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Paleohydrological history of Lake Allos (2200 m a.s.l.) since 13 500 cal a BP in the Mediterranean Alps inferred from an ostracod $\delta^{18}O$ record

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ABSTRACT: This paper presents the first Lateglacial/Holocene (the last 13 500 cal a BP) ostracod $\delta^{18}O$ record to infer hydroclimate variability in the Southern French Alps. Cytherissa lacustris ($\delta^{18}O_{sw}$) shells extracted from the sediments of Lake Allos allowed a reconstruction of $\delta^{18}O_{lake\ _water}$ ($\delta^{18}O_{lw}$) except for the interval 5800–2800 cal a BP. The shape of the Younger Dryas (YD) clearly differed from records documented in the northern Alps. First, $\delta^{18}O_{sw}$ values remained close to modern values before a marked drop ca. 12 000 cal a BP. Then, after several oscillations, $\delta^{18}O_{lw}$ values increased, reaching the highest value of the record ca. 6100 cal a BP during a thermal optimum for this latitude. Finally, low $\delta^{18}O_{lw}$ values occurred from 450 to 100 cal a BP during the Little Ice Age (LIA) following the Medieval Climate anomaly. At the beginning of the YD, $\delta^{18}O_{lw}$ probably reflected changes in local glacier dynamics and precipitation sources. The following decrease in $\delta^{18}O_{lw}$ values was associated with higher freshwater inputs during the second half of the YD. During the LIA, the low $\delta^{18}O$ values are consistent with a higher torrential activity and lower air temperatures.

KEYWORDS: Lateglacial/Holocene; Mediterranean Alps; ostracods; oxygen isotopes; paleohydrology

Introduction

The Alpine climate has changed significantly during the past century, with temperatures increasing by 2 °C (Auer et al., 2007), i.e. more than twice the global average. In the Southern French Alps, local climate conditions such as temperature, precipitation and wind are highly influenced by altitude, topography, and the relative contribution of air masses from the Atlantic Ocean and the Mediterranean Sea. For each of the most recent decades, the surface of the Mediterranean Sea has warmed by around 0.4 °C and sea level has risen by about 3 cm – comparable to global trends, but in part due to decadal variability related to the North Atlantic Oscillation (NAO) (Cramer et al., 2018). The diversity of alpine environmental contexts requires a better understanding of local hydroclimate responses to climate change to improve regional climate prediction.

Climate variability exerts a strong control on regional alpine weather and local-scale environmental processes that are well recorded in past environmental studies (Blennner et al., 2007; Amaud et al., 2016; Cartier et al., 2019; Regattieri et al., 2019). Lake sediment deposits are excellent archives to study climate evolution because of the acute sensitivity of lakes to environmental change and multi-scale processes throughout the hydrological cycle (Schwander et al., 2000). Therefore, producing oxygen isotope records from alpine lacustrine sediments allows a better understanding of high-altitude hydroclimate variability to compare with mid-European and Mediterranean records (von Grafenstein et al., 1999; Zanchetta et al., 2007; Magny et al., 2007, 2011; Regattieri et al., 2019). These regional comparisons can reveal local climate specificities through time as well as synchronicities and time lags in hydrological and environmental responses to global climate events (Lauterbach et al., 2011).

In the Southern French Alps, long-term paleoclimate records remain scarce and/or do not cover the entire Lateglacial/Holocene periods (Harrison et al., 1993; Digerfeldt et al., 1997; Drysdale et al., 2006; Wilhelm et al., 2012; Wirth et al., 2013; Cartier et al., 2019; Regattieri et al., 2019). Climate, environmental changes and vegetation succession that have occurred since the last glaciation are not entirely documented and understood (Brisset et al., 2015; Cartier et al., 2018). In the Mercantour Massif, deglaciation of cirque-glacier catchments occurred between 14 000 and 13 500 cal a BP, i.e. during the Lateglacial Interstadial (Brisset et al., 2015). In the same area, several moraines suggest glacier advances during the Younger Dryas (YD) associated with wet conditions, a different signature from elsewhere in the Alpine region and indicative of a regional specificity (Pauly et al., 2018; Spagnolo and Ribolini, 2019). The last retreat of a cirque glacier following deglaciation goes back to the beginning of the Holocene (ca. 11 000 cal a BP). Later, relatively wet conditions occurred during the Early and Late Holocene bracketed by drier conditions from ca. 7000 to 3000 cal a BP as suggested by lake level reconstructions and speleothem records (Harrison et al., 1993; Digerfeldt et al., 1997; Regattieri et al., 2019). Even though the literature has indicated glacier advances during the Holocene (Subboreal and Little Ice Age, LIA; Fedele et al., 2017), no clear pattern is seen in lake sediment records (Brisset et al., 2015). The watershed of Lake Allos (also in the Mercantour Massif) contains moraines which could be attributed to the Neoglacial period (ca. 4500 cal a BP) or the LIA (Jorda, 1975; de Beaulieu, 1977). In summary, questions remain regarding the local hydroclimate evolution in the Southern French Alps and its specificities at key periods of environmental changes.
In this paper, we present the first $\delta^{18}$O record covering the end of the Late Glacial, and Early and Late Holocene for the Mediterranean Alps, based on the analysis of ostracods buried in sediments from Lake Allos (2200 m a.s.l.). The $\delta^{18}$O signal in lake carbonates is a function of lake water oxygen isotope composition and temperature (Stuiver, 1970; Leng and Marshall, 2004). This relationship with lacustrine conditions has led to successful reconstructions of past $\delta^{18}$O lake water ($\delta^{18}$O$_{lw}$) for Mediterranean lakes (Develle et al., 2010; Roberts et al., 2010). $\delta^{18}$O$_{lw}$ provides a regional paleoclimate proxy, not influenced by local human activities, allowing a comparison with environmental and geomorphological studies (glacier advances, Holzhauser et al., 2005; Rea et al., 2020; torrential activity, Brisset et al., 2017; pollen assemblages, Cartier et al., 2018) and large-scale climate oscillations in Europe (e.g. Younger Dryas, Medieval Climate Anomaly (MCA), LIA). Finally, the hydrological response of Lake Allos is compared to a large set of records from central Europe, the Northern/Southern Alps and the Mediterranean basin to highlight the specificities of the region.

Watershed and lake properties

Lake Allos (44°14'N, 6°42'35"E) is characterized by a 40-m deep basin located in the subalpine zone at 2230 m a.s.l. in the Mercantour national park "Massif du Mercantour" in the Southern French Alps (Fig. 1). Lake Allos is the largest (1 km long and 700 m wide; 54 ha) natural mountain lake in Europe at an altitude above 2000 m. The lake is located in a karstic dissolution basin shaped by Quaternary glaciers (Cartier et al., 2018). The watershed of 520 ha culminates at 2740 m a.s.l. It consists, upstream, of sandstones of Triassic to Cretaceous age building the highest parts, and carbonate conglomerates south of the lake. The watershed is covered by scratched grasslands associated with larches. Lake Allos is composed of two basins constrained by lithology. In the south, the deeper basin (46 m water depth) basement is composed of limestone and karstified calcareous marls; north, a carbonate conglomerate unit constrains a shallower basin (20 m water depth) (Fig. 2). The lower limit of these conglomerates corresponds to a Paleocene erosional surface and Late Cretaceous limestones. Precipitation and snowmelt in the drainage basin feed three major torrents (Laus, Lac and Source). There is no surface outlet and tidal range can reach 13 m on an annual cycle (ONEMA, 2013). A natural underground outlet in the northern part of the lake feeds the downstream torrent (Chadoulin), which stops flowing during dry summers when the lake level is below the outlet level. The surface of Lake Allos is generally frozen from November to May and lake waters are stratified during summer. Annual water temperature in the epilimnion varies between 8 and 15 °C. In the hypolimnion (below 15 m depth), water temperature varies between 3.6 and 4.3 °C (annual monitoring between June and September in 2013; ONEMA; Supporting Information S1).

Regional climate and oxygen isotope composition of precipitation

Climate in the Southern French Alps is temperate. Winter snow depths average 122 cm at 2700 m a.s.l. and snow cover duration is about 182 days at 2100 m a.s.l. (Durand et al., 2009a). Mean annual temperature in the Southern French Alps at 1800 m a.s.l. is 4.8 °C, varying from −0.1 °C in winter to 9.6 °C in summer, and mean annual precipitation is 944 mm, mainly in spring and autumn (Durand et al., 2009b). The precipitation regime is characterized by a strong seasonality mainly determined by a north-westerly atmospheric flow and by the northward penetration of Mediterranean flows in the Southern Alps. The source...
areas of alpine precipitation can be traced with oxygen isotopes because precipitation of Mediterranean origin has a mean weighted oxygen isotope composition of $\delta^{18}O_p = -4.3 \text{% VSMOW}$ (SD = 1.7%), whereas those of Atlantic origin, which supply a large amount of rainfall during winter months (Bolle, 2003), have a $\delta^{18}O_p = -8.5 \text{% VSMOW}$ (SD = 3.51%) (Fig. 1; Celle-Jeantot et al., 2004).

Figure 3 shows monthly weighted means of $\delta^{18}O_p$ from GNIP stations around Lake Allos (IAEA/WMO, 2019 Thonon-les-Bains: 46°22′N, 6°28′E; Draix: 44°13′N, 6°33′E; Malaussène: 43°9′2″N, 7°13′E; Monaco: 43°7′3″N, 7°42′N). For Thonon-les-Bains (385 m a.s.l) and Draix (851 m a.s.l), two stations North-East of Lake Allos, mean $\delta^{18}O_p$ is $-7.4 \text{%}$ during summer months and $-11.3 \text{%}$ during winter months. South of Lake Allos and closer to the Mediterranean Sea, the mean $\delta^{18}O_p$ at Malaussène station (359 m a.s.l) is $-5.8 \text{%}$ during summer months and $-4.9 \text{%}$ during winter months; $-2.18 \text{%}$ and $-5.85 \text{%}$ for Monaco (2 m a.s.l), respectively (Fig. 3). At these stations, $\delta^{18}O_p$ values are not a function of the amount of precipitation but rather vary according to the season. $\delta^{18}O_p$ follows a linear relationship with air temperature (IAEA/WMO, 2019) and is lower during periods of lower air temperatures influenced by air masses from the Atlantic.

### Methods

The long sediment sequence of Lake Allos was sampled in July 2011 (name: ALO11) in the deep (45 m), southern basin (44°14′N, 6°42′29″E) using a UWITEC piston coring device mounted on a floating platform (laboratory EDYTEM). Four sites were cored (sites I to IV). The cored sediment sequences reached the geological basement at a coring depth of 14 m in sites 01 and 04, and at 13.5 m in site 03. In addition, a short core (ALO11-P1) was sampled using a UWITEC gravity corer to preserve the sediment interface. All the 18 core sections are presented in supplementary material in Cartier et al. (2018) and are available at https://doi.org/10.1016/j.quascirev.2018.02.016. Extensive figures are presented in Brisset et al. (2014) in open access at https://tel.archives-ouvertes.fr/tel-01095721. The chronology of core ALO11 is based on 23 accelerator mass spectrometry (AMS) $^{14}$C dates (Cartier et al., 2018) from terrestrial macro-remains measured by the Poznan Radiocarbon Laboratory and $^{210}$Pb accumulation rate constrained by $^{137}$Cs measured in the underground laboratory of Modane (Etienne et al., 2013). Considering temporal deposition differences between continuous and instantaneous sediment layers, age-depth modeling was performed after removing flood layer thicknesses (see details in Cartier et al., 2018).

**Lake water sampling and measurements of $\delta D$ and $\delta^{18}O_{lw}$**

Lake water samples were collected directly after spring snowmelt and following the drier summer season to evaluate the effect of summer evaporation on $\delta^{18}O_{lw}$. Water sampling was performed at Lake Allos from the shore using 50-ml polyethylene dark bottles fully filled at the following dates: 23 September 2019, 9 June 2020 and 12 October 2020.

Measurements of $\delta D$ and $\delta^{18}O_{lw}$ were performed in two laboratories because of logistic difficulties during the coronavirus pandemic. The sample collected in 2019 was measured at CEREGE (France) on a Picarro L2140i analyser coupled with a high-precision A0211 vaporizer and an A0325 autosampler. Standard deviation on routine measurements was ±0.023 ‰ for $\delta^{18}O$ and ±0.078 ‰ for $\delta D$. The two water samples taken in 2020 were measured at the BGS (British Geological Survey, UK). Oxygen isotope ($\delta^{18}O$) measurements were made using the CO$_2$ equilibration method with an Isoprime 100 mass spectrometer plus an Aquaprep device. Deuterium isotope ($\delta D$) measurements were made using an online Cr reduction method with a EuroPyroOH-3110 system coupled to a GVI IsoPrime mass spectrometer (Morrison et al., 2001). Standard deviation was ±0.05 ‰ for $\delta^{18}O$ and ±1.0 ‰ for $\delta D$.

**Extraction and preparation of ostracods for $\delta^{18}O$ analysis**

Directly after coring (autumn 2011), the entire 14-m-long sequence (half cores of the sections ‘OUT’ correlated to the master core ALO11 at a maximum error range of 5 mm; see Figure 3. On the left, location map of meteorological stations (black squares) and lakes (stars). On the right, $\delta^{18}O$ and $\delta D$ (in ‰ VSMOW) in Lake waters of Allos (in blue LA: 23 September 2019; 9 June 2020 and 13 October 2020) compared to other sites: Lake Petit (in green LP: 17 May 2011 and 17 September 2011; Cartier et al., 2019); Mean $\delta^{18}O$ and $\delta D$ in precipitation from meteorological stations (in yellow Station 1 Thonon-les-Bains 1999–2016, Station 2 Draix 2004–2013, Station 3 Malaussène 1997–1999 and Station 4 Monaco 1999–2016; IAEA/WMO, 2019). Therder line represents the global meteoric water line (GMWL). [Color figure can be viewed at wileyonlinelibrary.com]
supplementary material in Cartier et al., 2018) was sliced continuously every 5 cm (270 samples in total). Each sample covers on average 30 years ([min:max] = 5·63); see the accumulation rate in Cartier et al., 2018). The sample volume was 170 cm³ above 564 cm and 77 cm³ below. Samples were kept in closed bottles at low temperatures to maintain their humidity. All the 270 samples were analysed. Most samples were sieved from February to April 2012 and the remaining samples during autumn 2012. As the sediment was fresh and humid, hand-sieving with water was soft, allowing complete removal of detrital particles without mechanical or chemical actions. The sieved material was retrieved from 200- and 100-µm meshes with water, and ostracods were hand-picked with a fine brush using a stereo binocular microscope and Petri dishes. The ostracod valves were well preserved without any signs of mechanical stress or dissolution. Adhering sediments were removed using diﬀused water, ﬁne needles and brushes. Then, carapaces were rinsed with ethanol and dried in ambient air (Caporaletti, 2011). All ostracods were counted and identiﬁed using a speciﬁc ﬂora of Western and Central Europe (Meisch, 2000) to identify changes in ostracod abundances and ecology. These results have already been published in Cartier et al. (2018).

According to Cartier et al. (2018), Cytherissa lacustris valves are present in the sediments during periods of oligotrophic and eutrophic chemical actions. The sieved material was retrieved from 200- and 100-µm meshes with water, and ostracods were hand-picked with a ﬁne brush using a stereo binocular microscope and Petri dishes. The ostracod valves were well preserved without any signs of mechanical stress or dissolution. Adhering sediments were removed using diﬀused water, ﬁne needles and brushes. Then, carapaces were rinsed with ethanol and dried in ambient air (Caporaletti, 2011). All ostracods were counted and identiﬁed using a speciﬁc ﬂora of Western and Central Europe (Meisch, 2000) to identify changes in ostracod abundances and ecology. These results have already been published in Cartier et al. (2018).

Results and interpretation

Modern variability in δ18Owater and hydrological functioning of Lake Allos

A monitoring program of δ18Owater, carried out between 2004 and 2009 by the IAEA/WMO in 2015 was performed at Draix station (44°08’00”N, 006°20’00”E), located 25 km from Lake Allos (Supporting Information Material S1). Mean annual values of δ18Owater varied between −7.0 ‰ in (2006) and −10.4 ‰ in (2009). Mean δ18Owater for the 6 years of monitoring was −8.32 ‰.

The modern oxygen and deuterium isotope compositions of Allos’ lake waters at diﬀerent seasons of the year were compared to δ18Owater and δD values in Lake Petit waters located nearby, and δ18Owater values from weather stations in the region (Fig. 3). The values at Allos plot near the global meteoric water line and were slightly higher than at Lake Petit during spring 2011 (Fig. 3).

In June 2020, δ18Owater (% VSMOW) at Allos was −11.1 ‰ (SD = 0.01 ‰) and δD (‰) was −75.1 ‰ (SD = 0.71 ‰). In September 2019, δ18Owater (% VSMOW) was −10.4 ‰ (SD = 0.06 ‰, two replicates) and δD (% VSMOW) was −72.6 ‰ (SD = 0.29 ‰, two replicates). The following year in October 2020, δ18Owater (% VSMOW) at Allos was −10.5 ‰ (SD = 0.01 ‰) and δD (% VSMOW) was −71.6 ‰ (SD = 0.43 ‰). Both samples in September and October plot on the global meteoric water line, showing no eﬀect of lake water evaporation on the δ18O and δD values of lake waters.

These results suggest that Lake Allos behaves like an open system with high dilution and fast discharge due to an underground outlet in the karstic depression. Considering an average Chadoulin ﬂux of −275 L s⁻¹ (Carzon, 1958) and a volume of Lake Allos of ca. 9 × 10⁶ m³ based on the bathymetric data, the estimated water residence time is close to 1 year. Recent data (SAGE, 2014) provide a mean value of 112 L s⁻¹ of the ﬂux of Chadoulin over a 5-year survey. This gives a mean residence time of <2.5 years, similar to the estimation based on less recent data. In systems with a relatively short residence time of water, it is expected that δ18O values of lake waters are primarily inﬂuenced by the δ18O
signature of direct precipitation (depending on air temperature at the time of precipitation formation and precipitation origin) and the $\delta^{18}$O composition of the main water inflows from the watershed (i.e. snowmelt) (Roberts et al., 2008). The lake level of Allos can temporarily drop below the underground outlet during dry summers, meaning that an effect of evaporation could play a role only during exceptional years. Annual lake water mixing occurs twice, once during spring snowmelt and once in late autumn, as in other deep lake systems such as Lake Ammersee in southern Germany (von Grafenstein et al., 1996).

**Significance of the C. lacustris $\delta^{18}$O signal**

*Cytherissa lacustris* (Cytherideidae) is an endobenthic species and inhabits sublittoral and profundal zones of cold, deep lakes and the littoral zones of high-altitude alpine lakes (Meisch, 2000). *C. lacustris* is very sensitive to oxygenation conditions prevailing at the sediment–water interface and maximum abundance is found in waters between 4 and 15 °C throughout the year. Adults and juveniles of *C. lacustris* are found together without seasonal changes in relative abundance, meaning that *C. lacustris* reproduces continuously throughout the year (von Grafenstein et al., 1999). Therefore, variations in $\delta^{18}$O$_{sp}$ represent annual deep water variability.

According to annual monitoring (see Study site section and Supporting Information Material S1), deep lake waters of Lake Allos (below 15 m depth) where *C. lacustris* develops remained at 4 °C throughout 2013. Seismic surveys show that the lake sediment infill is well stratified with no evidence of sediment reworking (Wilhelm et al., 2012). Layers of sediment are continuous between the shallow basin and the deep basin, suggesting that the lake level did not drop by more than 20 m over the study period. As lake water temperature is close to 4 °C below 15 m, we consider that temperature at the bottom of the deep basin remained relatively constant. Therefore, $\delta^{18}$O$_{sp}$ variations are assumed to be representative of $\delta^{18}$O$_{lw}$ variations. Note that samples cover a longer period (ca. 30 years) compared to the *C. lacustris* calcification timespan.

**Reconstruction of past $\delta^{18}$O$_{lw}$**

Thick and strongly calcified valves of *C. lacustris* are well preserved in the sediments and show no signs of dissolution (Fig. 4). *C. lacustris* is almost the only species of ostracods found in the sediments. Valves of *Cypridopsis vidua*, *Candona candida* and *Cypria ophthalmica* are present in sediments from the last 1500 years (Cartier et al., 2018). Abundance of *C. lacustris* is variable along the core. Ostracod valves are absent in the sediments from 5800 to 2800 cal a BP during a period with high diatom concentrations (data published in Cartier et al., 2018; Figure 5). Mean *C. lacustris* abundance in core sediment slices 5 cm long is 3.1 valves from the bottom to 5800 cal a BP and 2.8 valves from 2800 cal a BP to the top of the record (Cartier et al., 2018). Concentrations in valves cm$^{-3}$ are presented in Fig. 5. The highest concentrations, up to 0.35 valves cm$^{-3}$, are observed at the end of the YD and from 10 000 to 8500 cal a BP. *C. lacustris* valves were sufficiently numerous to allow 73 oxygen isotope measurements.

Over the entire study period, minimum and maximum values of $\delta^{18}$O$_{sp}$ range from $-8.4$ ‰ to $-6.3$ ‰ VPDB (6100 cal a BP) to $-7.1$ ‰ VPDB (SD = 0.4‰) (Fig. 5). Mean $\delta^{18}$O$_{sp}$ along the core is $-7.1$ ‰ VPDB (SD = 0.4‰). The highest variability in $\delta^{18}$O$_{sp}$ is observed during the YD (12 700–11 500 cal a BP). A drop in $\delta^{18}$O$_{sp}$ is present at 11 900 cal a BP and followed by an increase in $\delta^{18}$O$_{lw}$, at the transition with the Holocene. After a peak, values decrease again until ca. 8500 cal a BP. High $\delta^{18}$O$_{sp}$ values are present from 7200 to 6100 cal a BP, ca. 2800 cal a BP and ca. 1000 cal a BP during a thermal optimum for mid-northern latitudes and during the MCA. $\delta^{18}$O$_{lw}$ drops again to low values from 500 cal a BP during the LIA before a rise in the topmost sample representing sub-modern conditions (Fig. 5). Unfortunately, *C. lacustris* is absent from the first top centimetre of sediments, preventing measurement of modern $\delta^{18}$O$_{lw}$ values. After correcting the $\delta^{18}$O$_{lw}$ for the vital effect and isotope fractionation between calcite and water at 4 °C, the reconstructed $\delta^{18}$O$_{lw}$ ranges between $-12.8$ and $-10.6$ ‰ VSMOW. Mean $\delta^{18}$O$_{lw}$ is $-11.5$ ‰ VSMOW (SD = 0.4‰) for the entire record (Fig. 5). The reconstructed oxygen isotope value in the top sample ($-11.3$ ‰) is consistent with the modern $\delta^{18}$O$_{lw}$ range ($-11.1$ ‰ to $-10.4$ ‰) for 2019 and 2020.

**Discussion**

**Major factors influencing the $\delta^{18}$O signal at Lake Allos**

The $\delta^{18}$O signal in lake carbonates is primarily a function of the lake water oxygen isotope composition and water temperature (Stuiver, 1970; Leng and Marshall, 2004). The lake water oxygen isotope composition is itself a product of (i) the $\delta^{18}$O value of the seawater from which it originally derived; (ii) rainout history, seasonality and air-mass trajectory; and (iii) oxygen isotope fractionation of lake water compared to mean meteoric precipitation, primarily by evaporation but also by groundwater flux (Develle et al., 2010; Roberts et al., 2010). According to the modern oxygen isotope composition of Lake Allos’ waters, $\delta^{18}$O$_{lw}$ plots along the global meteoric water line, showing no effect of evaporation after the summer season (Fig. 3). $\delta^{18}$O in precipitation entering the lake varies according to the season, due to changes in air temperatures and differential contribution in vapor of Atlantic and Mediterranean origin. Therefore, a lowering in $\delta^{18}$O$_{lw}$ is expected to reflect an increasing contribution of water inflow from snowmelt, a higher contribution of precipitation of Atlantic origin, and/or precipitation occurring primarily during colder seasons (Celle-Jeanton et al., 2004). In contrast, increasing $\delta^{18}$O$_{lw}$ is interpreted as a higher contribution of water inflow from rain versus snowmelt preferentially of Mediterranean origin and/or precipitation occurring mainly during warmer periods. In the catchment area, sources of signal change are evapotranspiration by vegetation, water losses by percolation into soils and delayed flows (stored in the ice, snow or soils). However, the $\delta^{18}$O value of waters having percolated into soils might be considered as the average $\delta^{18}$O value of local rainfall over several months (McDonnell et al., 2004). In contrast, increasing $\delta^{18}$O$_{lw}$ is interpreted as a higher contribution of water inflow from rain versus snowmelt preferentially of Mediterranean origin and/or precipitation occurring mainly during warmer periods. In the catchment area, sources of signal change are evapotranspiration by vegetation, water losses by percolation into soils and delayed flows (stored in the ice, snow or soils). However, the $\delta^{18}$O value of waters having percolated into soils might be considered as the average $\delta^{18}$O value of local rainfall over several months (McDonnell et al., 2004).
et al., 1991; Tang and Feng, 2001). At Lake Allos, a low but permanent flow of water currently persists from the remains of a rock glacier. Four phases of glacial advances have been identified in the Allos watershed (Jorda, 1975; de Beaulieu and Jorda, 1977). Stages 1 and 2 (respectively at 1850–1900 and 2265 m a.s.l.) pre-date the formation of Lake Allos and are attributed to the early Lateglacial (Brisset et al., 2014). Stage 3, located at 2310 m a.s.l., is attributed to the YD, indicating a glacier advance near Lake Allos during this period (Brisset et al., 2014). Finally, stage 4 is attributed to the last cooling period during the Late Holocene that might be related to the Neoglacial period (4500 cal a BP) or the LIA (Jorda, 1975; Brisset et al., 2014).

The comparison between the δ18Ow signal, vegetation evolution and the potential presence of a glacier, in particular during the YD, provides additional clues to identify factors influencing oxygen isotope variability. The marked drop in δ18Ow ca. 12 000 cal a BP (2σ error = 360) probably occurred during the second half of the YD. Pollen analysis shows the presence of open vegetation from the base of the record to 1150 cm depth (ca. 11 700 cal a BP). A high percentage (30 %) of steppic taxa is consistent with the dominance of runoff processes in a sandur-type outwash plain at the glacier snout during massive deglaciation of the Allos cirque. Then, steppic taxa (Artemisia, Chenopodiaceae, Caryophyllaceae) increased again during the YD (Fig. 5). A similar vegetation is recorded during the YD in the Mediterranean Alps (Curtair et al., 2018). Finally, stage 4 is attributed to the last cooling period during the Late Holocene that might be related to the Neoglacial period (4500 cal a BP) or the LIA (Jorda, 1975; Brisset et al., 2014).

Other studies, such as the study of Lake Momsee sediments in the north-eastern Alps, have shown that cooling at the onset of the YD is simultaneously reflected in ostracod δ18O and vegetation (Lauterbach et al., 2011). A similar synchronicity in the response of isotope and vegetation records is shown in a European synthesis by Reinig et al. (2021), recording the onset of the YD at 12 800 cal a BP (130 years earlier than thought). Therefore, the later drop in δ18O values observed at Allos (ca. 12 000 cal a BP) could be related to the influence of a local glacier in the watershed rather than temperatures, at least during the YD interval. Following this hypothesis, an increasing glacier/snowmelt contribution could explain decreases in δ18Ow when the presence of a glacier is suspected. During the mid-Holocene, vegetation starts to be highly influenced by humans, leading to an opening up of forests at lower altitudes, which limits the use of cross-comparison with the δ18O signal (Cartier et al., 2018; Figure 5). However, it can be seen that intervals with low δ18Ow values during the Late Holocene and in particular during the LIA correspond to occurrences of Ephedra sp., supporting the presence of cooler periods (Cartier et al., 2018).

**Paleohydrology in the Mediterranean Alps and comparison with other climate reconstructions**

**Beginning of lake infilling and the climate reversal of the YD (i.e., from 13 350 to 11 500 cal a BP)**

The first period of lake infilling of Lake Allos (13 350–12 700 cal a BP) can be attributed to the end of the Allerød considering the oldest 14C date, giving an age of 13 070–12 800 cal a BP (2σ) at 1260 cm depth. As only one 14C date pre-dates the onset of the YD, uncertainties remain regarding the chronology but climatic conditions must necessarily have been relatively warmer than previous periods to allow the massive deglaciation of the cirque of Allos. Additional
information can be obtained from the pollen diagram, which documents an open landscape characteristic of the pre-Holocene period from the base of the record to 1150 cm depth (ca. 11 700 cal a BP; min: 11 920; max: 11 570; 95 %) (Fig. 5). The corresponding age for this depth is consistent with recognized boundaries of the YD, i.e. 12 800–11 500 cal a BP from the Greenland ice-core (GS-1) and mid-European isotope records (Reinig et al., 2021) (Fig. 6).

In the Northern Alps, the $\delta^{18}$O record of lake Leysin (1255 m a.s.l., Switzerland), Schwander et al., 2000) shows quasi-simultaneous temperature changes between Greenland and Europe during the YD. Records from the northern Alps or its foreland display consistent shapes of the YD, similar to the Ammersee record (533 m a.s.l.) (Fig. 6). In addition, oxygen isotope records from Lake Mondsee (481 m a.s.l., Lauterbach et al., 2011), Lake Gerzensee (603 m a.s.l., von Grafenstein et al., 2013), Höllöch cave (700 m a.s.l., Li et al., 2021) and the TEX86 temperature record from Lake Lucerne (434 m a.s.l., Blaga et al., 2013) also document synchronous changes during the YD.

Located at higher altitudes, the $\delta^{18}$O$_{lw}$ record from Lake Allos (2230 m a.s.l.) in the Southern French Alps clearly differs from those documented in the Northern Alps. According to the age–depth model, the beginning of the YD is marked by relatively high $\delta^{18}$O values compared to the second half of the YD (ca. after 12 000 cal a BP; Fig. 5). Several hypotheses might explain the persistence of high $\delta^{18}$O values during this period, including (i) water storage induced by the presence of a local glacier in the watershed, (ii) a lower temperature shift at the Allerød–YD transition in the Southern French Alps and (iii) a greater influence of precipitation of Mediterranean origin to counteract a large cooling. Several factors could also have played a simultaneous role in the changes observed. The first hypothesis, i.e. water storage induced by the presence of a glacier, agrees with datings of moraines in the Southern French Alps (Darnault et al., 2012; Figure 6). A meltwater flux during summer is not excluded but was probably of less importance to the lake budget than during the second half of the YD. Concerning a lower temperature shift (hypothesis 2), the study of paleo-extents of the Argentière glacier close to the study site

**Figure 6.** Estimated $\delta^{18}$O ($\delta^{18}$O$_{lw}$, ‰ VSMOW) in the lake waters of Lake Allos compared to other records: oxygen isotope ratios in precipitation ($\delta^{18}$O$_{pw}$, ‰ VSMOW) based on the record of Lake Ammersee (Germany; von Grafenstein et al., 1999); Lake Ghirla plant wax ($\delta^{18}$O, ‰ SMOW) at the foot of the Southern Alps (Wirth and Sessions, 2016); oxygen isotope record ($\delta^{18}$O, ‰ VPDB) of Corchia Cave CC26 (Northern Italy; Zanchetta et al., 2007); lake-level fluctuations (m) at Accesa (Italy; Magny et al., 2007); lake level reconstruction at Preola (Southern Italy; Magny et al., 2011). Locations of the sites are shown on Fig. 1. Ages of end-moraine and polished bedrock (Maritime Alps) dated by $^{10}$Be and $^{14}$C methods are from: (1) Spagnolo and Ribolini (2019); (2) Darnault et al. (2012); (3) Federici et al. (2008); (4) Ribolini et al. (2007); and (5) Federici and Stefanini (2001). [Color figure can be viewed at wileyonlinelibrary.com]
(Protn et al., 2019) invalidates this hypothesis as reconstructed temperature shifts ($\Delta T$ varying between 3.6 and 5.5 °C compared to modern temperatures) are in the same range as temperature reconstructions from the Northern Alps (e.g. $\Delta T$ of 3.9 °C at the YD–Holocene transition in the Swiss Alps; Samartin et al., 2012). Finally, the third hypothesis (a higher influence of precipitation of Mediterranean origin) is in accordance with the hydrogen isotope record of plant waxes from Lake Ghirla in the Southern Alps showing unexpectedly high δDmax values during the YD (Wirth and Sessions, 2016). This signal was interpreted as a shift from a northern North Atlantic to a southern North Atlantic/western Mediterranean Sea source due to a southward migration of the westerlies with climate cooling. Assuming a temperature shift (YD–modern conditions) varying between 3.6 and 5.5 °C (Protn et al., 2019), an altitudinal effect of −0.2 % per 100 m (e.g. Schürch et al., 2003) and a correlation between δ18O in precipitation and air temperatures of 0.33 °C per °C (Drax station; $r^2 = 0.54$; Supporting Information Fig. S1), the precipitation reaching Allos at the beginning of the YD may have been the result of a mixture of 50 % Atlantic – 50 % Mediterranean (30 % / 70 %, respectively) to counteract the effect of cooling on the δ18O record.

At a broader scale, a higher contribution of Mediterranean precipitation in the Southern French Alps would fit a recent study published in Rea et al. (2020) based on glacier, pollen and chironomid assemblages, showing that the YD was certainly characterized by the presence of a positive Scandinavia (SCAND) climate configuration pushing storm tracks south and east. To summarize, while the temperature hypothesis can be excluded, glacier storage and a Mediterranean precipitation source remain plausible explanations for high δ18O values during this period.

During the second half of the YD, the isotopic record of Lake Allos also presents an original shape. The δ18O record is marked by a sharp drop to low δ18O values corresponding to the lowest values of the record (−12.8 ‰ VSMOW) ca. 12 000 cal a BP. These changes are probably the result of large freshwater inputs to the lake due to glacier melting. This implies a large influence of glacier dynamics in the watershed on the isotopic signal, as suggested by the comparison with the pollen diagram. Alternatively, the presence of humid conditions would fit the regional geomorphological studies from the Maritime Alps, indicating the presence of glacier advances ca. 12 500–12 300 cal a BP (Pauly et al., 2018; Spagnolo and Ribolini, 2019).

**The Holocene period from 11 500 cal a BP to the present day**

Isotope records covering the transition from the Lateglacial to the Holocene are very sparse in the Alps, and almost non-existent in the Southern French Alps. A moraine dating to the Preboreal period in the Maritime Alps (Fig. 6; Federici et al., 2008) suggests new glacial advances at the beginning of the Holocene. Although supported by only a few samples, a drop in δ18O is in the record of Allos (from −11 to −12 ‰ VSMOW) ca. 10 800 cal a BP seems to follow the cold and humid Preboreal oscillation ca. 11 300 cal a BP (Ilyashuk et al., 2009).

Between 9800 and 8400 cal a BP, δ18O is at Lake Allos increased, reaching a maximum of −10.7 ‰ VSMOW, and then decreased to −11.8 ‰ VSMOW. The millennial-scale change in the δ18O values is assumed to be related primarily to changes in air temperature and precipitation regime rather than to glacier influence. To the best of our current knowledge (Brisset et al., 2014, 2015), it seems unlikely that the upper moraines date back to this time interval in the watershed of Allos; however, remaining moraines not yet sampled are under investigation. Increasing δ18O values might then be the result of a higher contribution of precipitation occurring during warmer seasons or preferentially of Mediterranean origin. Indeed, the Early Holocene in the northern mid-latitudes is characterized by the highest summer and lowest winter solar insolation (Laskar et al., 2004). Therefore, higher summer temperatures are recorded in the Eastern Alps (Ilyashuk et al., 2011). In the Southern Alps, a high-resolution δ13C isotopic signal highlights an early Holocene warming and/or a climate oscillation called the ‘9.3 ka’ dry climate event (Audiard et al., 2021).

In contrast, the period 9200–8400 cal a BP suggests a higher contribution of snowmelt, precipitation of Atlantic origin and/or the presence of colder conditions. More broadly, the north-western Mediterranean region at the beginning of the Holocene generally experienced a long-term trend towards humid conditions from 9200 to 6800 cal a BP, as evidenced in lake isotope records (Roberts et al., 2008), caves (Rio Martino and Corchia Cave, Regattieri et al., 2019 and Zanchetta et al. 2007) and lake level reconstructions (Harrison and Digerfeldt, 1993; Jalut et al., 2009; Magny et al., 2013) (Fig. 6).

At the transition from the Early to Mid-Holocene (8200 cal a BP), low data resolution limits our ability to assess fine variations in the δ18O record. However, we observe a general trend towards increasing δ18Ow culminating ca. 6100 cal a BP, representing the highest value of the sequence (−10.6 ‰ VSMOW), followed by an abrupt decrease at 5700 cal a BP, unfortunately supported by only one data point. During that time period, precipitation reconstruction (Brayshaw et al., 2011) and paleoclimate data from lake isotope records (Roberts et al., 2011) indicate drier conditions from 8000 to 6000 cal a BP in both Western and Eastern Mediterranean regions. This period also represents a thermal optimum in the Northern Hemisphere between 30 and 60°N (Kaufman et al., 2020).

For the last 2800 cal a BP, our results suggest major paleohydrological changes near Lake Allos. A shift from high δ18Ow to low δ18O at 2300 cal a BP is concomitant with increasing torrential activity at Lake Allos (Brisset et al., 2017) and in the Southern French Alps during the Iron Age time interval interpreted as a cooler and more humid period (Jorda, 1992; Sivan et al., 2006); however, the low resolution limits further interpretation (Fig. 7). Then, at the beginning of the Roman Period ca. 1900–1800 cal a BP, higher δ18Ow suggests the presence of higher air temperatures and/or a higher contribution of rain to the lake (versus snowmelt) preferentially of Mediterranean origin. A drier period at lower altitudes in the valleys is illustrated by human occupation closer to or within current riverbeds (Bravard et al., 1992; Jorda, 1992). From 1800 to 1300 cal a BP, low δ18Ow values suggest lower air temperatures and/or a higher contribution of precipitation (mostly snow) of Atlantic origin to the lake. The Late Antiquity also coincides with higher torrential activity both at high altitude at Allos (Brisset et al., 2017) and in lowlands (Sivan et al., 2006), negative temperature anomalies in tree ring records (Büntgen and Tegel, 2011) and glacier advances in the European Alps (Holzhauser et al., 2005) (Fig. 7). Higher δ18Ow occurs again from 1300 to 500 cal a BP, which might correspond to the MCA also seen in the tree ring record of Corona et al. (2011) (Fig. 7). Regarding our results, the MCA shows several oscillations in the δ18O record with three peaks ca. 1200, 850 and 600 cal a BP. The transition between the MCA and LIA at 500 cal a BP is very sharp with δ18Ow highly depleted during two low excursions. These δ18O values are similar to the values obtained in the second part of the YD. This abrupt decrease might be explained by lower air...
temperatures and/or higher freshwater inputs from snowmelt to the lake preferentially of Atlantic origin. During the LIA, sedimentological studies show increasing fluvial activity in the Southern French Alps, at Allos (Wilhelm et al., 2012; Brisset et al., 2017) and downstream (Miramont et al., 1998; Sivan et al., 2006), a water level rise in the Jura (Magny et al., 2001), and glacial tongue advances in both the Northern and Southern Alps (Holzhauser et al., 2005; Ivi-Ochs et al., 2009; Figure 7). Overall, two moraines in the Maritime Alps showing glacial advances during the Iron Age ca. 2400 cal a BP (Ribolini et al., 2007) and the LIA ca. 450 cal a BP (Federici and Stefanini, 2001) are coherent with low δ18O values at Allos (Fig. 6). The fourth stage of glacial advance at Allos described in Jorda (1975) could then be linked to the LIA given the intensity of the event in the δ18O record. However, the sequence discontinuity and low periodic resolution require further isotopic studies for the Mediterranean Alps.

Finally, comparing oxygen isotope records from Northern and Southern Europe (Fig. 6) with the δ18O record at Lake Allos allows a better understanding of how air temperatures and hydrology have responded to climate change during the end of the Lateglacial and Holocene periods. The record of Allos shows an alternation of glacier growth and melting during the YD and a general high variability in freshwater inputs (as in Bakke et al., 2009) while air temperature proxies (von Grafenstein et al., 1999; Schwander et al., 2000) show similar boundaries with Greenland ice cores. During the Holocene, the record of Lake Allos highlights a general trend towards drier conditions from the Early to mid-Holocene (ca. 6000 cal a BP) followed by wetter conditions from 2800 cal a BP to the present day. Unfortunately, the resolution of the record prevents further interpretations for the mid-Holocene, and other events might have occurred (see Cartier et al., 2019). This trend is the opposite of lake water level variations in Southern Europe recorded at Lake Preola in Southern Italy (Magny et al., 2011; Figure 6) but in agreement with local lake water level reconstructions (Harrison et al., 1993; Digerfeldt et al., 1997) and isotope cave records (Regattieri et al., 2019). Whereas changes in global air temperatures in the Northern Hemisphere were relatively smooth during the Holocene with a progressive increase in air temperatures until 6000 cal a BP, followed by a decreasing trend until the 19th century (Kaufman et al., 2020), local hydroclimate records from the Mediterranean Alps show a higher variability with centennial and millennial climate oscillations.

Conclusions

Sediments from Lake Allos have allowed for the analysis of oxygen isotope ratios in valves of Cytherissa lacustris, a species encountered in deep lakes. Variation in δ18O covers the end of the Lateglacial and the Holocene (except from 5800 to 2800 cal a BP). δ18O was estimated after correcting ostracod δ18O values with the vital effect of C. lacustris and the effect of isotope fractionation at equilibrium between calcite and water at 4 °C. The main factors influencing the isotopic record are estimated to be: variation in air temperatures, freshwater inputs through melting glacier/snowmelt contribution, and meteoric precipitation sources (West from the Atlantic and South from the Mediterranean region). Despite only one 14C date before the Holocene, our data indicate the persistence of a steppic vegetation during the YD. Relatively high δ18O values at that time could be related to glacier water storage and Mediterranean precipitation source. Then, during the second half of the YD, the large drop in δ18O might be the result of higher freshwater inputs to the lake budget. During the Holocene, the highest δ18O value of the record was reached ca. 6100 cal a BP during a thermal optimum at this latitude, suggesting a potential role of climate in large vegetation succession in the Southern French Alps. Finally, the Late Holocene (from 2800 cal a BP to the present day) shows several oscillations in δ18O following major climate phases recognized at the European scale and glacier advances/retreat in the Western Alps: a higher contribution of ice/snowmelt inputs to the lake and/or lower temperatures during the Late Antiquity and LIA and a reverse trend during the Roman Warm Period and MCA. Therefore, the fourth stage of glacial advance in the watershed of Allos could be linked to the LIA given the intensity of the event in the δ18O record. However, new studies on hydroclimate in high-altitude environments are required to fully understand these questions due to the discontinuity of the sequence.
Supporting information

Additional supporting information can be found in the online version of this article. This article includes online-only Supplemental Data.

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Abbreviations. LIA, Little Ice Age; MCA, Medieval Climate Anomaly; NAO, North Atlantic Oscillation; YD, Younger Dryas.

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