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A chrysophyte-based quantitative reconstruction of winter severity from varved lake sediments in NE Poland during the past millennium and its relationship to natural climate variability

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ABSTRACT

Chrysophyte cysts are recognized as powerful proxies of cold-season temperatures. In this paper we use the relationship between chrysophyte assemblages and the number of days below 4 °C (DB4 °C) in the epilimnion of a lake in northern Poland to develop a transfer function and to reconstruct winter severity in Poland for the last millennium. DB4 °C is a climate variable related to the length of the winter. Multivariate ordination techniques were used to study the distribution of chrysophytes from sediment traps of 37 low-land lakes distributed along a variety of environmental and climatic gradients in northern Poland. Of all the environmental variables measured, stepwise variable selection and individual Redundancy analyses (RDA) identified DB4 °C as the most important variable for chrysophytes, explaining a portion of variance independent of variables related to water chemistry (conductivity, chlorides, K, sulfates), which were also important. A quantitative transfer function was created to estimate DB4 °C from sedimentary assemblages using partial least square regression (PLS). The two-component model (PLS-2) had a coefficient of determination of $R^2_{cross} = 0.58$, with root mean squared error of prediction (RMSEP, based on leave-one-out) of 3.41 days. The resulting transfer function was applied to an annually-varved sediment core from Lake Żabińskie, providing a new sub-decadal quantitative reconstruction of DB4 °C with high chronological accuracy for the period AD 1000–2010. During Medieval Times (AD 1180–1440) winters were generally shorter (warmer) except for a decade with very long and severe winters around AD 1260–1270 (following the AD 1258 volcanic eruption). The 16th and 17th centuries and the beginning of the 19th century experienced very long severe winters. Comparison with other European cold-season reconstructions and atmospheric indices for this region indicates that large parts of the winter variability (reconstructed DB4 °C) is due to the interplay between the oscillations of the zonal flow controlled by the North Atlantic Oscillation (NAO) and the influence of continental anticyclonic systems (Siberian High, East Atlantic/Western Russia pattern). Differences with other European records are attributed to geographic climatological differences between Poland and Western Europe (Low Countries, Alps). Striking correspondence between the combined volcanic and solar forcing and the DB4 °C reconstruction prior to the 20th century suggests that winter climate in Poland responds mostly to natural forced variability (volcanic and solar) and the influence of unforced variability is low.

1. Introduction

Comprehensive reconstructions of continental to global-scale temperature variability during the past millennia have demonstrated the value of paleoclimate proxy data and provided insight into natural forced and unforced variability, and anthropogenic disturbances (PAGES 2k Consortium, 2013). This information is a

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key to reduce uncertainties for future climate change (Hegerl et al., 2006).

Although the number of suitable proxy data sets has increased in recent times, some important challenges remain. Winter season reconstructions using paleolimnological records are scarce, as only few proxies, such as diatoms and chrysophytes, are sensitive to cold conditions in the lake via the amount or duration of ice-cover (e.g. Kamenik and Schmidt, 2005; Rühland et al., 2015; Weckström et al., 2014). Even for Europe, where the data base is arguably very good, most of the proxy series used for millennial-long regional climate reconstructions record predominantly the summer season (e.g. PAGES 2k Consortium, 2013 and references therein; Trachsel et al., 2010). However, at least for Europe it is very well known that the structure of summer temperature variability differed very much from the winter season (de Jong et al., 2013b; Luterbacher et al., 2004) implying that the picture about past climate variability as concluded from the summer season is incomplete.

Moreover, the proxy sites are often not evenly distributed in space. Using pseudo-proxies and climate model data Pauling et al. (2003) and Küttel et al. (2007) have shown for Europe that the location of predictor sites matters: while most of the proxy sites are located in Western Europe, sites in Central Europe, the Baltic and SE Scandinavia are missing; but information from these areas would be very helpful.

In this article we present a quantitative reconstruction of cold season climate from varved lake sediments in NE Poland for the past 1000 years. Information about winter temperature from this area is very important because of the very strong relationship between Polish and European temperatures both at the interannual and interdecadal time scales (Luterbacher et al., 2010). Moreover, winter climate in NE Poland is affected by major atmospheric circulation patterns and modes in the north Atlantic European domain, especially the North Atlantic Oscillation (NAO) and the East Atlantic/Western Russia (EA/WRUS) pattern (Luterbacher et al., 2010, 2004). This is clearly evidenced in snow cover duration (Falarz, 2007), lake ice-cover (Marszelewski and Skowron, 2006; Wrzesiński et al., 2013), documentary and early instrumental data (Luterbacher et al., 2010; Przybylak et al., 2005, 2003) for the late 19th and 20th century.

Poland is also interesting because of its wealth of long high-quality instrumental records back to AD 1780. For periods prior to instrumental observations, there exist a few successful attempts at reconstructing air temperature by means of documentary sources, chronicles and meteorological observations (Przybylak et al., 2005, 2010; Sadowski, 1991), or quantitative reconstructions of air temperature based on historical sources with high resolution (daily). Such data are available for shorter discrete periods of several dozens of years (e.g. Bokwa et al., 2001; Limanówka, 2000; Michalczewski, 1981; Przybylak and Marciniak, 2010; Przybylak et al., 2014). The state of knowledge of Polish climate before the 16th century is generally modest and the existing reconstructions are uncertain (Przybylak, 2011; Przybylak et al., 2010). Natural paleoclimate records with high (interannual to subdecadal) resolution that reach further back than AD 1550 are extremely scarce, and only based on tree-rings widths (Koprowski et al., 2012; Przybylak et al., 2005; Szychowska-Krąpiec, 2010). A synthesis of the longest tree-ring based climate reconstructions for Poland is presented by Zielski et al. (2010). Most surprisingly, studies using varved lake sediments are missing despite their demonstrated potential for quantitative seasonal paleoclimate studies (Amann et al., 2014; Bonk et al., 2015; Larocque-Tobler et al., 2015). Recent work has also highlighted the potential of raised bogs as paleoenvironmental and paleoclimate archives in Poland (De Vleeschouwer et al., 2009; Gałka et al., 2014; Lamentowicz et al., 2015, 2009).

Chrysophytes (Chrysophyceae and Synurophyceae group) are excellent candidates to provide information about winter climate. These golden brown freshwater algae have demonstrated skills in paleolimnological reconstructions due to their sensitivity to different environmental and climatic factors, and their abundance and good preservation in lake sediments (Smol, 1995). Although water chemistry is known to be one of the major factors controlling chrysophyte distribution (e.g. Cumming et al., 1992; Cumming et al., 1993; Dixit et al., 1989; Duff et al., 1997; Hernández-Almeida et al., 2014; Pla and Anderson, 2005; Pla et al., 2003; Zeeb and Smol, 1995), other studies have shown that temperature is also an influential factor. Cronberg (1973, 1980) reported blooms of chrysophytes beneath winter ice in Scandinavian lakes and observed some species only producing cysts after a specific temperature threshold was crossed. This suggests that some cysts forms may be useful paleoecological indicators of winter temperatures.

Quantitative methods relating chrysophyte assemblages and air/water temperature during winter have been developed on high-altitude sites in the Alps, the Pyrenees and the Andes (de Jong and Kamenik, 2011; de Jong et al., 2013b; de Jong et al., submitted for publication; Kamenik and Schmidt, 2005; Pla and Catalan, 2005). In the Alps, chrysophyte inference models for high altitude lakes have so far been developed for relatively small geographic regions. Kamenik and Schmidt (2005) developed a chrysophyte-based temperature transfer function in the Austrian Alps. Results in their paper showed high correlations between cold-season temperatures (October–May) and chrysophyte assemblages in modern samples of 29 high altitude lakes. The resulting cold-season temperature transfer function based on chrysophytes was later applied to varved sediments from Lake Silvaplana in the Swiss Alps by de Jong et al. (2013a; 2013b). Reconstructions show similar results when compared with other historical records from the Alps. Moreover the authors found high similarities to NAO and 'Siberian high pressure' indices for the last millennium. A similar approach was used by Pla and Catalan (2005) in high-altitude lakes from the Pyrenees. In that study, modern chrysophyte assemblages were highly correlated to air temperature anomalies along an altitudinal gradient among the studied lakes. Using a similar methodology as proposed in the present study, de Jong et al. (submitted for publication) developed a chrysophyte-based inference model to reconstruct the number of consecutive days with temperatures below 4 °C (length of winter) from a training set of lakes from the south-central Andes which were sampled along an altitude gradient substituting variations in austral winter temperature.

Although chrysophytes have been tested in high-altitude areas, the potential of these organisms as proxies of cold-season temperatures has been rarely explored in low-altitude regions. Brown et al. (1997) developed a temperature-based model using chrysophytes from 49 low-altitude lakes from northwestern Canada. Although the inference model was weak ($R^2_{cross} = 0.23$), results indicated that chysopyhtes may be used as supplement to other paleotemperature reconstructions. In the absence of temperature gradients with elevation (e.g. training sets in mountains), sampling along very large geographic areas is required in order to cover a significant thermal gradient in space (latitude or longitude). Poland is a good candidate to implement this kind of training set design because it is relatively flat (only 1% of the Polish area is above 1000 m), has a high portion of land covered by many lakes (Jańczak et al., 1996) and there is a significant longitudinal thermal gradient (Lorenc, 2005). Moreover, many of the lakes have varved sediments that allow for a precise chronology of paleoclimate reconstructions (Tylmann et al., 2013).

In this paper we develop and apply a quantitative chrysophyte cyst-based inference model of 'number of consecutive days below