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# EFFECTS OF SOLAR ACTIVITY AND CLIMATE VARIABILITY ON LARGE FLOODS IN SWITZERLAND

**Juan Carlos Peña Rabadán**
Servei Meteorològic de Catalunya. Generalitat de Catalunya
jpena@meteo.cat
**Lothar Schulte**
FluvAlps Research Group. Departament de Geografia Física i Anàlisi Geogràfica Regional. Universitat de Barcelona
schulte@ub.edu

## I. INTRODUCTION

Climate forcings and their influence on atmospheric circulation changes may have a decisive role in the generation of large floods. Nevertheless, there is no a general consensus of how these forcings influence on extreme floods (Glaser et al., 2010) and there is no a clear link between solar forcing and the physical processes that are involved in climate (Wanner et al., 2008).

The variability of large floods in Switzerland for the period 1800-2008, has been determined from an index of high summer flood damage (*INU*) that considers severe and catastrophic summer floods in Switzerland (Peña et al., *submitted 01/03/2013*). According to our prior results, the flood damage index provides evidences that the 1830-1851, 1881-1927 and 1977 to present flood clusters occur largely in phase with paleoclimate proxies and North Atlantic dynamics. Broadly, these episodes coincide with those reported from Switzerland (Schmocker-Fackel y Naef, 2010) and from some areas of the European continent such as the Czech Republic (Brázdil et al., 2006), Italy (Camuffo and Enzi, 1996) and the eastern half of the Iberian Peninsula (Barriendos and Rodrigo, 2006). However, the relationship is not so close when compared with the flood occurrences in Germany (Glaser et al., 2010). Power spectrum analysis of I*NU* revealed periodicities of 2, 11 and 110 years (Peña et al., *submitted 01/03/2013*). The periodicities of so-called «100-year events» could be explained by centennial-scale solar cycles, which have also been identified in other flood records, including those in eastern France, Switzerland, Netherlands, the UK, Spain and California (see, for example, Magny et al., 2003; Versteegh, 2005; Schulte et al., 2008; 2009).

## II. AIM

The paper analyzes the influences of climatic pulsations over the past 200 years (determined from solar variability, thermal fluctuations and changes in the large-scale atmospheric circulation) on changes in flood frequency of major floods in Switzerland. In order to evaluate the patterns related to phases of high flooding frequencies in Switzerland, the study is structured according to two main objectives:

- The first aim is to establish visual correlation between high-frequency flooding phases with climatic and solar proxies and the Summer North Atlantic Oscillation (SNAO).
- The second analysis focuses on the variability of the different driving forces that generate high-frequency periods in flooding.

## III. DATA AND METHODS

### 3.1. Data

Given the aims of our research, we use three data types: the database of floods in Switzerland between 1800 and 2008; proxies referred to climate ($\delta^{18}O$ record for the period 1800-1987) and solar variability ($^{10}Be$ record for the period 1800-1982); and, gridded data for the reconstruction of low-frequency atmospheric circulation indices. To cover the period 1800-2008 we used the *20th Century Reanalysis V2* (Compo et al., 2011) for the period 1871-2008 and the reconstruction of Luterbacher et al. (2002) of the sea level pressure fields over the Eastern North Atlantic and Europe, to encompass the period 1800-1999.

### 3.2. Methods

The concept of risk (*R*) is used to estimate the index of high summer (July and August months) flood damage (*INU*). *R* is considered to be the product of hazard (*P*) and vulnerability (*V*):

$$R = P * V \quad (1)$$

Floods are classified, according to the magnitude of the damage and economic losses, in severe, very severe or catastrophic floods. The variable *P* is estimated by assigning an arbitrary magnitude to each category (20, 50 or 100, respectively). The variable *V*, defined as the spatial distribution of the phenomenon, is based on the number of cantons affected by a flood episode, so that *V* is assigned a value ranging from 1 to 26. Finally, we obtain by applying equation (1) an *R* value for each flood event. The *INU* is calculated, first, from the sum of all the *R* values on an annual resolution, and, second, by the standardization (based on the mean and standard deviation, both parameters calculated for the period 1800-2008) of all yearly values.

To analyse the influence of atmospheric circulation dynamics, the SNAO is computed for July and August by the main EOF calculated from a Principal Component Analysis (PCA) in S-mode using the covariance matrix without applying any kind of rotation. The PCA is applied to the grid of EMSLP for the domain from 30°N to 70°N and from 30°W to 30°E for the period 1800-2008.

To evaluate possible links between flooding and short-term solar and climatic fluctuations (first objective outlined in section II), the $^{10}Be$, $\delta^{18}O$, and the SNAO records have been plotted alongside the INU index for Switzerland. All the series are shown as normalized values smoothed with an 11-year low-pass Gaussian filter. The second objective, the variability of the different driving forces, is analysed from the databases of the different climate proxies. From the total sample of 209 years, we have created eight categories distinguishing, firstly, between the years without flooding (INU lower than or equal to 0: INU<=0) and the years with at least one flood (INU greater than 0: INU>0); secondly, the flood years are classified into 6 different categories based on INU greater than 0.5 (INU>0.5), 1.0 (INU>1.0), 1.5 (INU>1.5), 2.0 (INU>2.0), 2.5 (INU>2.5) and 3.0 (INU >3.0) times the standard deviation (SD). Finally, the arithmetic mean of $\delta^{18}O$, $^{10}Be$, annual average temperature of Switzerland and SNAO is calculated for the years involved in each of the eight categories. In this way, we can determine the behaviour of each of the variables in relation to the INU, according to the flood intensity.

## IV. RESULTS

The relations between climate forcings, SNAO and INU are shown in figure 1. The main results are outlined below.

- Periods marked by a high flood frequency typically correspond to periods characterized by a predominance of positive $^{10}Be$ anomalies and, therefore, correlate with episodes of low solar activity. This pattern was particularly strong during the solar minimum of 1900.
- The $\delta^{18}O$ record from Greenland prone to the influence of the North Atlantic dynamics, provides a proxy of the temperature variability in the middle and high latitudes of the northern hemisphere. The peak clusters of the flood damage index INU can be related to periods dominated by negative $\delta^{18}O$ anomalies, principally to the cooler pulses of the 19$^{th}$ and the first three decades of the 20$^{th}$ centuries.
- From the correlations of the different proxies, we infer that periods of decreased solar activity and low-frequency cold climate pulses have a fundamental impact on the control of major summer floods in Switzerland. Nevertheless, the non-linear pattern of flood occurrences (e.g. since 1977) needs to be related to the complex relationship between exogenic, endogenic and autogenic climate forcing mechanisms. Therefore, the investigation of flood frequencies should consider hemispheric or global changes of the atmospheric general circulation or ocean currents that affect storm tracks and air mass limits.
- We have identified a qualitative relationship between the SNAO, which synthesize the summer climate in Western Europe, and the summer flood damage index INU. Figure 1 shows that the second, third and fourth clusters of major floods in Switzerland coincide, broadly, with positive phases of SNAO, whereas the first flood cluster is not in

phase with this atmospheric circulation pattern. However, we suggest that the origin of these flood clusters might be attributed to the location of the atmospheric action centres during the positive (or negative) phase.

Figure 1

*RELATION BETWEEN THE ANOMALIES OF INU, $^{10}$BE, δ$^{18}$O AND SNAO FOR THE PERIOD 1800-2008. ALL SERIES ARE PLOTTED AS NORMALIZED VALUES SMOOTHED WITH AN 11-YEAR LOW-PASS GAUSSIAN FILTER. PERIODS OF HIGH FLOOD FREQUENCY ARE OUTLINED ON THE CHART IN GREY. THE δ$^{18}$O SCALE IS REVERSE*

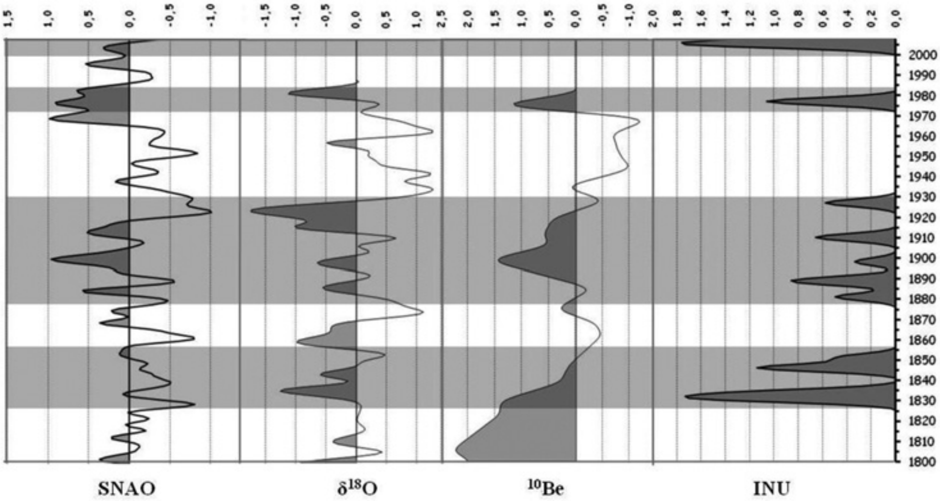



Table 1 shows the mean values of $^{10}$Be, δ$^{18}$O, annual average temperature of Switzerland and SNAO for the years assigned to eight categories of the INU whose thresholds were defined according to the standard deviation. From these values, we can infer two patterns of flood variability.

The first flood pattern is related to major flood events, showing a magnitude of the INU >2 SD. The INU >3 SD category includes the five largest floods events that affected Switzerland over the last 200 years: 1831, 1834, 1846, 1910 and 2005. These events occurred during periods of low solar activity (positive values of $^{10}$Be; mean $^{10}$Be = +0.85) and, with the exception of the 2005 flood, during episodes of cold climate pulses in Greenland (negative values of δ$^{18}$O; mean δ$^{18}$O = -0.83) and in the north-western Alps. During these cold pulses the accumulation of snow and ice in the headwaters is significant, increasing the flood risk during warm years when melting processes contribute markedly to summer discharge. This flood pattern occurs during positive SNAO phases (mean value = +0.58) when depressions are usually associated with the cyclones that develop or become more intense over the Mediterranean Sea, and follow a northeast to north-northeast track crossing the Alps (Fig. 2a). This path is known as Vb and produces long-lasting, intense rainfall due to (1) the high water vapour content from the Mediterranean, (2) the orographic uplift of air masses and (3) the reinforcement suffered by negative anomalies of temperature and geopotential height that occurs at the lower and middle levels of the troposphere.

The second flood pattern is determined by INU-values with a magnitude of the INU <2 SD. These events are related to periods that, firstly, are characterized by low solar activity (positive values of $^{10}Be$; mean values ranges between +0.46 and +0.70) and second, climatically cold (negative values of $\delta^{18}O$; mean values ranges between -0.11 and -0.23). But unlike the first pattern, the SNAO is in the negative phase, especially as regards the category of INU <0.5 times the standard deviation (Table 1; mean SNAO = -0.23). The synoptic configurations of this large-scale atmospheric circulation mode (Fig. 2b) are characterized by cold fronts originating over the Atlantic, tracing a northwest to southeast path.

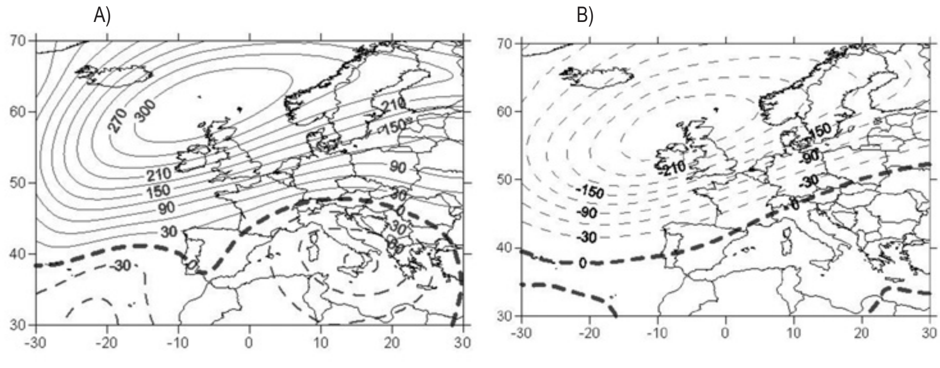
Table 1

*PRINCIPAL STATISTICAL PARAMETERS OF SNAO FOR EACH OF THE CATEGORIES OF THE FLOOD DAMAGE INDEX INU WHOSE THRESHOLDS WERE DEFINED ACCORDING TO THE STANDARD DEVIATION. INU<0 IS HIGHLIGHTED IN DARK GREY*

| | INUi<0 | INUi>0 | INUi>0,5 | INUi>1 | INUi>1,5 | INUi>2 | INUi>2,5 | INUi>3 |
|---|---|---|---|---|---|---|---|---|
| Media $^{10}Be$ | 0.32 | 0.49 | 0.46 | 0.46 | 0.70 | 0.52 | 0.52 | 0.85 |
| $^{10}Be$+ (años) | 96 | 16 | 10 | 9 | 9 | 6 | 6 | 4 |
| $^{10}Be$- (años) | 65 | 6 | 4 | 3 | 1 | 1 | 1 | 0 |
| Media $\delta^{18}O$ | 0.00 | -0.14 | -0.11 | -0.11 | -0.23 | -0.26 | -0.42 | -0.83 |
| $\delta^{18}O$+ (años) | 87 | 11 | 8 | 7 | 5 | 3 | 1 | 0 |
| $\delta^{18}O$- (años) | 79 | 11 | 8 | 7 | 7 | 6 | 6 | 4 |
| Media Tm | 0.00 | -0.02 | 0.02 | -0.04 | 0.02 | 0.08 | 0.31 | 0.95 |
| Tm+ (años) | 91 | 14 | 10 | 8 | 8 | 6 | 6 | 5 |
| Tm- (años) | 93 | 11 | 8 | 8 | 6 | 4 | 2 | 0 |
| Media SNAO | -0.03 | -0.10 | -0.23 | -0.09 | -0.13 | 0.03 | 0.20 | 0.58 |
| SNAO + (años) | 89 | 13 | 8 | 8 | 7 | 6 | 6 | 5 |
| SNAO - (años) | 95 | 12 | 10 | 8 | 7 | 4 | 2 | 0 |

Figure 2

*POSITIVE (A) AND NEGATIVE (B) PHASES OF SNAO MODE ESTIMATED FOR THE 1871-2008 PERIOD, COMPUTED BY THE MAIN EOF CALCULATED FROM A PCA ANALYSIS IN S-MODE. WE USED THE JULY AND AUGUST ANOMALIES (NOT STANDARDIZED) OF GEOPOTENTIAL AT 500 HPA PROVIDED BY 20TH CENTURY REANALYSIS PROJECT. UNITS ARE EXPRESSED IN METRES*




Finally, the enclosed area of negative anomalies of the geopotential at 500 hPa defined by the 0-meter height contour (thick dashed line in Fig. 2a) related to the positive SNAO phase, includes both the Mediterranean and southern Central Europe (including Switzerland) and these areas are characterized by atmospheric instability. This 0-metre height contour in the negative phase (Fig. 2b) separates northern Central Europe (negative anomalies) from southern Central Europe (positive anomalies) and, therefore, Switzerland lies in the area of negative SNAO instability. Thus, extreme hydrological events in Swiss catchments are controlled by the atmospheric processes operating both in the Mediterranean area (disturbance over the Gulfs of Genoa and Venice) and in the North Atlantic (cold fronts channelled between the Scandinavian low and the Atlantic anticyclone).

## V. CONCLUSIONS

From the obtained results we suggest that solar activity (exogenic forcing) and, furthermore, changes in large-scale atmospheric circulation (autogenic forcing), influence in the occurrence of flood periods in Switzerland. It can be concluded that Swiss river catchments are situated in atmospherically unstable areas defined by synoptic patterns related to positive and negative phases of the SNAO mode. Thus, Switzerland is a real 'hotspot' affected by a number of atmospheric processes which have their origin both in the Mediterranean area (the disturbances that develop or become more intense in the gulfs of Genoa and Venice), and in the Atlantic Ocean (cold fronts funnelled by a low located at the latitude of Scandinavia and a high over the Atlantic Ocean).

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