Evolution of lake surface temperatures of high-altitude lakes in the European Alpine region under climate change

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Abstract

Lake Surface Temperature (LST) is a key characteristic that reflects meteorological and climatological influences on lakes. In general, there is limited LST data from high elevation lakes available as these areas are remote and not part of regular monitoring programs. Nonetheless, it is crucial to understand their response to climate warming for the development of effective management strategies for high-altitude lakes. This study aims at projecting LSTs for 21 alpine lakes (1500-2300 m a.s.l.) in the Niedere Tauern region in Austria until the end of the century. For the determination of the relationship between atmospheric variables (temperature and precipitation), near-lake snow depth and observed LST, General Additive Models were trained with a daily temporal resolution for the years 1998 to 2003, 2009 to 2011 and 2019 to 2021. We subsequently employed the model with the highest fit to project LSTs until 2100 using an ensemble of regional climate projections for the RCP2.6 (in-line with the COP 21 Paris Agreement), RCP4.5 and RCP8.5 ("worst-case") scenario. Considering the RCP8.5 scenario, the average rise for August lake surface temperatures in the far future (2071-2100) is predicted to increase by 2.3°C compared to temperatures in the reference period (2021-2030). Consequently, the ice-free period is expected to rise on average 1-1.2—fold in the near future (2031-2060) and 1-1.5-fold in the distant future. Furthermore, we evaluated changes in the maximum temperatures of investigated lakes, indicating that 15°C to 17°C will be relatively common in the far future period. These alterations in the lakes' temperature regime probably affect multiple limnological parameters related to ecological quality such as primary productivity and trophic state.

Keywords: Lake surface temperature, Alpine ecosystems, climate change, Alpine lakes, climate projections

1 Introduction

Numerous studies have examined the impact of climate change on lake surface water temperature (Livingstone, 2003; O'Reilly et al, 2015; Woolway et al, 2019). It has been shown that lakes are warming on a global scale with an unprecedented rate, with some lakes warming faster than others (Woolway and Merchant, 2017; O'Reilly et al, 2015). It is current scientific consensus that remote alpine lakes' integrity is more threatened by climate change than the one of comparable lowland ecosystems (Thies et al, 2007; Huber et al, 2006; Pachauri et al, 2014). This is due to both the more pronounced temperature rise in the Alps as well as the higher vulnerability of alpine ecosystems (Rogora et al, 2018). Moreover, anthropogenic influences, for example, from agricultural activities and recreational use pose a risk to these ecosystems (Dynowski et al, 2019), which is of concern as soon as these services get reduced or competitive (Winkler, 2019). Such climatic and socio-ecological changes have strong impacts on the lakes' hydrological and ecological processes and functions (Xu et al, 2017; Battarbee et al, 2009; Schmeller et al, 2018), affecting the provision of ecosystem services such as aquatic products, water regulation, outdoor recreation opportunities as well as aesthetic experiences (Schirpke et al, 2018; Meisch et al, 2019; Colvin et al, 2019; Tallar and Suen, 2017). It is therefore important to understand and predict the effects of climate change on alpine lakes and related ecosystem services in order to provide a sound scientific basis for decision making and elaborating policy advices for a sustainable use (Grizzetti et al, 2016).

Lake surface temperatures (LSTs) of alpine lakes represent one of the most important indicators for the lake ecosystem, but they react - due to local habitat-specific influences - distinctively to altering climate conditions. The reaction of water bodies in both low and high altitudes to climate change has been subject to a plethora of studies. The constraint in both altitudinal belts is the availability of long-term time series which are a necessity for the derivation of robust statistical correlations and metrics.

In Austria, applicable data exists for 22 low-altitude lakes, allowing an attempt to characterize global warming by examining long-term trends of annual maximum LSTs (Dokulil, 2018). Regarding high alpine lakes, Niedrist et al (2018) investigated the impact of climate change to a small mountain lake in Tyrol (Austria) concerning vertical and seasonal water temperature differences by analyzing 44 years of LST measurements. Long-term monitored lakes in Northern Italy (LTER (Long-Term Ecological Research) Italia, sites IT09 and IT25) and a comprehensive physical-chemical lake data set from the Niedere Tauern region in the Austrian Alps (n=20) reveal a wide range in the decrease of summer epilimnion water temperature as a function of altitude (Kamenik et al, 2001; Thompson et al, 2005). Livingstone et al (1999) explored the decrease of summer surface water temperatures with elevation in Swiss lakes and compared water temperature lapse rates with less pronounced air temperature lapse rates.

Livingstone and Dokulil (2001) and Novikmec et al (2013), however, examined that not only altitude, but also topographic shading, lake morphometry, wind fetch and sheltering, river and groundwater inflows as well as heat exchange with sediments have a strong impact on lake surface temperatures. Topographic shading was the main reason for lake Haegelseewli (2339 m a.s.l.) to decouple from climate forcing, i.e., ice cover formation during large parts of the year minimized direct temperature effects during the short open water season (Lotter et al, 2002). Either relatively warm or undercooled lakes located at the same altitude are the result of distinct responses to a common driver. An example is the range in mean summer epilimnion water temperature from 7.5 to 11.3°C at elevations from 1929 to 1970 m a.s.l. in the Niedere Tauern region of the Austrian part of the European Alps (Thompson et al, 2005).

Hence, as variables affecting the resistance of each lake to altering conditions differ, general conclusions of how alpine lakes react to climate change cannot be drawn. Therefore, it is essential to apply strategies taking their individual character into account. Exchange processes through the air-water interface allow for depicting lake surface temperatures via models containing atmospheric covariates (Matulla et al, 2018; Ptak et al, 2017). LST has been shown to be strongly dependent on ambient air temperature and wind speed, and seems to be more affected by fluctuations in cloud cover and relative humidity than by fluctuations in air temperatures (Livingstone et al, 1999). Livingstone and Dokulil (2001) demonstrated the high correlation between wind speed from mountaintop stations and LST up to a distance of 300 km, especially during spring time when correlations with ambient air temperatures are lowest. Albeit wind mixing as well as radiative heat exchange processes can cause short-term distortions - particularly in spring and fall - the close linkage of LST to air temperature is generally observed for both medium and long-term scales of time (Livingstone and Lotter, 1998; Livingstone and Dokulil, 2001; Livingstone et al, 2005).

The establishment of LST models is of high importance for the assessment of changes in lake surface temperatures in the wake of climate change.

By using long series from nine Austrian lakes larger than 10 km^2, Dokulil (2013) estimated future LSTs in 2050 from a linear extrapolation of the time trend, exhibiting an increase of average present day LST by 3°C in summer. Piccolroaz et al (2013) developed the air2water model, a physical model that converts air temperature into lake surface water temperature by accounting for the overall heat exchanges with the atmosphere and the deeper layer by means of simplified relationships. Air2water can easily be used to predict the response of lakes to climate change considering different scenarios since projections of air temperature are available for different climate scenarios. Piccolroaz (2016) predicted LSTs of Lake Superior and Lake Erie in the U.S. by using the air2water model and discussed associated guidelines, challenges and future perspectives. Also employing the air2water model, LSTs for 14 lakes around the globe featuring different morphological and hydrological characteristics were projected. It has been shown that thermal dynamics can vary significantly with the lakes' morphological properties (Toffolon et al, 2014). Heddam et al (2020) investigated different approaches to model daily surface water temperature from air temperature comparing the air2water model to five different machine learning algorithms by using air temperature and information on year, month and day as input variables. Prats and Danis (2019) established a model for both epilimnion and hypolimnion temperature that is not only based on the surrounding air temperature, but also on the lake's geographical and morphological characteristics.

More atmospheric parameters have been considered in the study by Quan et al (2020). They built a LST prediction model based on support vector regression for large high-altitude water bodies in western China. Surface temperature, near-surface pressure, near-surface air specific humidity, near-surface wind speed and surface precipitation served as input variables in the machine learning algorithm.

For high-altitude lakes of the European Alps, however, similar analyses with multiple atmospheric parameters serving as input variables have not yet been conducted.

So far, the majority of studies employed data from meteorological stations that are often not in the lakes' immediate vicinity. This poses a problem especially for remote lakes as these measurements do not adequately reflect surrounding conditions. In these cases, high-resolution gridded data sets can remedy the situation. Nonetheless, the use of gridded data also has its drawbacks as parameters important for LST modeling, such as wind speed, are sometimes not available in suitable spatial resolution. Another constraint is the availability of gridded data with similar technical specifications for both the past and future time period.

The focus of this study, however, lies on LST modelling of 21 alpine lakes from multiple atmospheric parameters in the Austrian Niedere Tauern region using gridded meteorological data in the lakes' vicinity on a daily time resolution. We aim at providing lake surface water temperatures projections until 2100 for investigated lakes to assess the lakes' sensitivity towards climate change. Thereby, we consider three different climate scenarios (Vuuren et al, 2011): the 'climate-friendly' RCP2.6 that assumes that the global warming will stay below 2°C until the end of the century. The 'medium-low emission' scenario RCP4.5 is likely to result in a global temperature rise between 2.5 and 3 °C. The RCP8.5 is often referred to the so-called worst-case scenario and depicts an increase of global temperature of nearly 5 °C compared to pre-industrial conditions. Such simulations are necessary to ultimately attain the goal of associating ecosystem services of lakes and rate their value to society. On a daily resolution, future changes in the ice cover duration can be evaluated, being an important driver for altering biological and chemical conditions in lakes.

This study is embedded in the project *CLAIMES - Climate response of alpine lakes: resistance variability and management consequences for ecosystem services* (https://www.uibk.ac.at/projects/claimes/), which aims at the anticipatory management of potentially altered availability of alpine lakes' ecosystem services induced by climate change.

Following an description of the study area and introduction of data sources, we focus on data preparation and we lay out the procedure applied for modeling LST time series on a daily basis. We discuss the results and emphasize the evolution of LSTs throughout the ice-free summer months from June to September. We use results of derived LST models to evaluate changes in ice cover duration and maximum temperature, both representing important characteristics for the limnological state of the lake.

2 Data

Data used in this study are of two kind. On the one hand, we use LST measurements sampled by various institutions in the course of several scientific projects over the last years and decades. On the other had, we employ high-quality gridded observational data sets covering different atmospheric parameters over the Austrian territory on a daily basis provided by the Austrian weather service. Before focusing on the various data sets used within this study, we shortly introduce the study region and investigated lakes.

2.1 Study region

The lakes considered in this study are situated in the Niedere Tauern, a mountain range in the Central Eastern Alps consisting of crystalline and limestone bedrock (Thompson et al, 2005). The highest elevation in this region is the *Hochgolling* with 2862 m a.s.l.. Investigated lakes are located along an altitudinal gradient reaching from 1502 m to 2309 m; they all are situated within an area stretching 20 km from north to south and 30 km from east to west (see Figure 1)). Due to its inner alpine position, this region is meteorologically characterized by both Nord- and Südstau effects, reaching annual precipitation sums up to 1600 mm. July's mean temperature in an altitude of 2000 m is 8°C.

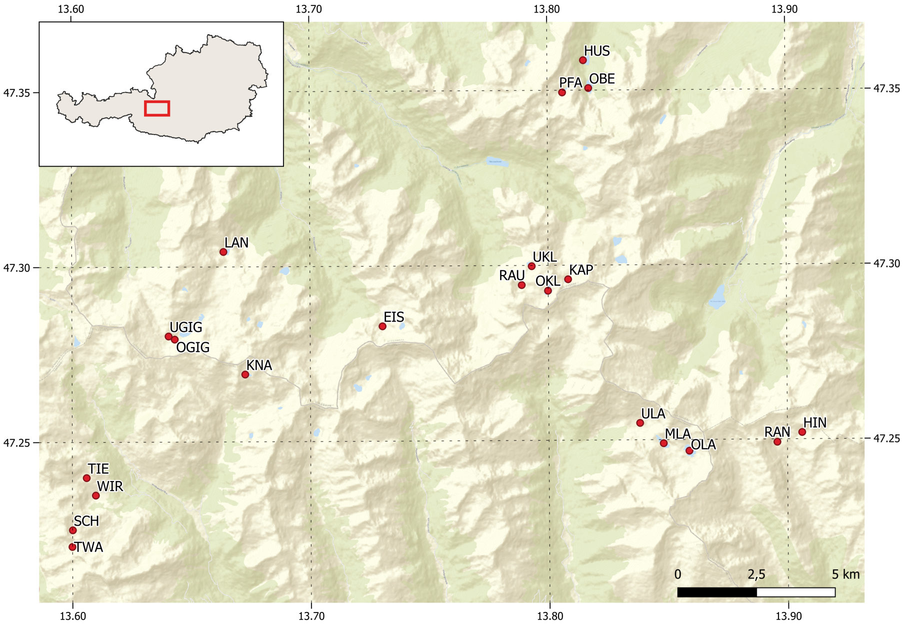


Fig. 1 Location of investigated lakes within the Niedere Tauern region in the Austrian part of the European Alps.

Investigated lakes were chosen based on both available data sources from Thompson et al (2005) in the period 1998 to 2003 and permissions from lake owners to take further measurements during the project duration. The smallest lake within the study region is represented by Hinterkarsee, featuring an area of 1.9 hectares. The Unterer Giglachsee, on the other hand, is the largest lake covering an area of 16.8 hectares. The shallowest and deepest lakes are Hüttensee and Oberer Klaffersee, respectively. The latter also represents the lake with the longest mean ice cover duration (referred to the time period 1998 to 2003) of 244 days. In contrast, Landauersee features the shortest mean ice cover duration of 163 days. Detailed characteristics as well as the lakes' abbreviations which will be used throughout the text can be found in table 1.

2.2 LST data

2.2.1 Niedere Tauern

Within this study, we employed the LST data collected and provided by Thompson et al (2005). For their analysis, epilimnetic water temperatures were recorded at two- and four-hour intervals from July 1998 to September 2003 to investigate the impact of climate change on 45 remote alpine lakes in the Niedere Tauern. Measurements were carried out with two thermistors in water depths ranging from 1.4 to 3.3 m. Technical details of the measurement procedure are found in Thompson et al (2005). Furthermore, University

Table 1 Morphological characteristics of investigated lakes in this study

Lake	Abbr	Elevation [m]	Surface area [ha]	Volume [m^3]	Depth (max) [m]
Eiskarsee	EIS	1940	2.3	107416	14.2
Hinterkarsee	HIN	2074	1.9	96333	11.3
Hüttensee	HUS	1502	4.6	166128	7.7
Kapuzinersee	KAP	2147	1.2	91039	20
Knappenkarsee	KNA	2257	1.4	41322	8
Landauersee	LAN	1653	3.6	271563	16.6
Mittlerer Landschitzsee	MLA	1940	6.6	626650	20.3
Oberer Giglachsee	OGIG	1930	3.5	182827	10.5
Oberer Klaffersee	OKL	2309	5.1	573844	32.5
Oberer Landschitzsee	OLA	2067	8.9	509710	13.6
Obersee	OBE	1672	5.1	186167	21.6
Schönalmsee	SCH	2111	7.2	801790	23.4
Pfannsee	PFA	1967	1.3	24832	7.7
Rantensee	RAN	1880	2.3	77856	7.6
Rauhenbergsee	RAU	2263	2.8	246078	26.3
Tiefenbachsee	TIE	1844	3.2	130028	8
Twenger Almsee	TWA	2118	3.1	399160	33.6
Unterer Giglachsee	UGIG	1922	16.8	1285012	18
Unterer Klaffersee	UKL	2103	3.9	502862	39.6
Unterer Landschitzsee	ULA	1782	12.0	997087	15.8
Unterer Wirpitschsee	WIR	1700	2.7	121038	8

of Innsbruck's limnological institute sampled additional LST data in the years from 2009 to 2011 at four lakes, i.e. OLA, TWA, WIR and UGIG. For redundancy reasons, they employed two observation systems in parallel in depths of 1.4 m and 3.3 meters. Within in the project CLAIMES, additional temperature measurements were performed at the 21 lakes considered in this study from September 2019 to September 2021. Detailed information on the data availability for each lake is listed in table A1 in the Appendix.

2.3 Meteorological data

2.3.1 Past

SPARTACUS

Meteorological data are taken from SPARTACUS, the *Spatiotemporal Reanalysis Dataset for Climate in Austria* (Hiebl and Frei, 2016, 2018). It provides both daily precipitation totals as well as maximum and minimum temperatures across Austria on a grid with 1 km spatial resolution. SPARTACUS is kept up to date by the Austrian geological and meteorological service (GeoSphere Austria) and available from 1961 onwards up to the present day for Austria, Southern parts of Germany and South Tyrol.

SNOWGRID

GeoSphere Austria also provides the SNOWGRID data set which is an operational snowpack model. In this study, we use the climate version of the model driven by SPARTACUS and the radiation model STRAHLGRID (Olefs and Schöner, 2012). The parameters covered in this data set are snow depth and the snow-water equivalent. SNOWGRID features the same technical specifications as SPARTACUS, i.e., the temporal resolution of one day and the spatial resolution of 1 km. However, solely the Austrian territory is covered (Olefs et al, 2020).

2.3.2 Future

OEKS15

The ÖKS15 data set (Chimani et al, 2016) comprises ensembles of regional climate projections for Austria on a 1 km grid and a daily resolution. These ensembles have been generated from CMIP5's (Taylor et al, 2012; Pachauri et al, 2014) downscaled 'EURO-CORDEX' data set (Jacob et al, 2014) and provide a plethora of meteorological parameters for three climate scenarios, i.e. RCP2.6 (8 ensemble members), RCP4.5 (13 ensemble members) and RCP8.5 (16 ensemble members). Within this study, we employ daily maximum and minimum temperature as well as precipitation totals. The data set only covers Austria.

FuSE-AT

The FuSE-AT project aims to extend the climate scenarios of the ÖKS15 data set. This extension includes the variables snow cover, snow depth and snow water equivalent. To perform simulations of these snow-related variables, the adapted climate version of the SNOWGRID snow model is employed and applied to the ÖKS15 ensembles. A set of future scenarios of the spatial and temporal evolution of snow cover with a resolution of 1 km in daily intervals was produced for the 21st century for the Austrian federal territory (https://fuse-at.ccca.ac.at/).

3 Methods

3.1 Data preparation

LST data

Since all data sets for LSTs in the region Niedere Tauern contain two simultaneously registered measurements, the corresponding mean was computed for further usage. In the event that one thermistor failed and therefore no LST values were registered for a certain period of time, measured data of the other gauge were applied. Subsequently, we aggregated the hourly data to a daily time resolution.

Meteorological data

Data preparation procedures were more extensive for the employed meteorological grid data sets. To estimate the ambient meteorological conditions of the different lakes, we determined for each lake the nearest grid point and its four neighbors to the west, east, south and north. For the parameters precipitation and snow depth, the values of these grid points are averaged for further usage. In the case of temperature, however, we need to perform an intermediate step to account for its height-dependence. As all the grid points in the data set are located at different heights, we apply the following steps to each of the considered grid point values: (i) identify the elevation of the grid point in the underlying digital elevation model, (ii) calculate the elevation difference between the lake and the grid point, and (iii) correct the temperature values with the moist adiabatic lapse rate of 6.5°C/km. After performing the height correction, we computed the mean of all five neighboring grid points of the respective lake.

3.2 General Additive Mixed Models (GAMMs)

For the establishment of Lake Surface Temperature models, we aim to link LST measurements with atmospheric covariates. When considering a monthly time resolution, it can be assumed that linear relationships exist between the target variable (LST) and predictors (atmospheric parameters) Matulla et al (2018). High alpine lakes, however, are not part of regular monitoring programs and, thus, long time series over several decades are not available, being a prerequisite to establish robust relationships between target variables and input parameters on a monthly basis. Given the availability of highly resolved LST as well as meteorological data and our interest in a detailed limnological assessment of future changes, we increased the temporal resolution of LST models to a daily basis. However, as far as the relationship between LST and atmospheric parameters such as temperature, precipitation, and snow depth on a daily resolution is concerned, nonlinear dependencies appear. Recent literature discusses various approaches and algorithms that can represent nonlinear relationships, most of them representing machine learning approaches such as tree models (Breiman, 2001) or neural networks (McCulloch and Pitts, 1943). In this project, Generalized Additive (Mixed) Models (Hastie and Tibshirani, 1990) are chosen for modeling LSTs due to both their high flexibility in model building and high interpretability.

3.2.1 General Additive Models (GAMs)

The mathematical structure of GAMs shares a high similarity to the one of linear regression and is represented by:

$$y_i = \beta_0 + \sum_j s_j(x_{ji}) + \epsilon_i \tag{1}$$

with y_i being the target variable, x_{ji} representing the predictors, s_j depicting smooth functions and ϵ_i illustrating the random error with $\epsilon_i \sim N(0, \sigma^2)$. Within GAMs, non-linear dependencies are estimated by using splines. These are defined as functions consisting of basis functions b_k weighted with coefficients β_k:

$$s(x) = \sum_{k=1}^{K} \beta_k b_k(x) \tag{2}$$

Depending on the characteristics of input features, it multiple types of basis functions can be chosen, e.g. cubic, cyclic or thin plate splines. Since they are not constrained by the assumption of linearity, these smooth functions allow to follow the shape of the data much more accurately.

The usage of splines with numerous basis functions may, however, easily lead to overfitting. This can be avoided by applying a penalty term representing the wiggliness of the fitted function:

$$\int_R [f'']^2 dx = \beta^T S \beta \tag{3}$$

with f'' exhibiting the curvature of the fitted function, β being the basis functions' weights and S representing the so-called penalty matrix. Therefore, the penalised fit is represented as:

$$\mathcal{L}_p(\beta) = \mathcal{L}(\beta) - \frac{1}{2}\lambda \beta^T S \beta \tag{4}$$

where λ described the weight of the penalty term.

3.2.2 General Additive Mixed Models (GAMMs)

As GAMs rely on the assumption that investigated data points are independent, they are not valid for time-series modeling. GAMMs feature the same flexibility as GAMs in terms of integrating splines, but they additionally account for the correlation between data points. This can be achieved by the specification of various types of correlation structures (Wood, 2004).

Unlike Autoregressive Integrated Moving Average processes, there is no necessity to difference or detrending time series when using GAMMs as those elements can correctly be taken into account as part of the model, i.e. including month and date as predictor for the consideration of seasonality.

We perform the data pre-processing steps using the Python modules pandas and xarray. LST models are built and applied by using R's mgcv package.

3.3 Model selection and validation process

The model selection process is characterized by a iterative identification of most suitable model parameters, followed by a cross validation procedure. This process is performed for every lake separately.

The first step consists of choosing suitable splines that best represent the non-linear relationship between the target variable and each of the investigated predictors, i.e. LST and respective meteorological parameters. In this study, we use different meteorological input variables (for details please refer to section 2.3.1): (i) daily minimum as well as maximum temperature (extracted from SPARTACUS), (ii) daily precipitation totals (extracted from SPARTACUS) and (iii) daily information on snow depth (extracted from SNOWGRID). Since the lakes' response to atmospheric parameters may be time-lagged, both 14 and 30 day mean values of considered variables were also incorporated. To account for seasonality we additionally include the day of year as a feature to our model. We use the default thin plate splines (Wood, 2003) in the R package mgcv as basis functions for the splines of meteorological parameters; for the day of the year, however, we employ cyclic cubic splines to account for its cyclicity. The complexity or wiggliness of splines is controlled by the k parameter which determines the dimensionality of the basis expansion for thin plate splines and the number of knots in case of cyclic cubic splines. The penalty of the model, which is employed to avoid overfitting, is represented by λ and can either be defined by the generalized cross-validation or by restricted maximum likelihood (REML) and maximum likelihood, respectively. In this study, we employed REML which offers a better solution as it has been shown to be much more robust under smoothing (Wood, 2004, 2011, 2017). The models' summary - that is available in R's mgcv package - provides information about the complexity of fitted splines for each parameter as well as its significance in the model. Moreover, the performance of the fitted model on the training data is given as the *R-squared value* and the *deviance explained*, respectively. For the determination of the model performance on the unseen test data, we employed a time series cross-validation, i.e. we trained our models on the first 80 % of the time series data and tested it on the last 20 %.

Model tuning and validation was performed separately for each lake by using R's mgcv package (Wood, 2017). Hence, the structures as well as significant parameters of individual models feature slight differences.

3.4 Determination of changes in ice cover duration

From the temperature measurements it was evident that the time of vertical mixing in autumn and spring is indicated by the intersection of the two temperature measurement series (surface and maximum depth) at 4°C, both in deep and in shallow lakes. Analogous to the measured data, the beginning and end of the (ice-free) growing season is determined for each year in the future by the respective intersection with 4 °C for all lakes individually.

4 Results

In this section we first focus on the model set up before emphasizing the evolution of LSTs from 2025 until the end of the century considering three climate scenarios. Furthermore, we evaluate the impacts of these changes relating to ice cover changes as well as changes in maximum summer temperatures as these parameters represent important features for further limnological assessments as the lakes' trophic status. In the following, we present outcomes of all analyses carried out for lake *Unterer Giglachsee (UGIG)* as an example.

4.1 Model set up

LST models were trained, tested, and validated for each lake specifically using the methodology described in 3. As part of this process, we could identify statistically significant atmospheric parameters in the LST models. For almost all lakes (except for UKL) the daily minimum temperature plays a decisive role for modeling daily LSTs. In contrast, the daily maximum temperature is an important parameter only for the lakes LAN, OLA and UKL. Likewise, the daily precipitation plays a subordinate role: it is solely considered significant at UKL and MLA. Note that daily snow depth was not found to be important for daily LST at any of the lakes studied. The 14-day means of maximum temperature, precipitation and snow depth, however, turned out to be highly significant for the vast majority of lakes. SCH is particularly striking, being the only lake where the 14-day mean of both precipitation and snow depth are not significant in modeling its LST.

4.2 Projections

Figure 2 represents the main outcome of this study, namely the projections of LSTs until the end of the century accounting for three considered climate scenarios. Dark blue elements refer to the climate-friendly RCP2.6, light blue items represent the RCP4.5 and bright red elements are related to RCP8.5.

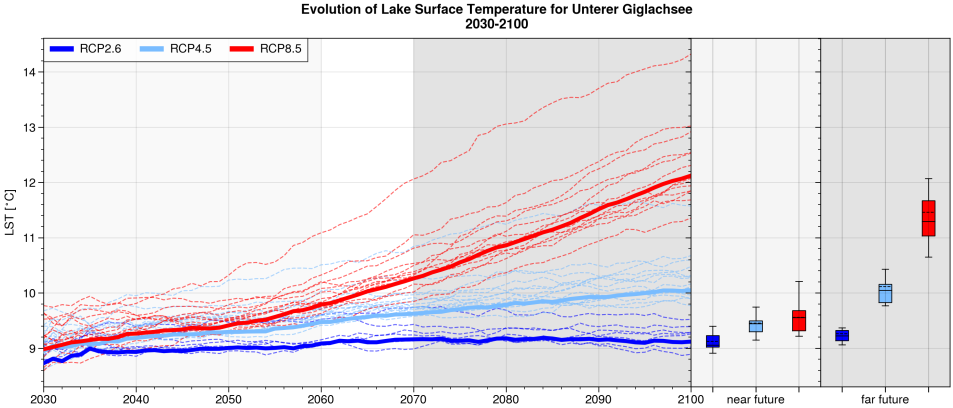
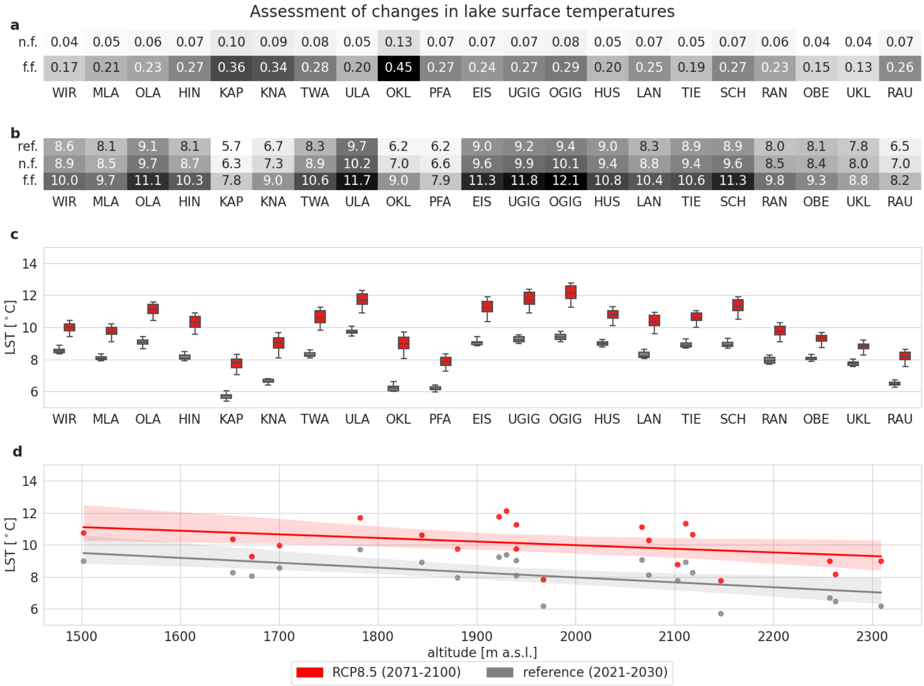


Fig. 2 Evolutions of Lake Surface Temperature for Unterer Giglachsee (1921 m a.s.l.). Solid intense-colored lines depict the ensemble mean of the respective scenario, thin dashed lines exhibit single members of the underlying ensemble. RCP2.6 is represented by dark blue, RCP4.5 by lightblue and RCP8.5 by bright red. The evolution of LSTs is illustrated as 30-year running means.

Figure 2 exhibits the projected course of mean summer LSTs (July to October) for Unterer Giglachsee (1921 m a.s.l.) accounting for all three scenarios from 2030 to 2100. On the left side of this figure, the evolution is shown as a 30-year running mean. The shaded boxes in the background represent two future time periods, i.e. the near future ranging from 2031 to 2060 in light grey and the far future, the period from 2071 to 2100 in dark grey. The intense-colored solid lines refer to the ensemble mean of the considered scenario; light-colored dashed lines represent the single runs of the respective scenario, i.e. 8 runs for

RCP2.6, 13 runs for RCP4.5 and 16 runs for RCP8.5. The boxplots on the right panel illustrate the distribution of mean values in both the near and the far future periods, featuring the mean (dashed line) and median (solid line) of the underlying ensemble.

Due to the inertia of the climate system and identical to the evolution of air temperature in Global Circluation Model (GCM) data, projected LSTs for all considered scenarios agree somewhat on same climatic conditions on the first half of the century. Starting from the 2050s onwards, however, scenarios begin to reveal differences in their evolution. While RCP2.6 trends remain at the same level until the end of the century, RCP4.5 and RCP8.5 both feature significant temperature increases. In the case of UGIG, RCP2.6 projects a summer mean surface temperature of around 9.2°C at the end of the century which equals the conditions that are expected in the near future. Outcomes for RCP4.5 shows an increase in LSTs from 9.4 °C in the near to 10 °C in the far future period. Considering RCP8.5, however, differences between the near and the distant future periods are more pronounced. While projections of this scenario in the near future exhibit summer mean LSTs of around 9.6 °C, those in the far future nearly reach 11.5 °C in terms of the ensemble median over the 30-year distribution of mean values.



	WIR	MLA	OLA	HIN	KAP	KNA	TWA	ULA	OKL	PFA	EIS	UGIG	OGIG	HUS	LAN	TIE	SCH	RAN	OBE	UKL	RAU
n.f.	0.04	0.05	0.06	0.07	0.10	0.09	0.08	0.05	0.13	0.07	0.07	0.07	0.08	0.05	0.07	0.05	0.07	0.06	0.04	0.04	0.07
f.f.	0.17	0.21	0.23	0.27	0.36	0.34	0.28	0.20	0.45	0.27	0.24	0.27	0.29	0.20	0.25	0.19	0.27	0.23	0.15	0.13	0.26

	WIR	MLA	OLA	HIN	KAP	KNA	TWA	ULA	OKL	PFA	EIS	UGIG	OGIG	HUS	LAN	TIE	SCH	RAN	OBE	UKL	RAU
ref.	8.6	8.1	9.1	8.1	5.7	6.7	8.3	9.7	6.2	6.2	9.0	9.2	9.4	9.0	8.3	8.9	8.9	8.0	8.1	7.8	6.5
n.f.	8.9	8.5	9.7	8.7	6.3	7.3	8.9	10.2	7.0	6.6	9.6	9.9	10.1	9.4	8.8	9.4	9.6	8.5	8.4	8.0	7.0
f.f.	10.0	9.7	11.1	10.3	7.8	9.0	10.6	11.7	9.0	7.9	11.3	11.8	12.1	10.8	10.4	10.6	11.3	9.8	9.3	8.8	8.2

Fig. 3 Assessment of the influence of climate change on summer LST considering the scenario RCP8.5. Subplot a) represents the percentage change of LSTs for the near future (n.f.; 2031-2060) as well as the far future (f.f., 2071-2100) compared with the reference period (ref; 2021-2030); b) reveals mean summer LSTs in all three time peiods; c) exhibits the distribution of summer LSTs for the reference period (grey) and the far future under RCP8.5; d) shows the LST-altitude relationship between the reference (grey) and far future (red) period.

Figure 3 displays the project mean summer LSTs for all considered lakes in the far future under RCP8.5 compared to the reference period. Lakes are ordered in terms of their trophic state with WIR representing the most oligotrophic lake. It can be seen that climate change impacts the lakes differently. Whereas high-altitude lakes will show only a slight warming of about 1 °C, lakes at lower elevation like HUS exhibit pronounced warming at the end of the century of more than 2 °C, respectively (median values).

4.3 Influence of climate warming on limnological development

4.4 Changes in ice cover duration

For the following analyses, the focus will again be laid on the far future period, taking into account the 'worst-case' scenario RCP8.5. Using the example of UGIG in the Niedere Tauern, differences between the reference and future periods can be identified in the projected annual course of the LST. These detailed analyses are possible due to the high (daily) temporal resolution of LST models. Examination of LST trends over the course of the year serves as a basis for determining future changes in the length of the ice-free period and the ice cover duration, respectively. The LST evolution during the year for UGIG is displayed in Figure 4. The gray lines represent the reference period from 2020 to 2030; the red lines refer to RCP8.5 in the far future period. The dashed lines illustrate the 15th and 85th quantiles, respectively, while the solid lines show the median of the underlying ensemble.

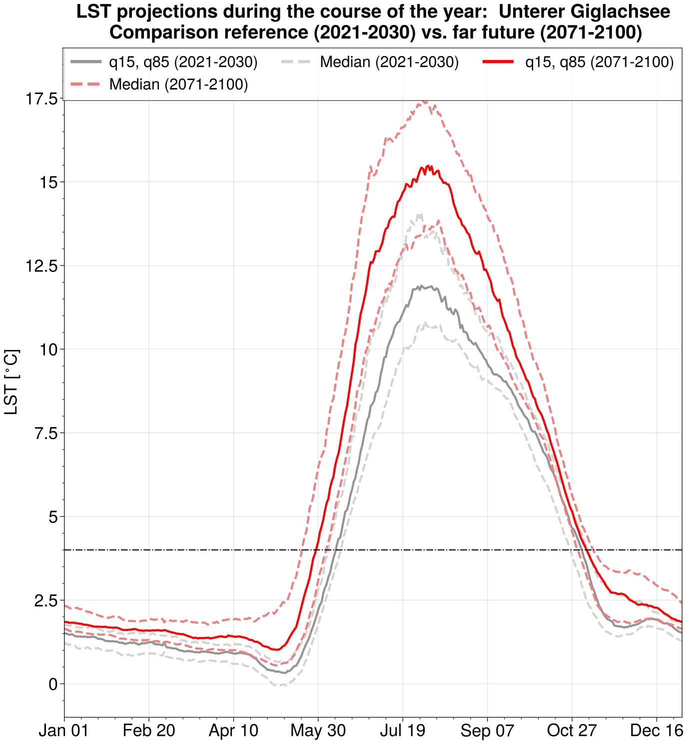


Fig. 4 Course of LST projections throughout the year for UGIG. Grey lines refer to the reference period. Dark lines correspond to the ensemble mean, light grey lines represent the 15th and 85th quantile of the underlying distribution. Red lines, showing the projections for RCP8.5 in the far future period, share same properties. The black dashed line refers to 4°C, an indicator for ice-off and ice-on dates, respectively.

The differences between the LSTs in the reference period and RCP8.5 in the far future are subject to seasonal variations. Surface temperature modeling usually shows a very steep temperature rise in May or June, which reaches a plateau in July and August and drops again similarly steeply in September and October (Figure 4). The differences between the projections and the reference period are largest during the summer months with about 4 °C difference between the respective median values (4). While August temperatures are projected to be 11 °C during the reference period, these are, however, projected to increase to 15 °C by the end of the century accounting for RCP8.5.

Annual temperature trends with daily resolution can further be employed to determine changes in the ice cover duration of the lakes studied. We identify that the lakes react rather distinctively to the altering climate conditions associated with RCP8.5 (Fig. 5). Looking at the relative changes in mean ice cover duration, we find that differences in the near future are equally slight across all lakes compared to the reference period. However, a more pronounced variability between lakes can be discerned for the far future. While Unterer Klaffersee (UKL) indicates only a small decrease of 3% in ice cover duration, the decrease for Eiskarsee (EIS) is pronounced at 27%. This is also represented in panel b of Fig. 5, showing the absolute values of ice cover duration for all three periods. In the case of the EIS, the ice cover duration is reduced from about 300 days per year in the reference period and the near future, respectively, to under 220 days in the far future. UKL, however, features the weakest decline in ice cover time, with only about 8 days difference between the reference period and the distant future.

As we use ensembles of climate projections for future LST estimations, we obtain distributions of possible evolutions in ice cover time which are presented in panel c. This chart again shows a high variability between lakes with some lakes (e.g., Hin, UGIG and UKL) featuring only a small uncertainty while the evolution for others (e.g. OKL and WIR) is characterized by higher uncertainty. Furthermore, it can be stated that the principal linear (atmospheric) influence of altitude on the duration of the ice-cover period remains in the far future, i.e., the regression line shifts practically in parallel (see panel d).

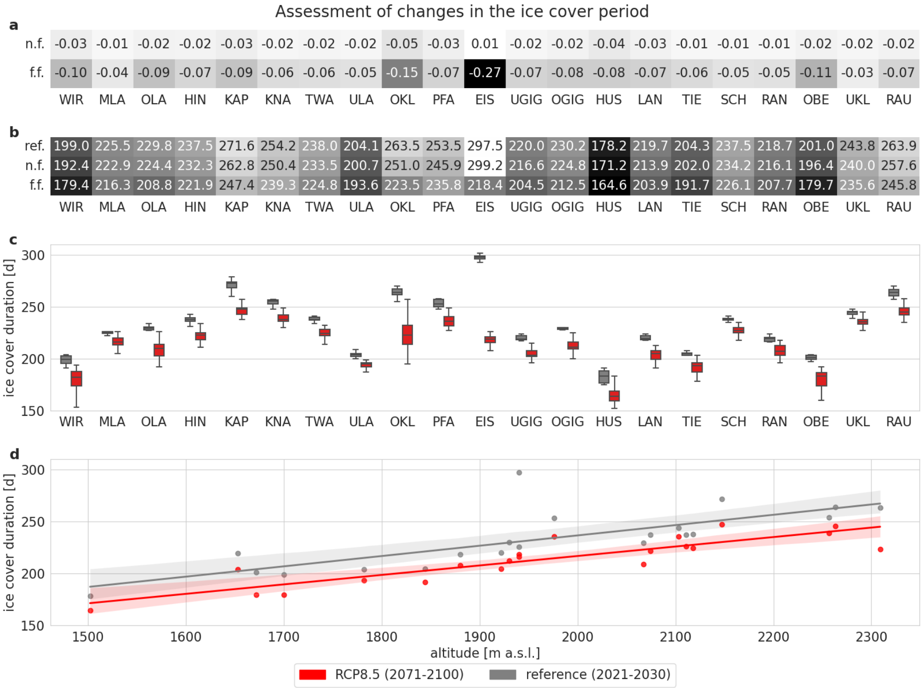
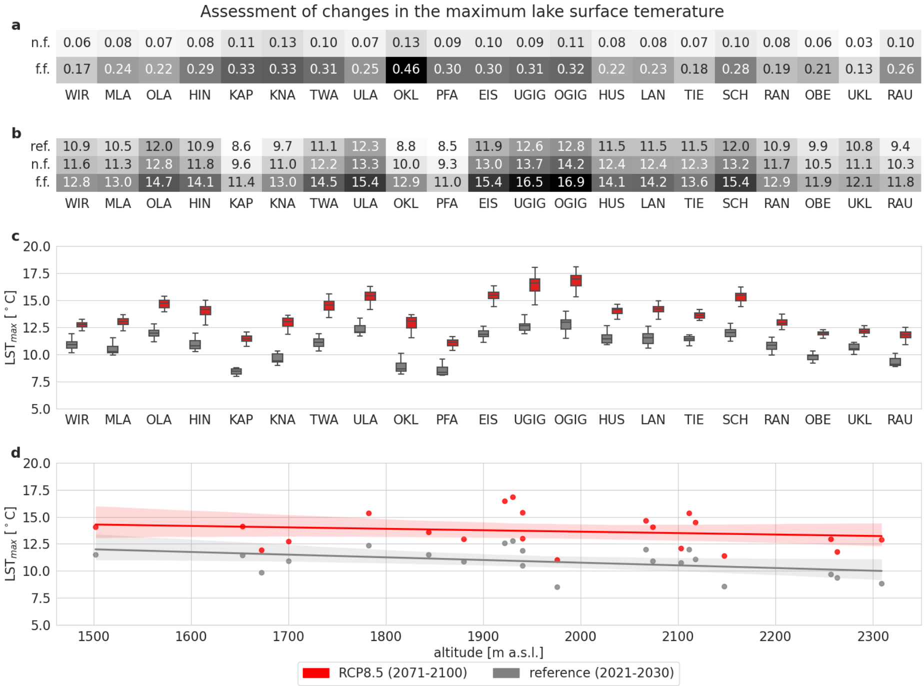


Fig. 5 Assessment of the influence of climate change on the ice cover duration considering the scenario RCP8.5. Subplot a) represents the percentage change of mean LSTs for the near future (n.f.; 2031-2060) as well as the far future (f.f., 2071-2100) compared with the reference period (ref; 2021-2030); b) reveals absolute mean summer LSTs in all three time periods; c) exhibits the distribution of summer LSTs for the reference period (grey) and the far future under RCP8.5; d) shows the LST-altitude relationship between the reference (grey) and far future (red) period.

4.5 Changes in maximum LST

As maximum temperatures can have a disruptive effect on the lake ecosystem and may lead to the extinction of entire populations, we evaluated the changes of maximum LST values (LST_{max}; Fig. 6). Inspecting relative changes (panel a), we can see that rises in LST_{max} in the near future are weakly marked; however, increases are more pronounced in the far future period and highest with OKL exhibiting 46 %. While the majority of lakes show an increase of about 30%, WIR and UKL feature the least percentage change of 17 and 13%, respectively. Absolute values (Panel b) reveal that LST_{max} increases by 1.3 up to 4.1 °C across all lakes, indicating that temperature maxima between 15to 17 °C will be relatively common at the surface of lakes in the future. The distribution of ensemble members displays only a very small uncertainty for all of them, indicating both high consistency and high robustness of the results (Panel c). There is also a dependence between maximum temperature and altitude, which is, however, less pronounced than that of ice cover duration. Nonetheless, this relationship will persist in the far future period.



	WIR	MLA	OLA	HIN	KAP	KNA	TWA	ULA	OKL	PFA	EIS	UGIG	OGIG	HUS	LAN	TIE	SCH	RAN	OBE	UKL	RAU
n.f.	0.06	0.08	0.07	0.08	0.11	0.13	0.10	0.07	0.13	0.09	0.10	0.09	0.11	0.08	0.08	0.07	0.10	0.08	0.06	0.03	0.10
f.f.	0.17	0.24	0.22	0.29	0.33	0.33	0.31	0.25	0.46	0.30	0.30	0.31	0.32	0.22	0.23	0.18	0.28	0.19	0.21	0.13	0.26

	WIR	MLA	OLA	HIN	KAP	KNA	TWA	ULA	OKL	PFA	EIS	UGIG	OGIG	HUS	LAN	TIE	SCH	RAN	OBE	UKL	RAU
ref.	10.9	10.5	12.0	10.9	8.6	9.7	11.1	12.3	8.8	8.5	11.9	12.6	12.8	11.5	11.5	11.5	12.0	10.9	9.9	10.8	9.4
n.f.	11.6	11.3	12.8	11.8	9.6	11.0	12.2	13.3	10.0	9.3	13.0	13.7	14.2	12.4	12.4	12.3	13.2	11.7	10.5	11.1	10.3
f.f.	12.8	13.0	14.7	14.1	11.4	13.0	14.5	15.4	12.9	11.0	15.4	16.5	16.9	14.1	14.2	13.6	15.4	12.9	11.9	12.1	11.8

Fig. 6 Assessment of the influence of climate change on maximum lake surface temperatures considering the scenario RCP8.5. Subplot a) represents the percentage change of maximum LSTs for the near future (n.f.; 2031-2060) as well as the far future (f.f., 2071-2100) compared with the reference period (ref; 2021-2030); b) reveals absolute maximum summer LSTs in all three time periods; c) exhibits the distribution of maximum summer LSTs for the reference period (grey) and the far future under RCP8.5; d) shows the LST-altitude relationship between the reference (grey) and far future (red) period.

5 Discussion

Our study focuses the evolution of lake surface temperature until the end of the century for 21 high alpine lakes in the Niedere Tauern region in Austria. To cover the entire range of possible developments, we applied derived LST models to three different climate scenarios, i.e. RCP2.6, RCP4.5 and RCP8.5. Our analyses reveal - depending on the scenario - more or less pronounced alterations in the temperature regime of investigated lakes. We presented the results and derived limnological assessments employing the ”worst-case” scenario RCP8.5.

Implemented models feature a daily resolution and couple the target variable (LST) with atmospheric covariates derived from two gridded observational data sets. We do not only consider daily values of minimum and maximum temperature, precipitation totals and snow depth, but additionally account for their 14-day and 30-day mean values. The 14-day means of meteorological parameters were found to be significant in the model evaluation which is line with Ohlendorf et al (2000) who identified a time lag of 15 days between air and water temperature for a high alpine lake in Switzerland. For each of the 21 lakes studied, a separate model was implemented by applying so-called General Additive Models.

Results indicate that while all lakes will warm significantly by the end of the century, there are differences in individual warming rates with higher lakes warming considerably less than lower lakes.

This higher resistance of the higher altitude lakes can be explained mainly by the influence of two parameters: temperature and snow depth. However, while future temperature increases significantly at elevations above 2500 m, most precipitation at these elevations continues to fall in solid form as snow, having a cooling effect on the lake temperature. This is in line with Gobiet et al (2022) who point out that most pronounced climatic changes in the alpine terrain are to be expected at altitudes up to 1500 m a.s.l., where the mean snow cover duration in Austria has already decreased by about 40 days since 1961. As climate change progresses, it is expected that the 0 °C as well as the snow line will shift further upwards in the future. Moreover, precipitation will fall in liquid form for most of the year in the mid-altitudes (Gobiet et al, 2022).

Climatic change has both direct and indirect consequences for the limnological development of lakes. The direct consequences include above all the average temperature change in the water column as well as alterations in both temperature extremes and ice cover duration. Indirect consequences are, for example, the stability of the water column, which controls mixing behavior in deep lakes, but also the development of vegetation in the shore area or catchment, which in turn alters runoff or nutrient input. For reasons of complexity and clarity, the focus of this study lies primarily on the projected direct effects of climate warming, particularly the duration of ice cover and the evolution of LST maxima.

The ice cover duration is an important limnological indicator and strongly altitude-dependent. Due to the altitudinal gradient of both snow and temperature conditions in the future, elevation has a positive effect with higher elevation lakes clearing ice later in the season than lower elevation lakes. The average ice cover duration for all lakes examined in this study is currently 211 days. However, the precise ice-on and ice-off dates vary strongly with altitude and show freezing dates between the end of October to the beginning of November as well as ice break-up dates between the end of May and the beginning of July.

The high temporal resolution of established models within this study allows to assess changes in the future evolution of the ice cover period and their meteorological drivers. In our analyses, the 14-day mean of both the prevailing snow depth as well as maximum temperature were found to be significant for the LST evolution and, hence, for the ice cover duration of almost all investigated lakes. This corresponds to findings of Preston et al (2016) who indicates spring snowfall to be the most strongly linked variable to ice-off timing. Moreover, they concluded that decreases in snowfall as well as increases in air temperature - particularly during spring – both accelerated the ice-off process.

Particularly for individual lakes at lower elevations with little snow cover in their catchment, the ice-free period will last significantly longer in the far future period. This can be inferred from the yearly LST course as a less steep temperature rise at the beginning of the year to the temperature maximum in July and August and a gradual decline at the end of the year. For these lakes, the formation of an ice (and snow) cover is unlikely, at least in individual years in the far future period.

The implications of a shortened ice cover period are multifaceted for the high alpine lake ecosystem and cover physical, chemical and biological consequences. As for limnological impacts, decreasing ice cover duration leads to the prolongation of the photosynthetic activity, starting earlier in spring and continuing later in fall. The elongation of algae growth leads to altering chemical conditions, i.e. the increase of chlorophyll a concentrations in the lakes. This change in chlorophyll a concentrations entails a shift in the lakes' trophic level from oligotrophic to mesotrophic conditions.

These higher concentrations may lead to the reduction of the so-called Secchi-depth, an indicator for the lakes' transparency. Water clarity is generally emphasized as an important ecological feature in mountain lakes, so the magnitude of the reduction in viewing depth may be considered an important gauge of anticipated change due to climate warming.

As indicated by Preston et al (2016), earlier ice-off years also lead to higher mean and maximum surface temperatures. Climatic effects on maximum temperatures feature, as single extremes, a much greater variability than the average lake temperature as a higher temporal resolution is necessary.

According to Gao and Stefan (1999), maximum temperature is the most important parameter for the ecology of lakes as habitat restrictions. Maximum temperatures were also found to be of highest importance for the distribution of fish species (Roubeix et al, 2017). The occurrence of high temperatures causes a number of processes to be initiated in lakes. In extreme cases, temperature maxima can have a disruptive effect and lead to the extinction of entire populations in the absence of refugia (e.g., in a shallow water body).

6 Conclusion

In this study we used time series of LST measurements and gridded meteorological datasets to establish LST models for 21 high alpine lakes in the Austrian Niedere Tauern region. Using regional climate models, we subsequently employed these models to project the evolution of lake surface temperatures to the year 2100, accounting for three different climate scenarios (i.e. RCP2.6, RCP4.5 and RCP8.5). Results for the worst-case scenario RCP8.5 indicate that all lakes will experience substantial warming in the second half of the century, with lakes at altitudes around 1500 m warming stronger than those above 2000 m. The average temperature rise over all 21 lakes features a warming of 2.23 °C in the far future period (2071 - 2100) compared to the reference from 2021 to 2030. These altering conditions impact the lakes' limnological conditions. The average ice cover period will shorten from 211 days in the present to xxx days in the far future and, thus, impose changes on the ecosystem function by, e.g., altering the lakes' trophic status from oligotrophic towards mesotrophic conditions. Furthermore, longer ice-free periods will induce higher maximum temperatures during summer months, being an important parameter for the lakes' ecology.

Supplementary information.

Declarations

The authors declare no conflict of interest.

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Appendix A Section title of first appendix

References

Battarbee RW, Kernan M, Rose N (2009) Threatened and stressed mountain lakes of europe: assessment and progress. Aquatic Ecosystem Health & Management 12(2):118–128

Breiman L (2001) Rand forests. Machine Learning 45(1):5–32. https://doi.org/10.1023/a:1010933404324, URL https://doi.org/10.1023/a:1010933404324

Chimani B, Heinrich G, Hofstätter M, et al (2016) Endbericht ÖKS15 – Klimaszenarien für Österreich. Daten - Methoden - Klimaanalyse. Tech. rep., CCCA Data Centre

Colvin SA, Sullivan SMP, Shirey PD, et al (2019) Headwater streams and wetlands are critical for sustaining fish, fisheries, and ecosystem services. Fisheries 44(2):73–91

Dokulil M (2018) Alpenrandseen im anthropocän: Verschlechterung und sanierung-eine österreichische erfolgsgeschichte. ACTA Zoobot Austria

Dokulil MT (2013) Predicting summer surface water temperatures for large austrian lakes in 2050 under climate change scenarios. Hydrobiologia 731(1):19–29. https://doi.org/10.1007/s10750-013-1550-5, URL https://doi.org/10.1007/s10750-013-1550-5

Dynowski P, Senetra A, Źróbek-Sokolnik A, et al (2019) The impact of recreational activities on aquatic vegetation in alpine lakes. Water 11(1):173

Gao S, Stefan HG (1999) Multiple linear regression for lake ice and lake temperature characteristics. Journal of Cold Regions Engineering 13(2):59–77. https://doi.org/10.1061/(asce)0887-381x(1999)13:2(59), URL https://doi.org/10.1061/(asce)0887-381x(1999)13:2(59)

Gobiet A, Abbeg B, Koch R, et al (2022) Future perspectives of natural and technical snow in austria. EGU General Assembly 2022 https://doi.org/10.5194/egusphere-egu22-11753, URL https://doi.org/10.5194/egusphere-egu22-11753

Grizzetti B, Lanzanova D, Liquete C, et al (2016) Assessing water ecosystem services for water resource management. Environmental Science & Policy 61:194–203

Hastie T, Tibshirani R (1990) Generalized Additive Models -. CRC Press, Boca Raton, Fla

Heddam S, Ptak M, Zhu S (2020) Modelling of daily lake surface water temperature from air temperature: Extremely randomized trees (ERT) versus air2water, MARS, m5tree, RF and MLPNN. Journal of Hydrology 588:125,130. https://doi.org/10.1016/j.jhydrol.2020.125130, URL https://doi.org/10.1016/j.jhydrol.2020.125130

Hiebl J, Frei C (2016) Daily temperature grids for austria since 1961 – concept, creation and applicability. Theoretical and Applied Climatology 124(1):161–178. https://doi.org/10.1007/s00704-015-1411-4

Hiebl J, Frei C (2018) Daily precipitation grids for austria since 1961 – development and evaluation of a spatial dataset for hydroclimatic monitoring and modelling. Theoretical and Applied Climatology 132(1):327–345. https://doi.org/10.1007/s00704-017-2093-x

Huber UM, Bugmann HK, Reasoner MA (2006) Global Change and Mountain Regions - An Overview of Current Knowledge. Springer Science & Business Media, Berlin Heidelberg

Jacob D, Petersen J, Eggert B, et al (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. Regional Environmental Change 14(2):563–578. https://doi.org/10.1007/s10113-013-0499-2

Kamenik C, Schmidt R, Kum G, et al (2001) The influence of catchment characteristics on the water chemistry of mountain lakes. Arctic, Antarctic, and Alpine Research 33:404. https://doi.org/10.2307/1552549

Livingstone D (2003) Impact of secular climate change on the thermal structure of a large temperate central european lake. Climatic Change 57:205–225. https://doi.org/10.1023/A:1022119503144

Livingstone DM, Dokulil MT (2001) Eighty years of spatially coherent austrian lake surface temperatures and their relationship to regional air temperature and the north atlantic oscillation. Limnology and Oceanography 46(5):1220–1227. https://doi.org/10.4319/lo.2001.46.5.1220

Livingstone DM, Lotter AF (1998) The relationship between air and water temperatures in lakes of the swiss plateau: a case study with paleolimnological implications. Journal of Paleolimnology 19(2):181–198. https://doi.org/10.1023/A:1007904817619

Livingstone DM, Lotter AF, Walkery IR (1999) The decrease in summer surface water temperature with altitude in swiss alpine lakes: A comparison with air temperature lapse rates. Arctic, Antarctic, and Alpine Research 31(4):341–352. https://doi.org/10.1080/15230430.1999.12003319, URL https://doi.org/10.1080/15230430.1999.12003319

Livingstone DM, Lotter AF, Kettle H (2005) Altitude-dependent differences in the primary physical response of mountain lakes to climatic forcing. Limnology and Oceanography 50(4):1313–1325. https://doi.org/10.4319/lo.2005.50.4.1313

Lotter A, Appleby P, Bindler R, et al (2002) The sediment record of the past 200 years in a swiss high-alpine lake: Hagelseewli (2339 m a.s.l.). Journal of Paleolimnology 28(1):111–127. https://doi.org/10.1023/a:1020328119961, URL https://doi.org/10.1023/a:1020328119961

Matulla C, Tordai J, Schlögl M, et al (2018) Establishment of a long-term lake-surface temperature dataset within the european alps extending back to 1880. Climate Dynamics https://doi.org/10.1007/s00382-018-4479-6

McCulloch WS, Pitts W (1943) A logical calculus of the ideas immanent in nervous activity. The bulletin of mathematical biophysics 5(4):115–133

Meisch C, Schirpke U, Huber L, et al (2019) Assessing freshwater provision and consumption in the alpine space applying the ecosystem service concept. Sustainability 11(4):1131

Niedrist GH, Psenner R, Sommaruga R (2018) Climate warming increases vertical and seasonal water temperature differences and inter-annual variability in a mountain lake. Climatic Change 151(3-4):473–490. https://doi.org/10.1007/s10584-018-2328-6, URL https://doi.org/10.1007/s10584-018-2328-6

Novikmec M, Svitok M, Kočický D, et al (2013) Surface water temperature and ice cover of tatra mountains lakes depend on altitude, topographic shading, and bathymetry. Arctic Antarctic and Alpine Research 45:77–87. https://doi.org/10.1657/1938-4246-45.1.77

Ohlendorf C, Bigler C, Goudsmit GH, et al (2000) Causes and effects of long periods of ice cover on a remote high alpine lake. Journal of Limnology 59(1s). https://doi.org/10.4081/jlimnol.2000.s1.65, URL https://doi.org/10.4081/jlimnol.2000.s1.65

Olefs M, Schöner W (2012) A new solar radiation model for research and applications in austria. EGU General Assembly 2012, held 22-27 April, 2012 in Vienna, Austria, p9705

Olefs M, Koch R, Schöner W, et al (2020) Changes in snow depth, snow cover duration, and potential snowmaking conditions in austria, 1961–2020—a model based approach. Atmosphere 11(12):1330. https://doi.org/10.3390/atmos11121330, URL https://doi.org/10.3390/atmos11121330

O'Reilly CM, Sharma S, Gray DK, et al (2015) Rapid and highly variable warming of lake surface waters around the globe. Geophysical Research Letters 42(24):10,773–10,781. https://doi.org/10.1002/2015GL066235, 2015GL066235

Pachauri RK, Allen MR, Barros VR, et al (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland

Piccolroaz S (2016) Prediction of lake surface temperature using the air2water model: guidelines, challenges, and future perspectives. Advances in Oceanography and Limnology 7(1). https://doi.org/10.4081/aiol.2016.5791, URL https://doi.org/10.4081/aiol.2016.5791

Piccolroaz S, Toffolon M, Majone B (2013) A simple lumped model to convert air temperature into surface water temperature in lakes. Hydrology and Earth System Sciences 17(8):3323–3338. https://doi.org/10.5194/hess-17-3323-2013, URL https://doi.org/10.5194/hess-17-3323-2013

Prats J, Danis PA (2019) An epilimnion and hypolimnion temperature model based on air temperature and lake characteristics. Knowledge & Management of Aquatic Ecosystems 420:8. https://doi.org/10.1051/kmae/2019001, URL https://doi.org/10.1051/kmae/2019001

Preston DL, Caine N, McKnight DM, et al (2016) Climate regulates alpine lake ice cover phenology and aquatic ecosystem structure. Geophysical Research Letters 43(10):5353–5360. https://doi.org/10.1002/2016gl069036, URL https://doi.org/10.1002/2016gl069036

Ptak M, Wrzesiński D, Choiński A (2017) Long-term changes in the hydrological regime of high mountain lake morskie oko (tatra mountains, central europe). Journal of Hydrology and Hydromechanics 65(2):146–153. https://doi.org/10.1515/johh-2017-0005, URL https://doi.org/10.1515/johh-2017-0005

Quan Q, Hao Z, Xifeng H, et al (2020) Research on water temperature prediction based on improved support vector regression. Neural Computing and Applications 34(11):8501–8510. https://doi.org/10.1007/s00521-020-04836-4, URL https://doi.org/10.1007/s00521-020-04836-4

Rogora M, Frate L, Carranza M, et al (2018) Assessment of climate change effects on mountain ecosystems through a cross-site analysis in the alps and apennines. Science of The Total Environment 624:1429–1442. https://doi.org/10.1016/j.scitotenv.2017.12.155, URL https://doi.org/10.1016/j.scitotenv.2017.12.155

Roubeix V, Daufresne M, Argillier C, et al (2017) Physico-chemical thresholds in the distribution of fish species among french lakes. Knowledge &amp Management of Aquatic Ecosystems (418):41. https://doi.org/10.1051/kmae/2017032, URL https://doi.org/10.1051/kmae/2017032

Schirpke U, Meisch C, Marsoner T, et al (2018) Revealing spatial and temporal patterns of outdoor recreation in the european alps and their surroundings. Ecosystem services 31:336–350

Schmeller DS, Loyau A, Bao K, et al (2018) People, pollution and pathogens–global change impacts in mountain freshwater ecosystems. Science of the Total Environment 622:756–763

Tallar RY, Suen JP (2017) Measuring the aesthetic value of multifunctional lakes using an enhanced visual quality method. Water 9(4):233

Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of cmip5 and the experiment design. Bulletin of the American Meteorological Society 93(4):485–498. https://doi.org/10.1175/BAMS-D-11-00094.1

Thies H, Nickus U, Mair V, et al (2007) Unexpected response of high alpine lake waters to climate warming. Environmental Science & Technology 41(21):7424–7429. https://doi.org/10.1021/es0708060, URL https://doi.org/10.1021/es0708060

Thompson R, Kamenik C, Schmidt R (2005) Ultra-sensitive alpine lakes and climate change. Journal of Limnology 64(2):139. https://doi.org/10.4081/jlimnol.2005.139, URL https://doi.org/10.4081/jlimnol.2005.139

Toffolon M, Piccolroaz S, Majone B, et al (2014) Prediction of surface temperature in lakes with different morphology using air temperature. Limnology and Oceanography 59(6):2185–2202. https://doi.org/10.4319/lo.2014.59.6.2185, URL https://doi.org/10.4319/lo.2014.59.6.2185

Vuuren D, Edmonds J, Kainuma M, et al (2011) The representative concentration pathways: an overview. climatic change. this issue. Climatic Change 109:5–31. https://doi.org/10.1007/s10584-011-0148-z

Winkler DE (2019) Contemporary human impacts on alpine ecosystems: The direct and indirect effects of human-induced climate change and land use. In: Encyclopedia of the World's Biomes. Elsevier, p 574–580, https://doi.org/10.1016/b978-0-12-409548-9.11879-2, URL https://doi.org/10.1016/b978-0-12-409548-9.11879-2

Wood SN (2003) Thin-plate regression splines. Journal of the Royal Statistical Society (B) 65(1):95–114

Wood SN (2004) Stable and efficient multiple smoothing parameter estimation for generalized additive models. Journal of the American Statistical Association 99(467):673–686

Wood SN (2011) Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. Journal of the Royal Statistical Society (B) 73(1):3–36

Wood SN (2017) Generalized Additive Models. Chapman and Hall/CRC, https://doi.org/10.1201/9781315370279, URL https://doi.org/10.1201/9781315370279

Woolway RI, Merchant CJ (2017) Amplified surface temperature response of cold, deep lakes to inter-annual air temperature variability. Scientific Reports 7(1). https://doi.org/10.1038/s41598-017-04058-0, URL https://doi.org/10.1038/s41598-017-04058-0

Woolway RI, Weyhenmeyer GA, Schmid M, et al (2019) Substantial increase in minimum lake surface temperatures under climate change. Climatic Change 155(1):81–94. https://doi.org/10.1007/s10584-019-02465-y, URL https://doi.org/10.1007/s10584-019-02465-y

Xu M, Dong X, Yang X, et al (2017) Using palaeolimnological data and historical records to assess long-term dynamics of ecosystem services in typical yangtze shallow lakes (china). Science of the Total Environment 584:791–802

Table A1 Morphological characteristics of investigated lakes in this study

Lake	Abbr	Altitude [m]	Surface area [m^2]	Volume [m^3]	Depth (max) [m]	Data availability
Eiskarsee	EIS	1940	22551	107416	14.2	09/1998 - 08/2003, 09/2019 - 09/2021
Hinterkarsee	HIN	2073	19209	96333	11.3	09/1998 - 07/2003, 09/2019 - 09/2021
Hüttensee	HUS	1502	46189	166128	7.7	08/1998 - 07/2003, 09/2019 - 09/2021
Kapuzinersee	KAP	2146	12252	91039	20	09/1998 - 07/2003, 09/2019 - 09/2021
Knappenkarsee	KNA	2256	13617	41322	8	09/1998 - 07/2003, 09/2019 - 09/2021
Landauersee	LAN	1652	36376	271563	16.6	07/1998 - 07/2003, 09/2019 - 09/2021
Mittlerer Landschitzsee	MLA	1940	66292	626650	20.3	08/1998 - 08/2003, 09/2019 - 09/2021
Oberer Giglachsee	OGIG	1930	35322	182827	10.5	09/1998 - 08/2003, 09/2019 - 09/2021
Oberer Klaffersee	OKL	2309	51220	573844	32.5	09/1998 - 08/2003, 09/2019 - 09/2021
Oberer Landschitzsee	OLA	2067	88811	509710	13.6	08/1998 - 08/2003, 08/2009 - 07/2011
Obersee	OBE	1672	50882	186167	21.6	08/1998 - 08/2003, 08/2009 - 07/2011
Schönalmsee	SCH	2111	72375	801790	23.4	07/1998 - 08/2003, 08/2009 - 07/2011
Pfannsee	PFA	1967	13619	24832	7.7	08/1998 - 08/2003, 08/2009 - 07/2011
Rantensee	RAN	1880	23183	77856	7.6	09/1998 - 07/2003, 08/2009 - 07/2011
Rauenbergsee	RAU	2263	28233	246078	26.3	09/1998 - 08/2003, 08/2009 - 07/2011
Tiefenbachsee	TIE	1844	32231	130028	8	07/1998 - 08/2003, 08/2009 - 07/2011
Twenger Almsee	TWA	2118	31084	399160	33.6	07/1998 - 08/2003, 07/2009 - 08/2011
Unterer Giglachsee	UGIG	1922	168259	1285012	18	09/1998 - 08/2003, 07/2009 - 07/2011
Unterer Klaffersee	UKL	2103	38631	502862	39.6	09/1998 - 08/2003, 07/2009 - 08/2011
Unterer Landschitzsee	ULA	1782	119947	997087	15.8	08/1998 - 08/2003, 07/2009 - 08/2011
Unterer Wirpitschsee	WIR	1700	27211	121038	8	07/1998 - 08/2003, 08/2009 - 07/2011