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Plant-wax D/H ratios in the southern European Alps record multiple aspects of climate variability

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ABSTRACT

We present a Younger Dryas–Holocene record of the hydrogen isotopic composition of sedimentary plant waxes (δD_{wax}) from the southern European Alps (Lake Ghirla, N-Italy) to investigate its sensitivity to climatic forcing variations in this mid-latitude region (45°N).

A modern altitudinal transect of δD values of river water and leaf waxes in the Lake Ghirla catchment is used to test present-day climate sensitivity of δD_{wax}. While we find that altitudinal effects on δD_{wax} are minor at our study site, temperature, precipitation amount, and evapotranspiration all appear to influence δD_{wax} to varying extents.

In the lake-sediment record, δD_{wax} values vary between −134 and −180‰ over the past 13 kyr. The long-term Holocene pattern of δD_{wax} parallels the trend of decreasing temperature and is thus likely forced by the decline of northern hemisphere summer insolation. Shorter-term fluctuations, in contrast, may reflect both temperature and moisture-source changes. During the cool Younger Dryas and Little Ice Age (LIA) periods we observe unexpectedly high δD_{wax} values relative to those before and after. We suggest that a change towards a more D-enriched moisture source is required during these intervals. In fact, a shift from northern N-Atlantic to southern N-Atlantic/western Mediterranean Sea sources would be consistent with a southward migration of the Westerlies with climate cooling. Prominent δD_{wax} fluctuations in the early and middle Holocene are negative and potentially associated with temperature declines. In the late Holocene (<4 kyr BP), excursions are partly positive (as for the LIA) suggesting a stronger influence of moisture-source changes on δD_{wax} variation. In addition to isotopic fractionations of the hydrological cycle, changes in vegetation composition, in the length of the growing season, and in snowfall amount provide additional potential sources of variability, although we cannot yet quantitatively assess these in the paleo-record. We conclude that while our δD_{wax} record from the Alps does contain climatic information, it is a complicated record that would require additional constraints to be robustly interpreted. This also has important implications for other water-isotope-based proxy records of precipitation and hydro-climate from this region, such as cave speleothems.

1. Introduction

The hydrogen isotopic composition (D/H ratio) of plant leaf waxes (δD_{wax}) has increasingly been used as proxy for reconstructing past hydro-climatic changes in many regions (e.g. Sauer et al., 2001; Schefuss et al., 2005; Nichols and Huang, 2012; Tierney and deMenocal, 2013; Feakins et al., 2014). Values of δD_{wax} from lacustrine and marine sedimentary sequences are considered to reflect past changes in the isotopic composition of the plants' source water, i.e. soil water recharged by infiltrating precipitation and river water (Sachse et al., 2012). However, a range of factors and processes controls the isotopic composition of the precipitation feeding the plants' source water, including the location and relative humidity of the initial moisture source, Rayleigh distillation by condensation processes during transport to the area of interest (i.e. temperature changes, rain- and snowfall events, and transport distance are important), and also re-evaporation during precipitation events (Craig, 1961; Dansgaard, 1964; Rozanski et al., 1997). A complete assessment of these isotopic fractionation processes is mostly unrealistic in the framework of paleo-climate studies, so simplifications have to be applied when interpreting

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δD_{wax} data. In addition, δD_{wax} is subject to physiological processes controlling isotope fractionation during plant-wax biosynthesis (e.g. Sessions et al., 1999; Smith and Freeman, 2006; Sachse et al., 2012; Kahmen et al., 2013). Despite these inevitable complications, δD_{wax} from sedimentary records has often been found to reliably record aspects of past climate, but a key question is often *which* aspect of climate is being recorded. In the tropics, δD_{wax} primarily reflects changes in the amount of precipitation, whereas at high latitudes it seems to record mainly changes in temperature (Niedermeyer et al., 2010; Thomas et al., 2012). At mid-latitudes, greater variability in moisture sources and transport pathways often lead to a more complex forcing of δD_{wax} (Dansgaard, 1964; Aichner et al., 2015).

The southern European Alps (hereafter 'southern Alps') and the Mediterranean area (30–45°N) is a heavily populated and hydro-climatically sensitive area, for which a significant decrease in mean precipitation and an increased risk of drought with ongoing climate warming is expected (Giorgi and Lionello, 2008; Rajczak et al., 2013). Climatic reconstructions from this area are therefore crucial to understand past hydrologic variability as well as its potential impact on human civilization (e.g. Roberts et al., 2011; Magny et al., 2013).

Moisture arrives in the southern Alps by advection from the western Mediterranean and from the North Atlantic (N-Atlantic), as well as through land evapotranspiration in summer (Sodemann and Zubler, 2010; Winschall et al., 2014). The relative amount of southern N-Atlantic (~20–35°N) and western Mediterranean moisture vs. northern N-Atlantic (~35–60°N) moisture reaching the southern Alps is influenced by the meridional position of the westerly storm tracks (Westerlies) above the N-Atlantic, and thus potentially by the state of the North Atlantic Oscillation (NAO) (Hurrell et al., 2003; Trouet et al., 2012). During positive NAO (NAO+) conditions the Westerlies have a more northerly position causing wet and warm conditions in Scandinavia, and dry and cool conditions in southern Europe (including the southern Alps); almost opposite conditions occur during a negative NAO (NAO−) state (Wanner et al., 2001). The more southern position of the Westerlies during NAO− conditions thus entails an increased moisture advection from the southern N-Atlantic and from the western Mediterranean to the southern Alps.

Northern N-Atlantic (~35–60°N) surface waters are depleted in ^{18}O by ~1‰ (corresponding to a ~8‰ D-depletion; Craig, 1961) relative to southern N-Atlantic (~20–35°N) and western Mediterranean surface waters (Celle-Jeanton et al., 2001; LeGrande and Schmidt, 2006). On the one hand, this difference provides a potential opportunity to reconstruct past moisture-source changes using water isotope proxies such as δD_{wax} or the oxygen isotopic composition of carbonate minerals ($\delta^{18}O_{carb}$) archived in sedimentary sequences. On the other hand, it is a potential complication for those proxies if one is primarily interested in interpreting them in terms of temperature or precipitation amount.

Previous studies from the south-alpine region investigating Holocene climate based on $\delta^{18}O_{carb}$ include a mollusc-based record from Lake Frassino (Baroni et al., 2006) and a stalagmite record from Grotta di Ernesto (McDermott et al., 1999; Scholz et al., 2012), both located in northeastern Italy (Fig. 1a). Whereas $\delta^{18}O_{carb}$ variations in the lake record are driven by lake-water evaporation and are therefore interpreted as wet-dry changes, the interpretation of $\delta^{18}O_{carb}$ variations at Grotta di Ernesto is complex and seems to reflect local effects as well as changing moisture sources (Scholz et al., 2012). In addition, the Holocene $\delta^{18}O_{carb}$ signal of stalagmites from the Spannagel Cave in the eastern Alps (Austria) (Fig. 1a) was intensively investigated over the last decade (e.g. Mangini et al., 2005; Fohlmeister et al., 2012). Spannagel Cave $\delta^{18}O_{carb}$ variations have primarily been interpreted as temperature changes, where lower $\delta^{18}O_{carb}$ corresponds to higher temperature. The mechanism proposed by the authors is that warm periods are characterized by relatively more winter precipitation compared to cool periods. As a result, speleothem $\delta^{18}O_{carb}$ integrating the annual, and not seasonal, precipitation $\delta^{18}O$ signal would decrease. Alternatively, it has also been proposed that the relative contribution of ^{18}O-enriched Mediterranean vs. ^{18}O-depleted N-Atlantic moisture is of importance (Mangini et al., 2005). In total, these $\delta^{18}O_{carb}$ studies indicate that the interpretation of water isotope data from sedimentary proxies is not unambiguous in the alpine region.

The primary aim of our study is to evaluate the potential value of δD_{wax} as a (hydro-)climatic proxy in the mid-latitude region of the Alps. In doing so, we address the possible effects of changes in the relative importance of temperature and moisture source, of shifts in the growing season, and of changes in vegetation in determining δD_{wax} values over the course of the past 13 kyrs. In order to approach these goals, we established a Younger Dryas–Holocene δD_{wax} record based on n-C_{28} alkanoic acids from the sediments of south-alpine Lake Ghirla (N-Italy). The sediments are well characterized and, importantly, hydro-climatic information is available in the form of a paleo-flood reconstruction (Wirth, 2013; Wirth et al., 2013). In addition, we conducted a catchment study, investigating the present-day factors controlling D/H of river water (δD_{river}), as well as δD_{wax} of modern tree leaves and of riverbed sediments. We compared our results to the water isotopic composition of precipitation and to meteorological data from the nearby Global Network of Isotopes in Precipitation (GNIP) and MeteoSwiss station Locarno (28 km north of Lake Ghirla).

2. Study area

2.1. Lake and catchment area

Lake Ghirla (45.916°N, 8.822°E) is a small lake with a surface area of 0.28 km^2 and a maximum water depth of 14 m situated at the foot of the southern Alps at an elevation of 442 m above sea level (asl) (Fig. 1). The maximum elevation in the catchment area is 1129 m asl. The lake is located in the N–S-oriented Valganna valley, which drains towards the north into Lake Maggiore (193 m asl). The southern limit of the Valganna coincides with a morphological step of ~60 m, in the north of the city of Varese (382 m asl), that represents the southernmost physiographic limit of the Alps (Fig. 1b).

Sediment cores used for this study were retrieved from the central, deepest (14 m) part of the lake (Fig. 1d). Complementary cores taken in the slightly shallower (13 m) area further south contain significantly less detrital material, indicating that the S–N-flowing stream entering the lake at its southern end provides only a minor portion of the sediment supply. Sediment is primarily delivered by tributaries draining the eastern and western slopes, leading to the accumulation of large delta structures extending into the lake (Fig. 1d). Detrital material found in the lake sediments reflects the mineralogy of the Permian granites and Triassic dolomites constituting the bedrock of the lateral slopes (Fig. 1c) (Atlas of Switzerland, 2010). Due to their steepness and thin soils they are unsuitable for agriculture and are therefore densely wooded. The most abundant tree species at present are beech (*Fagus*), hazel (*Corylus*) and chestnut (*Castanea*). A previous paleo-vegetation study reported an unusually low occurrence of agricultural activities in the Valganna until the Roman Period when pollen of *Castanea*, walnut (*Juglans*) and rye (*Secale*) appeared (Schneider and Tobolski, 1983).