Response to the reviewers' comments

We thank the 2 Reviewers and M. Trachsel for their critical and detailed comments, which helped to substantially improve our manuscript. The fact that the main point of criticism from all reviewers targeted on a similar subject, namely the significance levels of the correlations between solar activity and flood frequency at Lake Ammersee showed us that this point needs to be better developed (see Detailed Answer 1). Furthermore, Reviewers 1 and 2 mentioned shortcomings in the investigation of a possible mechanistic linkage between solar activity and River Ammer flood frequency (see Detailed Answer 2). Finally, the comment by M. Trachsel on the limitations of radionuclide production records as direct solar activity indicators reminded us to more carefully investigate Sun-climate linkages on paleo-time-scales (see Detailed Answer 3). In the following, we will give a detailed response to all concerns that have been raised, first answering the three main points of criticism, followed by a point-by-point reply.

(1) Statistical linkages between River Ammer floods and solar activity

The main criticism of all three reviewers dealt with the effects of serial correlation (smoothing) and long-term trends on the significance levels of the correlations between solar activity and River Ammer flood frequency from the discharge and flood layer records. To respond to this criticism we revised the calculation of the correlations and now perform random phase significance tests (*Ebisuzaki, 1997, Journal of Climate*). This test is designed for serial correlated time-series and, thus, takes into account the effects of smoothing and detrending. It is based on the creation of (here 10000) random time-series that have an identical frequency spectrum as the original data series A, but randomly differ in the phase of each frequency. To test the significance of the correlation between A and B, we than replace A with these random surrogates and infer a probability distribution of the correlations that may occur by chance (*Ebisuzaki, 1997*). Applying the random phase test to calculate correlations between the River Ammer flood frequency and solar activity records during the recent period and the Mid- to Late Holocene reveals significant correlations for both time-intervals:

1. *Flood layer frequency and reconstructed total solar irradiance (TSI) (Steinhilber et al., 2012): r=-0.4, p<0.0001*
2. *Flood layer frequency and ^{14}C production rate (Muscheler et al., 2007): r=0.37, p<0.0001*
3. *Flood composite from River Ammer discharge data and TSI (Lean, 2000): max. correlation when flood frequency lags TSI 2 years: =-0.37, p=0.01.*

Furthermore, as suggested by Reviewer 1, we now use cross wavelet analysis (*Grinsted et al., 2004, Nonlinear Processes in Geophysics*) to detect spectral similarities between solar activity and River Ammer flood frequency. Improving our previous investigations on the single time-series, cross wavelet analysis detects regions in two time-series with common high spectral power and reveals phase relationships (*Grinsted et al., 2004*).

Performing cross wavelet analyses between the River Ammer flood and solar activity time-series during the recent period and the last 5500 years yields common high spectral power in frequencies that are commonly associated to the solar Schwabe, Gleissberg and Suess cycles. In addition, cross wavelet analysis indicates that changes in total solar irradiance (TSI) lead River Ammer flood frequencies in the discharge record.

Supporting the solar activity-River Ammer flood frequency linkage, we added a reference to a novel study on instrumental and historical flood data to our discussion. This study concludes that, similar to our results from River Ammer, changes in flood occurrences in Switzerland (about 150 km away from Lake Ammersee) during summer are associated to varying solar activity (*Peña et al., 2015, Hydrology and Earth System Sciences*).

To summarize, the additional analyses strengthen our confidence in the conclusion of changes in River Ammer flood frequency on inter-annual to multi-centennial time-scales as modulated by varying solar activity.

(2) Mechanistic linkage between solar activity and River Ammer flood frequency

Reviewers 1 and 2 mentioned shortcomings in the investigation of a mechanistic linkage between solar activity and River Ammer flood frequency. We agree that such investigations are an important task in Sun-climate studies. A comprehensive investigation of the meteorology triggering River Ammer floods based on the discharge and flood layer record using statistical models is presented by Rimbu et al. (*2015, Climate of the Past Discussions*). To avoid repetition, we would therefore like to focus in the discussion of our manuscript on the (i) correlations between solar activity and River Ammer flood frequency and (ii) synchronicities/similarities between the atmospheric circulation patterns related to higher River Ammer flood frequencies (*Rimbu et al., 2015*) and reduced solar activity as expected to be caused by the so-called solar top-down mechanism by model studies (*e.g. Haigh, 1996, Science; Ineson et al., 2011, Nature Geoscience*). To improve the first, we calculated new significant correlations between River Ammer floods in the instrumental and flood layer record and solar activity (see also Detailed Answer 1). To be clearer about the latter, we rewrote the discussion on the relationships between the configurations of atmospheric circulation related to more River Ammer floods (annual pattern) and reduced solar activity (pattern mainly for winter):

One proposed solar-climate linkage is the so-called solar top-down mechanism, expected to modulate the characteristics of the mid-latitude storm tracks over the North Atlantic and Europe by model studies (Haigh, 1996; Ineson et al., 2011; Lockwood, 2012). During periods of reduced solar activity, the storm tracks are projected to be on a more southward trajectory. 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 synoptic-scale configuration of atmospheric circulation is associated to periods of higher River Ammer flood frequency. Periods of higher flood frequency are characterized by a pronounced through over western Europe intercalated between two ridges south of Greenland and North of the Caspian Sea (Rimbu et al., 2015). Meridional moisture transport mainly from the North Atlantic towards Central Europe increases the flood risk in the Ammer region (Rimbu et al., 2015). These similar atmospheric circulation patterns and the negative correlation between River Ammer flood frequency and solar activity might provide empirical support for a solar influence on hydrometeorological extremes in Central Europe via the so-called 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 might be reconciled by feedback-effects of cryospheric processes. Ice cover in the Barents Sea and snow in Siberia are suggested to be able to transfer the solar-induced winter climate signal into summer (Ogi et al., 2003).

A further extension of the discussion based on numerical climate model results for the observed Sun-hydroclimate-extreme linkage during spring and summer would require extensive analyses and is not the focus of this paper where we mainly concentrate on empirical data. For this reason, we prefer not to extend the discussion more than we have done.

(3) ^{14}C and ^{10}Be solar activity proxies vs. solar activity reconstruction

M. Trachsel correctly commented on the effects of changes in Earth's geomagnetic field on long-term trends in the ^{14}C and ^{10}Be solar activity proxy records. To circumvent this problem, he suggested to compare the Lake Ammersee flood layer frequency record to a total solar irradiance reconstruction (TSI) (*e.g. Steinhilber et al., 2012, PNAS*). Previously, we focused on the ^{14}C (and ^{10}Be) record, as this record is less likely influenced by ^{10}Be-related weather and climate effects (in contrast to the reconstructed TSI based on a combination of ^{14}C and ^{10}Be records (*Steinhilber et al. 2012*). Geomagnetic field influences on the ^{14}C record are minor on short time-scales, but do play a role when looking at changes on time-scales of 500 years and longer (*Snowball & Muscheler, 2007, The Holocene*).

To illustrate that our results do not depend on the chosen record, we now calculate correlations between flood layer frequency and both, the linearly detrended ^{14}C production record and the TSI reconstruction by Steinhilber et al. (*2012*). Significant correlations between flood frequency and both time-series suggest that, regardless of the chosen solar record, changes in flood layer frequency during the last 5500 years are very likely modified by varying solar activity (flood layer frequency and reconstructed TSI (*Steinhilber et al., 2012*): r=-0.4, p<0.0001; flood layer frequency and ^{14}C: r=0.37, p<0.0001).

(4) Point by point response

Reviewer 1

General comments:
This paper is an important contribution to the still widely debated topic of detection and attribution of solar forcing in climate records. While attempts to find a solar signal in the mean global temperature generally reveal at most a very weak contribution there is growing evidence for solar effects in the regional weather patterns. This paper analyses the flood frequency recorded in a sediment core of Lake Ammersee. It is a good example for such a regional study because it fulfils 3 basic criteria. It covers a considerably long period (5500 years) with a high temporal resolution (1 year). In addition the sediment based flood reconstruction is complemented by an instrumental record of the daily discharge of river Ammer upstream of the lake covering the years 1926 to 2002. As a proxy of solar forcing the authors use measured and modelled Total Solar Irradiance (TSI) for the recent period (1926-2002) and the flux of 10Be and the production rate of 14C for older times which reflect the solar magnetic activity with a resolution of 10 to 20 years. The detection is done by correlation and spectral analysis. Although the analysis reveals highly significant results correlation is not the best choice for this task. It is very sensitive to long-term trends. For example, changes in the Earth's orbit modulate the insolation and the flood frequency while changes in the geomagnetic field intensity cause fluctuations of the 10Be flux and the 14C production rate.

To account for long-term trends we calculated significance levels using a random phase test calculating correlations for detrended datasets (see also our Detailed Answer 1).

Spectral analysis is much less sensitive to these perturbations and shows periodicities such as the 11-year Schwabe cycle in the instrumental data and other well-known decadal to centennial cycles which can be unambiguously attributed to solar forcing in the sedimentary record. The potential of the spectral detection has not yet been fully exploited and probably could make the case much stronger. As shown by the wavelet spectrum in Fig. 4 these multi-decadal spectral lines are characterized by strong fluctuations in their power. By applying cross- and covariance- wavelet analysis between flood frequency and solar activity one would get much more detailed information about the relationship between the two records. An easier but less informative option would be to replace in Fig. 4 panel c by the wavelet spectrum of either the 14C production rate or the 10Be flux because these two records are very similar and a comparison of both of them with the flood frequency as done in panels b and c does not provide any really new information.

We now use cross wavelet analyses to detect spectral similarities between the River Ammer flood and solar activity records (see our Detailed Answer 1).

However, it would probably worth to consider specifically the pronounced peaks of the 10Be flux and the 14C production rate. These peaks correspond to grand solar minima such as the Maunder minimum and reflect therefore the other extreme of solar forcing compared to the well-studied last decades when the Sun was very active. Finally, the question arises how well the observed correlations with lags of 1-3 years and common periodicities can be attributed to solar forcing. Although only climate models taking into account all the feedback processes and additional forcing factors as well as internal variability can ultimately answer this questions the coincidence of high flood frequency with low solar activity seems to be consistent with the so-called top-down mechanism which couples dynamically the relatively strong solar effects in the stratosphere into the troposphere causing shifts in the storm tracks. The observed lags can be explained by buffering heat in the North Atlantic. It would be very desirable to use the most advanced climate models and to try to reproduce the observations at least for some interesting periods with large changes in solar forcing and little volcanic activity. Finally it may be worth mentioning that this attribution scenario leading to significant flood changes is also consistent with not finding any significant changes in the mean global temperature.

Please see our Detailed Answer 3.

4834/26 The measured TSI varies typically over an 11-year solar cycle by 0.1% which corresponds to 1.4 Wm-2. This is also visible in the top panel of Fig. 2.

We changed ‘1 W/m^2’ to ‘1.4 W/m^2’.

Figure 2: Would it not be possible to extend this figure by solar cycle 23? A statement that the data reflect the 11-year solar cycle would be appropriate in the figure caption.

We collected new River Ammer discharge data and extended the analysis from 1926-2002 to 1926-2010, now covering solar cycle 23. Comparable to the period 1926-2002, changes in River Ammer flood frequency follow TSI during solar cycle 23.

Generally the agreement between TSI and River Ammer floods is good, except for cycle 21. Are there any explanations?

We added to the discussion that the chosen discharge threshold levels and local climate might further influence River Ammer flood frequency, particularly during solar cycle 21.

Usually the time axis points to the right hand side.

We prefer, as commonly used in paleoclimatology, to go from left to right back in time.

4841/22 The statement that further effects beside TSI cannot be ruled out is certainly correct. However, while an influence due to the galactic cosmic rays is very unlikely, it should be mentioned that changes in the spectral distribution of the solar radiation plays an important role in the top-down mechanism as discussed on page 4835.

We write in the introduction that the solar top-down mechanism is related to changes in solar UV emissions.

4842/6 change ". . . changes in solar activity from the solar cycle to ..." to ". . . changes in solar activity from the 11-year solar cycle to ..." Technical corrections: (page/line) 4835/22 Change "Aim of this study is to the investigate. . ." to "The aim of this study is to investigate. . ." Figure 3: The label of the y-axis should be "power", not "spectrum" The label of the x-axis should have the unit "(1/year)" 4840/15 replace ". . . shielding and the flux . . ." by ". . . shielding the flux . . ." Figure 4 This figure looks rather busy. An expansion in the direction of the time axis would improve the readability. The grey lines are hardly visible. Again the time axis points to the left hand side.

Included. Thank you.

Reviewer 2

1. From figure 2 is seems clear that there exist serial correlation in the data and the number of independent observations will be less than the number of data points. This has to be taken into account when the p-values for the various correlations are calculated. If this is not done the p-values will be misleading. See for example Zwiers and von Storch, 1995. For the proxy data this becomes an even greater issue as the data is smoothed which will increase the serial correlation even more. Thus, the question arises if the correlations stated in the text really are significant. As there is no information on how they are calculated this is hard to judge and I encourage the authors to have a serious look at this issue as the strength of their main conclusions relies heavily on the correlation analysis being done properly.

Please see our Detailed Answer 1.

2. The physical mechanism proposed is the solar top-down mechanism where changes in solar UV change the stratospheric temperatures and then changing the near surface circulation. A mechanism that only work during the extended winter. To explain the 1-3 year lag in response of the flood frequency to the TSI the authors cite Scaife et al. (2013) and their simulated delayed circulation response due to accumulation of heat in the ocean mixed layer and later release of this heat. As the the solar top-down mechanism this mechanism will only be active during winter when the heat flux goes the right way (from the ocean to the atmosphere). For the above mechanisms to be important also for summer an additional mechanism is needed, by citing Ogi et al.(2003) the authors suggests that the ice cover in the Barents Sea or snow in Siberia may transfer the signal into a summer signal and thereby influence their summer flood record. The chain of reasoning that the winter solar top-down mechanism (or delayed winter solar top-down mechanism) is influencing the summertime flood records in the author's region of interest should be

substantiated by some proper analysis and not just by a few references. In its current state the manuscript does not offer any real analysis of the proposed mechanism and (at least for me) it is not easy to grasp from the cited literature how the delayed mechanism of Scaife and the faster winter NAO to summer response of Ogi could work together in the region analysed in this paper. As a starting point the authors should at least show that there is a significant correlation between TSI and the flood record on the timescale of the proposed mechanism (0-3 years) by bandpass filtering the data to get rid of the correlation possibly coming from covariations on other timescales. Then do some analysis on the connection between the solar activity (lagged) and the circulation patterns found to be important for the flooding in the River Ammer (Rimbu et al., 2015 under review).

Please see our Detailed Answer 2 on the mechanistic linkage between River Ammer floods and solar activity. In addition, as suggested by Reviewer 2, we calculated correlation coefficients and significance levels (now applying the random phase test) between TSI and the River Ammer flood frequency record (5-year running mean) from discharge data with different lags. This correlation is significant (above the 90% level) when River Ammer flood frequency lags solar activity 2 to 3 years. We also calculated correlation coefficients and significance levels between TSI and the bandpass filtered River Ammer flood frequency record from discharge data (9 to 14-year bandpass). Identical with the correlations above, the bandpass filtered River Ammer flood record is significantly correlated to TSI when the flood record lags TSI 2 to 3 years. However, we expect that other factors besides TSI like local climate and the chosen flood threshold influence River Ammer flood frequencies. Therefore, we prefer to use the correlations based on the simply smoothed (5-year running mean) River Ammer flood record, to show that, despite further influences, River Ammer flood frequency is significantly correlated to changes in solar activity.

3. Spectral analyses: According to the text all time-series (Ammer flood frequency, Hohenpeißenberg precipitation event and SLP) depict a 9–12 years significant oscillation at the 95% level. How is this significance calculated? It is not stated (but from the values it seems to be tested using white noise?). As the time series have serial correlation (which is amplified by the smoothing done prior to the spectral analysis) the confidence levels should be calculated using a red noise process with the same autocorrelation as the smoothed time series.

As suggested by Reviewer 1, we replaced the spectral analyses by cross wavelet analyses.

4. Wavelet analysis: What wavelet-transform is used? Is the wavelet power spectrum done on the raw flood layer time-series? If not the periods up to 30 year will be smoothed and should not be shown. If it is why does the 11 year oscillation from the spectral analysis not turn up? How is the confidence calculated?

We now perform cross wavelet analyses. These analyses are based on a Morlet mother wavelet and performed on the smoothed River Ammer flood frequency datasets (5-year running mean for the River Ammer flood frequency time-series from the discharge record; 30-year running window for the Lake Ammersee flood layer record). The significance levels were calculated against red noise. Due to the smoothing of the Lake Ammersee *flood layer record*, no 11-year oscillation can be detected. We added this information to that part of the methods section dealing with cross wavelet analysis and to the caption of Figure 6 (cross-wavelet: flood layer record/reconstructed TSI).

Interactive comment by M. Trachsel

Czymzik et al. compare air pressure, precipitation and flood data from southern Germany with total solar irradiance (TSI, Lean et al. 2000) for the period 1926 - 2002. After finding significant correlations ($p < 0.001$) between the records, a flood record from Lake Ammersee in southern Germany is compared to a 10 Be record by Vonmoos et al. (2006) and a 14C record by Muscheler et al (2007). The flood record is undoubtedly excellent. However, there are issues that should be addressed before publication. In this paper a 5-year running mean is applied to TSI and air pressure, precipitation and flood time-series. Applying a 5-year running mean to a time-series induces temporal autocorrelation: adjacent data points within the smoothed time-series are no longer independent. The test used to assess significance of correlations between smoothed solar activity and air pressure time-series assumes independence of the data points within one time-series. As temporal autocorrelation is not taken into account, the reported p-value of $p < 0.0001$ for $r = -0.47$ is most probably overoptimistic. In addition to the lack of independence within data series, leads and lags of up to 5 years are tested and the procedure is applied to six time-series, resulting in a multiple testing problem. There are several analytical ways to deal with these problems (e.g. Trenberth et al. 1984). There are also methods using simulated data to deal with the lack of independence in a time-series. A simple way is to apply methods used in a study (i.e. 5-year running mean and allowing for lags up to 5 years) to random data (e.g. white noise and to compare the results obtained using random data to the results obtained using the data tested (in this case pressure data). I generated 100000 series of white noise, applied a 5-year running mean to the white noise series and correlated (using lags of 0 to 5 years, but no leads) the smoothed white noise series with the TSI data by Lean et al. (2000). I then chose the maximum of the six correlations produced by one white noise series to generate a null distribution. Using this procedure, about 10% of the randomly generated time-series have a correlation of $|r| > 0.47$ with TSI, i.e. $p = 0.1$. A correlation of $r = -0.47$ (the highest correlation found in this paper) is therefore not significantly ($p<0.05$) different from results obtained using random data (only allowing for lags up to two years, or only for lags between 1 and 3 years, $p = 0.06$).

Please see our Detailed Answer 1.

In the analysis of the late Holocene flood record the data by Vonmoos et al. (2006) is used for comparison with the flood record. In the earlier paper by Czymzik et al. (2013) the flood record was compared to the record by hilber et al. (2009). Vonmoos et al. (2006) write: “The reconstructed Phi record displays a long-term trend. Inferring a varying solar activity on such long timescales is not possible as long as the mentioned uncertainties considering possible system effects of the 10Be record exist and geomagnetic field reconstructions during the Holocene exhibit such large errors. Within the uncertainties, the long-term changes in 10Be can be completely explained by the changes in the geomagnetic dipole field [Muscheler et al., 2005a; Wagner et al., 2000]. Taking into account the calculated errors of the Phi reconstruction, the long-term trend in Phi in fact turns out not to be significant, indicating that possible system effects on the 10Be flux would be small. Therefore the OBSERVED LONG-TERM TREND in the presented Phi record is MOST LIKELY CAUSED BY AN INCOMPLETE ELIMINATION OF THE GEOMAGNETIC FIELD INFLUENCE on the 10Be flux and/or a slight long-term change in the climate system. However, long-term changes in solar activity cannot be excluded either." As reviewer one states: "Although the analysis reveals highly significant results correlation is not the best choice for this task. It is very sensitive to long-term trends." Looking at Fig 4 the significant correlation between the flood record and the record by Vonmoos et al. (2006) is probably caused by long term trends that are not reliable. Regarding 10Be and 14C records, Steinhilber et al. (2012) state: "A comparison with changes in the geomagnetic dipole field strength [. . .] shows that the geomagnetic dipole shielding is the main cause of the observed multi millennial variability" In light of this information, providing further motivation for the use of the Vonmoos et al.(2006) record instead of the Steinhilber et al. (2009) or Steinhilber et al. (2012) record(or inclusion of the latter two records) would greatly improve the quality of this paper(Especially as the paper by Czymzik et al. (2013) used the Steinhilber et al. (2009) record for comparison).

See our Detailed Answer 3.

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

M. Czymzik[1,*], R. Muscheler[2] and A. Brauer[1]

[1] {Section 5.2 Climate Dynamics and Landscape Evolution, GFZ German Research Centre for Geosciences, 14473 Potsdam, Germany}

[2] {Department of Geology - Quaternary Sciences, Lund University, 22362 Lund, Sweden}

[*]{now at: Department of Geology, Lund University, Sweden}

Correspondence to: M. Czymzik (markus.czymzik@geol.lu.se)

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 during spring and summer on inter-annual to multi-centennial time-scales integrating daily discharge data of River Ammer (southern Germany) back to AD 1926 (~solar cycles 15-23) and the 5500-year flood layer record from varved sediments of the downstream Lake Ammersee. Flood frequency in the River Ammer discharge record is significantly correlated to changes in solar activity when the flood record lags the solar signal two to three years (two-year lag: r=-0.375, p=0.01, three-year lag: r=0.371, p=0.03). Flood layer frequency in the Lake Ammersee sediment record depicts distinct multi-decadal variations and significant correlations to a total solar irradiance reconstruction (r=-0.4, p<0.0001) and ^{14}C production rates (r=0.37, p<0.0001), reflecting changes in solar activity. On all time-scales, flood frequency is higher when solar activity is reduced. In addition, the configuration of atmospheric circulation associated to periods of increased River Ammer flood frequency broadly resembles that during intervals of reduced solar activity, as expected to be induced by the so-called solar top-down mechanism by model studies. Both atmospheric patterns are characterized by an increase in meridional airflow associated to enhanced atmospheric blocking over Central Europe. Therefore, the significant negative correlations as well as similar atmospheric circulation patterns might provide empirical support

for a solar influence on hydroclimate extremes in Central Europe during spring and summer by the so-called solar top-down mechanism.

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 1.4 W/m^2 are too small to substantially modify climate unless they can induce amplifying feedbacks in the climate system (IPCC, 2014). One amplifying feedback proposed by model studies 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 emissions influence stratospheric ozone concentration, heating and circulation and, consequently, strength and stability of the polar vortex. These disturbances are expected to communicate downwards to the troposphere via a chain of processes that is still under investigation to modify position and strength of the mid-latitude storm tracks mainly 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 eroded 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). Major aim of this study is to investigate the instrumental River Ammer discharge record from Gauge Weilheim reaching back to AD 1926 for high-frequency solar signals (Fig. 1). The analyses focus on May to August (MJJA), the flood season in the Ammer region today (Czymzik et al., 2010). For providing information on River Ammer flood activity in the more distant past, 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 Gauge Weilheim, recording discharge from 601 of the 709 km² 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

River Ammer has a length of 84 km and is located in the Bavarian Alpine Foreland (southern Germany) (Mangelsdorf and Zelinka, 1973) (Fig. 1). Its catchment is well suited for the investigation of flood occurrences. 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 (709 km²) and steep slopes of the alpine foothills produce short but intense flood peaks (Ludwig et al., 2003).

Lake Ammersee (48°00’N, 11°07’E, 533 asl.) has a surface area of 47 km² 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 lake during a flood. The gully shaped lake basin provides a well-defined deposition center for these detrital fluxes as distinct ‘flood layers’ (Czymzik et al., 2010). Varved sediments allow dating these flood layers to the season by varve counting and the position within an annual lacustrine sedimentation cycle (Czymzik et al., 2010).

Hydroclimate in the Ammer region, today, 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 atmospheric blocking (Petrow and Merz, 2009). Mean annual precipitation in the Ammer catchment is ~1200 mm/year.

2.2 River Ammer discharge data

Daily River Ammer discharge data provided by the Bavarian Environmental Agency were recorded at Gauge Weilheim (550 m asl.), located about 10 km upstream of Lake Ammersee (Fig. 1). The discharge data cover the period AD 1926-2010 and the analyses focus on May to August (MJJA). To better link the River Ammer discharge record to floods as represented by the Lake Ammersee flood layer time-series, flood frequency indices were calculated by counting days in MJJA with daily discharges between 27 and 34 m^3/s (discharges between the 90^{th} and 95^{th} percentile) and above 34 m^3/s (discharges above the 95^{th} percentile). Two threshold levels were chosen to extract more complete time-series of major River Ammer floods varying substantially in length and magnitude. A MJJA River Ammer flood frequency composite was calculated by averaging the indices related to both discharge thresholds. To reduce noise, the River Ammer flood frequency composite was filtered with a 5-year running mean.

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 if 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 moving window was applied to the flood layer time-series to emphasize multi-decadal variability.

2.4 Cross wavelet analysis

Cross wavelet analysis reveals regions in two time-series with common high spectral power and provides information on the phase relationship (Grinsted et al., 2004). The wavelets were produced using a Morlet mother wavelet. Significance levels were calculated against a red noise spectrum (Grinsted et al., 2004). Before the analyses, all datasets were standardized (zero mean, standard deviation).

2.5 Random phase significance test

Correlation coefficients and significance levels were calculated using a non-parametric random phase test (Ebisuzaki, 1997). This test is designed for serial correlated time-series and, thus, takes into account the effects of smoothing and detrending. It is based on the creation of (here 10000) random time-series that have an identical frequency spectrum as the original data series A, but randomly differ in the phase of each frequency. To test the significance of the correlation between A and B, A is than replaced with these random surrogates and the probability distribution of the correlations that may occur by chance calculated (Ebisuzaki, 1997).

3 Results

3.1 River Ammer flood frequency back to AD 1926

The MJJA River Ammer flood frequency indices for discharges between the 90th and 95th percentile and above the 95th percentile are significantly correlated from AD 1926 to 2010 (r=-0.38, p=0.08), suggesting the reflection of a common hydrological signal (Fig. 2). As already depicted by the two single flood indices, the MJJA River Ammer flood frequency composite exhibits distinct decadal-scale oscillatory behavior and a trend towards lower flood frequencies during the more recent years (Fig. 2).

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. 3). Mean flood layer recurrence time is 3.7 years.

4 Discussion

4.1 River Ammer floods and solar activity in the instrumental period

Comparing the MJJA River Ammer flood frequency composite from the discharge record to an annual 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 River Ammer flood frequency composite follows changes in TSI during solar cycles 15 to 23 (Fig. 2). Both records are broadly anti-phased (Fig. 2). Discrepancies between the MJJA River Ammer flood frequency composite and TSI might be caused by internal climate variability and local climate anomalies. Furthermore, particularly the weak increase in the River Ammer flood frequency composite during the TSI minimum between solar cycles 22 and 23 is likely due to the static nature of the chosen discharge thresholds. Nevertheless, even though no increase in flood frequency is visible during that time for floods with discharges above the 95^{th} percentile, an increase in the frequency of floods with discharges between the 90^{th} and 95^{th} percentile is recorded (Fig. 2). A trend towards lower River Ammer flood frequencies during the more recent years is paralleled by a trend towards higher solar activity (Fig. 2).

Cross correlation indicates significant negative correlations when the River Ammer flood frequency composite lags TSI 2 to 3 years (Fig. 4). A temporal lag of flood responses to changes in solar activity of a few years might be explained by a modelled ocean-atmosphere feedback (Scaife et al., 2013): Solar induced variations in the North Atlantic head 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). Cross wavelet analysis of the River Ammer flood frequency composite and TSI indicates significant common spectral power around 9-12 years similar to the solar Schwabe cycle and a negative phase relationship (Fig. 5).

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

Comparing the 5500-year flood layer frequency record to solar activity indicators 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, filtered with a 30-year moving window) depicts distinct multi-decadal variations and significant correlations with a total solar irradiance reconstruction (Steinhilber et al., 2012) ($r=-0.4$, $p<0.0001$) and the reconstructed ^{14}C production rate, a proxy record of changes in solar activity, especially on the sub-millennial time-scales (Muscheler et al., 2007;

Snowball and Muscheler, 2007) ($r=0.39$, $p<0.0001$) (Fig. 3). The atmospheric production of ^{14}C is influenced by the activity of the Sun. A more active Sun enhances heliomagnetic shielding and, thereby, reduces the flux of galactic cosmic rays to Earth's upper atmosphere forming ^{14}C by the interaction with N and O (Lal and Peters, 1967). Consequently, more ^{14}C is produced when solar activity is reduced. In addition to the multi-decadal variations, cross wavelet analysis of the flood layer frequency and TSI (Steinhilber et al., 2012) records yield significant common low-frequency oscillations around 90 and 210 years likely reflecting the solar Gleissberg and Suess cycles, particularly during periods of grand solar minima around 250, 2800 and 5300 vyr BP (Fig. 6). Furthermore, the analysis reveals a dominantly anti-phased behavior between flood layer frequency and TSI (Fig. 6).

4.3 Mechanism for a solar influence on flood frequency

Significant negative correlations between solar activity and River Ammer flood frequency on inter-annual to multi-centennial time-scales suggest a solar modulation of the frequency of hydrometeorological extremes in the Ammer region (Figs. 2-6). Further empirical associations between flood frequency and solar activity in records from the alpine region and Central Spain (Moreno et al., 2008; Peña et al., 2015; Vaquero, 2004; Wirth et al., 2013a, 2013b) 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.

One proposed solar-climate linkage is the so-called solar top-down mechanism, expected to modulate the characteristics of the mid-latitude storm tracks over the North Atlantic and Europe by model studies (Haigh, 1996; Ineson et al., 2011; Lockwood, 2012). During periods of reduced solar activity, the storm tracks are projected to be on a more southward trajectory. 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 synoptic-scale configuration of atmospheric circulation is associated to periods of higher River Ammer flood frequency (Rimbu et al., 2015). Periods of higher flood frequency are characterized by a pronounced through over western Europe intercalated between two ridges south of Greenland and North of the Caspian Sea (Rimbu et al., 2015). Meridional moisture transport mainly from the North Atlantic towards Central Europe along the frontal zones of these air-pressure fields increases the flood risk in the Ammer region (Rimbu et al., 2015). These similar atmospheric circulation patterns might suggest that the observed solar activity-flood frequency linkage is related to the so-called 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 might be reconciled by the effects of cryospheric processes. Ice cover in the Barents Sea and snow in Siberia are expected to transfer the dominant potentially solar induced winter climate signal into summer (Ogi et al., 2003).

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 identifying changes in flood frequency in Central Europe during spring and summer and their triggering mechanism on inter-annual to multi-centennial time-scales. Flood frequency in both records is significantly correlated to changes in solar activity from the solar Schwabe cycle to multi-centennial oscillations. These significant correlations suggest a solar influence on the frequency of hydroclimate extremes in Central Europe. Similar configurations of atmospheric circulation during periods of increased flood frequency and reduced solar activity, as expected to be caused by the so-called solar top-down mechanism by model studies, might indicate that the observed solar activity-flood frequency linkage is related to this feedback. The unexpected direct response of variations in River Ammer flood frequency to changes in solar activity might suggest that the solar top-down mechanism is of particular relevance for hydroclimate extremes. Future climate model studies might help to provide a better mechanistic understanding and test our hypotheses on the linkage between solar activity and flood frequency in Central Europe during spring and summer.

Acknowledgements

This study is a contribution to the Helmholtz Association (HGF) climate initiative REKLIM Topic 8 ‘Rapid climate change derived from proxy data’ and was carried out using TERENO infrastructure financed by the HGF. Lake Ammersee flood layer data files are archived in the PANGAEA data library (http://doi.pangaea.de/10.1594/PANGAEA.803369). We thank Florian Adolphi for providing the program for the random phase test.

References

Adolphi, F., Muscheler, R., Svensson, A., Aldahan, A., Possnert, G., Beer, J., Sjolte, J., Björck, S., Matthes, K. and Thiéblemont, R.: Persistent link between solar activity and Greenland climate during the Last Glacial Maximum, Nat. Geosci., 7, 662-666, 2014.

Alefs, J. and Müller, J.: Differences in the eutrophication dynamics of Ammersee and Starnberger See (Southern Germany), reflected by the diatom succession in varve-dated sediments, J. Paleolimnol., 21, 395-407, 1999.

Beer, J.: Long-term indirect indices of solar variability, Space Sci. Rev., 94, 53-66, 2000.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I. and Bonani, G.: Persistent solar influence on North Atlantic climate during the Holocene, Science, 294, 2130–2136, 2001.

Czymzik, M., Brauer, A., Dulski, P., Plessen, B., Naumann, R., von Grafenstein, U. and Scheffler, R.: Orbital and solar forcing of shifts in Mid- to Late Holocene flood intensity from varved sediments of pre-alpine Lake Ammersee (southern Germany), Quat. Sci. Rev., 61, 96–110, 2013.

Czymzik, M., Dulski, P., Plessen, B., von Grafenstein, U., Naumann, R. and Brauer, A.: A 450 year record of spring-summer flood layers in annually laminated sediments from Lake Ammersee (southern Germany), Water Resour. Res., 46, W11528, 2010.

Ebisuzaki, W.: A method to estimate the statistical significance of a correlation when the data are serially correlated, J. Climate, 10, 2147-2153, 1997.

Fleitmann, D., Burns, S. J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A. and Matter, A.: Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman., Science, 300, 2003.

Glaser, R., Riemann, D., Schönbein, J., Barriendos, M., Brázdil, R., Bertolin, C., Camuffo, D., Deutsch, M., Dobrovolný, P., Engelen, A., Enzi, S., Halíčková, M., Koenig, S. J., Kotyza, O., Limanówka, D., Macková, J., Sghedoni, M., Martin, B. and Himmelsbach, I.: The variability of European floods since AD 1500, Clim. Change, 101, 235–256, 2010.

Gray, L. J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M., Matthes, K., Cubasch, U., Fleitmann, D., Harrison, G., Hood, L., Luterbacher, J., Meehl, G. A., Shindell, D., Geel, B. Van and White, W.: Solar influences on climate, Rev. Geophys., 48, RG4001, 2010.

Grinsted, A., Moore, J.C. and Jevrejeva, S.: Application of the cross wavelet transform and wavelet coherence to geophysical time series, Nonlin. Processes Geophys., 11, 561–566, 2004.

Haigh, J. D.: The impact of solar variability on climate, Science, 272, 981–984, 1996.

Ineson, S., Scaife, A. A., Knight, J. R., Manners, J. C., Dunstone, N. J., Gray, L. J. and Haigh, J. D.: Solar forcing of winter climate variability in the Northern Hemisphere, Nat. Geosci., 4, 753–757, 2011.

IPCC: Climate Change 2013: The physical basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate change, edited by T. F. Stocker., 2013.

Kämpf, L., Brauer, A., Swierczynski, T., Czymzik, M., Müller, P. and Dulski, P.: Processes of flood-triggered detrital layer deposition in the varved Lake Mondsee sediment record revealed by a dual calibration approach, J. Quat. Sci., 29, 475–486, 2014.

Lal, D. and Peters, B.: Cosmic ray produced radioactivity on the Earth, in Encyclopedia of Physics, edited by K. Sitte, pp. 551–612, Springer, Berlin Heidelberg., 1967.

Lean, J.: Evolution of the Sun's spectral irradiance since the Maunder Minimum, Geophys. Res. Lett., 27, 2425–2428, 2000.

Lockwood, M.: Solar Influence on Global and Regional Climates, Surv. Geophys., 33, 503–534, 2012.

Ludwig, R., Taschner, S. and Mauser, W.: Modelling floods in the Ammer catchment: limitations and challenges with a coupled meteo-hydrological model approach, Hydrol. Earth Syst. Sci., 7, 833–847, 2003.

Mangelsdorf, J. and Zelinka, K.: Zur Hydrochemie der Ammer (Oberbayern) und ihrer Zuflüsse, Wasserwirtschaft, 63, 1–5, 1973.

Moreno, A., Valero-Garcés, B. L., González-Sampériz, P. and Rico, M.: Flood response to rainfall variability during the last 2000 years inferred from the Taravilla Lake record (Central Iberian Range, Spain), J. Paleolimnol., 40, 943–961, 2008.

Muscheler, R., Joos, F., Beer, J., Müller, S. A., Vonmoos, M. and Snowball, I.: Solar activity during the last 1000 yr inferred from radionuclide records, Quat. Sci. Rev., 26, 82–97, 2007.

Ogi, M., Tachibana, Y. and Yamazaki, K.: Impact of the wintertime North Atlantic Oscillation (NAO) on the summertime atmospheric circulation, Geophys. Res. Lett., 30, 1704, 2003.

Peña, J.C., Schulte, L., Badoux, A., Barriendos, M. and Barrera-Escoda, A.: Influence of solar forcing, climate variability and modes of low-frequency atmospheric variability on summer floods in Switzerland, Hydrol. Earth Syst. Sci., 19, 3807–3827, 2015.

Petrow, T. and Merz, B.: Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002, J. Hydrol., 371, 129–141, 2009.

Rimbu, N., Czymzik, M., Ionita, M., Lohmann, G. and Brauer, A.: Atmospheric circulation patterns associated to the variability of River Ammer floods: evidence from observed and proxy data, Clim. Past Discuss., 11, 4483–4504, 2015.

Scaife, A. A., Ineson, S., Knight, J. R., Gray, L., Kodera, K. and Smith, D. M.: A mechanism for lagged North Atlantic climate response to solar variability, Geophys. Res. Lett., 40, 434–439, 2013.

Snowball, I. and Muscheler, R.: Palaeomagnetic intensity data: an Achilles heel of solar activity reconstructions, The Holocene, 17, 851–859, 2007.

Steinhilber, F., Abreu, J.A., Beer, J., Brunner, I., Christl, M., Fischer, H., Heikkilä, U., Kubik, P.W., Mann, M., McCracken, K.G., Miller, H., Miyahara, H., Oerter, H. and Wilhelms. F.: 9400 years of cosmic radiation and solar activity from ice cores and tree rings, Proc. Natl. Acad. Sci., 109, 5967–5971, 2012.

Svensmark, H. and Friis-Christensen, E.: Variation of cosmic ray flux and global cloud coverage-a link in solar-climate relationships, J. Atmos. Solar-Terrestrial Phys., 59, 1225–1232, 1997.

Vaquero, J. M.: Solar signal in the number of floods recorded for the Tagus river basin over the last millennium, Clim. Change, 66, 23–26, 2004.

Wirth, S. B., Gilli, A., Simonneau, A., Ariztegui, D., Vannière, B., Glur, L., Chapron, E., Magny, M. and Anselmetti, F. S.: A 2000 year long seasonal record of floods in the southern European Alps, Geophys. Res. Lett., 40, 4025–4029, 2013a.

Wirth, S. B., Glur, L., Gilli, A. and Anselmetti, F. S.: Holocene flood frequency across the Central Alps – solar forcing and evidence for variations in North Atlantic atmospheric circulation, Quat. Sci. Rev., 80, 112–128, 2013b.

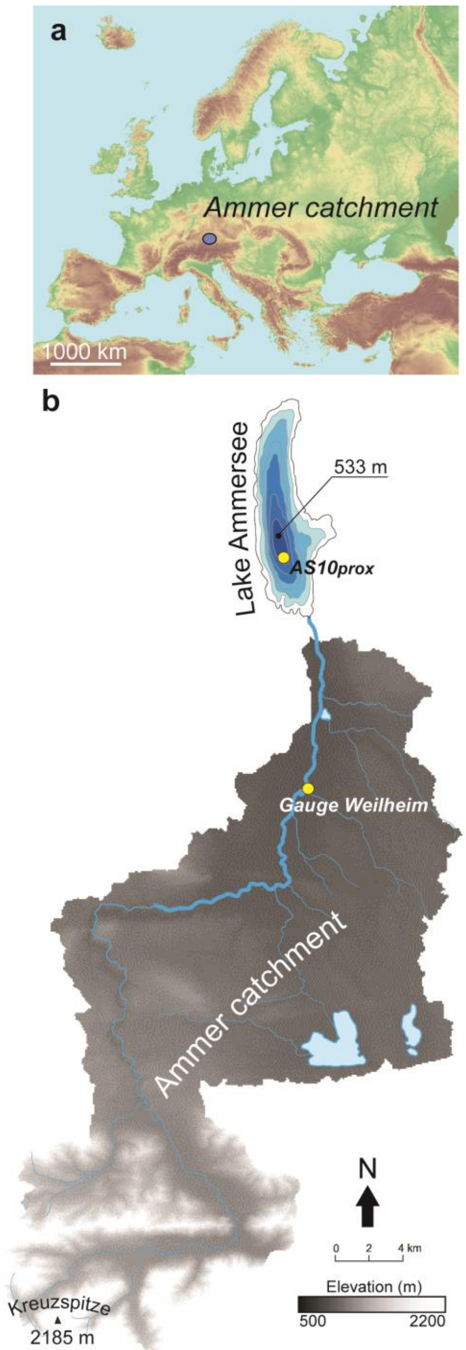

Figure 1. (a) Geographical position of the Ammer catchment. (b) Hydrological map of the Ammer catchment (modified after: Ludwig et al., 2003) and bathymetric map of Lake Ammersee with positions of Gauge Weilheim and sediment core $AS10_{prox}$.

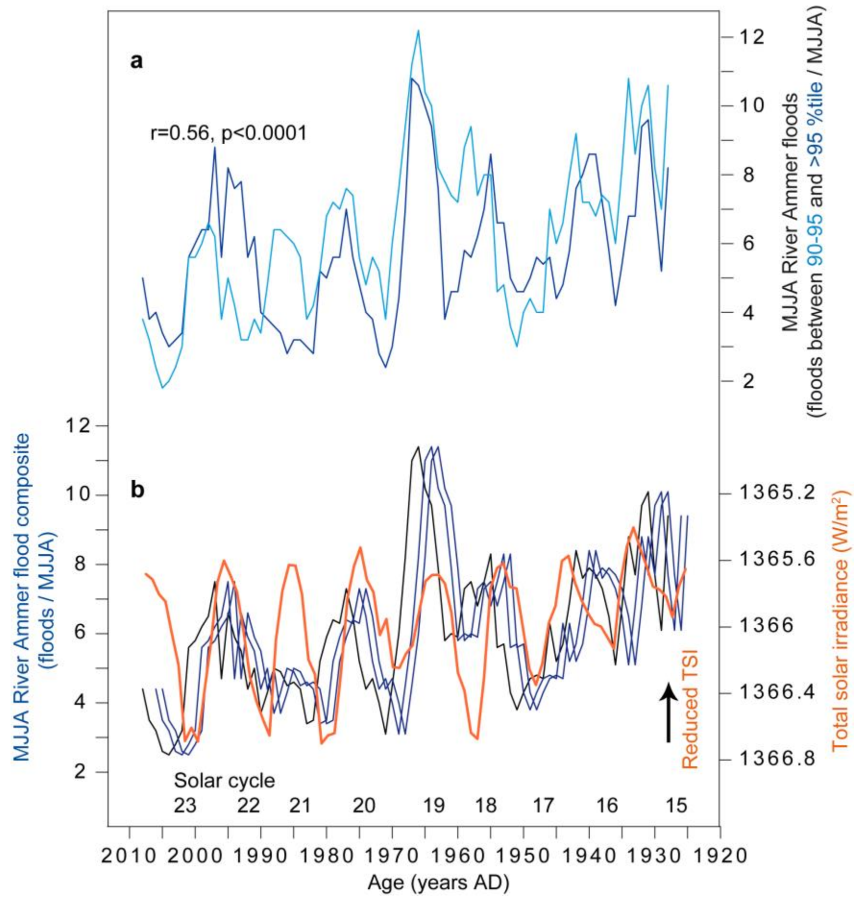

Figure 2. River Ammer flood frequency in the discharge record and solar activity. (a) Frequency of River Ammer floods during MJJA with discharges between the 90th and 95th percentile as well as above the 95th percentile. (b) River Ammer flood frequency composite (see Methods) and total solar irradiance (TSI) during solar cycles 15-23 (Lean, 2000). The black line indicates the original River Ammer flood frequency composite. The blue lines represent the River Ammer flood frequency composite shifted for two and three years into the past revealing significant correlations with TSI (see Fig. 4). The River Ammer flood records were filtered using a 5-year running mean. Correlations were calculated using a random phase test (Ebisuzaki, 1997).

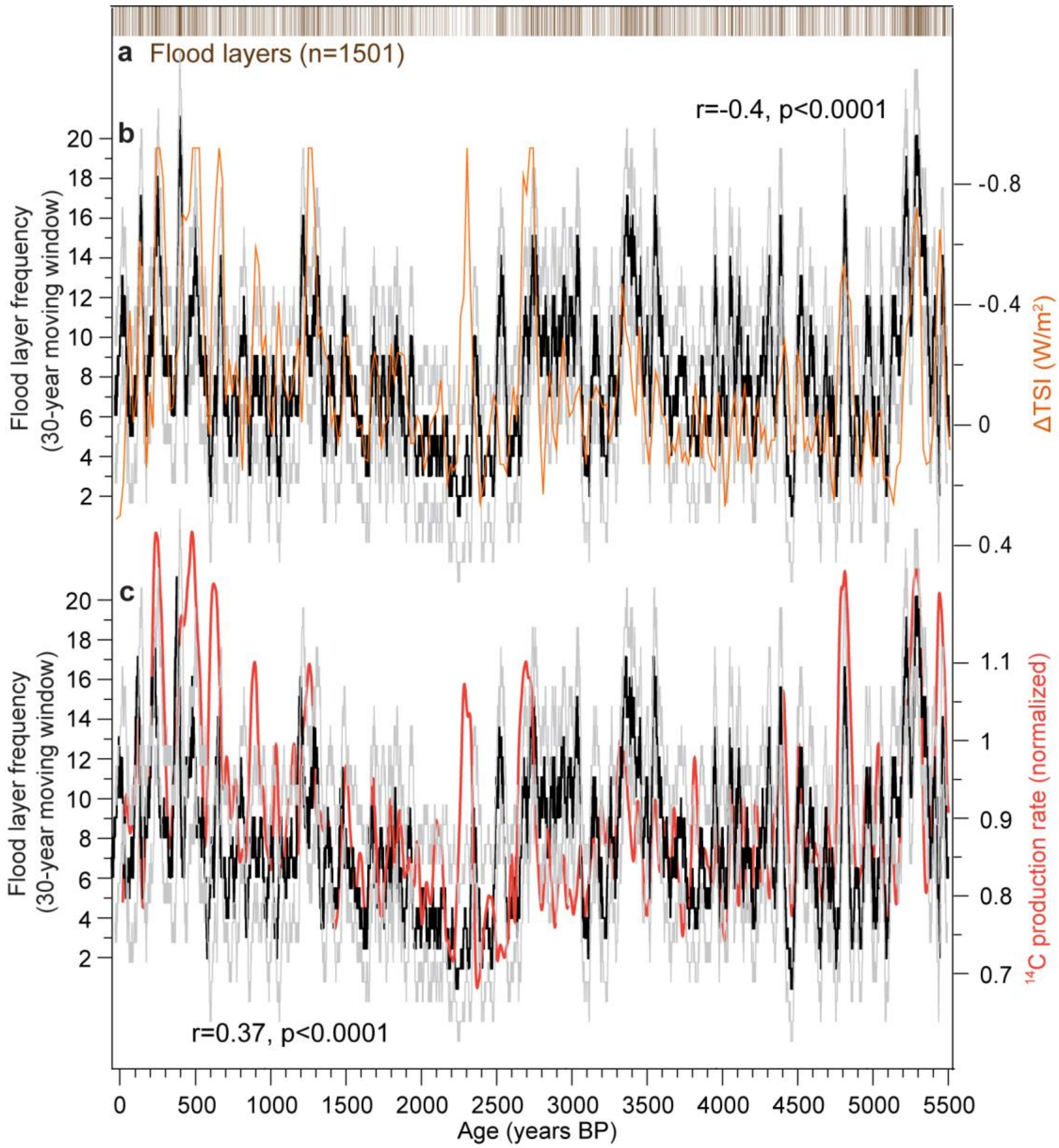

Figure 3. Flood layer frequency and solar activity. (a) Flood layers in Lake Ammersee sediment core $AS10_{prox}$. (b) Flood layer frequency (30-year moving window) and reconstructed total solar irradiance (difference to the value of the PMOD composite during the solar cycle minimum in AD 1986) (Steinhilber et al., 2012). (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. Correlations were calculated using a random phase test (Ebisuzaki, 1997).

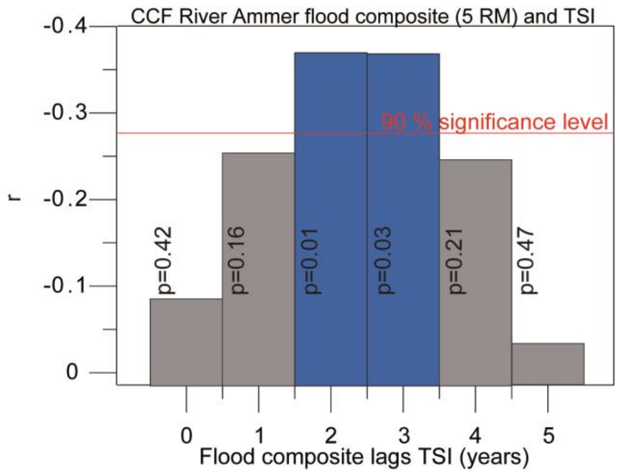

Figure 4. Cross-correlation between the MJJA River Ammer flood frequency composite from the discharge record and total solar irradiance (TSI) (Lean, 2000) indicating significant negative correlations when TSI leads the River Ammer flood frequency composite two to three years. Prior to the analysis, the River Ammer flood frequency composite was filtered with a 5-year running mean. Correlations were calculated using a random phase test (Ebisuzaki, 1997).

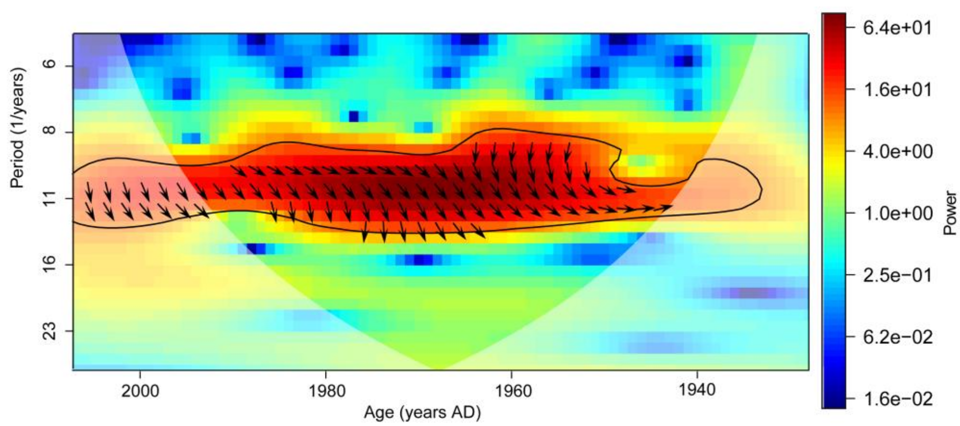

Figure 5. Cross wavelet analysis of MJJA River Ammer flood frequency composite and total solar irradiance (TSI) (Lean, 2000) indicating significant common spectral power (exceeding the 90 % significance level against a red noise spectrum) around 11 years. Arrows pointing down indicate that TSI leads the River Ammer flood frequency composite. Before the analyses the River Ammer flood composite was filtered with a 5-year running mean. Shaded areas indicate the cone of influence where wavelet analysis is affected by edge effects.

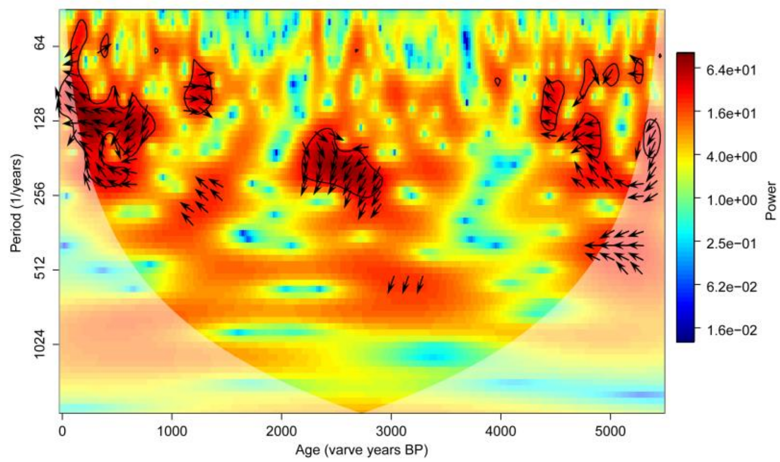

Figure 6. Cross wavelet analysis of the Lake Ammersee flood layer (30-year running window) and reconstructed total solar irradiance records (Steinhilber et al., 2012). Contoured areas exceed the 90 % significance level against a red noise spectrum. Arrows pointing to the left indicate that the time-series are anti-phased. Before the analysis, the Lake Ammersee flood layer record was resampled to the resolution of the TSI time-series (approx. one data point in 20 years). Shaded areas indicate the cone of influence where wavelet analysis is affected by edge effects.