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SEASONAL VARIABILITY OF TEMPERATURE IN ALPINE LAKES FROM THE RETEZAT NATIONAL PARK, ROMANIA

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INTRODUCTION

The study of abiotic and biotic responses to climate change is of great importance for the assessment of its potential risks. Some studies have suggested that the effect of climate change at high altitudes is likely to be above average (e.g. Beniston et al., 1997). Remote alpine lakes are extremely useful for this type of study because of their relative ecological simplicity and recent origin (Catalan, 1992; Catalan and Camarero, 1991), and because they represent some of the least impacted natural environments existing in Europe today (Ohlendorf et al., 2000). They are also more sensitive to changes than larger aquatic systems. Despite their remoteness which makes them vulnerable only to long-range atmospheric pollution, in some European mountain regions these lakes are far from pristine (Grimalt et al., 2001).

Lake surface temperature is one of the most important physical parameters of any lacustrine system. It reflects meteorological forcing more immediately and more precisely than any other lake parameter and it is strongly related to the mean temperature of the photosynthetically productive zone, thus playing a major role in lake's biology (Livingstone and Dokulil, 2001).

Surface water temperature, surface temperature variability and thermal resilience in lakes are influenced by three categories of factors: geographical (altitude, exposition), morphometric (surface, length, maximum width, volume, perimeter, maximum depth, average depth, relative depth, average depth/maximum depth ratio etc.) and climatic (e.g. air temperature). We investigated the influence of these three categories of factors on the thermal characteristics of alpine lakes in the Retezat Mountains of Romania.

The aim of the present study was (1) to establish the influence of climatic and geographical versus morphometric factors on surface water temperature in alpine lakes, and (2) to study the annual thermal stratification and mixing in an alpine lake.

MATERIAL AND METHOD

Location

Retezat National Park, located in the western part of Romania, is the oldest national park in Romania, having been established by law in 1935. The park has a surface of 38,047 ha, of which 1,630 ha have been declared as a strictly protected area called "Gemenele". The universal value of the park was recognized by the Man and Biosphere Program of UNESCO in 1979 through its inclusion in the international network of biosphere reserves. The lower parts of the park have deep narrow valleys, while in the higher parts there are glacial plateaus. The mountain range consists of Danubian metamorphic rocks dominated by slightly metamorphosed crystalline schists. The glacial and crionival relief is extremely widespread, allowing lakes to form in the deeper parts of the moraines (Schreiber and Sorocovschi, 1992). A total of 58 permanent glacial lakes and almost as many temporary lakes have been recorded at altitudes between 1700-2300 m (Pişotă, 1971). Retezat Mountains have the highest humidity and runoff in Romanian Carpathians. Specific runoff varies with altitude, from 14.3 $l/s \cdot km^2$ between 600-800 m to 28 $l/s \cdot km^2$ between 1600-1800 m and up to 36.6 $l/s \cdot km^2$ at altitudes higher than 2200 m. The highest monthly runoff is recorded in May (Schreiber and Sorocovschi, 1992).

The climate is moderately cold and humid, with yearly average temperatures of 6^0C in the valleys and -2^0C in the alpine areas. Annual rainfall varies between 900-1300 mm, reaching higher values below the timberline (Fărcaş and Sorocovschi, 1992).

Characteristics of the alpine lakes studied

Five alpine lakes were included in this study. Except for Lake Porții, the lakes are located in the strictly protected area (table 1). Geographical coordinates were measured with a GPS (Garmin 12 XL) and water depth with a Speedtech portable sonar. Based on the morphometric data provided by Pişotă (1971) we also computed mean depth and relative depth. While mean depth is calculated as the lake's water volume divided by its surface area, relative depth is given by the maximum depth as a percentage of the mean diameter of the lake and is generally considered as a measure of the lake's resistance to mixing. Small sized lakes with a high resistance to mixing usually have relative depth values higher than 4% (Wetzel and Likens, 1995).

Lake Negru is the deepest and largest (with respect to volume) of the lakes studied here. It has a surface area of 4.05 ha and a catchment area of 38 ha (Pişotă, 1971). The hydrological balance of the lake catchment, according to Pişotă (1971), is 532,000 m^3 annual input from rainfall and output of 136,800 m^3 through

Table 1. Geographic location and morphometric parameters of the studied lakes (partly from Pişotă, 1971)

Lake	Latitude N	Longitude E	Altitude (m a.s.l.)	Surface (m^2)	Maximum depth (m)	Mean depth (m)	Relative depth (m)	Maximum width (m)	Length (m)	Perimeter (m)
Caprelor	45.3613	22.8451	2140	3630	1.1	0.39	1.62	31	141	390
Gemenele	45.3662	22.8416	1920	24800	5.3	2.71	2.98	120	276	691
Negru	45.3601	22.8289	2036	40480	24.8	11.03	10.92	196	280	792
Porții	45.3619	22.8625	2260	4900	4.3	0.21	5.43	67	92	264
Ştirbu	45.3646	22.8546	2082	9540	8.7	5.04	7.89	96	131	435

evaporation. For the lake itself the input within the lake from rainfall on the surface of the lake is 56,800 m^3/year and 395,200 m^3 from inlets and springs. The outputs are 437,500 m^3 through the outlet and 14,500 m^3 through evaporation.

The lake is positioned below the Şesele Peak (2324 m) to its south-east. The shores of the lake are high and steep, and mostly deprived of vegetation, except for *Luzula alpino-pilosa* which forms associations typical for areas with snow cover lasting for 8-9 months (Luzuletum alpino-pilosae) (Coldea, 1992). No macrophytes occur in the lake itself.

The lake has two permanent inflows and a single outlet with a relatively constant rate of flow during the year (Decei, 1981). Water level can vary by up to one meter during the year. Only two of the limnological studies that have been conducted in the park covered Lake Negru: one focused only on chemistry (Vasiliu, 1964) and a later one also included the lake biota (Prunescu-Arion and Toniuc, 1967).

Sampling

The present study was carried out during 2000-2002. Lake water temperature data were obtained using miniature thermistors with integrated data loggers with a resolution of 0.1^{0}K (Vemco Minilog-T, Vemco Ltd., Halifax, Nova Scotia, Canada). During 2000-2001 five thermistors were deployed attached to a surface buoy to measure surface water temperature in Lakes Gemenele, Ştirbu, Negru, Caprelor and Porții. During summer 2000, the thermistor in Lake Gemenele did not operate. During 2001-2002 the five thermistors were deployed as a chain at depths of 1, 5, 10, 15, and 20 m to measure the temperature profile in Lake Negru. The chain was attached to a large floating buoy and anchored to prevent displacement.

Chemical and physical parameters were measured on water samples taken using a horizontal alpha water sampler (Cole-Parmer Inc.) from a boat above the deepest part of the lake. Conductivity and pH were measured using an Oakton portable device. Daily air temperature measurements were provided by Țarcu Meteorological Station.

Statistical analyses

Since the temperature measurements are not mutually independent observations but time-series with a degree of inherent temporal persistence (the variation within a month is lower than the variation between months) we accounted for autocorrelation using the month as a random factor in linear mixed-effect models fitted by REML (restrictive maximum likelihood). The daily mean and daily standard deviation of the temperature were considered fixed factors. Due to the anomalous properties of water around and below 4°C related with lake mixing and freezing, when assesing correlation between surface water temperature and air temperature, only temperatures above 4^{0}C were considered. General linear models (GLM) were computed using R 1.9.1. (R Development Core Team, 2004).

RESULTS

Surface water temperature shows a high degree of short-term coherence in four of the five lakes studied (Fig. 1). A linear model with monthly means as dependent variable and month, year and lake as predictors showed significant differences between the surface temperatures of the lakes (F3,33=21.626, p<0.001) (Fig. 2).

Surface water temperature was correlated with air temperature for each of the four lakes for which the complete data set allowed comparisons (Fig. 3). The correlation was highly significant both for daily mean temperature ($F_{1,464}$=356.75, p<0.0001) and daily average temperature at noon (mean of values measured between 11:00 and 13:00) ($F_{1,462}$=413.9, p<0.0001).

The influence of air temperature on lake surface temperature did not differ between lakes regardless of whether daily mean temperature ($F_{3,464}$=1.78, p=0.149) or daily temperature at noon ($F_{3,462}$=1.72, p=0.163) were considered.

Ice cover lasted in all lakes from mid-November to the end of May (Fig. 1). In order to compare the influence of the three categories of parameters (i.e. geographic, morphometric, and climatic) on the surface water temperature of the lakes, we considered only the months when lake surface temperature is likely to be under the influence of all three categories, namely the ice-free period, when monthly mean surface water temperature exceeds 0°C (June to October). The influence of the above-mentioned parameters on lake surface temperature was investigated in four lakes: Caprelor, Porții, Ştirbu and Negru. Morphometric parameters were found to have a stronger influence (table 2) on lake surface temperature than altitude, probably due to the rather small differences in altitude between the lakes.

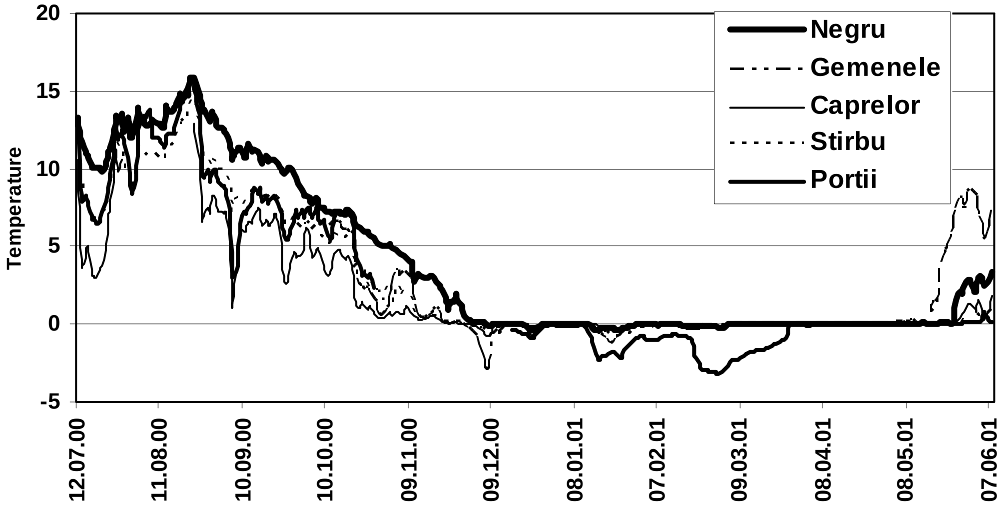

Fig. 1 Surface water temperature measured at noon during July 2000-June 2001.

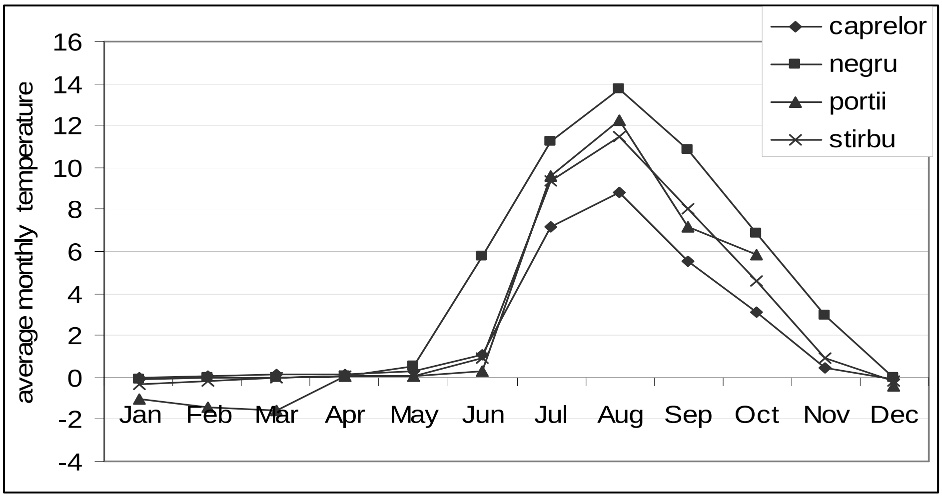

Figure 2. Changes in average monthly surface water temperatures (2001) in four lakes.

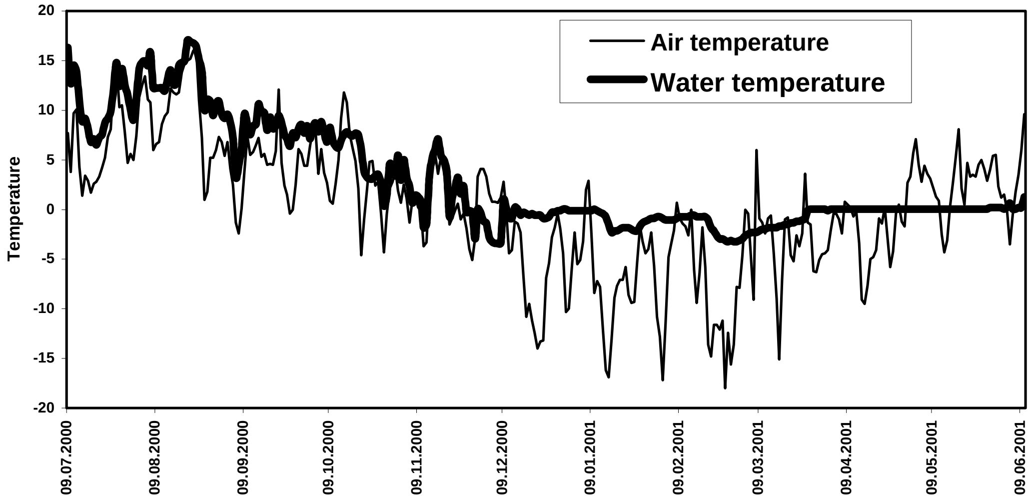

Figure 3. Air and surface water temperature at noon in Lake Portii during July 2000 - June 2001.

Table 2. Correlations between water surface temperature and morphometric parameters in four lakes

Surface water temperature correlation with:	R^2	$F_{1,2}$	p
surface	0.86	12.32	0.073
maximum width	0.95	38.84	0.025
maximum depth	0.92	22.9	0.041
average depth	0.79	7.364	0.113
relative depth	0.88	14.33	0.063
volume	0.83	9.941	0.088

Diurnal surface water temperature variability (expressed as the standard deviation of surface water temperature measurements during a day) was directly correlated with the daily mean surface water temperature (i.e. the amplitude of temperature variation is larger at higher surface temperatures, Fig. 4). This can be explained by linear regression, the slope of the linear regression being characteristic for each of the lakes studied. The same correlation was obtained when using daily mean air temperature instead of daily mean surface water temperature. This is explained by the highly significant correlation between air temperature and surface water temperature.

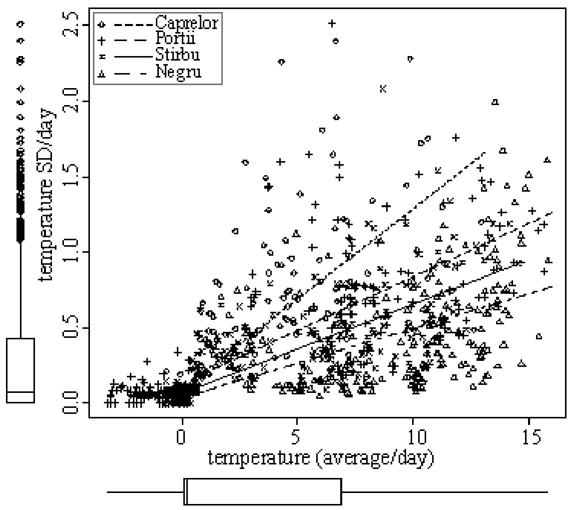

Fig. 4. Correlation between average daily surface water temperature and daily surface water temperature variability (estimated as the standard deviation).

We tested the relationship between these linear regression slopes and the following parameters: altitude, lake area, length, maximum width, volume, perimeter, maximum depth, average depth, relative depth and average depth/maximum depth ratio. We found inverse correlations between the linear regression slopes and lake surface (R^2=0.42), maximum depth (R^2=0.57), maximum width (R^2=0.66), volume depth (R^2=0.37), average depth (R^2=0.53) and relative depth (R^2=0.86). Because of the small sample size, only the correlation with relative depth is statistically significant (t=-4.457, $p<0.05$).

The depth temperature profile of Lake Negru (fig. 5) proves that the lake is dimictic, with two mixing periods, that affect the entire water mass.

Irregular mixing during summer occurs only in the upper 5 m, while the temperature profile below 5 m is rather constant throughout the summer. The lake is thermally stratified for only three months during the summer. During winter the formation of surface ice eliminates wind action and reduces heat exchange, so that vertical transport is severely reduced. Along the water column of Lake Negru conductivity does not vary during the entire year, but pH and dissolved oxygen vary greatly during the thermal stratification period, depending on photosynthesis and respiration.

DISCUSSION

According to Hutchinson (1957), lakes can be classified into six categories, based on four criteria: presence of mixing, depth of mixing, number of mixing events per year and water temperature at the time of mixing. These categories can be predicted from the altitude and latitude of the lake (Wetzel, 2001). Based on these criteria, all five lakes in our study are predicted to be cold monomictic (frozen over the cold season, ice free during summer but never warming above 4°C). As showed by fig.1 this is not the case of any of the five lakes in the present study. The prediction error comes from the fact that the Hutchinson-Loffler prediction model modified by Wetzel (2001) does not take into account the morphometry of the lakes.

The revised classification of Lewis (1983) identifies two classes of lakes, each containing eight lake types. A lake's type can be predicted from its altitude, latitude and maximum depth. Based on this prediction model, all the five lakes considered should be holomictic (the mixing involves the entire lake) and belong to one of two types: Lakes Caprelor, Portii, Gemenele and Ştirbu are predicted to be cold continuous polimictic, while Lake Negru is predicted to be cold discontinuous polimictic. Both types are frozen during winter, ice-free during summer, and reach temperatures over 4°C. The difference lies in the fact that cold continuous polimictic lakes stratify during summer for at most a day while cold discontinuous polimictic lakes stratify for several days to weeks, mixing irregularly. While this prediction is correct in the case of shallower lakes like Caprelor and Porţii, in the case of deeper lakes it has to be validated by profile measurements. The temperature profile data showed the limits of such predictions of the thermal and mixing behaviour of alpine lakes even when considering morphometric parameters. Since thermal stratification and mixing in alpine lakes can be strongly influenced by the particular local conditions given by the size and the shape of the lake and of the catchment, the exposition, the predominant wind direction and other internal and external factors, any prediction has to be validated with field data, at least for different classes of lakes (i.e. deep versus shallow).

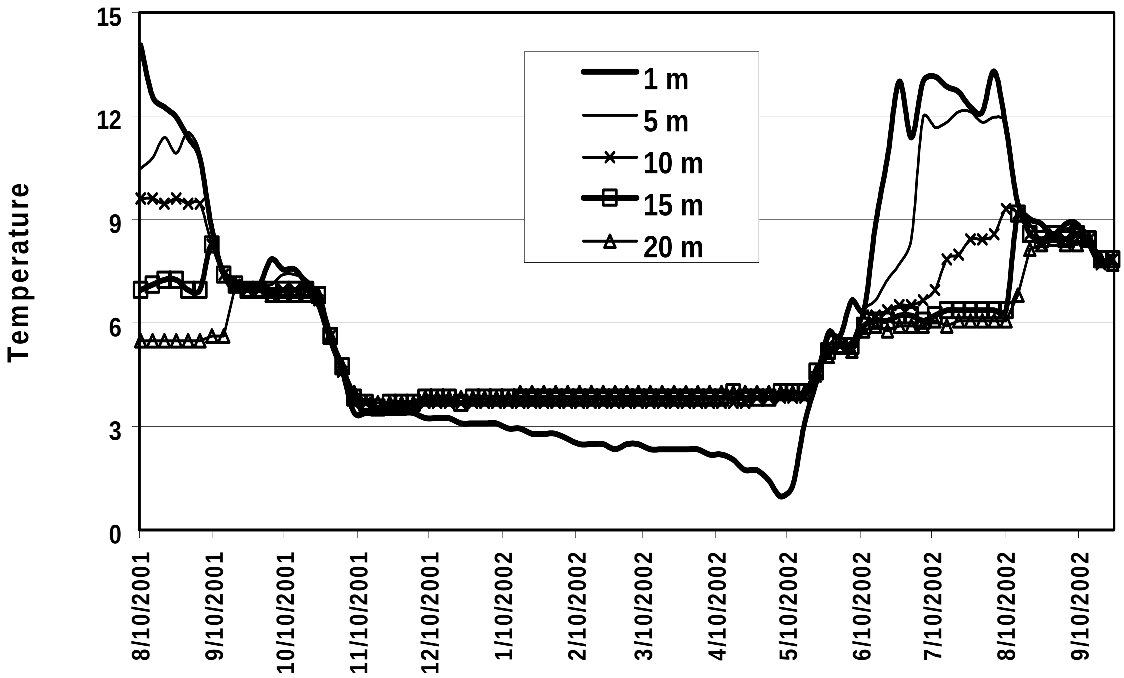

Fig. 5. Thermal stratification in Lake Negru during August 2001- September 2002.

The surface water temperature of Lake Negru shows less high-frequency variability than that of the other lakes, possibly because of the higher water volume and thermal resilience. In the case of Lake Negru spring mixing lasts only for about two weeks, while autumn mixing is longer, lasting for almost four weeks. Overall, only for about six weeks/year of mixing oxygen uptake, nutrient inflow, water exchange occurs. There is more variability in the timing of spring overturn than in the timing of autumn overturn, probably because of the variability in winter ice cover characteristics that influence spring mixing (Ventura et al., 2000). Understanding the dynamics of ice cover is extremely important since the primary climate effect on the aquatic biota of high-altitude lakes may be mediated by the timing of this parameter (Livingstone et al., 1999).

There is a good correlation between air temperature and surface water temperature between the two freezing seasons. Surface water temperature varies within a narrow range in Lake Negru, which has the highest water volume among the lakes studied. Lake surface water temperatures decrease approximately linearly with increasing altitude at a rate slightly greater than the surface air temperature lapse rate. The altitude effect was found to decrease surface water temperature with $0.5\text{-}0.7^0$K per 100 m in the Swiss Alps (Livingstone et al., 1999). We might thus predict differences of $1.5\text{-}2.1^0$K between the lowest (Lake Gemenele, 1920m) and the highest (Lake Porții, 2260m).

Lake surface water temperature proves to be an important physical parameter in understanding high altitude aquatic systems and their dependence on external driving forces. It is also a simple and precise parameter to measure which provides useful information. It is difficult to understand why long-term series of lake surface water temperature data are available for only one alpine lake in Romania (Lake Bâlea, Făgăraş Mountains, cited by Pişotă, 1971). We strongly recommend that temperature data loggers be deployed in selected alpine lakes on a regular basis. The data obtained could add to the traditional meteorological data routinely measured and provide useful insights in understanding the climate variability and a basis for long-term ecological studies.

REZUMAT

Măsurarea temperaturii apei la suprafață în cinci lacuri alpine din Parcul Național Retezat în intervalul 2000-2002 a evidențiat o similaritate mare între lacurile studiate. Temperatura apei la suprafață în Tăul Negru variază într-un domeniu mai mic de amplitudine, probabil datorită volumului mare de apă şi rezilienței termice. Temperatura apei a fost corelată semnificativ cu temperatura aerului în afara perioadei de îngheț. Altitudinea nu influențează mult dinamica temperaturii, parametrii morfometrici având o influență mai mare. Dintre aceştia, adâncimea relativă este cel mai bine corelată cu temperatura. Lacurile au fost acoperite de gheață mai mult de şase luni (noiembrie-mai). Profilul termic pe adâncime în Tăul Negru a evidențiat două perioade de amestecare, una primăvara (cu durata de două săptămâni) şi una toamna (cu durata de patru săptămâni). Lacul se dovedeşte a fi dimictic, amestecarea afectând întregul volum al lacului. Pe toată durata verii lacul este stratificat termic. Studiul a evidențiat importanța temperaturii apei la suprafață ce furnizează date utile pentru înțelegerea factorilor de comandă şi poate completa seriile de date meteorologice colectate în mod curent.

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