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Palaeoclimate records 60–8 ka in the Austrian and Swiss Alps and their forelands

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A B S T R A C T

The European Alps and their forelands provide a range of different archives and climate proxies for developing climate records in the time interval 60–8 thousand years (ka) ago. We review quantitative and semi-quantitative approaches for reconstructing climatic variables in the Austrian and Swiss sector of the Alpine region within this time interval. Available quantitative to semi-quantitative climate records in this region are mainly based on fossil assemblages of biota such as chironomids, cladocerans, coleopterans, diatoms and pollen preserved in lake sediments and peat, the analysis of oxygen isotopes in speleothems and lake sediment records, the reconstruction of past variations in treeline altitude, the reconstruction of past equilibrium line altitude and extent of glaciers based on geomorphological evidence, and the interpretation of past soil formation processes, dust deposition and permafrost as apparent in loess-palaeosol sequences. Palaeoclimate reconstructions in the Alpine region are affected by dating uncertainties increasing with age, the fragmentary nature of most of the available records, which typically only incorporate a fraction of the time interval of interest, and the limited replication of records within and between regions. Furthermore, there have been few attempts to cross-validate different approaches across this time interval to confirm reconstructed patterns of climatic change by several independent lines of evidence. Based on our review we identify a number of developments that would provide major advances for palaeoclimate reconstruction for the period 60–8 ka in the Alps and their forelands. These include (1) the compilation of individual, fragmentary records to longer and continuous reconstructions, (2) replication of climate records and the development of regional reconstructions for different parts of the Alps, (3) the cross-validation of different proxy-types and approaches, and (4) the reconstruction of past variations in climate gradients across the Alps and their forelands. Furthermore,

Abbreviations: AAR, Accumulation area ratio; AMS, Accelerator Mass Spectrometry; ELA, Equilibrium Line Altitude; GIS, Greenland Isotope Stage; GRIP, Greenland ice core project; IRSL, Infrared-stimulated Luminescence; LGM, Last Glacial Maximum; LIA, Little Ice Age; LPS, Loess-palaeosol sequence; MIS, Marine Isotope Stage; NGRIP, North Greenland Ice Core Project; OSL, Optically Stimulated Luminescence; UV, Ultraviolet.

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the development of downscaled climate model runs for the Alpine region 60–8 ka, and of forward modelling approaches for climate proxies would expand the opportunities for quantitative assessments of climatic conditions in Europe within this time-interval.

1. Introduction

Mountain regions provide excellent opportunities for developing palaeoclimatological records and approaches. The pronounced altitudinal and often also spatial climatic gradients allow the development and rigorous calibration of palaeotemperature proxy-indicators in archives as different as lake sediments and peat, speleothems, or tree-ring sequences (e.g. Lotter et al., 1997; Mangini et al., 2005). The landscapes in mountain regions are often strongly influenced by the steep climatic gradients and by past variations in climatic conditions. Therefore, the study of geological landscape features such as moraines, landslides and rock glaciers with appropriate geochronological approaches allows insights into past variations in climate (e.g. Ivy-Ochs et al., 2006; Kerschner and Ivy-Ochs, 2007). Other landscape features, such as the position of the Alpine treeline, are also strongly influenced by climate. Reconstructions of the past altitudinal limits of vegetation zones can, therefore, provide a further approach for constraining past variations in temperature (e.g. Tinner et al., 1996; Nicolussi et al., 2005).

In the European Alps and their forelands the earliest attempts to reconstruct past climate variations include interpretations of glacial landforms such as moraine ridges and erratic boulders as evidence of past glaciations (e.g. Venetz, 1833; Penck and Brückner, 1901/1909). Palynological (pollen-based) records and, more recently, macroscopic plant fossils preserved in lake sediment and peat have been used to make inferences about past vegetation and, indirectly, climatic change (e.g. Tinner et al., 1996; Lotter et al., 2000). In recent decades, stable isotope analyses and radiometric dating methods have broadened the range of archives that can be exploited for developing climate proxy records. Widely-used approaches in the European Alps and their forelands now include stable isotopic analyses in speleothems (e.g. Spötl et al., 2006; Boch et al., 2011) and lake sediment records (e.g. von Grafenstein et al., 1999; Lauterbach et al., 2011), dating of landforms such as terminal and lateral moraines as well as high-precision dating of organic matter deposited in glacier forefields (e.g. Joerin et al., 2006), analysis of fossil assemblages in lake sediment and peat to reconstruct past variations in biota and, indirectly, temperature (e.g. Heiri et al., 2004; Jost-Stauffer et al., 2005; Ilyashuk et al., 2011), and the study of past soil development to reconstruct phases of soil formation, aeolian sediment transport and permafrost (e.g. Terhorst et al., 2013).

Although palaeoclimate records from the Alpine region have a long tradition, are often based on rigorous calibration studies, and have in many cases the potential for providing quantitative estimates of past climatic changes, they are presently underused in studies that examine climatic variations during the Last Glacial-to-interglacial cycle. A number of reasons may be responsible for this discrepancy. Many climate archives in the Alpine region are discontinuous over longer time intervals, since conditions ideal for accumulation of archives and suitable for recording climatic variations change both spatially and altitudinally during the examined time interval. Furthermore, dating accuracy and reliability varies dramatically in most archive types across the glacial–interglacial transition. As a consequence, many Late Pleistocene palaeoclimate records from the Alpine region do not have the resolution necessary for resolving leads or lags with other components of the climate systems, or with potential climate forcing factors. However, palaeotemperature or palaeoprecipitation signals may actually be recorded more reliably than in many other archives in adjacent lowland regions. In contrast to records produced in large, multinational projects, most palaeoclimatic reconstructions from the Alpine region are the products of collaborations between a small number of investigators or even single-author datasets. Although reconstructions are usually available and provided to interested colleagues upon request, many of the climate records from the Alps cannot be found in online climate data repositories. This is another reason why palaeoclimate records from the Alpine region may have been overlooked in synoptic studies of past climatic change.

The INTIMATE project aims at compiling proxy-based palaeoclimate records from Europe for the period 60–8 ka and facilitating the use of these data by the user community. This community includes climate modellers, who depend on independent climate records for evaluating model simulations, palaeoclimatologists developing and interpreting climate proxy records across Europe, and researchers studying the effects of past climatic changes on ecosystems and landscapes. Here we report the results of a workshop supported by INTIMATE which aimed at compiling and reviewing available palaeoclimate records from the Austrian and Swiss sectors of the Alpine region. The workshop, and therefore also the scope of this review, was intentionally restricted to Austria and Switzerland to reduce the complexity of the task and the number of records to be examined (Fig. 1). However, we also discuss a few selected records from eastern France and southernmost Germany since they help to constrain the past climate development in the northern Alpine forelands. Furthermore, it was decided to mainly focus on established proxies which allow quantitative, or at least semi-quantitative estimates of past variations in climate variables, since these reconstructions are directly comparable with other quantitative records of past climate change, climate model output data, and can be used as input variables to derive model based assessments of past ecosystem change (e.g. Heiri et al., 2006; Henne et al., 2011). However, an effort was made to cover a wide range of archives and palaeoclimatological methods, including palaeoecological, geochemical and geomorphological approaches. We first provide an overview of the examined archives and proxy types (Section 2) and the available palaeoclimatic records published for the study region within the time window 60–8 ka (Section 3). In a second step we discuss the spatial and temporal coverage of the presently available records and challenges faced by the community of researchers working with them. Finally, we list future steps necessary to increase the quality, accessibility and usefulness of palaeoclimatic records from the Alpine region in general, using the situation in Austria and Switzerland as an example. This review is complemented by parallel efforts by members of the INTIMATE group focusing on palaeoclimate data 60–8 ka available for Western Europe (Moreno et al., 2014), and Eastern Europe (Feurdean et al., 2014).

As in all other attempts of inter-comparing independently dated late Quaternary records, chronological issues play an important role when compiling climate reconstructions in the Alpine region (Brauer et al., this issue). This is especially true if attempts are made to compare records from different archives, which are dated by different direct dating methods (e.g. radiocarbon, U/Th, annual