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Interactive comment on "Solar modulation of flood frequency in Central Europe during spring and summer on inter-annual to millennial time-scales" *by* M. Czymzik et al.

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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 14C 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 timescales 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) 14C and 10Be 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 14C and 10Be 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 14C (and 10Be) record, as this record is less likely influenced by 10Be-related weather and climate effects (in contrast to the reconstructed TSI based on a combination of 14C and 10Be records (Steinhilber et al. 2012). Geomagnetic field influences on the 14C 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 14C 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 14C: $r=0.37$, $p<0.0001$).

(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

We changed ‘1 W/m2’ to ‘1.4 W/m2’.

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

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

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 10and 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.

Interactive comment on Clim. Past Discuss., 11, 4833, 2015.