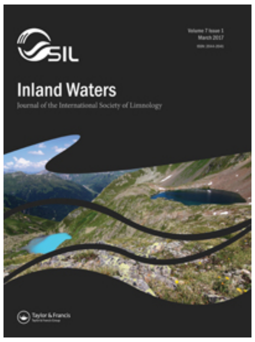

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Irregular changes in lake surface water temperature and ice cover in subalpine Lake Lunz, Austria

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ABSTRACT
Evidence is growing that the surface water temperature increases and the duration of ice cover has decreased in many lakes worldwide during the past few decades. Here, we present changes in surface water temperature and ice-cover duration of Lake Lunz from 1921 to 2015 and evaluate how fast these changes occur over time, in particular with respect to other lakes with similar long-term data series. Since 1921, the surface water temperature of this Austrian subalpine lake has increased by 0.8 °C, with the most intense increase recorded during the spring and summer months (~1–2 °C) and less during fall (~0.3 °C). The duration of full lake ice cover has decreased significantly since 1921. During the 1921–2015 study period, Lake Lunz was ice covered for 92 of 94 winters, with ice-free winters in 2006 and 2013. The interannual decrease of the lake ice cover corresponds to 0.36 days less ice cover per year from 1921 to 2015. Freeze dates now occur 17.4 d/100 yr later, and the ice breakup date change is similar to the freeze date, 17.6 d/100 yr earlier. Although the duration of interannual ice cover varied by only 8.3 days between 1921 and 1930, on 32 days between 2006 and 2015 this interannual variability increased by almost 4 times. Thus, the observed decrease of ice cover is accompanied by increasing interannual variability, during which the lake was fully ice covered. When comparing days of full ice cover to other lakes until 2005, Lake Lunz had a similar decline in ice-cover duration (1.85 d/decade), but a dramatic decrease in full ice cover during 2005 and 2015 indicates that the overall decline in lake ice-cover duration was sensitive to changes in lake ice cover during the past decade. This study emphasizes the importance of continuous and collaborative measurements in other (subalpine) lakes worldwide to test, and also manage, the sensitivity of lakes to ongoing effects of climate change.

KEYWORDS
lake ice-cover; lake temperatures; long-term ecological research; seasonal; Subalpine lake; time series

Introduction

Evidence is growing that global change causes higher lake temperatures worldwide (e.g., Magnuson et al. 2000, Jeppesen et al. 2014, O'Reilly et al. 2015). Lake warming has considerable, but as yet not fully understood, effects on lake functions, including lake thermodynamics, metabolism, and changes in biota. A long-term survey of European lakes revealed that within the past few decades, even hypolimnetic water temperatures increased, which demonstrates that lake warming affects upper and also lower water layers (Dokulil et al. 2006). Moreover, Yvon-Durocher et al. (2012) reported higher respiration response to increasing temperature from lake (pelagic and benthic) than from forested ecosystems, suggesting that the overall ecosystem response to global warming is stronger in aquatic than terrestrial ecosystems. Increasing water temperature also has direct effects on aquatic food webs; for example, plankton cell size may decrease with increasing water temperature (Rasconi et al. 2015). In a survey of lake fish data from 24 European lakes, Jeppesen et al. (2012) found a dramatic shift from stenothermal (e.g., salmonids) to eurythermal (e.g., cyprinids) species.

In addition to increasing lake temperature, global climate models also predict increasing frequency, intensity, and/or amount of heavy precipitation, in particular in the temperate zone of the Northern Hemisphere (IPCC 2013). Catchments with arable soils and agriculture are especially more prone to supply higher carbon and nutrients to lakes that in turn will increase the trophic status and lake metabolism (Jeppesen et al. 2009), in particular in shallow lakes (Jeppesen et al. 2014). Thus, in addition to higher temperatures, lakes with higher nutrient loadings are likely to be more strongly altered than lakes in nutrient-poor catchments with little human impact, as is often the case in high latitude (arctic and subarctic) and high altitude (e.g., alpine and subalpine) lakes.

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Long-term data, especially from oligotrophic and deeper lakes, provide an important contrast to nutrient-rich and shallow lakes, of which much is already known regarding their response to global warming (e.g., Jeppesen et al. 2014). Magnuson et al. (2000) presented temperature and ice-cover trends in mostly deeper lakes of the Northern Hemisphere based on long-term data series dating back to 1845; their study revealed an overall air temperature increase of 1.2 °C per 100 years, and 5.8 days later freeze and 6.5 days earlier breakup dates per 100 years. Such long-term data provide important information on interannual temperature and ice-cover changes and hence allow among-lake comparisons across the globe. For example, O'Reilly et al. (2015) examined lake summer surface water temperatures in 235 lakes worldwide between 1985 and 2009 and found that lakes are significantly warming by 0.34 °C/decade; however, such warming is largely dissimilar at regional scales. By contrast, Livingstone and Dokulil (2001) reported a large degree of spatial coherence in lake surface temperatures within 8 subalpine lakes in Austria between 1911 and 1990, suggesting that lakes in relatively close proximity (<150 km within peri-alpine Austria) and with similar morphometry respond strongly to their regional climate.

At Lake Lunz, a subalpine, oligotrophic, 34 m deep lake in Austria, daily epilimnetic temperature and seasonal ice-cover measurements are available since 1921, and daily air temperature taken close to the lake is available since 1909. These detailed data records elucidate the intensity of lake temperature and ice-cover changes on a short time scale (days) and allow comparisons with other lakes. The presence of this large lake dataset of Lake Lunz thus provides an opportunity to compare trends of lake surface water temperatures and ice-cover duration with other lakes. The objectives of this study were to (a) determine changes in epilimnetic temperature and ice cover of Lake Lunz since the beginning of daily measurements to 2015, and (b) evaluate how fast epilimnetic lake temperature and the duration of ice cover change over time, in particular with respect to other lakes with similar long-term data series.

Materials and methods

Lake Lunz (47°51′10″N, 15°02′50″E) is an oligotrophic (<10 µg L^{-1} of P), subalpine (608 m.a.s.l; maximum depth = 34 m; area = 68 ha) lake in the eastern Austrian Alps. The lake surface water temperature (LSWT) has been measured daily as part of the official national water and air sampling at 0.5 m lake depth during the ice-free time at the same sampling station (7 m from lake shore, which was never affected by shading) and time (0700 h) since 1921, using thermometers regularly calibrated according to official guidelines followed by the Austrian Hydrographic Office. In addition, the duration of full ice cover has been recorded annually since 1921 and is available at the Austrian Hydrographic Office (www.zamg.ac.at; or directly at the research center WasserCluster Lunz). The period of lake ice cover per year refers to days during which the lake was fully covered by ice; however, this time measure does not refer to ice thickness, which is not reported or discussed here.

Lake surface water temperature data from 1 April to 30 November 1921–2015 were used for this study and correspond to the ice-free period. No data were reported between 1 December and 31 March because no consistent water measurements are taken during ice cover. For the ice-free time period, daily measurements are available and make detailed, long-time series analysis possible. For mean monthly or annual temperature data, all daily measurements during this ice-free season were averaged; no lake surface temperature data were missing during this reported long-time series.

Time trends in LSWT exhibit a nonlinear pattern over the entire study period (1921–2015). As an estimate of overall time trends and for comparison with other studies, we fitted linear regression models after testing for normal data distribution (Shapiro-Wilk test). We repeated this analysis for the monotonic increase seen from 1980 onward. In addition, a smooth regression spline using a generalized additive model (Wood 2006) was fitted over the entire study period. We partitioned the dataset into months from 1921 to 2015 to detect which months have been most sensitive to changes in LSWT. The change in LSWT for the respective month and time interval (1921–2015 and 1980–2015) was then extracted from the linear models calculated for the respective time intervals. Linear regression analysis was also applied to examine the relationship between air temperature, measured near shore of Lake Lunz, and LSWT. Finally, to illustrate the nonlinear change in days with full ice cover, we fitted a generalized additive model over the entire time period. Residuals of the nonlinear regression spline were used to assess the increase in interannual variability during which the lake was fully ice covered.

Results

The mean annual LSWT in Lake Lunz and air temperature data were normally distributed (Shapiro-Wilk test; mean annual air temperature: $p = 0.722$; mean annual lake surface temperature: $p = 0.176$) and used for linear regression analysis. Mean annual LSWT increased during the ice-free period (Apr–Nov) by 0.8 °C from 1921 to 2015, which corresponds to an LSWT increase of 0.0085 °C per year since 1921 (94 years). The lowest mean annual LSWT

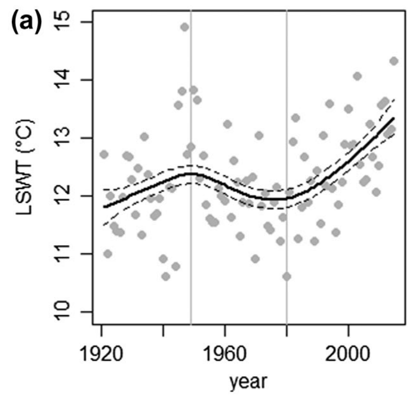

Figure 1. Annual mean lake surface water temperature (LSWT; °C) during the ice-free time periods (Apr–Nov); (a) 1921–2015 (generalized additive model fit; adj. $R^2 = 0.196$, error probability of smooth term $p < 0.001$), and (b) 1980–2015 (linear regression; adj. $R^2 = 0.27$, $p < 0.001$). Vertical lines (a) separate study years from 1921–1950, 1951–1980, and 1981–2015.

was measured in 1980 (10.6 °C) and the highest in 1947 (14.9 °C). As in other studies, we subdivided the entire dataset into 30-year sets (e.g., Benson et al. 2012) and noted (based on linear regression analysis) that between 1921 and 1950 the LSWT increased by 1.3 °C, with strong annual LSWT differences between 1940 (10.9 °C) and 1947 (14.9 °C). Conversely, the mean annual LSWT decreased between 1951 and 1980 by 0.9 °C, with highest mean LSWT in 1951 (13.6 °C) and lowest in 1980 (10.6 °C; Fig. 1a). Between 1980 and 2015, the LSWT increased again by 1.5 °C, during which time the lowest mean LSWT was recorded in 1980 (10.6 °C) and the highest in 2015 (14.3 °C; Fig. 1b).

Between 1921 and 2015, 63% of the mean annual LSWT variability was explained by changes in air temperatures measured during the ice-free period from April through November (Fig. 2). The mean LSWT increased steadily from April (by 0.5 °C), to May (by 0.96 °C), June (by 0.99 °C), July (by 1.3 °C), and August (by 1.9 °C), but remained almost unchanged in September (even with a slight decrease of 0.08 °C since 1921). During the fall months of October and November, however, the LSWT in Lake Lunz increased again by 0.3 °C in both months. During the past 35 years (1980–2015), LSWT increased the most in June (Fig. 3a), whereas the LSWT remained fairly stable in October (Fig. 3b). The mean annual air temperature at Lake Lunz increased on average by 0.74 °C between 1921 and 2015 (i.e., from calculated annual averages of 10.6 to 11.4 °C). Although the average air temperature was below 0 °C in December, January, and February throughout the study period, we noted that during the past 10 years (2006–2015), air temperatures in December (−0.9 °C) and January (−2.0 °C) were warmer than during all preceding time periods (Table 1).

Based on the same 30-year time partitioning as above (1921–1950, 1951–1980) and further separating the most

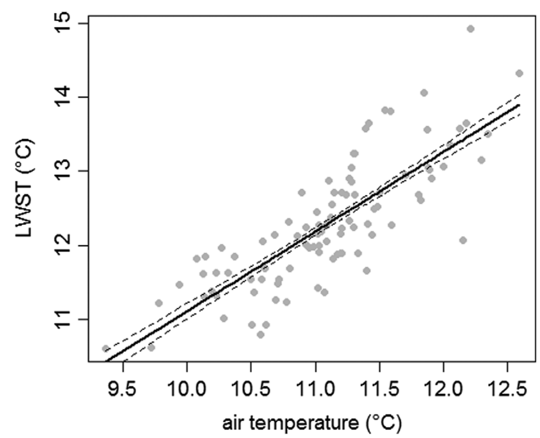

Figure 2. Linear relationship between the mean air temperature and the mean lake surface water temperature (measured during the ice-free periods; Apr–Nov) at Lake Lunz.

recent study period into 1981–1997 and 1998–2015, we observed that the number of days per year during which the mean LSWT of Lake Lunz was >18 °C decreased from 24 days (1921–1950) to 17 days (1951–1980) but increased steadily thereafter to 52 days (1981–1997), and most recently even to 64 days (1998–2015). In particular, higher temperatures were increasingly noted in spring, but less in fall (Table 2, Fig. 4).

The duration of full lake ice cover decreased dramatically from 1921 to 2015 (Fig. 5a). During that period, Lake Lunz was ice covered for 92 of 94 winters, with ice-free winters in 2006 and 2013. The interannual decrease of the lake ice cover corresponds to 0.36 days fewer ice cover per year from 1921 to 2015 (i.e., 3.5 days fewer lake ice cover per decade). On average, freeze date was 16.3 d/94 yr (or 17.4 d/100 yr) later, and a breakup date, similar to the freeze date, was 16.5 d/94 yr (or 17.6 d/100 yr) earlier. The overall decrease of ice cover was accompanied by increasing interannual variability, during which the lake was fully

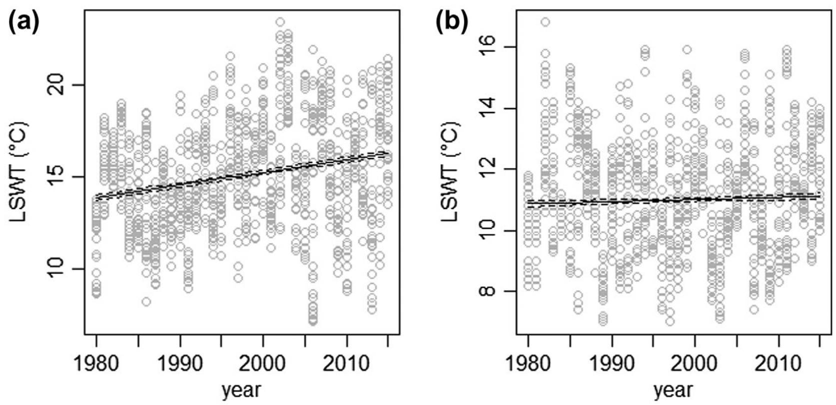

Figure 3. Changes in daily lake surface water temperature (LSWT; °C) for the most contrasting months; (a) June and (b) October between 1980 and 2015.

Table 1. Average air temperatures (in °C) per month at Lake Lunz (without data between 1916 and 1918) in 10-year intervals (from 1909 to 1925) since 1909.

Year/ month	1909–1925	1926–1935	1936–1945	1946–1955	1956–1965	1966–1975	1976–1985	1986–1995	1996–2005	2006–2015
Jan	−2.4	−3.5	−5.0	−3.6	−4.3	−3.0	−3.4	−2.2	−3.7	−2.0
Feb	−1.6	−3.1	−2.1	−1.7	−3.1	−0.2	−1.9	−1.2	−1.3	−0.9
Mar	2.2	1.3	2.1	1.7	1.4	1.8	2.7	2.4	2.0	2.7
Apr	5.6	6.2	5.9	7.1	6.6	6.0	5.3	6.6	6.4	7.7
May	11.2	10.8	10.8	11.5	10.4	11.3	11.5	11.6	12.0	11.9
Jun	13.2	14.1	14.3	14.3	14.2	13.8	14.5	14.0	15.0	15.4
Jul	15.0	16.0	15.8	15.9	15.5	15.7	15.9	16.7	15.6	17.2
Aug	14.1	15.0	15.2	15.2	14.8	15.4	15.0	16.1	15.6	16.1
Sep	10.8	12.2	12.0	12.7	12.2	12.0	12.0	12.3	11.4	12.4
Oct	6.4	7.4	7.4	6.9	7.2	6.8	7.8	7.9	8.0	7.6
Nov	0.4	3.8	1.9	2.2	2.9	1.8	1.6	1.8	2.6	3.6
Dec	−1.5	−2.1	−3.0	−1.5	−2.3	−2.2	−1.5	−1.8	−2.3	−0.9

Table 2. Summary statistics from linear regressions fitting the time trend of LSWT with year. The analyses were performed on daily measurements for the entire study period (1921–2015) and for the recent phase of monotonic increase (1980–2015). Both fits for entire years and split by months are reported. ΔT is the change in °C for a given time interval and also used for Figure 4a and b.

Period	Month	Adj. R^2	Intercept	SE	Year	SE	*p*	ΔT
1921–2015	(ice free)	0.002	−4.5	2.2	0.009	0.001	<0.001	0.8
1921–2015	April	0.005	−5.0	2.8	0.006	0.001	<0.001	0.5
1921–2015	May	0.012	−9.1	3.3	0.010	0.002	<0.001	0.9
1921–2015	June	0.010	−6.2	3.8	0.011	0.002	<0.001	1.0
1921–2015	July	0.019	−10.8	3.6	0.014	0.002	<0.001	1.3
1921–2015	August	0.048	−23.1	3.3	0.020	0.002	<0.001	1.9
1921–2015	September	0.000	16.1	3.1	−0.001	0.002	0.616	−0.1
1921–2015	October	0.003	3.2	2.5	0.004	0.001	0.002	0.4
1921–2015	November	0.004	−0.1	2.0	0.004	0.001	<0.001	0.3
1980–2015	(ice free)	0.008	−72.4	9.8	0.043	0.005	<0.001	1.5
1980–2015	April	0.087	−112.3	11.6	0.059	0.006	<0.001	2.1
1980–2015	May	0.080	−121.9	13.4	0.066	0.007	<0.001	2.3
1980–2015	June	0.056	−123.0	17.1	0.069	0.009	<0.001	2.4
1980–2015	July	0.050	−98.7	15.0	0.058	0.008	<0.001	2.0
1980–2015	August	0.014	−38.9	14.1	0.028	0.007	<0.001	1.0
1980–2015	September	0.007	−25.6	13.5	0.020	0.007	0.003	0.7
1980–2015	October	0.001	−2.9	10.6	0.007	0.005	0.188	0.2
1980–2015	November	0.051	−56.8	8.3	0.032	0.004	<0.001	1.1

ice covered; for example, the duration of interannual ice cover varied by only 8.3 days between 1921 and 1930 but was almost 4 times higher between 2006 and 2015, with 32 days of interannual ice cover variability (Fig. 5b).

Discussion

As in many other lakes, subalpine Lake Lunz clearly shows increasing LSWT and an overall decrease in the annual

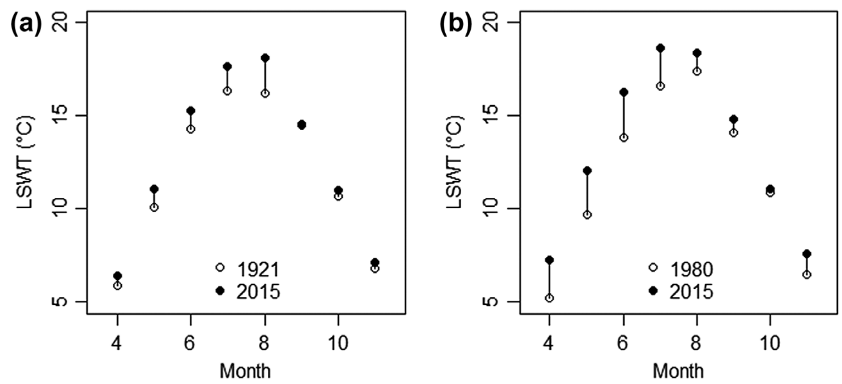

Figure 4. Changes in LSWT per month between (a) 1921 and 2015 and (b) 1980 and 2015. The changes correspond to the endpoints of linear regressions fitted for a given month and time interval (see also Table 2).

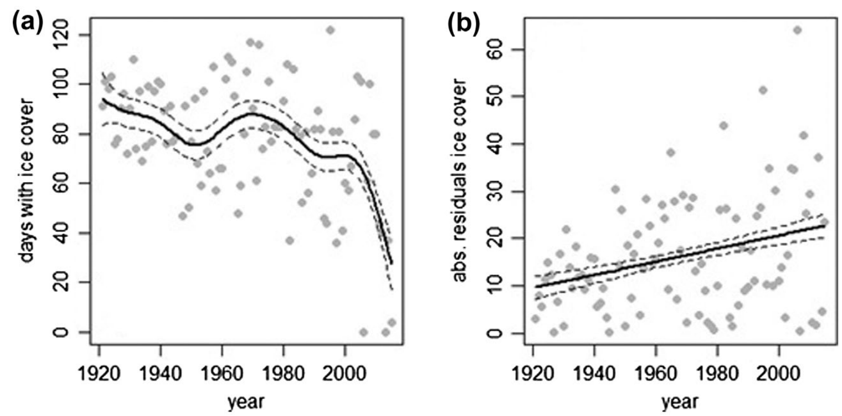

Figure 5. (a) Changes in full ice cover of Lake Lunz in days from 1921 to 2015. Generalized additive model with smooth term, adj. R^2 = 0.26, error probability of smooth term $p < 0.001$. (b) Residuals from Figure 5a over time. Adj. $R^2 = 0.088$; intercept: −256 (SE 88), $p = 0.004$; slope (year): 0.14 (SE 0.04), $p = 0.002$.

duration of full ice cover since 1921. The overall increase in LSWT between 1921 and 2015 (0.8 °C within 94 years) does not parallel other Austrian subalpine lakes investigated for a similar time period (1910–1990; Livingstone and Dokulil 2001). Livingstone and Dokulil (2001), however, detected a 1.1 °C/100 yr increase in LSWT of their 8 study lakes to occur only during fall. By comparison, even though the 35 years since 1980 have been among the warmest on record, the largest increase of the LSWT in Lake Lunz was recorded during spring and summer (~1–2 °C) but was much less during fall (~0.3 °C). This different pattern of lake surface warming suggests that the location, regional climate, and perhaps morphometry of these subalpine lakes may cause differences in the LSWT. Livingstone and Dokulil (2001) identified that the LSWT within these subalpine lakes was strongly associated with regional air temperature, and, similarly, local air temperature significantly predicted the variability in LSWT at Lake Lunz in this study.

Comparing water temperatures among lakes is difficult because sampling time and duration are often unequal. To compare LSWT data from Lake Lunz with a global dataset of summer surface water temperatures of >200 lakes between 1985 and 2009, however, we adjusted our LSWT data accordingly and noted that the increase in LSWT of Lake Lunz during that time was equal (+0.34 °C/decade) to the reported water increase for these >200 lakes (+0.34 °C/decade; O'Reilly et al. 2015).

We speculated that recent decadal patterns of lake surface temperature are more similar than long-term lake comparisons. For example, when compared with Lake Baikal, for which a long-term average water temperature profile (since 1946) is available, the LSWT data of Lake Lunz differ again considerably; the surface water temperature in Lake Baikal has increased by 1.21 °C since 1946 (Hampton et al. 2008), whereas the LSWT in Lake Lunz has actually decreased by 0.18 °C during the same period. When comparing LSWT of Lake Lunz with those of Lake Garda, Italy, investigated between 1986 and 2015 (Pareeth et al. 2016), the LSWT of small Lake Lunz (0.046 °C/yr) increased more than twice as much as the LSWT of Lake Garda (0.020 °C/yr), which is much larger (368 km²) and deeper (300–350 m maximum depth; Pareeth et al. 2016). These differences in LSWT clearly suggest that lake location, morphometry, size, and regional climate strongly effect how LSWT develop over the same time period.

Extremes are becoming more frequent in Lake Lunz, as demonstrated by the first ever recorded winters free of ice cover in 2006 and 2013, and by the increasing variability in ice-cover duration (i.e., vertical distance of residuals from the regression line) since 1921. The recent increasing variability of interannual lake ice cover is similar to observations in other lakes. For example, Sharma et al. (2016) recorded an unprecedented 5 years free of ice cover between 2005 and 2014 in Lake Suwa, a large (13 km^2), shallow (maximum depth = 7 m) lake in Japan, but with similar altitude (760 m a.s.l.) as Lake Lunz (608 m a.s.l.). On a broader scale, Benson et al. (2012) investigated temporal patterns of annual ice cover in 75 lakes in North America, Europe, and Asia and showed that the number of lakes without full ice cover has increased, particularly during the past 30 years. Although the average winter air temperatures at Lake Lunz were <0 °C since the beginning of the data record, the winter months December, January, and February between 2006 and 2015 had higher air temperatures than any prior period in this dataset (Table 1), suggesting that even low increases in winter air temperatures may cause lakes to remain ice free.

The general decrease in duration of lake ice cover in Lake Lunz since 1921 is more pronounced than in many other lakes worldwide (e.g., Magnuson et al. 2000, Blenckner et al. 2007, Benson et al. 2012). For example, Magnuson et al. (2000) reported 5.8 d/100 yr later freeze dates and 6.5 d/100 yr earlier breakup dates for 26 lakes and rivers in the Northern Hemisphere. Compared to these aquatic ecosystems, the freeze dates in Lake Lunz occur on average much later (i.e., 17.4 d/100 yr) and breakup days much earlier (i.e., 17.6 d/100 yr). Moreover, the decline in ice-cover duration for Lake Lunz (1921–2015) is twice as fast (3.6 d/decade) than for Lake Mendota, Wisconsin (1.87 d/decade), based on data from 1855 to 2005 (Benson et al. 2012).

Such drastic differences in ice-cover duration are, however, sensitive to the years used for this comparison (i.e., Lake Mendota until 2005, Lake Lunz until 2015). When adjusting the dataset to the same end dates (i.e., 2005) for both lakes, Lake Lunz has a similar decline of the ice-cover duration (1.85 d/decade) as Lake Mendota. The dramatic differences between 2005 or 2015 as end dates indicate that changes in lake ice-cover duration during the past decade are crucial for determining the overall temporal changes in lake ice cover. It is, however, clear that lake ice formation, growth, and decay are the result of an energy surplus or deficit in the energy balance of the lake, which is also determined by lake and catchment morphometry, wind fetch, and insolation. Unfortunately, long-term data on water temperature profiles in Lake Lunz are scarce and thus make a reverse projection of its interannual energy budgets difficult, but when comparing Lake Lunz with other (mostly larger) lakes, it is also important to consider the relatively short retention time of this subalpine lake (~4 months; data not published). This short retention time results in a more dynamic heat budget compared to large lakes with longer retention times.

The observed general increase in LSWT and decrease in lake ice cover has far-reaching and direct and indirect consequences for nutrient loading, lake biota dynamics (Winder and Schindler 2004, De Senerpont Domis et al. 2013), and aquatic food web structure in general (Jeppesen et al. 2012, Hansson et al. 2013). For Lake Lunz, ongoing research indicates rapid changes in biochemical carbon composition and concentration (dissolved and particulate; Kainz, unpubl. data), which in turn can directly affect carbon respiration, especially in colder lakes that warm rapidly (Kosten et al. 2012). Similarly, lake transparency is currently dramatically reduced, and changes in the taxonomic composition of phytoplankton and zooplankton is the subject of current investigations (Kainz, unpubl. data).

Based on the rapid changes in Lake Lunz, but also many other subalpine lakes (e.g., Livingstone and Dokulil 2001, Dokulil et al. 2006), it is crucial to further investigate how ongoing increases in water temperature affect lake physics and biology, and, importantly, how to manage lake ecosystems to sustain as many ecological and societal services as possible. Clearly, a well-concerted, interconnected scientific effort is required at regional, national, and international levels to address the sensitivity of aquatic ecosystem changes for alpine (e.g., Preston et al. 2016) and other subalpine lakes.

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