Biologia, Bratislava, **61**/Suppl. 18: S77—S90, 2006

Water temperatures and ice cover in lakes of the Tatra Mountains

Ferdinand Šporka[1], David M. Livingstone[2], Evžen Stuchlík[3], Jan Turek[4] & Joanna Galas[5]

[1] *Department of Hydrobiology, Institute of Zoology, Slovak Academy of Sciences, Dúbravská cesta 9, SK–84506 Bratislava, Slovakia; e-mail: ferdinand.sporka@savba.sk*
[2] *Water Resources Department, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Überlandstrasse 133, CH–8600 Dübendorf, Switzerland*
[3] *Hydrobiological Station, Institute for Enviromental Studies, Charles University in Prague, P.O. Box 47, CZ–38801 Blatná, Czech Republic*
[4] *Hydrobiological Institute, Academy of Sciences of the Czech Republic, Na Sádkách 7, CZ–37005 České Budějovice, Czech Republic*
[5] *Institute of Nature Conservation, Polish Academy of Sciences, av. Mickiewicza 33, PL–31120 Krakow, Poland*

Abstract: In 2000 and 2001, miniature thermistors with integrated data loggers were employed to measure lake surface water temperatures (LSWTs) and temperature profiles in high-altitude mountain lakes lying between 1580 and 2145 m a.s.l. on both the Slovak and Polish sides of the Tatra Mountains. This allowed the annual cycle of water temperatures and ice cover in these lakes to be described quantitatively, and their dependence on lake altitude above sea level to be investigated. LSWTs in the Tatra Mountains are found to decrease approximately linearly with increasing altitude from late spring to autumn. LSWT in summer can be modelled well in terms of exponentially smoothed ambient air temperature. Although the timing of ice-off is dependent on altitude, the timing of ice-on is not; the dependence of the duration of ice cover on altitude is therefore wholly due to the altitudinal dependence of the timing of ice-off. The temperature profile measurements allow quantitative characterization of summer and winter stagnation, and spring and autumn turnover.

Key words: High-altitude mountain lakes, surface water temperatures, temperature profiles, timing of ice-off, Slovakia, Poland.

Introduction

Lake water temperatures are important not only for individual organisms but also for entire lake ecosystems (e.g., Regier et al., 1990). In high-altitude lakes, in which temperatures generally tend to be very low during much of the annual cycle and in which the ice-free period is short, the biological significance of water temperature as an environmental factor is particularly great.

The heat balance of a lake is determined predominantly by the absorption of short-wave radiation from the sun and long-wave radiation from the atmosphere, by the emission of long-wave radiation from the lake surface, by the exchange of sensible and latent heat with the air, and (less importantly) by heat gains and losses due to throughflow. Air temperature is involved in several of these processes (Edinger et al., 1968; Sweers, 1976), so that lake surface water temperature (LSWT) often follows air temperature quite closely, allowing LSWT to be modelled well empirically as a function of air temperature alone (e.g., McCombie, 1959; Webb, 1974; Shuter et al., 1983; Lister et al., 1998; Livingstone & Lotter, 1998; Kettle et al., 2004). In mountain areas in summer, temperature inversions are rare and the ambient air temperature generally decreases approximately linearly with altitude (Tabony, 1985; Barry, 1992). The surface water temperatures of mountain lakes therefore also tend to exhibit an approximately linear decrease with altitude (Livingstone et al., 1999), although in early summer, lakes at very high altitudes can constitute an exception to this (Livingstone et al., 2005b).

In the Tatra Mountains (Mts) of Slovakia and Poland, the monitoring of lake water temperatures has a long tradition. Pacl & Wit-Joźwikowa (1974) have summarised all data on the temperature regimes of the lakes of the Tatra Mts known up to the early 1970s. In addition, Łajczak (1982) compiled the early data available on the surface water temperature of two lakes located in the Tatra Mts: Morskie Oko and Štrbské pleso. However, the early temperature data consist mainly of spot measurements carried out manually. Recently, the quasi-continuous monitoring of water temperature in high-altitude lakes has been made possible by the employment of small, combined thermistors and data loggers that are able not only to measure water temperatures at a high sampling rate, but also to

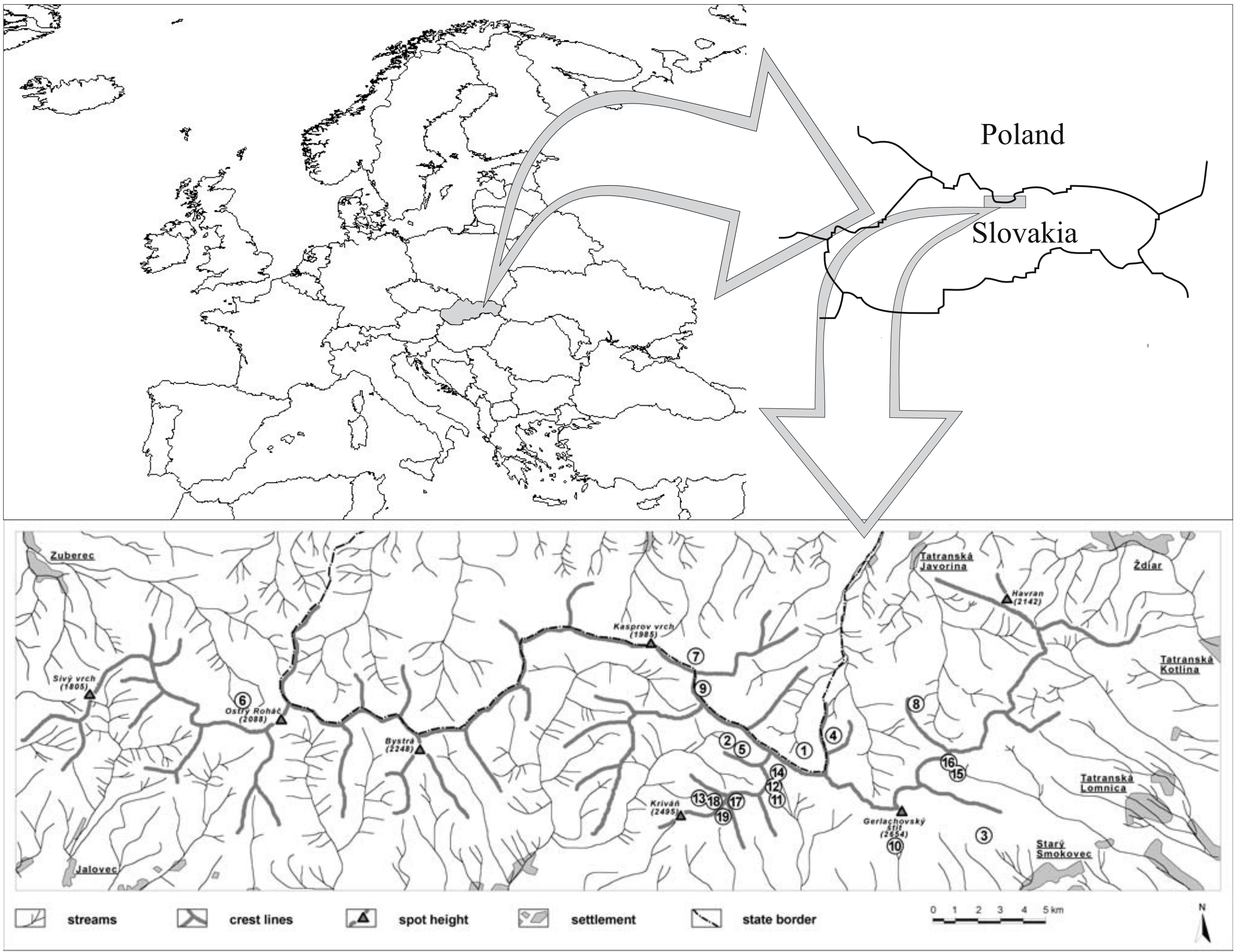

Fig. 1. Location of the Tatra Mts (upper panel) and study lakes (lower panel). See Table 1 for lake names.

record automatically the temperatures measured. Their small size, large data storage capacity, low electricity consumption and physical robustness allow these thermistors to be deployed even under the harsh conditions prevailing in remote alpine lakes. The availability of these combined thermistors and data loggers allowed, for the first time, the quasi-continuous monitoring of water temperatures in the lakes of the Tatra Mts. These measurements were conducted within the framework of the EU project "EMERGE", one aspect of which was concerned with obtaining information on lake water temperatures in high-mountain areas throughout Europe.

Material and methods

Miniature thermistors with integrated data loggers (8-TR Minilogs, Vemco Ltd., Shad Bay, Nova Scotia, Canada) were employed to measure LSWTs in 19 mountain lakes located between 1580 m a.s.l. and 2145 m a.s.l. on the Slovak and Polish sides of the Tatra Mts (Fig. 1, Tab. 1), and to measure water temperature profiles in four of these lakes. Sampling began in some lakes in June 2000 and ended in October 2001, but in most lakes sampling extended over the 12-month period from October 2000 to September 2001. The sampling interval was generally one hour.

For measuring LSWTs, each thermistor was inserted into the underside of a float consisting of a rectangular styrofoam block (13 cm × 13 cm × 5 cm) in such a way that the thermistor's sensor was approximately 5 cm under the lake surface. Water temperatures measured at this depth in Swiss mountain lakes have been shown to represent well the temperature of the epilimnion (Livingstone et al., 1999). In addition to acting as floats, the styrofoam blocks shaded the temperature sensors from direct solar radiation. The thermistors were anchored near the lake outflow to ensure a continual flow of epilimnetic water around them and to avoid any local littoral effects. In small lakes with no lake outflow, the thermistors were installed in the deep central region, far enough from shore to minimise disturbance and to make unauthorised retrieval unlikely. Despite these precautions, in three of the Slovak lakes and four of the Polish lakes some disturbance did occur, with storm events causing physical reversal of the styrofoam blocks. However, the resulting spurious measurements were easily identifiable and were eliminated from the data set. When the thermistors were frozen into the ice in winter, temperatures below 0 °C were recorded. In such cases, the LSWT was defined as the surface liquid water temperature, and set to 0 °C. For

Table 1. Information on the 19 lakes in the Tatra Mts, in order of increasing altitude.

No.	Lake	Location	Altitude (m a.s.l.)	Maximum depth (m)	Surface area (km^2)	Maximum daily mean LSWT in 2001 (°C)	Date of maximum daily mean LSWT
1	Czarny Staw pod Rysami	49°11′19.7″ N, 20°04′40.1″ E	1580	76.4	0.205	–	–
2	Nižné Temnosmrečinské pleso	49°11′34.4″ N, 20°01′50.2″ E	1677	38.1	0.117	14.9	9 August
3	Slavkovské pleso	49°09′09.0″ N, 20°11′04.9″ E	1676	2.5	0.001	17.8	18 August
4	Vyšné Žabie bielovodské pleso	49°11′39.1″ N, 20°05′39.5″ E	1699	24.8	0.095	14.1	18 August
5	Vyšné Temnosmrečinské pleso	49°11′20.7″ N, 20°02′22.2″ E	1725	20.0	0.056	12.9	18 August
6	Štvrté Roháčske pleso	49°12′20.5″ N, 19°37′37.2″ E	1719	8.2	0.014	15.5	9 August
7	Długi Staw Gąsienicowy	49°13′38.3″ N, 20°00′38.5″ E	1784	10.6	0.016	–	–
8	Zelené javorové pleso	49°12′22.0″ N, 20°08′34.4″ E	1815	9.1	0.007	13.8	10 August
9	Zadni Staw Gąsienicowy	49°13′31.8″ N, 20°00′42.8″ E	1852	8.0	0.005	–	–
10	Batizovské pleso	49°09′08.3″ N, 20°07′53.4″ E	1884	10.5	0.035	11.9	18 August
11	Vyšné Satanie plesko	49°10′12.7″ N, 20°03′45.7″ E	1894	3.5	0.002	17.0	18 August
12	Malé Hincovo pleso	49°10′26.4″ N, 20°03′30.6″ E	1921	6.4	0.022	13.9	19 August
13	Nižné Terianske pleso	49°10′11.3″ N, 20°00′51.5″ E	1940	47.3	0.056	11.8	18 August
14	Veľké Hincovo pleso	49°10′46.9″ N, 20°03′38.2″ E	1945	54.0	0.201	–	–
15	Starolesnianske pleso	49°10′48.0″ N, 20°10′04.1″ E	1988	4.2	0.007	–	–
16	Ľadové pleso	49°11′02.8″ N, 20°09′46.4″ E	2057	18.0	0.017	12.8*	17 August*
17	Okrúhle pleso	49°10′14.5″ N, 20°02′10.7″ E	2105	10.2	0.007	10.2*	21 August*
18	Vyšné Terianske pleso	49°10′04.8″ N, 20°01′18.5″ E	2124	4.3	0.006	13.3	16 August
19	Vyšné Wahlenbergovo pleso	49°09′51.1″ N, 20°01′37.6″ E	2157	20.6	0.052	11.6	19 August

Explanation: The numbers refer to the lake locations shown in Fig. 1. Dashes denote missing data. Asterisks denote maximum daily mean LSWT measurements which may lie below the real maximum daily mean LSWT because some data were not recorded during part of August 2001. Data on altitude, maximum depth and surface area are from GREGOR & PACL (2005).

our purposes, we further assumed that the calendar date on which the LSWT decreased to 0 °C was the date on which the lake froze over (ice-on), and, analogously, that the calendar date on which the LSWT increased above 0 °C was the date on which the lake ice thawed (ice-off).

Water temperature profiles were measured in Nižné Terianske pleso, Ľadové pleso (in Veľká Studená dolina valley), Starolesnianske pleso and Długi Staw Gąsienicowy (Lakes 13, 16, 15 and 7, respectively, in Fig. 1) using thermistor chains that were constructed by attaching thermistors to a steel cable 2 mm in diameter. The cable was fastened to an anchored buoy consisting of a 5-litre polystyrene bottle filled with styrofoam, and was weighted with a 1-kg lead weight. The thermistor chains were anchored at the deepest points of the four lakes in summer and autumn 2000. Deployment depths were: 0.05, 1.0, 2.5, 5.0, 7.5, 10.0, 15.0, 20.0, 30.0 and 43.0 m in Nižné Terianske pleso; 0.05, 1.0, 3.0, 5.0, 7.0, 10.0 and 16.0 in Ľadové pleso; 0.05, 1.0 and 3.0 in Starolesnianske pleso; and 0.05, 1.0, 3.0 and 6.0 m in Długi Staw Gąsienicowy. Several problems were encountered while measuring the temperature profiles. The thermistor chain in Nižné Terianske pleso was installed on 30 June 2000 and removed on 6 October 2001. However, because of damage to the thermistors, measurements in this lake were interrupted from 26 October 2000 to 14 March 2001. The thermistor chain in Ľadové pleso was installed on 30 September 2000 and removed on 29 September 2001, but the thermistor at 16 m depth was lost on 7 December 2000. In Starolesnianske pleso, the thermistor chain was installed on 1 October 2000, and measurements ceased on on 8 June 2001 because of thermistor loss. In Długi Staw Gąsienicowy, the thermistor chain was installed on 26 September 2000, but the surface thermistor ceased to function correctly in November 2000. Although the measured values were able to be corrected, the measurements ceased entirely on 11 June 2001 due to loss of the chain. Extreme fluctuations in lake level (more than 5 m) during the measuring period were a source of severe problems in this lake. Simultaneously with water temperature, air temperature was measured quasi-continuously at automatic weather stations (AWS) located close to three of the lakes (Nižné Terianske pleso, Ľadové pleso and Długi Staw Gąsienicowy).

To determine how representative the sampling period was with respect to ambient air temperature, the monthly mean air temperatures in the Tatra Mts during this period were compared with the long-term (10-yr) monthly means from 1992–2001. The monthly mean air temperatures are based on data measured at the Skalnaté pleso meteorological station, located at 49°11′24″ N, 20°14′00″ E at an altitude of 1778 m a.s.l. (OSTROŽLÍK & JANÍČKOVIČOVÁ, 1992–2001). Of the 17 months during which sampling was conducted (June 2000 – October 2001), only one, July 2000, could be considered climatically extreme, with a monthly mean air temperature (7.9 °C) that was 2.3 standard deviations below the long-term July mean (10.2 °C). For the other 16 months, the measured monthly mean air temperature always lay within 2 standard deviations of the respective long-term monthly mean, and for 10 of these it lay within 1 standard deviation of the respective long-term mean. The months in which the air temperature differed by more than 1 standard deviation from the long-term mean were mostly warmer than average (October – December 2000, March 2001, October 2001), but two were colder than average (July 2000, June 2001).

Results and discussion

Lake surface water temperature

As in other mountain regions (LIVINGSTONE et al., 1999, 2005b), fluctuations in LSWT in the Tatra Mts were generally similar in all lakes monitored (Fig. 2),

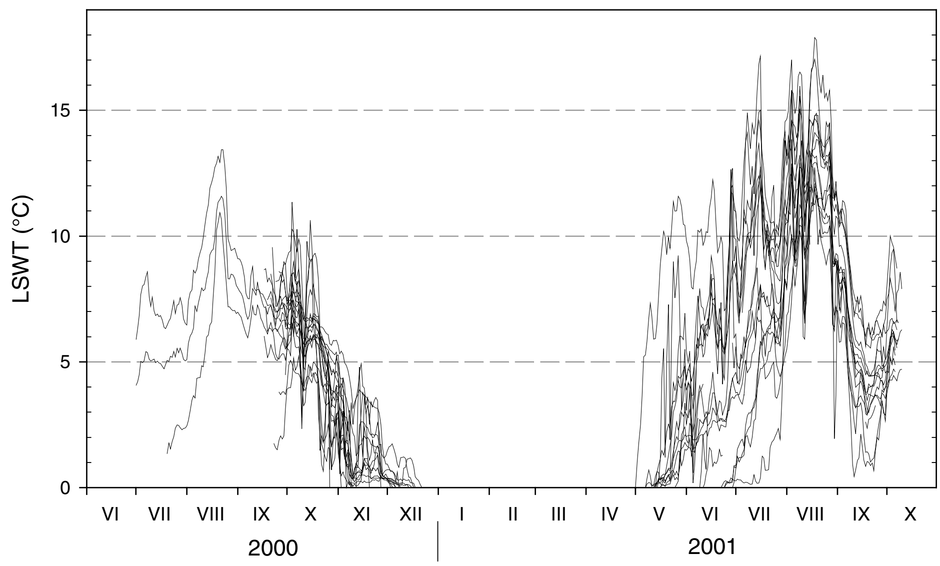

Fig. 2. Daily mean water temperatures measured at 0.05 m depth in 19 lakes in the Tatra Mts (Tab. 1) from July 2000 to October 2001.

indicating a coherent response to regional climatic forcing within the region. The largest absolute differences in LSWT between individual lakes were recorded from May – July 2001, with maximum differences occurring in mid-July. The large temperature differences of up to 17.0 ℃ that occurred at this time were a result of altitudinally dependent differences in the timing of ice-off among the lakes (see below). While the LSWT of relatively low-lying Slavkovské pleso (1676 m a.s.l.) had reached 17.0 ℃ by mid-July, many of the highest lakes (e.g., Okrúhle pleso, 2105 m a.s.l.; Vyšné Terianske pleso, 2124 m a.s.l.; Vyšné Wahlenbergovo pleso, 2145 m a.s.l.) were still ice-covered at this time.

In both 2000 and 2001, the highest recorded LSWTs occurred in August. The maximum daily mean LSWTs in 2001, along with the dates of their occurrence, are listed in Table 1. In 2001, the difference between the maximum measured daily mean LSWT of the warmest lake (Slavkovské pleso, 1676 m a.s.l., 17.8 ℃) and the coldest lake (Vyšné Wahlenbergovo pleso, 2145 m a.s.l., 11.6 ℃) was 6.2 ℃. In the majority of the lakes monitored, the LSWTs recorded by us in 2000 and 2001 were considerably higher than those recorded earlier by PACL & WIT-JOŹWIKOWA (1974). The largest differences were found in Okrúhle pleso and Ľadové pleso, which were classified by PACL & WIT-JOŹWIKOWA (1974) as having maximum LSWTs between 5.0 ℃ and 6.0 ℃. In contrast to their data, we recorded temperatures as high as 10.2 ℃ and 12.8 ℃, respectively, in these lakes (Tab. 1). Since some data from these lakes are missing during part of August 2001, it is likely that the actual maximum daily mean LSWTs were even higher. We explain these differences (which are too large to be caused by climate change) primarily as a result of our quasi-continuous sampling, which is more likely to record the true maximum daily mean LSWT than are the earlier spot measurements. However, differences in the sampling location and in the time-span during which the measurements were made might also contribute to the discrepancy.

The decrease in monthly mean LSWT with altitude above sea level is illustrated in Fig. 3 for the lakes of the Tatra Mts from October 2000 to September 2001. From December 2000 to April 2001, monthly mean LSWTs were at or close to zero in all lakes above ~1800 m a.s.l. (as most of these lakes were ice-covered at that time). Our data indicate that LSWT decreases approximately linearly with increasing altitude from June to November; this also applies to May if the anomalously high value of LSWT for Slavkovské pleso (see below) is disregarded. To confirm this, linear regressions of LSWT on altitude were computed for the months of October – November 2000 and May – September 2001 (Fig. 3, Tab. 2). The linear decrease in LSWT is statistically significant on at least the $P < 0.1$ level in all months from May (disregarding the Slavkovské pleso outlier) to November, allowing an LSWT lapse rate (defined as the rate of decrease of LSWT with increasing altitude) to be computed (Tab. 2). Based on Fig. 3 and Table 2, the seasonal processes of thawing, warming, and cooling as they occur at various altitudes can be followed quite well. The lower lakes generally thawed in May 2001 and their LSWTs increased rapidly during May and June 2001, while the highest lakes – those over ~2000 m a.s.l. – were still ice-covered. The LSWT lapse rate therefore increases rapidly during this time of year, attaining values well over 1.4 ℃ per 100 m in June 2001 and thus exceeding the adiabatic air temperature lapse rate for moist air, which is ~0.6 ℃ per 100 m (e.g., TABONY, 1985) by more than a factor of 2. During July 2001, all lakes were ice-free and the LSWTs increased at approximately the same rate regardless of altitude. Thus LSWT increased substantially at all altitudes in early summer (e.g., at 2000

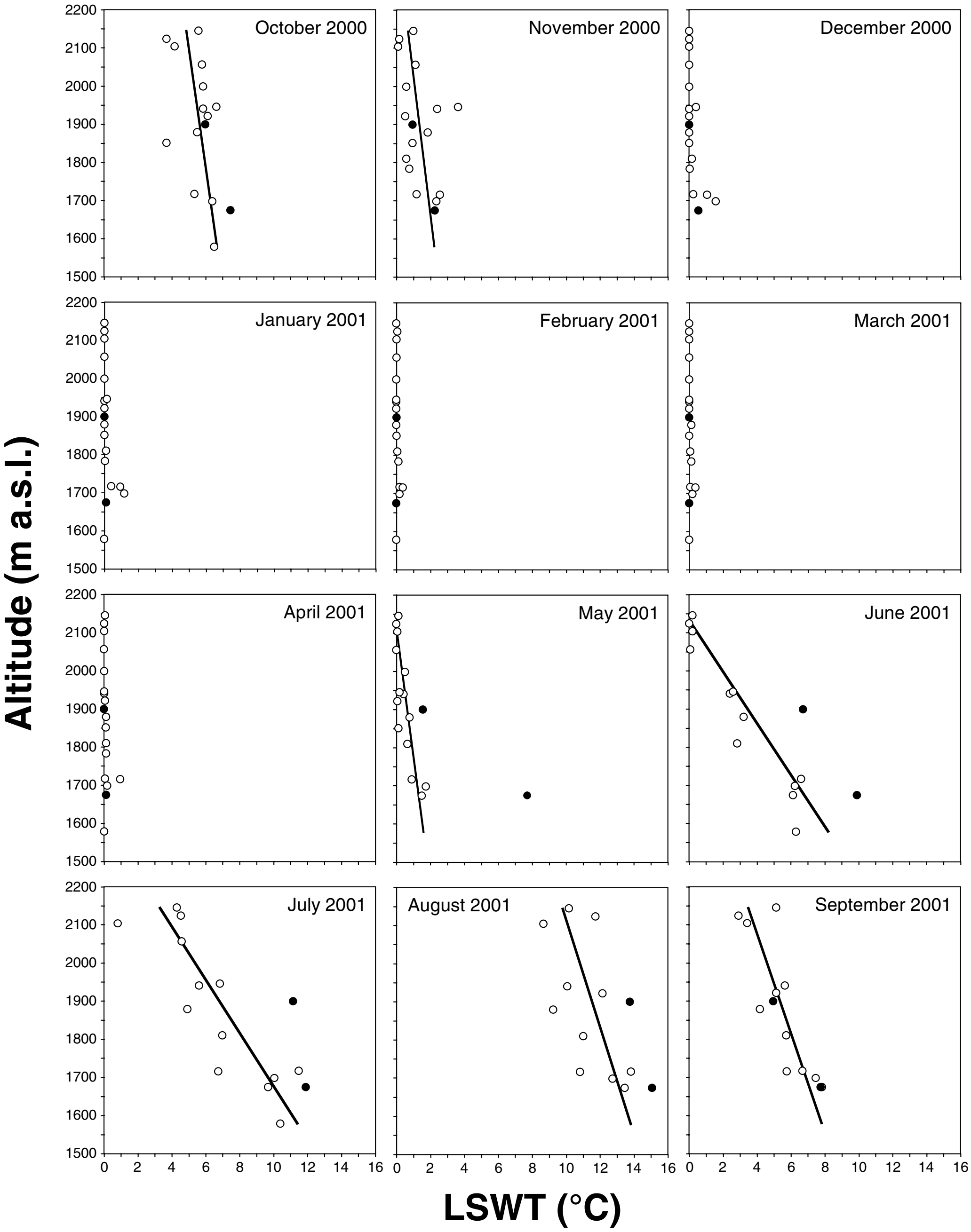

Fig. 3. The decrease in monthly mean lake surface water temperature (LSWT) with altitude in the lakes of the Tatra Mts from October 2000 to September 2001. Linear regressions of LSWT on altitude are illustrated for October–November 2000 and May–September 2001; the regression parameters are listed in Table 2. The two shallowest lakes (Vyšné Satanie pliesko at 1894 m a.s.l. and Slavkovské pleso at 1676 m a.s.l.) with anomalously high LSWTs during the warming phase in late spring and summer, are represented by black dots (see Tab. 1 for maximum lake depths). The extreme Slavkovské pleso outlier in May 2001 was not included in the computation of the regression line for this month.

m a.s.l., from 1.9 °C in June 2001 to 5.4 °C in July 2001), but the LSWT lapse rate remained essentially unchanged (Tab. 2). During August 2001, the lower lakes reached their peak summer surface temperature while LSWTs in the higher, colder lakes were still increasing. This led to a decline in the LSWT lapse rate to less than half the values found in June and July, while the 2000-m benchmark LSWT simultaneously increased to 10.8 °C. From August to September 2001, the LSWT lapse rate remained approximately constant, while the 2000-m benchmark LSWT fell substantially, implying that autumn cooling proceeds at a rate that is essentially independent of altitude. These results agree well with those of Livingstone et al. (1999, 2005b) for Swiss Alpine lakes in summer, but in contrast to Livingstone et al. (2005b), no change in the gradient of the relationship between LSWT and altitude is apparent at very high altitudes. In July 2001, the LSWT

Table 2. Results of linear regressions of lake surface water temperature (LSWT) on altitude for the lakes of the Tatra Mts, as illustrated in Fig. 3.

Month	Number of lakes	LSWT lapse rate (℃ km^{-1})	2000-m intercept (℃)	r^2 (%)	Significance level
October 2000	15	3.2	5.3	26.1	$P < 0.1$
November 2000	17	2.8	1.1	18.3	$P < 0.1$
May 2001	15	3.0	0.3	56.7	$P < 0.01$
June 2001	14	14.7	1.9	76.7	$P < 0.001$
July 2001	15	14.3	5.4	65.0	$P < 0.001$
August 2001	13	7.0	10.8	38.4	$P < 0.05$
September 2001	13	7.6	4.6	71.8	$P < 0.001$

Explanation: The LSWT lapse rate is the rate of decrease of LSWT with increasing altitude and the 2000-m intercept is the estimated LSWT at 2000 m a.s.l. The coefficient of determination (r^2) gives the proportion of variance of the LSWT explained by lake altitude.

lapse rate in the Tatra Mts (1.43℃ per 100 m) is approximately double the LSWT lapse rate found in July 2000 by Livingstone et al. (2005b) for Swiss lakes < 2000 m a.s.l. (0.71℃ per 100 m), but is only slightly greater than that found for Swiss lakes > 2000 m a.s.l. (1.26℃ per 100 m).

The LSWT of some lakes behaves anomalously in some months. This is most obvious in the case of Slavkovské pleso, a shallow, dystrophic lake in which LSWT is often substantially higher than would be expected based on the altitudinal dependence of the other lakes (Fig. 3). This anomalously high LSWT is particularly evident in May 2001, when it was ∼6℃ higher than that of other lakes at the same altitude, but smaller anomalies are apparent in later months, e.g. ∼3℃ in June 2001. Slavkovské pleso is the second shallowest of the 19 lakes, with a maximum depth of only 2.9 m (Tab. 1). It is known that the absorption of solar energy by lake sediments tends to be greater in shallower lakes than in deeper lakes (Dale & Gillespie, 1977); also, the littoral sediments of bog lakes tend to be considerably warmer than the sediments beneath the open water (Likens & Johnson, 1969; Reif, 1969). Specifically for the Tatra Mts, Borowiak (2002) has described the important role played by bottom sediments in modifying lake temperature profiles. Thus the anomalously high values of LSWT, which are essentially confined to the warming phase of the lake in late spring and early summer, are likely to be partly a result of the comparative shallowness of the lake. If this is so, similar LSWT anomalies would be expected in the case of the shallowest lake, Vyšné Satanie pliesko, which has a maximum depth of only 1.5 m (Tab. 1). From Fig. 3, this is indeed seen to be the case, with LSWTs being 3–4℃ higher than expected during the warming phase of the lake in June and July 2001. In the case of Slavkovské pleso, the lake's setting – in a morphological depression facing south, surrounded by a dwarf pine stand that reduces the influence of the wind – is likely to contribute to the extremely high values of LSWT found. Thus, although altitude, acting via air temperature, is probably the most important geographical determinant of LSWT, other geographical factors also play an important role. Łajczak (1982) demonstrated the importance of a northern or southern exposure for LSWT in the lakes of the Tatra Mts, and Livingstone et al. (2005a) have shown for lakes in the Swiss Alps that the pattern of deviation from a linear altitudinal decrease displayed by LSWT remains approximately constant from month to month and year to year, suggesting that it is lake morphometry and geographical setting, and not differences in local meteorology, that determine the major deviations from linearity.

The availability of meteorological data from the three AWSs located close to Nižné Terianske pleso, Ľadové pleso and Długi Staw Gąsienicowy allowed us to compare the LSWT of these three lakes with ambient air temperature. Our results confirmed that air temperature exhibited a high degree of regional coherence in the Tatra Mts, and that LSWT was highly correlated with the regional air temperature during much of the open-water season. Fig. 4 illustrates the example of Nižné Terianske pleso, for which the longest overlapping air temperature and LSWT data are available. Using the approach described by Kettle et al. (2004) and Livingstone et al. (2005b), an exponential smoothing filter was applied to the daily mean air temperature as follows:

$$\mathrm{S}_i = (1-\alpha)\mathrm{S}_{i-1} + \alpha\mathrm{T}_i, \qquad (1)$$

where S_{i-1} and S_i are the smoothed daily mean air temperatures on days $i-1$ and i, respectively; T_i is the measured daily mean air temperature on day i; and α is an exponential smoothing coefficient lying between 0 and 1 (smoothing is weak when α is close to 1 and strong when α is close to 0). For each month separately, the optimum value of α was determined that minimises the root mean square error (RMSE) between the smoothed air temperature data and the LSWT data (Tab. 3). Simultaneous air temperature and LSWT data were available from Nižné Terianske pleso covering July – November 2000 and June – September 2001. The daily mean air temperature is illustrated in Figs 4A, B and a comparison of the LSWT with the smoothed air temperature data in Figs 4C, D. From Figs 4C, D it is clear that LSWT follows the smoothed air temperature extremely closely. However, the differences in the monthly optimum values obtained for α (Tab. 3) in-

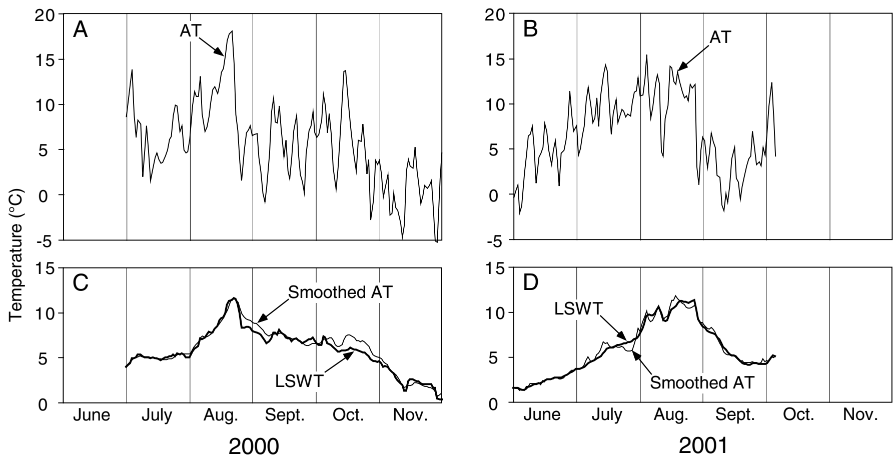

Fig. 4. The relationship between the lake surface water temperature (LSWT) of Nižné Terianske pleso and ambient air temperature (AT). A – daily mean air temperature, July – November 2000; B – daily mean air temperature, June – September 2000; C – LSWT and exponentially smoothed daily mean air temperature, July – November 2000; D – LSWT and exponentially smoothed daily mean air temperature, June – September 2000. Exponential smoothing (equation 1) was conducted for each month separately; the monthly smoothing coefficients and statistics describing the relationship of LSWT to the smoothed air temperature are listed in Table 3.

dicate that the empirical dependence of LSWT on air temperature is not constant; this is particularly evident in August 2001, when the relatively high value of α implies that LSWT followed air temperature much more rapidly, and thus exhibited more high-frequency variability, than in the other months (Fig. 4D, Tab. 3). In addition, LSWT deviated markedly from the smoothed air temperature during some periods (e.g., late August and early September 2000, or late October 2000), implying that processes such as wind mixing that depend on meteorological factors other than air temperature also played an important role in determining LSWT during these periods (cf. Kettle et al., 2004).

Ice cover

For the purposes of this study, the calendar date on which the LSWT decreased to 0 ℃ was taken to represent the date of ice-on, and the calendar data on which it increased above 0 ℃ was taken to represent the date of ice-off. Although this assumption might not always hold in an absolute sense, it does allow some general conclusions to be drawn about the altitudinal dependence of the timing of ice-on and ice-off in the Tatra Mts. Defined thus, the timing of ice-on in the study lakes occurred between 27 October 2000 (in Zelené javorové pleso) and 18 December 2000 (in Batizovské pleso), spanning 52 d. From Fig. 5A it is clear that the timing of ice-on exhibited no detectable dependence on altitude: a linear regression of the timing of ice-on on altitude above sea-level was not statistically significant ($P > 0.3$), and the proportion of variance in the timing of ice-on explained by altitude was extremely low ($r^2 = 1\%$). The timing of ice-off occurred between 2 May 2001 (in Slavkovské pleso) and 30 June 2001 (in Vyšné Terianske pleso), spanning 59 d; i.e., only a few days longer than the timing of ice-on. In contrast to ice-on, however, ice-off exhibited a strong dependence on altitude, with the highest lakes thawing much later than the lower lakes (Fig. 5B). The average date of ice-off for lakes lying between 1550 and 1700 m a.s.l. was 9 May, whereas that for lakes lying between 2100 and 2150 m a.s.l. was 26 June, i.e., 47 d later. A linear regression of the timing of ice-off on altitude was highly significant ($P < 0.001$), with a high proportion of explained variance ($r^2 = 61\%$). The rate of change of the timing of ice-off with altitude, given by the gradient of the regression, was 9.1 d per 100 m. The duration of ice cover varied from 136 d (in Slavkovské pleso) to 232 d (in both Okrúhle pleso and Vyšné Terianske pleso), and also ex-

Table 3. Monthly smoothing coefficients and statistics describing the relationship between the lake surface water temperature (LSWT) of Nižné Terianske pleso and the exponentially smoothed ambient air temperature during the parts of the open-water seasons of 2000 and 2001 for which simultaneous LSWT and air temperature data were available (Fig. 4).

Month	α	RMSE (℃)	r^2 (%)
July 2000	0.033	0.2	73.6
August 2000	0.072	0.5	91.6
September 2000	0.034	0.5	44.1
October 2000	0.065	0.9	55.0
November 2000	0.057	0.4	88.5
June 2001	0.028	0.1	97.0
July 2001	0.030	0.6	76.2
August 2001	0.123	0.5	73.4
September 2001	0.050	0.3	95.9

Explanation: For each month separately, the exponential smoothing coefficient (α), the root mean square error between LSWT and smoothed air temperature (RMSE) and the coefficient of determination between LSWT and smoothed air temperature (r^2) are tabulated. Smoothing was performed according to equation 1.

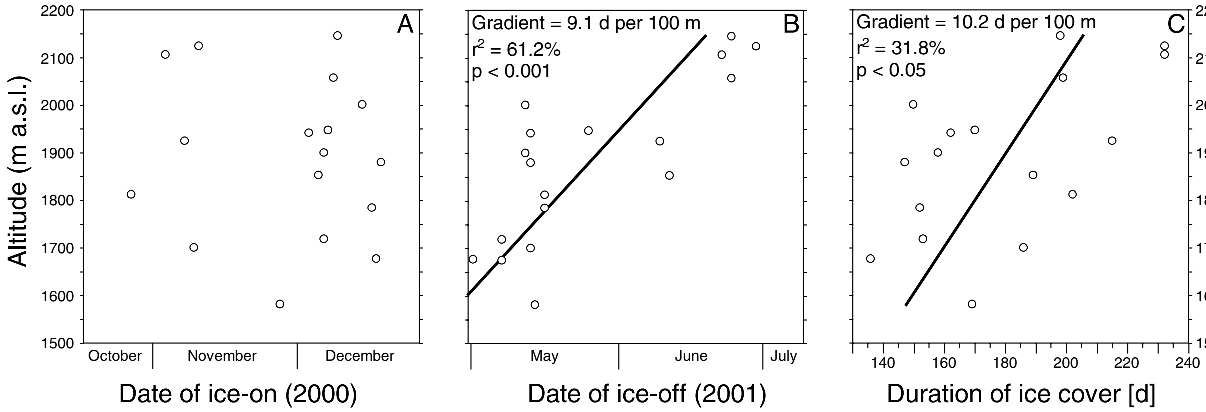

Fig. 5. The altitudinal dependence of the timing of ice-on in 2000 (A), the timing of ice-off in 2001 (B) and the resulting duration of ice cover for the lakes of the Tatra Mts (C). Linear regressions of the timing of ice-off and the duration of ice cover are also illustrated, and the relevant gradients, coefficients of determination (r^2) and significance levels (P) of the regressions are given.

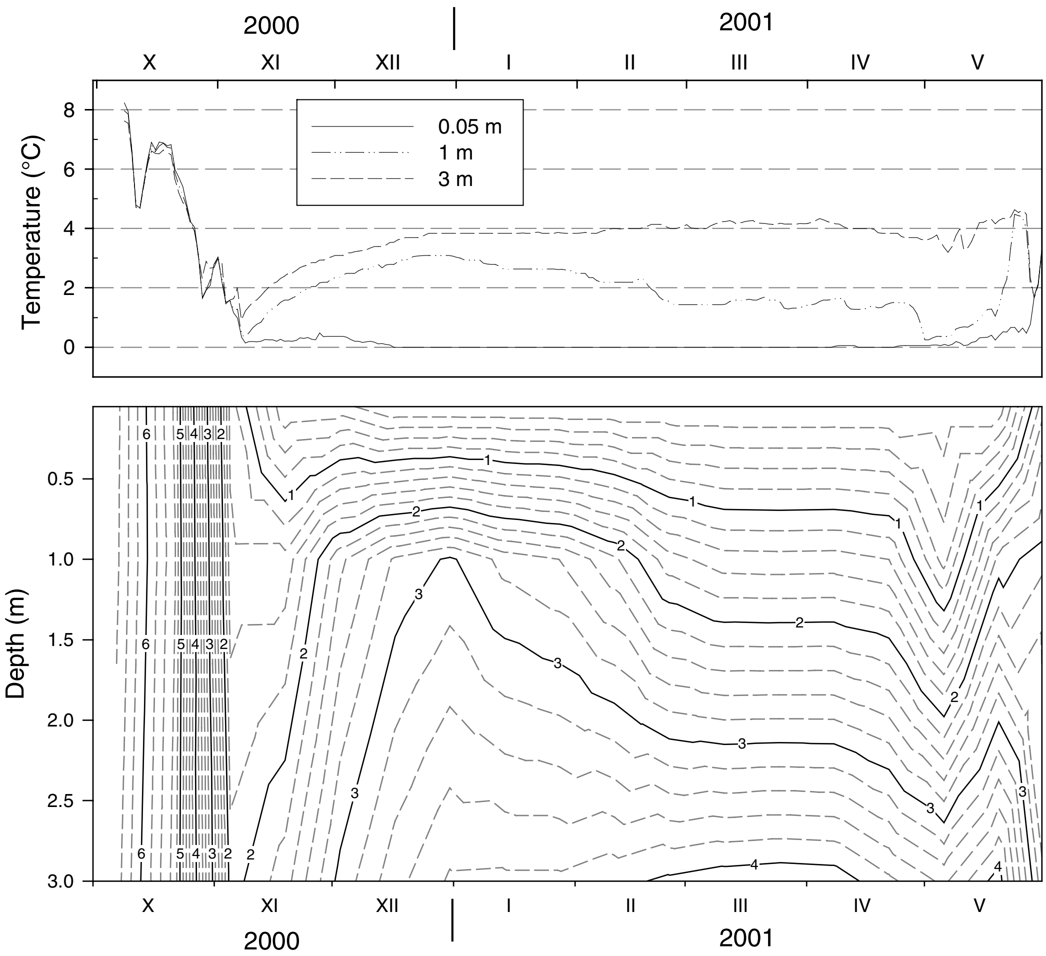

Fig. 6. Daily mean water temperature profiles in Starolesnianske pleso in 2000–2001, shown in terms of the temperatures at individual sampling depths (upper panel) and as a contour plot (lower panel). The contour plot is based on 14-day means, and the contours are labelled in °C.

hibited a significant ($P < 0.02$) linear dependence on altitude, at a rate of 10.2 d per 100 m, with 32% variance explained (Fig. 5C). Therefore, as the timing of ice-on is essentially independent of altitude, the altitudinal dependence exhibited by the duration of ice cover is due almost completely to the altitudinal dependence of the timing of ice-off in late spring and early summer.

The high degree of variability in the timing of ice-on can be assumed to result from differences in individual lake morphometry, lake setting (which governs

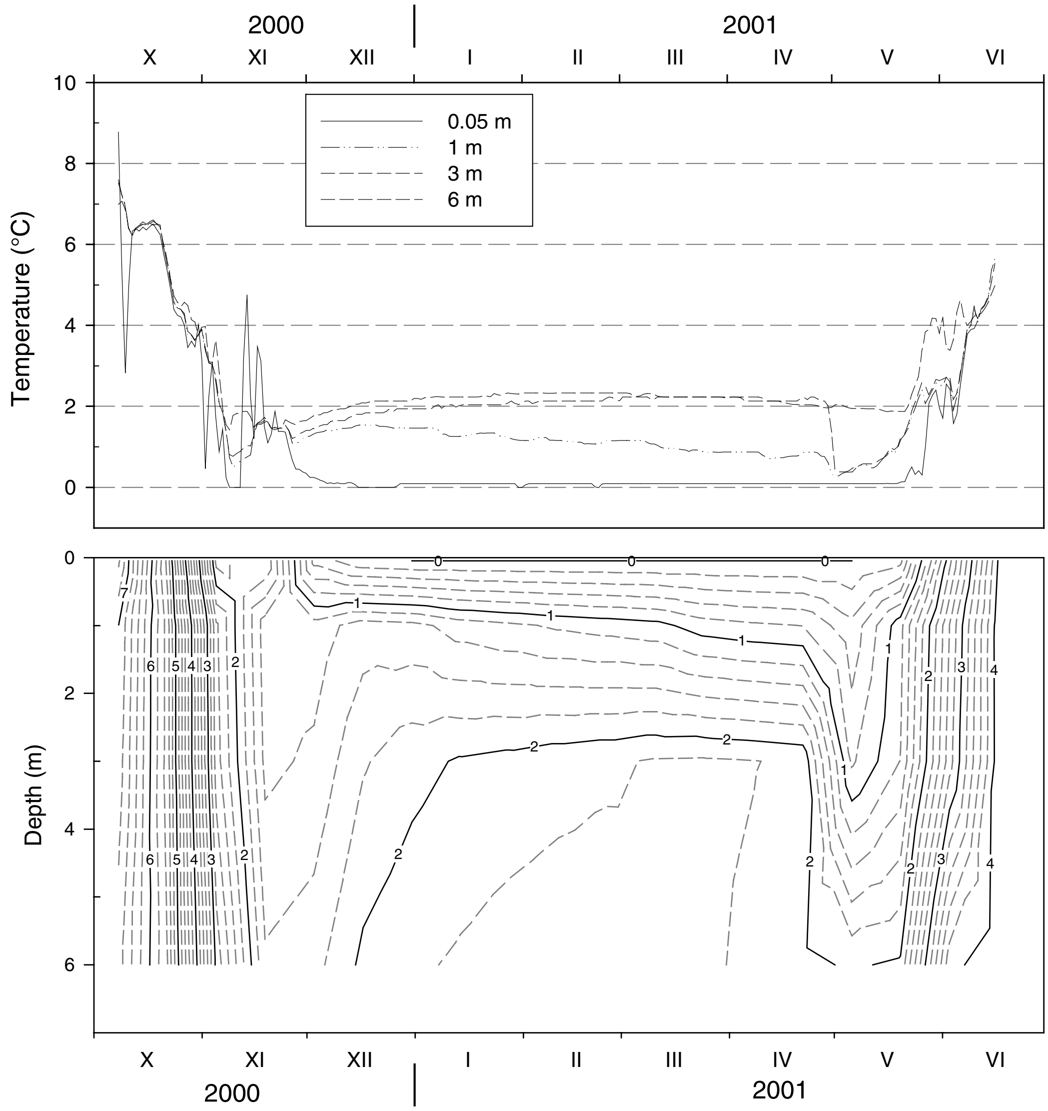

Fig. 7. Daily mean water temperature profiles in Długi Staw Gąsienicowy in 2000–2001, shown in terms of the temperatures at individual sampling depths (upper panel) and as a contour plot (lower panel). The contour plot is based on 14-day means, and the contours are labelled in ℃.

exposure to radiation and wind), and rate of inflow. These factors affect the mixing depth, and hence the LSWT, in autumn and early winter, when the epilimnion is deepening. Internal lake processes are much less relevant in governing the timing of ice-off, which is therefore much more clearly regulated by external meteorological forcing, although lake setting also plays a role. The importance of lake setting was demonstrated by Łajczak (1982), who showed that the duration of ice cover on Tatra Mts lakes differs markedly depending on whether they face north or south. Additionally, although surface air temperature decreases linearly with altitude in mountain regions during spring and summer, this is not necessarily the case later in the year owing to the occurrence of air temperature inversions.

Thermal stratification
The temperature profiles measured in Starolesnianske pleso (Fig. 6), Długi Staw Gąsienicowy (Fig. 7), Ľadové pleso (Fig. 8) and Nižné Terianske pleso (Figs 9, 10) allowed the thermal stratification in these four lakes to be characterized during the measuring period.

Starolesnianske pleso
The temporal variations in the temperature profile in Starolesnianske pleso, the shallowest of the four lakes (maximum depth = 4.1 m, Tab. 1), are illustrated in Fig. 6. From the beginning of the measurements on 1 October 2000 up till 5 November 2000, the lake was homothermic and presumably circulating fully. Winter stagnation set in on 5 November 2000, and an LSWT of 0 ℃ was reached on 14 December 2000. Inverse stratification lasted until at least 8 June 2001; loss of the thermistor chain in June 2001 unfortunately made it impossible to monitor the subsequent development of the stratification.

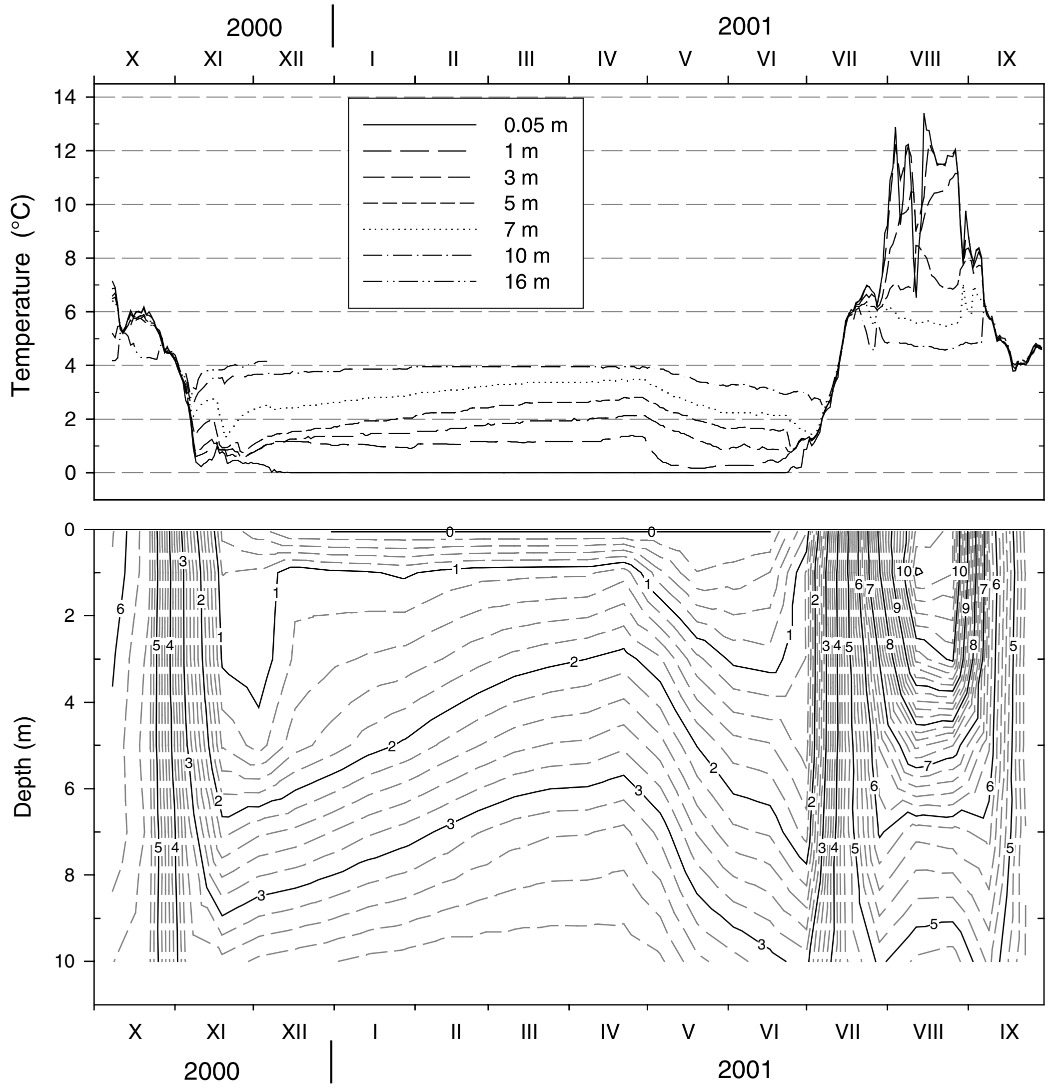

Fig. 8. Daily mean water temperature profiles in Ľadové pleso in 2000–2001, shown in terms of the temperatures at individual sampling depths (upper panel) and as a contour plot (lower panel). The contour plot is based on 14-day means, and the contours are labelled in °C.

Długi Staw Gąsienicowy

The temperature profile in Długi Staw Gąsienicowy is presented in Fig. 7. This lake has a maximum depth of 10.6 m (Tab. 1) when the lake level is at its highest, but an extreme drop in lake level during the measuring period (3–4 m) meant that the maximum depth decreased accordingly. Early loss of the lowermost thermistor meant that the deepest temperature measurements in this lake were made at 6 m depth. The period of homothermy in Długi Staw Gąsienicowy lasted from the first part of October until the onset of inverse stratification on 26 November 2000. By 16 December 2000, the LSWT had decreased to 0 °C. During winter stagnation, which lasted up to the second half of May, the highest temperature recorded at 6 m depth was 2 °C. From the second half of May up until at least 11 June, the lake was approximately homothermic, implying that the lake was then circulating. As in the case of Starolesnianske pleso, the thermistor chain was unfortunately lost in June 2001, which precluded any further monitoring.

Ľadové pleso

As in the case of Długi Staw Gąsienicowy, Ľadové pleso, which has a maximum depth of 18 m (Tab. 1) when the lake level is at its highest, also experienced a drop in lake level during the measuring period, and in this lake the deepest thermistor was also lost early on. The variations in the temperature profile of Ľadové pleso during the measuring period are illustrated in Fig. 8. Autumn homothermy began during the second half of October 2000 and lasted until the onset of inverse stratification on 6 November 2000. By 8 December 2000, the LSWT had decreased to 0 °C. Winter stagnation in Ľadové pleso lasted up to late June 2001. At the beginning of July 2001, the lake was homothermic, and

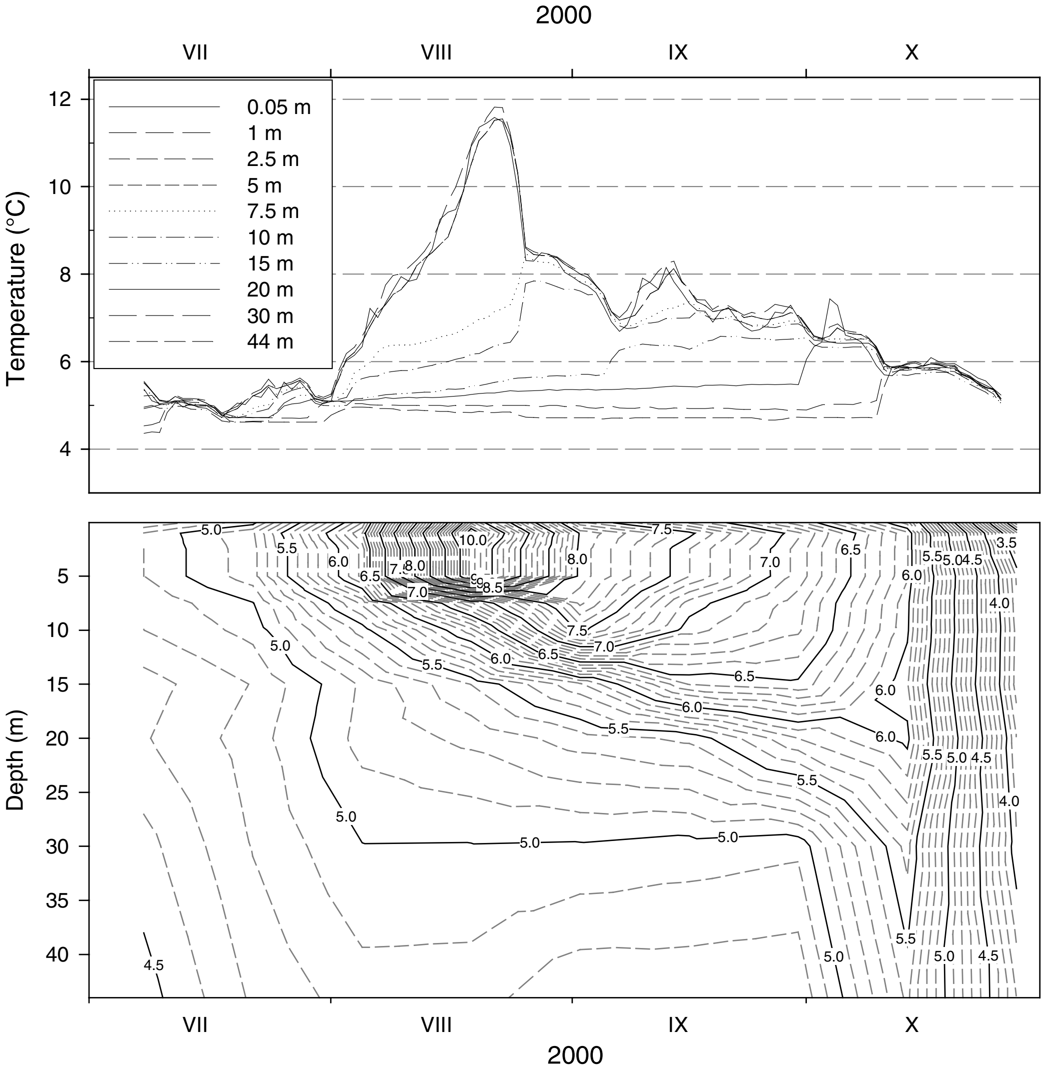

Fig. 9. Daily mean water temperature profiles in Nižné Terianske pleso in 2000, shown in terms of the temperatures at individual sampling depths (upper panel) and as a contour plot (lower panel). The contour plot is based on 14-day means, and the contours are labelled in ℃.

presumably circulating fully, at 4℃. Summer stagnation set in during the first half of July and lasted until the first part of September, so that winter stagnation was approximately four times longer than summer stagnation.

Individual temperature profiles measured in Ľadové pleso during summer stagnation in August 2001 are illustrated in Fig. 11A. The temperature in the uppermost 10 m of the lake – the epilimnion and metalimnion – fluctuated substantially during summer stagnation. Surface cooling resulted in a sub-surface temperature maximum at ~1 m depth that can be assumed to have led to thermal instability and convection in the uppermost part of the water column. It is apparent from Fig. 11A that the borders between epilimnion, metalimnion and hypolimnion were not particularly well defined, with thermal discontinuities being greatly reduced by the action of wind and penetrative convection. Temperatures in the hypolimnion were not recorded. In April 2001, the temperature profile showed a classical inverse stratification extending from 0℃ at the surface to 4℃ at ~10 m depth (Fig. 11B).

Nižné Terianske pleso

The temperature profile in Nižné Terianske pleso, the deepest lake studied (maximum depth = 43.2 m, Tab. 1), is illustrated in Figs 9, 10. Early deployment of the thermistor chain in this lake (30 June 2000) made it possible to monitor temperature profiles in summer 2000 as well as summer 2001, but measurement was interrupted between 26 October 2000 and 14 March 2001. In 2000, summer stagnation lasted until around the middle of October, with differences between the water temperature at the surface and at the bottom of the lake fluctuating between 5℃ and 8℃. The beginning of the period of winter stagnation was not recorded, but its end was observed in mid-June 2001. Spring turnover lasted only two weeks, but encompassed the entire wa-

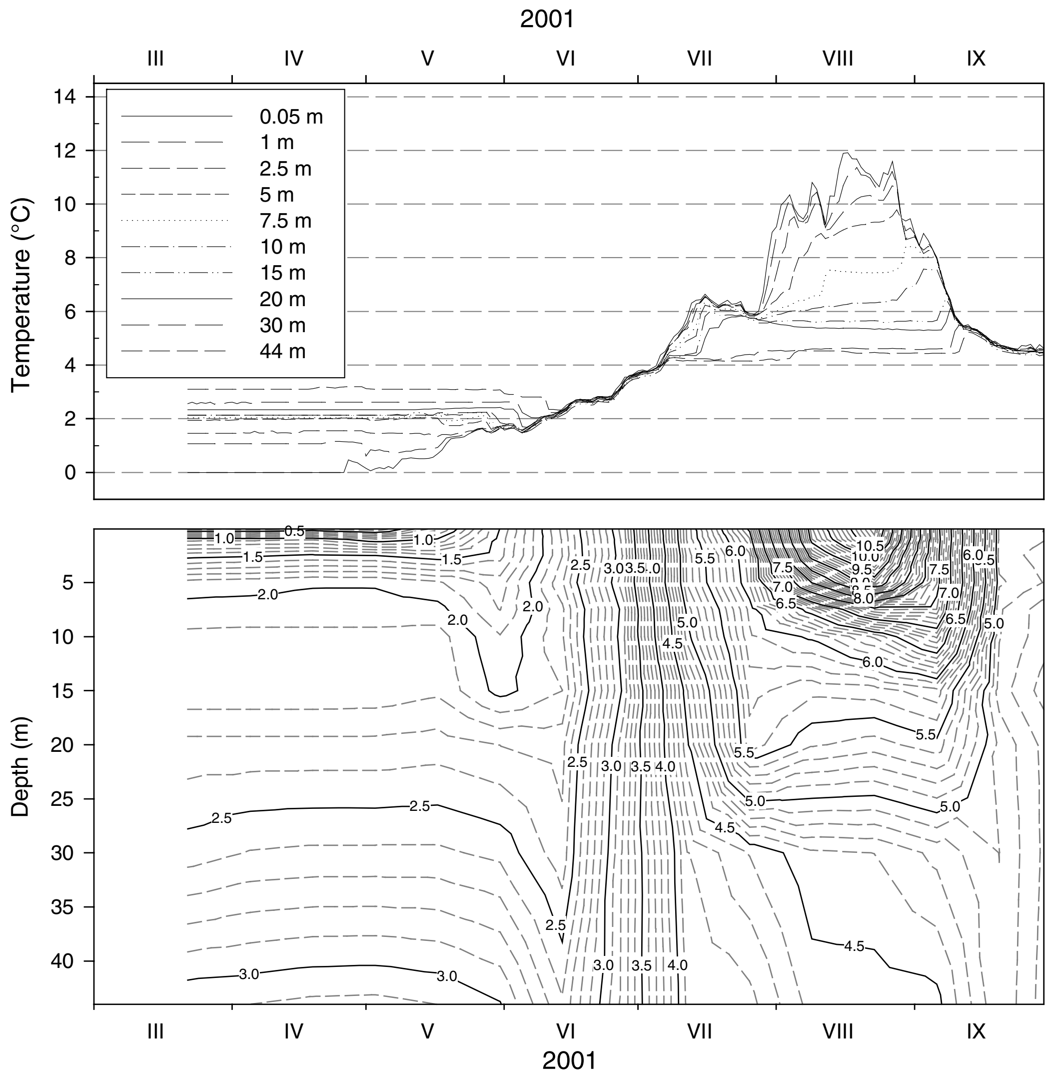

Fig. 10. Daily mean water temperature profiles in Nižné Terianske pleso in 2001, shown in terms of the temperatures at individual sampling depths (upper panel) and as a contour plot (lower panel). The contour plot is based on 14-day means, and the contours are labelled in ℃.

ter column. Summer stagnation in 2001 lasted over 3 months, about 0.5 months less than in 2000. We estimate the duration of winter stagnation to have been ∼8 months (November 2000 – 15 June 2001).

In August 2000, temperature gradients in Nižné Terianske pleso were sharp (Fig. 11C), with a distinct epilimnion, metalimnion and hypolimnion. The boundary between the epilimnion and metalimnion lay at ∼5 m depth, and that between the metalimnion and hypolimnion at ∼10 m depth. In August 2001, neither the boundary between the epilimnion and metalimnion nor that between the metalimnion and hypolimnion was well-defined, but both lay substantially deeper (∼10 m and ∼30 m, respectively) than in the previous year (Fig. 11D).

In April 2001, an inverse temperature stratification existed that was characterized by a rapid increase in temperature from 0 ℃ at the surface down to ∼2 ℃ at a depth of 5 m (Fig. 11E). The temperature remained constant at ∼2 ℃ down to ∼15 m, and increased very slowly from 15 m to 3.1 ℃ at the lake bottom. The weak, relatively deep thermocline observed in both Ľadové pleso and Nižné Terianske pleso in winter is also known to occur in other lakes in the region; e.g., in the lakes Wielki Staw Polski and Przedni Staw Polski in the Dolina Pięciu Stawów Polskich valley (Pacl & Wit-Jóźwikowa, 1974).

Conclusions

We have presented here, for the first time, an overview of the annual cycle of water temperatures and ice cover in a large selection of mountain lakes on both the Slovak and Polish sides of the Tatra Mts, based on automatic, quasi-continuous measurements of LSWTs and temperature profiles. The results indicate that LSWTs in the Tatra Mts exhibit an approximately linear decrease with increasing altitude not only during the sum-

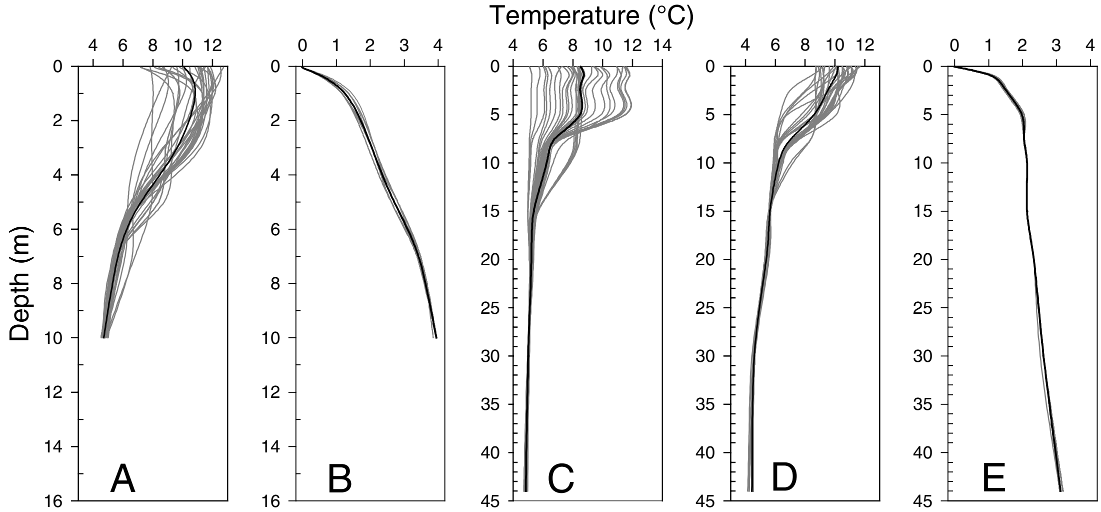

Fig. 11. Water temperature profiles in two lakes in the Tatra Mts: A – Ľadové pleso during August 2000; B – Ľadové pleso during April 2001; C – Nižné Terianske pleso during August 2000; D – Nižné Terianske pleso during August 2001; E – Nižné Terianske pleso during April 2001. Individual daily mean water temperature profiles are shown as grey curves, monthly mean water temperature profiles are shown as black curves.

mer months, but also, unexpectedly, during late spring and during the entire autumn season. During the open-water period, LSWTs can be modelled empirically very well in terms of ambient air temperature alone by employing an exponential smoothing filter. Changes in the value of the smoothing coefficient from month to month indicate that the sensitivity of LSWT to high-frequency air temperature variability is not constant. Although the timing of ice-on of the lakes of the Tatra Mts is essentially independent of altitude, the timing of ice-off becomes successively later with increasing altitude, resulting in an increase in the duration of ice cover with altitude at a mean rate of 10.2 d per 100 m. Temperature profile measurements allowed the timing and duration of summer and winter stagnation, and of spring and autumn turnover, to be characterized quantitatively.

Acknowledgements

Funding was provided by the European Commission and the Swiss Federal Office of Education and Science within the framework of the European Union Environment and Climate projects EMERGE (uropean mountain lake systems – regionalisation, diagnostics and socio-economic evaluation', EU Contract No. ENVKI-CT-1999-00032), CLIME ('Climate and lake impacts in Europe', EU Contract No. EVKI-CT-2002-00121) and Euro-limpacs (EU Contract No. GOCE-CT-2003-505540).

References

Barry, R.G. 1992. Mountain weather and climate. 2nd ed. Routledge, London and New York, 402 pp.

Borowiak, D. 2002. Zmiany właściwości termicznych jezior tatrzańskich [Changes in the thermal properties of the Tatra lakes], pp. 89–94. In: Borowiec, W., Kotarba, A., Kownacki, A., Krzan, Z. & Mirek, Z. (eds) Przemiany Úrodowiska Przyrodniczego Tatr, Kraków-Zakopane.

Dale, H.M. & Gillespie, T. 1977. Diurnal fluctuations of temperature near the bottom of shallow water bodies as affected by solar radiation, bottom color and water circulation. Hydrobiologia **55:** 87–92.

Edinger, J.E., Duttweiler, D.W. & Geyer, J.C. 1968. The response of water temperatures to meteorological conditions. Water Resour. Res. **4:** 1137–1143.

Gregor, V. & Pacl, J. 2005. Hydrology of the Tatra mountain lakes. Acta Hydrologica Slovaca **6:** 161–187.

Kettle, H., Thompson, R., Anderson, N.J. & Livingstone, D.M. 2004. Empirical modeling of summer lake surface water temperatures in southwest Greenland. Limnol. Oceanogr. **49:** 271–282.

Łajczak, A. 1982. Wahania temperatury przypowierzchniowej warstwy wody w jeziorach tatrzańskich o różnej ekspozycji [Fluctuations in the temperature of the surface water layer in Tatra lakes of different exposure]. Czas. Geogr. **53:** 29–44.

Likens, G.E. & Johnson, P.L. 1969. Measurement and analysis of the annual heat budget for the sediment in two Wisconsin lakes. Limnol. Oceanogr. **14:** 115–135.

Lister, G.S., Livingstone, D.M., Ammann, B., Ariztegui, D., Haeberli, W., Lotter, A.F., Ohlendorf, C., Pfister, C., Schwander, J., Schweingruber, F., Stauffer, B. & Sturm, M. 1998. Alpine paleoclimatology, pp. 73–169. In: Cebon, P., Dahinden, U., Davies, H.C., Imboden, D.M. & Jaeger, C.C. (eds) Views from the Alps: regional perspectives on climate change, Chapter 3, MIT Press, Cambridge, Mass.

Livingstone, D.M., Jankowski, T. & Lotter, A.F. 2005a. Patterns of deviation from linearity in the relationship between lake surface temperature and altitude above sea level in the Swiss Alps. Verh. Int. Verein. Limnol. **29:** 300–305.

Livingstone, D.M. & Lotter, A.F. 1998. The relationship between air and water temperatures in lakes of the Swiss Plateau: a case study with palæolimnological implications. J. Paleolimnol. **19:** 181–198.

Livingstone, D.M., Lotter, A.F. & Kettle, H. 2005b. Altitude-dependent differences in the primary physical response of mountain lakes to climatic forcing. Limnol. Oceanogr. **50:** 1313–1325.

Livingstone, D.M., Lotter, A.F. & Walker, I.R. 1999. The decrease in summer surface temperature with altitude in

Swiss Alpine lakes: a comparison with air temperature lapse rates. Arct. Antarct. Alp. Res. **31:** 341–352.

McCombie, A.M. 1959. Some relations between air temperatures and the surface water temperature of lakes. Limnol. Oceanogr. **4:** 252–258.

Ostrožlík, M. & Janíčkovičová, Ľ. 1992–2001. Results of meteorological measurements at the observatories of the Geophysical Institute of the Slovak Academy of Sciences.

Pacl, J. & Wit-Joźwikowa, K. 1974. 7. Teplota vôd, pp. 181–204. In: Končeк, M. (ed.) Klíma Tatier, Veda, Bratislava.

Regier, H.A., Holmes, J.A. & Panly, D. 1990. Influence of temperature changes on aquatic ecosystems: an interpretation of empirical data. Trans. Am. Fish. Soc. **119:** 374–389.

Reif, C.B. 1969. Temperature profiles and heat flow in sediments of Nuangola. Proc. Pennsylvania Acad. Sci. **43:** 98–100.

Shuter, B.J., Schlesinger, D.A. & Zimmerman, A.P. 1983. Empirical predictors of annual surface water temperature cycles in North American lakes. Can. J. Fish. Aquat. Sci. **40:** 1838–1845.

Sweers, H.H. 1976. A nomogram to estimate the heat-exchange coefficient at the air-water interface as a function of wind speed and temperature; a critical survey of some literature. J. Hydrol. **30:** 375–401.

Tabony, R.C. 1985. The variation of surface temperature with altitude. Meteorol. Mag. **114:** 37–48.

Webb, M.S. 1974. Surface temperatures of Lake Erie. Water Resour. Res. **10:** 199–210.

Received August 16, 2005
Accepted May 9, 2006