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Holocene flood frequency across the Central Alps – solar forcing and evidence for variations in North Atlantic atmospheric circulation

Stefanie B. Wirth [a,*,1,2], Lukas Glur [b,2], Adrian Gilli [a], Flavio S. Anselmetti [b,c]

[a] Geological Institute, ETH Zurich, Zurich, Switzerland
[b] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland
[c] Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

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ABSTRACT

The frequency of large-scale heavy precipitation events in the European Alps is expected to undergo substantial changes with current climate change. Hence, knowledge about the past natural variability of floods caused by heavy precipitation constitutes important input for climate projections. We present a comprehensive Holocene (10,000 years) reconstruction of the flood frequency in the Central European Alps combining 15 lacustrine sediment records. These records provide an extensive catalog of flood deposits, which were generated by flood-induced underflows delivering terrestrial material to the lake floors. The multi-archive approach allows suppressing local weather patterns, such as thunderstorms, from the obtained climate signal. We reconstructed mainly late spring to fall events since ice cover and precipitation in form of snow in winter at high-altitude study sites do inhibit the generation of flood layers. We found that flood frequency was higher during cool periods, coinciding with lows in solar activity. In addition, flood occurrence shows periodicities that are also observed in reconstructions of solar activity from ^{14}C and ^{10}Be records (2500–3000, 900–1200, as well as of about 710, 500, 350, 208 (Suess cycle), 150, 104 and 87 (Gleissberg cycle) years). As atmospheric mechanism, we propose an expansion/shrinking of the Hadley cell with increasing/decreasing air temperature, causing dry/wet conditions in Central Europe during phases of high/low solar activity. Furthermore, differences between the flood patterns from the Northern Alps and the Southern Alps indicate changes in North Atlantic circulation. Enhanced flood occurrence in the South compared to the North suggests a pronounced southward position of the Westerlies and/or blocking over the northern North Atlantic, hence resembling a negative NAO state (most distinct from 4.2 to 2.4 kyr BP and during the Little Ice Age). South-Alpine flood activity therefore provides a qualitative record of variations in a paleo-NAO pattern during the Holocene. Additionally, increased South Alpine flood activity contrasts to low precipitation in tropical Central America (Cariaco Basin) on the Holocene and centennial time scale. This observation is consistent with a Holocene southward migration of the Atlantic circulation system, and hence of the ITCZ, driven by decreasing summer insolation in the Northern hemisphere, as well as with shorter-term fluctuations probably driven by solar activity.

1. Introduction

1.1. Recent and future alpine flood occurrence

Future geographical and temporal distribution of floods caused by extreme precipitation events is one major concern in the current climate-change discussions (CH2011, 2011; IPCC, 2012). In recent decades, the Alpine realm has experienced exceptionally heavy and disastrous floods that caused extensive social, economic, and infrastructural damage (e.g. 1978, 1987, 1999, 2005) (Hilker et al., 2009). Furthermore, a very recent worldwide increase in heavy floods (e.g. Pakistan (2010), Australia (2010–11) and Thailand (2011)) has intensified the scientific but also the broad public sensibility for this natural hazard. Based on the Clausius–Clapeyron equation (Berg et al., 2009; Trenberth, 2011), it could generally be expected that heavy precipitation events become more frequent and/or intense with global warming due to an increasing water vapor carrying capacity with higher air temperatures. However,

* Corresponding author.
E-mail address: stefanie.wirth@alumni.ethz.ch (S.B. Wirth).
[1] Present address: Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA.
[2] Both authors contributed equally to this work.

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changes in mean precipitation and especially in heavy precipitation events are highly variable since their distribution is controlled by complex atmospheric circulation cells whose position and meridional expansion are governed by changes in air and sea-surface temperature (Trenberth, 2011).

Climate simulations project an increase/decrease in annual mean precipitation for Northern/Southern Europe by the end of the 21st century (CH2011, 2011; Rajczak et al., 2013). The Alpine realm is located at the North–South transition zone, where projection uncertainties for fall and spring precipitation are high (CH2011, 2011). During summer (winter), however, the transition zone is located in Northern (Southern) Europe, thus simulations predict dry (wet) conditions for the Alps. Concerning precipitation intensity, a general intensification of the events due to increasing air temperatures (i.e. intensified convection) is expected, regardless of the season and the magnitude of change in mean precipitation (Berg et al., 2009; CH2011, 2011; Rajczak et al., 2013). Thus, an intensification of precipitation but a decreasing event frequency is for instance expected for summer. Yet, there are uncertainties in precipitation simulations, mostly arising from unexpected changes in large-scale atmospheric circulation, convection, and the role of soil feedbacks (Frei et al., 2006; Christensen and Christensen, 2007; Seneviratne et al., 2010; CH2011, 2011).

The increase in financial damage caused by summer and autumn floods in the Swiss Alps during recent decades (e.g. in 1987, 1993, 2005, 2007) (Hilker et al., 2009) contrasts to the from climate warming expected decrease in the frequency of heavy summer precipitation. This discrepancy could be explained by an increase in precipitation intensity, or, alternatively, by the high susceptibility of modern and cost-intensive infrastructure to damage. Infrastructure is, due to a lack in space, often built at locations exposed to natural hazards. Furthermore, awareness for floods was lost because of the so-called 'disaster gap' between 1882 and 1976 (Röthlisberger, 1991; Pfister, 2009; Schmocker-Fackel and Naef, 2010b) and therefore prevention measures were neglected. Hence, in order to gain more clarity on the recent flood occurrence, improved knowledge on the natural variability of intense precipitation and related floods is needed. However, instrumental data series and historic documentations cover at most the past 500 years (Schmocker-Fackel and Naef, 2010a), which are heavily influenced by the Little Ice Age (LIA) cold period and are therefore little representative for a warmer climate. Thus, for reconstructing flood recurrence rates on a longer, multi-millennial time scale, geological climate archives have to be used.

1.2. Lakes as recorders of past flood events

Lacustrine sediment records are an excellent archive for reconstructing past flood occurrence as they record flood events in a continuous and high-resolution mode (e.g. Noren et al., 2002; Moreno et al., 2008; Debret et al., 2010; Giguet-Covex et al., 2012; Støren et al., 2012; Wilhelm et al., 2012; Czymzik et al., 2013; Gilli et al., 2013). Lake sediments also have the advantage that they are not prone to subsequent erosion such as e.g. riverine overwash deposits and fluvial sedimentary sequences (e.g. Sheffer et al., 2003; Macklin et al., 2005; Thorndycraft et al., 2005).

Extreme precipitation mobilizes and entrains large amounts of sediment particles in the catchment area that are consequently fed into the river drainage. When this dense sediment-laden river water reaches the next down-stream lake, the plume plunges down and proceeds as a turbiditic underflow (Siegenthaler and Sturm, 1991; Mulder et al., 2003). Once the deepest lake area is reached, the underflow spreads out, flow velocities decrease and sediment particles are deposited forming characteristic 'turbidite' layers (Mulder and Chapron, 2011; Gilli et al., 2013). These 'turbidites' or 'flood layers' show a characteristic particle-size grading reflecting the waxing (i.e. coarsening up) and waning (i.e. fining up) of the flood hydrograph (Mulder et al., 2003; Lamb and Mohrig, 2009; Mulder and Chapron, 2011). In addition, they are composed of detrital mineral grains and terrestrial organic material, and are often covered by a clay cap, representing the final fine-grained rain out of the turbidity flow.

Similarly, subaquatic mass movements triggered by e.g. earthquake-induced shaking, delta overloading or lake-level fluctuations generate turbiditic underflows (e.g. Girardclos et al., 2007; Strasser et al., 2007; Wirth et al., 2011). Hence, it is important to distinguish between flood- and mass-movement-induced turbidite layers (Beck, 2009; Wirth et al., 2011; Simonneau et al., 2013). In contrast to flood turbidites, mass-movement turbidites consist of remobilized lake sediments, thus showing a different mineralogical and organic composition characterized by a higher content of authigenic minerals and a dominance of aquatic organic material. In addition, they are often, but not necessarily, thicker than flood layers. Moreover, the grain-size pattern differs from flood layers due to the different dynamics of the sedimentary processes. In contrast to flood material, mass-movement material is released instantaneously, which often results in a weaker grain-size sorting (Arnaud et al., 2002; Simonneau et al., 2013). In addition, different sedimentary facies of the lake-slope sediments (e.g. clay-, silt-, organic-, diatom-rich) result in less characteristic and thus less commonly valid grain-size patterns than in the case of flood deposits.

Snowmelts are not expected to provoke turbiditic underflows in the investigated lakes. Since the catchments of the lakes are relatively small and snow melting is a gradual process, released water volumes are not large and powerful enough to mobilize considerable sediment amounts (Lamoureux, 2000; Parris et al., 2010).

1.3. Study area and setup

We investigated 15 lacustrine sediment records from the Northern (N-Alps) and Southern (S-Alps) Central Alps (Fig. 1) and established a comprehensive flood catalog for the past 10,000 years. Covering this long time period provides the possibility to investigate flood occurrence during warm (e.g. Holocene Thermal Maximum) and cool (e.g. Neoglaciation) Holocene periods, potentially providing information on characteristic atmospheric circulation patterns during different climatic conditions. This aspect might be particularly interesting in terms of the position of the westerly storm tracks (Westerlies), for which a northward shift is expected with current climate warming (Toggweiler, 2009; Woollings et al., 2012). Applying a multi-archive approach seems necessary for the reconstruction of large-scale precipitation in an orographic setting like the Alps. Single enclosed Alpine valleys are prone to convective, thus spatially limited, events such as thunderstorms. Using multiple archives we aim to exclude the scattered occurrence of such events from the overall signal. In addition, undesired and possibly unknown lake-specific peculiarities like glacier influence or strong variations of vegetation in the catchment, modifying the lake's susceptibility to record heavy precipitation events, can be reduced. Moreover, variation in the frequency pattern between low- and high-altitude lakes might provide information on the seasonal occurrence of the floods, since lakes located at high altitudes are ice-covered during the winter half year and thus do not record events during the cold seasons. In addition, differences between the N-Alps and the S-Alps potentially provide information on variations in North Atlantic and Mediterranean climate (strength and meridional position of westerly winds; circulation patterns over the North Atlantic such as the North Atlantic Oscillation (NAO)) (e.g. Trigo et al., 2006; Trouet et al., 2009; Martin-Puertas et al., 2012). Finally, comparing our results to climate reconstructions from lower latitudes, in particular tropical areas, offers the possibility to