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Reconstructing air temperature at eleven remote alpine and arctic lakes in Europe from 1781 to 1997 AD

MOLAR
Mountain Lake Research

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Abstract

Pristine and sensitive environments, such as remote alpine and arctic lakes, are particularly susceptible to the effects of climate change. However, these remote environments do not have sufficiently long instrumental climate records to support studies on contemporary climate change. The issue of the scarcity of instrumental climate data at remote regions is addressed by reconstructing monthly mean air temperatures from 1781 to 1997 AD at eleven remote alpine and arctic lakes in Europe, as part of the MOuntain LAke Research (MOLAR) project. Stepwise multiple regression is applied to establish linear transfer functions of temperatures between each of eleven upland records and twenty homogenised long lowland records. Twelve monthly transfer functions are obtained for each lake. The skill of these transfer functions is found to range typically between 60 and 99%. The lower skill values generally correspond to winter months. The temperature reconstructions obtained using the transfer functions need to be corrected with vertical temperature gradients. Air-temperature lapse rates were obtained for each lake region by spatial interpolation of radiosonde air-temperature data (1990–1997). The resulting reconstructions at each lake were checked using air-temperature data (1996–1997) from automatic weather stations installed at the lakes during the MOLAR project. We estimate the typical reconstruction errors to be about 1.3 °C for low-sun months and about 0.98 °C for high-sun months. Trend analyses on the reconstructed annual mean air temperatures at the lakes show two distinct types of trends for the 19th and 20th centuries. During the period 1801–1900, the western European lakes show no significant trend whereas annual mean air temperatures at the eastern European lakes decrease significantly. The period 1901–1997 presents a warming trend at all but the Fennoscandian lakes. Our results are in good agreement with previous studies on the spatial distribution and magnitude of temperature change in Europe. Principal component analysis performed on the reconstructed annual mean air temperature reveals two different regimes of trends for the past two centuries. It also allows a regional clustering of the inter-annual variability of air temperature at the lakes to be identified.

Introduction

Climate plays an important role in the environmental history of lakes, providing a physical forcing which conditions their physical (e.g., water temperature, evaporation and ice cover), chemical (pH) and ecological (ecosystem dynamics) features in both direct and indirect ways (Schindler et al., 1990). Remote alpine and arctic lakes present an ideal environment in which to detect this climatic forcing because they are very sensitive to environmental changes (Sommaruga-Wögrath et al., 1997) and they provide the most unpolluted and pristine conditions for the study of climate change. Air temperature, in particular, is recognised as influencing the timing of the ice cover break-up (Livingstone, 1997;

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Palecki & Barry, 1986) and Sommaruga-Wögrath et al. (1997) have suggested it can also affect pH at alpine lakes. Unfortunately, in such remote alpine and arctic environments, instrumental climate records are scarce, short or non-existent. Thus, the main instrumental data source for the study of climate change at these remote alpine and arctic lakes must come from either lowland or nearby mountain observatories.

The longest instrumental climate records that exist are those from the European lowlands. Much painstaking work has been put into constructing and analysing individual long homogeneous air-temperature series from the lowland historical instrumental records in Europe (e.g., Manley, 1974; Parker et al., 1992; Kozuchowski et al., 1994; Moberg & Bergström, 1997). The longest record is from Central England (Manley, 1974; Parker et al., 1992) and it spans more than three centuries (1659 AD to the present). In addition, extensive historical climate databases have recently been created, such as Global Historical Climate Network (Peterson & Vose, 1997; Peterson et al., 1998) and North Atlantic Climate Dataset (Frich et al., 1995). Following this effort, several studies have been carried out on climate change in lowland Europe during the last two centuries, (e.g., Jones et al., 1986; Thompson, 1995, Balling et al., 1998). European annual mean temperature anomalies (Balling et al., 1998) indicate there has been a statistically significant warming of 0.5 °C in the European lowlands during the period between 1751 and 1995.

On the other hand, upland records (from meteorological stations above 1000 m a.s.l) are scarcer and the longest, Sonnblick in the European alps, does not start until 1887. Consequently, studies of climate change in alpine areas have been limited mostly to this century (Manley, 1949; Bücher & Dessens, 1991; Barry, 1992; Beniston, 1993; Beniston et al., 1994, 1997; Weber et al., 1994, 1997; Dessens & Bücher, 1995, 1997; Beniston & Rebetez, 1996). Beniston et al. (1997) and Diaz and Bradley (1997) give an overview of climatic change at high-elevation sites. Their studies suggest that the climate signal at high-elevation sites not only shows a spatial diversification but also displays a change with elevation. According to Diaz and Bradley (1997), the available instrumental records seem to indicate that the strongest warming in recent decades, at the higher elevations of the European continent, has been experienced in western Europe – excluding the Scandinavian region, where warming has been much reduced.

The motivation of the present study is to provide a reconstruction of air temperatures from 1781 to 1997 at eleven remote alpine and arctic lakes (Table 1), which are part of the Mountain Lake Research (MOLAR) project. A description of some of these eleven lakes and their catchments can be found in the other articles of this special issue. The period of reconstruction has been chosen to include as many long instrumental air-temperature records as possible. Most long records in Europe are complete and most reliable from 1781 onwards (see Table 2). Our method of reconstruction makes use of many of the longest lowland and upland instrumental records of air temperature available.

Mountain ranges exert a strong influence on the local weather and climate. They both modify approaching synoptic systems and trigger new weather systems. In addition alpine topography leads, through the production of enhanced orographic precipitation, strong rain-shadows, severe frost-hollow effects and the generation of Föhn and valley winds, to much stronger

Table 1. Location of 11 lakes^{+}

Lake	Latitude			Longitude			Elevation	Country
	Deg	Min	Sec	Deg	Min	Sec	(m)	
Jörisee III (JRS)	46	46	41	09	58	35	2519	Switzerland
Gossenköllesee (GKS)	47	14	00	11	01	00	2417	Austria
Hagelseewli (HAG)	46	40	29	08	02	12	2339	Switzerland
Paione Superiore (PSU)	46	10	26	08	11	27	2269	Italy
Estany Redó (RED)	42	38	34	00	46	13	2240	Spain
Laguna Cimera (CIM)	40	15	50	–5	18	15	2140	Spain
Terianske Pleso (TER)	49	10	13	20	00	54	1941	Slovakia
Jezero Ledvicah (LED)	46	20	00	13	47	00	1829*	Slovenia
Lochnagar (NGE)	56	57	29	03	13	05	0785	Scotland
Øvre Neådalsvatn(NEA)	62	46	30	09	00	00	0728	Norway
Saanajärvi (SAA)	69	03	00	20	52	00	0679	Finland

$^{+}$In order of lake elevation. *Elevation of AWS, 1720 m from September 1996.

Table 2. Reference series[+]

Current series	Station number	Country	Longitude	Latitude	Elevation (m)	Main long series
Orland	12410	Norway	9.6° E	63.7° N	7	Trondheim
Uppsala	20760	Sweden	17.6° E	59.9° N	15	Uppsala
Stockholm	24640	Sweden	18.1° E	59.4° N	52	Stockholm
Dyce	30910	UK	2.1° W	57.2° N	59	Aberdeen
Turnhouse	31600	UK	3.4° E	56.0° N	35	Edinburgh
Birmingham	35340	UK	1.7° E	52.5° N	96	C. England
Bournemouth	38620	UK	1.8° E	50.8° N	10	Exeter
De Bilt	62600	Netherlands	5.2° E	52.1° N	8	Utrecht
Zurich Ville	66600	Switzerland	8.6° E	47.4° N	569	Zurich
Geneva	67000	Switzerland	6.2° E	46.2° N	416	Geneva
Le Bourget	71500	France	2.5° E	48.8° N	53	Paris
Munich Riem	108660	Germany	11.7° E	48.1° N	529	Munich
St Polten	110280	Austria	15.6° E	48.2° N	282	Kremsmüenster
Höhe Warte	110350	Austria	16.4° E	48.2° N	212	Vienna
Innsbruck	111200	Austria	11.4° E	47.3° N	582	Innsbruck
Prague	115180	Czech. Rep.	14.3° E	50.1° N	381	Prague
Budapest	128400	Hungary	19.0° E	47.5° N	130	Budapest
Milan Linate	160800	Italy	9.2° E	45.5° N	103	Milan
St Petersburg	260630	Russia	30.3° E	60.0° N	4	St Petersburg
Minsk	268500	Belorussia	27.5° E	53.9° N	234	Vilnius

[+]In order of current WMO station number.

spatial variations than usual. Furthermore Europe's mountain ranges act as climatic divides. The Scandinavian Mountains lie along the particularly steep climatic gradient, which in northern Europe separates the oceanic zone, in the west, from the continental zone, to the east. Similarly the Alps mark the boundary between the major climatic zones of the mid-latitude temperate and the Mediterranean. The Pyrenees also act as an impediment to the moist winds coming from the Atlantic and conversely to hot, dry air masses moving from northern Africa. Such pronounced, varied and multifaceted climatic effects of mountain regions suggest that great care should be taken before using climatic time-series from the neighbouring lowlands to reconstruct climate change at upland lakes. Here we address such concerns through quantitative validation studies and calculations of reconstruction skill.

Methodology

The basic method

The method used to reconstruct air temperature at the lakes is based on multiple regression (Agustí-Panareda et al., 2000). The key to the reconstruction is the transfer of air temperature recorded at the lowlands to the uplands. Agustí-Panareda et al. (2000) showed it is indeed possible to relate temperatures in the lowland to the uplands. They computed correlation coefficients for several pairs of lowland versus upland daily mean temperature series. The correlation coefficients decay with separation distance. The values are generally high (above +0.7) if the separation between the lowland and upland meteorological stations is less than 400 km. Here we are typically dealing with lowland-upland separations of 50–100 km with a proportion of explained variance (r^2) of 0.72 ($p < 0.1$). Multiple regression, rather than correlations between single sites, provides even stronger statistical linkage between the lowlands and the uplands as it is able to take into account the gross atmospheric circulation conditions over Europe. Exceptions occur, to these lowland/upland linkages, during prolonged winter episodes of thermal inversions when lower co-variation is to be found.

The flowchart in Figure 1 gives an overview of the different stages involved in our reconstructions. The method requires input data (dark boxes) which have been obtained from the different sources shown at the top of Figure 1. The data sets are analysed and transformed by processes.

First, twenty long, monthly, air-temperature series (1781–1997 AD), here called *reference series*, have been gathered together for different regions of lowland Europe. Each series was established independently. Data from twenty-six regions were examined. It was

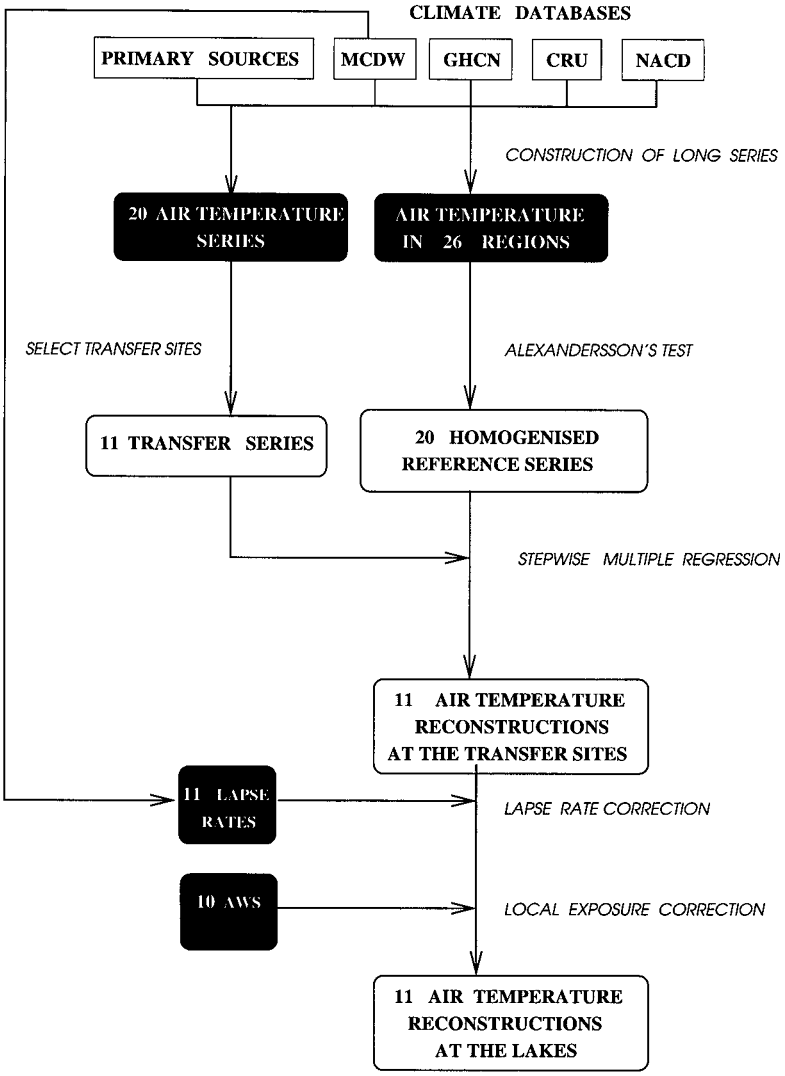


Figure 1. Flowchart illustrating the method of reconstructing surface air temperature at remote lakes. The dark boxes show the data sources. The data have been mainly obtained from climatic databases (square white boxes). The rounded white boxes show products of the various data manipulation stages. The six different stages in processing the air-temperature time series and transforming them into reconstructions at the eleven lakes are shown in bold face.

finally decided not to use the data from six regions on account of currently insurmountable problems with short data gaps or unresolvable homogenization difficulties. Data from the remaining twenty regions were extensively tested for possible inhomogeneities using the normalised standard homogeneity test from Alexandersson and Moberg (1997). Any inhomogeneities detected were corrected by the use of local bridging series. Urban warming effects were minimized by bridging from the 18th and 19th century data to airport series and by checking the homogenized series against data from rural networks. Finally, following homogenization, a very small number of outliers were identified. These were replaced using multiple regression estimates from neighbouring series to yield the twenty homogeneous reference series that form the basis of our linear regression work.

Secondly upland series which we judged to be most representative of the air temperature prevailing at the eleven lakes were selected from available databases of air-temperature records. Mountain observatories provide most of these upland series. We refer to these upland observations of mean monthly air temperature as *transfer series* because they constitute the sites through which air temperature is transferred to the lakes. Our procedure of selection was based on a spatial study of correlation coefficients and on the consideration of accurate transfer from the mountain observatories to the lakes. Small elevation differences between the transfer site and the lake were preferred as they make any lapse rate corrections much easier to perform accurately. In particular transfer sites located above the winter thermal inversion layer were greatly preferred. The shortage of upland data restricted the choice of transfer sites. Nevertheless, transfer sites, which are longer than 30 years, located above the winter inversion layer and within 100 km of the lakes, were available for nine of the eleven lakes.

Thirdly, once the reference and transfer series had been established, their relationship was modelled by fitting a parsimonious multiple-regression model. The outcome is a linear equation, which expresses the temperature, at a particular transfer site, in terms of a linear combination of temperatures from a subset of the lowland sites. Twelve models were derived for each transfer site, one model for each calendar month, i.e. a total of 132 regression equations. The earlier data of the lowland reference series which has not been used in the regression can then be used as the input to the regression equation in order to retrodict air temperature at the transfer sites back to the beginning of the reference series at 1781 AD.

In addition, for the reconstruction of air temperature at the MOLAR lake sites, certain corrections may have to be applied to the retrodicted transfer series to account for any differences in elevation and micro-climate between the transfer site and the lake. The need for such corrections and the validity of the reconstructions has been tested by (i) comparing the model outputs with on-site measurements during 1996/7 and by (ii) cross-validation calculations.

The data

Monthly mean air-temperature records for sites across Europe have been gathered together. We have classified the data available to us into three different types as depicted in Figure 2 namely: (i) twenty long series from the lowlands (squares) spanning the period from 1781 AD to 1997 AD; (ii) eleven upland and arctic series (circles) spanning different periods of time; and (iii) ten very short series (black stars) from automatic weather stations at the lakes spanning a maximum period from July 1996 to July 1998. The group of twenty long lowland series (1781–1997 AD) are the reference series (see Table 2). Eighteen of these reference series have been built up from the Global Historical Climate Network (GHCN) and Climate Research Unit (CRU) databases. Moberg and Bergström (1997) provided the homogenised records for Uppsala and Stockholm in Sweden.

The eleven series near the lakes come mostly from mountain observatories (Table 3). The length of these transfer series varies. The shortest series is the arctic site of Kilpisjärvi in Finland (1951–1996 AD) while the longest series is from Säntis (1883–1995 AD), a mountain observatory in Switzerland. Again most data have been obtained from the GHCN and CRU databases. Exceptions are the long series from Pic du Midi (Bücher & Dessens, 1991), the series for Obergurgl (Nickus, personal communication) and the records for Navacerrada in Spain and Kilpisjärvi in Finland which were obtained from national meteorological institutes.

The ten series from the automatic weather stations located at ten of our remote mountain lakes were installed in summer 1996, or later, as part of the MOLAR project. The series are therefore very short (1–2 years long) but invaluable, since they provide the only knowledge of contemporary climate at these remote mountain and arctic lakes.

Statistical modelling

The model which transfers the air temperature from the lowlands to the sites near the lakes (transfer sites) is obtained by fitting a linear multiple regression equation to each of the transfer series for each month separately. The reference series included in the models have been chosen by stepwise regression by stepping down from the full model involving all twenty reference series.

$$T_t = k_0 + k_1 \,.\, T_{r1} + k_2 \,.\, T_{r2} + \ldots + k_n \,.\, T_{rn} \qquad (1)$$

where T_t is the transfer series, T_{rn} is the reference series and k_n is the coefficient of the n^{th} reference series. The standard AIC statistic (Akaike, 1974) was used to control the step-down procedure and determine which reference series should be included in the model.

It is worth pointing out that in this form of statistical modelling work the emphasis is solely on estimating the temperature at the transfer site (T_t in equation 1). No physical significance should be attributed to the coefficients (k_n of equation 1) nor any climatological significance to the particular reference series selected by the stepwise model.

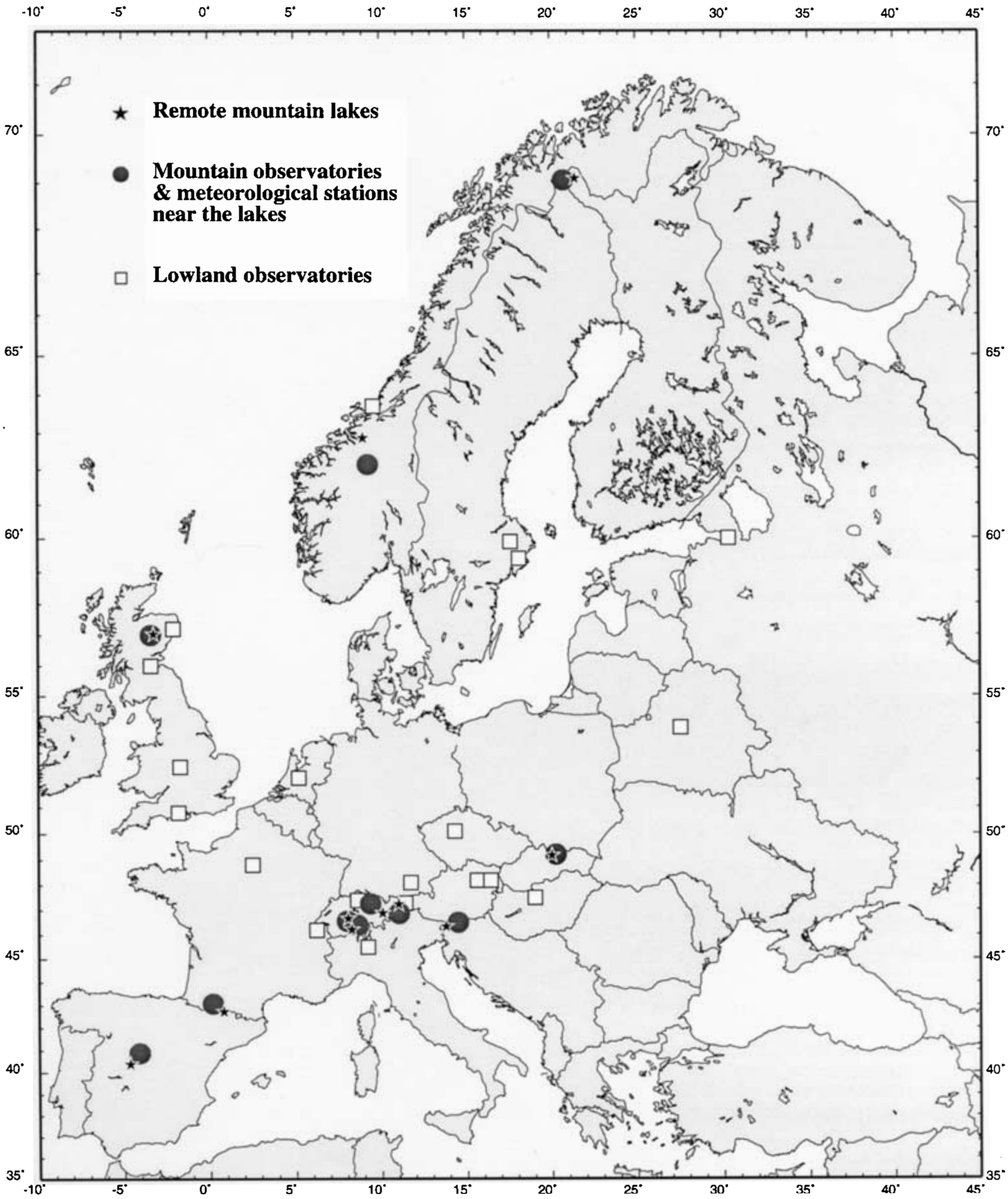


Figure 2. Location of the various monthly air-temperature records used in the reconstruction work. The regions used to build up the twenty reference series (from 1781 to 1997) are depicted by white squares. The locations of the transfer series, mostly from mountain observatories, are depicted by circles. The Automatic Weather Stations, at ten remote mountain and arctic lakes, are depicted by stars.

Validating the model

Even more important than model selection is model validation. Cross-validation (e.g., Stone, 1974) has been performed for each of our temperature reconstructions. Data are set aside (as a validation set) and then the modelling procedure run on the remaining data. Air temperatures are then predicted for the validation data and a skill factor calculated.

$$Skill = [1 - mean\{(T_o - T_p)^2\}/mean\{(T_o - \bar{T}_o)^2\}] * 100 \qquad (2)$$

Table 3. Transfer series[+]

Lake	Transfer series	Latitude (degrees)	Longitude(degrees)	Elevation(m a.s.l.)	Time-interval
Jörisee III (JRS)	Säntis	47° 15′N	09° 21′E	2500	1883–1995
Gossenköllesee (GKS)	Obergurgl	46° 52′N	11° 02′E	1937	1953–1995
Hagelseewli (HAG)	Jungfraujoch	46° 33′N	07° 59′E	3576	1961–1996
Paione Superiore (PSU)	St.Gotthard	46° 24′N	08° 36′E	2095	1864–1960
Estany Redó (RED)	Pic du Midi, Bigorre	43° 04′N	00° 09′E	2862	1882–1984
Laguna Cimera (CIM)	Navacerrada	40° 53′N	04° 07′W	1892	1951–1997
Terianske Pleso (TER)	Lomnicky Stit	49° 12′N	20° 13′E	2635	1941–1989
Jezero Ledvicah (LED)	Obir	46° 30′N	14° 30′E	2044	1851–1944
Lochnagar (NGE)	Braemar	57° 0′N	03° 24′W	339	1856–1990
Øvre Neådalsvatn (NEA)	Fokstua II	62° 09′N	09° 17′E	974	1923–1989
Saanajärvi (SAA)	Kilpisjärvi	69° 03′N	20° 47′E	478	1952–1996

[+]In order of lake elevation.

where T_o is the observed air temperature, T_p is the air temperature predicted by the model, and *skill* is the skill factor as a percentage.

The skill factor defined in equation (2) effectively indicates how well the model performs the reconstruction. If the reconstruction is perfect, i.e. the model prediction matches the observed values, then the skill factor is 100 (%). On the other hand, if the prediction only does as well as finding the mean air temperature (e.g., $\bar{T}_o$) then the skill of the model is zero. Even worse prediction can lead to negative skill factors. Validation data can be selected in various ways. Here we employed the widely used and well-established leave-out-one-at-a-time approach (e.g., Geisser, 1975). The cross-validation procedure is simple to apply. Cook et al. (1999) provide a very clear description of the method. They point out that various measures of skill can be adopted. Our measure (equation 2) has a range from $-\infty$ to +100%, and is effectively the same as Cook et al.'s (1999) RE factor.

Local corrections: topographical temperature gradients and the microclimate

In order to transfer the retrodicted air-temperature series to a particular lake we need to apply an elevation correction. This correction involves knowledge of the local gradient of air temperature with elevation, which here is referred to as the topographical temperature gradient. In addition some of our automatic weather stations were installed on non-standard sites (e.g., on rock shelves, or cottage roofs), on account of practical or security problems, and so may record local exposure effects.

Temperature generally decreases with elevation according to a topographical temperature gradient that varies with season. In summer and spring topographical temperature gradients are generally stronger than in winter or autumn. Episodes of thermal inversions tend to occur most frequently during winter, especially in the valleys of mountainous areas. Such thermal inversions can reverse the sign of the lapse rate.

Upper-air radiosonde data from the MCDW database (1990–1997 AD) for 31 stations in Europe were used to estimate the upper-air lapse rate. For each station we computed the lapse rate for two different vertical layers in the atmosphere. The first air-temperature lapse rate was between the earth surface and the 850 mb pressure surface (approximately equivalent to 1500 m a.s.l.). The second air-temperature lapse rate was from above the winter inversion layer being limited by the 850 and 700 mb pressure surfaces, which approximately correspond to 1500 and 3000 m a.s.l. respectively. The mean monthly lapse rates and monthly standard deviations were calculated for the period 1990–1997, for which radiosonde data were freely available. In addition, a spatial interpolation was performed on the mean values of the lapse rates from the 31 stations in order to obtain lapse rates at the remote lakes both above and below the thermal winter inversion layer. Linear interpolation was used in the triangles bounded by the 31 data points from the radiosonde stations. As the 31 free-atmospheric lapse rates in Europe show a large spatial coherence, the interpolated mean monthly lapse rates are thought to be reliable.

Since most transfer sites are located above the thermal winter inversion layer (i.e., above 1500 m) the second lapse rate (Table 5) was used for our final elevation correction. For those transfer sites below 1500 m, the first lapse rate (Table 4) was applied as a correction.

In this study upper-air temperature lapse rates are used instead of apparent lapse rates obtained from surface observations. The reason for this is that surface observations in mountainous areas can be very dependent on the specific microclimate of their location (e.g., Tabony, 1985; Barry, 1992). Thus apparent lapse rates can be difficult to interpolate spatially. On the other hand, upper-air stations give a more synoptic view of the vertical structure of the atmosphere and so are representative of a larger area. Because radiosonde data is much more spatially coherent, it can be interpolated more accurately to the locations of the MOLAR lakes.

Results

Air temperature change from 1781 to 1997 AD

The time series of the reconstructed air temperatures for each lake is displayed in Figure 3. The inter-annual variability, measured as the standard deviation, σ, of the annual mean air temperature, is similar at all eleven lakes averaging 0.8 °C. Lochnagar, being the lake with the smallest annual range of air temperatures, has the lowest inter-annual variability (σ = 0.6 °C). The lake with the largest annual range of air temperatures (Saanajärvi) has the highest inter-annual variability (σ = 1.0 °C). Although the long-term trends differ somewhat between lakes, geographically consistent patterns are found as expected. For example in the early part of the series, from 1781 to 1900, air temperatures from the northern and western sites show little linear trend (e.g., Lochnagar, Øvre Neådalsvatn, Saanajärvi, Lago Paione, Hagelseewli, Estany Redó and Laguna Cimera) while the more south-easterly sites experienced a general cooling trend (e.g., Jörisee III, Gossenköllesee, Terianske Pleso and Jezero Ledvicah). In contrast, in the later part of the series, from 1900 to 1997, there is a significant general warming with a warm episode

Table 4. Free-atmosphere temperature lapse rates (°C / km] for the layer between the earth surface and 850 hPa

Lake	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
JRS	–0.2	–2.7	–4.8	–6.4	–6.2	–6.4	–6.0	–5.6	–5.1	–3.0	–2.3	–1.5
GSK	–0.3	–2.7	–4.9	–6.4	–6.2	–6.4	–6.1	–5.7	–5.2	–3.0	–2.4	–1.5
HAG	–0.5	–2.8	–4.9	–6.4	–6.2	–6.4	–6.0	–5.6	–5.2	–3.3	–2.5	–1.7
PSU	–0.7	–2.9	–4.8	–6.1	–5.9	–6.1	–5.8	–5.3	–4.9	–3.3	–2.6	–1.8
RED	–3.9	–4.4	–5.1	–5.1	–5.1	–5.0	–4.4	–4.7	–5.1	–4.2	–4.0	–3.9
CIM	–3.5	–4.5	–6.4	–7.3	–8.1	–8.1	–7.8	–7.6	–7.2	–6.3	–4.2	–3.6
TER	+0.7	–2.9	–5.8	–6.1	–6.1	–6.0	–5.7	–5.7	–4.8	–4.6	–3.6	–0.9
LED	–0.9	–3.1	–5.2	–6.5	–6.2	–6.4	–6.1	–5.9	–5.4	–3.5	–2.8	–1.9
NAG	–4.0	–5.3	–5.4	–6.3	–5.9	–5.6	–5.6	–5.9	–6.4	–5.6	–5.0	–4.7
NEA	–4.3	–4.5	–5.5	–6.3	–6.1	–5.8	–5.1	–5.7	–5.8	–4.9	–1.7	–4.4
SAA	–1.8	–2.1	–3.7	–5.7	–5.9	–5.1	–4.8	–5.2	–5.1	–4.8	–2.9	–2.5

These lapse rates are an estimate of the typical vertical temperature gradient at the lakes. They have been obtained by interpolating mean lapse rate values from 31 sites with radiosonde data in Europe during the period from 1990 to 1997.

Table 5. Free-atmosphere temperature lapse rates (°C / km) in the layer between 850 and 700 hPa

Lake	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
JRS	–4.8	–5.4	–5.6	–6.0	–6.3	–6.2	–6.1	–6.3	–5.7	–5.2	–5.0	–4.7
GSK	–4.8	–5.4	–5.6	–6.0	–6.3	–6.2	–6.1	–6.3	–5.7	–5.2	–5.0	–4.6
HAG	–4.8	–5.3	–5.5	–6.0	–6.2	–6.1	–6.0	–6.2	–5.6	–5.2	–5.0	–4.6
PSU	–4.7	–5.3	–5.5	–5.9	–6.2	–6.1	–6.1	–6.3	–5.6	–5.1	–5.0	–4.6
RED	–5.2	–5.1	–5.4	–5.8	–5.7	–5.8	–5.7	–5.8	–5.5	–5.3	–5.4	–5.2
CIM	–4.6	–5.0	–6.0	–6.7	–7.2	–6.8	–7.1	–7.1	–6.6	–5.5	–4.8	–4.6
TER	–4.2	–4.4	–5.0	–6.0	–6.5	–6.3	–6.1	–6.3	–5.3	–4.4	–4.5	–3.9
LED	–4.6	–5.2	–5.6	–5.7	–6.2	–6.1	–6.0	–6.3	–5.7	–5.1	–4.8	–4.4
NAG	–4.7	–5.0	–4.9	–4.9	–5.1	–5.1	–5.1	–5.2	–4.1	–4.5	–5.2	–5.1
NEA	–5.6	–5.8	–5.3	–5.8	–5.3	–5.4	–5.6	–5.5	–5.2	–5.4	–5.6	–5.8
SAA	–5.3	–5.4	–5.2	–5.3	–5.4	–5.5	–5.1	–4.9	–4.9	–4.4	–5.2	–5.4

These lapse rates are an estimate of the typical vertical temperature gradient at the lakes. They have been obtained by interpolating mean lapse rate values from 31 sites with radiosonde data in Europe during the period from 1990 to 1997.

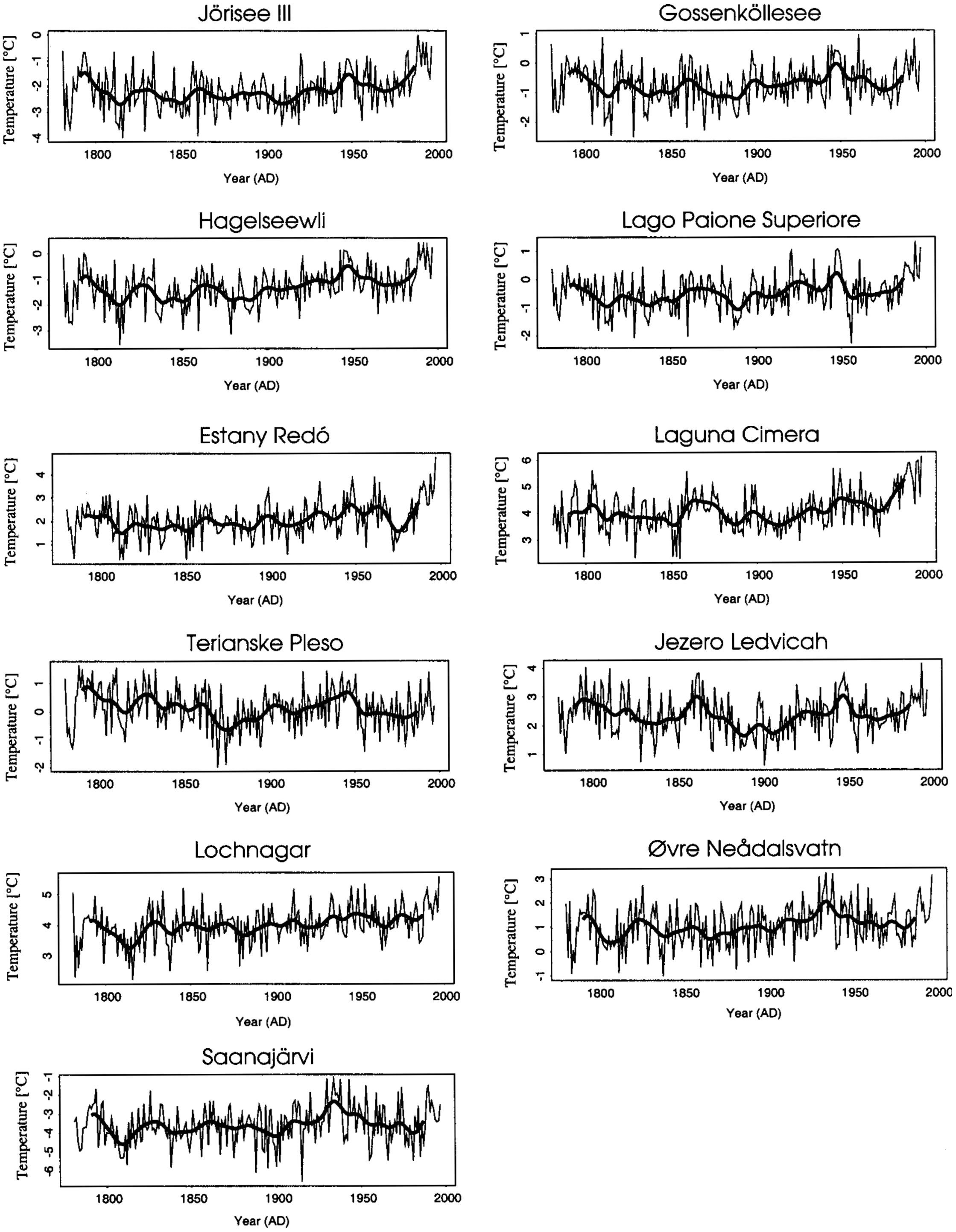


Figure 3. Time series of air-temperature reconstructions from 1781 to 1997 at the eleven remote mountain lakes in Europe. The annual means are represented by the thin lines and the decadal variabilities are depicted by the smoothed curves (thick lines).

between the 1930s and 1940s and a cold episode in the 1970s at all lakes. Finally, there is a particularly steep rise in air temperature at all lakes from the mid-1980s to 1997. Decadal fluctuations repeat well between geographically adjacent sites. For example, the 1790s and late 1940s were warm in the Alps while the 1930s were warm in Fenno-Scandinavia. Similarly, the 1870s were warm in Spain and the Alps. Some extreme cold years at the lakes are 1812, 1814, 1816, 1829, 1838 and 1860. Warm years include 1811, 1943, 1947 and 1994 at lakes in central and southern Europe, and 1826 and 1934 in the northern lakes (i.e., Øvre Neådalsvatn, Lochnagar and Saanajärvi).

In order to compute the linear trends, the annual temperature series have been divided into two time periods: from 1801 to 1900 and from 1901 to 1997. The choice of these two separate periods has been made simply to coincide with the two different centuries and for ease of comparison with other climate change studies. Trend calculations using a regression approach are based on an assumption of independence (e.g., Ch. 15 in Ramsey & Schafer, 1996). Von Storch and Zwiers (1999, p. 114) emphasize the need to check this assumption with climatic series when the time increment between observations is not large. From an examination of the autocorrelation structure of the first differences of the annual means, we find that serial correlations, additional to the trend, are very small at most of the lakes. Also the first serial correlation coefficient based on the residuals to the linear trend is typically only +0.15 or less (i.e. the original temperature series follow a linear trend and follow no other clear time-series process). This means that at each site it is not unreasonable to compute the linear temperature trends by performing standard linear regression but that the significance of the trends should be interpreted conservatively. The linear trends of the reconstructed annual mean air temperatures for the period 1801–1900 are listed in Table 6. Eight lakes show no significant linear trends during the 19th century. Only the Scottish lake Lochnagar has a small significant positive trend while the two easternmost lakes have significant negative trends. In contrast, the linear trends for this century (1901–1997) are positive and significant for most lakes, ranging between +0.3 and +1.7 °C /100 yr (Table 6). However, no significant linear trends are observed in Terianske Pleso, Øvre Neådalsvatn and Saanajärvi during the whole of the 20th century.

Validation of the transfer functions and the temperature reconstructions

The skill of the models, used to retrodict air temperatures at each transfer site, has been calculated following equation (2). The skill factor associated with each transfer function varies from month to month. As shown in Figure 4, the skill of the transfer functions for continental regions such as the Alps and the Tatra Mountains presents a similar yearly pattern. Generally the skill is highest during summer and lower during winter. In maritime areas such as Scotland (Braemar) and Norway (Fokstua) the variation of skill through the year again follows a characteristic pattern (Figure 4b) but here the skill is higher during the period from the autumn through to the early spring. In the outlying areas, such as the Iberian peninsula (Pic du Midi and Navacerrada) and Finland (Kilpisjärvi) a lower more variable skill is found throughout the year.

The lowest skills partly coincide with prolonged occurrences of thermal inversions in the lowland valleys during winter. These thermal inversions, caused by low temperatures in the lowlands and high temperatures in the uplands, have the effect of decoupling the variations of upland and lowland air temperatures.

Table 6. Estimated mean air temperatures (1781–1997) (°C) and linear trends (°C /100 yr) during the 19th and 20th centuries

Lake	Annual (°C)	Range (°C)	Winter (°C)	Spring (°C)	Summer (°C)	Autumn (°C)	Linear trend (°C/100 yr) 1801–1900	Linear trend (°C/100 yr) 1901–1997
JRS	–2.1	16.3	–7.9	–3.9	4.4	–0.9	–	+1.1*
GSK	–0.7	18.2	–7.8	–2.1	6.8	0.5	–	–
HAG	–1.3	17.9	–8.0	–2.9	6.0	–0.2	–	+0.8*
PSU	–0.5	17.5	–7.1	–2.7	6.7	1.3	–	+0.5*
RED	2.1	17.0	–3.7	–0.3	9.2	3.0	–	+0.9*
CIM	4.1	18.8	–2.3	1.1	12.4	5.3	–	+1.7*
TER	0.1	20.4	–7.9	–1.1	8.6	0.8	–0.9*	–
LED	1.8	18.4	–5.3	0.1	9.5	2.8	–0.5*	+0.8*
NAG	4.0	13.8	–1.2	2.9	9.9	4.5	+0.3*	+0.5*
NEA	1.1	22.0	–7.3	–0.2	10.6	1.2	–	–
SAA	–3.6	28.0	–13.9	–6.0	8.4	–2.7	–	–

The significance levels of the linear trends are denoted by *($p < 0.1$). (–) indicates that the trend is not significant at the $p < 0.1$ level.

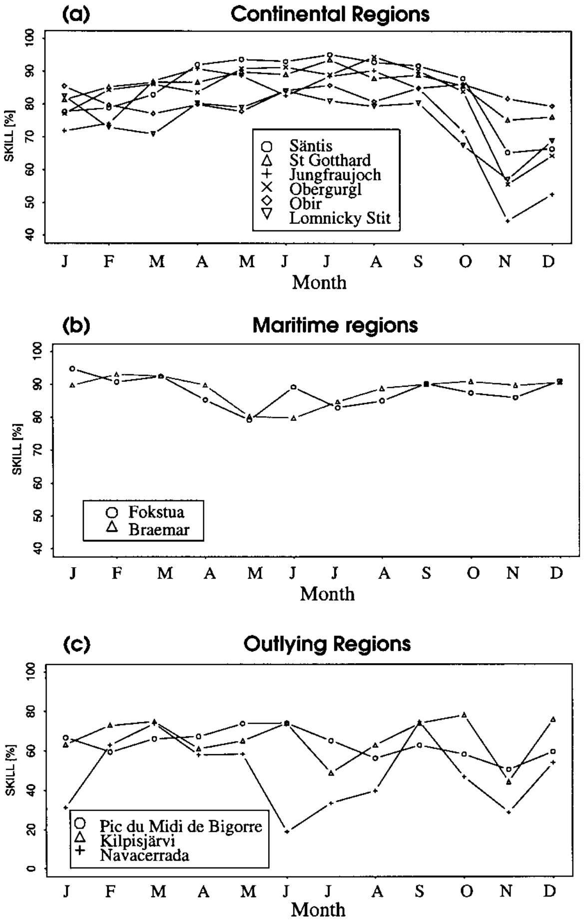


Figure 4. Monthly skill values (%) associated with the transfer functions: 100% skill represents perfect reconstruction of the mean monthly air temperature at the transfer site; 0% skill represents reconstruction of only the mean climate. In continental regions the skill is generally good (averaging 81%) but poorest in November and December. At the maritime sites the skill is very good (88% on average) especially in the winter. At the most remote sites, the skill is noticeably poorer (typically 57%).

To get a first estimate of the errors of the retrodicted temperature series at the lakes we can use the leave-one-out-at-a-time, cross-validation, root mean square error associated with the transfer functions (Table 7). However, a more complete validation of the reconstruction can be made, by comparing our retrodicted air temperatures with the observations from the automatic weather stations (AWS) at the lakes. The AWS data only begin in summer 1996, and so the records at the lakes do not yet provide a sufficiently long series to compute statistically significant errors associated with the air-temperature reconstructions at the lakes. Nevertheless, an insight into the accuracy of these reconstructions is provided in Table 8 and Figure 5.

In Figure 5 the reconstructed and the observed air temperatures are plotted for the period between January 1996 and December 1997 for the ten lakes with AWS. Only months with more than 90% of data present are plotted. The average monthly misfit is found to be about 1 °C. Overall our predictions are best for June with a median absolute misfit of 0.35 °C and worst for April with a median absolute misfit of 1.6 °C. For those lakes with at least one full year's worth of data, we can observe that months in winter and early spring have the largest errors in the reconstructions. This is particularly clear for Lago Paione Superiore. The predicted mean air temperature in late-winter/early-spring 1997 is 3.1–3.8 °C colder than observed. At other lakes in the Alps, except for Jörisee III, the predicted temperatures are also lower than measured, although within our error limits (Figure 5). Summer and late spring temperatures are much better predicted, in the Alps, with errors ranging between –0.6 and 1.9 °C.

At Lochnagar predicted air temperatures are generally higher than the observations for all months. The errors range from +1.3 to –1.5 °C with a mean bias of

Table 7. Cross-validated root mean square error (°C) associated with the transfer functions for each month

Lake	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
JRS	1.1	1.1	0.9	0.5	0.4	0.4	0.4	0.4	0.6	0.8	1.1	1.1
GKS	1.0	1.1	0.8	0.7	0.5	0.4	0.5	0.3	0.5	0.8	1.1	1.1
HAG	1.3	1.2	0.8	0.5	0.5	0.5	0.5	0.4	0.7	1.2	1.3	1.5
PSU	0.9	0.9	0.7	0.6	0.5	0.5	0.4	0.5	0.6	0.7	0.9	0.9
RED	1.3	1.6	1.3	1.0	1.0	0.9	0.9	1.0	1.1	1.3	1.4	1.2
CIM	1.3	1.3	1.1	1.2	1.4	1.4	1.2	1.1	1.1	1.6	1.4	1.1
TER	1.0	1.4	1.2	0.8	0.8	0.6	0.7	0.8	0.9	1.0	1.3	0.9
LED	0.9	1.1	0.9	0.8	0.9	0.6	0.6	0.7	0.8	0.8	0.9	1.0
NAG	0.6	0.5	0.5	0.4	0.5	0.5	0.4	0.4	0.3	0.4	0.4	0.6
NEA	0.7	1.0	0.7	0.6	0.7	0.6	0.6	0.6	0.4	0.6	0.8	0.8
SAA	2.3	2.1	1.5	1.2	0.9	1.0	1.0	0.8	0.7	1.0	2.1	2.1

Table 8. Validation of the monthly air-temperature reconstructions at ten lakes as based on AWS data

Lake	Mean bias$^+$ (°C)	Max absolute bias$^+$ (°C)	Min absolute bias$^+$ (°C)	Root mean square error (°C)
JRS	–0.7	2.8	0.0	±1.2
GKS	0.6	3.1	0.1	±1.7
HAG	0.8	2.9	0.2	±1.3
PSU	0.9	3.8	0.1	±1.7
RED	–0.4	2.0	0.0	±1.0
CIM	NA	NA	NA	NA
TER	–1.7	3.2	0.4	±1.9
LED	1.2	3.0	0.2	±1.6
NAG	–0.6	1.5	0.1	±0.9
NEA	–6.1	7.1	4.6	±6.1
SAA	–0.1	3.6	0.1	±1.6

$^+$Bias is defined as the difference between the observed air temperature and the reconstructed air temperature. NA = Not available – no AWS.

–0.6 °C (Table 8). Estany Redó has the lowest reconstruction errors, of the nine lakes validated by AWS measurements, with a median absolute error of 0.45 °C and a mean bias of –0.36 °C (Table 8). At Estany Redó the largest errors, –1.7 and –1.9 °C, are in July and August respectively. At Saanajärvi the mean bias is –0.1 °C, however the individual monthly discrepancies between the predicted and observed temperatures range between –1.9 and +0.8 °C, except for December 1996 when the error is +3.6 °C. At Terianske Pleso the AWS has not been reliable enough to assess the accuracy of our reconstructions. At Øvre Neådalvatn a clear discrepancy of over –6 °C is seen. We initially wondered if the low air temperatures recorded at the lake could have been caused by cold winds blowing off neighbouring glaciers. However the difference was traced to a major calibration error on the AWS, so vindicating our reconstructions. Air-temperature readings of below –3.94 °C were subsequently found to have been recorded incorrectly and consequently to have biased the mean temperatures at the AWS. Unfortunately Laguna Cimera does not have an AWS. So we have been unable to validate our work at Laguna Cimera.

In summary we find the mean reconstruction errors at the MOLAR lakes to be 1.3 °C for low-sun months and 1.0 °C for high-sun months. These monthly errors translate into errors of around 0.3 °C for annual means and even lower errors for decadal means.

The air temperature climatology at the lakes

From a biological point of view it is important to reconstruct the typical climate at the lakes. This is especially useful when developing training sets (Lotter et al., 1997). The average climate (1781–1997) at the eleven remote lakes has been calculated from the reconstructed air-temperature series (Figure 3; Table 6). The lake with the lowest, annual mean air temperature is the arctic lake Saanajärvi (–3.6 °C) and the highest, annual mean air temperature corresponds to Laguna Cimera (4.1 °C) in the Iberian Peninsula (Table 6). The average air temperature at these eleven MOLAR lakes is +0.46 °C. The annual range in mean air temperature reflects the continentality of the climate at the lakes. Saanajärvi is the lake with the most continental climate with an annual air-temperature range of 28.0 °C, followed by Øvre Neådalsvatn (22.0 °C) and Terianske Pleso (20.4 °C). The lake with the most oceanic climate is Lochnagar with an annual mean air-temperature range of 13.8 °C followed by Estany Redó at 16.3 °C. Seasonal air temperatures, as tabulated in Table 6, are also important. For example summer temperatures are frequently used with training sets for generating diatom, chironomid or cladocera-based climatic transfer functions (Lotter et al., 1997), while spring and autumn temperatures control lake ice-melt and ice-formation.

Regionalization of temperature change at the lakes

In order to find the common features in the variability of air temperature at the different lakes we applied principal component analysis (PCA) to the air temperatures reconstructed at the eleven lakes. We analysed the annual mean air temperatures spanning the full period 1781–1997 after standardization. Out of the eleven principal components (PC) obtained, only the first three were considered here because they alone describe 85% of the total variance for the eleven series, and they can be easily interpreted in a physically meaningful way. The first PC explains 61% of the total variance, whereas the second and the third PCs explain 14 and 10% of the total variance respectively.

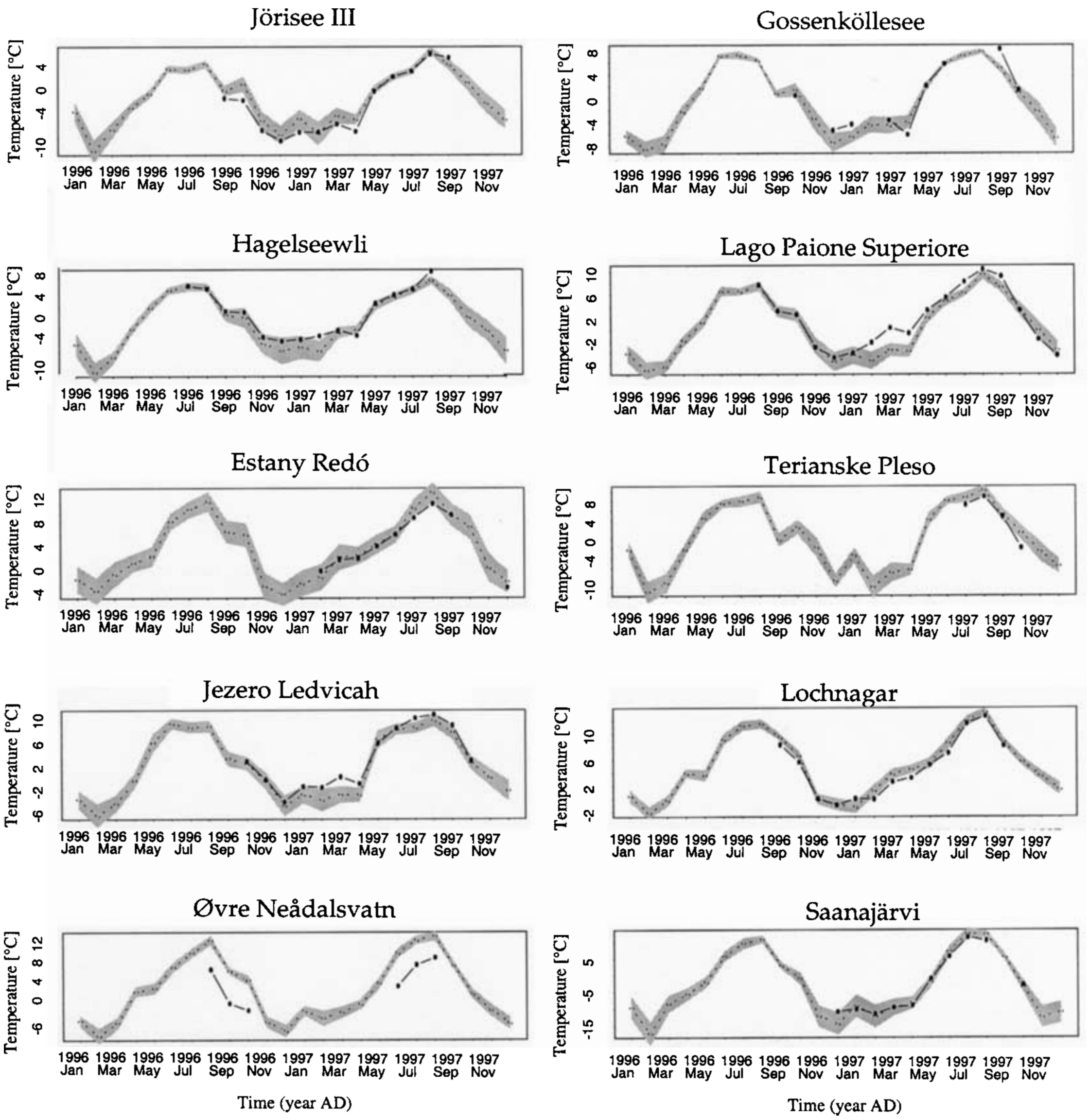
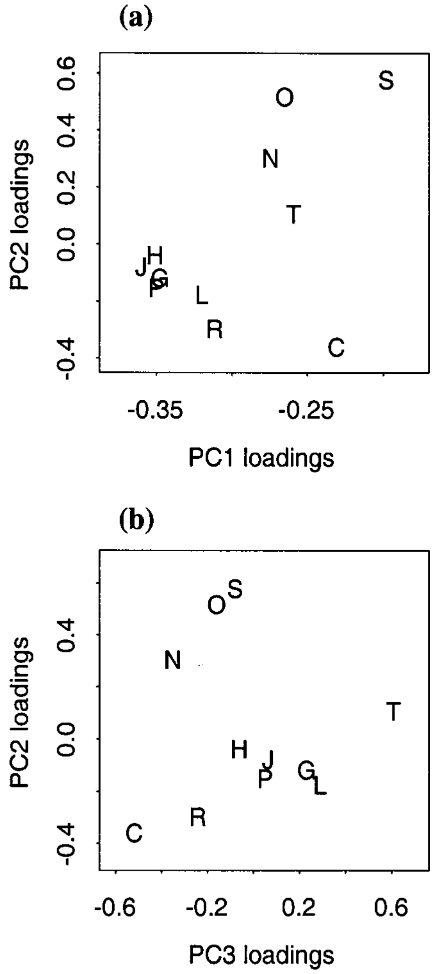


Figure 5. Final validation of air-temperature reconstructions (dashed lines) by comparing them to the direct air-temperature observations (solid line) at ten of the remote lakes for the validation period 1996–1997. The shading shows the 90% confidence intervals for the monthly mean air-temperature reconstructions obtained from the cross validation.

A physical interpretation of the PCs can be made by studying the loadings for each PC. Figure 6a shows a plot of the loadings for PC2 vs. PC1, and Figure 6b those for PC2 vs. PC3. The first PC (x-axis in Figure 6a) has negative loadings associated with all lakes. Thus, PC1 represents a weighted average of the annual mean air temperatures at all eleven lakes. The weights or loadings are larger for the lakes in the Alps, followed by the more Mediterranean lakes (Jezero Ledvicah and Estany Redó), the northern and central European lakes (Øvre Neådalsvatn, Lochnagar, Terianske) and, finally, the outlying lakes (Laguna Cimera and Saanajärvi).

The second and third PCs have loadings with both negative and positive values. Judging from the distribution of the lakes we arrive at the conclusion that negative loadings for PC2 are associated with lakes at low latitudes and positive loadings with lakes at high latitudes. Therefore PC2 represents the variability associated with the meridional temperature gradient of the annual mean air temperature for the eleven lakes.



J	-	Jörisee III
G	-	Gossenköllesee
H	-	Hagelseewli
P	-	Lago Paione Superiore
R	-	Estany Redó
C	-	Laguna Cimera
T	-	Terianske Pleso
L	-	Jezero Ledvicah
N	-	Lochnagar
O	-	Øvre Neådalsvatn
S	-	Saanajärvi

Figure 6. Loadings of (a) the first vs. second and (b) the second vs. third principal components of the annual mean air-temperature reconstructions at the eleven remote mountain lakes (1781–1997 AD). The five lakes in the Alps (J, H, P, G & L) form a tight cluster. The Fennoscandian (O & S) and Scottish (N) lakes tend to form a cluster near the top of the diagrams. The Spanish lakes (C & R) similarly lie together at the bottom of the diagram.

Similarly, PC3 represents the variability associated with the zonal gradient of annual mean temperature. That is to say, lakes in Eastern Europe have positive loadings whereas lakes in Western Europe have negative loadings. Thus Figure 6b can be seen as a geographical map: the x-axis corresponding to longitude and the y-axis to latitude.

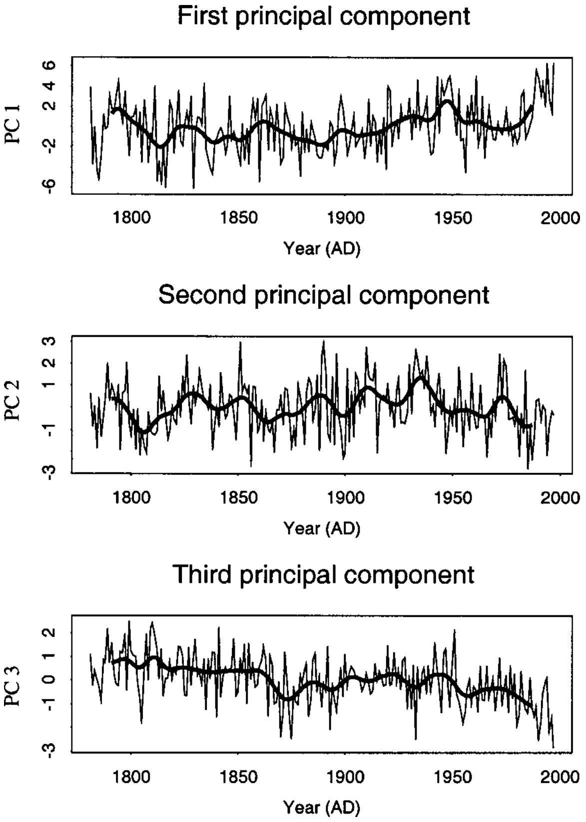
The evolution with time of the three modes of variability described above is depicted in Figure 7. The positive weighted average of the annual temperature anomaly for the eleven lakes is represented as a time series of PC1 in Figure 7a. The average, annual mean air temperature for the eleven lakes does not show any significant trend during the 19th century (1801–1900), but it has significantly increased by 2.9 °C during the 20th century (1901–1997). Years when PC1 has positive anomalies tend to coincide with high values of the North Atlantic Oscillation (NAO) index. The correlation coefficient between the NAO index and PC1 for the period 1860–1997 is +0.46 and is significant at the $p < 0.01$ level.

The meridional gradient of annual mean air temperature is reflected in the time series of PC2 in Figure 7b. Positive values indicate a positive north-south air-temperature gradient and vice versa. The time series of PC2 indicates that during the period from 1900 to 1950 the north-south annual temperature gradient was greater than normal. Finally, PC3 presents the time series for the east-west, annual mean, air-temperature gradient in Figure 7c. The zonal gradient has decreased from 1781 to 1997.

The significance and stability of the three different principal components and their loadings have been demonstrated by breaking the time series from 1781 to 1997 AD into seven sub-periods, each 30 years long as in Gray (1981). It is found that the variance explained by the first three PCs and the clusters formed by the PC loadings are consistent for all seven sub-periods.

Discussion

The reconstructions of air temperature at eleven remote lakes in Europe provide a unique data set to study the air-temperature change at alpine and arctic sites during the last two centuries. The results show two distinct trends for the 19th and 20th centuries. According to these trends there has been a significant general warming at the lakes during this century, but not during the previous century.


First principal component

Second principal component

Third principal component

Figure 7. Scores of the first, second and third principal components of the annual mean air-temperature reconstructions at the eleven remote mountain lakes. PC1 is effectively the mean air-temperature of the eleven sites, showing the rapid rise in temperature in the last decade. Lines are as in Figure 3.

While the climate and weather in mountain valleys are distinct from that of the nearby lowlands, the *climate change* tends to follow similar trends. In our reconstructions the air temperatures at the mountain lakes have very similar long-term trends to those of the temperatures in the neighbouring lowlands. This similarity does not always apply to the decadal variability, which shows a more local signal. Nevertheless, there are common warm and cold decades. The warm periods around 1790–1800, the 1940s and the 1980s, plus the steep rise from the 1980s to the present, as well as the cold period around 1890 (Figure 3), are all features noted in numerous previous studies involving various regions of Europe (e.g., Metaxas et al., 1991; Auer & Böhm, 1994; Kozuchowski et al., 1994; Beniston et al., 1997; Weber et al., 1997; Balling et al., 1998).

During the 19th century, most European lowland sites show no significant trend in air temperature except for Eastern Europe, where trends of the order of –1 °C /century are found. The cooling in the 19th century is more widely extended in the lowlands than in the uplands. There is also a good similarity between the 20th-century warming reconstructed at the lakes and that of the neighbouring lowlands. The temperature changes at the lakes are consistent with the regional trends of temperature in Europe summarised in the Intergovernmental Panel of Climate Change (IPCC) report (Beniston et al., 1998). Recent studies by Jones et al. (1999) show that global surface temperatures have risen by 0.62 °C from 1901 to 1997. According to the latter investigation, most warming in the 20th century has occurred during the two periods 1925–1944 and 1978–1997, but arctic temperatures have only risen slightly on an annual basis. Thus, annual mean air-temperature trends at the lakes are also comparable with the annual global surface temperature changes, although the magnitude of the warming at the lakes during this century has been much greater. We find no evidence of higher trends at the alpine lakes compared with their neighbouring lowland sites. Such enhancement of temperature trends as investigated by Diaz and Bradley (1997) might be evident if minimum and maximum temperatures were used instead of their mean. The eleven temperature trends show strong west-east and south-north gradients, in agreement with the results presented in Diaz and Bradley (1997), Weber et al. (1997) and Beniston et al. (1998) for the 20th century. The western and southern regions show the largest increase in air temperature, whereas the eastern and northern regions show small or insignificant increases. This gradient is represented by the second and third principal components (PC) of the annual mean temperatures at the eleven lakes.

Despite the differences between the lakes, there is a common pattern of temperature change represented by the first PC. This common pattern can be related to the changes in atmospheric circulation over Europe. The correlation between the first PC and the North Atlantic Oscillation index indicates a link between the air-temperature variability at the lakes and the strength of the zonal westerly winds coming from the Atlantic. Extreme warm/cold years (particularly in western and central Europe) are generally connected to high/low intensities of the westerly winds (Kozuchowski, 1993; Beniston et al., 1994). In turn, these temperature changes have a direct effect on ice-cover break-up at alpine lakes (Livingstone, 1997).

The use of temperature reconstructions at alpine and arctic lakes by the community of palaeolimnologists is very wide. Some of the possible applications include:

(i) reconstructing ice cover duration and growing season (Agustí-Panareda et al., 2000), (ii) evaluating the response of ecosystems to climatic variability in alpine and arctic lakes (Lotter et al., 1997) and (iii) verifying palaeoclimatic reconstructions based on lake-sediment cores (cf. other papers in this special issue).

Conclusions

- The statistical procedure of multiple regression can be used to transfer air temperatures recorded in the lowlands to the uplands.
- Monthly mean air-temperature reconstructions from 1781 to 1997 have been generated for 11 remote alpine and arctic lakes in Europe.
- The skill scores of the transfer functions range typically between 60 and 99 %. In winter months and outlying lakes the skill can drop to values around 40%.
- We estimate the errors associated with the reconstructions to be typically around 1 °C for individual months.
- The long-term annual mean air-temperature change at the 11 lakes has different trends in the 19th and 20th centuries.
- During the 19th century, the annual mean air temperature shows a significant cooling trend below –1 °C/century at the easternmost lakes and no significant trend at the other lakes.
- During the 20th century there was a general warming trend at the lakes except for the northernmost Fennoscandian lakes, which showed no significant trend.
- We estimate the errors associated with fitting the least square trends to be around 0.2 °C/century.
- Both the magnitude and spatial distribution of the annual mean air-temperature trends at the lakes are consistent with previous studies of climate change in Europe.

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