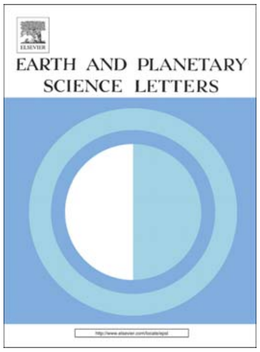

Multi-decadal climate cycles controlled by the periodic reversals of solar magnetic field polarity

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Multi-decadal climate cycles controlled by the periodic reversals of solar magnetic field polarity

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Abstract

[1] The linkage between multi-decadal climate variability and activity of the sun has been long debated based upon observational evidence from a large number of instrumental and proxy records. It is difficult to evaluate the exact role of each of solar parameters on climate change since instrumentally measured solar related parameters such as Total Solar irradiance (TSI), Ultra Violet (UV), solar wind and Galactic Cosmic Rays (GCRs) fluxes are more or less synchronized and only extend back for several decades. Here we report tree-ring carbon-14 based record of eleven-year / twenty-two year solar cycles during the Maunder Minimum (17th century) and the early Medeival Maximum Period (9-10th century) to reconstruct the state of the sun and the flux of incoming GCRs. The result strongly indicates that the influence of solar cycles on climate is persistent beyond the period after instrumental observations were initiated. We find that the actual lengths of solar cycles vary depending on the status of long-term solar activity, and that periodicity of the surface air temperatures are also changing synchronously. Temperature variations over the twenty-two-year cycles seem, in general, to be more significant than those associated with the eleven-year cycle and in particular the case around the grand solar minima such as the Maunder

Minimum (1645-1715AD). The polarity dependence of cooling events found in this study suggests that the GCRs can not be excluded from the possible drivers of decadal to multi-decadal climate change.

Keywords: solar cycle, cosmic ray, climate change

1. Introduction

[2] The role and exact extent of natural and anthropogenic forcing for the climate evolution has being under much debated and one of the major sources of external forcing can be through solar variability. As is well summarized by Hoyt and Schatten (1997), several meteorological phenomena, such as temperature variations, cloud coverage, frequency of lightning strikes, and droughts, seem to be responding to solar variables over a wide range of time scales such as the 27-day solar rotation period, 11-year activity cycle, 22-year polarity reversal cycle and the other longer quasi cyclic periods. Although the most straightforward mechanism of the sun-climate connection is the direct heating of the earth by solar radiation, it is unlikely that the entire solar influence on climate can be attributed simply to the variation of TSI (Foukal et al., 2004, 2006). For example, the present maximum estimate for the possible TSI change during the

last a few centuries (Lean, 2000) can not explain the whole magnitude of estimated solar influence on Northern Hemisphere temperature change (as is listed in (Jansen et al., 2007)) unless there are significant positive feedbacks in the climate system. Other major possible mechanisms could include solar ultraviolet radiation which promotes the chemical reaction in the upper atmosphere (Hood, 1986; Hood and Soukharev, 2003) and the galactic cosmic rays which could promote cloud formation (Svensmark, 2007). Most of these parameters, however, are well synchronized over the last several decades and do not appear to be a significant factor in climate change.

[3] Decadal to millennial scale variations in the surface temperature of the earth can be obtained through proxy records. Millennial scale global and northern hemispheric temperatures have been reconstructed by calibrating the tree-ring growth rate with the instrumental record for the last century (e.g. Mann, Bradley and Hughes, 1999). Borehole temperature records have also provided a direct history of the heat budget of the earth (Huang et al., 2000; Goto et al., 2005). Although some discrepancies are remained among the various reconstructions, the overall consistency of the records indicates that the earth experienced both

cold and warm periods. These include the Little Ice Age (LIA) between the 14th and the 19th centuries and the so called Medieval Warm Period (MWP) around the 9th to the 12th century. The history of solar activity, on the other hand, has been investigated through cosmogenic radionuclides, such as carbon-14 and beryllium-10, embedded in the tree-rings and ice cores for decadal (Beer et al., 1998) and centennial changes (Stuiver and Braziunas, 1989; Stuiver and Quay, 1980; Usoskin, et al., 2004). The reconstructed records show that the sun has gone through several prolonged activity minima as well as maxima roughly in sync with the cold and warm spells such as the LIA and the MWP (Stuiver and Braziunas, 1989; Eddy, 1976), although it is still difficult to evaluate solar variations quantitatively. The patterns of climate and solar variations are similar, but the global warming trend has not leveled off during the last a few decades when the activity of the sun has peaked (Lockwood and Fröhlich, 2007), pointing that the anthropogenic greenhouse gasses is the major factor responsible for the global warming.

[4] The sunspot numbers since the prolonged sunspot minimum occurred 1645-1715 AD so called the Maunder Minimum (Eddy, 1976) indicate gradual

increasing trend in addition to the ~88 year quasi periodicity. Solanki et al. (2004) concluded that the sun is currently experiencing one of the most active periods over the past 8000 years as estimated from thousand year long records of carbon-14 dated tree-rings. However, the original interpretation by Solanki et al. is strongly model dependent (Muscheler et al., 2005) and there is a discrepancy with the long-term trend in beryllium-10 from a Greenland ice core (Vonmoos et al., 2006). The difficulty of interpreting the carbon-14 data is partly due to the complexity of the global carbon cycle. This is particularly true for the period since anthropogenic CO2 has been released to the atmosphere and for which instrumental climate records are available. Therefore, careful evaluation of long term and high resolution carbon-14 records are necessary to understand possible sun-climate linkages especially from GCRs flux variations.

[5] Here we examine the relationship between the sun and climate by measuring the carbon-14 content in tree-rings with annual time resolution. The GCR flux and hence the activity level of the Sun can be monitored by carbon-14. Our particular focus is around the period of the Maunder Minimum and the early Medieval Maximum Period (EMMP) in the 9-10th century. Sunspot numbers and

the activity levels of the sun gradually change in time with quasi cycles of about 11-years (Schwabe cycle). The polarity of the solar intrinsic magnetic field, which is more or less a simple dipole at every activity minima, reverses at every activity maximum. It changes the track of protons, the positively charged main constituent of GCRs, due to the spirally expanding interplanetary magnetic field formed by solar wind (Kota and Jokipii, 1983) and hence changes the attenuation level of GCRs in the heliosphere. Bulk of the GCRs comes from the polar region of the heliosphere when the polarity of the Sun is positive, while GCRs come from the horizontal direction when negative. The attenuation of GCRs in the heliosphere is, therefore, more sensitive when the polarity is negative to the intensity of solar magnetic field and the tilt angle of the current sheets which expand horizontal direction. Thus the variation of the GCR flux on the earth has a “22-year” cyclic component, and will be transferred to the variations in carbon-14. Although the magnitude of the variations of carbon-14 is strongly attenuated through the carbon cycle after being produced by the GCRs in the atmosphere (Siegenthaler and Beer, 1988), carbon-14 in tree-rings preserve the information on the variations in solar cycles and the magnetic dipole polarity of the sun. Therefore, the variability of the “11-year” solar cycle in association with the century-scale variations of solar activity can be monitored to asses its influence on climate.

[6] The lengths of sunspot periods have been modulated by a few years since the 11-year sunspot cycle was firstly found by Schwabe (1843). The maximum range observed so far is ~9 to ~14 years, but most of the cycles fit in ~10-12 years with the overall average being 11 years. However, we have previously found a change in average cycle length during the Maunder Minimum ((Miyahara et al., 2004); see Supplementary Figure S1). The sunspots were scarce through 1645-1715 AD due to the anomalous weakening of the magnetic activity at this time, yet the carbon-14 abundances show the appearance of significant cyclic changes in magnetic activity. The average length of the cycles through the 70 years was about 14-years with the 28-year period of magnetic polarity reversals. The relationship between the cycle length of the “11-year” variation in sunspots and its magnitude has been investigated in several papers (Clough, 1905; Solanki et al., 2002; Rogers et al., 2006). A consistent feature is the inverse correlation between cycle amplitudes and cycle lengths that maybe related to the change of the meridional flows inside the convection zone of the

sun (Hathaway et al., 2003).

2. Results

[7] Our new annual carbon-14 data for the EMMP not only confirm this relationship but also provide some important insights on the state of solar activity during this period. Figure 1 shows the signal of solar cycles detected in the carbon-14 data and Figure 2-a shows the frequency analysis of the data, showing the change in solar cycles and their amplitude. The power spectrum remarkably indicates a 9-year cyclicity (+/-1 for the 68% confidence level against the high-frequency noise (<3 yrs)) through 880-960 AD, together with an 18-year period of solar polarity reversals. The overall significances of the two signals are 3 sigma and 2.7 sigma, respectively. The length of the eleven-year solar cycle is ~2 years shorter than that observed for the last 150 years, and ~5 years shorter than those during the Maunder Minimum. The difference of solar cycle lengths between the two characteristic solar dynamo events confirms that the cycle length of the “11-year” sunspot cycle generally has an inverse correlation with the intensity of magnetic activity. Also, the relationships in temperature and the cycle lengths during the time in the Maunder Minimum and EMMP, as is inverse

correlation between solar cycle lengths and temperatures, do not contradict to the result by Friis-Christensen and Svensmark (1997). And more importantly, it suggests that the level of solar activity during the EMMP might have been stronger than present as is opposed to the previous study that the current Sun is in an anomalously active state (Solanki et al., 2004), though the relations between solar cycle length and activities need further investigations.

[8] The fact that the average solar cycle lengths can change over centennial time-scales enables us to distinguish the influence of the “11-year” and “22-year” solar cycles from other, multi-decadal time scale, peculiar internal cycles of climate change. One such process is the decadal oceanic circulation which could also cause changes in atmospheric temperatures with similar time scales (Moore et al., 2006). We have obtained frequency spectra of temperature anomalies during the Maunder Minimum and the EMMP by wavelet analyses in order to compare the states of climate variations during the times when the actual solar cycle length was ~14 years and ~9 years, respectively. Figure 2-b shows the power spectrum of the temperature variations for 880-960 AD (Esper et al., 2002), and figure 3 shows the spectrum of temperatures during 1500-1900

AD. Temperatures show significant ~19-year cycles during 880-960AD (+/-1 for the 90 % confidence level), whereas ~29-year cycle is seen around 1645-1715 AD (+/-1 for the 95 % confidence level). Each period is close to the lengths of the "22-year" solar cycle during the time, and can be attributed to solar variations. The signal of the "22-year" cycle seems to be dominant when the activity of the sun is relatively low. The "22-year" cycle is also seen at the beginning of the 18th century, corresponding to the Dalton Minimum (1800-1820 AD). The periodicity of temperatures is ~25 years (+/-1 for the 99 % confidence level), and again near to the actual length of the "22-year" solar cycle during this period. Such amplified appearance of the "22-year" cycle at the grand solar minima is also seen in the reconstructed temperature by Mann, Bradley and Hughes (1999) (see Supplementary Figure S2). The "22-year" cycle of solar polarity reversals is not apparent in solar irradiative outputs, and strongly affects only to the modulation factor of GCRs consisting mainly of protons, and hence these "22-year" cycles can be assumed to be related to GCRs. The prominent signal of stretched "22-year" cycles during the Maunder Minimum is also detected in the reconstructed sea surface salinity with a time lag of several years to decade (see Supplementary Figure S3), suggesting that the anomalous variation of atmospheric temperature caused by solar cycle eventually affect the oceanic circulation.

[9] Further detailed analysis of our carbon-14 data provides additional multi-decadal features of the influence of GCRs on climate. It has been suggested by Jokipii (1991) that the modulation of GCRs in the heliosphere depends on the level of solar activity resulting in the difference in GCR variations between the present period and the grand solar minima (Figure 4). During the “normal” state as in the recent decades, the flux of GCRs keeps relatively higher intensity when solar polarity is positive since the GCRs are less sensitive to the intensity of solar magnetic field during the time, resulting in a component of “22-year” variability in the GCRs. However, the relationship between the relative intensity of GCRs and the polarity is inverted during the prolonged inactive periods of the sun as is indicated as the “Maunder Minimum mode” in Figure 4. The flux could be relatively higher when the solar polarity is negative at this mode because the possibly more flattened current sheet could gather the GCRs from the horizontal direction. The variation of temperatures around the Maunder Minimum shows exactly the same behavior and strongly suggests that the GCRs

affect the climate on decadal to multi-decadal time scales. Reconstructed solar cycle and solar magnetic polarity using carbon-14 record by Stuiver et al. (1998) and the oxygen isotope records from a Greenland ice core (Vinther et al., 2003) for 1600-1780 AD are plotted together with group sunspot numbers (Hoyt and Schatten, 1998) in Figure 5-a and 5-b. The solar cycles have been obtained by filtering the carbon-14 content by Stuiver et al. (1998) with the bandwidth of 8-18 years. The measurement errors are smaller than our carbon-14 record (Miyahara et al., 2004), but the short-term variations of the two carbon-14 records are consistent each other (Miyahara et al., 2007). We have used oxygen-18 in ice core data as a climate proxy instead of the dendro-climatology data since the oxygen data better preserves the detail in annual variations. The rapid cooling as indicated as the sharp drop in delta oxygen-18 by ~2 permil can be seen just around the “11-year” solar minima at solar polarity negative during the Maunder Minimum, indicating an apparent “22-year” cycle in temperature variations. On the other hand, large decline in delta oxygen-18 occurs when the polarity is positive before and after the Maunder Minimum. The transitions into /out from the “Normal Mode (colder event at polarity positive)” to/from the ”Maunder Minimum mode (colder event at polarity negative)” are resulting in the appearance of significant “11-year” cycle in temperature variations. The correlation coefficient of carbon-14 (considering 2-yr lag in the carbon cycle) and dendro-data with the “22-year” solar cycle band during EMMP (band-width: 16-20 years) is -0.71, which implies drops in temperature correspond to the period when higher GCRs flux is observed. The features of solar forcing on climate found in this study can be schematically described as shown in Figure 6 where ⊗t represents the changing length of the “11-year” cycle, which tends to

be longer at the Maunder Minimum mode. The wavelet spectra of temperatures support this proposition showing a significant signal of 11-year period only around the transition time getting into / out of the Maunder Minimum (Figure 3).

3. Discussion

[10] It is often difficult to assess the influence of decadal time scale variation of solar activity on climate, and to distinguish which of solar parameters are mediating the sun-climate relationship, however, the record of solar cycle back to 1200 years extended by the annual resolution carbon-14 content in tree-rings has enabled us to find the persistent influence of solar eleven-year / twenty-two-year cycles on climate even during the Maunder Minimum; the period

of prolonged sunspot absence. The extended/shortened solar cycles during the Maunder Minimum and the EMMP respectively are detected in climate variations, indicating that climate cycles of decadal time scales are probably solar origin. The significant “22-year” cycles in climate suggest the importance of the property of solar magnetic field as a driver of climate probably through GCRs. Since the “11-year” cycles appearing at the transition times of the two climate modes are originated in the phase shift of the “22-year” cycle, they are not related to the actual amplitude of the 11-year cycle in solar activity itself. The component of the “22-year” cycle in climate seems to be enhanced as the level of the long-term activity of the sun decreases as can be explained by the nature of GCRs, and thus, it can be concluded that the sun has a nature that could acts more as the driver of decadal to multi-decadal time scale climate change as its activity is suppressed. For the further analyses, more records with 1-yr time resolution well retaining the high frequency signals (less than decadal variation) are needed. The mediums of sun-climate relationship for the other time scales are yet unsolved important question.

[11] The 9-year solar cycle through the EMMP might be suggesting that the sun

was more active than the recent centuries. The rapid global warming of the 20th century appears to have exceeded the level that can be explained by the increased solar activity. Reconstructions of climate during the EMMP with high time-resolution, high precision and high spatial resolution are urgently needed to compare the states of climate during EMMP and present and to deepen the knowledge about the effect of anthropogenic and natural causes on the global warming.

Methods

The record of carbon-14 content for the medieval maximum period was obtained using a ~2000 year-old Japanese cedar tree (Cryptomeria Japonica) taken at the Yakushima Island in Japan (30.18 N, 130.30 E). For the measurements of carbon-14 content in annual rings with absolute date, dendro-chronology has been applied. The dated rings were separated carefully and washed using (1) HCl solution (70 deg. C), (2) NaOH solution (70 deg. C) and (3) NaClO2/HCl solution (75 deg. C) to extract cellulose from every tree-ring sample. The cellulose samples were combusted and converted to graphite on Fe powder by hydrogen reduction. The graphite samples were introduced to Accelerator Mass

Spectrometer (AMS) to measure the ^{14}C/^{12}C and ^{13}C/^{12}C ratios. We have used HVEE AMS at Nagoya University in Japan (Nakamura et al., 2000), which achieves accuracy of 0.3 permil. The $\otimes^{14}$C was calculated according to the method by Stuiver and Polach (1977).

Acknowledgments

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Figure caption

Figure 1. Newly obtained carbon-14 record around the early Medieval Maximum Period. (a) The raw data with Intcal04 (Reimer et al., 2004) and (b) the high-pass filtered data (<35 years; gray line) and the band-pass filtered variation (8-35 years; black line).

Figure 2. Wavelet spectra of (a) the carbon-14 content and (b) the temperature anomaly (Esper et al., 2002) around the early Medieval Maximum Period. The dashed lines correspond to 9 and 18 years. The spectrum outside of the black curve has less reliability due to the nature of the analysis.

Figure 3. Wavelet spectrum of the reconstructed temperature for 1500-1900 AD (Esper et al., 2002). The dashed lines correspond to 11 and 22 years.

Figure 4. Two modes of GCRs modulation (for 1GeV protons); the normal mode and the Maunder Minimum mode (lower; Based on (Jokipii, 1991)), against the sunspot activity (upper). The dotted line of the lower panel is the typical GCRs

variation at the time of normal (intense) solar activity; while the solid line is the assumable GCR variation at the Grand Solar Minima. Note that the solar polarity changes every solar cycle at sunspot maximum.

Figure 5. Solar cycle and magnetic polarity during the Maunder Minimum reconstructed by the carbon-14 content by Stuiver et al. (1998) (a, upper) and the reconstructed temperatures by oxygen-18 (b, upper (Vinther et al., 2003)), both together with the group sunspot numbers (lower, (Hoyt and Schatten, 1998)). The shades indicate the periods when higher intensity of GCRs in 22-years are expected as shown in Figure 4; when the polarity is positive before/after the Maunder Minimum (red), and when the polarity is negative during the Maunder Minimum (blue).

Figure 6. Schematic description of the response of climate to solar activity and the polarity. Sunspot cycle (a) and the two modes of climate change; the Normal mode (b) and the Maunder Minimum mode (c). The lowest panel (d) shows the transition time from (b) to (c). ⊗t is the period of one solar cycle at any given time.

Supplemental materials

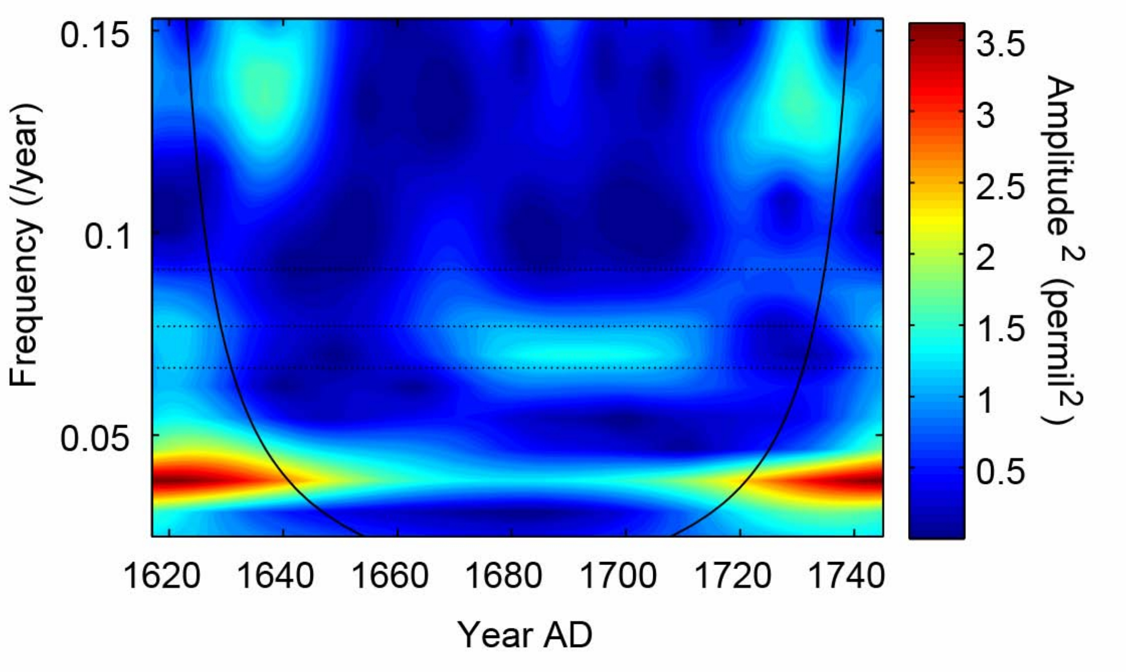


Fig. S1. Wavelet spectrum of the carbon-14 content in tree-rings around the Maunder Minimum (1645-1715 AD) (after (Miyahara et al., 2004)). The dotted lines correspond to 11, 13 and 15 years respectively. The spectrum outside of the solid line has less reliability.

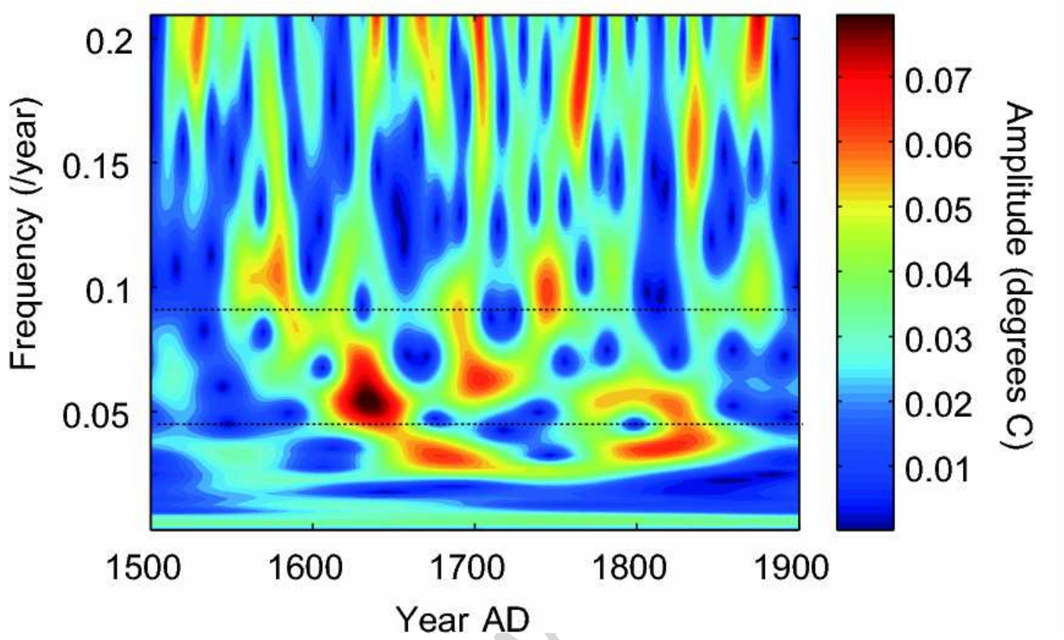


Fig. S2. Wavelet spectrum of the reconstructed northern hemisphere temperature for 1500-1900 AD (Mann, Bradley and Hughes, 1999). The dotted lines correspond to 11 and 22 years respectively. Stretched “22-year” cycles are detected around the Maunder (1645-1715 AD) and the Dalton (1800-1820 AD) grand solar minima.

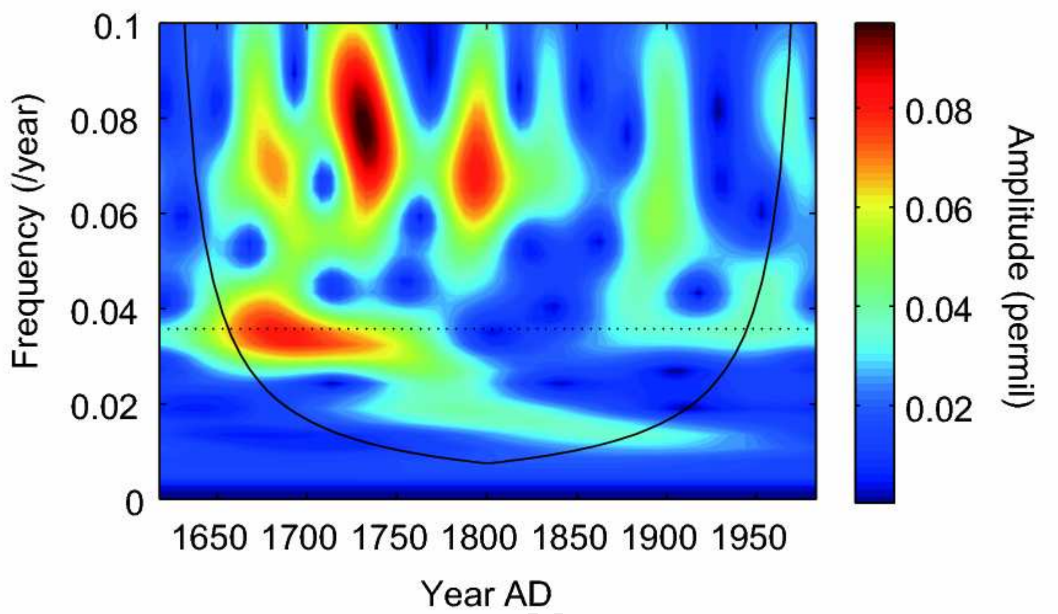


Fig. S3. Wavelet spectrum of the sea surface salinity deduced from oxygen-18 (Hendy et al., 2002). The dotted line corresponds to 28 years. The period of ~28 years, consistent with the length of solar “22-year” cycle during the Maunder Minimum, is detected around 1660-1730 AD.

Reference

39. Hendy, E. J. et al., 2002. Abrupt decrease in tropical pacific sea surface salinity at end of Little Ice Age. *Science*, **295**, 1511-1514.

Fig 1

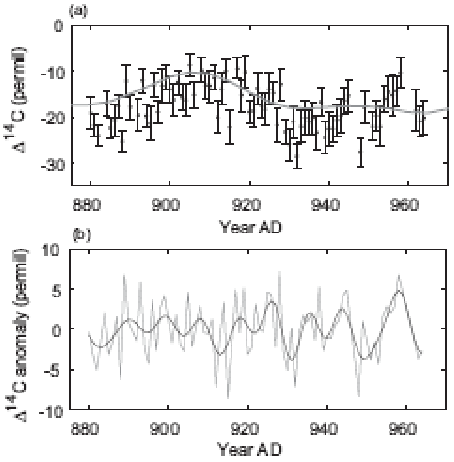

(a)
Δ^{14}C (permil)
0
-10
-20
-30
880
900
920
940
960
Year AD
(b)
Δ^{14}C anomaly (permil)
10
5
0
-5
-10
880
900
920
940
960
Year AD

Fig 2

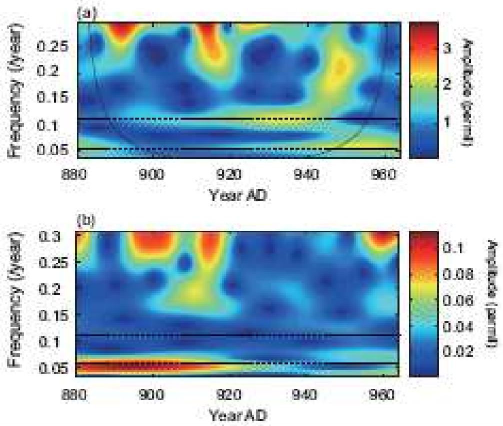

(a)
Frequency (/year)
0.25
0.2
0.15
0.1
0.05
880
900
920
940
960
Year AD
Amplitude (permil)
3
2
1
(b)
Frequency (/year)
0.3
0.25
0.2
0.15
0.1
0.05
880
900
920
940
960
Year AD
Amplitude (permil)
0.1
0.08
0.06
0.04
0.02

Fig 3

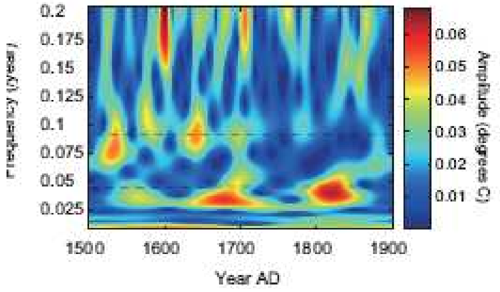

0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
Frequency (year)
1500
1600
1700
1800
1900
Year AD
0.06
0.05
0.04
0.03
0.02
0.01
Amplitude (degrees C)

Fig 4

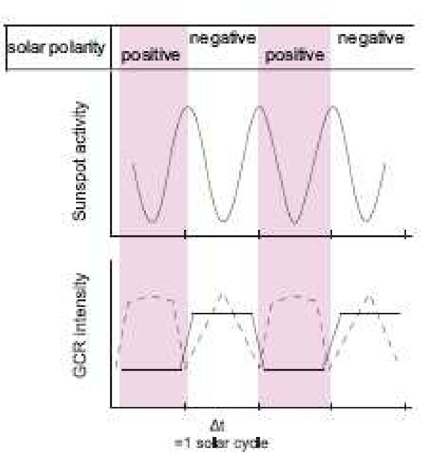

solar polarity
positive
negative
positive
negative
Sunspot activity
GCR intensity
Δt
=1 solar cycle

Fig 5

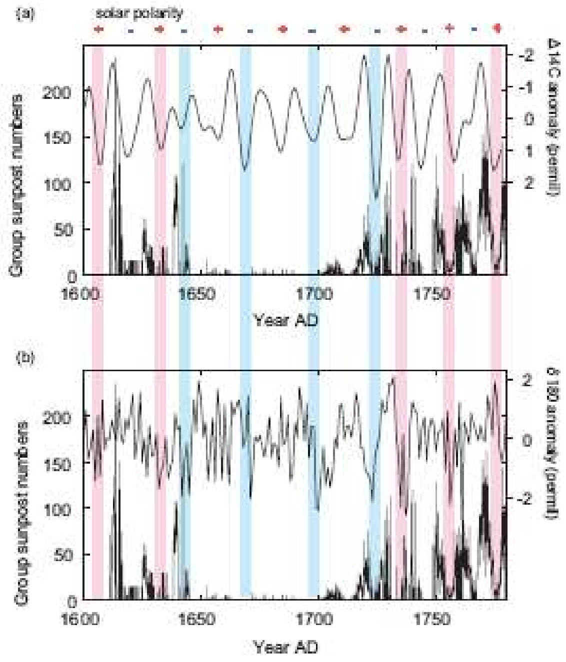
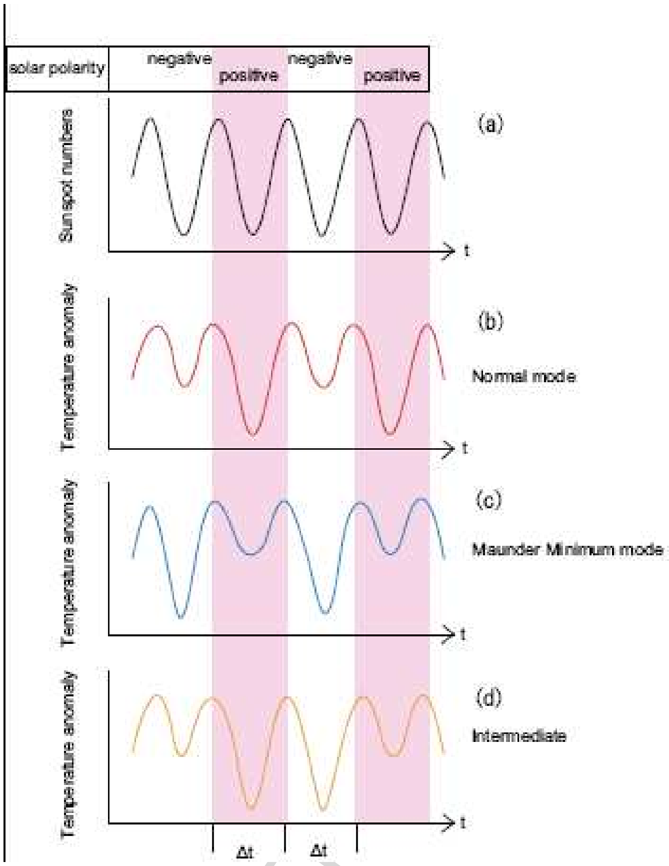

(a)
solar polarity
+ - + - + - + - + - + - + - +
Group sunpost numbers
0
50
100
150
200
1600
1650
1700
1750
Year AD
Δ14C anomaly (permil)
-2
-1
0
1
2
(b)
Group sunpost numbers
0
50
100
150
200
1600
1650
1700
1750
Year AD
δ 18O anomaly (permil)
2
0
-2

Fig 6


solar polarity
negative
positive
negative
positive
Sun spot numbers
(a)
t
Temperature anomaly
(b)
Normal mode
t
Temperature anomaly
(c)
Maunder Minimum mode
t
Temperature anomaly
(d)
Intermediate
t
Δt
Δt