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# Climate variability and ecosystem dynamics of remote alpine and arctic lakes: the MOLAR project

Mountain Lake Research

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## Abstract

This paper introduces the results of an integrated project designed to compare high resolution analysis of proxy records of climate change in the sediments of seven mountain lakes across Europe with reconstructed instrumental records of climate change over the last 200 years. Palaeolimnological methods used include radiometric dating ($^{210}$Pb, $^{137}$Cs), mineral magnetics, dry weight, loss-on-ignition, carbon, nitrogen, sulphur, pigments, diatoms, chrysophyte cysts, cladocera and chironomids. Changes in fossil assemblages were summarised using principal components analysis. The stratigraphic data were compared with the instrumental record using linear regression techniques. The dated sediment records for each proxy from each site were treated as the response variables and the various attributes of the instrumental climate record as the predictor variables. The predictor variables were generated for each site for the period 1781 to 1997 using temperature reconstructions based on meteorological records. To harmonise the climatic predictors and the response variables, the climatic variables were smoothed along time with a LOESS regression. The results of the various analyses at the seven sites are presented in the following papers. A synthesis of the project and the relative performance of the different proxy methods are discussed in the final paper.

## Introduction

There is increasing recognition that arctic and alpine aquatic ecosystems are being influenced by climate change (Douglas et al., 1994; Sorvari & Korhola, 1998). As surface water temperatures tend to vary closely with air temperature, especially during spring and summer months (Livingstone & Lotter, 1998), one of the effects of global warming is an increase in lake-water temperature. Changes in wind speed, wind direction, rain and snowfall are also associated with climate change and, together with temperature, these changes affect the timing and intensity of thermal stratification, ice-cover, turbidity and light penetration (e.g., Catalan & Camero, 1990). Chemical and biological changes ensue. If changes in weather patterns are sustained over longer periods, changes in water column productivity and in the species composition of plant and animal populations can be expected, both by direct (e.g., temperature) and indirect (e.g., pH, ice-cover) effects.

Equally, changes in weather patterns will also cause catchment changes to occur that will additionally influence lake-water conditions. In mountain lakes increased temperatures lead to a reduction in catchment snow and ice cover that cause changes in hydrology, speed up weathering processes and may accelerate soil erosion.

These effects of climate change are potentially recorded in lake sediments and lake sediments can thus be used as a means of reconstructing past climate over long time-scales. However, the usefulness of this ap-

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This is the first of 11 papers published in this special issue on the palaeolimnology of remote mountain lakes in Europe resulting from the MOLAR project funded by the European Union. The guest editor was Richard W. Battarbee.

proach depends on the sensitivity and accuracy of the various proxy methods that are used for climate reconstruction and the extent to which the climate signal in the sediment record is obscured by noise from other influences (e.g., associated with human disturbance).

To maximise the climate signal we have selected sites for study that are as pristine as possible, situated above the timber-line, without apparent catchment disturbance and largely unaffected by air pollution. To avoid problems of acidification the sites are either located in areas of low acid deposition or in areas with calcareous bedrock. At each site we have data from automatic weather stations, modelled climate data spanning the last 200 years, water column data and detailed multi-proxy analyses of $^{210}$Pb-dated sediment cores. We selected 200 years as a key period for data comparison as this is the period of time for which reliable climate records based on instrumental data are available and also the time period over which a reasonably reliable sediment chronology can be established from $^{210}$Pb dating.

In this volume we describe the results of this project and evaluate the sensitivity and usefulness of the different proxy-climate methods used. The work was carried out under the auspices of the EU-funded project MOLAR: "Measuring and modelling the dynamic response of remote mountain lake ecosystems to environmental change: A programme of Mountain Lake Research" (Battarbee et al., 2001). The papers are based on the results from Work Package 3 of the MOLAR project that was specifically concerned with climate change. The following papers deal with the methods used to establish the instrumental climate time-series for each site, with the limnological characteristics of the lakes and with a comparison between the instrumental record of climate change spanning the last 200 years and the proxy records of climate change, on a site by site basis. Additional data from these sites and from the wider MOLAR project has already been published (Straškrabová et al., 1999; Lami et al., 2000).

## Sites

The lakes in this study share the same basic limnological characteristics. They are oligotrophic, typically dimictic and have a winter ice-cover and a summer thermocline. They are all situated above or beyond the regional tree-line, and they have poorly vegetated catchments.

Most of the sites were included in the AL:PE.2 study (Wathne et al., 1997), and belong to the group of sites identified in that study to be least influenced by acid deposition. In the MOLAR project a number of new sites were added to provide the study with a wider geographical and chemical range. These are located in Finland, Austria, Switzerland and Slovenia.

The sites are shown in Figure 1 and their main characteristics are listed in Table 1. They include sites in the Arctic and northern Latitudes (Øvre Neådalsvatn in Norway, Saanajärvi in Finland), sites in the Alps (Gossenköllesee in Austria, Hagelseewli in Switzerland, Jezero v Ledvici in Slovenia), sites in Spain (Estany Redó in the Pyrenees, Cimera in the Gredos Mountains), and a site in the Slovakian Tatra Mountains (Nižné Terianske).

## Approach

In order to assess how well remote mountain lake sediments record climate variability it is necessary not only to carry out a high resolution multi-proxy study of well-dated sediments from a range of sites, but also to establish, if possible, the mechanisms that link climate

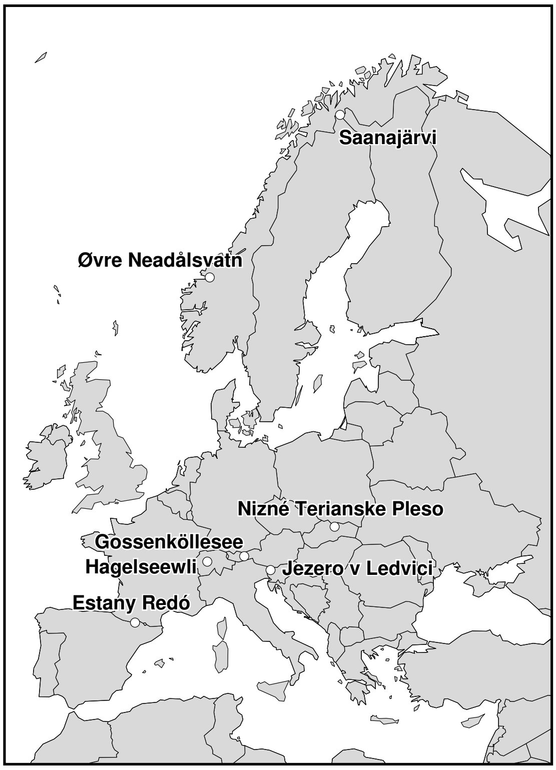

*Figure 1.* Map of Europe showing the location of the seven mountain lales studied in this project.

*Table 1.* Lake location, morphology and catchment features

| | Gossenköllesee | Jezero v Ledvici | Hagelseewli | Øvre Neådalsvatn | Saanajärvi | N. Terianske pleso | Estany Redó |
|---|---|---|---|---|---|---|---|
| Latitude | 47° 13′ N | 46° 20′ N | 46° 40′ N | 62° 46′ N | 69° 03′ N | 49° 10′ N | 42° 38′ N |
| Longitude | 11° 0′ E | 13° 47′ E | 8° 02′ E | 9° 00′ E | 20° 52′ E | 20° 00′ E | 0° 46′ E |
| Altitude (m a.s.l) | 2417 | 1830 | 2339 | 728 | 679 | 1941 | 2240 |
| Mountain range | Tyrolean Alps | Julian Alps | Central Swiss Alps | Caledonian | Northern Finland | Tatra | Pyrenees |
| Maximum depth (m) | 9.9 | 15 | 18 | 18 | 24 | 44.4 | 73 |
| Mean depth (m) | 4.7 | 5.7 | 8.3 | 4.0 | 5.1 | 18.4 | 32.3 |
| Lake area (ha) | 1.7 | 2.37 | 2.37 | 50 | 69.9 | 4.83 | 24 |
| Lake volume ($10^6$ $m^3$) | 0.08 | 0.135 | 0.197 | 1.996 | 3.6* | 0.891 | 7.750 |
| Watershed area (ha) | 20 | not defined- | 36 | 1600 | 461 | 114 | 155 |
| Renewal time (years) | 0.2* | 0.1 | 0.3* | 0.07 | 1* | 0.8 | 4 |
| Watershed to lake area ratio | 11.8 | – | 15.2 | 32.0 | 6.6 | 22.8 | 6.5 |
| Main lithology | Granite, gneiss, amphibolite | Limestone | Limestone | Gneiss | Schist, gneiss and limestone | Granite | Granodiorite |
| Soil cover (%) | 20 | < 10 | – | 40 | – | 50 | 60 |
| Main vegetation | Alpine meadows | Alpine meadows | Alpine meadows | Alpine heath, pasture | Subalpine vegetation | Alpine meadows | Festuca eskia meadows |

change to the sediment record. Although there are major logistical difficulties working in remote mountain lakes, we have approached this challenge by attempting to (i) generate 200 year-long meteorological records for each site; (ii) verify these records by comparison with data from on-site automatic weather stations; (iii) relate climate records to water column characteristics, (iv) relate sediment records to climate records using regression analysis, and (v) interpret the sediment records in terms of water column and mud-water interface processes.

## Establishing weather and climate records on site

Establishing a time series of climate data that can be used for comparisons with sediment cores over the last 200 years is a three-step process: constructing homogenous air-temperature series from lowland historical instrumental records; transferring these records to the mountain sites taking into account differences in elevation and local microclimate; and testing the accuracy of the modelled data for mountain stations using established high elevation meteorological stations and data from on-site automatic weather stations (Agustí-Panareda et al., 2000, Agustí-Panareda & Thompson, this issue).

Europe is particularly fortunate in having the longest and densest network of historical climate records of any part of the world. A unique body of climate data has been assembled over the last five centuries and much of the data, the earliest reaching back to January 1525 AD, have been converted into machine-readable form. In many cases these data have been unified, compared, corrected and standardised in order to construct long-term homogenous air temperature time series (e.g., Jones et al., 1986), and extensive historical climate databases have been created e.g., the Global Historical Climate Network (Peterson et al., 1998) and the North Atlantic Climate Data set (Frich et al., 1995).

Using these data and data from a more limited range of upland meteorological stations we have attempted to reconstruct air temperatures from 1781 to the present day for our remote alpine and arctic lake study sites in Europe. The results are presented by Agustí-Panareda & Thompson (this issue).

## Relating meteorological data to water column characteristics

Although some proxy-methods are designed to reconstruct temperature directly from the sediment record (e.g., in the case of chironomid-temperature transfer functions (Walker et al., 1997)) most methods deal with this relationship indirectly. In these cases reconstructions depend on an understanding of the responses of the water column to climate change and on the responses of the sediment record to water column change (Battarbee, 2000).

A complete limnological study of each site was beyond the scope of the present project, but an attempt has been made to explore a number of key relationships between the climate record and the water column. In particular these include the links between air temperature, lake-water temperature, ice-cover and growing season (e.g., Agustí-Panareda et al., 2000), and, for the two year period of the study, the relationship between weather patterns, ice cover, thermal stratification, and water column chemistry and biology (Catalan et al., this issue). These data are essential in interpreting the sediment record and are needed to develop dynamic lake models that couple climate forcing and lake response. Whilst we have made some progress in developing a modelling approach, our current knowledge is restricted to the direct measurements we have made at each site over the period of the project. These data include water column measurements of temperature, oxygen, pH, conductivity and chlorophyll-a collected at bi-weekly intervals in the ice-free season, and at the beginning, middle and end of the ice-cover period when conditions allowed. In addition samples for major ion (Ca, Mg, Na, K, alkalinity, Cl and $SO_4$) and nutrient (N, P, dissolved $SiO_2$) chemistry, phytoplankton (diatoms and chrysophytes) and zooplankton analysis were collected at approximately monthly intervals. Benthic diatom and chironomid sampling was also carried out along transects perpendicular to the shoreline using scuba to sample deep-water habitats, and sediment traps were deployed in order to assess the quantity and timing of material fluxes to the sediment, both of biogenic (autochthonous) and abiogenic (allochthonous) material. The traps were emptied each month in the ice-free season. The results of these studies are presented in Lami et al. (2000) and by Catalan et al. (this issue).

## Establishing an understanding of the sediment record

In this project no prior assumptions were made as to which climate proxy would provide the strongest signal. The intention instead was to explore as many methods as possible using a high resolution (sub-decadal), multi-proxy approach. To ensure comparability between sites, analyses were carried out either at central laboratories e.g. mineral magnetics (Liverpool), pigments (Pallanza), or, most usually, at local laboratories using common protocols and quality control techniques. The analyses include mineral magnetics, dry weight, loss-on-ignition, carbon, nitrogen, sulphur, pigments, diatoms, chrysophyte cysts, cladocera and chironomids. Changes in fossil assemblages were summarised using principal components analysis.

At each site, cores of the uppermost sediment were taken with a wide-diameter piston corer. Replicate cores were taken at all sites to provide adequate material for all analyses. The uppermost sediment was subsampled at contiguous 2 mm (or in some cases 2.5 mm intervals) to provide an average sample resolution of 5–10 years and one core was dated at the Environmental Radioactivity Laboratory in Liverpool using $^{210}$Pb, $^{137}$Cs and $^{241}$Am measurements (Appleby et al., 1986). Replicate cores were then correlated to the dated master core on the basis of their loss-on-ignition and dry weight records using a slot-sequencing procedure (Thompson & Clark, 1993).

The results of the sediment core analyses for the seven major study sites are presented in the following papers in this issue. However, at each site only data covering the last c. 200 years are included in order to match the 200 years instrumental record as closely as possible. Additional data for some sites are presented in Lami et al. (2000).

## Comparing the proxy record with the instrumental climate record

At the centre of our approach is the statistical comparison, using linear regression techniques, between the dated sediment records for each proxy from each site (the response variables) with various attributes of the instrumental record (the predictor variables). For the non-biological analyses data have not been transformed in any way, but for the biological records (diatoms, chironomids, chrysophytes, and cladocerans) assemblage composition was summarised as principal component axes prior to being used as response variables. Due to the short time span relative to the resolution of the samples, a linear response was assumed for the biological compositions along the major underlying gradient. Therefore, a default analysis for principal component analysis (PCA) in CANOWIN 4.0 (ter

*Table 2*. The climatic variables that are used as predictors and their abbreviations

| Predictor | Definition | Abbreviation |
|---|---|---|
| Summer 1 temperature | Mean June, July and August | JJA |
| Summer 2 temperature | Mean July, August and September | JAS |
| Winter temperature | Mean December, January and February | Winter |
| Continentality index | Difference between JJA and Winter | Contin |
| Annual temperature | Mean of all the twelve months | Annual |

Braak & Šmilauer, 1998) was used, with the exception that a square root transformation of the species abundance data expressed as percentages was used prior to the PCA. All four PCA axes are used as response variables, but only relationships with axes that have a larger eigenvalue than expected under a broken-stick model (Joeliffe, 1986; Jackson, 1993), are likely to be numerically important.

Climate predictor variables were generated for each site for the period 1781 to 1997 from the instrumentally-based temperature reconstructions of Agustí-Panareda & Thompson (this issue). These included yearly mean data for two estimates of summer temperatures, winter temperature, an index of continentality, and annual temperature (Table 2).

To harmonise the climatic predictors and the response variables, the individual climatic variables were smoothed along time with a LOESS regression (Cleveland et al., 1993). From this, an estimate of the climate variable was interpolated for the midpoint of each sample that was used for the biological and sedimentological analyses. LOESS smoothers are non-parametric local regressions using a parametric regression within a span defined by the user that subsequently combines all these parametric regressions into one regression. The span defines the fraction of neighbours around the target to be included in each parametric regression and must be defined by the user. Within these spans, we used a quadratic polynomial regression, which allows more variation to be captured in the final model. Because the results may be sensitive to the degree of smoothing applied to the climatic variables, three different spans were applied to the five climatic predictors. This also gives the opportunity to study the relationships at different temporal scales, and to investigate whether the different biological groups in this study respond to climatic changes at different temporal scales. The interpolated climatic values for the corresponding year of the midpoint of each sample were used as predictor variables and a linear regression was performed. Due to temporal autocorrelation p-values must be interpreted with caution, and therefore only the resulting $R^2$ values are reported as a guide for comparing the different regression models.

The relationships established using this approach are indicated on a site-by-site basis in the following papers in this issue and a review of the performance of the various proxies is presented in the final paper (Battarbee et al., this issue). The final paper also considers possible explanations for the observed relationships both in terms of limnological and sedimentological processes, assesses the potential of mountain lake sediment records for reconstructing Holocene climate change, and suggests what further work is required to enhance their use.

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