Global and Planetary Change 71 (2010) 242–248

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Humid climate during deposition of sapropel 1 in the Mediterranean Sea: Assessing the influence on the Alps

Christoph Spötl [a,*], Kurt Nicolussi [b], Gernot Patzelt [c], Ronny Boch [a] and Daphne team [1]

[a] Institut für Geologie und Paläontologie, Universität Innsbruck, Innrain 52, 6020 Innsbruck, Austria
[b] Institut für Geographie, Universität Innsbruck, Innrain 52, 6020 Innsbruck, Austria
[c] Patscher Straße 20, 6080 Innsbruck-Igls, Austria

ARTICLE INFO

Article history:
Received 23 January 2009
Accepted 2 October 2009
Available online 22 October 2009

Keywords:
Holocene
Alps
palaeoclimate
stable isotopes
precipitation

ABSTRACT

Cave and lake isotope records from the circum-Mediterranean realm show anomalously low O isotope values suggesting high rainfall intensity during the time of sapropel 1 deposition (9.5 to 6.5 ka; all ages are given before the year AD 2000, i.e. b2k), coincident with an interval of conspicuously low sea-surface salinities in the entire Mediterranean Sea. Speleothem data from Corchia Cave (Tuscany) currently provide the most precise terrestrial chronology and constrain the wettest interval to ca. 8.2 to 7.3 ka. We have traced this isotopic signal to the north and observe a synchronous isotopic change in stalagmites from southalpine and eastalpine caves, but in opposite direction. We attribute this to a shift in the local moisture balance, i.e. to a higher proportion of moisture advected from the Mediterranean Sea relative to the otherwise dominant northwesterly air masses in the Alps. This isotopic source effect can be traced up to the northern rim of the Alps, albeit with decreasing amplitude. Forest density at the treeline in the Central Alps decreased during this time interval indicating short vegetation periods consistent with rainy summers. The glaciers in the Eastern Alps, which did not show far-reaching advances during the preceding 8.2 ka event, responded strongly (positively) to this humid phase. Additionally, two of the largest alluvial fans in the Eastern Alps showed a massive accumulation peak radiocarbon dated to between ca. 8.3 to 7.4 ka and thus providing one of the strongest pieces of evidence for anomalously high rainfall intensities coeval with 'pluvial' conditions in the Mediterranean region.

1. Introduction

The early Holocene was a time of major re-organisations of the ocean-cryosphere-atmosphere system. It marks the final stages of the decay of mid- to high-latitude ice sheets (until ca. 6 ka), the further rise in global sea level (starting from ca. -50 m at 11.7 ka), the flooding of formerly emerged shelf areas and freshwater bodies (e.g., Black Sea), the final rise in greenhouse-gas concentrations, as well as the poleward expansion of vegetation zones (e.g., Mayewski et al., 2004; Kaplan and Wolfe, 2006; Battarbee and Binney, 2008). The principle forcing, precession-driven change in insolation, reached a maximum for the Northern Hemisphere boreal summer during the early Holocene and has been declining since then (Berger and Loutre, 1991). As a consequence of this orbitally forced change in short-wave radiation the Intertropical Convergence Zone and its associated rainfall belt migrated north and penetrated beyond the central Saharan watershed during summer monsoon giving rise to the (Holocene) African Humid Period (ca. 9 to ca. 5.5 ka; Ritchie et al., 1985; Gasse, 2000; deMenocal et al., 2000; Adkins et al., 2006; Tjallingii et al., 2008). During largely the same time interval sediment records show evidence of a reduction in the near-surface salinity, increased stratification and anoxia in the seawater column of the eastern Mediterranean and the Adriatic Sea and the deposition of sapropel S1 (ca. 9.5 to 6.5 ka; Rohling, 1994; Ariztegui et al., 2000; Kallel et al., 2000; Emeis et al., 2003; de Lange et al., 2008). This hydrological change has been linked to the humid ('pluvial') period in North Africa, i.e. enhanced freshwater input via the Nile and smaller African rivers (Rossignol-Strick et al., 1982; Rohling, 1994; Scrivner et al., 2004). Other work has suggested that there was a concomitant increase in direct rainfall over the Mediterranean region, associated with increased westerlies (Rossignol-Strick, 1987; Kallel et al., 1997; Bar-Matthews et al., 2003; Kotthoff et al., 2008). As expected lake records from the eastern Mediterranean region show low O isotope values during the time of sapropel formation which are attributed to increases in local precipitation (Roberts et al., 2008). No such isotopic pattern, however, exists for lake isotope records from the western

* Corresponding author. Tel.: +43 512 507 5593; fax: +43 512 507 2914.
E-mail address: christoph.spoetl@uibk.ac.at (C. Spötl).
[1] www.fg-daphne.de.
[2] All ages in this article are given before the year AD 2000 (b2k).

0921-8181/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2009.10.003

Mediterranean region, which may be related to the fact that this part of the Mediterranean Sea stayed well ventilated during the Holocene. Speleothem isotope data show a slightly more complex picture: there is a trend from generally low $\delta^{18}O$ values in the early Holocene to higher values during the mid- to late Holocene in the eastern Mediterranean region (Israel: Bar-Matthews et al., 2003; Sicily: Frisia et al., 2006), whereas in the western part some cave records show no trend (southern France: McDermott et al., 1999) and others show low values during the early Holocene (Italy: Frisia et al., 2005; Zanchetta et al., 2007). In essence, there is isotopic evidence for humid ('pluvial') conditions at least in the eastern and partly also the central Mediterranean area during the time of sapropel S1 deposition.

In this contribution we address the question of how far north these humid conditions reached. We have compiled published and new records from northern Italy to southern Germany, i.e. across the Alps, using mainly stable isotope data from speleothem and some lake sediments, as well as data from subfossil trees, glaciers and debris-flow deposits. Our selection focuses on those archives and sites which are well dated and sensitive to changes of palaeo-precipitation.

2. Archives and records

2.1. Lakes

Holocene O isotope records have been reported from two small lakes from the Southern Alps of northern Italy, Lago Terlago and Lago Frassino (Fig. 1). Lago Terlago, located 6 km NW of Trento, yielded an early to mid-Holocene clastic sediment succession and molluscs retrieved from these sediments show high $\delta^{18}O$ values in the Preboreal (unfortunately the dating quality is poor), followed by lower values between ca. 9.3 and 7.2 ka (Baroni et al., 2001). The authors tentatively attributed this isotope trend to a progressive lowering of the lake water level but did not rule out that climate may also have played a role. Located 78 km SSW of Lago Terlago, Lago Frassino is a small lake from which stable isotope data obtained on molluscs show slightly higher values during the early Holocene, followed by lower values subsequent to ca. 8 ka (Baroni et al., 2006; note that the age control is also poor in this section; Fig. 2). Modern lake water samples define an evaporation trend, i.e. the higher the precipitation/evaporation ratio the lower the $\delta^{18}O$ values. The authors therefore associate the drop in $\delta^{18}O$ with a trend toward slightly wetter conditions.

No isotope data of the time interval of interest are currently available from lakes in the interior of the Alps, but an important isotope record based on benthic ostracods was published from Ammersee (von Grafenstein et al., 1999). This lake is located in the alpine foreland southwest of Munich (Fig. 1) and receives its water from precipitation falling in the Ammer Mountains west of Garmisch-Partenkirchen. This record therefore provides an archive of palaeo-precipitation from the northern margin of the Eastern Alps. Given that the lake hydrology is well understood (von Grafenstein et al., 1996, 1999) and ostracods precipitate their calcitic valves in the hypolimnion at temperatures close to 4 °C, the measured values solely reflect changes in $\delta^{18}O$ of palaeo-precipitation. The record is reasonably well dated using radiocarbon and shows a clear isotopic expression of the 8.2 ka event (von Grafenstein et al., 1998, 1999) followed by a period of slightly elevated $\delta^{18}O$ values which lasted until ca. 7.2 ka (Fig. 2).

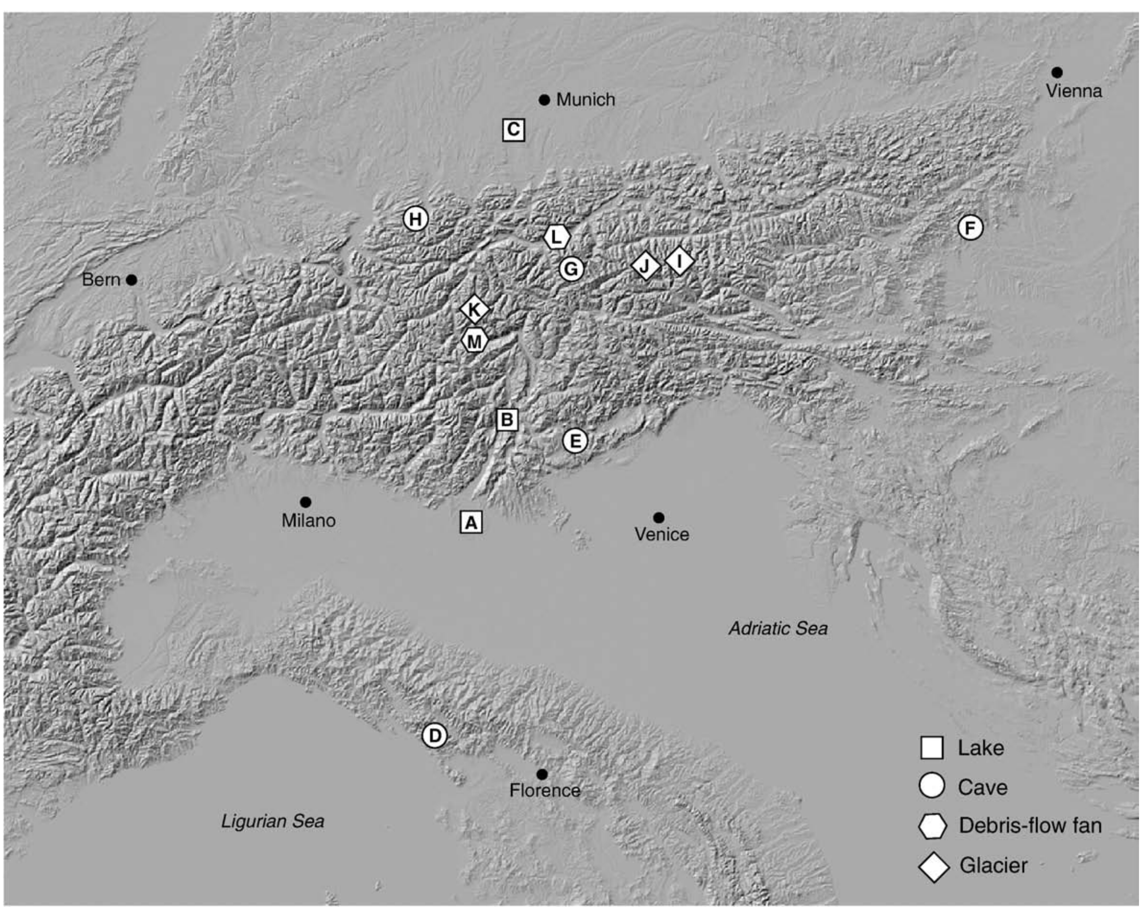

Fig. 1. Map of northern Italy and the Alps showing the locations of the early Holocene records discussed in this paper. *Lakes*: A Frassino, B Terlago, C Ammersee. *Caves*: D Monte Corchia, E Ernesto, F Katerloch, G Spannagel, H Hölloch. *Glaciers*: I Pasterze (Glockner Group), J Zettalunitzkees (Venedinger Group), K Gurgler and Gepatsch Ferner (Ötztal Alps). *Debris-flow fans*: L Hall in Tirol, M Gadria.

2.2. Caves

The starting point of our transect is Corchia Cave (Antro del Corchia) in the Apuan Alps of NW Tuscany, an extensive high-altitude cave system (Piccini et al., 2008) from which a stalagmite (CC26) was retrieved. The key feature of this well-dated stalagmite, which grew between 11.3 and 0.8 ka, is an interval of low $\delta^{18}O$ values between ca. 8.2 and 7.3 ka (Zanchetta et al., 2007). Although the amplitude is only ca. 0.6‰ this interval stands out prominently, while other known climate events, e.g. the 8.2 ka event, are not present (Fig. 2). The authors considered three possible mechanisms to explain this negative excursion: changes in the air temperature, the amount of rainfall, and the source of the water vapour, and concluded that the 'amount effect' (Dansgaard, 1964) is the most likely cause. This is substantiated by other studies of (older) speleothems from this cave system (e.g., Drysdale et al., 2005) and other cave sites in the Mediterranean (Bar-Matthews et al., 2003), as well as by atmospheric modelling which shows that the rainfall amount is the most significant long-term driver of speleothem $\delta^{18}O$ in this region (Bard et al., 2002). Although a quantification of the isotope excursion in terms of rainfall amount was not attempted, the CC26 record is the first precisely dated evidence of enhanced rainfall in the western Mediterranean basin during the time of S1 deposition (Zanchetta et al., 2007).

A small cave located south of the Dolomites, Grotta di Ernesto (Fig. 1), is one of the most thoroughly studied caves in Europe, both with respect to the modern cave meteorology and hydrology and speleothem records (e.g., McDermott et al., 1999; Frisia et al., 2000, 2003; Huang et al., 2001; Borsato et al., 2007). An early study showed high speleothem $\delta^{18}O$ values between ca. 9.3 and 7.8 ka, which were interpreted as dry or dry-warm conditions (McDermott et al., 1999). This particular stalagmite, ER76, was recently re-examined using additional U-Th dates and higher resolution stable isotope analyses and this interval of anomalously high $\delta^{18}O$ values was re-dated to 8.2 to 7.4 ka (Scholz et al., submitted for publication). This growth phase coincided exactly with the period of maximum rainfall, as recorded in CC26 from Corchia Cave (8.2 to 7.3 ka; Zanchetta et al., 2007; Fig. 2). Hence, the initial interpretation of McDermott et al. (1999), which was based on a wrong age model, needs to be reconsidered.

A cave site which has recently revealed high-resolution records from the southeastern rim of the Alps is Katerloch, located 22 km NE of Graz (Fig. 1). One stalagmite (K1) grew between 10.3 and 7.2 ka and records a prominent increase in $\delta^{18}O$ following a negative excursion at 8.2 ka (Boch, 2008; Boch et al., 2009; Fig. 2). This interval of high $\delta^{18}O$ values reached a maximum at ca. 7.3 ka and coincided precisely with the humid interval of Corchia Cave, as well as with high values in Ernesto Cave (Fig. 2).

Moving further north into the interior of the Alps, a series of stable isotope records have been reported from Spannagel Cave, located close to the main crest of the Central Alps, i.e. at the main water/

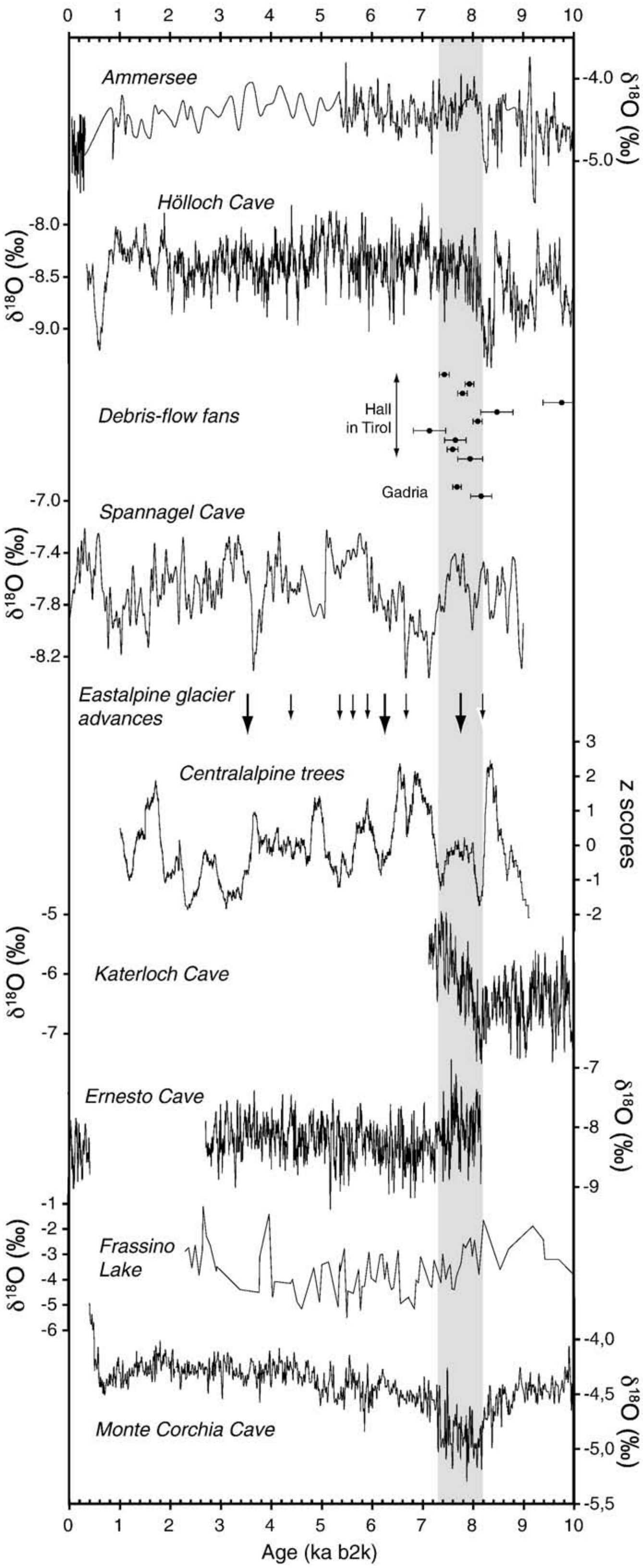

Fig. 2. Selected stable isotope and other proxy records of the past 10 ka arranged along a S-N transect (bottom to top) and plotted on a common calendar-age timescale. Calibrated radiocarbon dates in BP (AD 1950) notation (Frassino, debris-flow fans, Ammersee) were adjusted by adding 50 years. Oxygen isotope data are consistently plotted with values increasing upward but absolute scales vary. The vertical gray bar highlights the wettest interval according to the CC26 record from Corchia Cave. *Monte Corchia Cave*: data of stalamite CC26 from Zanchetta et al. (2007). *Frassino Lake*: data based on two different mollusc taxa with slightly different mean values (Baroni et al., 2006; Roberts et al., 2008). *Ernesto Cave*: stalagmite ER76 (Scholz et al., submitted). *Katerloch Cave*: stalagmite K1 (Boch et al., 2009). *Centralalpine trees*: abundance of subfossil trees at the treeline based on the Eastalpine Conifer Chronology (Nicolussi et al., 2009). The data are presented in standardised values (z-scores) after linear detrending in order to exclude the sampling-based long-term trend. High values indicate high forest density at the treeline in the Central Alps. *Eastalpine glacier advances*: advance phases of glaciers in the Glockner and Venediger Group as well as in the Ötztal Alps and the Engadin prior to 3.5 ka (Nicolussi and Patzelt, 2000a, 2000b; Joerin et al., 2008; Patzelt and Nicolussi, unpublished data). *Spannagel Cave*: Comnispa stack (Vollweiler et al., 2006). *Debris-flow fans*: radiocarbon-dated samples (mean and 2-sigma uncertainties of calibrated ages) from the large fans of Hall in Tirol (Inn Valley, Austria) and Gadria (Vinschgau, Italy). Sources: Patzelt, 1987, 2008, and unpublished data, Fischer, 1965, 1990. *Hölloch Cave*: stalagmite HÖL1 based on Wurth et al. (2004), but using revised U-Th dates (Niggemann, 2006) and high-resolution stable isotope data (Spötl, unpublished data). *Ammersee*: data from von Grafenstein et al. (1999).

weather divide (e.g., Spötl et al., 2004; Fig. 1). Three stalagmites were combined to form a stack which covers the last 9 ka (dubbed Comnispa; Vollweiler et al., 2006; Fig. 2). The O isotope variability of this stack shows a striking similarity to the record of ice-rafted debris from North Atlantic deep-sea cores (Bond et al., 2001), i.e. periods of abundant ice-rafted debris correspond to intervals of relatively high $\delta^{18}O$ values in stalagmites from this high-alpine cave and vice versa. Comnispa thus demonstrates the dominant control of the North Atlantic Ocean on climate in central Europe throughout the Holocene (Mangini et al., 2007; see Heiri et al., 2004 for a similar study on lake sediments). The exact climate-proxy relationship in case of Spannagel Cave samples, however, is still a subject of ongoing research, but recent work (including climate modelling) indicates a strong component of the North Atlantic Oscillation (NAO) in the more recent segment of this record (Trouet et al., 2009; Graham, 2009). During the humid climate interval in Corchia Cave, the Comnispa stack shows high $\delta^{18}O$ values, but the anomaly is less pronounced when compared to ER76 and K1. We speculate that this may be related to the specific high-altitude setting of Spannagel Cave being highly sensitive to winter precipitation (and the winter NAO mode). On an seasonally weighted basis the infiltrating water feeding the stalagmites in this cave is therefore always dominated by Atlantic-derived moisture, even during the humid phase in Corchia Cave. The subsequent long episode of low $\delta^{18}O$ values in Comnispa coincides with the Holocene Climate Optimum in the Alps (e.g., Joerin et al., 2006, 2008) and a period of low abundance of ice-rafted debris in North Atlantic sediments (Bond et al., 2001).

Moving to the northern fringe of the Eastern Alps, an interesting stalagmite record is available from Hölloch, Germany's largest cave system which extends beneath the border to Austria, located 15 km SW of Oberstdorf (Fig. 1). HÖL-1 started to grow ca. 12.9 ka ago, recorded the Younger Dryas stadial, and covers most of the Holocene, possibly interrupted by two short hiati (Wurth et al., 2004). The original low-resolution stable isotope analyses were recently reproduced at higher resolution (Spötl, unpublished data) and the original U-Th dates were refined due to a new spike calibration (Niggemann, 2006). The data show the 8.2 ka event, but lack a clear structure during the time of wet climate in Corchia Cave, i.e. between 8.2 and 7.3 ka (Fig. 2).

2.3. Glaciers and trees

Holocene fluctuations of glaciers in the Eastern Alps have been thoroughly studied over the past several decades by dating moraine deposits and/or peat bogs (e.g., Patzelt and Bortenschlager, 1973; see recent review by Ivy-Ochs et al., 2009) and, more recently, by focussing on glacier mimina as identified by subfossil tree remains. These studies demonstrate, for instance, that Austria's largest glacier, Pasterze, was smaller than today between 10.1 and 8.9 ka (Nicolussi and Patzelt, 2000a). There is also strong evidence for at least one significant re-advance of glaciers in the Glockner and Venediger Group (Pasterze and Zettalunitzkees) and in the Ötztal Alps (Gurgler and Gepatsch Ferner) at ca. 7.8 ka (individual dates range from 7.4 to 7.9 ka; Nicolussi and Patzelt, 2000b; Patzelt, unpublished data; Fig. 2). This period of glacier advances was again followed by a prolonged interval of small glacier extents (often referred to as the Holocene Climate Optimum in the Alps; 7.5 to 6.5 ka), well documented by abundant subfossil trees from glacier forefields (Hormes et al., 2001; Joerin et al., 2006, 2008).

Recently, a continuous 9 ka-long tree-ring chronology was established for the Eastern Alps (Nicolussi et al., 2005; Nicolussi et al., 2009). This data set is based primarily on *Pinus cembra* obtained from the treeline in the western part of the Central Alps. One aspect of these new data is the temporal variability in the abundance of recovered trees, which shows a period of low values between ca. 8.2 and 7.2 ka (Fig. 2). The occurrence of trees at the treeline is limited by the length of the vegetation period, i.e. long and warm (dry) summers favour tree establishment (Bortenschlager, 1977; Tranquillini, 1979; Nicolussi, 1995; Vittoz et al., 2008). Conversely, a series of wet and cool summers result in a lowering of the treeline elevation, a reduced density of high-elevation forests, and hence a statistically lower probability of finding trees which grew during this time interval. Note that the latter conditions also give rise to reduced ice ablation during summer, thus favouring glacier advances. The interval of low tree densities at the treeline coincided not only with independent evidence of glacier advances, but also with the wettest interval in Corchia Cave (Fig. 2).

2.4. Debris-flow deposits

In addition to lacustrine, cave, and glacial sediments, as well as subfossil trees, there is another archive which is sensitive to rainfall variations, fans built by debris-flows. The best studied of these fans in the Eastern Alps, whose dated history goes back to the early Holocene, is the one from Hall in Tirol, 10 km E of Innsbruck. Covering an area of 8 km^2 this is also one of the largest fans in the Eastern Alps, only the huge fans of the Vinschgau south of the main alpine crest are larger (Fischer, 1965, 1990; Patzelt, 1987). Radiocarbon dates of organic matter (mostly charcoal) constrain the main debris-flow activity to ca. 8.3 to 7.4 ka (Patzelt, 1987, 1994, 2008; Fig. 2). Only two radiocarbon dates are available from the Gadria fan in the Vinschgau (Patzelt, 1987; Fischer, 1990), but both dates fall within the range of the Hall in Tirol fan.

3. Discussion

3.1. Significance and synopsis of individual records

The Alps are undoubtedly the most thoroughly studied mountain range on Earth with a wealth of evidence of past and contemporary environmental change, and a unique density and quality of proxy and instrumental data. Yet a detailed reconstruction of Holocene climate change – ideally using quantified proxy data – is still lacking. This is particularly true for climate variables other then air temperature. While there is evidence for changes in air temperature (e.g., Davis et al., 2003) our focus here is on precipitation, which is difficult to constrain using e.g. pollen data. Stable isotopes can provide important constraints on the source, and locally also the amount of, precipitation. The challenge, however, is to separate these two parameters from the temperature effect. In the following discussion we make an attempt to combine information from other archives with the available isotopic records into a coherent model.

Stable isotopes have been studied in lake sediments, speleothems, ice cores, and wood cellulose. Currently, there are no early Holocene records of cellulose $\delta^{18}O$ available from the Alps and the probability of finding undisturbed (cold) ice of this age in the Alps is very low. Alpine lake sediments have frequently been studied but no isotope record goes back to the early Holocene, largely due to the lack of biogenic carbonate sediments. Roberts et al. (2008) recently summarized stable isotope studies of lake sediments from Italy and concluded that they are also hampered by the lack of endogenic/biogenic carbonate. The two southalpine lake records from Lake Frassino and Terlago that do contain biogenic calcite are difficult to interpret, because lake-specific processes may mask climate forcing (Baroni et al., 2001, 2006). An important lake site north of the Alps is Ammersee, which yielded a rather well resolved stable isotope record obtained on benthic ostracods, and data of even higher resolution will soon become available from Mondsee (U. von Grafenstein, pers. comm. 2008), a large lake at the northern foothills of the Austrian Alps. The Ammersee record shows a strong rise in $\delta^{18}O$ values following the 8.2 ka event, which is within dating uncertainties synchronous with the onset of wet conditions in Corchia Cave (Fig. 2).

The subsequent decrease in $\delta^{18}O$ occurred slightly earlier in Ammersee than in Corchia. In southern Bavaria the O isotopic composition of meteoric precipitation is strongly correlated to the mean air temperature as shown by a comparison of high-resolution ostracod isotope data from this lake and a ca. 200 year-long instrumental record from a nearby meteorological station (Hohenpeißenberg; von Grafenstein et al., 1996). If this relationship is applied to the early Holocene, the increase in $\delta^{18}O$ values following the 8.2 ka event could be ascribed to a rise in air temperature in the recharge area of the lake. Comparisons with other records from the Alps, however, indicate that the Holocene Optimum was reached later, i.e. between ca. 7.5 and 6.5 ka (e.g., Joerin et al., 2006, 2008), which is difficult to reconcile with relatively low $\delta^{18}O$ values in Ammersee ostracods during that time (Fig. 2). We therefore propose that the high $\delta^{18}O$ values following the 8.2 ka event reflect a source effect, i.e. enhanced precipitation of ^{18}O-enriched moisture derived from the Mediterranean basin, coincident with the wet interval recorded in Corchia Cave. We note that there is independent evidence of high humidity northwest of the Alps as documented by high levels of lakes in the Jura Mountains between ca. 8.3 and 7.3 ka (Magny, 2004), i.e. largely coeval with the wet phase in Tuscany.

The stalagmite data compiled in this study are well-dated and have a high resolution. The most conspicuous feature of these records is the $\delta^{18}O$ increase in ER76, K1 and partly also in Comnispa coeval with the $\delta^{18}O$ decrease in CC26 commencing at ca. 8.2 ka (Fig. 2). Rather than attributing this increase to a temperature signal we interpret this as a result of advection of moisture derived from the Mediterranean basin towards the Alps. Rainfall sourced from the Mediterranean Sea has higher $\delta^{18}O$ values than moisture from the Atlantic due to the lower humidity in the Mediterranean (e.g., Celle-Jeanton et al., 2001, 2004). These relatively high $\delta^{18}O$ values recorded in speleothems are therefore interpreted as resulting from an increase in the proportion of rainfall sourced from the Mediterranean relative to moisture which originated in the North Atlantic. A study of back-trajectories in (not involving O isotopes) showed that modern precipitation in the Southern Alps is indeed related to the origin of the air masses (Bertò et al., 2004). The Comnispa stack from the high-elevation Spannagel Cave is consistent with the model of enhanced southerly moisture transport towards the Alps. Given the remarkable correlation between these stable isotope data and the marine Bond et al. (2001) record we propose that during times of sea-ice expansion in the North Atlantic, storm tracks preferentially took more southerly routes, picking up moisture from the Mediterranean and delivering ^{18}O-enriched precipitation to and across the Alps. Conversely, during the subsequent Climate Optimum (when the abundance of ice-rafted debris dropped) this Mediterranean influence waned, giving rise to low $\delta^{18}O$ values in Spannagel Cave and negative glacier mass balances (Joerin et al., 2006). The northernmost cave site, Hölloch, does not show an increase in $\delta^{18}O$ during the wet interval in Corchia Cave (Fig. 2) which either suggests that the influence of southerly air masses was not significant at this site, or that the 'source effect' was not the dominant control on the $\delta^{18}O$ composition of this stalagmite.

Alpine glaciers have long been known to respond sensitively to changes in air temperature and precipitation (e.g., Hoinkes, 1968; Kuhn et al., 1997; Schöner et al., 2000). Several eastalpine glaciers re-advanced at the time of the presumed wet climate period (Fig. 2). This is supported by the very low abundance of subfossil wood and other organic remains in glacier forefields during this time interval (Joerin et al., 2006). This again is consistent with the marked decrease in the abundance of tree remains at the treeline of the main alpine divide (Nicolussi et al., 2009; Fig. 2). It is quite unlikely that this glacier advance at ca. 7.8 ka was a response to cooling as the time interval of interest is subsequent to the 8.2 ka event, during which there is no evidence of a major re-advance of glaciers - on the scale of 'Little Ice Age' (LIA) advances - either in the western or in the eastern part of the Alps. During the 8.2 ka event eastalpine glaciers were as large or slightly larger than during the second half of the 20th century, but certainly smaller than during the middle of the 19th century, the maximum extent during the LIA (Patzelt, unpublished data). Surface exposure dating suggested a larger advance of a glacier in the western part of Tyrol to a position beyond its LIA margin during the 8.2 ka event (Kerschner et al., 2006), but more recent work has cast doubts on this assignment (H. Kerschner, pers. comm. 2008). The 8.2 ka event was a cold and dry spell in the Alps as recognized by pollen from southalpine (Pini, 2002), westalpine (Tinner and Lotter, 2001), and centralalpine peat bogs (Kofler et al., 2005), as well as by isotope data in lake sediments (von Grafenstein et al., 1998) and speleothems (Wurth et al., 2004; Boch et al., 2009). It is therefore unlikely that the advance at ca. 7.8 ka (Fig. 2) was in response to a cooling because the same glaciers did not react strongly to the widely recognized cold interval around 8.2 ka. This is supported by the observation that the temperature-sensitive centralalpine treeline was clearly higher at 7.8 ka than during the former period (Nicolussi et al., 2005). In both cases, glacier mass balances therefore contained a strong precipitation component, i.e. relatively low accumulation during the dry 8.2 ka cold spell and above-average accumulation during the following 8.2-7.3 ka phase, apparently over-compensating for the then higher air temperature.

The final piece of evidence is the geomorphological activity on the slopes and in the valleys of the Alps which gave rise to large alluvial fans. These sediment bodies are present in virtually all valleys and numerous studies have shown that, although the dynamics of these mass movements is partly stochastic, the principal trigger of debris flows is (high) rainfall intensity (Stiny, 1910; Caine, 1980; Jomelli et al., 2004; Irmler et al., 2006; Stoffel et al., 2005, 2008; Prager et al., 2008). The radiocarbon-dated debris-flow chronology of the two large fans of Hall in Tirol and Gadria strongly implies high rainfall intensities both south and north of the main Alpine crest precisely when trees at the centralalpine treeline became less abundant, more snow accumulated on the glaciers than ablated during the year, and Corchia Cave experienced high rainfall amounts. It is interesting to note that accumulation at the Hall in Tirol fan ceased after ca. 7 ka and the stream has subsequently incised deeply into this fan. In the Vinschgau valley, however, the Gadria and adjacent large fans have been intermittently active up to recent times (although at a lower level compared to the early Holocene - Koch, 1883; Fliri, 1984; Brugger and Marseiler, 1987). The trigger of these catastrophic historic debris-flow events, as well as of concomitant catastrophic river floods further south, was almost exclusively very intense rainfall as a result of advection of warm and moist air from the Mediterranean towards the southern part of the Alps (e.g., Schär et al., 1998; Maugeri et al., 1999). Rarely, however, did these air masses reach across the main alpine crest in historic times.

3.2. Towards a model of early Holocene climate change in the Alps

The Alps constitute a border between the Mediterranean and the North Atlantic climate zones and their climate is strongly controlled by large-scale atmospheric patterns, in particular processes over the North Atlantic ocean and its sea-ice system (Wanner et al., 1997). This relationship is dynamic, however, and e.g. correlations between the NAO and meteorological parameters are high in certain decades but break down during others (Schmidli et al., 2002; Wanner et al., 2003). This is substantiated by a recent stable isotope study of the past few decades which found a significant correlation between wintertime $\delta^{18}O$ in precipitation and the winter NAO index for the central European mid-latitudes, but concluded that this relationship is complicated by orographic effects near the Alps and by moisture recycling and the 'amount effect' in the Mediterranean region (Baldini et al., 2008).

In order to reconstruct the climate variability in the Eastern Alps during the Holocene stable isotope data of well-dated high-resolution archives are essential, but the key to a plausible model lies in the comparison and integration of palaeo-data from the adjacent Mediterranean region. The Mediterranean Sea was characterised by a strong salinity decrease between ca. 8 and 5 ka, water-column stratification, and formation of the last of a series of sapropels in the eastern basin (e.g. Kallel et al., 1997, 2004). A strong precipitation increase transformed the whole Mediterranean Sea into a non-concentration basin where mean surface salinities dropped to 35‰ (cf. 37-39‰ today – Kallel et al., 2004).

The most precisely-dated record witnessing this 'pluvial' interval is stalagmite CC26 from Corchia Cave, which tightly constrains the duration of the wettest phase to 8.2 to 7.3 ka (Fig. 2). Correlating the isotope record of Corchia Cave with other continuous isotope records along a S-N transect across the Alps reveals that this isotope anomaly can indeed be traced all the way to the northern rim of the Alps. The signal, however, changes sign upon reaching the southern side of the Alps (Fig. 2): starting as a negative anomaly in Tuscany (largely attributed to the 'amount effect' – Zanchetta et al., 2007) it develops into a positive anomaly in the southern, central, and locally also in the northern, part of the Alps. We attribute this change in the isotopic composition to a simple mass-balance effect, i.e. the proportion of rainfall in the Alps which was sourced from the Mediterranean greatly increased relative to that of North Atlantic provenance (the former being characterised by elevated $\delta^{18}O$ values). This positive anomaly appears to decrease towards the northern fringe of the Alps (Fig. 2), likely reflecting progressive rainout.

This model has been tested against evidence from other (non-isotopic) archives in the region and these multi-proxy data show that the interval of high rainfall intensity indeed reached at least as far north as the Inn valley triggering massive debris flows and giving rise to wet and presumably also cool summers which manifested themselves as a decrease in forest density at the treeline, as well as in positive glacier mass balances.

Acknowledgments

CS, KN and RB acknowledge support from the Austrian Science Fund and comments by two journal referees.

References

Adkins, J., deMenocal, P., Eshel, G., 2006. The "African humid period" and the record of marine upwelling from excess ^{230}Th in Ocean Drilling Program Hole 658C. Paleoceanography 21. doi:10.1029/2005PA001200.

Ariztegui, D., Asioli, A., Lowe, J.J., Trincardi, F., Vigliotti, L., Tamburini, F., Chondrogianni, C., Accorsi, C.A., Mazzanti, M.B., Mercuri, A.M., Van der Kaars, S., McKenzie, J.A., Oldfield, F., 2000. Palaeoclimate and the formation of sapropel S1: inferences from Late Quaternary lacustrine and marine sequences in the central Mediterranean region. Palaeogeogr. Palaeoclimat. Palaeoecol. 158, 215–240.

Baldini, L.M., McDermott, F., Foley, A.M., Baldini, J.U.L., 2008. Spatial variability in the European winter precipitation $\delta^{18}O$-NAO relationship for reconstructing NAO-mode climate variability in the Holocene. Geophys. Res. Lett. 35, L04709 doi:10.1029GL032027.

Bard, E., Delaygue, G., Rostek, F., Antonioli, F., Silenzi, S., Schrag, D.P., 2002. Hydrological conditions over the western Mediterranean basin dyuring the deposition of the cold Sapropel 6 (ca. 175 kyr BP). Earth Planet. Sci. Lett. 202, 481–494.

Bar-Matthews, M., Ayalon, A., Gilmour, M., Hawkesworth, C.J., 2003. Sea-land isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implications for paleorainfall during interglacial intervals. Geochim. Cosmochim. Acta 67, 3181–3199.

Baroni, C., Zanchetta, G., Fallick, A.E., Longinelli, A., 2006. Mollusca stable isotope record of a core from Lake Frassino, northern Italy: hydrological and climatic changes during the last 14 ka. The Holocene 16, 827–837.

Baroni, C., Bruschi, G., Veronese, L., Zanchetta, G., 2001. Younger Dryas to early Holocene palaeoenvironmental evolution of the Lake Terlago (Southern Alps). Geogr. Fis. Dinam. Quat. 24, 13–24.

Battarbee, R.W., Binney, H., 2008. Natural climate variability and global warming: A Holocene perspective. Chichester, Wiley-Blackwell. 276 pp.

Berger, A., Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. Quat. Sci. Rev. 10, 297–317.

Bertò, A., Buzzi, A., Zardi, D., 2004. Back-tracking water vapour contributing to a precipitation event over Trentino: a case study. Meteorol. Z. 13, 189–200.

Boch, R., 2008. Stalagmites from Katerloch Cave, Austria: Growth dynamics and high-resolution records of climate change. Unpublished Ph.D. thesis Univ. of Innsbruck. 223 pp.

Boch, R., Spötl, C., Kramers, J., 2009. Coincident high-resolution isotope records of early Holocene climate change from two stalagmites of Katerloch Cave. Austria. Quat. Sci. Rev. 28, 2527–2538.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294, 2130–2136.

Borsato, A., Frisia, S., Fairchild, I.J., Somogyi, A., Susini, J., 2007. Trace element distribution in annual stalagmite laminae mapped by micrometer-resolution X-ray fluorescence: Implications for incorporation of environmentally significant species. Geochim. Cosmochim. Acta 71, 1494–1512.

Bortenschlager, S., 1977. Ursachen und Ausmaß postglazialer Waldgrenzschwankungen in den Ostalpen. In: Frenzel, B. (Ed.), Dendrochronologie und postglaziale Klimaschwankungen in Europa, vol. 13. Erdwissenschaftliche Forschung, pp. 260–266.

Brugger, L., Marseiler, S., 1987. Dunkle Tage. Die Unwetterkatastrophe im Vinschgau zu Pfingsten 1983. Ereignisse - Folgen - Maßnahmen zur Schadensbehebung. Eine Dokumentation. 127 pp., Bozen, Tappeiner.

Caine, N., 1980. The rainfall intensity-duration control of shallow landslides and debris flows. Geogr. Annaler 62A, 23–27.

Celle-Jeanton, H., Gonfiantini, R., Travi, Y., Sol, B., 2004. Oxygen-18 variations of rainwater during precipitation: application of the Rayleigh model to selected rainfalls in southern France. J. Hydrol. 289, 165–177.

Celle-Jeanton, H., Travi, Y., Blavoux, B., 2001. Isotopic typology of the precipitation in the western Mediterranean region at three different time scales. Geophys. Res. Lett. 28, 1215–1218.

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16, 436–468.

Davis, B.A.S., Brewer, S., Stevenson, A.C., Guiot, J., Contributors, Data, 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quat. Sci. Rev. 22, 1701–1716.

de Lange, G., Thomson, J., Reitz, A., Slomp, C.P., Principato, M.S., Erba, E., Corselli, C., 2008. Synchronous basin-wide formation and redox-controlled preservation of a Mediterranean sapropel. Nature Geoscience 1, 606–610.

deMenocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L., Yarusinsky, M., 2000. Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. Quat. Sci. Rev. 19, 347–361.

Drysdale, R.N., Zanchetta, G., Hellstrom, J.C., Fallick, A.E., Zhao, J.-X., 2005. Stalagmite evidence for the onset of the Last Interglacial in southern Europe at 129 ± 1 ka. Geophys. Res. Letters 32. doi:10.1029/2005GL024658.

Emeis, K.-C., Schulz, H., Struck, U., Rossignol-Strick, M., Erlenkeuser, H., Howell, M.W., Kroon, D., Mackensen, A., Ishizuka, S., Oba, T., Sakamoto, T., Koizumi, I., 2003. Eastern Mediterranean surface water temperatures and $\delta^{18}O$ composition during deposition of sapropels in the late Quaternary. Paleoceanography 18. doi:10.1029/2000PA000617.

Fischer, K., 1990. Entwicklungsgeschichte der Murkegel im Vinschgau. Der Schlern 64, 93–96.

Fischer, K., 1965. Murkegel. Schwemmkegel und Kegelsimse in den Alpentälern. Mitt. Geogr. Ges. München 50, 127–159.

Fliri, F., 1984. Die Pfingstkatastrophe 1983 im Obervinschgau im Lichte von 126 Jahren Niederschlagsbeobachtung in Marienberg. Der Schlern 58, 123–128.

Frisia, S., Borsato, A., Spötl, C., Villa, I., Cucchi, F., 2005. Climate variability in the SE Alps of Italy over the past 17000 years reconstructed from a stalagmite record. Boreas 34, 445–455.

Frisia, S., Borsato, A., Mangini, A., Spötl, C., Madonia, G., Sauro, U., 2006. Holocene climate variability in Sicily from a discontinuous stalagmite record and the Mesolithic to Neolithic transition. Quat. Res. 66, 388–400.

Frisia, S., Borsato, A., Preto, N., McDermott, F., 2003. Late Holocene annual growth in three alpine stalagmites records the influence of solar activity and the North Atlantic Oscillation on winter climate. Earth Planet. Sci. Lett. 216, 411–424.

Frisia, S., Borsato, A., Fairchild, I.J., McDermott, F., 2000. Calcite fabrics, growth mechanisms, and environments of formation in speleothems from the Italian Alps and southwestern Ireland. J. Sed. Res. 70, 1183–1196.

Gasse, F., 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. Quat. Sci. Rev. 19, 189–211.

Graham, N., 2009. Practical experience using speleothem data in multi-proxy climate reconstructions. Geophys. Res. Abstr. vol. 11, EGU2009–11545.

Heiri, O., Tinner, W., Lotter, A.F., 2004. Evidence of cooler European summers during periods of changing meltwater flux to the North Atlantic. Proc. Natl. Acad. Sci. USA 101, 15,285–15,288.

Hoinkes, H.C., 1968. Glacier variation and weather. J. Glaciol. 7, 3–19.

Hormes, A., Müller, B.U., Schlüchter, C., 2001. The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the central Swiss Alps. The Holocene 11, 255–265.

Huang, Y.M., Fairchild, I.J., Borsato, A., Frisia, S., Cassidy, N.J., McDermott, F., Hawkesworth, C.J., 2001. Seasonal variations in Sr, Mg and P in modern speleothems (Grotta di Ernesto, Italy). Chem. Geol. 175, 429–448.

Irmler, R., Daut, G., Mäusbacher, R., 2006. A debris flow calendar derived from sediments of lake Lago di Braies (N. Italy). Geomorphology 77, 69–78.

Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., Schlüchter, C., 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. Quat. Sci. Rev. 28, 2137–2149.

Joerin, U.E., Stocker, T.F., Schlüchter, C., 2006. Multicentury glacier fluctuations in the Swiss Alps during the Holocene. The Holocene 16, 697–704.

Joerin, U.E., Nicolussi, K., Fischer, A., Stocker, T.F., Schlüchter, C., 2008. Holocene optimum events inferred from subglacial sediments at Tschierva glacier, eastern Swiss Alps. Quat. Sci. Rev. 27, 337–350.

Jomelli, V., Pech, V.P., Chochillon, C., Brunstein, D., 2004. Geomorphic variations of debris flows and recent climatic change in the French Alps. Climatic Change 64, 77–102.

Kallel, N., Duplessy, J.-C., Labeyrie, L., Fontugne, M., Paterne, M., 2004. Mediterranean sea palaeohydrology and pluvial periods during the late Quaternary. In: Batterbee, R.W., Gasse, F., Stickley, C.E. (Eds.), Past Climate Variability through Europe and Africa. Springer, Dordrecht, pp. 307–324.
Kallel, N., Duplessy, J.C., Labeyrie, L., Fontugne, M., Paterne, M., Montacer, M., 2000. Mediterranean pluvial periods and sapropel formation over the last 200000 years. Palaeogeogr. Palaeoclimat. Palaeoecol. 157, 45–58.
Kallel, N., Paterne, M., Duplessy, J.C., Vergnaud-Grazzini, C., Pujol, C., Labeyrie, L., Arnold, M., Fontugne, M., Pierre, C., 1997. Enhanced rainfall in the Mediterranean region during the last sapropel event. Oceanologica Acta 20, 697–712.
Kaplan, M.R., Wolfe, A.P., 2006. Spatial and temporal variability of Holocene temperature in the North Atlantic region. Quat. Res. 65, 223–231.
Kerschner, H., Hertl, A., Gross, G., Ivy-Ochs, S., Kubik, P.W., 2006. Surface exposure dating of moraines in the Kromer valley (Silvretta Mountains, Austria) - evidence for glacial response to the 8.2 ka event in the Eastern Alps? The Holocene 16, 7–15.
Koch, G.A., 1883. Die Ursachen der Hochwasser-Katastrophe in den Süd-Alpen. Z. Dt. Oesterr. Alpenver. 14, 136–169.
Kofler, W., Krapf, V., Oberhuber, W., Bortenschlager, S., 2005. Vegetation responses to the 8200 cal BP cold event and to long-term climatic changes in the Eastern Alps: possible influence of solar activity and North Atlantic freshwater pulses. The Holocene 15, 779–788.
Kotthoff, U., Pross, J., Müller, U., Peyron, O., Schmiedl, G., Schulz, H., Bordon, A., 2008. Climate dynamics in the borderlands of the Aegean Sea during formation of sapropel 1 deduced from a marine pollen record. Quat. Sci. Rev. 27, 832–845.
Kuhn, M., Schlosser, E., Span, N., 1997. Eastern Alpine glacier activity and climatic records since 1860. Annals Glaciol. 24, 164–168.
Magny, M., 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations andits probable impact on prehistoric human settlement. Quat. Int. 113, 65–79.
Mangini, A., Verdes, P., Spötl, C., Scholz, D., Vollweiler, N., Kromer, B., 2007. Persistent influence of the North Atlantic hydrography on central European winter temperature during the last 9000 years. Geophys. Res. Lett. 34, L02704. doi:10.1029/2006GL028600.
Maugeri, M., Bacci, P., Barbiero, R., Bellume, M., 1999. Reconstruction of heavy rainfall events on the southern part of the Alpine region from 1868 to the end of the 19th century. Phys. Chem. Earth (B) 24, 637–642.
Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rsoqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate dynamics. Quat. Res. 62, 243–255.
McDermott, F., Frisia, S., Huang, Y., Longinelli, A., Spiro, B., Heaton, T.H.E., Hawkesworth, C.J., Borsato, A., Keppens, E., Fairchild, I.J., van der Borg, K., Verheyden, S., Selmo, E., 1999. Holocene climate variability in Europe: evidence from $\delta^{18}O$, textural and extension-rate variations in three speleothems. Quat. Sci. Rev. 18, 1021–1038.
Nicolussi, K., 1995. Jahrringe und Massenbilanz. Dendroklimatologische Rekonstruktion der Massenbilanzreihe des Hintereisferners bis zum Jahr 1400 mittels Pinus cembra-Reihen aus den Ötztaler Alpen. Tirol. Z. Gletscherk. Glazialgeol. 30, 11–52.
Nicolussi, K., Kaufmann, M., Melvin, T.M., Van Der Plicht, J., Schiessling, P., Thurner, A., 2009. A 9111 year long conifer tree-ring chronology for the European Alps: a base for environmental and climatic investigations. The Holocene 19, 909–920.
Nicolussi, K., Kaufmann, M., Patzelt, G., van der Plicht, J., Thurner, A., 2005. Holocene tree-line variability in the Kauner Valley, central Eastern Alps, indicated by dendrochronological analysis of living trees and subfossil logs. Veget. Hist. Archaeobot. 14, 221–234.
Nicolussi, K., Patzelt, G., 2000a. Discovery of early-Holocene wood and peat on the forefield of the Pasterze glacier, Eastern Alps, Austria. The Holocene 10, 191–199.
Nicolussi, K., Patzelt, G., 2000b. Untersuchungen zur holozänen Gletscherentwicklung von Pasterze und Gepatschferner (Ostalpen). Z. Gletscherk. Glazialgeol. 36, 1–87.
Niggemann, S., 2006. Das Hölloch als Archiv des Paläoklimas. In: Stautz, G., Wolf, A. (Eds.), Das Hölloch im Mahdtal. Höhlenverein Sonthofen, Sonthofen, pp. 254–257.
Patzelt, G., 2008. Der Schwemmkegel von Hall. In: Schmitz-Esser, R. (Ed.), Neues zur Geschichte der Stadt, vol. 2. Hall in Tirol, pp. 12–21.
Patzelt, G., 1994. Holocene development of alluvial fans and the floor of the Inn valley, Tyrol. Mountain Res. Dev. 14, 283–284.
Patzelt, G., 1987. Untersuchungen zur nacheiszeitlichen Schwemmkegel- und Talentwicklung in Tirol. 1.Teil: Das Inntal zwischen Mötz und Wattens. Veröff. Tiroler Landesmus. Ferdinandeum 67, 93–123.
Patzelt, G., Bortenschlager, S., 1973. Die postglazialen Gletscher- und Klimaschwankungen in der Venedigergruppe (Hohe Tauern, Ostalpen). Z. Geomorph. Suppl. 16, 25–72.
Piccini, L., Zanchetta, G., Drysdale, R.N., Hellstrom, J., Isola, I., Fallick, A.E., Leone, G., Doveri, M., Mussi, M., Mantelli, F., Molli, G., Lotti, L., Roncioni, A., Regattieri, E., Meccheri, M., Vaselli, L., 2008. The environmental features of the Monte Corchia cave system (Apuan Alps, central Italy) and their effects on speleothem growth. Int. J. Speleol. 37, 153–172.
Pini, R., 2002. A high-resolution Late-Glacial-Holocene pollen diagram from Pian di Gembro (Central Alps, Northern Italy). Veget. Hist. Archaeobot. 11, 251–262.
Prager, C., Zangerl, C., Patzelt, G., Brandner, R., 2008. Age distribution of fossil landslides in the Tyrol (Austria) and its surrounding areas. Nat. Hazards Earth Syst. Sci. 8, 377–408.
Ritchie, J.C., Eyles, C.H., Haynes, C.V., 1985. Sediment and pollen evidence for an early to mid-Holocene humid period in the eastern Sahara. Nature 314, 352–355.
Roberts, N., Jones, M.D., Benkaddour, A., Eastwood, W.J., Filippi, M.L., Frogley, M.R., Lamb, H.F., Leng, M.J., Reed, J.M., Stein, M., Stevens, L., Valero-Garces, B., Zanchetta, G., 2008. Stable isotope records of Late Quaternary climate and hydrology from Mediterranean lakes: the ISOMED synthesis. Quat. Sci. Rev. 27, 2426–2441.
Rohling, E.J., 1994. Review and new aspects concerning the formation of eastern Mediterranean sapropels. Marine Geol. 122, 1–28.
Rossignol-Strick, M., 1987. Rainy periods and bottom water stagnation initiating brine accumulation and metal concentrations: 1. The late Quaternary. Paleoceanography 2, 333–360.
Rossignol-Strick, M., Nesteroff, W., Olive, P., Vergnaud-Grazzini, C., 1982. After the deluge: Mediterranean stagnation and sapropel formation. Nature 295, 105–110.
Schär, C., Davies, T.D., Frei, C., Wanner, H., Widmann, M., Wild, M., Davies, H.C., 1998. Current alpine climate. In: Views from the Alps. Regional Perspectives of Climate Change. In: Cebon, P., Dahinden, U., Davies, H., Imboden, D.M., Jaeger, C.C. (Eds.), MIT Press, Cambridge, Mass, pp. 21–72.
Schmidli, J., Schmutz, C., Frei, C., Wanner, H., Schär, C., 2002. Mesoscale precipitation variability in the region of the European Alps during the 20th century. Int. J. Climatol. 22, 1049–1074.
Scholz, D., Frisia, S., Borsato, A., Spötl, C., Fohlmeister, J., Kromer, B., Mühlinghaus, C., Miorandi, R., Mudelsee, M., Mangini, A., submitted for publication. Alternating influence of central European and Mediterranean climate in northern Italy during the Holocene documented by stalagmite data. Quat. Sci. Rev.
Schöner, W., Auer, I., Böhm, R., 2000. Climate variability and glacier reaction in the Austrian eastern Alps. Annals Glaciol. 31, 31–38.
Scrivner, A.E., Vance, D., Rohling, E.J., 2004. New neodymium isotope data quantify Nile involvement in Mediterranean anoxic episodes. Geology 32, 565–568.
Spötl, C., Burns, S.J., Frank, N., Mangini, A., Pavuza, N., 2004. Speleothems from the high-alpine Spannagel Cave, Zillertal Alps (Austria). In: Sasowsky, I.D., Mylroie, J. (Eds.), Studies of Cave Sediments. Physical and Chemical Records of Paleoclimate, Dortrecht, Kluwer, pp. 243–256.
Stiny, J., 1910. Die Muren. Versuch einer Monographie mit besonderer Berücksichtigung der Verhältnisse in den Tiroler Alpen. Innsbruck, Wagner. 139 pp.
Stoffel, M., Conus, D., Grichting, M.a., Lièvre, I., Maître, G., 2008. Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: Chronology, environment and implications for the future. Global Planet. Change 60, 222–234.
Stoffel, M., Lièvre, I., Conus, D., Grichting, M.A., Raetzo, H., Gärtner, H.W., Monbaron, M., 2005. 400 years of debris-flow activity and triggering weather conditions: Ritigraben, Valais, Switzerland. Arctic, Antarctic Alpine Res. 37, 387–395.
Tinner, W., Lotter, A.F., 2001. Central European vegetation response to abrupt climate change at 8.2 ka. Geology 29, 551–554.
Tjallingii, R., Claussen, M., Stuut, J.-B.W., Fohlmeister, J., Jahn, A., Bickert, T., Lamy, F., Röhl, U., 2008. Coherent high- and low-latitude control of the northwest African hydrological balance. Nature Geosci. 1, 670–675.
Tranquillini, W., 1979. Physiological ecology of the alpine timberline. Tree existence at high altitudes with special reference to the European Alps. Springer, Berlin. 137 pp.
Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., Frank, D.C., 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. Science 324, 78–80.
Vittoz, P., Rulence, B., Largey, T., Freléchoux, F., 2008. Effects of climate and land-use change on the establishment and growth of Cembran Pine (Pinus cembra L.) over the altitudinal treeline ecotone in the central Swiss Alps. Arctic, Antarctic. Alpine Res 40, 223–232.
Vollweiler, N., Scholz, D., Mühlinghaus, C., Mangini, A., Spötl, C., 2006. A precisely dated climate record for the last 9 kyr from three high alpine stalagmites, Spannagel Cave. Austria. Geophys. Res. Lett. 33, L20703. doi:10.1029/2006GL027662.
von Grafenstein, U., Erlenkeuser, H., Brauer, A., Jouzel, J., Johnsen, S.J., 1999. A mid-European decadal isotope-climate record from 15, 000 to 5000 years B.P. Science 284, 1654–1657.
von Grafenstein, U., Erlenkeuser, H., Müller, J., Jouzel, J., Johnsen, S., 1998. The cold event 8200 years ago documented in oxygen isotope records of precipitation in Europe and Greenland. Climate Dyn. 14, 73–81.
von Grafenstein, U., Erlenkeuser, H., Müller, J., Trimborn, P., Alefs, J., 1996. A 200 year mid-European air temperature record preserved in lake sediments: an extension of the $\delta^{18}O_p$-air temperature relation into the past. Geochim. Cosmochim. Acta 60, 4025–4036.
Wanner, H., Luterbacher, J., Casty, C., Böhm, R., Xoplaki, E., 2003. Variabilität von Temperatur und Niederschlag in den europäischen Alpen seit 1500. In: Jeanneret, F., Wastl-Walter, D., Wiesmann, U., Schwyn, M. (Eds.), Welt der Alpen - Gebirge der Welt, Bern, Haupt, pp. 61–76.
Wanner, H., Rickli, R., Salvisberg, E., Schmutz, C., Schüepp, M., 1997. Global climate change and variability and its influence on alpine climate - concepts and observations. Theor. Appl. Climatol. 58, 221–243.
Wurth, S., Niggemann, S., Richter, D.K., Mangini, A., 2004. The Younger Dryas and Holocene climate record of a stalagmite from Hölloch Cave (Bavarian Alps, Germany). J. Quat. Sci. 19, 291–298.
Zanchetta, G., Drysdale, R.N., Hellstrom, J.C., Fallick, A.E., Isola, I., Gagan, M.K., Pareschi, M.T., 2007. Enhanced rainfall in the Western Mediterranean during deposition of sapropel S1: stalagmite evidence from Corchia cave (Central Italy). Quat. Sci. Rev. 26, 279–286.