Response to Reviewer 2

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A 2600-year history of floods in the Bernese Alps, Switzerland: frequencies, mechanisms and climate forcing

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Response to Reviewer #2.

We are grateful to the Reviewer #2 for his comments concerning the interpretation of the time series. Following his advice we have improved our paper.

General comments, point 1:

"…my comments will mainly directed at the interpretation of the time series and the claimed linked with the other climatic proxy records. In my opinion, the interpretation of this link is strongly based on previous studies - which also claimed to have found relationships with solar activity and the index of the Summer North Atlantic Oscillation."

The following response is to clarify the general comment point 1:

Yes, there are several papers that deals with a possible correlation between sedimentary flood proxies (slack water deposits, lake sediments) and solar activity (e.g. Benito et al., 2003; Versteegh, 2005; Stewart et al., 2011; Wirth et al., 2013). Regarding the interpretation of the geochemical variability of flood plain sediments, we reported in several papers (Schulte et al., 2004; 2008; 2009a) that there exists a possible coincidence between sedimentary flood proxies in the Lütschine and Lombach catchment and the radiocarbon anomalies (solar activity). We also detected mean periodicities similar to solar cycles such as the Geissberg cycle of 80-90 yrs in the generated flood series (Schulte et al., 2008). Not yet detailed published results of spectral analysis of geochemical data of the Lütschine and Lombach delta flood plain supports this findings (Schulte et al., 2011; Quaternary International 279-280, 439). Therefore, the frequencies of the variability of the geochemical records of core AA-02, AA-05 and AA-10 in the Hasli-Aare valley shown in Table 2 contribute to a better understanding of the previously analyzed neighbor catchments.

With regard to the SNAO the reviewer's observation is correct that the interpretation is based on the findings of our pervious paper in HESSD (Peña et al., 2014; Hydrol. Earth Syst. Sci. Discuss., 11, 13843–13890) as indicated by the citation in the manuscript.

Discussion point 1:

"This figure shows the 40-year low-pass filter record of Total Solar Irradiance, the 11-year low-pass filtered record of summer temperature and precipitation, and the sedimentary paleoflood record. Why is the time filtering different (the TSI data are available also at decadal time scale)? what is the time filtering of the paleo flood record? what is the resolution and dating uncertainty of the original paleoflood record."

We agree that these meta data are important for readers. They will be included in the paper in section 3.2 and in the figure captions:

- The mean resolution of the sediment accumulation rate of our original sedimentary record is 0.25 cm yr^{-1}. Each sample taken at intervals of 1 cm integrates 4 years. (included at p. 3399, L.10; and figure caption 3, p. 3442)
- In figure 5 we do not apply any filter to our data series. In figure 8 we used a 3-data-moving average that correspond to a 13-yr resolution, which is comparable to the 11-yr moving average applied to the precipitation and temperature reconstruction of Büntgen et al. (2006 and 2011). In the new manuscript we plotted the temperature and precipitation reconstruction applying a 13-yr Gaussian filter (p. 3447, figure caption 8).
- With regard to Figure 9 we unified the time resolution of the flood proxy, ^{18}O and precipitation reconstruction to 21 years (p. 3448, figure caption 9). Nevertheless, we have to consider the variation of chronological uncertainties of geoarchives. We maintain the 40 yr low pass filter plot of the TSI in both figures to avoid the high frequency 11-yr cycle.
- The uncertainty of the original paleoflood record is defined by radiocarbon dating and by changes in the sedimentation rate: ^{14}C-dating and 2σ uncertainty intervals are already presented in table 1 of the supplementary data and are provided in the text. ^{14}C dating shows uncertainty ranges between ±30 and ±40 yrs. 2σ calibrated ages of the composite record (Fig. 9) indicate ranges between ±50yr and ±94 yrs, only the lowest dating of core AA-02 provide a range of ±129 yrs due to mayor radiocarbon anomalies. Ages of the youngest sediments were corrected by historical documented flood layers and Pb and Zn peaks as described in section 4.2 (P. 3408, L. 1-10).

Discussion point 2:

"I cannot see e real correspondence between TSI a) and plain floods: the minimum in TSI around 1480 occurs later than the corresponding minimum in the flood record; the flood maximum around 1580 (one of the highest maxima in this record) corresponds to lower than normal TSI; the Late Maunder Minimum in TSI around 1700 corresponds to a normal flood frequency. There are some peaks to agree in both records, like the Dalton Minimum around 1820 , but even in these case, TSI presents one single minimum, whereas the flood record actually presents a double minimum more reminiscent of the early 19th century volcanic forcing."

Regarding to the correspondence between our flood records and paleoclimate proxies we must consider the following points:

1) Chronological models of sedimentary archives show a particular pattern: changes in the sedimentation rate can displace the (interpolated) ages of samples. These displacements between events of different series can occur in both directions. Positive and negative displacements must not necessarily result only from physical atmospheric processes and/or hydrological response but are also introduced by variations in the sedimentation rate. This general problem is stated also by the comments of referee 1: "*In addition, when we tried to fit 1 to 1 peaks on these records it is totally impossible to get a good match, and then we blame the chronology.*" (Hydrol. Earth Syst. Sci. Discuss., 12, C1022–C1023, 2015). It should be mentioned that this phenomena occurs also in lake sediments and interfere with the chronology unless those layers are varved sediments and the 14C age based chronology can be corrected. With regard our time series correction were performed by flood layers of historically recorded events and by metal peaks in the geochemical record (P. 3405, L. 16, P. -3406, L. 5; P. 3408, L. 1-10).

2) We tested our flood series by cross-correlation with the TSI, summer Temperature and spring precipitation (paleoclimate records illustrated in Figure 8) to study the displacements between the series. Preliminary results show a time lag of 8 years of the paleoflood data regarding the temperature record and TSI, whereas regarding the spring-summer precipitation record the lag rises to 20 years. Further investigation is necessary to validate these findings.

3) With regard the correspondence of the specific flood episodes we suggest that despite of the chronological uncertainties of geoarchives, there is an agreement between paleoflood proxy and TSI. The TSI minimum of 1460 corresponds to the maxima of flooding recorded around 1450 and lays inside the uncertainty interval (P. 3422, L. 6). The same occurs regarding the Maunder and Dalton Minimum, that coincide with maximum flood period. However, there exists also flood periods such as the pulse around 1580 that do not follow this pattern. Nevertheless, the maximum of TSI around 1600 coincides with the lowest summer temperature reconstructed by dendrochronology. The disagreement between TSI and T(JJA) needs further research. Our data are in agreement with the lower summer temperature in the Alps that could be influenced by two episodes of volcanic eruption.

We included the following text at P. 3422, L. 11:

"However, there are also flood periods such as the pulse around 1580 that do not follow the pattern of the TSI: the maximum of TSI around 1600 coincides with the lowest summer temperature (T_{JJA}) reconstructed by dendrochronology. The disagreement between TSI and T_{JJA} needs further research. Our flood data are in agreement with the lower T_{JJA} in the Alps that could be influenced by two episodes of volcanic eruption."

Concerning the double minimum at the early 19th century we suggest that the first flood peak (F1) matches to T minimum, lower TSI and volcanic eruption (Tambora). The increased base discharge of larger glaciers and the melting of snow cover contributed probably to the second flood peak as consequence of the summer temperature rise as discussed in the manuscript (p. 3423, L. 1-4).

4) Regarding the last 150 years we must consider the anthropogenic influence. After AD 1875 the signal of the sedimentary proxy of core AA-05 is masked due to the river management. However, the record of core AA-10 (Fig. 3), located very close to the lake shore and frequently flooded by the river (sometimes also by the lake), show correlation with TSI (Fig. 8) still after 1875.

Discussion point 3:

"Comparing the flood record with the reconstructed summer temperature (b) in this figure, the agreement in my view is still worse: the cooler temperatures in the LIA do not correspond to higher or lower flood frequency, but rather this period is hovering over normal flood frequency. The recent warming seen in the instrumental and reconstructed temperatures does not correspond to any increase or decrease of flood frequency. The period from 1300 until 1550 contains the strongest maxima and minima of flood activity and yet the reconstructed temperature was flat. Can these mismatches be explained by uncertainties in the reconstructions of temperature?"

We agree with the referee 2 concerning the period from 1300 to 1550. A plateau of summer temperature is recognize looking at a lower time resolution (which could be a problem of the temperature curve). But geochemical flood proxy and coarse grained flood layers follow TSI and precipitation reconstruction series. At a decadal resolution the flood periods from 1310-1340 and 1430-1480 coincide with lower temperature pulses.

Discussion point 4:

"*I would strongly recommend to quantify these claimed correlations with series that have been smoothed in a similar way. I may be wrong but I think that the correlation between these records will be quite low. Also, the spectral analysis of these records, whereas suggestive of a causal link, is certainly not sufficient to claim it. First, the uncertainty in the estimated periods is large, in particular for the longer periodicities, so that for periodicities of the order of 100 years, almost everything can be claimed to match. Secondly, do the phases of these periodicities also agree ? This latter point could be addressed by estimating the cross-spectra or more simply by the correlation. It is not expected that there may be a lag between TSI and flood frequency, since temperature proxies do show a simultaneous response to TSI and volcanic forcing."*

As pointed out in the response of discussion point 1 the series has been smoothed homogeneously. In addition, in the response to discussion point 2 we estimated the lags between sedimentary flood proxy and paleoclimate records. Furthermore, we used a method to express the similarities between series: the product moment correlation coefficient (Maddy and Brew, 1995). The results show negative and significant ($p<0.01$; $N=566$) correlations between F1 and precipitation ($r=-0.46$), temperature ($r=-0.32$) and TSI ($r=-0.53$). We also applied cross-spectral analysis between flood damages and sunspot number (Peña et al., 2014; Hydrol. Earth Syst. Sci. Discuss., 11, 13843–13890, 2014) that show periodicity of 105 yr significantly at 95% level.

We included the following text at P. 3421, L. 8:

"The possible correlations of periods of low flood frequencies with the regional climate variability are shown in Fig. 8. In addition, we used a method to express the similarities between series: the product moment correlation coefficient (Maddy and Brew, 1995). The results show negative and significant ($p<0.01$; $N=566$) correlations between F1 scores and late spring and early summer precipitation ($r=-0.46$), summer temperature ($r=-0.32$) and TSI ($r=-0.53$)."

Regarding the methodological scope and limits of spectral analysis we refer to our response to referee #1.

Discussion point 5:

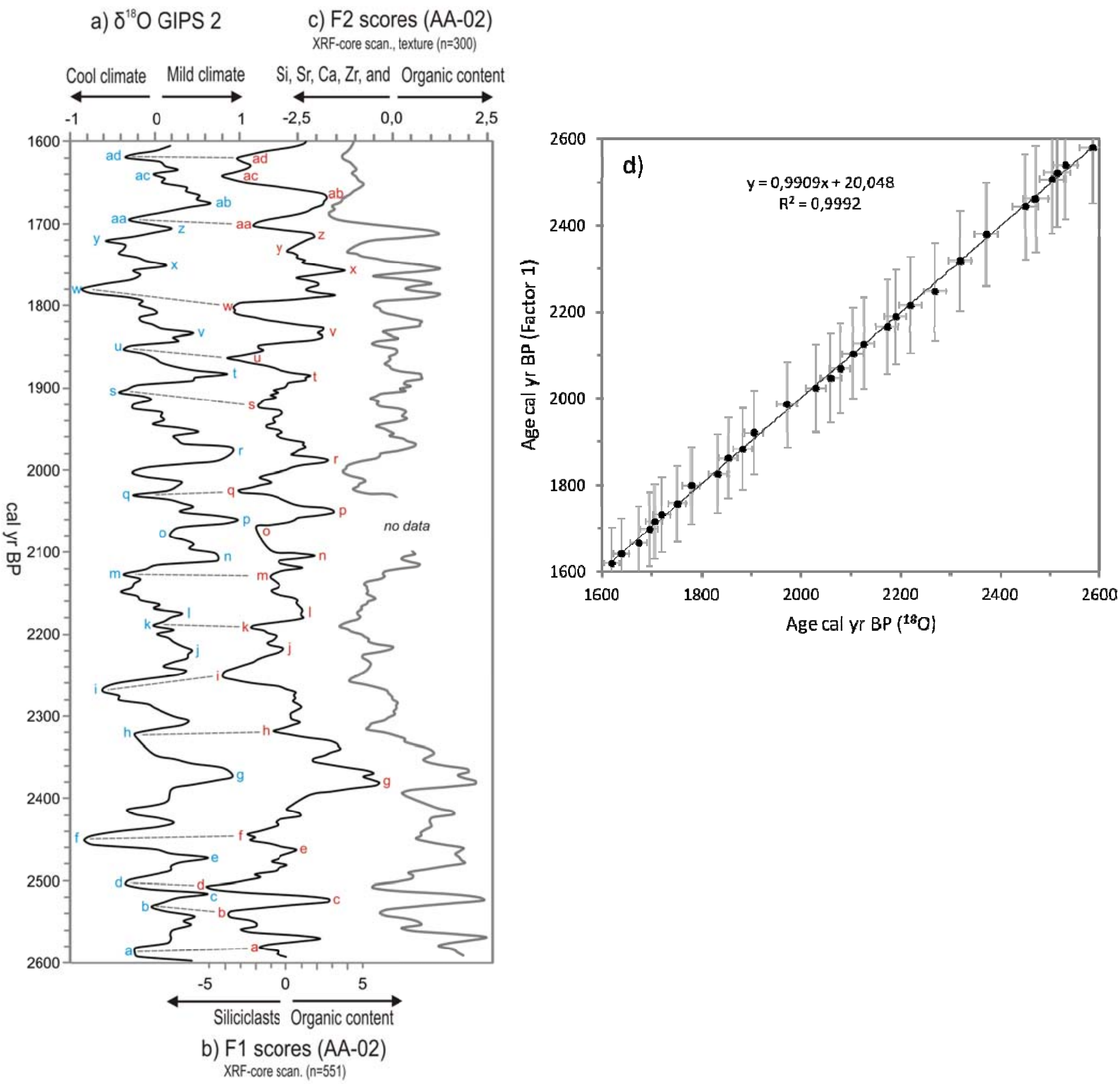
"*Figure 5 presents in my view similar problems. Why does the matching between maxima and minima requires modifying the timescale of the sediment record ? Again, which is the dating uncertainty and which is the approximate time resolution of the flood record . Even allowing for some leeway to re-date the maxima and minima, there are clearly sustained periods of lower and higher values of the delta 18O record that do not match the flood record. For instance between 1700 and 1800 BP, the low-frequency variability of both records is opposite. This happens in many other extended periods*."

As pointed out in the response to the discussion point 2, flood sediments such as the AA-02 series do not maintain a constant sedimentation rate. An appropriate method of comparison of paleoclimate proxies with sedimentary records is to analyze sections of times series which show the same pattern. For example, during the period from 2600 to 1600 cal yrs BP the maxima of organic matter coincide with mild climate, whereas the differences in ages regarding the ^{18}O records are inherent of the problem of the calibration of the chronological model based on radiocarbon datings. However, Figure 5a) shows a good coincidence between ^{18}O (GISP2) and Factor 1 scores. Windward displacements are observed from 1700 and 1800 cal yr BP peaks by 20 years. However, we think that this displacement is acceptable considering the uncertainty range of records approximately 2 millenia old. In addition, leeward displacements up to 40 years are also known from ^{18}O records (Stuiver et al., 1997; Versteegh, 2005) as mentioned on page 3412 (L. 27).

We introduced a new figure to support our findings of correspondance. First, we labeled in Figure 5a maxima and minima of both series with characters from "a" to "ad". Second, we plotted the corresponding pairs of maxima and minima events in figure 5d). This technique is widely used in the interpretation of paleoclimate proxies (e.g. Pèlachs et al., 2011; The Holocene 21 (1), 95-104). When we compare the timing of local minima and maxima of the two series, the time lag between the respective peaks are always within the dating error intervals. The timing of events in both records is consistent.

Figure 5. Comparison of a) $\delta^{18}O$ isotope record from Greenland Ice Sheet (GISP2; Stuiver et al., 1997) and b) Factor 1 scores of scanned Core AA-02 samples from 2600 to 1600 cal yr BP. Correspondence of cool climate pulses and siliciclasts (negative values) are assigned by dashed

lines. Maxima and minima of both series ($\delta^{18}O$ and Factor 1) were labeled with characters from “a” to “ad”. c) Scores of scanned Core AA-02 samples and grain size are plotted for comparison. d) Comparison of maximum and minimum local events a-ad (N=30; Figures 5a) and 5b) of $\delta^{18}O$ isotope record from Greenland Ice Sheet (x axis; GISP2; Stuiver et al., 1997) and Factor 1 scores of scanned core AA-02 samples (y axis) from 2600 to 1600 cal yr BP. Error bars shown at ±5.0% for Factor 1 scores according to ^{14}C chronology after calibration and at ±1.0% for ^{18}O (GISP2) according to Stuiver et al. (1997) indicate that the timing of the selected events is consistent.



Furthermore we introduced the following text in P. 3412, L.18

"Finally, Fig. 5d compares the maximum and minimum peaks between $\delta^{18}O$ and Factor 1 were labeled with characters from "a" to "ad" (Fig. 5a and 5b). This technique is widely used in the interpretation of paleoclimate proxies (e.g. Pèlachs et al., 2011). When we compare the timing of local minima and maxima of the two series, the time lag between the respective peaks are always within the dating error intervals. Thus the timing of events in both records is consistent."

Discussion point 6:

"*A third important concerned is related to the explanations of the link between the flood activity and the Summer North Atlantic Oscillation. This explanation can also be found in other cited manuscripts, like Peña et al. I think it make sense dynamically, but the I also think that the authors are overseeing substantial uncertainties in those reconstruction of atmospheric circulation. Luterbacher et al. state that the SLP reconstructions are skilful in the winter season and that previously to 1700 AD the skill for the summer season is 'lower'. This also makes sense dynamically, since the atmospheric circulation in summer has a smaller scale character- for instance the leading PC in this season explain less variance than in wintertime . Also, previously to around 1700, the set of proxies used for the SLP reconstruction do not contain early instrumental records, but only temperature and precipitation proxies. This poses the problem that any comparison between say flood activity and reconstructed SLP bears the risk of circularity - precipitation proxies explaining precipitation proxies - and it is not guaranteed that this purported relationship is really due to a real dynamical mechanism. An additional point is that temperature proxies do not necessarily record atmospheric circulation anomalies when interpreted at long time scales. The external forcing , like TSI, is different, and so we may have say colder winters caused by lower TSI without any change per se in the NAO. We have to bear in mind that climate model results do not indicate any discernible influence of external forcing on atmospheric circulation over the past millennium , apart from the possible effect of strong tropical volcanic eruptions.*

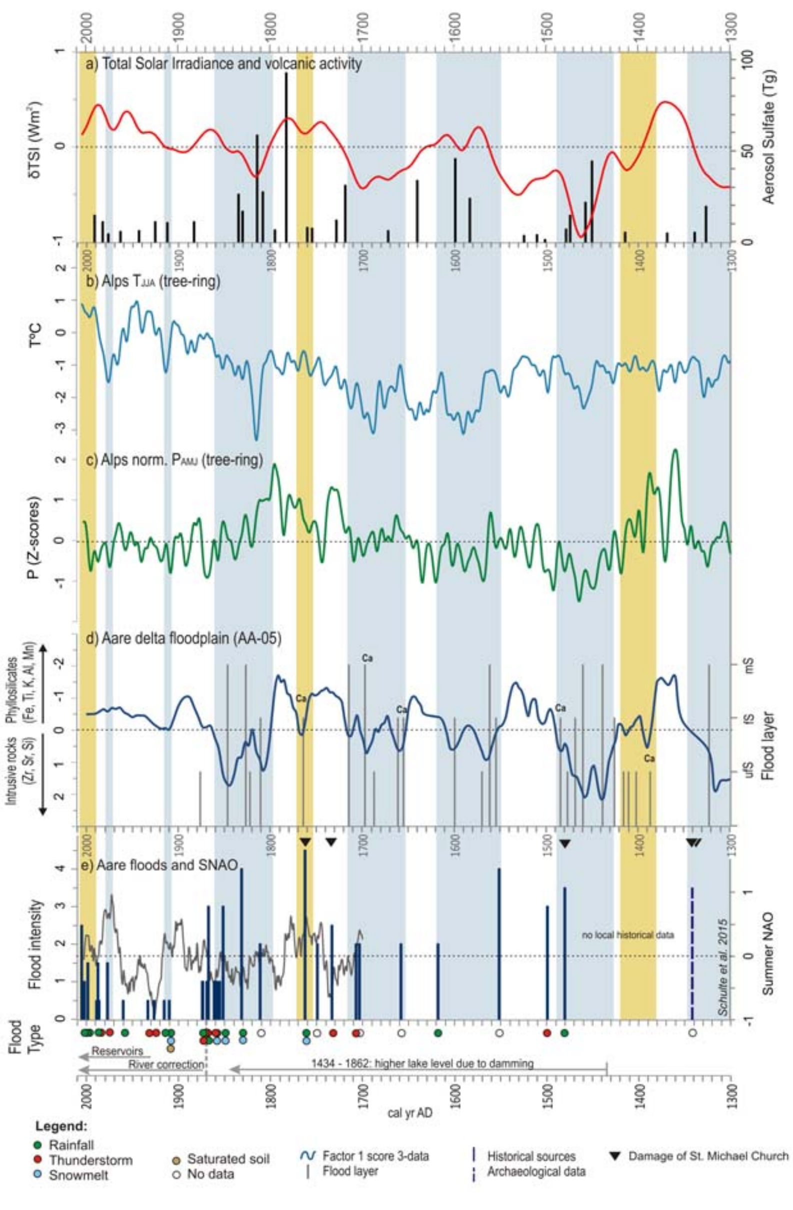
I am aware that it is not easy to disentangle all these links, but I would welcome if these caveats were critically acknowledged and that the SLP and temperature reconstructed were not simply taken as given and used uncritically."

We agree with the Reviewer and introduced the following text at p. 3423 L.20:

"The Summer North Atlantic Oscillation is inferred from the monthly sea level pressure fields over the North Atlantic and Europe, generated by Luterbacher et al. (2002) for the years 1659-2000. This grid was developed, under the assumption of stationarity in the statistical relationships, using a transfer function based on the combination of early instrumental station series and documentary proxy data from Eurasian sites. The function is derived over the 1901–1990 period and was used to reconstruct the 500-year large scale SLP fields (Luterbacher et al., 2002)."

The following figures were slightly modified:

"Figure 8. Comparison between historical flood reconstruction of the Hasli-Aare and solar and volcanic activity and climate proxies (1300-2010 cal yr AD). a) 40-yr averaged variations of Total Solar Irradiance (Steinhilber et al., 2009) and annual stratospheric volcanic sulfate aerosol injection, Northern Hemisphere (Gao et al., 2008). b) JJA temperature anomalies (13-yr Gaussian low-pass filter) in the European Alps reconstructed from larch density series (Büntgen et al., 2006). c) AMJ precipitation anomalies (13-yr Gaussian low-pass filter) in the European Alps reconstructed from larch density series (Büntgen et al., 2006). d) Sedimentary palaeoflood proxy from the Aare delta plain in the Lower Hasli valley (this paper). Factor 1 scores (3-data centred moving average equivalent to 13-year resolution) of chemical composition of core AA-05 samples and coarse grained flood layers (ufS = silty fine sand; fS = fine sand; mS = middle sand). e) Historical flood chronology of the Aare River (Hasli valley) from documentary, archaeological and geomorphological evidences like in figure 7 (this paper). Triangles represent damage of the Sankt Michael church by flooding and severe aggradation caused by the Alpbach river."



"Figure 9. Comparison between reconstructed palaeofloods in the Hasli Valley and solar and volcanic activity and climate proxies from 600 cal yr BC to 2000 cal yr AD. a) Annual stratospheric volcanic sulphate aerosol injection, Northern Hemisphere (Gao et al., 2008). b) 40-yr averaged variations of Total Solar Irradiance (Steinhilber et al., 2009). c) Composite sedimentary palaeoflood proxy at a 21-yr resolution from the Aare delta plain in the Lower Hasli valley (this paper). Factor 1 scores of chemical composition of delta plain samples. Peat and organic soils are shown by dark shaded rectangles. Stars indicate the stratigraphical position of datings. d) $\delta^{18}O$ of the GISP2 ice core from Greenland (Stuiver et al., 1997) at a 21-yr resolution. e) 21-yr smoothed AMJ precipitation anomalies in Central Europe reconstructed from oak ring width series (Büntgen et al., 2011). f) Flood chronology derived from flood deposits of ten lakes from the northern slope and central area of the Swiss Alps (50-year moving average; Glur et al., 2013)."