A 2000 year long seasonal record of floods in the southern European Alps

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A 2000 year long seasonal record of floods in the southern European Alps

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[1] Knowledge of past natural flood variability and controlling climate factors is of high value since it can be useful to refine projections of the future flood behavior under climate warming. In this context, we present a seasonally resolved 2000 year long flood frequency and intensity reconstruction from the southern Alpine slope (North Italy) using annually laminated (varved) lake sediments. Floods occurred predominantly during summer and autumn, whereas winter and spring events were rare. The all-season flood frequency and, particularly, the occurrence of summer events increased during solar minima, suggesting solar-induced circulation changes resembling negative conditions of the North Atlantic Oscillation as controlling atmospheric mechanism. Furthermore, the most extreme autumn events occurred during a period of warm Mediterranean sea surface temperature. Interpreting these results in regard to present climate change, our data set proposes for a warming scenario, a decrease in summer floods, but an increase in the intensity of autumn floods at the South-Alpine slope.
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1. Introduction

[2] Floods as a result of heavy precipitation events represent a major natural hazard in the Alpine region, with an increasing trend of infrastructural, financial, and social damages during the past 30–40 years [*Hilker et al.*, 2009]. Climate projections for the Alpine region show a decrease in the frequency of heavy precipitation events in summer and an increase in winter for the coming decades, as well as a potential intensification of heavy rainfall during all seasons due to the Clausius-Clapeyron relationship [*CH2011*, 2011, and references therein]. However, uncertainty of intensification predictions is considered as relatively large as influences of circulation dynamics and precipitation processes are not fully understood. In this respect, Alpine lake sediments provide ideal archives for improving our knowledge on the natural flood occurrence. They record floods in a continuous and high-resolution mode as washed-in detrital material intercalated into the regular lacustrine sediments. Due to their different chemical and mineralogical compositions, these deposits are detectable within the authigenic sediment succession using different methodological approaches [*Gilli et al.*, 2013]. In the case of varved sediments, microfacies analysis even allows determining the season in which the floods occurred [*Mangili et al.*, 2005; *Swierczynski et al.*, 2012] and, thus, provides exceptionally highly resolved flood catalogues.

2. Study Site and Methods

[3] Lake Ledro (45°52′36″N/10°45′2″E, 46 m maximum water depth, 2.18 km^2 surface area, 111 km^2 catchment area) is situated on the South Alpine slope (Trento province, North Italy) at 653 m above sea level (asl) (Figure 1). The carbonate-dominated (Mesozoic sediments) catchment area, as well as a water depth large enough to facilitate the formation of anoxic bottom waters, enables the formation and preservation of biochemical calcite varves [*Hsü and McKenzie*, 1985].

[4] Seasonal precipitation distribution in the study area is characterized by highest amounts during summer and autumn (Figure S1 in the supporting information). Heavy precipitation events are generated by Atlantic frontal systems, which are potentially combined with convective-orographic cyclones developing over the northern Mediterranean Sea, with the Gulf of Genoa as the nearest cyclogenetic hot spot (Figure 1) [*Trigo et al.*, 2002; *Winschall et al.*, 2012]. The described combined scenario may trigger torrential rainfall events in autumn when the land-sea temperature contrast in the Mediterranean area is at the highest [*Trigo et al.*, 2002; *Lebeaupin et al.*, 2006].

[5] The studied sediment succession was retrieved from the deepest area of the lake, which is most susceptible to record flood events (for details on lake-basin stratigraphy and sediment description, see the supporting information) [*Simonneau et al.*, 2013; *Vannière et al.*, 2013]. Exemplary thin sections, as well as XRF core scanning and μ-XRF mapping (see the supporting information for methodological details) on selected core sections and areas, in combination with continuous high-resolution core pictures (60 pixels per millimeter), served for microfacies analysis of the annual lamination and of flood deposits (Figure 2). Age control for the 2000 year long record (Figure S4) is based on ^{137}Cs

Additional supporting information may be found in the online version of this article.

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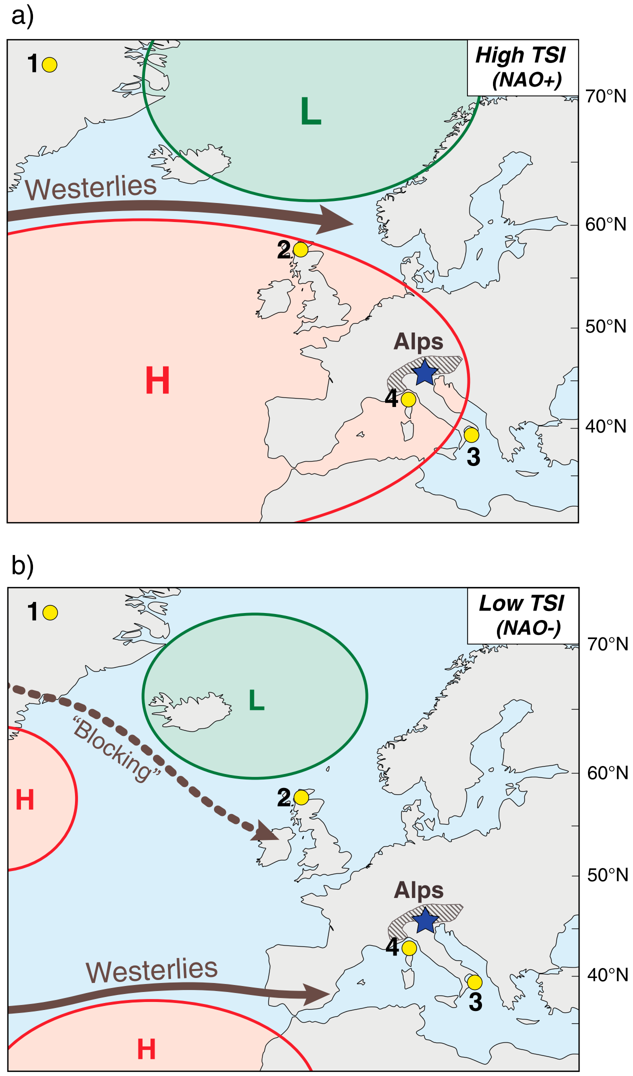

Figure 1. Study site (blue star) and simplified sketch of position of westerlies as well as NAO state during periods of (a) high and (b) low TSI. Yellow dots indicate other locations mentioned in this study: (1) ssNa record from the GISP2 ice core (Figure 3a) [*Mayewski et al.*, 1997]; (2) stalagmite growth rate record from Scotland (Figure 3b) [*Proctor et al.*, 2002]; (3) δ^{18}O record from the Gulf of Taranto (Figure 3g) [*Grauel et al.*, 2013]; and (4) the Gulf of Genoa, representing for the study site the most important Mediterranean hot spot of cyclogenesis [*Trigo et al.*, 2002].

activity dating and event stratigraphy (earthquakes, human impact) for the most recent century and, prior to 1901 A.D., on varve counting (estimated error of the varve age model: ±2.5%; e.g., ±13 years at 1500 A.D., ±50 years at 1/1 B.C./A.D.). The flood deposit thickness is considered to reflect the river discharge volume and is therefore often used as a relative indicator of flood intensity [e.g., *Wilhelm et al.*, 2012]. Yet the mobilization of sediment material may be influenced by sedimentary changes in the catchment area, e.g., due to natural variations in vegetation cover or deforestation. In the case of Lake Ledro, lake level reconstructions, which constitute an independent paleohydrological record, match the flood layer signal, indicating that precipitation changes must be the main control on flood layer generation [*Vannière et al.*, 2013] (S. B. Wirth et al., Holocene flood frequency across the Central Alps—Solar forcing and evidence for variations in North Atlantic atmospheric circulation, submitted to *Quaternary Science Reviews*, 2013). Nevertheless, we do not interpret here the subtle thickness variations among flood layers <10 mm but concentrate on the large thickness contrasts and on the thickest deposits, i.e., the most extreme floods, in particular.

3. Results

[6] µ-XRF analysis indicates that the light beige laminae of the Lake Ledro sediments are nearly exclusively composed of fine-grained calcite, while the elements Fe, Si, K, Al, and Ti occur in the dark brown laminae (Figure 2b). The former are therefore interpreted as summer laminae consisting of authigenically precipitated calcite, triggered by increased water temperatures facilitating algal blooms and increasing the lake water pH [*Hsü and McKenzie*, 1985]. The latter represent the winter laminae, reflecting the slow settling of fine-grained organic and clay particles [*Hsü and McKenzie*, 1985]. Flood layers are brown-colored sediment intervals of millimeter to centimeter thickness generally characterized by grain size–dependent elemental concentration trends. Coarse-grained parts, i.e., flood deposit bases, are rich in Ca (Figure 2a), indicating a predominant occurrence of the minerals calcite and dolomite. Decreasing grain size toward the flood layer tops coincides with increasing concentrations of Fe, Si, Al, K, and Ti, reflecting an increasing amount of clay minerals. Basal erosion due to underflow currents at the core location is minor. Only below the thickest flood deposit (10.4 cm thick) recorded during the past 2000 years, erosion of 1 or 2 varve years is evident, indicated by fragments of lamination incorporated into the deposit's basal part (Figure S3).

[7] The flood frequency pattern incorporating all seasons (Figure 3d) presents strong variations over the past 2000 years with major peaks at 90–220, 680–730, 1200–1300, 1480–1530, 1650–1780, and 1810–1900 A.D. On the longer time scale, a conspicuous two-part division characterized by a higher flood frequency level during the more recent millennium than in the first half of the record is observed. The overall seasonal distribution reveals a dominance of summer (129 floods; 26.2%) and autumn (312; 63.4%) floods, while winter (18; 3.7%) and spring (33; 6.7%) events are rare.

[8] Summer events (Figure 3e) show frequency peaks at 80–210, 680–720, 1200–1280, 1490–1570, 1650–1780, and 1810–1900 A.D. and are primarily responsible for the above-described two-part division of the frequency pattern. Furthermore, the temporal behavior of the intensity of summer floods resembles one of the frequencies. The autumnal flood frequency pattern (Figure 3f) strongly resembles the summer record between 1000 and 2000 A.D. but is characterized by a higher flood recurrence rate in the first half of the record. Moreover, frequency and intensity of autumn events do not seem to be as strongly linked as observed for summer events. The largest discrepancy between the summer and autumn records is observed from 500 to 1000 A.D., when the autumn record is characterized by a clearly higher flood recurrence rate and when four out of the five most intense autumn events occur (at 616, 718, 896, and 903 A.D.) (Figure 3f). Spring events (Figures 3d and S6i) approximately follow the frequency pattern of summer events.

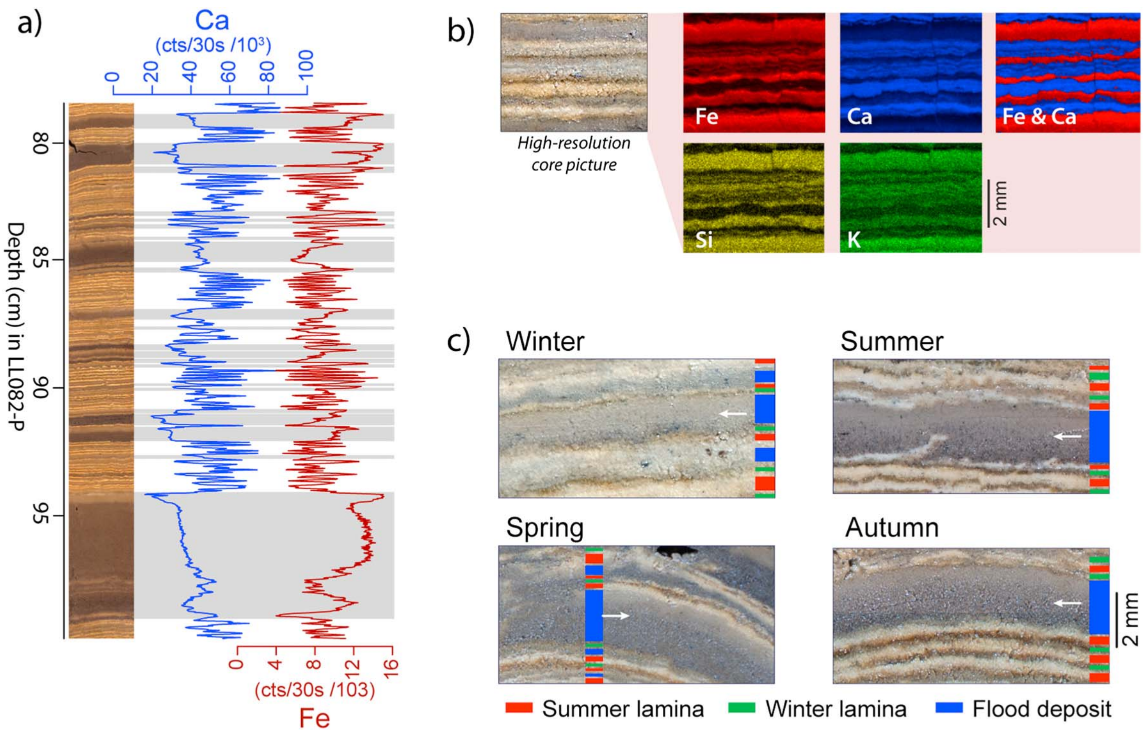

Figure 2. (a) XRF core scanning results (down-core resolution of 0.2 mm) with core picture illustrating the contrasting pattern of Ca and Fe (also representing Al, Si, K, and Ti) within flood deposits (marked by grey areas) and lamination. (b) Chemical characterization of the varve components using µ-XRF maps (spot size of 50 µm; area of 6 × 5 mm), presenting Ca-dominated summer laminae and winter laminae rich in Fe, Si, and K. (c) Examples for the seasonality determination of flood deposits given by the stratigraphic position within the annual varve cycle. Winter and summer flood layers split the winter and summer laminae into two parts; spring and autumn layers occur on top of them.

Winter events (Figures 3d and S6j) show a scattered occurrence, except for a slight frequency increase during the nineteenth and twentieth centuries. The thickness of both spring and winter deposits is small (<4 mm).

4. Discussion

[9] The dominance of summer and autumn events in our flood reconstruction agrees with the seasonality of floods in the Alpine region during the past 500 years as evidenced by instrumental and historic data [*Hilker et al.*, 2009; *Schmocker-Fackel and Naef*, 2010]. With this confidence of a representative flood reconstruction, climate factors and atmospheric circulation patterns potentially underlying our seasonal flood signal are discussed in the following paragraphs.

[10] The comparison of the stacked seasonal flood signal with variations in total solar irradiance (ΔTSI) [*Steinhilber et al.*, 2009] reveals a conspicuous similarity between the records, characterized by a higher flood occurrence during phases of low TSI (Figures 3c and 3d). This resemblance is even more distinct for summer (Figure 3e) than autumn events (Figure 3f). In particular, during the past 800 years, the synchronicity of summer floods with the well-known solar minima Dalton, Spoerer, Maunder, and Wolf is evident. The effect of ΔTSI on the Earth's climate has been intensively discussed in the scientific literature [e.g., *Gray et al.*, 2010; *Martin-Puertas et al.*, 2012]. The absolute variation of TSI lies in the range of ±1 Wm^{-2} only, and therefore, the direct influence on air temperature must be relatively small. Yet feedback mechanisms affecting ocean-surface, ozone, or cloud-cover response have been proposed for the comparably large observed impact of small solar variations on atmospheric circulation and on the Hadley and Walker circulation in particular [*Gray et al.*, 2010, and references therein]. Paleoclimatic studies from Europe and northern Africa [*Trouet et al.*, 2009; *Martin-Puertas et al.*, 2012; Wirth et al., submitted manuscript, 2013], as well as general circulation model experiments [*Shindell et al.*, 2001] demonstrated that solar variations induce circulation shifts over the North Atlantic. Specifically, solar lows have been attributed to a more negative state of the North Atlantic Oscillation (NAO) (or a corresponding paleocirculation pattern), thus, to a reduced north-south pressure gradient over the North Atlantic and a southerly position of the westerlies (Figure 1b). These settings lead to positive precipitation anomalies in the northwestern Mediterranean area [*Xoplaki et al.*, 2004]. Therefore, we compared our flood reconstruction with records reflecting NAO variations over 2 kyrs, i.e., sea salt sodium (ssNa) from the Greenland Ice Sheet Project 2 (GISP2) ice core (Figure 3a) [*Mayewski et al.*, 1997] and a growth rate stalagmite record from Scotland (Figure 3b) [*Proctor et al.*, 2002; *Trouet et al.*, 2009]. These NAO-proxy records show striking similarities with our flood reconstruction, suggesting that more negative NAO conditions fostered more frequent floods in the southern Alps during the past 2 kyrs. However, one noticeable feature is the missing signal for the Wolf solar minimum (1280–1350 A.D.) in the two NAO-proxy records, which is, to our knowledge, unexplained at the current time, and an also currently unexplained offset of about 50 years for

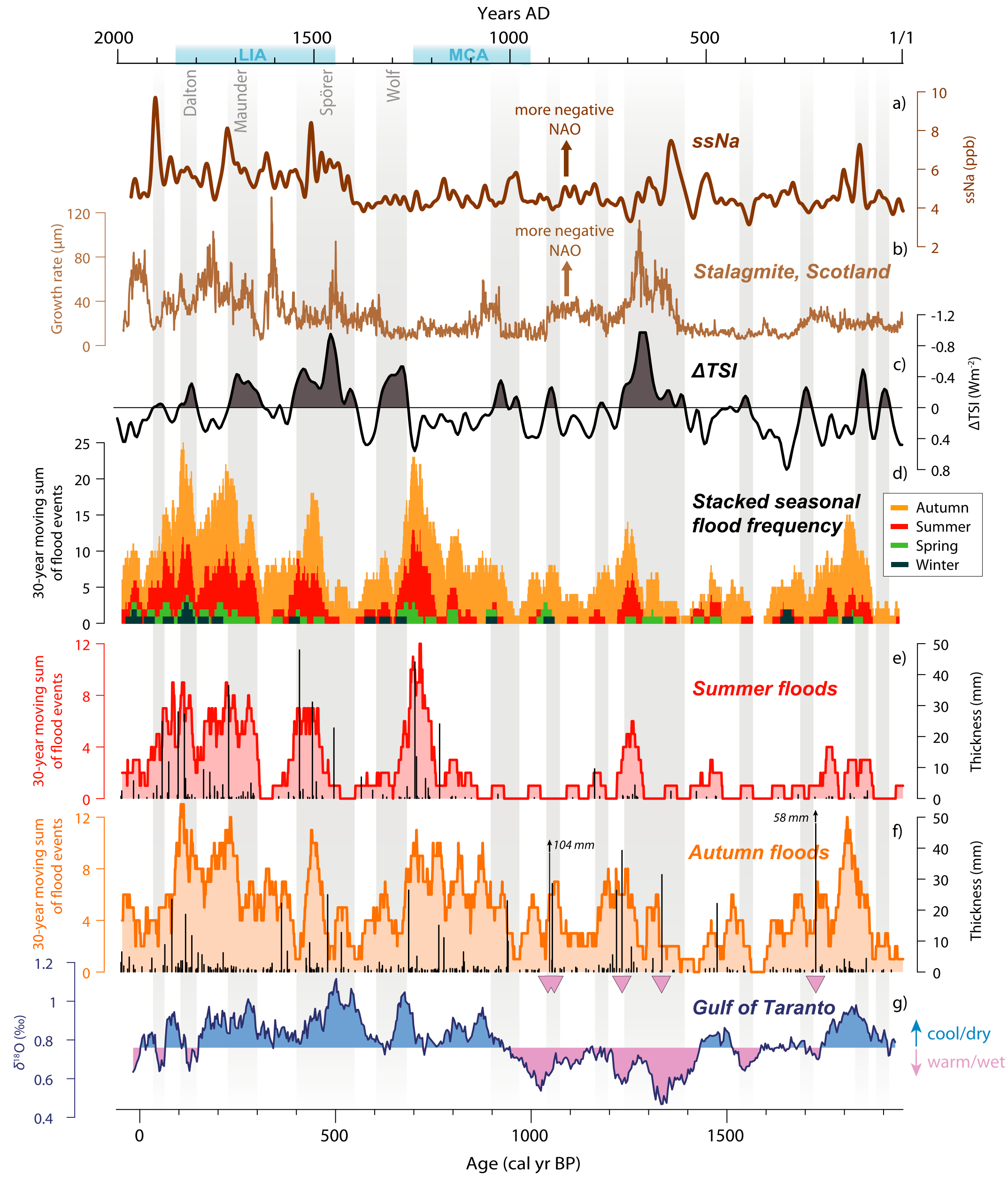

Figure 3. The 2000 year long seasonally resolved flood frequency (as 30 year moving sum of events) and intensity (~flood layer thickness; black vertical bars in Figures 3e and 3f) reconstruction from Lake Ledro compared to other climate records. (a) Stalagmite growth rate record from Scotland [*Proctor et al.*, 2002]. (b) ssNa record from the GISP2 ice core (30 year low-pass filtered) [*Mayewski et al.*, 1997]. (c) ΔTSI [*Steinhilber et al.*, 2009] (note reversed *y* axis). (d) Stacked seasonal flood frequency. (e) Summer flood frequency and intensity. (f) Autumn flood frequency and intensity; purple triangles mark five most intense events. (g) Foraminifera-based $\delta^{18}O$ record from the Gulf of Taranto, South Italy [*Grauel et al.*, 2013]. Grey shaded areas mark solar lows. LIA: Little Ice Age. MCA: Medieval Climate Anomaly.

the same solar minimum in our flood reconstruction. The proposed solar and NAO influence on summer and autumn floods at our study site is supported by frequency analysis revealing significant (95% confidence interval) periodicities characteristic for NAO variations (2.5, 6–10 years) [*Hurrell and Van Loon*, 1997] and for the solar Schwabe cycle (11 years) (Figure S5). Interpreting this high-frequency range asks for particularly precise dating, which is for Lake Ledro, in fact, given by the annual resolution of the varve-based age model.

[11] Summer flood intensity, as well as frequency, seems to be higher during solar lows and lower during solar highs. This may indicate that not only the frequency but also the intensity of summer floods is controlled by shifts of the westerlies, which are responsible for moisture advection from the North Atlantic to the Mediterranean area. Variations in air temperature are not considered as an essential controlling factor of summer flood intensity since summer air temperatures are generally high enough for promoting large water vapor uptake. In addition, the high altitude of the Alpine

snowline (certainly above 1800 m asl) in summer leads to intense and immediate riverine runoff after heavy rainfall. The similar pattern of spring and summer floods, but the comparably rare occurrence and low intensity of spring events (Figures 3d and S6i), may therefore indicate the opposite case of a low snowline, which reduces immediate riverine runoff. This process could thus be responsible for the comparably small thickness of the spring (and also winter) flood layers (Figures S6i and S6j). Apart from shifts in North Atlantic circulation, precipitation recycling in the Alps might constitute an additional mechanism contributing to heavy rainfall during the warm months [*Sodemann and Zubler*, 2010; *Winschall et al*., 2012].

[12] The most extreme autumn floods occurred during the period 500–1000 A.D., which is characterized by an only moderate correlation of autumn floods to summer floods and ΔTSI (Figure 3). In order to investigate this autumn signal, we used an oxygen-isotope record from a sediment core from the Gulf of Taranto (South Italy), which indicates cool sea surface temperature (SST) with higher foraminiferal δ^{18}O values and vice versa (Figure 3g) [*Grauel et al*., 2013]. As a whole, the δ^{18}O record is in agreement with the TSI record, indicating cooler temperatures during phases of low solar irradiance. However, from 500 to 1000 A.D., the Gulf of Taranto record indicates comparably warm SSTs. These conditions could have led to increased Mediterranean moisture contribution to autumn precipitation [*Trigo et al*., 2002; *Winschall et al*., 2012] and, thus, to extreme autumn floods at our study site. Warmer conditions would also be accompanied by a higher Alpine snowline and, thus, additionally promote intense riverine runoff.

[13] On the basis of microfacies analysis of the varved sediments of Lake Ledro, we established an exceptional record of floods and their seasonal occurrence in the southern Alps in the past 2000 years. Interpreting the outcome of this study in regard to climate warming, our results indicate a decrease in the occurrence of summer floods and an increase in extreme autumn events, a scenario that is, in fact, consistent with current climate projections. Yet in contrast to these projections, our data show no indication for a concurrent intensification of summer events in a warmer climate.

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