Environmental Research Communications

LETTER

Complex imprint of solar variability on tree rings

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Keywords: 14C production, Europe, solar variability, tree rings

Abstract

Many studies have investigated the role of solar variability in Holocene climate. Beyond sunspot observations, solar activity can be reconstructed from 14C in tree rings. Due to the lack of sub-decadal resolution of 14C records, these studies focused on long-term processes. In this study, we use an annually-resolved 14C record to examine solar variability (e.g. 11-year Schwabe solar cycle) and its connection to European seasonal climate inferred from tree-ring records during the entire past millennium with spectral and wavelet techniques. The 11-year Schwabe solar cycle shows a significant impact in European moisture- and temperature-sensitive tree-ring records. Complex ‘top-down’/ ‘bottom-up’ effects in the strato-tropospheric system are assumed to affect European spring and summer climate with a temporal-shift as evident from observed changes in phase behavior. Significant evidence is also found for the ~60- and ~90-year band during the first half of the past millennium.

1. Introduction

Annually resolved total ring width or maximum latewood density chronologies are powerful tools in paleoclimate studies. For the Northern Hemisphere, numerous datasets exist, mainly covering the previous one to two millennia, which provide insight into climate drivers, such as temperature and precipitation, and they can be used to study the role of internal and external climate forcing. For the latter, signals of solar variability in total ring width chronologies have been widely discussed (Douglass 1919, Hughes 1982, Rigorzo et al 2007, Breitenmoser et al 2012, Prestes et al 2018). So far, direct comparison to solar variability, e.g. the 11-year Schwabe solar cycle, was limited to the interval of sunspot number observations over the past ~250 years. Further back in time, cosmogenic isotopes, mainly 14C preserved in tree rings and 10Be in polar ice cores, provide the best proxies to investigate solar variability (Stuiver and Quay 1980, Solanki et al 2004, Steinhilber et al 2012, Roth and Joos 2013).

The 11-year solar cycle in cosmogenic isotopes was resolved for 1510 CE onwards, obtained in the pioneering work of Stuiver and Braziunas (1993) on annual tree-ring 14C measurements, for AD 998–1510 in Sequoia (Eastoe et al 2019) and during the Spörer solar minimum (Fogtmann-Schulz et al 2019). Eastoe et al found indication of the 11-yr cycle between AD 1000 and 1120, but quote analytical uncertainties as limitation in analysis of this time range. The earlier interval of the Holocene was measured in decadal resolution; hence the Schwabe solar cycle could not be reconstructed, but only longer solar cycles on century scales. However, we recently extended the annual 14C dataset back to 972 CE (Brehm et al in press), enabling the variability of the open solar flux to now be reconstructed for the full previous millennium. It is employed here as reconstructed 14C production (see methods) with high production indicating low solar activity and vice versa. We note that this new 14C production record displays the activity of the Sun more precisely than the sunspot number because the 14C production on Earth is highly influenced by changes in the solar open flux, whereas the sunspot number...
record only yields information about the activity on the Sun’s surface observed visually, and solar open flux exists also during intervals of no sunspots (Owens et al 2012).

It is therefore now feasible to compare total ring width or maximum latewood density records to a \(^{14}\)C production series on annual resolution for the first time in order to derive information of an imprint of the 11-year solar cycle in tree-ring climate proxies during the past millennium.

Here we use three temperature-sensitive (Büntgen et al 2013, Esper et al 2014, Helama et al 2014) and four moisture-sensitive (Griggs et al 2007, Büntgen et al 2011, Wilson et al 2013, Land et al 2019) records from Europe over the period of annually measured \(^{14}\)C. We observe significant cross-correlation of reconstructed moisture and temperature and solar variability, both in the Schwabe solar cycle and in the \(~60\) and \(~90\)-year spectral window.

2. Methods

2.1. Tree-ring records
We used a set of seven tree-ring climate reconstruction series from Europe (figure S1 available online at stacks.iop.org/ERC/2/101003/mmedia). These records were chosen due to their geographical distribution (41–62\(^{\circ}\)N and 30\(^{\circ}\)E–1\(^{\circ}\)W), climate signal (moisture-, temperature-sensitivity), foliage of tree species (evergreen/deciduous) and length of record (from \(~2000\) CE back to at least 1089 CE). These reconstruction records are accessible via the National Oceanic and Atmospheric Administration, NOAA (https://www.ncdc.noaa.gov). Five of the reconstruction records were inferred from total ring width (TRW) data and two from wood density (MXD) measurements holding sub-annual (spring and/or summer) information. In various studies, different methods have been applied to detrend the individual tree-ring series before the final tree-ring record (chronology) was developed (such as regional curve standardization or spline function) to preserve high- to low-frequency variability (for more information regarding the standardization method applied the reader is referred to the original publications). The tree species used in the various studies range from evergreen species, for instance Pine (Pinus sylvestris) and Larch (Larix decidua), to deciduous species, for instance sessile oak (Quercus petrea) and common oak (Quercus robur). For detailed specifications see table S1.

2.2. \(^{14}\)C production
\(^{14}\)C production was calculated from the annual time series of the atmospheric \(^{14}\)C level, \(\Delta^{14}\)C, outlined in detail by (Güttler et al 2015), and expanded in (Brehm et al in press). In short, a carbon cycle box model of 22 boxes (11 for each hemisphere) is used to calculate monthly \(^{14}\)C production from the balance of \(^{14}\)C production and decay, taking into account the carbon fluxes between the carbon reservoirs, and the difference in \(^{14}\)C between annual data, interpolated at monthly intervals.

2.3. Spectral and wavelet analysis
Cross wavelet analysis has been performed with the MATLAB\(^{\circ}\) software package of Grinsted et al (2004). Cross wavelet allows for studying frequencies at different time domains, which is useful when dealing with non-stationary time series. To mitigate the influence of low frequency (>100 years) signals in the \(^{14}\)C production and the tree-ring records a 5–100-year bandpass filter was applied before cross wavelet analysis. This pre-step is necessary because the \(^{14}\)C production record and some of the tree-ring records hold very low-frequency signals tending to suppress the outcome of the cross wavelets at high–to mid-frequencies and thus the interpretation at different time-frequency domains. In the following figures the 5% significance level against red noise is indicated by a black line. Light shading shows cone of influence where edge effects may have great influence.

Additionally, the software REDFIT-X (Björg Ólafsdóttir et al 2016) was used for independent spectral analysis. REDFIT-X applies Lomb-Scargle Fourier transform for the cross-spectral analysis. A Monte Carlo approach was used to estimate the uncertainty associated with phase and coherency. The significance of the spectral content against red noise (first-order autoregressive (AR1) process) was estimated using 1,000 simulations (testing against a proper null hypothesis). The REDFIT-X analysis was performed with the original and unfiltered records as presented in the figures 2(c)–(f) and figure S2.

Applying both methods (cross wavelet and REDFIT-X) ensure for independent interpretation of the results and avoid misinterpretation of spurious behavior.

3. Results and discussion

The datasets used are presented in detail in the methods section and in table S1 and their locations illustrated in figure S1.
In tree-ring research non-climatic growth trends in individual tree-ring series are usually removed by various techniques which often eliminate low frequency, century-scale signals. Hence, here we focus on a spectral window of 5 to 100 years.

We start by analyzing the spectral frequency domains of the $^{14}$C production and in the tree-ring record from the Main Region in southern Germany (Land et al. 2019) which has been shown to be highly correlated to local precipitation. As the spectral properties of all time series used cannot be assumed to be stationary, we perform the continuous wavelet transform for $^{14}$C production (figure 1(a)) and for the precipitation reconstruction of the Main Region (figure 1(b)) using the Grinsted et al. (2004) toolbox.

As expected for cosmogenic isotopes, significant spectral power is found in $^{14}$C production in the 11-year band as well as high spectral power for 60 and 90 years (figures 1(a), 2(f)). However, the continuous wavelet transform exhibits multiple periods in which the solar signal fades out partly during grand minima of the Schwabe solar cycle during the past millennium. These minima are centered at $\sim$1030 CE (Oort), $\sim$1310 CE (Wolf), $\sim$1470 CE (Spörer), $\sim$1680 CE (Maunder) and $\sim$1810 CE (Dalton). The continuous wavelet transform shows high power on the $\sim$60-year frequency domain until $\sim$1500 CE but appears highly significant only in the second half of the 18th century. The $\sim$90-year frequency band is inherent in the $^{14}$C production record (except of the 15th and 16th century). In the continuous wavelet transform of the precipitation reconstruction of the Main Region (figure 1(b)) the spectral power on the decadal range is wider (8–20 years), including the Schwabe solar cycle, and quite similar to $^{14}$C production in the 60-year band. The REDFIT-X analyses confirm these results (figure 2(e)).

When these two records are compared via cross wavelet transform (figure 2(a)) common power for the Schwabe solar cycle between both records is significantly evident and absent only in some intervals of several decades. The independent analysis with REDFIT-X confirms this result (figure 2(c)) with high cross power at 12.6, 14.1 and 56.4-years.

The same conclusion is offered from the visual comparison of the two records, separated in two bandpass regimes, 5–30 and 30–100 years respectively (figure S5). In the 5–30-year band, dominated by the Schwabe solar cycle in $^{14}$C production, we observe that the Main Region precipitation record is either synchronous to inverted solar activity, or slightly delayed by 2.4 years (Main Region precipitation record appears later on the non-lagged time scale). We note that some temporal offsets between the precipitation record and $^{14}$C production could result from $^{14}$C measurement uncertainties, which lead to a standard deviation of the definition of year of $^{14}$C production minima/maxima by ca. 2 years (for more details the reader is referred to Brehm et al. in press). On the longer bandwidth window, the precipitation record signal appears strongly anti-correlated to solar activity, even in the trend of the amplitudes.

The discussion thus far has focused on the precipitation record of the Main Region (southern Germany). We arrive at similar conclusions when regarding other published tree-ring chronologies in Europe (figures 3(a)–(f), figure S1–4, table S1).
Once again the Schwabe solar cycle is seen in most of these tree-ring records (figure S2–3) with high cross power to the $^{14}$C production (figure 3). The two temperature records of Finnish Lakeland and Northern Europe show the weakest Schwabe solar cycle signal, whereas the temperature record of Eastern Europe equals the Schwabe solar cycle signal of the used precipitation records. Strong common power also exists for the 60- and 90-year bands (except North Aegean) during the first half of the millennium, showing higher common power for the temperature records than for the precipitation records (figure 3, figure S2).

One more measure is given by the cross coherence, a close analogue to the correlation coefficient. The cross coherence of $^{14}$C production and all tree-ring records used are provided in figure 2(b), S2, S4.

Significant spectral coherences between $^{14}$C production and tree-ring records in the ~11-year frequency band appear scattered during the past millennium (figure 2(b), figure S4) and thus is only significantly expressed for the records Main Region, Central Europe, North Aegean, Eastern Europe and Northern Europe (figure 2(b),
This finding is independent of the sensitivity type (moisture-, temperature-sensitivity) of the tree-ring records or the geographical location.

What could be the cause(s) of a solar imprint to tree growth in Europe? There are many studies, both based on observations (Hood et al 2013, Dorado Liñán et al 2015, Czymzik et al 2016, Turner et al 2016, Wang et al 2017, Laurenz et al 2019) and modelling (Shindell 1999, Scaife et al 2013, Kodera et al 2016, Yukimoto et al 2017) which examine a link between solar variability and (North Atlantic) surface climate. The ‘top-down’ link caused by stratospheric ozone variation between solar minima and maxima onto North Atlantic tropospheric circulation (Kodera and Kuroda 2005, Gray et al 2010, Thiéblemont et al 2015) including blocking at mid latitudes (Moffa-Sánchez et al 2014, Woollings et al 2018) and the delayed response of North Atlantic sea surface temperature to changing atmosphere-ocean heat fluxes (Gray et al 2016, Wang et al 2019) are discussed as potential mechanisms. On the other hand, Chiodo et al (2019) showed that the 11-year solar cycle has no significant influence on the North Atlantic Oscillation, and thus a possible link coupling solar signals and surface climate variability through ‘bottom-up’ effects (e.g. Zhou et al 2018, Frederick et al 2019) seem to be also likely mechanisms, which receive increasing attention. These mechanisms involve cosmic ray flux and solar wind magnetic field, among others, affecting the current flow in the global electric circuit and subsequently influence the weather and climate by electric-cloud microphysics at high but also down to lower latitudes (for detailed explanations see Lam and Tinsley 2016, Frederick et al 2019 and references therein). Nevertheless, the complex response of tropospheric clouds to solar activity (like solar wind and cosmic rays) may account for the 11-year solar cycle in the tree-ring records continuing also during solar minima as well as the intermittency of the found correlations.

There is a complex interplay between purely atmospheric responses at zero lag and slowly changing sea surface temperature, leading to delay of several years (Scaife et al 2013). In Laurenz et al (2019) it is observed that for the past 115 years precipitation in Central and Western Europe is most significantly influenced by solar variability, and that the solar influenced zone of rainfall in June and July in Europe migrates from Britain via Germany into SE Europe. Similarly, Zanchettin et al (2008) find correlations between Po river discharge and regional precipitation in the Po plain with solar variability and North Atlantic Oscillation.

4. Conclusions

Most previous studies focused on solar influence on North Atlantic winter climate or long-term solar variability on Earth’s climate due to missing annually resolved $^{14}$C records. For the first time European tree-ring records and $^{14}$C production, both annually-resolved, have been investigated regarding their common signals for the full past millennium. Thus, this study extends the ongoing discussion twofold: (1) the tree-ring climate proxies used

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Figure 3. Cross wavelet transform of $^{14}$C production record and European tree-ring reconstruction series. Moisture-sensitive series from a, South-central England (Wilson et al 2013), b, Central Europe (Büntgen et al 2011), c, North Aegean (northeastern Greece and northwestern Turkey, (Griggs et al 2007)) and temperature-sensitive series from d, Eastern Europe (greater Tatra region, (Büntgen et al 2013)), e, Finnish Lakeland (Helama et al 2014), f, Northern Europe (Esper et al 2014). Black line indicates significance at 5% level and light shadings for cone of influence where edge effects may have great influence.
here are sensitive to spring and/or summer climate and (2) the annual resolution of tree-ring chronologies and the reconstructed annual $^{14}$C production open the view into the spectral band of the 11-year Schwabe solar cycle.

We find significant Schwabe-cycle signals in European tree growth indicating a clear forcing of the respective regional climate by changing solar activity on this short-term timescale. However, the previously mentioned ‘top-down’/’bottom-up’ links are complex and may lead to a time delay at a specific geographical area which is finally manifested in the tree-ring records. The presented results show the complexity of the Sun-tree interaction at high-frequency variability and underlines at the same time that further studies on regional as well as on hemispheric/global scales are required to resolve the legacy of A E Douglass.

Acknowledgments

We thank Margaret Eppli for language editing. The authors declare no competing interests.

Author contributions

A L, B K and S R performed the spectral and wavelet analysis. N B and L W modelled the $^{14}$C production inferred from annual radiocarbon measurements. A L, B K, S R, N B and L W designed the research. All authors helped in discussing ideas, interpreting results and writing the paper.

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