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A millennial-long record of warm season precipitation and flood frequency for the North-western Alps inferred from varved lake sediments: implications for the future

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A B S T R A C T

The recent warming of the global climate is well recognized. However, does a warmer climate also mean a moister climate? Does dry get drier and wet get wetter? There are important questions as they relate to changes in the water cycle and impacts the water resources as well as the frequency and intensity of storms and floods in the near future. In Europe, regional climate models do not show consistent and robust results for future hydroclimatic changes and how extreme events will evolve in response to future climate change.

Paleo-hydroclimatic data from natural archives are one of the few means to assess such changes in the longer context. Here, we present an annually-resolved record of warm season (MJJA) precipitation and summer flood frequency from the varved (annually laminated) sediments of proglacial Lake Oeschinen (46°30′N–7°44′E, 1580 m, NW Swiss Alps) back to AD 884. These data sets are inferred from the thickness of annual sediment deposits and the occurrence of flood event layers in the sediments. The chronology of the sediment record is based on multiple varve counts and validated with historical floods chronicled in written documents (back to the 14th century) and ^{14}C AMS dates.

The precipitation record shows pronounced interannual to centennial variability with humid warm season phases between AD 920–950, AD 1100–1180, AD 1300–1400, AD 1590–1650, AD 1700–1790, AD 1820–1880, and AD 1960–2008. Driest conditions are reconstructed for AD 960–1080, AD 1250–1300 and for AD 1880–1900. Our precipitation record is consistent with the few multi-centennial warm-season precipitation records available for Europe.

We did not find a persistent relationship between warm-season precipitation and temperature. In contrast, results show that the relation between precipitation and temperature has oscillated between positive correlations (warmer gets wetter, cooler gets drier) and negative correlations (warmer gets drier, cooler gets wetter) with a highly significant ($\chi^2 = 99\%$) multidecadal (60–70 yrs) periodicity over the last millennium. Possible explanations for this phenomenon are changes in the weather type statistics or the within-weather-type variability, which influence the combinations between precipitation and temperature over continental central Europe and operate at multidecadal scales. Such multidecadal effects might also be important for precipitation scenarios in the Alpine area under future warming.

Our record of flood frequency suggests more frequent floods under cool and humid climate during the warm seasons. This picture is consistent with other studies from small and medium size catchments at mid- and high elevations in the Alpine area. However, the 13th century reveals a period with high flood frequency during warm and moderately dry (average precipitation) conditions. This anomalous situation is currently not understood; nonetheless, this is also one out of several possible scenarios for the future. From the different combinations found in our record, we conclude that the relation between floods, precipitation and temperature and, in consequence, future projections remain poorly constrained.

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1. Introduction

Our climate is warming. The recent warming is unequivocal and many of the observed changes are unprecedented over decades to millennia. This is one of the key findings of the latest comprehensive scientific assessments of climate change (IPCC, 2013) based on observations and multiple lines of other independent evidence.

However, does a warmer climate also mean a moister climate? A theoretical response to the warming is an increase in evaporation and precipitation following the Clausius–Clapeyron relation. Although at slower rates, Held and Soden (2006) showed that 'moistening' is the case at global and hemispheric scales. Yet, this thermodynamic relationship between temperature, moisture and precipitation can be complicated at regional scales and a pattern "dry gets dryer and wet gets wetter" is rather expected (Held and Soden, 2006; O'Gorman and Muller, 2010). However, in a recent study Greve et al. (2014) found that only 10.8% of the global land area show a robust 'dry gets drier, wet gets wetter' pattern (DDWW paradigm); 9.5% of global land area show robust opposite patterns ('dry gets wetter and wet gets drier'), and for most of the land areas the relationship is not conclusive. Thus, large uncertainties still remain due to differences in hydroclimatic conditions among regions and among seasons, and due to spatial and temporal data scarcity (Trenberth and Shea, 2005; Huntington, 2006).

Changes in the hydroclimate are most relevant since they relate to changes in regional water resources directly. Moreover, changes in the hydroclimate may also lead to changes in the frequency and intensity of storms and floods in the near future (Köplin et al., 2014). Changes in the properties of such extreme events are of particular concern to society, especially in vulnerable Alpine areas (IPCC, 2012; Christensen et al., 2013; Smith, 2013). However, it remains poorly understood how changes in temperature, precipitation and regional synoptic-scale weather patterns interact and how the properties of extreme events (floods but also droughts) might eventually change. In Europe for instance, future projections of strong 72 h rainfall events from high-resolution regional climate models do not show a consistent and robust climate change signal (CH2011, 2011).

This leads to the following questions we want to address in the present study:

- Has the climate in the region of the NW Swiss Alps responded according to the Clausius–Clapeyron relation (positive correlation between temperature and precipitation) and to the 'wet gets wetter' scheme over the past millennium? Or is the climatological relation between temperature and precipitation not stationary over time and modulated by other effects?
- Was flood frequency dependent on air temperature and precipitation in the past? For instance, were floods more frequent in warmer, colder, wetter or drier climates?

Over the past few decades, the study of past precipitation variability has received relatively little attention, while considerable efforts have been devoted to investigate past temperature changes at regional scales (PAGES 2k Consortium, 2013). This can be attributed to the paucity of precipitation-sensitive proxies and a lack of data, which makes comprehensive assessments of long-term regional changes in precipitation difficult. This data situation has been described as "low confidence", "geographical inconsistency", "difficult spatial interpretations", "syntheses too limited to support regional assessment", or "substantial uncertainty due to large regional differences" (Büntgen et al., 2010; Wilson et al., 2013; Masson-Delmotte et al., 2013; PAGES 2k Consortium, 2013).

Scarcity of data is also the case in Europe where only a few multi-centennial- to millennial-long quantitative precipitation reconstructions exist. These were produced from documentary data and moisture-sensitive tree rings mainly (Brázdil et al., 2002; Linderholm and Chen, 2005; Wilson et al., 2005, 2013; Jönsson and Nilsson, 2009; Büntgen et al., 2011; Dobrovolný et al., 2015), and from a few lake sediment records (Trachsel et al., 2008; Romero-Viana et al., 2011).

Besides, growing attention has been paid to the reconstruction of floods and flood frequency in Europe, notably using lake sediments. Lakes are excellent natural archives that offer the great opportunity to study past flood events (Glur et al., 2013). Detrital flood layers found in the sediment cores can be linked directly to flood events recorded in instrumental or documentary sources (Debret et al., 2010; Giguet-Covex et al., 2012; Wilhelm et al., 2012a, 2013; Gilli et al., 2013; Wirth et al., 2013b). Further, particularly valuable records have been recovered from varved (annually laminated) lake sediments. These varves provide up-to-seasonal resolutions and may reduce chronological uncertainties significantly (Zolitschka, 2007; Czymzik et al., 2010, 2013; Stewart et al., 2011; Swierczynski, 2012, 2013; Wirth et al., 2013a; Corella et al., 2014).

Recently, Lake Oeschinen, a high elevation (1580 m a.s.l.) proglacial varved lake in the North-western Swiss Alps has shown to be an excellent archive to record past warm-season precipitation and flood frequency variability with a reliable and precise varve chronology (Amann et al., 2014). For the calibration period 1901–2008, varve thickness was found to be a quantitative predictor for warm season (MJJA and MJ) precipitation ($r_{MJJA} = 0.6$; $r_{MJ} = 0.7$, $p < 0.01$, $n = 108$).

This calibration model 'varve thickness–precipitation' is the basis for the precipitation reconstruction back to AD 884 presented here. We use the varve thickness record from Lake Oeschinen to reconstruct past spring/summer precipitation conditions in the North-western Swiss Alps, which we then compare with temperature variability reconstructed from tree ring data for the same region. Finally, we use the occurrence of flood layers in the sediment of Lake Oeschinen to investigate, for the first time, the long-term relationship between flood frequency and the amount of precipitation from the same location and the same archive.

2. Study site and sediment formation

Lake Oeschinen (46°30′N, 7°44′E) is a proglacial lake situated at 1580 m a.s.l. in the North-western Alps, 55 km south of Bern, Switzerland (Fig. 1A). A Holocene rockslide formed the lake basin about 9.5 cal ka BP (Niklaus, 1967). The 56-m deep lake has a subsurface outflow through the rockslide and drains into the Kander River (Fig. 1B and D). In winter, ice cover generally develops in December and melts in late April.

Mesozoic limestone predominates in the catchment; however, it is interrupted by two sizable belts of Tertiary Flysch deposits (Fig. 1D) that consist of easily erodible siliciclastic-rich sandstones (Suchy et al., 1997). Glacier cover accounts for 30% of the lake catchment.

The mineralogical composition and distribution of the bedrock (limestone in the high-elevation glaciated areas, siliciclastics in the lower elevation Flysch areas) is important for the varve formation (Amann et al., 2014). During spring snowmelt and summer rainfall, a coarse-grained dark basal layer is formed. This layer is enriched in siliciclastics eroded from the northern Flysch catchment. During winter, clay-size bright calcite particles settle through the water column under very calm conditions when the lake is frozen. These fine particles are produced by glacier abrasion in the limestone part of the catchment and transported by meltwater into the lake during the entire ice-free season. The thin winter layer has been shown to