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Frequent floods in the European Alps coincide with cooler periods of the past 2500 years

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Severe floods triggered by intense precipitation are among the most destructive natural hazards in Alpine environments, frequently causing large financial and societal damage. Potential enhanced flood occurrence due to global climate change would thus increase threat to settlements, infrastructure, and human lives in the affected regions. Yet, projections of intense precipitation exhibit major uncertainties and robust reconstructions of Alpine floods are limited to the instrumental and historical period. Here we present a 2500-year long flood reconstruction for the European Alps, based on dated sedimentary flood deposits from ten lakes in Switzerland. We show that periods with high flood frequency coincide with cool summer temperatures. This wet-cold synchronism suggests enhanced flood occurrence to be triggered by latitudinal shifts of Atlantic and Mediterranean storm tracks. This paleoclimatic perspective reveals natural analogues for varying climate conditions, and thus can contribute to a better understanding and improved projections of weather extremes under climate change.

Mean Central European summer temperatures are projected to increase under global climate change, while summer precipitation totals will likely decrease[1,2]. However, the frequency of climate extremes, such as intense precipitation events, is more difficult to project, as such events strongly depend upon season, location, and spatial extent[3–5]. Therefore, the analysis of long climate time series supports the identification of climatic processes naturally governing the occurrence of intense precipitation and thus improves the projection of these climate extremes. Instrumental measurements that cover the last 150 years reveal highly resolved precipitation records over space and time[6,7], but are too short to detect the natural multi-decadal to centennial variability in the climate system. Longer time series can be reconstructed from historical documents[8,9], as well as from geological archives such as riverine overwash deposits[10,11]. However, both approaches do not provide continuous records over the past millennia[11,12], and thus only yield an incomplete palaeoclimatic picture.

Lake sediments, in contrast, reflect past flood activity very accurately, as they record individual events as distinct sediment layers. These 'turbidites' or flood deposits provide a continuous flood archive over thousands of years[13]. The flood deposits are composed of terrigenous material, which is mobilized during intense precipitation in the catchment area and eventually deposited at the bottom of the next downstream lake[13–15] (Fig. 1). Several studies have established flood records from single lakes[16–18], however, these records may only reveal a local climate signal and/or may loose their pristine natural signal due to human activity in the corresponding catchment area[13,14].

Here we present a multi-archive Alpine flood reconstruction based on ten lacustrine sediment records, covering the past 2500 years. The 10 investigated lakes are situated north of the Central Alpine arc along a montane to Alpine transect, spanning an elevation gradient from 447 to 2068 m asl (Fig. 2). This multi-lake compilation allows the extraction of a synoptic, rather than a merely local rainfall signal revealed by a single-lake study[14].

Results

The complete flood reconstruction contains 842 dated flood layers (Fig. 3a), deposited dominantly from mid-spring to late-fall, since the higher elevated lakes are ice-covered and/or receive precipitation in the form of snow
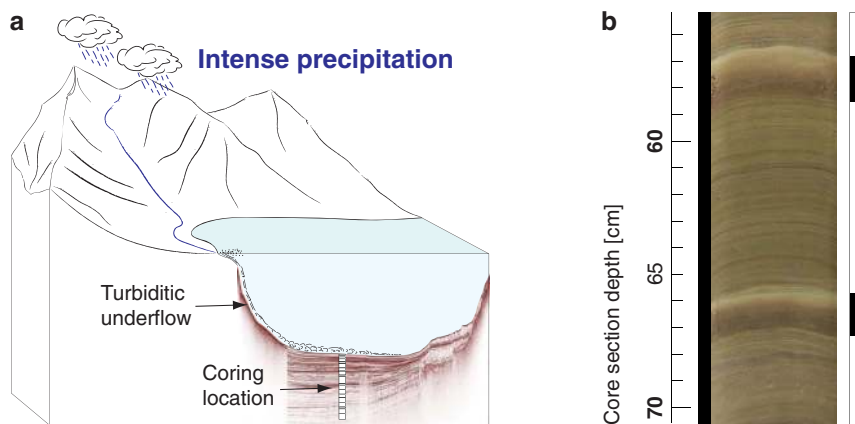
Figure 1 | Flood-layer generation. (a), Sketch illustrating erosion and mobilization of terrestrial material during intense precipitation in the catchment area. The sediment material is fed into the river drainage and upon entering the next downstream lake. The sediment-laden river water proceeds as turbiditic underflow to the deepest part of the lake basin, where the sediment load is deposited as characteristic flood-layer (illustration modified after[13]). (b), Core photograph with two flood-layers (indicated by black bars) from Lake Glattalp.
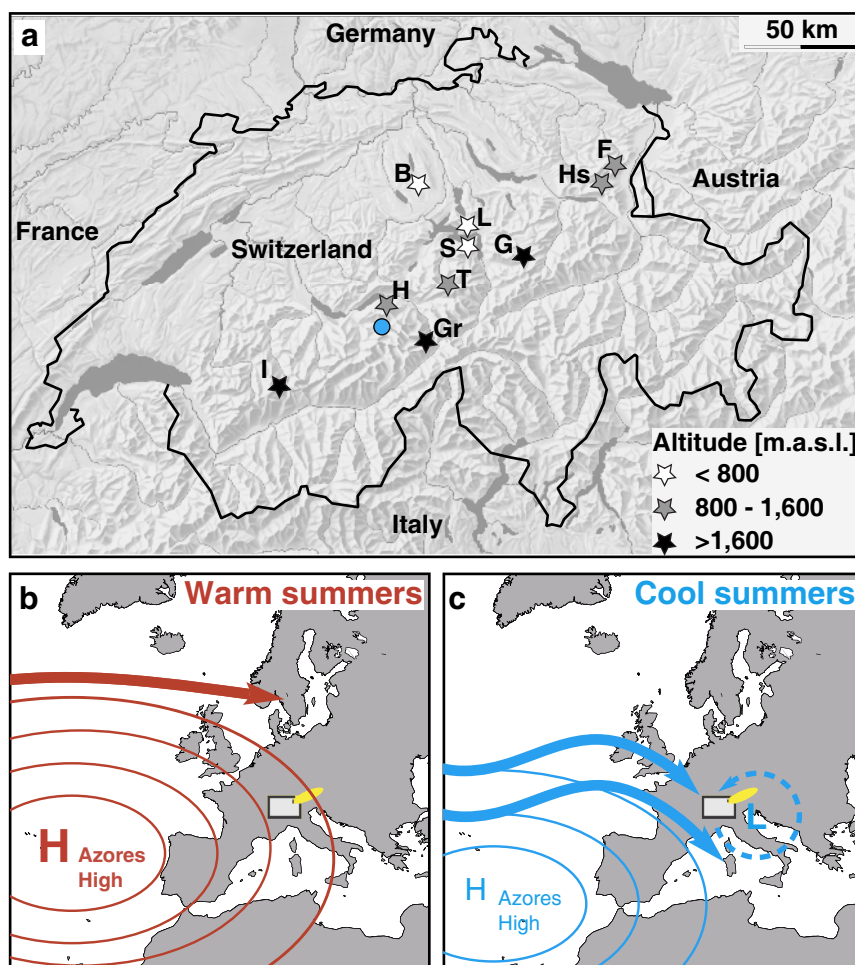

Figure 2 | Alpine study sites. (a), Location of studied lakes: B: Baldegg, F: Fälen, G: Glattalp, Gr: Grimsel, H: Hinterburg, Hs: Hinterer Schwendisee, I: Iffig, L: Lauerz, S: Seelisberg, T: Trüeb. Blue circle indicates the location of the Lower Grindelwald Glacier that was used for reconstruction of glacier-length change[22]. Relief data and map of Switzerland reproduced with permission of swisstopo/JA100119. (b–c), Schematic illustration of the meridional location and expansion of the Azores high-pressure system during warm and cool summers, controlling the pathways of westerly storm tracks (bold arrows) and the occurrence of Vb cyclones (dashed line). Varying expansion of the Hadley Cell leads to a northward-shift (southward-shift) and strengthening (weakening) of the Azores high-pressure system and of the westerly storm tracks, generating warm (cool) summers with less (more) intense precipitation in the Alps. White rectangle indicates the Alpine study area and yellow ellipse shows the location of the tree-ring-based summer temperature reconstruction used for comparison[21].
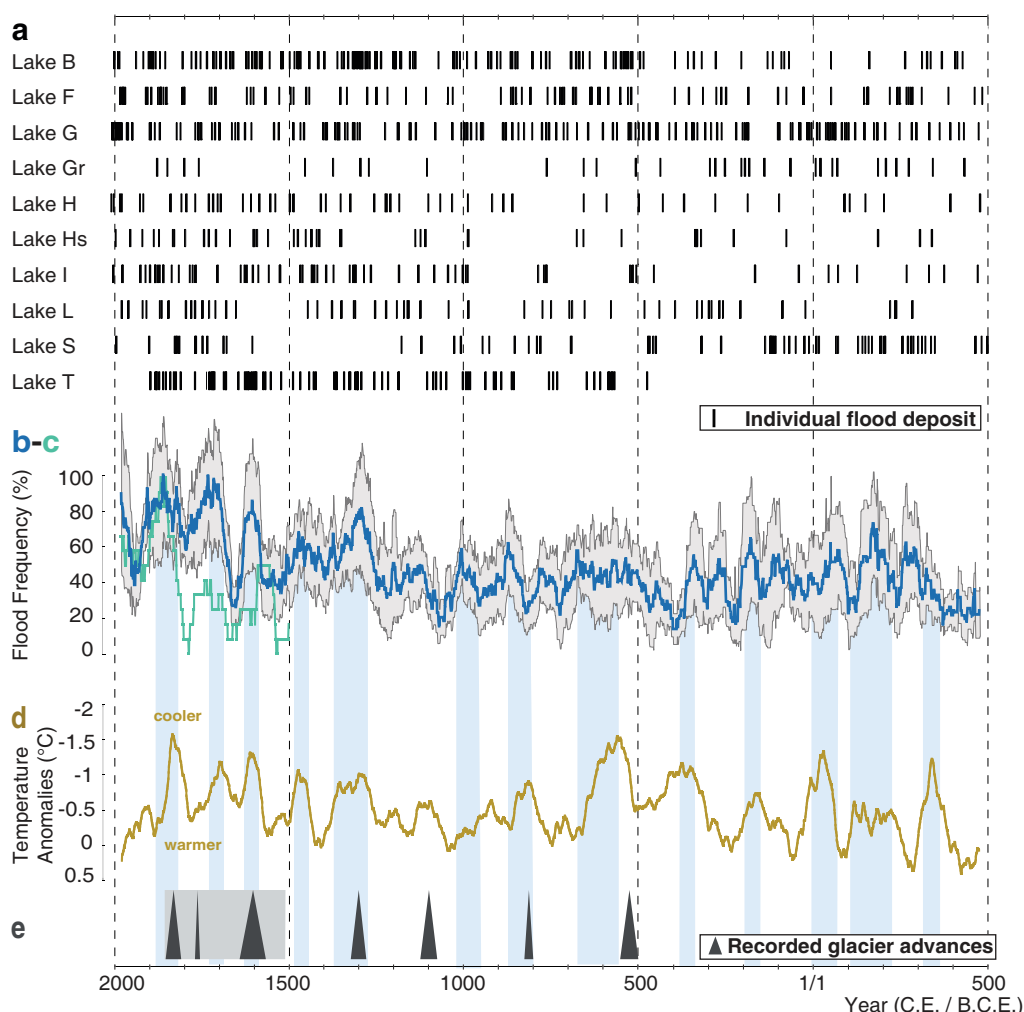
Figure 3 | Alpine flood reconstruction. (a), Flood chronologies of the ten studied lakes. Bars represent individual dated flood deposits. (b), Combination of the ten individual lake records represented as a 50-year moving average of flood events. The resulting frequency values are normalized between no flood activity (0%) and the maximal value (100%). The standard deviation is indicated with grey bars. (c), Historical flood reconstruction from Northern Switzerland (50-year moving average, normalized between 0 and 100%)[8]. (d), Tree-ring-based Central European summer temperature reconstruction (50-year moving average)[21]. (e), Major glacial advances reconstructed from the Lower Grindelwald Glacier (Northern Switzerland) indicated with triangles[22]; grey area marks period of large Alpine glacial extension[22]. Blue shaded bars indicate periods of high flood frequency that correlate with lower summer temperatures.

during winter. This seasonal pattern does not impede our flood record, as large floods occur mainly between June and October[6,8,19]. In order to verify our approach, the established Central Alpine flood reconstruction was compared against an independently established flood record over the past 500 years, which is based on historical documents[8]. Apart from the early times when the historical evidence appears to be particularly sparse, the two independent datasets are in good agreement (Figs. 3b–c).

Our data show thirteen distinct periods of high flood frequency around 1850, 1740, 1610, 1480, 1380–1300, 1010, 880, 680–580, 350, 180 C.E., and 60, 170, 300 B.C.E. The highest flood frequency is found around 1740 C.E. with events occurring seven times more frequently than during the calmest period at 400 C.E., emphasizing high natural variability of the climate system. The robustness of the flood frequency peaks was tested with a Jackknife analysis (Supplementary notes online). The performed analyses reveal that the main peaks are robust and unlikely of random origin, but also underscore the need of combining records from different lake sites to reconstruct a synoptic rainfall signal. This is illustrated with the uncertainty estimate of the frequency signal, which considerably increases the more lakes from the Central Alpine flood reconstruction are omitted

(Supplementary Fig. S1 online). Regarding the best-characterized climatic periods during the past 2500 years[20], the flood activity was generally enhanced during the Little Ice Age (1430–1850 C.E.; LIA) compared to the Medieval Climate Anomaly (950–1250 C.E.; MCA) (Fig. 3b). This result is confirmed by other studies documenting an increased (decreased) flood activity during the LIA (MCA) in the Alps[8,16–18], but our data further documents distinct centennial-scale natural variations in flood occurrence during these contrasting climate periods.

The observed relation between varying flood frequencies and climatically different periods suggests synchronisms between intense precipitation and temperature during the extended summer season. Therefore, our flood chronology was compared to a tree-ring-based summer temperature reconstruction for Central Europe[21] (Fig. 3d). The two independent paleoclimatic datasets correlate negatively at $r = -0.44$ and -0.25 over the past 1300 and 2500 years, respectively. Statistical tests indicate that this anti-correlation is significant (Supplementary Fig. S2 online). In particular, the most distinct cooling events revealed by the summer temperature reconstruction are accompanied by high flood activity. Furthermore, 6 out of 7 major advances of the Lower Grindelwald Glacier that is situated in the

studied area[22] (Fig. 2a) correspond to periods characterized by enhanced flood frequency during the past 1500 years (Fig. 3e). As the crucial conditions for major glacial advances in the Alps are low summer temperatures[22,23], this adds to the important observation that floods occur more frequently during cool summers. However, a distinct advance of Lower Grindelwald Glacier that is accompanied by only slightly enhanced flood frequencies is recognized at around 1100 C.E. (Fig. 3). Yet, as the tree-ring based summer temperature reconstruction does not reveal distinct cool conditions during this period, this specific glacier advance may reflect only slightly decreased summer temperatures, maybe in combination with other climatic factors. Consequently, Central Alpine flood frequency is not considerably enhanced during this period.

Discussion

We interpret the correlation between lower (higher) summer temperatures and enhanced (decreased) flood frequency in terms of North Atlantic atmospheric circulation patterns (Figs. 2b–c): Under current climatic conditions, warm and dry Alpine summers are usually accompanied by anticyclonic (high pressure) circulations that deflect the moist westerly flow towards more northern latitudes[24,25] (Supplementary Fig. S3 online). In contrast, cooler summers are rather characterized by zonal westerly or meandering circulations. The latter are generally associated with above-normal precipitation, or may even lead to heavy precipitation events, for instance associated with the Vb cyclone track[26] (Supplementary Figs. S4 and S5 online). These tracks are characterized by low-pressure systems moving northeastward from the Adriatic Sea, bringing orographic rainfall that potentially leads to severe flooding along the Alpine crest (Fig. 2c)[19,26]. Such Vb circulation tracks may occur during both cool and warm conditions[27]. Nevertheless, we propose that a more southerly position and a weaker expression of the subtropical high-pressure zone favor the occurrence of Vb circulation patterns. In particular, in the late 19th century, which was characterized by generally cool summer conditions[28,29], an accumulation of Vb circulation tracks led to a clustering of floods in the Alps[8,27].

The scientific literature puts varying emphasis on the different elements of the aforementioned circulation anomaly, and the terminology may invoke the northward extent of the subtropical dry zone (Hadley cell)[24,25], or the North Atlantic Oscillation (NAO)[18,30]. For the purpose of the current publication, we consider all these elements as part of one main circulation pattern. Evidence for its importance in shaping European summer climate variability is widespread[1]. Likewise, climate models yield a poleward expansion of the Hadley cell in response to greenhouse gas forcing[24,25]. This is related to a strengthening of the subtropical high-pressure zone and a poleward shift of the westerly storm tracks (Fig. 2B). Accordingly, Central European flood occurrence is expected to be lower than today, which is in good agreement with our finding of less frequent floods during warmer periods.

Our study implies that enhanced (decreased) occurrence of westerly and Vb storm tracks during cooler (warmer) summers increase (decrease) the frequency of flood events in the Alps. As the main determining factor for the frequency of intense precipitation events in the Alps, we propose a variable extent of the Hadley Cell and consequently changing atmospheric circulation patterns. This relationship appears applicable to a warmer climate as the subtropical dry zone is expected to expand poleward in response to greenhouse-gas forcing under climate change[24]. This pattern of less frequent intense precipitation events with warmer summers is regional in nature, thus underscoring the importance of incorporating the different effects of spatial changes in atmospheric circulation patterns in flood frequency reconstruction, as well as in projecting weather extremes under global climate change.

Methods

Sediment retrieval and flood-layer detection. Before sediment coring, every lake (Supplementary Tab. S1 online) was investigated by a high-resolution (3.5 kHz) reflection seismic survey that provided information on the sediment thickness, seismic stratigraphy and lake-basin morphology. The ideal coring location was determined based on the interpretation of the seismic data, and the complete sediment succession was retrieved with a UWITEC percussion piston coring system. Afterwards, the sediment cores were longitudinally cut into halves and the sediment surface was photographed in fresh and oxidized (after few hours exposure) state. The flood-layers were identified by macroscopic observations in combination with measurements of the physical characteristics of the retrieved cores performed by a GEOTEK multi-sensor core logger at a 5 mm sampling interval (gamma-ray attenuation bulk-density, magnetic susceptibility and p-wave velocity). Depending on the individual sediment composition of the different study sites, the flood-layer analysis was supported and complemented by image-analyses techniques, laser-diffraction grain-size analysis, carbon and nitrogen analysis (C/N ratio) and/or computer tomography[13,15].

Age model. The topmost core sections were dated using the activity profiles of the radionuclide ^{137}Cs, providing well-constrained age models for the past decades[13]. The older sections of the sediment sequences were dated by AMS radiocarbon measurements on terrestrial macrofossils (Supplementary Tab. S2 online). Based on the established age-depth models calculated with clam[31] (Supplementary Figs. S6 and S7 online), we determined the age of every individual flood-layer (Fig. 3a).

Compiled Alpine flood reconstruction. The individual flood records show strong decadal to centennial fluctuations with site-specific average flood-recurrence rates between 16.7 and 80.7 years over the last 2500 years (Fig. 3). This high variability in the absolute number of recorded floods reflects different susceptibilities of the lakes to record floods. Therefore, we established 50-year moving sums of events and normalized these data sets from 0% (corresponding to no flood-layer) to 100% (maximum number of flood deposits)(Supplementary Fig. S8 online). Comparing the ten flood records, we find no consistent correlation between the individual single lake records (Pearson correlation coefficient between $r = -0.3$ and $r = 0.5$). The same observation is made when comparing instrumentally measured single heavy precipitation events in small catchments[8]. This underscores the complexity of precipitation and flood response and reflects the influence of local phenomena such as spatially confined thunderstorms and/or flood formation. It also emphasizes the importance and advantage of working with a multiple-lake record[13,14]. In order to combine the ten individual records into one Central Alpine flood reconstruction, we calculated the mean of the normalized flood records and resulting frequency values were again normalized to 0 and 100%. This flood record compilation shows a standard deviation between 5.3 and 44% (Fig. 3) and was tested for its significance by comparing the observed flood frequency variation with the 2σ-range of 10 000 randomized events series and different window sizes of running sum calculations (Supplementary Figs. S9 and S10 online).

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Author contributions

F.S.A., A.G. and G.H.H. designed the project and rose the funding. L.G., S.B.W., F.S.A. and A.G. performed the fieldwork. L.G. established the flood records of the individual lakes. C.S., J.B. and U.B. contributed to the interpretation of the results. All of the authors discussed the data and provided significant input to the final manuscript. The writing of the manuscript was led by L.G.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

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