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Cold-season temperatures in the European Alps during the past millennium: variability, seasonality and recent trends

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ABSTRACT

This study presents a proxy-based, quantitative reconstruction of cold-season (mean October to May, $T_{Oct-May}$) air temperatures covering nearly the entire last millennium (AD 1060–2003, some hiatuses).

The reconstruction was based on subfossil chrysophyte stomatocyst remains in the varved sediments of high-Alpine Lake Silvaplana, eastern Swiss Alps (46°27′N, 9°48′W, 1791 m a.s.l.). Previous studies have demonstrated the reliability of this proxy by comparison to meteorological data. Cold-season air temperatures could therefore be reconstructed quantitatively, at a high resolution (5-yr) and with high chronological accuracy. Spatial correlation analysis suggests that the reconstruction reflects cold season climate variability over the high- Alpine region and substantial parts of central and western Europe.

Cold-season temperatures were characterized by a relatively stable first part of the millennium until AD 1440 (2σ of 5-yr mean values = 0.7 °C) and highly variable $T_{Oct-May}$ after that (AD 1440–1900, 2σ of 5-yr mean values = 1.3 °C). Recent decades (AD, 1991-present) were unusually warm in the context of the last millennium (exceeding the 2σ-range of the mean decadal $T_{Oct-May}$) but this warmth was not unprecedented. The coolest decades occurred from AD 1510–1520 and AD 1880–1890. The timing of extremely warm and cold decades is generally in good agreement with documentary data representing Switzerland and central European lowlands.

The transition from relatively stable to highly variable $T_{Oct-May}$ coincided with large changes in atmospheric circulation patterns in the North Atlantic region. Comparison of reconstructed cold season temperatures to the North Atlantic Oscillation index (NAO) during the past 1000 years showed that the relatively stable and warm conditions at the study site until AD 1440 coincided with a persistent positive mode of the NAO. We propose that the transition to large $T_{Oct-May}$ variability around AD 1440 was linked to the subsequent absence of this persistent zonal flow pattern, which would allow other climatic drivers to gain importance in the study area. From AD 1440–1900, the similarity of reconstructed $T_{Oct-May}$ to reconstructed air pressure in the Siberian High suggests a relatively strong influence of continental anticyclonic systems on Alpine cold season climate parameters during periods when westerly airflow was subdued. A more continental type of atmospheric circulation thus seems to be characteristic for the Little Ice Age in Europe.

Comparison of $T_{oct-May}$ to summer temperature reconstructions from the same study site shows that, as expected, summer and cold season temperature trends and variability differed completely throughout nearly the entire last 1000 years. Since AD 1980, however, summer and cold season temperatures show a simultaneous, strong increase, which is unprecedented in the context of the last millennium. We suggest that the most likely explanation for this recent trend is anthropogenic greenhouse gas (GHG) forcing.

1. Introduction

To place recent warming in a long term context, large efforts have been made to provide global (Mann et al., 2009) and continental scale (PAGES 2k Consortium, 2013) temperature reconstructions for the past millennium and beyond. In the latter study, a very large number of proxy data, historical records, early-

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instrumental and meteorological data were compiled for each continent to provide high resolution temperature reconstructions. This study shows that in most regions, the 20th century was on average the warmest century since AD 1400, whereas the mean temperature of the last three decades (AD 1970–2000) were the warmest, or among the warmest 30-year periods on record (PAGES 2k Consortium, 2013). However, these temperature reconstructions reflect mean annual or summer temperatures (PAGES 2k Consortium, 2013). For the European continent, for example, the reconstruction was based mostly on tree ring data, which primarily reflect environmental conditions during the growing season. Unfortunately, due to a strong bias in biological proxy records to the warm season, currently little information is available on past winter temperature variability. Past cold season temperature variability may, however, differ strongly from warm season patterns, as demonstrated by e.g. Xoplaki et al. (2005) for the European mainland since AD 1500. This lack of cold season temperature records therefore strongly undermines our understanding of past climatic variability and drivers.

In Europe, large-scale temperature reconstructions that provide information specifically for the cold seasons are primarily based on documentary records (e.g. Luterbacher et al., 2004; Casty et al., 2005). However, in general these do not provide continuous records beyond ca AD 1500 (e.g. Pfister et al., 1996; Shabalova and van Engelen, 2003; Dobrovolný et al., 2010), since documentary data become sparse further back in time. Moreover, the main strength of documentary data is on annual to decadal timescales and it is debated whether documentary data sources can reliably reflect long term (multi-decadal and longer) temperature patterns (e.g. Zorita et al., 2010). The only proxy-based ‘winter record’ currently available for the Alpine region, which does contain a multi-decadal to centennial scale climatic signal, was based on a speleothem record from Spannagel cave, Austria (Mangini et al., 2005). However, as indicated in the original paper, the authors do not claim that the signal contained in the speleothem record is purely winter temperature (as suggested in subsequent publications, e.g. Graham et al., 2011). In summary, the state of knowledge on past cold season temperature variability in Europe is highly limited, spatially as well as temporally. Several important research questions therefore remain unresolved.

Due to the scarcity of long, continuous time series reflecting decadal/multi-decadal cold season temperature variability, it has so far been very difficult to place recent winter warmth in a long term perspective, as was done for mean annual and summer temperatures by e.g. the PAGES 2k Consortium (2013). For example, in our study area in the south-eastern Swiss Alpine region (Fig. 1), meteorological data show that the warmest cold-season temperatures so far were measured in 2006/2007, when the average Oct–May temperature was +0.8 °C (www.meteoswiss.ch). This was the only year since the start of the measurement period (AD 1864) for which positive cold-season temperatures were measured. For comparison, the mean of Oct–May temperatures from AD 1961–1990 was −2.2 °C. Interestingly, out of only seven years during which a cold-season temperature warmer than −1 °C was measured, six occurred during the last 25 years. However, a longer time perspective (beyond AD 1864) is required to fully assess recent climatic developments in the context of natural, forced and unforced variability.

In addition, it is difficult to assess changes in seasonality over the past millennium. Current knowledge on the characteristics and causes of the Little Ice Age (LIA, 1550–1900) and the Medieval Climate Anomaly (MCA, 900–1200) in Europe is largely based on annual or warm season temperature records (Jones et al., 2001; Moberg et al., 2005). For example, it is currently not clear whether the frequently reconstructed warmth during the MCA (e.g. Jones et al., 2001; Trachsel et al., 2012) was typical for summer only, or for all seasons. The ‘warm season bias’ is a particular disadvantage when trying to address the causes of past temperature variability. In Europe, the influence of important climatic drivers varies strongly over the course of a year. One of the most important controls on contemporaneous European-Atlantic climate variability is the North Atlantic Oscillation (NAO; Hurrel, 1995), which strongly influences the position, strength and frequency of passing winter cyclones associated with the northern Hemisphere Westerly wind belt. The NAO dominates temperature and precipitation patterns over large parts of Europe and has its strongest influence during the winter months (Wanner et al., 1997). However, NAO variability is difficult to reconstruct beyond ca AD 1500 due to sparseness of data reflecting the winter period. The NAO reconstruction by Trouet et al. (2009), which covers the entire last millennium, was therefore based on the comparison of only a very small number of datasets.

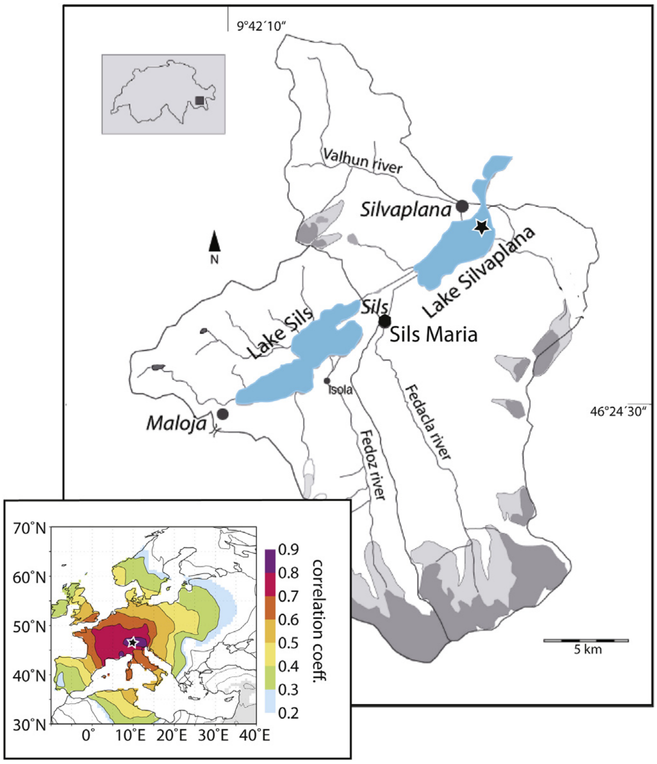

Fig. 1. Location of the study area in the SE Swiss Alpine region. Shown is Lake Silvaplana and its partly glaciated catchment area (light grey shading: glacier extend in AD, 1850; dark grey shading: glacier extent in AD, 1991), the main tributary streams and the coring location. The nearby meteorological station at Sils Maria is also indicated. Inset: Correlation map showing significant ($p < 0.01$) correlations between detrended homogenized meteorological mean Oct–May temperature time series at the Sils Maria meteorological (Begert et al., 2005) and CRU-TS3.1 gridded (0.5° × 0.5°) maximum temperature for the same months (AD, 1901–2000).

In this study we present a highly resolved (5-yr), quantitative reconstruction of past cold season (mean Oct–May) temperatures covering the period from AD 1070–2003. The reconstruction is based on the subfossil remains of chrysophyte stomatocyst (see below) in the varved sediments of high-Alpine Lake Silvaplana (46°27′N, 9°48′E, 1791 m.a.s.l.: Fig. 1). Lake Silvaplana was selected as the study area for this project because 1) its sediments are varved, providing excellent age control (Trachsel et al., 2010), 2) summer temperature reconstructions are available based on the same sediment cores as used in this project (Larocque-Tobler et al., 2010; Trachsel et al., 2010), thus allowing for the internally