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A Note on Solar Cycle Length During the Medieval Climate Anomaly

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Abstract The growing interest in the Medieval Climate Anomaly (MCA) and its possible link to anomalous solar activity has prompted new reconstructions of solar activity based on cosmogenic radionuclides. However, these proxies do not sufficiently constrain the total solar irradiance (TSI) range and are often defined at low temporal resolution, inadequate to infer the solar-cycle length (SCL). We have reconstructed the SCL (average duration of 10.72 ± 0.20 years) during the MCA using observations of naked-eye sunspot and aurora sightings. The solar activity was probably not exceptionally intense, supporting the view that internal variability of the coupled ocean–atmosphere system was the main driver of the MCA.

Keywords Solar activity · Medieval Climate Anomaly · Solar cycle length · Climatic system variability

1. Introduction

The two most important climate events of the last millennium, the Medieval Climate Anomaly (MCA: AD 1000 – 1300) and the Little Ice Age (LIA: AD 1350 – 1850), have been linked to relatively prolonged anomalous activity of the Sun, namely the Medieval Solar Maximum (Jirikowic and Damon, 1994) during the twelfth and thirteenth centuries and the Maunder Minimum (Eddy, 1976) between the mid-seventeenth and early eighteenth centuries.

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An increasing number of proxies have become available in the last two decades, allowing a growing number of more robust paleoclimate reconstructions and modelling studies for the last millennium (Mann *et al.*, 2009). Several possible mechanisms responsible for these two major climate events have been suggested, including external forcing factors (*e.g.* changes in solar output or volcanism) and internal variability of the coupled ocean–atmosphere system, *e.g.* North Atlantic Oscillation (Trouet *et al.*, 2009) and El Niño–Southern Oscillation (Cobb *et al.*, 2003). Nevertheless, solar activity has long been assumed to have played the most relevant role during the late Holocene Epoch, particularly in establishing the contrast between the MCA and LIA periods (Díaz *et al.*, 2011).

The most common proxies of solar activity are those relative to cosmogenic radionuclides ^{10}Be and ^{14}C, which are produced by cosmic rays in the Earth's atmosphere (Usoskin, 2008). These proxies do not sufficiently constrain the total solar irradiance (TSI) range, and additionally are often defined with low temporal resolution (decadal), inadequate to infer the accurate solar-cycle length (SCL). However high-resolution proxy data of solar activity have became available through the compilation of ancient observations of naked-eye sunspot and aurora sightings recorded with fairly precise dates (Vaquero and Vázquez, 2009). Here, we explore this topic, using the annual number of naked-eye sunspot observations (NE) and the annual number of auroras (NA) observed during the period AD 1000 – 1300.

2. MCA and Solar Proxies

Our knowledge of solar activity around the MCA period (AD 1000 – 1300) associated with both types of solar proxies is summarised in Figure 1. The black lines show two different reconstructions of the TSI based on ^{10}Be and ^{14}C records (Steinhilber, Beer, and Fröhlich, 2009; Vieira *et al.*, 2011). We have used the NE series constructed by Vaquero, Gallego, and García (2002) with updated records from Korean sources (Lee *et al.*, 2004). For NA we have used the well-known dataset developed by Křivský and Pejml (1988) that has been updated by the National Geophysical Data Center (NOAA). The total number of NE and NA events accounted for in these two datasets for the period considered in Figure 1 is 50 and 246, respectively. We note the capacity revealed by both NE and NA series to reproduce the long-term variability of solar activity throughout the entire millennium (Vaquero and Vázquez, 2009).

These solar proxies show that the main phase of the MCA corresponds to a period with moderate-to-high solar magnetic-activity levels in comparison with the modern grand maximum, being delimited by two grand minima episodes, the Oort Minimum (AD 1010 – 1070) and the Wolf Minimum (AD 1270 – 1340), respectively. Moreover, both reconstructions present four local maxima of TSI during the MCA with an approximate 50-year periodicity. The high-resolution solar proxies NE and NA (blue and orange lines in Figure 1) also show an active period clustered between the Oort and Wolf Minima.

3. Results

We have estimated the timings of 11-year solar cycle maxima using the relative maxima of both proxies (as shown by the blue and orange arrows in Figure 1). We have looked for the local maxima in the NE and NA series to detect maxima of the 11-year solar cycle during the MCA. Although both time series have very high temporal resolution (*i.e.* day, month, year), we have used only the annual frequency of NE and NA to infer the annual

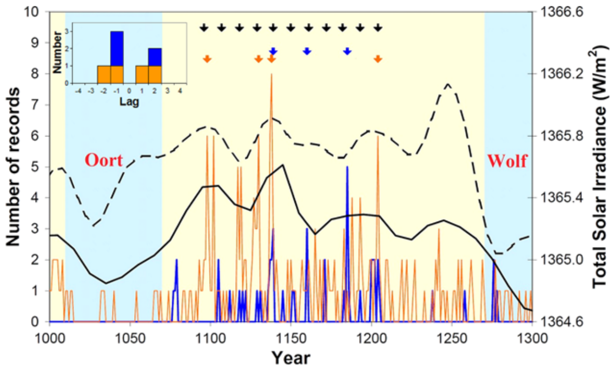
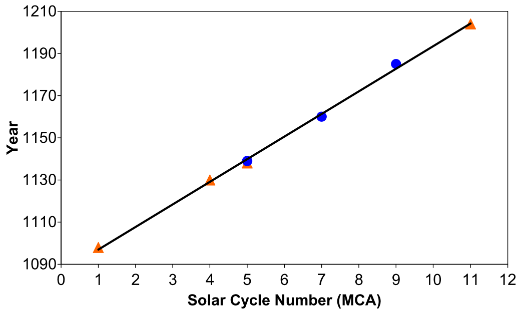


Figure 1 Different solar activity proxies during the period 1050 – 1300: TSI reconstructed by Steinhilber, Beer, and Fröhlich (2009) (dashed black line), TSI reconstructed by Vieira *et al.* (2011) (continuous black line), annual number of naked-eye observations of sunspots (Vaquero, Gallego, and García, 2002) (blue line), and annual number of auroral nights (Křivský and Pejml, 1988) (orange line). Black arrows are evenly spaced and correspond to our estimated maxima of solar cycle derived from the linear fit represented in Figure 2. Arrows correspond to estimated maxima of solar cycle using naked-eye observations (blue) and auroral nights sightings (orange). Inset shows, using the same colour code, a histogram of the delays (in years) between the fitted and estimated maxima of solar cycle.

Figure 2 Years of estimated solar cycle maxima from NA (orange triangles) and NE (blue circles) series *versus* solar cycle number during Medieval Climate Anomaly.



level of activity. Using the period 1050 – 1300, the annual average values of NA and NE are, respectively, 0.892 (1.287) and 0.199 (0.607), where the number in parentheses indicates the standard deviation. Afterwards, we considered a local maximum of the two series whenever the peak value exceeded the mean value plus three standard deviations, *i.e.* 4.753 and 2.019 for NA and NE, respectively. These maxima were dated in the following years: (NE) AD 1139, 1160, and 1185; (NA) AD 1098, 1130, 1138, and 1204. Interestingly, Miyahara (2010) estimated independently, based on annual-resolution measurements of a ^{14}C record from tree rings, the years AD 1098, 1131, and 1140, dates that fall close to our estimations of solar maxima.

We have computed the coefficients of linear relationships between the dates of solar cycle maxima and the solar cycle number (Figure 2). In this representation the slope value represents the mean value of the solar cycle, 10.61 ± 0.21, 11.50 ± 0.58 for the NA and NE time series, respectively, and 10.72 ± 0.20 years when both series are merged. These values represent the estimation of mean SCL for ten consecutive solar cycles (110 years approximately) between 1095 and 1204. The black arrows in Figure 1 represent our theoretical ≈ 11-year solar-cycle maxima. The embedded plot depicts a histogram of the delays

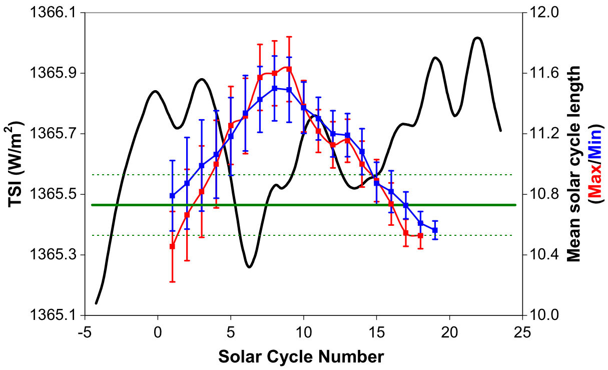


Figure 3 Evolution of mean SCL during the last three centuries using (red) max to max or (blue) min to min estimations. Each value represents the estimation of mean SCL for ten consecutive solar cycles (110 years approximately), and the error bars the corresponding standard error. Black line represents the TSI from Steinhilber, Beer, and Fröhlich (2009). Green line shows our estimation of mean SCL during MCA including the standard error (dashed lines).

(in years) between the mean value from the linear fit and direct measured peak position, respectively, i.e. the vertical distance between each point and the fitted line.

4. Discussion

We have used the same approach to compute the mean SCL for consecutive sub-periods of ten solar cycles from the late Maunder Minimum until the present (Figure 3, red line) using the well-known Group Sunspot Number (Hoyt and Schatten, 1998; Vaquero, 2007). The results show that the average SCL obtained for the period AD 1095 – 1204 is similar to the recent period AD 1870 – 1979.

Note that we are comparing results obtained without instrumental observation with telescopic observations. It would be very interesting to compare our results directly with the more recent NE observations, but, unfortunately, NE series are poor after approximately 1600 due to a change in the type of documents used. In any case, modern naked-eye observations of sunspots using filters clearly reproduce the solar cycle (see Chapter 2 in Vaquero and Vázquez, 2009).

Several methods have been proposed to define the SCL (Mursula and Ulich, 1998; Fligge, Solanki, and Beer, 1999; Benestad, 2005; Vaquero, García, and Gallego, 2006). Thus, following the more standard procedure, we have also computed the mean SCL using the time intervals from minimum to minimum (Figure 3, blue line). One can confirm from Figure 3 that there is some additional variability of SCL based on the maxima time series (red curve) compared to the analysis performed with the minima (blue curve). Unfortunately, documentary sources such as NA or NE are not sufficiently detailed to define the times of solar cycle minima.

Several studies in the last decades have focused on the relationships between solar-cycle amplitude (SCA) and solar-cycle length (SCL), *e.g.* Dicke (1978) and Hoyng (1993). Part of this growing interest has been fuelled by the forecasting potential associated with such relationships, particularly taking into account the fact that the SCL precedes the SCA. For example, Solanki *et al.* (2002) have found a simple empirical relationship between SCL and SCA using cycle-length information from the preceding solar cycles. This empirical model allows us to reproduce the SCA of a given cycle with an average error of 20 in sunspot number. However, the exact relationship might be complex and non-stationary (Solanki *et al.*, 2002; Vaquero and Trigo, 2008). In fact, the correlation between SCA and the preceding SCL is only strongly significant in a statistical sense during the first half of the historical record using the International or Wolf Sunspot Number, and it is less significant for the Group Sunspot Number (Vaquero and Trigo, 2008).

Based on the maximum (red) and minimum (blue) values of mean SCL represented in Figure 3, one can observe two clusters of low values for sub-periods of ten solar cycles just before the Dalton Minimum and during the more recent decades. Moreover, we can state that the average SCL obtained for the period AD 1095 – 1204 (green line) is similar to those of periods AD 1720 – 1829 and AD 1870 – 1979. These periods correspond to time intervals of relatively high solar activity at century scale. The minimum value of mean SCL for the last three centuries corresponds to the last sub-period (AD 1894 – 2001), which is considered as the Modern Maximum of solar activity (last value of blue curve), characterised with the highest TSI values for the last millennium (Steinhilber, Beer, and Fröhlich, 2009; Vieira *et al.*, 2011).

5. Conclusion

In conclusion, high-resolution solar proxies show a very well-defined solar cycle with a duration of 10.72 ± 0.20 years (average, AD 1095 – 1204). In this context, we can state that the solar activity during the MCA was not exceptionally anomalous, and probably neither was the corresponding TSI, assuming that the relationship between SCL and SCA established primarily for the recent cycles is universally valid for any other period of time in the past evolution of the solar cycle. This result provides further support for the rationale that either a lack of volcanic activity or the internal variability of the coupled ocean–atmosphere system was the main driver of the MCA. Moreover, contradicting results on the solar-forcing hypothesis have been published in recent years. According to the last IPCC assessment report (Jansen *et al.*, 2007), several model simulations for the last millennium do show warmer temperatures for the MCA (relative to the LIA) when forced with estimated natural forcings. However, a significant number of paleoclimatic modelling efforts do not support the idea that increased solar irradiance implies surface warming in all locations (Ammann *et al.*, 2007; Meehl *et al.*, 2009).

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