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#### Notes

# Sub-Milankovitch solar forcing of past climates: Mid and late Holocene perspectives

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## ABSTRACT

A comparison was performed of solar activity and terrestrial temperature records, both derived from tree rings (i.e., without dating uncertainties), with identification of detailed and highly quantified time- and timescale-dependent characteristics of solar forcing on climate through the current interglacial in the context of oceanic variability. The tree-ring-derived temperature record from high latitudes of Europe (Lapland) exhibits persistent annual-to-millennial-scale variations, with multidecadal to multicentennial periodicities reminiscent of the Sun's periodicities. At millennial scales, cool temperatures coincided with large-scale glacial maxima. Moreover, millennial and bimillennial modes of climate variability were correlative with variations in sunspot numbers on similar scales, with near-century and near-zero lags, respectively. Although they were subtle in amplitude, the sub-Milankovitch-scale changes in the reception of the Sun's energy could thus suffice to noticeably modulate interglacial climate variations. The relative significance of timescale-dependent, Sun-climate linkages has likely varied during the mid and late Holocene times, respectively. Thus, the warmer and cooler paleotemperatures during the Medieval Climate Anomaly and Little Ice Age were better explained by solar variations on a millennial rather than bimillennial scale. The observed variations may have occurred in association with internal climate amplification (likely, thermohaline circulation and El Niño–Southern Oscillation activity). The near-centennial delay in climate in responding to sunspots indicates that the Sun's in-

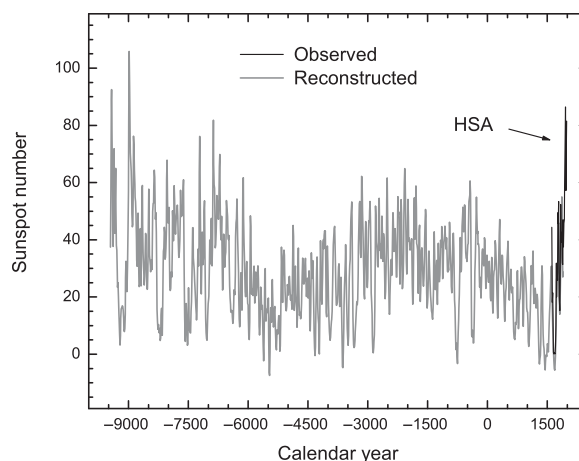
fluence on climate arising from the current episode of high sunspot numbers may not yet have manifested itself fully in climate trends. If neglected in climate models, this lag could cause an underestimation of twenty-first-century warming trends.

## INTRODUCTION

Changes on the surface of the Sun, observed and measured for the past several centuries as sunspots, vary at different timescales (Ogurtsov et al., 2002; de Jager, 2005). These variations are separate from changes in the geometry of Earth's orbit due to the Milankovitch theory (Berger, 1978, 1988) of shorter duration and either periodic or nonperiodic character. Sunspots represent concentrations of magnetic flux at the solar surface and can thus be used as tracers of solar activity. Variations in the sunspots are evident, whether determined from direct observational tables or indirect natural proxy records that can be derived from the chemistry of tree rings and ice cores (Beer, 2000). Although consensus or solid evidence regarding the pathways

of solar influence to Earth's conditions has been difficult to ensure, the variations in the Sun's activity have often been suggested to influence our climate and environment. Instead of estimates concerning the causality, estimations and evaluations of the Sun's influence on Earth's conditions have more frequently been drawn in the geological literature by stratigraphical comparisons and empirical correlation analyses (Hu et al., 2003; Niggemann et al., 2003; Magny, 2004; Nederbragt and Thurow, 2005; Turney et al., 2005; Debret et al., 2007; Mangini et al., 2007). Hence, the sunspots have become a relevant tool for geoscientists because these records, either direct or indirect, provide the scholars with information on the existence of physical associations between our star and our planet.

Sunspot diaries are available due to regular telescopic observations since the beginning of the seventeenth century (Hoyt and Schatten, 1998) (Fig. 1). It is, however, obvious that this observational record is not able to provide geoscientists the data needed for comparisons making use of variations at centuries and even millennia and over much longer intervals of



**Figure 1. Sunspot variability.** Observed (Hoyt and Schatten, 1998) and reconstructed (Solanki et al., 2004) sunspot numbers during the Holocene, both depicted using 10 yr averages. The recent period of high solar activity (HSA) is shown. Years BCE (CE) are shown negative (positive) here and in other figures.

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time, the Holocene. Importantly, recent progress in solar proxy studies has enabled reconstructions of sunspot numbers for the past 11,400 yr (Solanki et al., 2004). The most notable feature of the compound record is the period of high solar activity, inferred from the abundance of sunspot numbers, during modern times and especially since 1940 CE (Fig. 1). Strikingly, the period of high solar activity thus overlaps and positively correlates with the twentieth-century rise of temperatures on hemispheric and larger scales (e.g., Jones and Moberg, 2003). Accordingly, the Sun could have noticeably contributed to the temperature anomaly (Solanki and Krivova, 2003).

Regarding the millennial-scale variations, Bond et al. (1997, 2001) suggested that some of the long-period variations in the Sun could be understood to represent a climatic pacemaker on millennial timescales, at least for the North Atlantic sector, through glacial as well as post-glacial times. Fluctuations in solar proxy records are correlated with concentrations of ice-rafted debris (IRD) in marine sediments through the Holocene. This correlation was proposed to be the result of cool surface waters advecting southward and eastward in the subpolar North Atlantic during the periods of reduced solar activity (Bond et al., 2001). Thus, subtle variations in solar irradiance might have played an important role in Holocene climate dynamics on sub-Milankovitch timescales. If they are found to have real-world applications, these Sun-climate linkages would bear implications far beyond the field of paleoclimatology and for predictions of twenty-first-century climate patterns at a global scale. The explanatory mechanisms and validity of the linkages are, however, subject to ongoing debate (Bond et al., 2001; Rind, 2002; Goosse and Renssen, 2004; Bard and Frank, 2006; Renssen et al., 2006; Debret et al., 2007; Emile-Geay et al., 2007). Variations in solar output and oceanic circulation are the constituents of these continuing climatic debates and, as a consequence, Sun-climate relationships have probably never been as controversial as today (Bard and Frank, 2006).

A number of papers have sought to address the veracity of the suggested solar forcing against paleoclimatic proxy records that can be derived from different types of sedimentological, archeological, and paleontological archives (Hu et al., 2003; Niggemann et al., 2003; Magny, 2004; Nederbragt and Thurow, 2005; Turney et al., 2005; Debret et al., 2007; Mangini et al., 2007). In geological context, and especially from stratigraphical viewpoints, it is vital to understand that the basic difficulty underlying these paleoclimatic proxy comparisons arises from the large chronological uncertainties

inherent to radiocarbon dating. Ideally, a pair of proxies should be recovered from the very same depositional sequence to minimize uncertainties in stratigraphy. Such a comparison would similarly enable evaluations of temporal lags between the forcing and climate system. Understanding the lags in Sun-climate relationships is of particular importance in the current situation where the high solar activity of the twentieth century is confronted with potentially dropping levels of activity as predicted for the twenty-first century (Solanki et al., 2004; Ogurtsov, 2005). That is, if considerable lags in solar forcing exist, the temperatures may inevitably continue their rise even in the case of future decline in the Sun's activity.

Importantly, temporal control for the reconstructions of sunspot numbers is derived from the isotopic composition of tree rings (Solanki et al., 2004). These proxies bear the superior advantage in that tree-ring series can be reliably dated to calendar years (Fritts, 1976; Baillie, 1995). Thus, any set of tree-ring chronologies can, in theory, be compared year by year and at global distances. A perfect solution for comparisons between solar reconstructions and Earth's climate would therefore use two or more proxies from tree rings. Here we present an analysis that perfectly fulfills these criteria. The current study uses paleontological tree rings from a vast collection of megafossils highly sensitive to temperature variations because of their timberline provenance. As a main result, a new paleoclimatic reconstruction of past temperature variability was derived using a compound chronology of fossil and modern tree rings over the past 75 centuries. The reconstructed temperature variations are compared to multiproxy paleoclimate evidence around the Northern Hemisphere: North America, Greenland, Europe, and the North Atlantic. Topically, the exploited proxy data include the Holocene reconstruction of sunspot numbers. This study thus aims to implement a novel evaluation of solar forcing on interglacial climate instability.

## MATERIAL AND METHODS

A high number of pine megafossils were previously collected in the area of subarctic timberline in northernmost Europe (Eronen et al., 1999, 2002). This material was preserved as stems in small lakes in the region of northern Lapland, Finland, and Norway (70°–68°N to 30°–20°E). The data consist of 1249 tree-ring-width series of megafossils and enable a continuous tree-ring chronology that covers the interval between the years 5634 BCE and 2007 CE (Helama et al., 2008). Importantly, all series were dendrochronologically dated to calen-

dar years without dating imprecisions (Eronen et al., 1999, 2002; Helama et al., 2008).

Individual series of tree-ring widths commonly exhibit an ontogenetic (i.e., nonclimatic) trend that is subject to elimination prior to construction of an actual tree-ring chronology (i.e., a mean series of all individual series) (Fritts, 1976). An empirically designed detrending approach was applied in this study to remove the nonclimatic variations from the tree-ring series, with tuning to account for paleoecological information on the nonclimatic changes in the trend shape. We thus determined the reference curve that was derived as an ontogenetic mean of all series (details in GSA Data Repository Eq. DR4<sup>1</sup>). This curve was modeled by a modified negative exponential formula with a concavity value assigned based on the level of the mean concavity of a high number of trees of the same period. Thus, the tree-ring indices were derived as ratios between the observed and reference values, and the chronology was averaged to produce annual values of mean indices. The nonclimatic trends therefore were removed from the individual series using an approach resembling the regional curve standardization (Briffa et al., 1996), with the exception that the concavity of the growth trend was adjusted for the past changes in the pine population density in the study region.

Site- and time-independent sensitivity of pine tree-ring indices in the region to mid-summer temperatures has been demonstrated elsewhere (Lindholm et al., 1995; Helama et al., 2004, 2009a; Macias et al., 2004). Here, the obtained chronology was calibrated against the instrumental climate data from a nearby weather station of Karasjok to transform the tree-ring indices into estimates of summer temperatures (see Table DR3 [footnote 1]).

Reconstruction of sunspot numbers was available in decadal resolution from the early Holocene (Solanki et al., 2004). Following Solanki et al. (2004), this reconstruction was spliced with the decadal averaged group sunspot number record based on telescopic observations (Hoyt and Schatten, 1998). In addition, prior to solar-climate comparisons, the temperature reconstruction was subsampled to similar (nonoverlapping decadal) time blocks. Recent studies have emphasized the importance of two distinct timescale-dependent modes of variations, those acting on 1000 yr and 2500 yr scales, in studying the history of the Sun's activity and the Holocene climate around the North Atlantic (Nederbragt and Thurow, 2005; Debret

<sup>1</sup>GSA Data Repository item 2010107, Mathematical methods, is available at <http://www.geosociety.org/pubs/ft2010.htm> or by request to [editing@geosociety.org](mailto:editing@geosociety.org).

et al., 2007). The variations on these scales were of special interest here and were isolated from the original records using band-pass filtering that resulted in the element series of millennial and bimillennial modes of variability. These timescale-dependent elements of the reconstructions of temperatures (this study) and sunspots (Solanki et al., 2004) were correlated for lags of 0 to 400 yr (where sunspots increasingly predate temperatures).

## RESULTS

### Paleoclimate Reconstruction

The reconstruction accounts for more than 40% of the total observed climate variability and more than 90% of the low-frequency variability over the instrumental period (Fig. 2). The new paleoclimatic record evidenced highly fluctuating temperatures through the mid and late Holocene times (Fig. 3A). A periodic character was evident for a number of temperature frequencies on centennial and multicentennial scales but not on millennial timescales (Fig. 4). This would indicate that variations on similar timescales are at best quasiperiodic. We note that the significant spectral peaks at centennial and bicentennial scales are very similar to those peaks recorded previously in records of solar activity (Beer, 2000; Ogurtsov et al., 2002; de Jager, 2005).

The lowest frequencies of the temperature fluctuations showed notable correlation to the Denton-Karlén oscillation of the major Holocene glacier expansions in Alaska and Scandinavia, showing two major advances between ~1600 and 500 BCE and 1500 and 1916 CE and a more subtle expansion between 4600 and 3700 BCE (Denton and Karlén, 1973) (Fig. 3B). This information shows that the long-term minima in reconstructed temperatures were broadly coterminous to these glacier maxima; moreover, the climatic coolings during the two major advances appeared more severe than the relative cooling during the less intense glacier expansion. Assuming that these glacial maxima are linkable to climatic coolings (Denton and Karlén, 1973) and that the low-frequency climatic changes are especially well archived in the past variations of mountain snowlines (Broecker, 2001), the described proxy consistency (Fig. 3B) would imply that the reconstruction probably captured much of the appreciable signals of paleoclimatic events on millennial scales. The Denton-Karlén coolings have previously been associated with lake-level fluctuations near the Alps (Magny, 1993) and large-scale climate events imprinted in Greenland ice core evidence (O'Brien et al., 1995),

which in turn were coupled to climate-sensitive sedimentary variations off California (Nederbragt and Thurow, 2005). Because of these findings, it is suggested that the reconstructed low-frequency temperature variations may actually represent climatic changes that prevailed over considerably wide spatial scales.

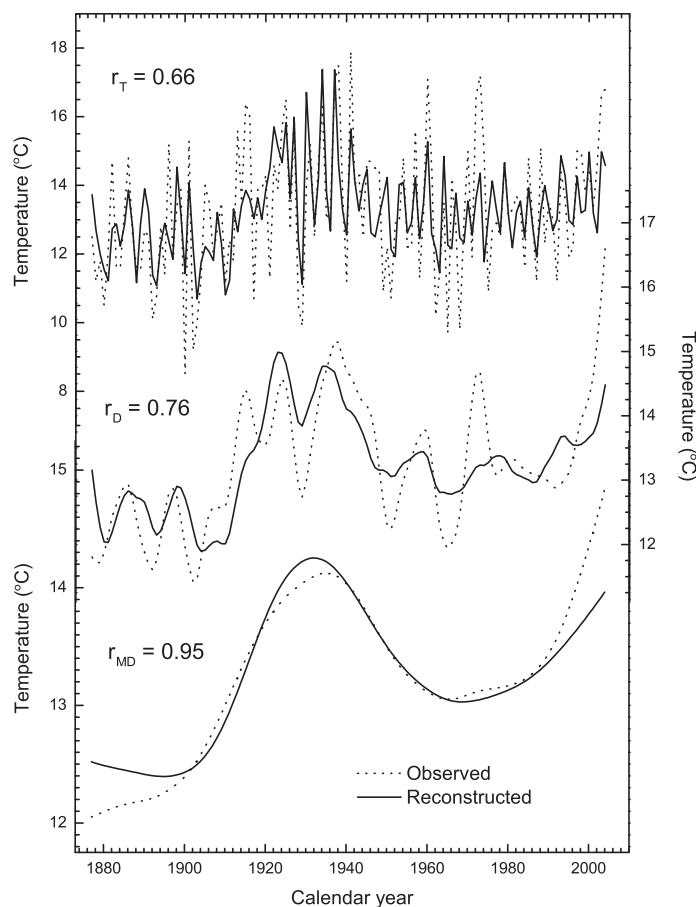
### Sunspots and Climate Variations

We statistically quantified the potentially timescale-dependent association between sunspots and climate. First, a millennial band-pass filtering revealed a clear correlation over the mid Holocene on bimillennial timescales (Fig. 5A). These results agreed with previous findings indicating a solar-climate connection at similar timescales (Bray, 1968, 1971, 1972; Denton and Karlén, 1973; Magny, 1993, 2004; O'Brien et al., 1995; Nederbragt and Thurow, 2005). Moreover, the level of correlation quanti-

fied the degree of this association. The correlation appeared strongest within the 0–30 yr lag (Fig. 6A), indicating instant forcing or at least forcing without a noticeable lag. Secondly, the two records show a notable positive correlation on millennial timescales (Fig. 5B). The highest synchrony between the records was found when the temperature record lagged 60–80 yr behind the sunspots (Fig. 6B). Furthermore, this association was strongest over the past two millennia (this study, 1 CE onwards), at the same time that the bimillennial association was indefinite.

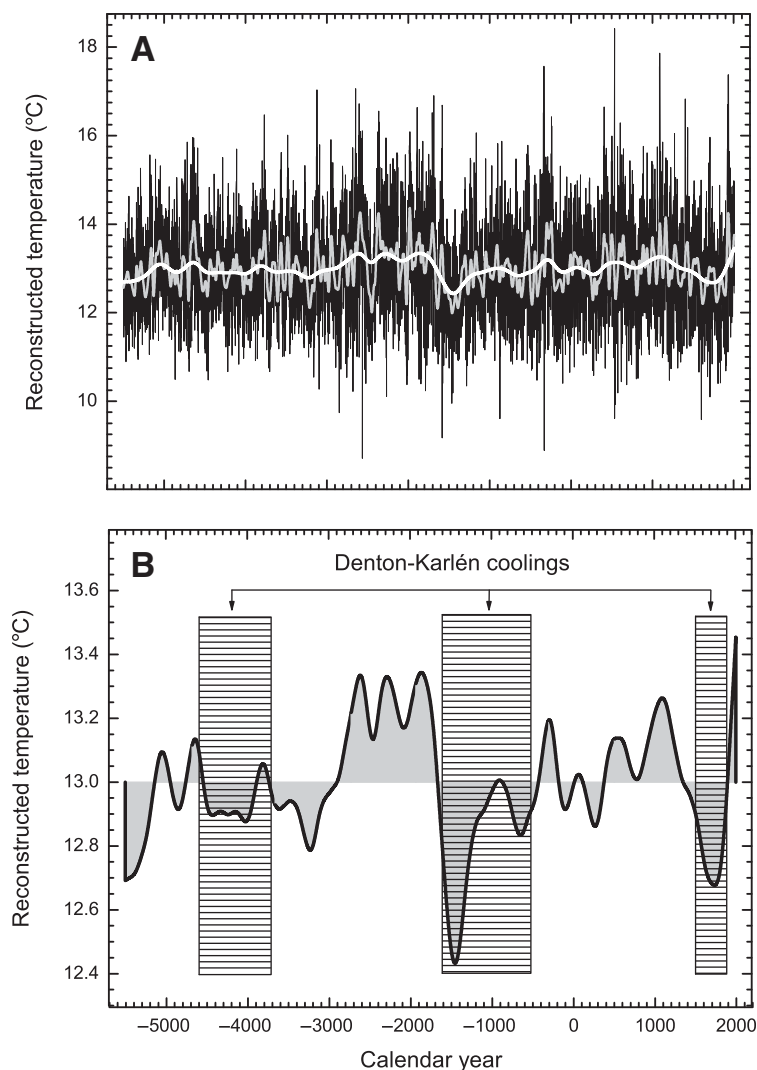
## DISCUSSION AND IMPLICATIONS

Using the tree-ring data set from high-latitude subarctic Europe, we reconstructed the temperature variations of summer climate for a large part of the present interglacial, from 5500 BCE to present. In doing so, we identified periodic and quasiperiodic variations on different timescales.



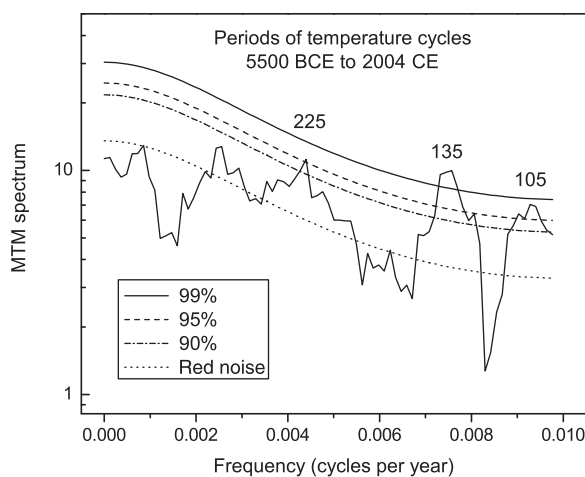
**Figure 2. Climate-proxy associations. Visual and statistical (coefficient of correlation,  $r$ ) comparison of observed and reconstructed temperatures over the common period (1877–2004 CE) for total ( $r_T$ ), decadal ( $r_D$ , 10 yr spline), and multidecadal variability ( $r_{MD}$ , 50 yr spline).**





**Figure 3. Reconstructed temperatures (5500 BCE to 2004 CE). (A) Temperatures are depicted for total variability (black line), multidecadal (gray line), and multicentennial (white line) variations. (B) Comparison of the multicentennial component of the reconstructed temperature variability (black line) and the Denton-Karlén coolings (shaded area).**

**Figure 4. Spectral characteristics of reconstructed temperature. Spectrum was estimated by the multi-taper method (MTM; Ghil et al., 2002; details in Fig. DR1 [see footnote 1]). The estimated red-noise background and the associated significance levels are shown by the smooth curves. Seven signals at the centennial to bicentennial timescales are significant at the 95% level and are shown as their estimated periodicities in years.**

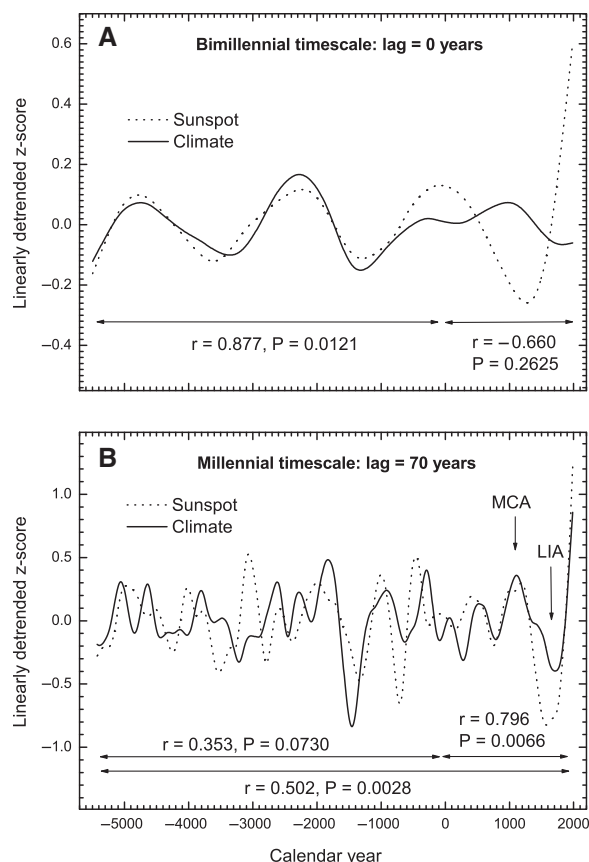


Statistically significant spectral peaks, suggesting solar forcing, were detected on multidecadal and multicentennial scales. Regarding the millennial scales, no variations with a strictly periodic character were discovered. This finding points to a conclusion that quasiperiodic variability rather than spectral peaks of statistical significance may actually be typical for such variations, as depicted in paleoclimatic records (Wunsch, 2000). Alternative to the potentially oversimplified view (Bond et al., 1997, 2001) of the Holocene climate as punctuated by a rough 1500 yr cyclicity, we are here reinterpreting the Sun-climate relationships as involving several timescale-dependent modes of their own genesis, as suggested elsewhere (Nederbragt and Thurow, 2005; Debret et al., 2007).

### Multiple Suborbital Timescales

Assessments of anthropogenic climate change and its agents necessitate correct interpretation of natural climate instability. Both solar radiation and oceanic circulation have been proposed to drive this instability, through glacial and interglacial times, with ramifications in anthropogenic climate trends. Previous studies have shown terrestrial evidence for the Holocene paleoclimatic proxy variations of millennial and bimillennial scales (Bray, 1968, 1971, 1972; Denton and Karlén, 1973; Magny, 1993, 2004; O'Brien et al., 1995; Hu et al., 2003; Nederbragt and Thurow, 2005; Debret et al., 2007; Mangini et al., 2007). Chronological uncertainties in paleoclimatic records have, however, so far left the geological correlations ambiguous. Compared to the previously mentioned studies, the present approach benefited from comparisons of solar and climate records both originating from tree rings, thus enabling correlation analysis without dating imprecisions. Moreover, the tree-ring variability was reliably transformed into temperature variations, further quantifying the time- and timescale-dependent evaluation of the existence and magnitude of potential solar forcing on climate. A statistically confident linkage between the reconstructed sunspot numbers and summer temperatures was identified separately on millennial and bimillennial timescales. Furthermore, we showed that the relative importance of these two timescale-dependent modes of variability changed from the mid to late Holocene because the forcing on bimillennial scales appeared stronger during the mid Holocene (this study, 5500–1 BCE); on the other hand, the millennial scale forcing was more pronounced during the late Holocene (this study, 1–1990 CE). In addition, we demonstrated that the two timescale-dependent forcing modes

**Figure 5. Sunspot-climate associations. Visual and statistical (Pearson correlation,  $r$ ) comparison of the bimillennial (A) and millennial (B) components of sunspot and temperature reconstructions over the mid (this study, 5500–1 BCE) and late (this study, 1–1990 CE) Holocene. Intervals of Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) are shown by downward arrows.**



showed differentiated lag structures. Thus, we argue that solar forcing has influenced the Holocene climate fluctuations differently on several suborbital timescales (Bray, 1972; Nederbragt and Thurow, 2005; Debret et al., 2007).

#### Medieval Climate Anomaly and the Little Ice Age

We hypothesize that the timescale-dependence of the solar-climate correlations may have been best exemplified over the past two millennia during the multicentennial temperature anomalies known as the Medieval Warm Period (Lamb, 1965) or the Medieval Climate Anomaly (MCA; Stine, 1994) and Little Ice Age (LIA; Grove, 2004). This became evident because the late Holocene showed a discrepancy between the proxies on bimillennial scales that culminated around the twelfth and thirteenth centuries CE (Fig. 5A). The low sunspot number at the bimillennial scales over this period contrasted with the warming of temperatures over the same interval. Evidently, this shows that the bimillennial scale of sunspots could not contribute markedly to the MCA. However, the high temperatures during the MCA are known to be partly explained by the medieval

solar maximum (Jirikowic and Damon, 1994). We quantify here that the warmth of the MCA could instead be reproduced by the millennial-scale sunspots but not using sunspot variability of bimillennial timescales. Likewise, the subsequent cooling during the LIA, recorded by our reconstruction and over large areas of Europe as well as the Northern Hemisphere (Denton and Karlén, 1973; Bradley and Jones, 1993; Nesje and Dahl, 2003; Grove, 2004; Matthews and Briffa, 2005), coincided particularly well with the transient low in millennial-scale sunspot numbers. We showed that the interval of the severest cooling was centered at the seventeenth century A.D., synchronously with the millennial-scale sunspot minimum, whereas on bimillennial scales, the solar activity was already in a transient low during the early fourteenth century. Thus, it could not be ruled out that the bimillennial solar activity minima may instead have contributed to the 1300–1450 MCA-LIA transition (Trouet et al., 2009).

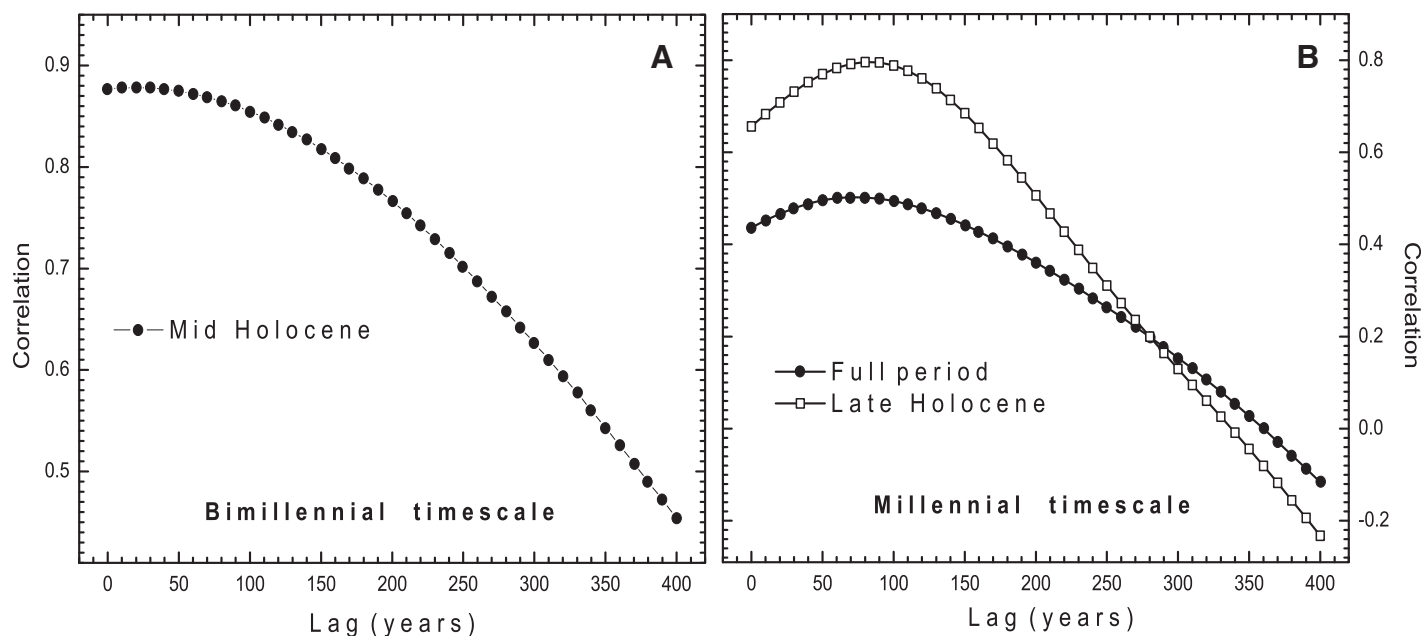
#### Denton-Karlén Coolings

We further discuss the paleoclimatic results with regard to the Denton-Karlén coolings (Denton and Karlén, 1973). Several previous

studies have associated these coolings with solar activity variations because the coolings as well as the evidence from  $\Delta^{14}\text{C}$  in tree rings both indicate qualitative coherence on a 2000–3000 yr scale through much of the present interglacial (Denton and Karlén, 1973; Magny, 1993, 2004; O'Brien et al., 1995; Nederbragt and Thurow, 2005). Our results greatly detailed this view with an indication that the mid Holocene Denton-Karlén coolings were coherent with bimillennial sunspot variability but with millennial variability during the late Holocene. An advanced explanation of these coolings and their origins could thus be proposed. Given that the Denton-Karlén coolings are related to long-period solar activity minima, we argue that they may actually result from a mixture of millennial and bimillennial timescales of solar activity variations.

#### Oceanic and Atmospheric Pathways of Solar Signal

A time lag of 60 to 80 yr, with the temperatures lagging behind the sunspots, yielded the best agreement between the solar and climate proxies on millennial scales. However, no clear lag was found for the bimillennial forcing. Our results thus suggest that the Sun's past activity changes have likely invoked climatic variations in subarctic Europe via complex pathways. The near century-long lag between the solar and climatic proxies is in accordance with previous findings that have suggested lags of similar duration over the North Atlantic sector as inferred from paleorecords (Mangini et al., 2007; Swindles et al., 2007). Furthermore, the lag structure we found is strikingly similar to that shown by Mangini et al. (2007), who reconstructed the climate variability for the Central Alps over the past 9000 yr as derived from the oxygen isotopes of stalagmites. They observed maximal solar-climate correlations with a lag of 74 yr for timescales centered on millennial variability ( $r = 0.89$ , band-pass filtering of 900–1100 yr), and a shorter lag of 45 yr for scales centered on bimillennial variability ( $r = 0.76$ , band-pass filtering of 1150–3000 yr). The similarity of the lags between their study and our analyses supports the credibility of the results. In addition, these findings hint at the possibility that oceanic factors may have acted as mediators between Sun's output and Earth's climate (Mangini et al., 2007). These results augment the view that the Holocene climate has undergone independent millennial and bimillennial variations and suggest that the climatic pathways and their physical mechanisms could actually be dissimilar, as indeed proposed previously (Nederbragt and Thurow, 2005; Debret et al., 2007).



**Figure 6. Sunspot-climate lags.** Correlations between the timescale-dependent components of bimillennial (A) and millennial (B) modes in sunspot and temperature reconstructions for lags (i.e., sunspots predating temperatures) of 0 to 400 yr.

As suggested, solar activity changes through the Holocene could have driven the advection of cooler surface waters southward and eastward in the subpolar North Atlantic, influencing the production of North Atlantic deep water. This idea was originally suggested by the varying concentrations of the Holocene IRD, thus providing a putative thermohaline, circulation-related, amplifying mechanism of transmitted solar signals to the global climate system (Bond et al., 2001). Moreover, paleoclimatic simulations have targeted quantifying the suggested role of the paleoceanographic changes on the Holocene fluctuations of climate (Goosse and Renssen, 2004; Weber et al., 2004; Renssen et al., 2006; Emile-Geay et al., 2007). The models forced by historical sea surface temperatures have provided evidence that the North Atlantic climate variation may to some degree originate from the equatorial Pacific (Hoerling et al., 2001; Emile-Geay et al., 2007). Recently, Emile-Geay et al. (2007) proposed that wind patterns needed to produce the Holocene IRD events could actually be driven by the El Niño–Southern Oscillation (ENSO) because the El Niño–like conditions could promote northeasterly winds and ocean circulation over the North Atlantic. On shorter scales, at least, the thermohaline circulation can be associated with the variations in the sea surface temperature patterns in the North Atlantic (Latif et al., 2004; Knight et al., 2005), known as the Atlantic Multidecadal Oscillation (AMO; Kerr, 2000). According to Dima and Lohmann

(2007), also the AMO could be explained by a causal relation between the Atlantic and Pacific regions, however, by an amplifier role played by the North Pacific basin.

Alternatively, it has been shown that the solar forcing may have influenced the hemispheric and regional temperatures during the pre-industrial era due to atmospheric mechanisms by changing tropospheric-stratospheric as well as latitudinal temperature gradients (Shindell et al., 2001). According to Bond et al. (2001), the atmospheric mechanism could not explain the ice-drafting on the multicentennial to millennial timescales, at least not over the past millennium. Interestingly, we showed that the period of the past two millennia was the specific point at which the bimillennial mode of solar forcing greatly dissipated and the millennial mode became more important. Thus, we are confident to suggest, in accordance with the difference in the lag structure, a relatively greater importance of the oceanic component for the millennial than for the bimillennial mode of natural instability. Our suggestion appears consistent with the paleoceanographic evidence indicating North Atlantic origins for the MCA and LIA climate conditions over the adjacent continents (Keigwin, 1996; Bianchi and McCave, 1999; deMenocal et al., 2000; Andersson et al., 2003; Sicre et al., 2008; Helama et al., 2009c), with considerable ENSO influence on the European climate during the MCA (Helama et al., 2009b). In fact, Hughes and Diaz (1994) already posited

the importance of ocean-atmosphere interactions in producing the anomalous climate conditions during the MCA.

### Implications for Future Climates

Regardless of the physical mechanisms of the described forcing, our new evidence suggests that low-frequency solar activity changes could have had a notable influence on interglacial climates, an association that could hold in the future. Here, the multidecadal and/or subcentennial delay in climatic response to sunspots was detected. It is clear that this delay provides important implications for the ongoing climate trends and future climate scenarios. Particularly, the Sun has remained highly active over the twentieth century and especially since 1940 CE. This episode is actually among the most notable features of solar behavior in the Holocene context. During the preceding centuries and millennia, the level of the Sun's activity remained variable, thus the recent episode in the solar activity is not only anomalously high but also the high level of activity has lasted for an unusually long period of time. During the past 11 millennia, the number of sunspots averages 28.7, whereas since 1940 CE, the average has reached an anomalous number of 75 per decade (Solanki et al., 2004). This anomalous episode is expected to contribute to the modern-era rise of temperature trends. In fact, according to Solanki and Krivova (2003), the solar variability could have contributed to



the global temperature changes, at decadal and longer times, over about the past 150 yr. Moreover, they obtained particularly high correlation between the records of solar activity and temperature using a response time of 11 yr. However, since 1970 CE, the rise of temperatures has occurred more rapidly than expected purely by solar quantities; accordingly, the conclusion that the Sun likely could have contributed less than 30% of the global warming since that date was drawn in that study (Solanki and Krivova, 2003). In this context it is vital to notice that although the solar activity has recently been anomalously high, there has occurred a secondary decline in the activity since the end of the 1980s and that it appears that the Sun has returned to a state that last prevailed in the 1920s CE (Lockwood, 2009). In addition, it has been predicted that the Sun's highly active state will unlikely continue during the ongoing century (Solanki et al., 2004; Ogurtsov, 2005). Consequently, the trends in solar forcing and global temperatures are currently oppositely directed (Lockwood and Fröhlich, 2007, 2008). However, the aforementioned implications have been drawn from studies delving into short-period solar forcing (Solanki and Krivova, 2003; Lockwood and Fröhlich, 2007, 2008), whereas our results show the primary evidence of long-timescale solar forcing, the essential component of which is the twentieth-century episode of solar activity. Physically, the response times tend to be longer when the periodicity of the variation is longer (Lockwood, 2008). Moreover, the time needed for climate to respond to anomalously high solar forcing sets the amount of warming that the Earth is committed to in the future (Lockwood, 2008). The multidecadal and/or subcentennial delay in climatic response to this forcing detected in this study indicates that the Sun's influence on climate due to the twentieth-century episode of anomalously high sunspot numbers may not yet have manifested itself fully in climate trends, but that the temperatures may continue to rise more than expected due to the contemporary level of solar forcing and even if greenhouse gas abundances were stabilized. Consequently, if neglected in climate models and projections, this particular lag could be anticipated to cause an underestimation of twenty-first-century warming trends.

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