1955 A.D., recent warming trends are not influencing the model estimation process.

(7) The Thornalley et al. (2009) North Atlantic density stratification data (which are not a direct temperature proxy)
were found to have a period of 1527 years with $R^2 = 0.23$ (Fig. 7), which is concordant with the 1500-year period found in the original analysis using spectral methods. (8) The Came et al. (2007) North Atlantic temperature series showed a reasonable fit ($R^2 = 0.32$) over a 10,000-year period (the entire Holocene), with a cycle length of 1200 years. It was first detrended to remove a 10,897-year cycle (Fig. 8a). The resulting model (Fig. 8b) appears to fit better before 2000 years b2k.

(9) The Indo-Pacific SST data of Oppo et al. (2009) show a linear cooling trend over the 2000-year record, as has been seen in other studies. After removal of this linear trend, the best-fit model has a strikingly good visual match ($R^2 = 0.53$) and a period of 1067 years (Fig. 9).

Discussion

If the 1500-year cycle can be found in both the Pleistocene and Holocene; this suggests that whatever causes it has operated over this entire interval. We thus consider the entire period since 45,000 years ago in our evaluation of results.

Models fit to all data sets are broadly coherent (Table 1). The periods found were 1486, 1571, 1681, 1152, 1408, 1479, 1230, 1527, 1200, and 1067 years. Three of these records show the periodic behavior to extend across the entire Holocene. Four of the records (Moberg, Kitigawa, Came, and Oppo) show a tight clustering around 1200 years (mean periods...
Table 1. Summary of results.

<table>
<thead>
<tr>
<th>Proxy</th>
<th>Time interval (years b2k)</th>
<th>Period (years)</th>
<th>$R^2$</th>
<th>Peak-to-trough amplitude (°C)</th>
<th>MWP date (A.D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenland GIIC05 $\delta^{18}$O</td>
<td>30,000 – 37,000</td>
<td>1486</td>
<td>0.48</td>
<td>2.6</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>40,000 – 46,000</td>
<td>1571</td>
<td>0.35</td>
<td>2.2</td>
<td>–</td>
</tr>
<tr>
<td>Loehle (2007) multiproxy</td>
<td>65–1984</td>
<td>1681</td>
<td>0.68</td>
<td>0.59</td>
<td>798</td>
</tr>
<tr>
<td>Moberg et al. (2005) multiproxy</td>
<td>75–1867</td>
<td>1152</td>
<td>0.69</td>
<td>0.39</td>
<td>1036</td>
</tr>
<tr>
<td>Sicre et al. (2008) SST</td>
<td>51–1924</td>
<td>1408</td>
<td>0.20</td>
<td>0.85</td>
<td>1138</td>
</tr>
<tr>
<td>Mangini et al. (2007) speleothem</td>
<td>6500–9000 and (–4)–3500</td>
<td>1479</td>
<td>0.27</td>
<td>0.33</td>
<td>907</td>
</tr>
<tr>
<td>Kitagawa and Matsumoto (1995) C-13 tree rings</td>
<td>45–2875</td>
<td>1230</td>
<td>0.22</td>
<td>1.95</td>
<td>1047</td>
</tr>
<tr>
<td>Thornalley et al. (2009) stratification</td>
<td>50–8389</td>
<td>1527</td>
<td>0.23</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Came et al. (2007)</td>
<td>554 – 10,423</td>
<td>1200</td>
<td>0.32</td>
<td>0.94</td>
<td>—</td>
</tr>
<tr>
<td>Oppo et al. (2009)</td>
<td>0–2000</td>
<td>1067</td>
<td>0.53</td>
<td>0.58</td>
<td>1151</td>
</tr>
</tbody>
</table>

Note: Values in parentheses are for forced cycles at 1470 years before 2000 A.D. (b2k). MWP, Medieval Warm Period; SST, sea-surface temperature; $-4$ b2k, 2004 A.D.

Fig. 9. Best-fit model to Oppo et al. (2009) Indo-Pacific sea-surface temperature after linear cooling trend removed. The best-fit model has a cycle length of 1067 years ($R^2 = 0.53$), b2k, before 2000 A.D.

For the other six results, the period found is consistent: a 1528.5-year mean for the two Pleistocene results; a 1523.8-year mean for the four Holocene results; and a 1525.3-year mean for all six combined. This latter value is only 3.8% above the hypothetical 1470-year value. A 1470-year cycle was also shown to be compatible with the Loehle, Moberg, and cedar data sets.

A test for coherence of the fitted models is the extent to which the MWP peaks line up. For the six Holocene temperature records (i.e., except Thornalley et al. 2009, which is not temperature, and Came et al. 2007, which does not cover the last 500 years), the estimated MWP peaks (Table 1) cluster in time and have a mean date of 1013 A.D., which is coherent with many other studies.

In all data sets but one, the Greenland Holocene record, the periodic signals found clustered around either 1200 or 1500 years. The Greenland ice core data for the Holocene may fail to show this signal because the noise ratio is too high or because other factors, such as source region, have influenced the $\delta^{18}$O levels.

While our data sources cluster near the North Atlantic, three of these other data sets include data quite remote from this region. Furthermore, the use of multiple proxies helps assure that the signals detected are not artifacts of sampling or dating error or other local issues at any particular site. It would, in fact, be quite striking if multiple sites showed the same periodic signals purely from spurious factors.

In several proxy studies (not used by either Loehle or Moberg), periodic models have been found useful for capturing historical patterns of temperature. Campbell et al. (1998) in a study at Pine Lake, Canada, showed that their 4000-year temperature record could be fit very well ($R^2 = 0.88$) by a multicycle model with dominant peaks near 1500 and 1000 years. The reconstruction (their fig. 3) shows a MWP before 1000 A.D., the LIA, and a temperature upturn after 1850 A.D. Debret et al. (2007) showed that a 1500-year cycle is coherent with the mid-Holocene ice-rafted debris data of Bond et al. (2001), but a 1000-year cycle is coherent with this same data over 12,000 to 7000 years b2k and 2000 years b2k to the present. The 1000-year temperature cycle in the Bond data is coherent with both $^{14}$C and $^{10}$Be data over the entire Holocene (Bond et al. 2001). These cosmogenic isotopes have been linked to solar activity and temperature changes over long intervals (Oeschger and Beer 1990; Bond et al. 2001; Neff et al. 2001; Wagner et al. 2001; Hu et al. 2003; Christl et al. 2004; Harrison and Stephenson 2006) and clearly correspond to the Maunder Minimum (Oeschger and Beer 1990). Also, fluctuations in Earth’s magnetic field over the past three millennia have been linked closely to the MWP and LIA timings (Gallet et al. 2005). Both the ice-raftered debris data (Bond et al. 2001) and 1000-year fit to it (Debret et al. 2007) show the MWP, LIA, and modern upturn. The ice-raftered debris dates (Bond et al. 2001) are also strongly coherent with severe drought dates from stalagmite data in West Virginia (Springer et al. 2008). Other studies also show these two cycles (Denton and Karlen 1973; Pestaiaux et al. 1988; Bond and Lotti 1995; Keigwin 1996; Bond et al. 1997; Mayewski et al. 1997; Campbell et al. 1998; deMenocal et al. 2000; Broecker 2001; McDermott et al. 2001; Neff et al. 2001; Wang et al. 2001; Berger and von Rad 2002; Schulz 2002a, 2002b; Viau et al. 2002; Anderson et al. 2003; Benson et al. 2003; Hu et al. 2003; Niégemann et al. 2003; Patterson et al. 2004; Jouzel et al. 2007). Because different cycle lengths showed up in the different analyses and the same data in our study were compatible with both cycle components, it seems possible that the 1000-year and 1470-year cycles are interacting in recent millennia, as also shown in the Debret et al. (2007) study.
These two cycles can both be linked to solar activity, as noted earlier in the text.

Our study, thus, lends support to the existence of an underlying ~1470-year climate cycle as first hypothesized for DO events during the Pleistocene (Ganopolski and Rahmstorf 2002; Rahmstorf 2003; Braun et al. 2005, 2007, 2008) and Bond events during the Holocene and lends less support for the 1400-year cycle of Dima and Lohmann (2009). There has been speculation that the cause is solar-related (Denton and Karlen 1973; Bond et al. 2001; Hu et al. 2003; Braun et al. 2005; Clemens 2005; Debret et al. 2007), but our results do not shed light on this question. The fact that this cycle can be detected in the Holocene and particularly during the most recent, well-dated two millennia suggests that Pleistocene DO events were unique only in their greater magnitude. That forcings operative during the Pleistocene should continue to operate today is consistent with other geologic processes. The results here cannot be used to directly test the proposed mechanisms governing DO or Bond events, but the fact that the mean length of the cycle over the six data sets (1525 years) is so close (3.8% longer) to 1470 years is certainly suggestive of this.

It is difficult to assess the amplitude of the ~1470-year cycle detected in this study. The estimated Holocene peak-to-trough cycle amplitude in the models evaluated here ranges from 0.33 to 1.5 °C, with even larger amplitudes being found during the Pleistocene. It has been shown (Loehle 2005) that when proxies with large dating error are combined, the cycle amplitudes are damped, so the amplitudes in the multiproxy Loehle and Moberg studies are likely conservative. Shorter term cycles and random fluctuations are no doubt superimposed on top of this broad cycle.

Conclusions

Clearly anomalous temperature peaks during the Pleistocene have been argued to be periodic — a controversial idea. Models have been proposed to explain quasi-periodic climate events as resulting from a threshold process. We set out to evaluate this hypothesis using Holocene data and the updated Greenland chronology. We detected ~1200- and 1500-year cycles using periodic models fit to the data. The mean period at 1525 years was within 3.8% of the hypothesized value, lending support to threshold models. The mechanism behind these cycles, which can be detected for more than 45,000 years, thus, deserves further examination.

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