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Solar modulation of flood frequency in Central Europe during spring and summer on inter-annual to millennial time-scales

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Abstract

Solar influences on climate variability are one of the most controversially discussed topics in climate research. We analyze solar forcing of flood frequency in Central Europe on inter-annual to millennial time-scales using daily discharge data of River Ammer (southern Germany) back to AD 1926 and revisiting the 5500 year flood layer time-series from varved sediments of the downstream Lake Ammersee. Flood frequency in the discharge record is significantly correlated to changes in solar activity during solar cycles 16–23 ($r = -0.47$, $p < 0.0001$, $n = 73$). Flood layer frequency ($n = 1501$) in the sediment record depicts distinct multi-decadal variability and significant correlations to ^{10}Be fluxes from a Greenland ice core ($r = 0.45$, $p < 0.0001$) and ^{14}C production rates ($r = 0.36$, $p < 0.0001$), proxy records of solar activity. Flood frequency is higher when solar activity is reduced. These correlations between flood frequency and solar activity might provide empirical support for the solar top-down mechanism expected to modify the mid-latitude storm tracks over Europe by model studies. A lag of flood frequency responses in the Ammer discharge record to changes in solar activity of about one to three years could be explained by a modelled ocean–atmosphere feedback delaying the atmospheric reaction to solar activity variations up to a few years.

1 Introduction

Solar forcing of climate variability is one of the most controversially discussed topics in climate research. On the one hand, numerous empirical associations between the activity of the Sun and climate variables like temperature, precipitation, atmospheric circulation, and frequency and intensity of hydrometeorological extremes indicate a solar influence on climate on regional scales (Adolphi et al., 2014; Bond et al., 2001; Fleitmann et al., 2003; Gray et al., 2010; Lockwood, 2012; Wirth et al., 2013b). On the other hand, it is assumed that the measured variations in total solar irradiance (TSI) of about 0.1 W m^{-2} are too small to substantially modify climate unless they can induce ampli-

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fying feedbacks in the climate system (IPCC, 2013). One proposed feedback is the so-called solar top-down mechanism (Gray et al., 2010; Haigh, 1996; Ineson et al., 2011; Lockwood, 2012). Larger changes in solar UV emission influence the ozone concentration, heating and circulation in the stratosphere. These disturbances are expected to modify strength and stability of the polar vortex and communicate downwards via a chain of processes that is still under investigation to influence position and strength of the tropospheric storm tracks over the North Atlantic and Europe (Gray et al., 2010; Haigh, 1996; Ineson et al., 2011; Lockwood, 2012). Under further consideration are the effects of energetic particles from the Sun and galactic cosmic rays on cloud cover and precipitation. However, their climate impact is not well understood (Gray et al., 2010; Lockwood, 2012; Svensmark and Friis-Christensen, 1997).

In addition to model studies, a way to investigate potential solar-climate linkages and their underlying mechanisms on short and long time-scales and with high temporal precision is to integrate short instrumental records and long paleoclimate proxy time-series reflecting the same type of data (Kämpf et al., 2014). Flood layers in the varved Lake Ammersee sediment record form after major River Ammer floods transporting detrital catchment material into the lake (Czymzik et al., 2010, 2013). *Flood layer frequency* has been shown to follow changes in solar activity during the last 450 years (Czymzik et al., 2010). In addition, millennial-scale shifts in *flood intensity* at Lake Ammersee are likely related to a successive reduction in Northern Hemisphere orbital summer forcing and multi-millennial solar activity variations (Czymzik et al., 2013). Aim of this study is to the investigate the instrumental River Ammer discharge record as well as meteorological data from the German Weather Service (DWD) Observatory Hohenpeißenberg in the Ammer catchment (Fig. 1) for high-frequency solar signals. The analyses focus on the period AD 1926 to 2002 and on May to August (MJJA), the flood season in the Ammer region today (Czymzik et al., 2010). For providing information on past River Ammer flood activity beyond the last 450 years, we perform novel analyses on the previously published 5500 year flood layer time-series from Lake Ammersee sediment core $AS10_{prox}$ (Fig. 1). The proximity between the Gauge Weilheim,

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recording discharge from 601 of the 709 km^2 Ammer catchment, and the downstream lake ensures comparability of the flood signals in both records (Fig. 1).

2 Material and methods

2.1 Study site

The Ammer catchment is located in the Bavarian Alpine Foreland (southern Germany), about 30 km southwest of Munich (Fig. 1). The Ammer lake/catchment setting is well suited for the investigation of flood occurrences. River Ammer has a length of 84 km and a catchment area of 709 km^2 (Fig. 1) (Mangelsdorf and Zelinka, 1973). High water tables of the moorlands in vicinity to Lake Ammersee and low water holding capacities of the alpine soils favor the translation of precipitation extremes into floods by surface discharge. The rather small catchment and steep slopes of the alpine foothills produce short but intense flood peaks (Ludwig et al., 2003). River Ammer discharge data back to AD 1926 and meteorological data from the DWD Observatory Hohenpeißenberg provide instrumental data for investigating flood occurrences and their triggering meteorology.

Lake Ammersee (48°00′ N, 11°07′ E, 533 m a.s.l.) has a surface area of 47 km^2 and a maximum water depth of 81 m (Alefs and Müller, 1999). Late moraine, flysch and molasse formations in the Ammer catchment provide abundant easy erodible detrital material for downstream transport into the gully shaped lake during a flood and the deposition of detrital "flood layers" on the lake floor (Czymzik et al., 2010). The varved nature of Lake Ammersee sediments allows dating these flood layers to the season by varve counting and the position within an annual lacustrine sedimentation cycle (Czymzik et al., 2010).

Contemporary hydroclimate in the Ammer region is characterized by varying influences of mid-latitude westerly weather regimes transporting moisture from the North Atlantic and Mediterranean into Europe and continental high-pressure cells causing

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atmospheric blocking and dryer conditions (Petrow and Merz, 2009). Mean annual precipitation in the Ammer catchment is ~ 1200 mm year^{-1}.

2.2 River Ammer discharge and meteorological data

Daily River Ammer discharge data provided by the Bavarian Environmental Agency were recorded at Gauge Weilheim (550 m a.s.l.), located about 10 km upstream of Lake Ammersee (Fig. 1). Meteorology related to River Ammer floods was investigated using daily sea level pressure (SLP) and precipitation data from the Meteorological Observatory Hohenpeißenberg (977 m a.s.l.), located in the Ammer catchment (Fig. 1) (Hohenpeißenberg station level air pressure was transferred to SLP within the EMULATE project). The analyses focus on the period AD 1926–2002 and on May to August (MJJA). To link the instrumental discharge and meteorological records to floods as represented by the Lake Ammersee flood layer record, time-series were calculated by counting days in MJJA with the lowest 5 and 10 % Hohenpeißenberg SLP (low SLP anomalies) and highest 5 and 10 % River Ammer discharges (River Ammer floods) and Hohenpeißenberg precipitation amounts (precipitation events). Two threshold levels were chosen to extract more complete time-series of major meteorological and discharge events varying substantially in length and magnitude. To reduce the effects of short-term variations and better distinguish climate signals, all indices were filtered with a 5 year running mean. Time-dependent contributions to the variance in the River Ammer flood, low SLP anomaly and precipitation event time-series were isolated applying spectral analysis on the smoothed, detrended and normalized records (Ghil et al., 2002). To reduce further short-term noise, the spectra were filtered using a Daniell smoother (3 in both directions). For investigating flood lags to solar forcing, cross-correlation was performed between the MJJA River Ammer flood record and MJJA total solar irradiance (TSI) (Lean, 2000). Before spectral analysis and cross-correlation, the MJJA River Ammer flood, Hohenpeißenberg low SLP anomaly and precipitation event records related to both threshold values were merged by averaging them.

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2.3 Lake Ammersee flood layer record

Detrital layers in the varved Lake Ammersee sediment core $AS10_{prox}$ have been previously interpreted to reflect major River Ammer floods during spring and summer by their (1) sediment microfacies indicating deposition after major surface discharge events, (2) increases in Ti evincing the terrestrial origin of the material, (3) proximal-distal deposition pattern pointing towards River Ammer as the introductory source, (4) position within an annual sediment deposition cycle and (5) calibration against instrumental River Ammer discharge data (Czymzik et al., 2010, 2013). A 30 year running window was applied to the flood layer time-series to reduce noise and emphasize multi-decadal variability. Time dependent modes of variability and their temporal significances were isolated from the flood layer time-series applying wavelet analysis (Torrence and Compo, 1998). The analysis was performed using the R software for statistical computing working with a Morlet mother wavelet.

3 Results

3.1 River Ammer flood frequency and local meteorology back to AD 1926

The frequency of MJJA River Ammer floods in the discharge record is significantly correlated to the frequency of precipitation events ($r = 0.39$, $p = 0.0007$, $n = 73$) and low SLP anomalies ($r = 0.33$, $p = 0.004$, $n = 73$) at Hohenpeißenberg during the period AD 1926–2002 (Fig. 2). All time-series depict a decadal-scale oscillatory behavior (Fig. 2). Spectral analyses on the MJJA River Ammer flood frequency, Hohenpeißenberg precipitation event and low SLP anomaly time-series quantify the length of this oscillation to about 9–12 years, significant at the 95 % level (Fig. 3).

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3.2 Flood layer frequency over the last 5500 years

Flood layers in Lake Ammersee sediment core AS10$_{prox}$ during the last 5500 years reveal distinct decadal-scale frequency fluctuations, ranging from 2 layers every 30 years to 20 layers every 30 years (Fig. 4). Mean flood layer recurrence time is 3.7 years (Fig. 4). Wavelet analysis applied to the flood layer time-series depicts low-frequency periodicities of about 90, 210 and 900–1000 years, significant at the 95 % level (Fig. 4).

4 Discussion

4.1 River Ammer floods and solar activity in the instrumental period

Comparing the frequency of MJJA River Ammer floods in the instrumental record to a monthly resolved TSI reconstruction (Lean, 2000) allows examining solar-flood correspondences at very high temporal resolution based on fixed chronologies. Interestingly, inter-annual variability in the frequency of River Ammer floods correlates (significant at the 99 % level) to changes in TSI during solar cycles 16 to 23 when the flood record lags solar activity 1 to 3 years (max. correlation at a lag of 2 years: $r = -0.47$, $p < 0.0001$, $n = 73$) (Figs. 2 and 5). The frequency of River Ammer floods is higher when TSI is reduced (Fig. 2). The temporal lag between solar activity and flood responses might be explained by a modelled ocean–atmosphere feedback (Scaife et al., 2013): solar induced variations in the North Atlantic heat budged are expected to delay the atmospheric response to solar activity variations up to a few years through the later release of previously accumulated energy to the air (Scaife et al., 2013). Further significant correlations between the frequency of MJJA River Ammer floods and the frequency of precipitation events ($r = 0.39$, $p = 0.0007$, $n = 73$) as well as low SLP anomalies at Hohenpeißenberg ($r = 0.33$, $p = 0.004$, $n = 73$) indicate an atmospheric origin of the observed solar-flood link (Fig. 2). Oscillations of 9–12 years in the MJJA River Ammer

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flood and meteorological records from Hohenpeißenberg resemble oscillations in the TSI record related to the solar cycle (Fig. 3).

4.2 Flood layer frequency and solar activity during the last 5500 years

Comparing the 5500 year flood layer frequency record to solar activity reconstructions from cosmogenic radionuclides enables investigating solar-climate linkages on long time-scales. Comparable to the last 450 years (Czymzik et al., 2010), the 5500 year flood layer frequency time-series (n = 1501, smoothed with a 30 year moving window) depicts distinct multi-decadal variations correlating to varying ^{10}Be fluxes in the GRIP ice core (Vonmoos et al., 2006) ($r = 0.45$, $p < 0.0001$) and reconstructed ^{14}C production rates (Muscheler et al., 2007) ($r = 0.36$, $p < 0.0001$) (Fig. 4). Taking modulations in geomagnetic field strength into account, both isotopes are tracers of solar activity through time (Muscheler et al., 2007; Vonmoos et al., 2006), especially on the sub-millennial time-scales (Snowball and Muscheler, 2007). Their atmospheric production rates are directly influenced by the activity of the Sun modifying heliomagnetic shielding and the flux of galactic cosmic rays to Earth's upper atmosphere forming ^{10}Be and ^{14}C by the interaction with N and O (Beer, 2000; Lal and Peters, 1967). Consequently, more radionuclides are produced when the activity of the Sun and heliomagnetic shielding is reduced (Lal and Peters, 1967). However, ^{10}Be fluxes into archives might be modified by weather induced noise and reconstructed ^{14}C production rates biased by varying exchange rates between carbon reservoirs. Nevertheless, the common production and varying deposition mechanisms allow us to infer that the shared variance between of the ^{10}Be and ^{14}C records reflects changes in solar activity (Beer, 2000; Muscheler et al., 2007). In addition to the multi-decadal variations, the flood layer frequency record depicts significant low-frequency oscillations around 90, 210 and 900–1000 years (Fig. 4). Similar spectral power was detected for the ^{14}C record and attributed to long-term solar activity changes (Damon and Sonett, 1991).

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4.3 Mechanism for a solar influence on flood frequency

Significant correlations between solar activity and the frequency of River Ammer floods on inter-annual to millennial time-scales suggest a causal relationship (Figs. 2–5). Further empirical associations between flood frequency and solar activity in records from the southern Alps and Central Spain (Moreno et al., 2008; Vaquero, 2004; Wirth et al., 2013a, b) as well as the agreement with a flood reconstruction from multiple large European rivers of the last 500 years (Glaser et al., 2010) suggest a larger spatial relevance (Central Europe) of the flood signal from the Ammer catchment.

The solar top-down mechanism is expected to modulate the characteristics of the mid-latitude storm tracks over the North Atlantic and Europe, according to model studies (Haigh, 1996; Ineson et al., 2011; Lockwood, 2012). During periods of reduced solar activity, the storm tracks are predicted to be on a more southward trajectory transporting moisture from the North Atlantic and the Mediterranean into central and southern Europe. Reduced zonal pressure gradients favor atmospheric blocking and meridional air flow (see the introduction for details) (Adolphi et al., 2014; Haigh, 1996; Ineson et al., 2011; Lockwood, 2012; Wirth et al., 2013b). A similar atmospheric pattern occurs during periods of higher River Ammer flood frequency. Periods of higher flood frequency are associated to a wave train pattern with a prominent negative center over western Europe (Rimbu et al., 2015). Therefore, the negative correlation between solar activity and River Ammer flood frequency might provide empirical support for a solar influence on hydrometeorological extremes in Central Europe via the solar top-down mechanism. However, we cannot rule out further effects of changes in TSI and/or galactic cosmic rays on River Ammer flood occurrences. The inconsistency that the solar top-down mechanism is active mainly during winter and early spring while River Ammer floods occur during late spring and summer could be reconciled by the effects of cryospheric processes as ice cover in the Barents Sea and snow in Siberia that are expected to transfer the dominant potentially solar induced winter climate signal into summer (Ogi et al., 2003).

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5 Conclusions

Integrating daily River Ammer discharge data back to AD 1926 and a 5500 year flood layer record from varved sediments of the downstream Lake Ammersee allowed deducing changes in flood frequency in Central Europe during spring and summer and their triggering mechanism on inter-annual to millennial time-scales. Flood frequency in both records is significantly correlated to changes in solar activity from the solar cycle to millennial-scale oscillations. These correlations provide empirical support for a solar influence on climate via the solar top-down mechanism expected to influence the mid-latitude storm tracks over the North Atlantic and Europe. The unexpected direct response of variations in flood frequency to changes in solar activity might suggest that the solar top-down mechanism is of particular relevance for hydroclimate extremes. In addition, River Ammer flood frequency in the instrumental record lags changes in solar activity about one to three years. This temporal lag might be explained by a modelled ocean–atmosphere feedback that delays climate reactions to changes in solar activity by a few years through buffering and later releasing solar derived energy from the North Atlantic.

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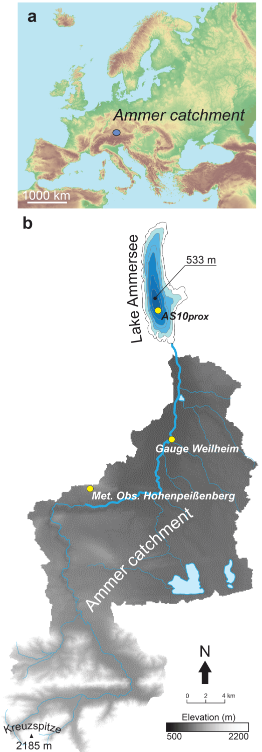

Figure 1. (a) Geographical position of the Ammer catchment. **(b)** Hydrological map of the Ammer catchment (modified after: Ludwig et al., 2003) and bathymetric map of Lake Ammersee with positions of the Gauge Weilheim, the Meteorological Observatory Hohenpeißenberg and sediment core $AS10_{prox}$.

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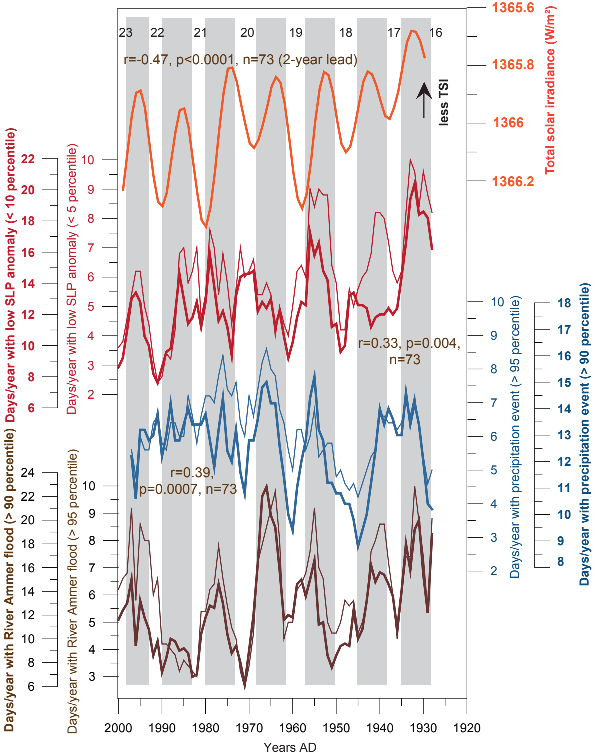

Figure 2. Correlations between low SLP anomalies at Hohenpeißenberg, precipitation events at Hohenpeißenberg, TSI during solar cycles 16–23 (Lean, 2000) and the frequency of River Ammer floods during MJJA. All datasets were filtered with a 5 year running mean, prior to calculating correlations.

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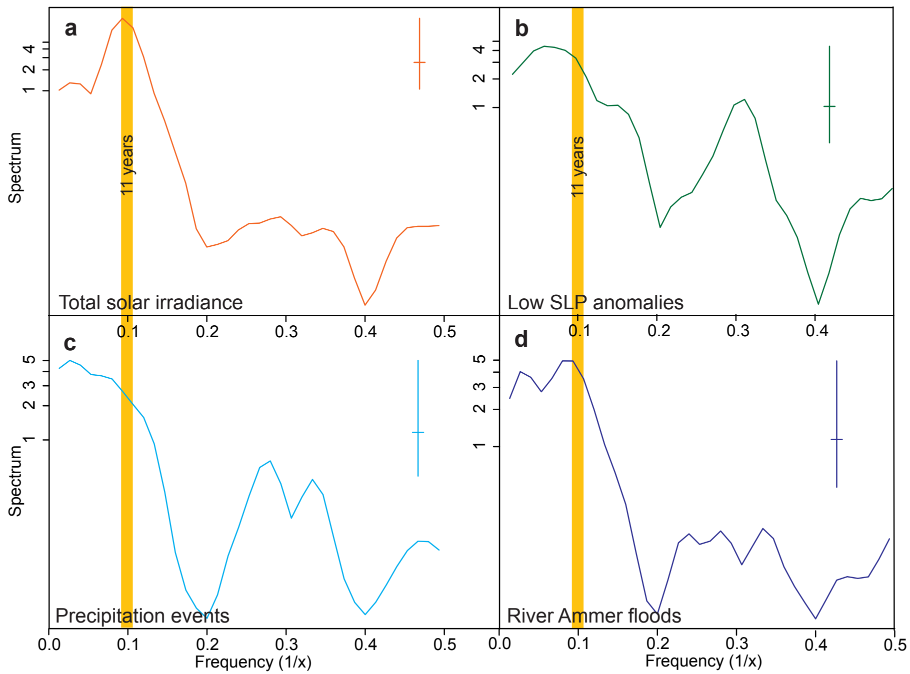

Figure 3. Spectral analyses of **(a)** total solar irradiance (Lean, 2000), the frequency of **(b)** low SLP anomalies at Hohenpeißenberg, **(c)** precipitation events Hohenpeißenberg and **(d)** River Ammer floods during MJJA in the period AD 1926 to 2002. Before the analysis, the time-series were smoothed with a 5 year running mean, detrended and normalized to the standard deviation. Crosses indicate 95 % confidence intervals. The spectra are further smoothed with a Daniell filter (3 in both directions) to reduce high-frequency noise.

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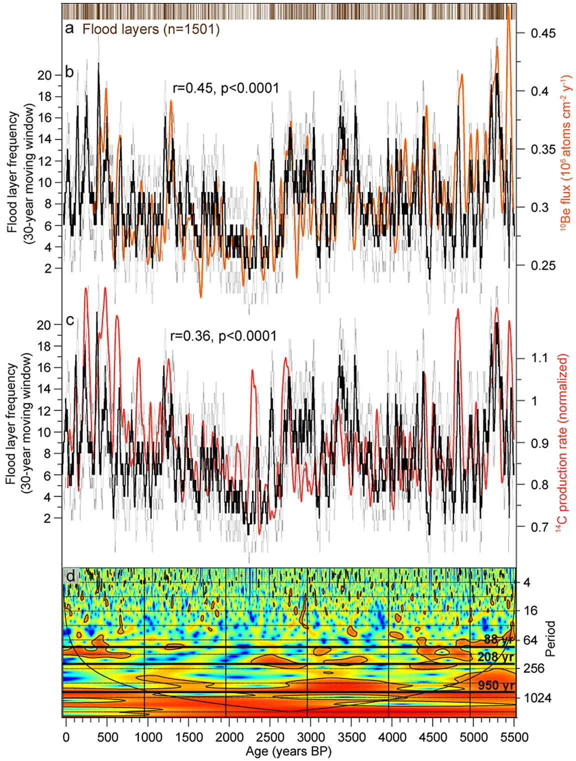

Figure 4. Flood layer frequency and solar activity. **(a)** Flood layers in Lake Ammersee sediment core $AS10_{prox}$. **(b)** Flood layer frequency (30 year moving window) and ^{10}Be flux in the GRIP ice core (Vonmoos et al., 2006). **(c)** Flood layer frequency (30 year moving window) and ^{14}C production rate (Muscheler et al., 2007). Gray lines indicate the standard deviation of the smoothed flood layer record. **(d)** Wavelet power spectrum of the flood layer time-series. High wavelet power is indicated by red colors. Contoured areas exceed the 95 % confidence level.

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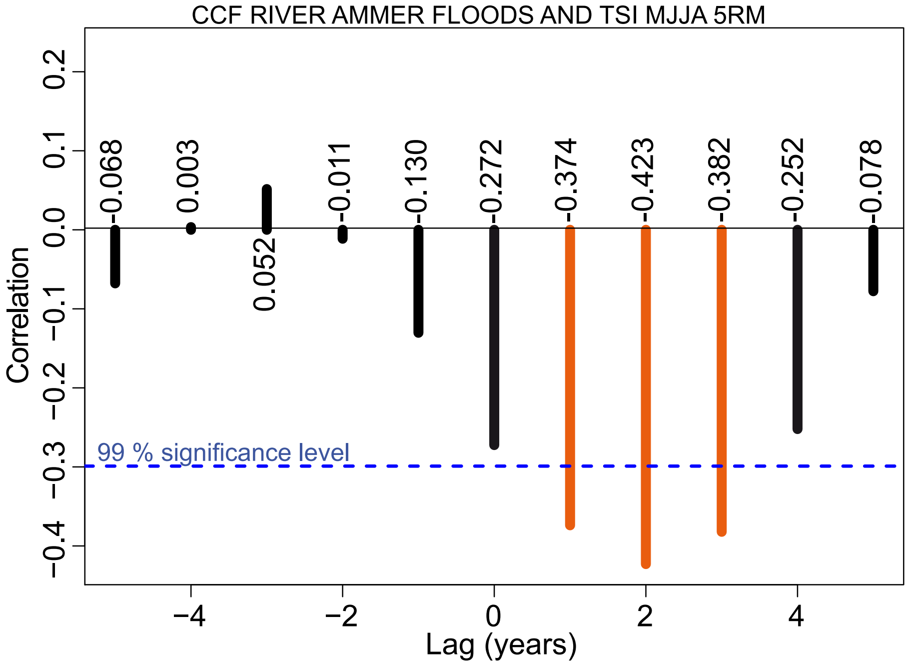

Figure 5. Cross-correlation between the frequency of MJJA River Ammer floods in the instrumental record and TSI indicating a maximum negative correlation when River Ammer flood frequency lags solar activity one to three years. The blue line indicates the 99 % significance level. Both datasets were filtered with a 5 year running mean prior to the analysis. A slight different correlation coefficient between the River Ammer flood record and TSI occurs in Sect. 4.1 because the River Ammer flood record was shifted for two years, prior to calculating correlations.

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