Verh. Internat. Verein. Limnol. | 27 | 479–483 | Stuttgart, April 2000

Reconstructing temperature variations at high elevation lake sites in Europe during the instrumental period

Anna Agustí-Panareda, Roy Thompson and David M. Livingstone

Introduction

The longest instrumental climate records that exist anywhere in the world are those from lowland Europe. In contrast, instrumental climate records from European upland areas are generally short and scarce. The study of mountain climate is nevertheless important, since alpine areas represent some of the most pristine and unpolluted environments on Earth, and provide a variety of palæoclimate proxy records (e.g. mountain lake sediments and alpine glaciers). Furthermore, air-temperature anomalies at mountain sites in the European Alps show an amplification of the climate signal with respect to nearby lowland stations (BENISTON et al. 1997), emphasizing the value of mountain areas for the study of climate change.

Our aim here is to construct a statistical model to provide transfer functions from lowland to upland climates. This is made possible by the high correlation we find between lowland and upland temperature records (after removing seasonal effects). Our statistical model, which is based on stepwise multiple linear regression, provides the basis for the climate reconstruction at several remote mountain lakes in Europe now being studied as part of the MOLAR project.

Climatic forcing is important for high altitude lakes (SOMMARUGA-WÖGRATH et al. 1997). In particular, climate has an important effect on the duration of ice cover (e.g. RUOSTEENOJA 1986) and growing season (MELA 1996). Both ice cover and growing season condition the seasonal evolution of the lakes chemically (e.g. pH), physically (e.g. lake stratification and circulation) and ecologically (e.g. productivity). This paper describes the use of reconstructed surface air temperatures to derive long series (1781–1997) of estimates of ice-cover and growing season duration for five alpine lakes in Europe.

Lowland and upland climate variability

The co-variability of upland and lowland climates was analysed by plotting the mean of the monthly correlation coefficient between deseasonalized pairs of daily mean air temperature series (January 1994–December 1997) versus station separation (Fig. 1). The meteorological stations analysed are all located in Europe within the area bounded by 5° W, 30° E, 41° N and 54° N. Figure 1 shows that the correlation coefficient decays with station separation nearly isotropically for all station pairs, and that the spatial variability of air temperatures measured at upland stations (≥1,000 m, Fig. 1a) is very similar to that of air temperatures measured at lowland stations (≤500 m, Fig. 1c). Furthermore, the high correlation existing between air temperatures measured at lowland and upland stations suggests that the former may be used to reconstruct the latter. In summary, more than 50% of the variance (corresponding to r = 0.71) in daily mean air temperature at an upland station can typically be explained by the air temperature measured at a lowland station located within 400 km. The proportion of variance explained can

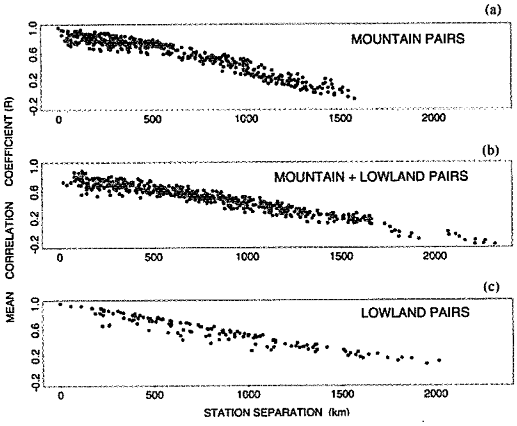

Fig. 1. Correlation coefficient as a function of station separation for daily mean air temperature series (January 1994–December 1997) from 28 lowland (≤500 m) and 15 upland (≥1,000 m) stations.

0368-0770/00/0027-0479 $ 1.25

be increased by combining data from several lowland stations using multiple regression, as explained below.

Reconstructing air temperature at remote mountain lakes

Methodology

The air temperature reconstructions were carried out in three stages. First of all, instrumental climate data were gathered and homogenised. Secondly, statistical techniques were applied to transfer the long climate series from the lowland observatories to a mountain observatory close to each lake. Finally, a correction for the elevation difference between the mountain observatory and the lake was applied to the retrodicted temperature series.

Data

Series of monthly mean air temperatures from (i) 21 lowland regions in Europe spanning the period from 1781 to 1997, as well as from (ii) five mountain observatories in Europe covering periods varying from 34 to 113 years were gathered and homogenised. Air temperatures at the MOLAR lake sites (from July 1996 onwards) were provided by automatic weather stations which had been installed as part of the MOLAR project.

Statistical modelling

The process of retrodicting air temperatures at the mountain sites using instrumental records is illustrated in Fig. 2, taking the July air temperature series (1883–1995) of the Säntis mountain observatory in the Swiss Alps as an example. The same process is applied for each individual calendar month. First of all, about one-third of the data from the mountain observatory are set aside for validation purposes. Secondly, stepwise multiple regression is applied to the remaining data. For example, the statistical modelling illustrated in Fig. 2 is performed using July data from 1913 to 1995. The resulting regression equation, which constitutes the model in Fig. 2, is used to retrodict the mountain air-temperature series for the rest of the period. Thirdly, the performance of the model is validated by comparing the results with the independent observed values set aside at the start. In Fig. 2, 30 years (1883–1912) have been used as the validation period. A skill factor

$$\text{Skill} = \left(1 - \frac{\overline{(T_{\text{obs}} - T_{\text{pred}})^2}}{\text{var}(T_{\text{obs}})}\right) \times 100\%$$

is then computed for the validation period. Fourthly, stepwise multiple regression is applied to the full upland series (1883–1995) to give the full model relating the mountain and lowland series:

$$\begin{aligned} T_{\text{Säntis}} = {} & 0.10\,T_{\text{De Bilt}} + 0.27\,T_{\text{Geneva}} + 0.18\,T_{\text{Vienna}} + \\ & 0.57\,T_{\text{Innsbruck}} + 0.07\,T_{\text{Milan}} - 0.06\,T_{\text{St. Petersburg}} + \\ & 0.10\,T_{\text{Minsk}} - 17.38 \end{aligned}$$

Finally, the series is retrodicted back to 1781 using the full multiple regression model produced for each individual calendar month.

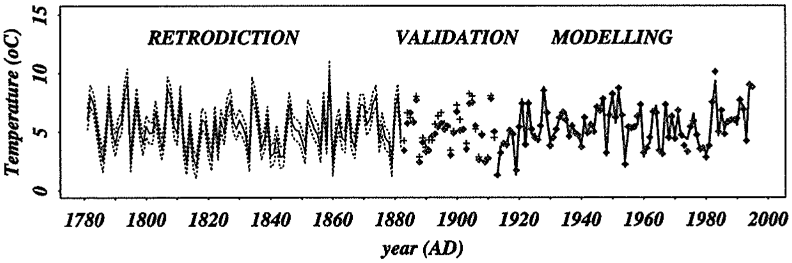

Fig. 2. Reconstruction of July air temperatures for the Swiss mountain observatory Säntis (2,500 m a.s.l., 47° 15' N, 9° 21' E). The observed July air temperatures at Säntis (1883–1995) are depicted by rhomboids. The thick line (1912–1995) is the fit given by the statistical model relating Säntis July air temperatures to lowland air temperatures. The predicted air temperatures produced by the model are represented by crosses for the validation period (1883–1912) and by a solid line for the retrodiction period (1781–1882). The validation period yields a skill factor of 88% for July temperatures. Furthermore, 90% confidence intervals (deduced from the goodness of fit during the validation period) are plotted during the retrodiction period as dashed lines. They correspond to ±0.92 °C.

Lapse rate correction

A small correction factor needs to be applied to the retrodicted mountain series in order to account for the difference in elevation between the mountain observatory and the remote mountain lake. Regional topographic air temperature gradients ("lapse rates") were calculated for this purpose. Fig. 3 illustrates the decrease in air temperature with elevation in February and August 1997 based on data from 40 Swiss meteorological stations. This decrease is highly linear at all altitudes in summer, and at altitudes above 1,500 m (i.e. above the thermal inversion layer) in winter. Most of the mountain observatories in this study are located above the thermal inversion layer and at similar elevations to the remote mountain lakes. Thus, a linear decrease in temperature with altitude can be applied as an elevation correction factor. The offset of the temperatures at the different stations with respect to the lapse rate line can be explained by the differences in local microclimates and local exposure effects at each particular site.

Results

Monthly mean surface air-temperature series, each 217 years long, were reconstructed at five of the MOLAR lake sites (Øvre Neådalsvatn: 728 m a.s.l., 62° 46' 30" N, 9° 00' 00"E, Norway; Estany Redó: 2,240 m a.s.l, 42° 38' 34" N, 0° 46' 13" E, Spain; Saanajärvi: 679 m a.s.l, 69° 03' 05" N, 20° 52' 41" E, Finland; Hagelseewli: 2,339 m a.s.l, 46° 40' 29" N, 8° 02' 12" E, Switzerland; and Jörisee III: 2,519 m a.s.l, 46° 46' 41" N, 9° 58' 35" E, Switzerland) following the method described above.

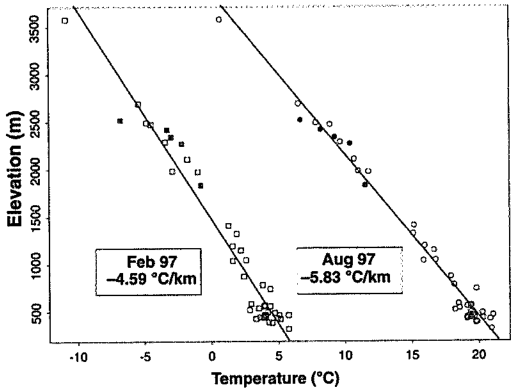

Fig. 3. The relationship between air temperature and elevation for the north slope of the Swiss Alps in February 1997 and August 1997, based on monthly mean data from 40 meteorological stations (open symbols). Also shown are the corresponding air temperature data from automatic weather stations at five remote mountain lakes in the European Alps (solid symbols).

The errors associated with the transfer functions for the air temperature reconstructions at the five mountain observatories are estimated to be ±0.54 °C for Neådalsvatn, ±0.90 °C for Estany Redó, ±1.11 °C for Saanajärvi, ±0.54 °C for Hagelseewli and ±0.58 °C for Jörisee III. As an additional check on our approach, during 1997 and 1998, monthly mean air temperatures from the automatic weather stations installed at the MOLAR sites were compared with our regression models. Here, errors of between ±0.5 °C and ±2 °C were found.

Estimated duration of ice cover and growing season

Surface air temperature is the most important meteorological variable controlling the duration of ice cover (Ruosteenoja 1986) and the duration of the growing season (Mela 1996). Thus, we may be able to use the reconstructed air temperature series to estimate the duration of ice cover and growing season at the lakes in the past.

The duration of the period of ice cover on a lake is given simply by the difference of the break-up and freeze-up dates, both of which are highly dependent on air temperature. Various studies have shown these dates to be related to (although by no means identical to) the calendar dates on which the air temperature at the lake passes through 0 °C (e.g. Ruosteenoja 1986). Unfortunately, data on the freezing and thawing of mountain lakes are scarce. Thus, as a first approximation, the duration of the period of ice cover will be defined arbitrarily for the purposes of this paper as the number of days on which the mean air temperature is below 0 °C. Similarly, the duration of the growing season at each lake will be defined as the number of days on which the mean air temperature exceeds 5.5 °C (Mela 1996). On this basis, estimates of ice-cover and growing season duration (Fig. 4) were computed from the reconstructed air temperature series at the five MOLAR lakes by

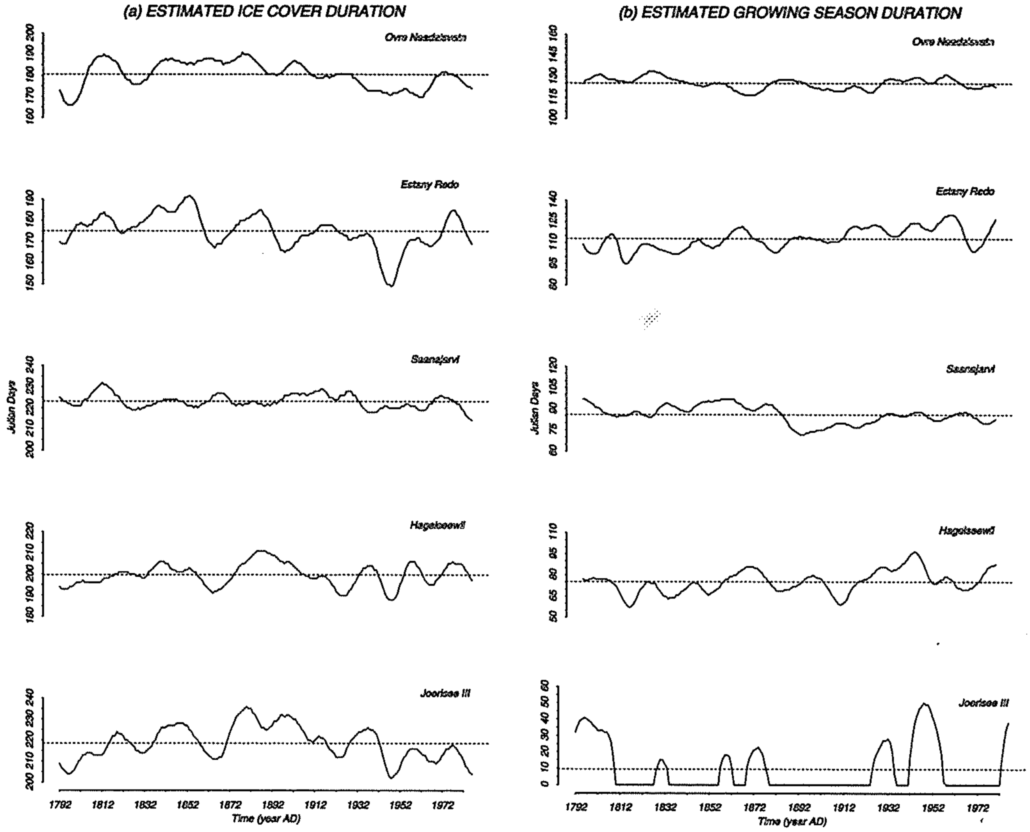

Fig. 4. Estimated duration of (a) the period of ice cover and (b) the growing season at five remote mountain lakes in Europe, calculated from reconstructed air-temperature series (1781–1997).

applying a 10-year lowpass filter to the monthly air temperature series and subsequently employing cubic-spline interpolation to give daily mean air temperature estimates. Preliminary comparisons with real ice data from two Finnish lakes (Kallavesi and Näsijärvi) reveal that 75% of the decadal variance in the duration of the period of ice cover can be explained by this simple approach, although in the mean, the estimated duration of ice cover is 10 days shorter than the observed duration.

As expected, with increasing elevation and/or latitude, the mean estimated duration of the period of ice cover (Fig. 4a, dashed lines) increases, while that of the growing season (Fig. 4b, dashed lines) decreases. Above a certain altitudinal threshold, the growing season duration falls to zero, implying that terrestrial vegetation cannot maintain itself. Some remote mountain lakes, such as Jörisee III (2,519 m a.s.l.), lie near this threshold, implying that during cold years there is likely to be no growing season. The altitudinal threshold for permanent ice cover is higher than that of the growing season, and all five alpine lakes lie below this threshold, so that the estimated ice-cover duration is more highly correlated between the lakes than is the growing season.

The decadal-scale variability of the estimated durations of ice cover and growing season is also illustrated in Fig. 4 (solid lines). In the case of the growing season, this variability is low at Øvre Neådalsvatn (from 115 to 135 days), but very high at Jörisee III (with abrupt changes

from 0 to 50 days). At the other lakes, the estimated growing season length can vary by up to 30 days. The range of ice-cover duration is estimated to be particularly low at Saanajärvi, and highest at Estany Redó and Jörisee III.

At all five lakes, the long-term trends in the estimated duration of the growing season and the period of ice cover follow the trend in mean air temperature found in the lowlands. As would be expected, the estimated durations of the growing season and the period of ice cover are inversely correlated. There are particular decades during which the growing season was especially long and the duration of the period of ice cover much shorter than average, and vice-versa. In the 1940s the estimated duration of the period of ice cover in most lakes was 10–20 days below average (1792–1982), and the growing season length increased from 6 days (at Øvre Neådalsvatn) to 20 days at Hagelseewli and 50 days at Jörisee III. However, in the 1880s, it is estimated that the period of ice cover probably reached a maximum at most lakes (except Saanajärvi) and was accompanied by a short growing season.

Conclusions

- It is possible to reconstruct surface air temperatures at European upland sites from long lowland instrumental climate records.
- On average, at least 50% of the variability in air temperature at an upland station can be explained in terms of the air-temperature series measured at an individual lowland station located within 400 km. Parsimonious multiple regression models allow even better relationships between the lowland and upland stations to be established and have been used to reconstruct air temperatures at five mountain meteorological stations in Europe.
- Annual mean absolute errors in these reconstructions range from ±0.5 °C to ±1.1 °C and skill factors vary from 63% to 88%.
- Air temperatures measured at alpine lakes in the European Alps do not deviate significantly from the vertical temperature gradient line, despite the fact that in mountain areas, lakes, by their very nature, tend to be situated in sheltered valleys, whereas meteorological stations tend to be situated in more exposed locations.
- The method of ice-cover reconstruction used here when applied to two Finnish lakes explains 75% of the decadal variability of the observed ice-cover duration.

Acknowledgements

Funding was provided by the European Union Framework IV project MOLAR (MOuntain LAke Research: Measuring and monitoring the response of remote mountain lakes to environmental change; contract no. ENV4-CT95-007) and by an associated grant (no. 95.0518-1) from the Swiss Federal Office of Education and Science. The authors are grateful to all the MOLAR automatic weather station operators, and to H. Alexandersson, J. Dessens, A. Drebs, E. Kuusisto, A. Moberg, H. Tuomenvirta, Météo-France, The Finnish Meteorological Institute and The Swiss Meteorological Institute for providing valuable climate data.

References

Beniston, M., Diaz, H. F. & Bradley, R. S., 1997: Climate change at high elevation sites: an overview. – *Clim. Change* 36: 233–251.

Mela, T. J. N., 1996: Northern agriculture: constraints and responses to global climate change. – *Agric. Food Sci. Finland* 5: 229–234.

Ruosteenoja, K., 1986: The date of break-up of lake ice as a climatic index. – *Geophysica* 22: 89–99

Sommaruga-Wögrath, S., Koining, K.A., Schmidt, R., Sommaruga, R., Tessadri, R. & Psenner, R., 1997: Temperature effects on the acidity of remote alpine lakes. – *Nature* 387: 64–67.

Authors' addresses:

Anna Agustí-Panareda, Roy Thompson, Department of Geology and Geophysics, The University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, UK.

David M. Livingstone, Department of Environmental Physics, Swiss Federal Institute of Environmental Science and Technology (EAWAG), Überlandstrasse 133, CH-8600 Dübendorf, Switzerland.