

# Siliceous algae-based seasonal temperature inference and indicator pollen tracking ca. 4,000 years of climate/land use dependency in the southern Austrian Alps

Roland Schmidt · Christian Kamenik ·  
Monika Roth

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**Abstract** Diatom and chrysophyte cyst-based reconstructions of the dates of spring and autumn lake-mixing enabled us to estimate spring ( $ST_{anom}$ ) and autumn ( $AT_{anom}$ ) temperature anomalies as well as ice-cover of the last ca. 4,000 years in a lake sediment core (Oberer Landschitzsee, 2,076 m a.s.l.) from the southern slopes of the Austrian Central Alps. The two independently inferred temperature anomalies were significantly correlated. On average, spring and autumn temperatures were lower during the two millennia B.C than during 0–1,300 A.D. Marked spring and autumn temperature minima occurred at about 1,300 and 600 B.C. At about 1,300 A.D,  $ST_{anom}$  declined again. Spring-temperature anomalies during Roman and Medieval times equaled or slightly exceeded the modern values and paralleled tree-line and glacier fluctuations. The de-coupling of autumn and spring climates, which began during the Medieval period, might indicate changes in major circulation modes. It was assumed that the North-Atlantic influence, triggering winter-rain climate in the

Northern Mediterranean, became weaker during Medieval times, resulting in a trend towards warmer autumns and overall more continental climate conditions in the study area. Four pulses of land use, inferred from indicator pollen, occurred during (1) the Early to Late Bronze, (2) the transition from Late Bronze to Early Iron Age (Hallstatt), (3) Late Iron Age (La Tène, Celtic time) to Roman times, and (4) during high to late Medieval times. Climate seemed to be an important, though complex, trigger of Alpine land use.

**Keywords** Diatoms · Chrysophyte stomatocysts · Alpine lake · Lake mixing · Air temperature anomalies · Ice-cover · Pollen tracers · Land use

## Introduction

Climate change considerably affected settlement and land-use activities of pre-historic and historic European societies (van Geel et al. 1996; Maise 1998; deMenocal 2001). Similarly, Alpine climate and land use are connected (Kamenik et al. 2000; Hausmann et al. 2002). During warm periods, pastures extended to higher elevations. Humid and cold climate increased losses of harvest and domesticated animals. Tinner et al. (2003) stressed, however, the complexity of the climate/land-use dependency.

The southern Austrian Alps lie in a transition zone between the central European and the

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R. Schmidt (✉) · M. Roth  
Institute of Limnology, Austrian Academy of Sciences,  
Mondseestraße 9, 5310 Mondsee, Austria  
e-mail: roland.schmidt@oeaw.ac.at

C. Kamenik  
Institute of Plant Sciences, University of Bern,  
Altenbergrain 21, 3013 Bern, Switzerland

Mediterranean climate (Auer et al. 2005; Böhm 2006). Winter climate in the Alps is affected by the North Atlantic Oscillation (NAO) (e.g. Beniston and Junco 2002). Mediterranean climate is mainly characterized by winter-rain pattern and warm and dry summers. The so-called Genua depression of the northern Mediterranean is mainly active from autumn until spring and its impact on the southern Alps can vary (Auer et al. 2001; Böhm et al. 2001, 2003; Kaiser et al. 2001; Casty et al. 2005; Böhm 2006). Hence, climate proxies are needed that can infer seasonal autumn to spring climates. Most of the terrestrial (glaciers, tree-line, tree-rings) and aquatic (midges) proxies that were used for climate reconstruction in the Alps are, however, controlled by summer temperatures (e.g. Wick and Tinner 1997; Nicolussi and Patzelt 2000; Tinner and Ammann 2001; Tinner and Theurillat 2003; Heiri et al. 2003; Nicolussi et al. 2004, 2005; Büntgen et al. 2005; Frank and Esper 2005).

Diatoms and resting stages of chrysophytes (stomatocysts or simply cysts) show seasonal (Siver and Hamer 1992; Rautio et al. 2000; Smol and Cumming 2000; Kamenik et al. 2001; Catalan et al. 2002) and altitudinal (Lotter et al. 1997; Heegaard et al. 2006) distribution patterns. Recently, diatoms and cysts were shown to be indicators for autumn and spring temperatures in relation to lake stratification and mixing (Schmidt et al. 2004a; Kamenik and Schmidt 2005a; Köster and Pienitz 2006). Snow-height and snow cover duration (summarized as snow-pack) play an important role in Alpine environments (Beniston et al. 2003). They are linked to large-scale climate forcing (Beniston 1997; Hantel et al. 2000). Pollen abundance variation of *Alnus viridis* (Chaix) DC. appeared to be a good indicator of snow-pack and the duration of snow-cover (Schmidt et al. 2002, 2006). *Fagus* L., which does not tolerate late frost, at present is excluded from the sub-continental, snow-poor, inner-alpine study area of Lungau, Niedere Tauern, (Gams 1931/32; Kilian et al. 1994). Under these climate conditions, *Larix* Mill. is common at timberline. Indicator pollen of herbs and the total percentage of herbs (non-arboreal pollen = NAP) are commonly used to track land-use changes in the Alps (e.g. Drescher-Schneider 2003; Tinner et al. 2003).

In the Austrian Alps, pollen records indicate that humans have been present at high altitudes since Neolithic times (Öggel 1994). Pollen records were supported by the discovery of the Tyrolian Ice-Man (Bortenschlager and Öggel 2000) and by archaeological findings from high altitudes nearby the study area (Hebert 2003; Mandl-Neumann and Mandl 2003). Pollen of anthropophytes occurred in the Niedere Tauern first during Neolithic times and increased in abundance during the Bronze Age (Bortenschlager 1967; Kral 1981, 1985; Krisai 1991; Brosch 2000; Schmidt et al. 2002; Drescher-Schneider 2003).

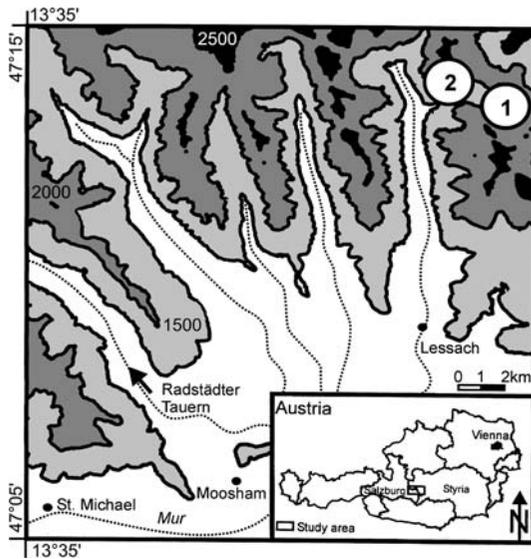
In the present study we combine seasonal (spring, autumn) climate reconstructions based on siliceous algae and pollen tracers from an Alpine lake-sediment core to evaluate climate impact on Alpine land use during the last 4,000 years. We compare our results with those from another lake in the drainage area (Unterer Landschitzsee, 1,778 m a.s.l.), with the local history, and with other climate proxies on Alpine and Northern Hemispheric (e.g. von Grafenstein et al. 1998, 1999) scales.

#### Study site

Oberer Landschitzsee (ObLAN, 2,076 m above sea level; 47°14' 52" N/13°51' 40" E) is located in Lungau (Fig. 1) at the southern slopes of the Austrian Central Alps (Niedere Tauern). The lake lies slightly above the present tree-line, which is formed by *Pinus cembra* L., associated with *Larix decidua* Mill. and shrubs of *P. mugo* Turra and *Alnus viridis*. Cattle and horse pastures currently extend to ca. 1,900 m a.s.l. At higher altitudes they are replaced by sheep. Thompson et al. (2005) showed that ObLAN's summer epilimnion-water temperature follows the usual altitude/air temperature relation illustrated by Livingstone and Lotter (1998).

#### Methods

A sediment core (ObLAN) was sub-sampled (1 cm<sup>3</sup> of fresh material) in 1 and 2 cm intervals for diatom, chrysophyte cyst, and pollen analyses. For details on coring of ObLAN, AMS <sup>14</sup>C dating and preparation techniques see Schmidt et al.



**Fig. 1** Contour-map of the study area Lungau (the insert shows its position in Austria) with the location of Lake Oberer Landschitzsee (1) and the reference site Unterer Landschitzsee (2), the Mur tributary-river system (dotted), villages (mentioned in the text) and the main road crossing the Central Alps (Radstätter Tauern, arrowed). Black areas indicate elevations >2,500 m

(2004a) and Kamenik and Schmidt (2005a, b). All given dates are calibrated calendar years before (B.C) and after Christ (A.D), calculated with the age/depth model of Heegaard et al. (2005). Diatoms (500 valves per sample) and pollen (minimum 500 grains) were counted using a light microscope (Leitz “Diaplan”). Chrysophyte cysts (200 per sample) were counted by scanning electron microscopy (Jeol JSM-35) equipped with an image analyzing system (QUANTEL Crystal) (Kamenik and Schmidt 2005b). Diatom taxonomy followed Krammer and Lange-Bertalot (1986–1991, 2000) and Krammer (2000). For chemical treatment of the pollen samples and pollen identification see Schmidt et al. (2002). For plants identified by pollen, we used the taxonomic list from Ehrendorfer (1973). Cyst types were determined according to Facher and Schmidt (1996), Duff et al. (1995), Wilkinson et al. (2001), and Kamenik et al. (2001, 2005).

The diatom-based “date of autumn mixing” ( $A_{\text{mix}}$ ) and the stomatocyst-based “date of spring mixing” ( $S_{\text{mix}}$ ) inference models were described in detail by Schmidt et al. (2004a) and Kamenik and Schmidt (2005a), respectively.  $A_{\text{mix}}$  and  $S_{\text{mix}}$  (given

in Julian days) were calculated using the program C2 (Juggins 2003). Reconstructed  $A_{\text{mix}}$  and  $S_{\text{mix}}$  were converted into corresponding altitudes using simple empirical models that were derived from a lake survey on 45 mountain lakes (Schmidt et al. 2004b; Thompson et al. 2005):  $\text{Altitude} = 6855 - 16.324 * A_{\text{mix}}$  ( $R^2_{\text{adj}} = 0.34$ ,  $P < 0.001$ );  $\text{Altitude} = 2441 - 3.47 * 10^{10} * S_{\text{mix}}^{-3.6}$  ( $R^2_{\text{adj}} = 0.88$ ,  $P < 0.001$ ). Altitudes were transformed into temperature anomalies assuming a constant lapse-rate of  $5^\circ\text{C km}^{-1}$  (Agustí-Panareda and Thompson 2002); inferences for the surface sediments were used as reference temperatures. Potential errors of the inferred  $T_{\text{anom}}$  signals result from (1) the errors of prediction of the diatom and chrysophyte-cyst models and (2) the conversion of  $S_{\text{mix}}$  and  $A_{\text{mix}}$  into altitude-dependent air temperature anomalies. Hence, the estimations are discussed in the context with other climate proxies. Thermistor measurements from the 45 mountain lakes showed that ice-on (freeze) and ice-out dates were highly correlated with the dates of autumn and spring mixing, respectively ( $R = 0.76$  and  $0.95$ , respectively,  $P < 0.001$ ). Hence, we estimated “ice-cover” as duration (in days) between  $A_{\text{mix}}$  and  $S_{\text{mix}}$  ( $365 - A_{\text{mix}} + S_{\text{mix}}$ ). For the comparison of  $ST_{\text{anom}}$  with oxygen isotopes ( $\delta^{18}\text{O}$ ) from Greenland ice-cores we used the GRIP data set (<ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/grip/isotopes/grip18o.txt>; Dansgaard et al. 1993; Grootes et al. 1993; Johnsen et al. 1997).

We summarized pollen percentages of *Cirsium* Mill., *Plantago* L. (*P. major/media* and *lanceolata* types), *Rumex* L. and *Urtica* L. as anthropophytes and used their sum together with Cerealia, Poaceae, and the total of the non-arboreal pollen (NAP) as indicators for land use. *Calluna* Salisb. and Chenopodiaceae naturally occur in alpine plant communities. Since they can, however, expand during land use, they were also included into the sum of anthropophytes. *Pteridium* Scop. spores were excluded from this sum. NAP commonly reflect more local vegetation than arboreal pollen. At Unterer Landschitzsee, up to 40% of arboreal pollen originated from lower altitudes (Schmidt et al. 2002). Hence, long-distance pollen transport (including anthropophytes) from lower altitudes cannot be excluded at Oberer Landschitzsee, although the valley is bordered by steep mountain ranges.

Diatom and chrysophyte cyst stratigraphies were plotted in Tilia\*Graph (Grimm 1992). Stratigraphic zones were established with the optimal sum of squares partitioning method (Birks and Gordon 1985) as implemented in the computer program ZONE (Lotter and Juggins 1991). The significance of zone boundaries was assessed with the broken-stick model (Bennett 1996). Time series were smoothed by locally weighted regression (Cleveland and Devlin 1988) using the LOESS smoother implemented in the program SigmaPlot 2000. For Principal Component Analysis (PCA) of pollen assemblages we used Canoco version 4.5. (ter Braak and Šmilauer 2002).

## Results

### Diatom stratigraphy

Two-hundred diatom taxa were identified, of which 80 occurred with an abundance >1% in at least one sample. Five stratigraphic zones were significant (Fig. 2).

Zone 1 (ca. 2,000–1,300 B.C): *Aulacoseira alpigena* (Grunow) Krammer dominated (20–37%). It was associated with *Achnanthes levanderi* Hustedt (<6  $\mu\text{m}$ ) (5–15%), *Achnanthes minutissima* Kützing, *Navicula laevissima* Kützing, *Navicula pupula* Kützing, and various *Pinnularia* taxa with an abundance between 2% and 10%.

Zone 2 (ca. 1,300–400 B.C): *A. levanderi* (< 6  $\mu\text{m}$ ) (10–20%) prevailed.

Zone 3 (ca. 400 B.C–200 A.D): *Achnanthes subatomoides* (Hustedt) Lange-Bertalot & Archibald (5–12%), *N. laevissima* and *N. pupula* (10–20%) became abundant.

Zone 4 (ca. 200–1,900 A.D): *A. alpigena* increased towards the top. Additionally, several species were encountered that ranged between 2% and 15%, such as *Aulacoseira lirata* (Ehrenberg) Ross, *A. alpigena*, *Achnanthes marginulata* Grunow, *A. levanderi*, *A. minutissima*, *A. subatomoides*, *N. laevissima* and *N. pupula*.

Zone 5 (ca. 1,900 A.D until present): *A. alpigena* dominated again (up to 25%), associated with *Aulacoseira distans* var. *nivalis* (W. Smith) Lange-Bertalot (10%). *Achnanthes kuelbsii* Lange-Bertalot (10%), *Fragilaria delicatissima* (W. Smith) Lange-

Bertalot and *F. exiguiformis* Lange-Bertalot (<30  $\mu\text{m}$ ), and *Pinnularia anglica* Krammer became more abundant (3–12%).

### Chrysophyte cyst stratigraphy

Sixty-eight cyst types were distinguished, of which 27 occurred with an abundance >3% in at least one sample. Six stratigraphic zones were significant (Fig. 3).

Zone 1 (ca. 2,000–600 B.C): ST 13 prevailed (20–30%). Types without ornamentation (regular pore, 5.3–8.8  $\mu\text{m}$ ), ST42, ST114c+d and ST210 were frequent (10–45%, 5–14%, 3–14% and 5–12%, respectively).

Zone 2 (ca. 600 B.C–300 A.D): Types without ornamentation (regular pore, 3.3–5.3  $\mu\text{m}$ ) were dominating.

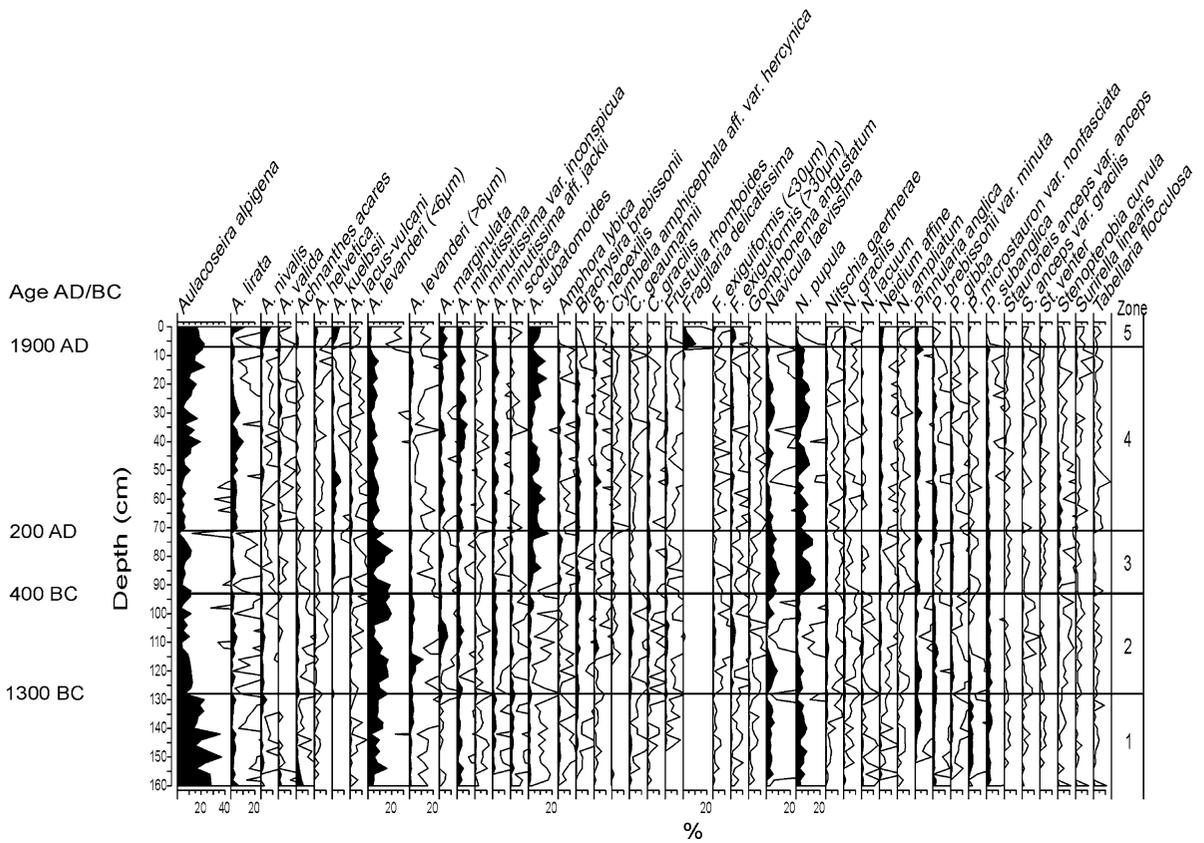
Zone 3 (ca. 300–250 B.C): ST13 had a low abundance and ST210 increased.

Zone 4 (ca. 100–1,900 A.D): ST13 re-appeared and types without ornamentation (regular pore, 3.3–5.3  $\mu\text{m}$ ) decreased.

Zone 5 (ca. 1,900 A.D until present): Types without ornamentation (regular pore, 3.3–5.3  $\mu\text{m}$ ), ST55, ST84 and ST113 increased.

Dates of spring and autumn mixing, ice-cover and mean air-temperature anomalies

The date of spring mixing ( $S_{\text{mix}}$ ) varied within 20 days throughout the 4,000 years. This corresponds with an inferred mean spring air temperature change of 1.4°C.  $S_{\text{mix}}$  was earliest from 0 to 1,400 A.D and rose again during the last centuries. The inferred mean spring air temperature anomaly ( $ST_{\text{anom}}$ ) showed minima between ca. 1,400 and 1,100 B.C, and around 500 B.C. It declined from ca. 1,400 A.D to present, contrasting higher values between ca. 200 and 1,400 A.D. Variation of  $A_{\text{mix}}$  ( $AT_{\text{anom}}$ ) paralleled  $S_{\text{mix}}$  ( $ST_{\text{anom}}$ ) during the first two millennia B.C. The independently inferred time series of  $ST_{\text{anom}}$  and  $AT_{\text{anom}}$  were significantly correlated (bootstrapped Pearson's  $r$  95% confidence interval: 0.2–0.5), taking into account serial autocorrelation (Mudelsee 2003). During the last two millennia,  $A_{\text{mix}}$  ( $AT_{\text{anom}}$ ) increased towards present (Fig. 4). Duration of ice-cover varied within 25 days. It was highest between ca. 1,300 and 1,100 B.C and lowest between ca. 200 and 1,300 A.D (Fig. 4).



**Fig. 2** Diatom percentage diagram of the sediment core ObLAN spanning the last ca. 4,000 years. The significant zones with their calibrated ages before (B.C) and after (A.D) Christ are indicated

Indicator pollen

NAP (maximum % 38), Poaceae (maximum % 20) and anthropophytes (maximum % 4.3) showed similar long-term trends. Their abundance was highest during the last millennium. During the same time Cerealia (<1%) and Larix (maximum % 1.8) had frequent occurrences, whereas Fagus (maximum % 7.5) decreased. Alnus viridis (maximum % 16) followed trends in anthropophytes, peaking around ca. 1,700 B.C, 800 B.C, 100 A.D, and 1,300 A.D (Fig. 4).

Discussion

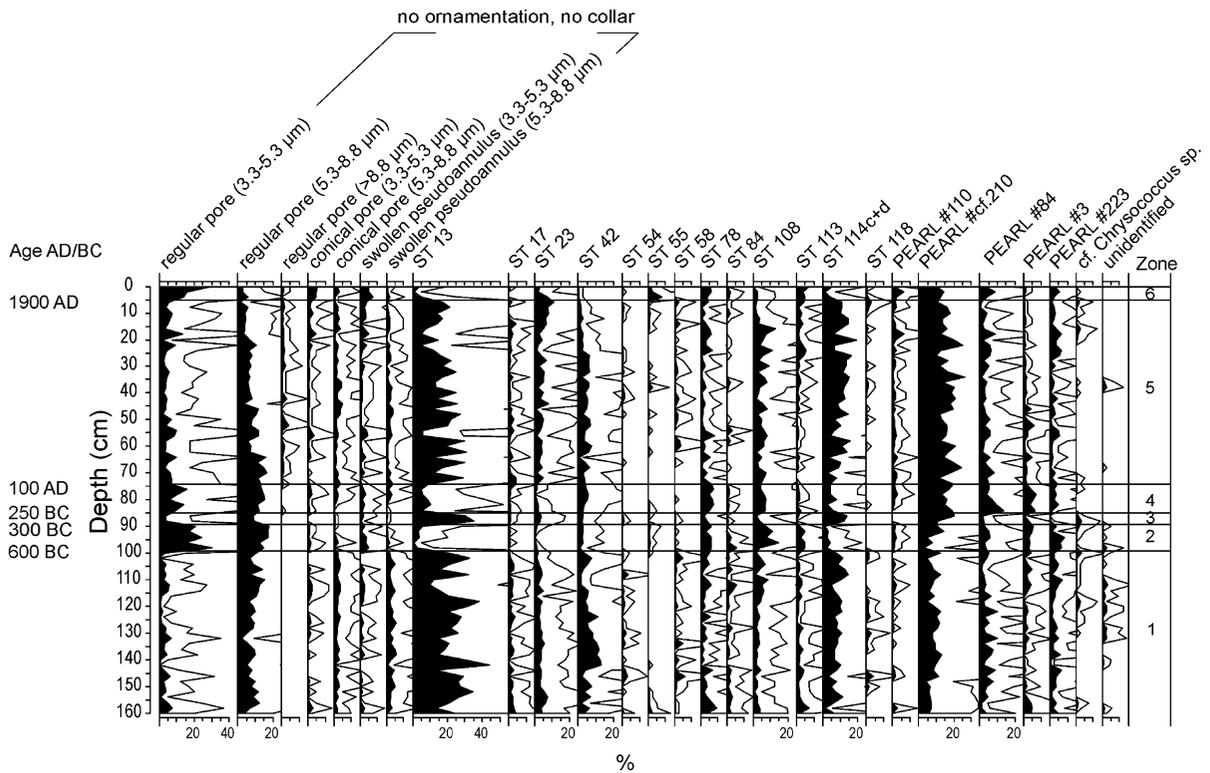
Comparison between spring and autumn temperatures

Estimated autumn-temperature anomalies fluctuated within a narrower range than estimated spring-

temperature anomalies. The smaller amplitude of AT<sub>anom</sub> was probably caused by lower R<sup>2</sup><sub>boot</sub> of the diatom-based A<sub>mix</sub> inference model and lower R<sup>2</sup><sub>adj</sub> of the AT<sub>anom</sub> regression model (compare with Esper et al. 2005). In addition, the planktonic chrysophytes might have responded more sensitively to short-term fluctuations than the diatom assemblages, which were dominated by benthic species. Until Medieval times, parallel trends of spring and autumn temperatures suggested that diatoms and chrysophytes responded to the same climate forcing (see discussion below).

Comparison of our results with other climate proxies on Alpine and Northern Hemispheric scales

During the two millennia B.C, estimated spring temperature anomalies and GRIP δ<sup>18</sup>O showed similar long-term trends, except from 1,200 to



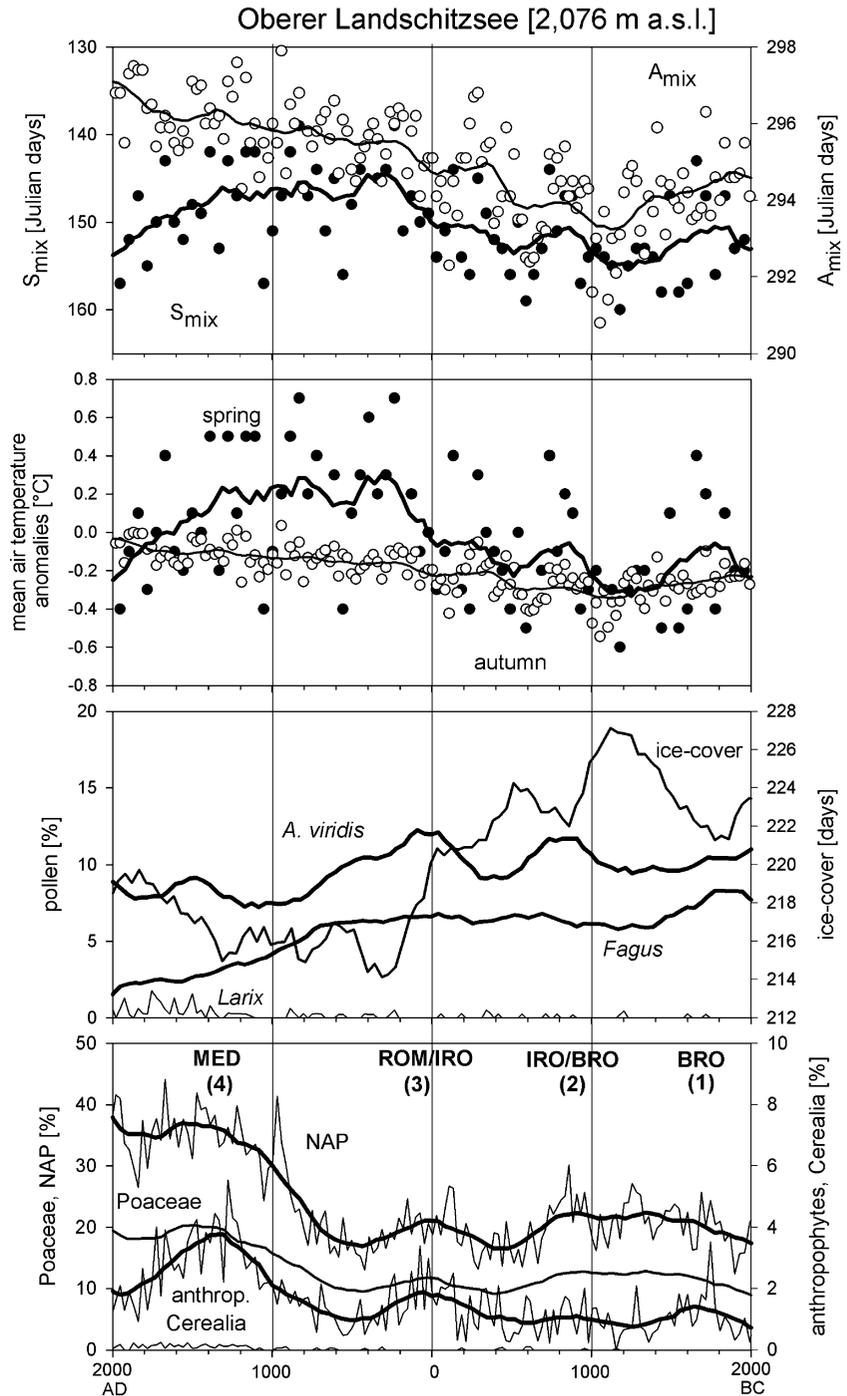
**Fig. 3** Chrysophyte cyst percentage diagram of the sediment core ObLAN spanning the last ca. 4,000 years. The significant zones with their calibrated ages before (B.C) and after (A.D)

Christ are indicated. Numbering of cyst types according to Duff et al. (1995, PEARL), Facher and Schmidt (1996) and Kamenik et al. (2001, 2005)

1,000 B.C (Fig. 5). Their short-term fluctuations (GRIP  $\delta^{18}\text{O}$  averaged over 50 years) were, however, not significantly correlated ( $P > 0.1$ ). The parallel trends suggested that on centennial-scale they followed a Northern Hemispheric climate pattern. According to Beniston and Jungo (2002), high elevation temperature in the Alps is significantly linked with the Northern Hemisphere zonal circulation. Both AT and  $ST_{\text{anom}}$  minima at ca. 1,300 and ca. 500 B.C corresponded with GRIP  $\delta^{18}\text{O}$  minima, indicating marked climate deteriorations. Low  $ST_{\text{anom}}$  between ca. 1,500 and 1,000 B.C and ca. 700 to 400 B.C also coincided with the episodes 6 (1,500–1,100 B.C) and 5 (750–350 B.C) of high lake levels in northern Switzerland and the French pre-Alps (Magny 2004).  $ST_{\text{anom}}$  during these periods equaled  $ST_{\text{anom}}$  during the Little Ice-Age (LIA, 15th and 19th century) corresponding with a glacier extension in the southern Hohe Tauern during the so-called Lössen Oscillation (ca. 1,500 B.C; Nicolussi and Patzelt 2000): at Frosnitzkees, maximum

glacier extension during this advance exceeded its extension of 1850 A.D by 100–150 m (Patzelt and Bortenschlager 1973). Higher winter precipitation on southern glaciers might have favored larger extensions. Periods of glacier advances are generally cool and humid, with reduced sunshine duration and increased precipitation (Schöner et al. 2000). Increased precipitation in the study area could have been triggered by a southerly drift of the westerly jet-stream system (Magny et al. 2003), as it was assumed for the Holocene climate oscillations (Schmidt et al. 2006), and by enhanced cyclon formation in the Northern Mediterranean. Schmidt et al. (2006) assumed that winter precipitation increased in the southern Alps with the establishment of Mediterranean climate in the northern Adriatic region between ca. 3,000 and 2,000 B.C (Schmidt et al. 2000). This hypothesis is supported by corresponding long-term trends in autumn and spring temperature anomalies during the two millennia B.C suggesting that northern Mediterranean cyclones (e.g. the Genua depression)

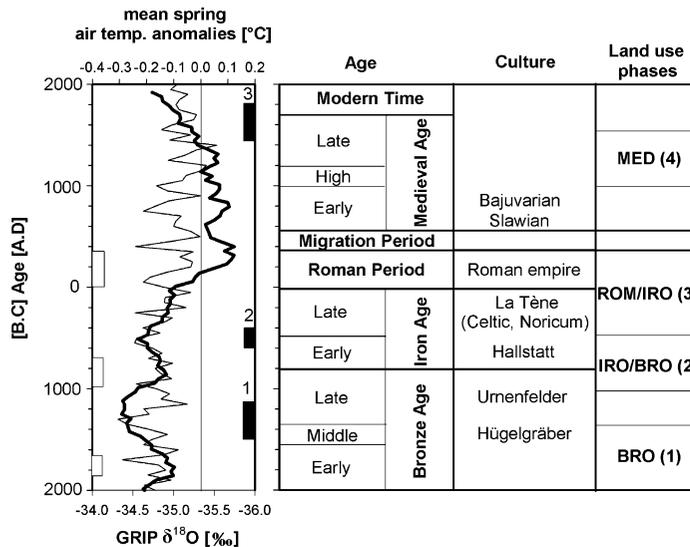
**Fig. 4** Chrysophyte cyst and diatom-based reconstructions and indicator pollen of the sediment core ObLAN spanning the last ca. 4,000 years. From top to bottom: Chrysophyte cyst inferred date of spring mixing ( $S_{mix}$ , inverted y-axis) and diatom inferred date of autumn mixing ( $A_{mix}$ ) in Julian days;  $S_{mix}$  and  $A_{mix}$ -based mean spring and autumn air-temperature anomalies in °Celsius; pollen-abundance (%) of *Alnus viridis*, *Fagus*, and *Larix*, and ice-cover (in days); pollen abundance (%) of total non-arboreal pollen (NAP), Poaceae, anthropophytes, and Cerealia. Land-use phases 1–4 are indicated (BRO = Bronze Age; IRO = Iron Age; ROM = Roman Age; MED = Medieval Age). Data were smoothed using LOESS (span = 0.1)



could have been similarly active during autumn and spring. Humid (snow-rich) winter-climate, which contrasted warm summers during climate amelioration (Schmidt et al. 2006), could explain both the on average lower autumn and spring temperatures and

the increased pollen abundances of *Abies* and *Fagus* during the two millennia B.C.

Low  $ST_{anom}$  and  $AT_{anom}$  between ca. 1,500 B.C. and 0 at ObLAN reflected severe climate oscillations, probably with humid, snow-rich conditions. Minima



**Fig. 5** Overview of ages and cultures (Urban 2000), land use phases 1–4 and inferred mean spring air-temperature (this study, compare with Fig. 4), and oxygen isotopes ( $\delta^{18}\text{O}$ , running average of 50 years, thinner line) from Greenland ice-cores (GRIP) (Dansgaard et al. 1993; Grootes et al. 1993;

Johnsen et al. 1997) for the last ca. 4,000 years. Major glacier advances in the Tauern area (Nicolussi and Patzelt 2000; 1 = Lössen, 2 = Advances ca. 700–400 B.C., 3 = LIA) and periods with tree-lines higher than 1980 A.D. (Nicolussi et al. 2005; white boxes) are indicated by time-bars

in *A. viridis* pollen coincided with ice-cover peaks between ca. 1,300 and 1,100 B.C. and between ca. 700 and 400 B.C. Prolonged snow-cover and/or high snow-pack during these cold climate conditions probably suppressed flowering of *A. viridis*. Humid conditions between ca. 1,400 and 1,000 B.C. were also indicated by a distinct peak in *Abies* pollen found at nearby Unterer Landschitzsee (Schmidt et al. 2002).

Peaks in  $ST_{\text{anom}}$  during the Early to Middle Bronze Age, during Hallstatt and Roman times (ca. 200–450 A.D.) corresponded with a tree-line approximating the present (Nicolussi et al. 2005) and glacier retreat in the Austrian Alps (Patzelt 1995; Nicolussi and Patzelt 2000).

$AT_{\text{anom}}$  showed a slight but steady increase from Roman to modern times. From ca. 700 A.D. onwards this trend was paralleled by a decrease of *Fagus* (Fig. 4) and *Abies* pointing to a more continental Lungau during Medieval times (Schmidt et al. 2002) and/or clear cutting (increased NAP). The decoupling of autumn and spring temperatures could indicate a change in major circulation mode. We hypothesize that the North-Atlantic influence, e.g. by the North Atlantic Oscillation (NAO), which also triggers winter-rain climate in the Northern Mediterranean, has become weaker in Lungau since Medieval times. Mangini et al. (2001) also assumed changes in

circulation patterns during the last ca. 2,000 years from  $\delta^{18}\text{O}$  of Alpine speleothems.

Temperature reconstructions from different proxies of the so-called Medieval Warm Period (MWP, ca. 900–1,400 A.D.) in relation to present global warming are controversial (e.g. Mann et al. 1999; Crowley 2000; Crowley and Lowery 2000; Broecker 2001; Briffa et al. 2002; Bradley et al. 2003; Jones and Moberg 2003; Jones and Mann 2004). Since  $ST_{\text{anom}}$  accumulates model errors (see methods), at least the minor fluctuations of  $ST_{\text{anom}}$  during Medieval times range, however, within the error of prediction. Nevertheless, the  $ST_{\text{anom}}$ -curve corresponded with Alpine tree-ring data. They indicated warm phases similar to present between ca. 850–1,000 A.D. and 1,200–1,300 A.D., followed by climate deterioration at ca. 1,300 A.D., which culminated during LIA (Büntgen et al. 2005). Pla and Catalan (2005) reconstructed altitude anomalies from chrysophyte cyst assemblages at Lake Redon (2,240 m a.s.l.) in the Pyrenees, which at about 1,000 A.D. approximated present values.

During the past millennium,  $ST_{\text{anom}}$  varied within  $1^\circ\text{C}$ , corresponding with the  $1^\circ\text{C}$  amplitude of the 30-year Gaussian low-pass filtered European mean winter temperatures from ca. 1,500 to 1,900 A.D. (Luterbacher et al. 2004). The decrease of  $ST_{\text{anom}}$ ,

and to a lower range of  $AT_{anom}$ , between ca. 1,400 and 1,600 A.D corresponded with the climate deterioration during the Little Ice Age. According to the stomatocysts,  $ST_{anom}$  did not increase recently; however, our time resolution (25–50 years) was probably insufficient to resolve the strong short-term fluctuations in Alpine mean spring temperatures during the last 50 years (Böhm et al. 2001; Luterbacher et al. 2004; Auer et al. 2005; Xoplaki et al. 2005). Additionally, other environmental drivers, such as acid rain, could have affected our proxies during more recent times.

#### Climatic and anthropogenic impacts

With the exception of the Medieval times, the percentage of anthropophytes was <4% of the total pollen sum. Nevertheless, they indicated four pulses of land use. As illustrated in Fig. 4, these occurred during (1) the Early to Middle Bronze Age (ca. 1,800–1,300 B.C), (2) the transition from Late Bronze to Hallstatt times of the Early Iron Age (ca. 1,000–500 B.C), (3) the Late Iron Age (La Tène, Celtic time) and the Roman period (ca. 0–200 A.D), and (4) the High to Late Medieval periods (ca. 1,000–1,600 A.D). At about ca. 1,300 to 1,500 A.D land use peaked.

Extended ice-cover from ca. 1,300 to 1,100 B.C and ca. 700 to 400 B.C occurred between the land use phases (1) and (3). A marked peak in the saturated isothermal remanent magnetism (SIRM) at around ca. 1,300 B.C at Unterer Landschitzsee (Schmidt et al. 2002) suggested enhanced erosion. It was followed by a marked change in the total carbon/nitrogen (C/N) ratio, which, together with pollen of anthropophytes, indicated forest clearing during the Late Bronze Age. A charcoal layer from the foundation of an alpine hut at 1,980 m a.s.l. in the adjacent Dachstein Mountains was dated at 1,360 B.C (Mandl 2003) and was associated with pollen indicators of land use (Drescher-Schneider 2003).

Phase (2) of ObLAN, at the transition from Late Bronze to Early Iron Age (Hallstatt), coincided with climate warming and high tree-line (Nicolussi et al. 2005). Although NAP peaked, pollen of anthropophytes were lower than during the Early Bronze Age. The NAP peak could indicate that during climate warming the local vegetation became more dense, whereas the lower numbers of anthropophytes were explained by different land-use types; the use of

natural meadows near tree-line as pastures during Early Bronze Age, and forest clearing (probably by the use of fire) at Unterer Landschitzsee during the Late Bronze Age.

The re-establishment of Alpine land use after the climate deterioration between ca. 700 and 400 B.C corresponded approximately with the invasion of Celtic tribes in the southern Austrian Alps in the 4th century B.C and the following foundation of the kingdom of Noricum at around 200 B.C (Dopsch 1981). Land-use phase (3) culminated during the Roman period, corresponding with maxima in  $ST_{anom}$ . A Roman Alpine settlement, found at 1,640 m a.s.l. in the adjacent Dachstein area, also indicated intense Roman high-altitude land use (Mandl 2003). Alpine land use in Lungau was probably associated with trading routes. Archaeological excavations showed a Roman settlement (Immurium, the present village Moosham), probably with Celtic origin, along the Roman road that passed through the Lungau Mur valley (Fleischer and Moucka-Weitzel 1998).

Between Roman and Medieval land use, anthropophytes declined. This decline was associated with the collapse of the Roman epoch (between 488 and 476 A.D) and the subsequent migration of the populations.

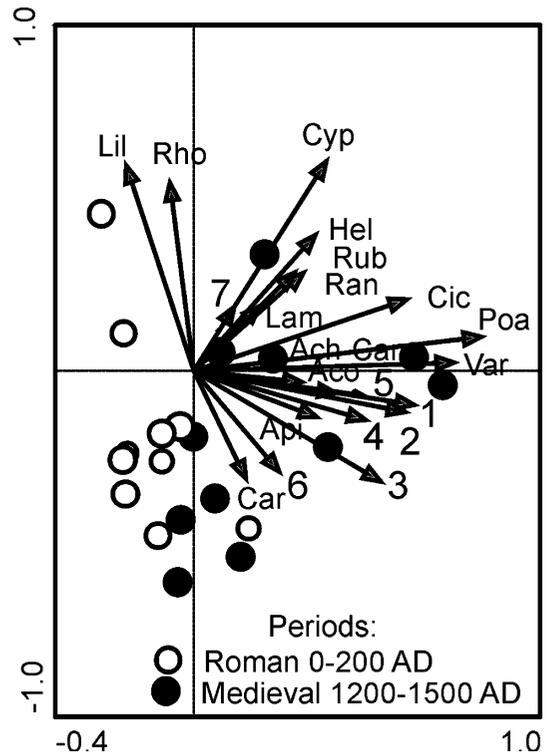
The Medieval re-establishment of high-altitude land use after the migration period started between ca. 1,000 and 1,200 A.D, and culminated between ca. 1,300 and 1,500 A.D. The expansion of *Larix* was probably favored by both continental climate conditions and increasing anthropogenic impact at timberline. Clear cutting during the extension of Medieval land use probably weakened the link between ice cover and *Alnus viridis* pollen. The more continental climate resulted in extended warm summers/autumns and less snow and earlier snow-melt. The Medieval Warm Period probably favored the extension of pastures to high altitudes. During phase (4), indicators of nitrophilous plant communities (*Urtica*, *Rumex*), of pastures (*Achillea*-type, *Campanula* L., *Ranunculus* L.), of *Calluna* heathlands (Tinner et al. 1999), of tall-herbs (*Aconitum* L., *Apiaceae* and *Heracleum*-type, Cichoriaceae, *Mentha*-type), of *Pteridium* thickets, and of species-rich meadows (*varia*), gained in importance (Fig. 6). They indicated an increase in high-altitude cattle pasturing, at the expense of sheep and goats, which had commonly

dominated the preceding Roman Alpine land-use phase (Mandl 2003). According to tree-ring records from the Alps (Nicolussi and Patzelt 2000; Büntgen et al. 2005), the Late Medieval land-use phase (4) (between ca. 1,300 and 1,500 A.D) was characterized by a cooling trend that was accompanied by significant inter-decadal climate variation. Hence, land use was decoupled from climate. In Lungau, mining activities boomed during Late Medieval times (von Kürsinger 1853; Mutschlechner 1967; Ortner and Sagmeister 1992). Alpine land use was probably a prerequisite for high-elevation mining activities (up to 2,800 m a.s.l., Katschner 1984) in the upper Lessach Valley. Demographic and political changes might also have affected Alpine land-use. The population increased, and during the 13th century Lungau became part of the archbishopric of Salzburg (Keusch 1948; Klebel 1960; Dopsch 1981; Hübl 1983; Katschner 1984; Ortner and Sagmeister 1992).

From ca. 1,400 A.D onwards,  $ST_{anom}$  decreased. This decrease was not paralleled by  $AT_{anom}$ . Corresponding with  $ST_{anom}$ , anthropophytes declined. At present the upper limit of permanent farming is around 1,400 m a.s.l.; cattle pastures (“Hüttstäten”) extend up to 1,920 m a.s.l. (Mandl 2003).

## Conclusions

- (1) During the two millennia B.C and during Roman times, the significantly correlated mean spring and autumn temperatures indicate common climate forcing. Predominant Atlantic climate forcing could explain two cold climate oscillations (ca. 1,500–1,000 B.C and ca. 700–400 B.C), which corresponded with minima in the GRIP oxygen isotopes ( $\delta^{18}O$ ). By triggering winter-rain climate in the Northern Mediterranean, it could explain similar spring and autumn temperatures, which on average were lower during the two millennia B.C.
- (2) Warm periods were inferred for the Early Bronze Age, the transition from the Late Bronze to Early Iron Age, the Roman Period, and Medieval periods between ca. 800 and 1,300 A.D. Roman and Medieval spring warming corresponded with increased Alpine summer temperatures inferred from tree-rings and tree-line. Our estimates of spring temperature



**Fig. 6** Principal Components Analysis (PCA) on total non-arboreal pollen percentages (NAP) of the sediment core ObLAN. Only samples of the Roman and High Medieval land use phases and selected pollen types are shown. Anthropophytes: 1 = *Rumex*, 2 = *Plantago*, 3 = *Urtica*, 4 = *Artemisia*, 5 = *Calluna*-type; 6 = Chenopodiaceae; 7 = *Cirsium*. Other herbs: Ach = *Achillea*-type, Aco = *Aconitum*, Api = Apiaceae, Cam = *Campanula*, Car = Caryophyllaceae, Cic = Cichoriaceae, Cyp = Cyperaceae, Hel = *Helianthemum*, Lil = Liliaceae, Poa = Poaceae, Ran = *Ranunculus*, Rho = *Rhododendron*-type, Rub = Rubiaceae, Var = *Varia*

anomalies for the Roman and Medieval warm periods suggested that spring climate was at least as warm as today.

- (3) Autumn and spring climates appeared to have been decoupled since Medieval times. Changes in circulation modes, such as a weakening of the North Atlantic (NAO) impact, might have caused warmer autumns. In sum, the study area has probably become more continental.
- (4) Although climate appeared to be the primary trigger of alpine land use, the relationships were complex. From Early to Late Bronze Age, the type of land use probably changed from natural pastures near tree-line to forest clearing. Unfavorable climate separated the land use phases

(1)–(3). During Medieval land use, which culminated between ca. 1,300 and 1,500 A.D (land-use phase (4), Late Middle Ages), mining, demographic and political changes probably affected high-alpine land use in addition to climate—or even decoupled land use and climate.

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