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Long-term temperature, oxygen and water clarity trends in Swiss lakes

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Abstract. Water temperature, electrical conductivity, dissolved oxygen concentration, and water clarity are key variables routinely measured in Swiss lakes by lake monitoring programs run by cantonal environmental offices and international lake commissions. In most lakes, data is collected at bi-weekly to monthly intervals; however, the data processing pipelines remain largely manual, non-automated, and decentralized, making data access and use difficult. The Swiss Federal Office for the Environment (FOEN) consolidates and stores this information at the national level, but this process is not always done on a regular basis, and the data are not directly accessible to the public. This limited accessibility restricts their use in scientific research, particularly for comparative studies across different lakes. Here, we present a harmonised dataset of temperature, electrical conductivity, dissolved oxygen and Secchi depth (a widely used proxy of water clarity) collected by cantonal offices, and research institutes in 21 large Swiss lakes and lake basins from the beginning of consistent records (between 1938 and 2001 depending on the lake) to the end of 2023. In addition, we provide consistently calculated variables including lake heat content, Schmidt stability, thermocline depth and hypolimnetic oxygen. We used the measured and calculated variables to identify long term trends in large Swiss lakes. Specifically, we investigated whether the effects of climate change and re-oligotrophication led to a coherent pattern across Switzerland or whether the responses varied from lake to lake. We found a clear warming trend in all lakes with consistently increasing mean annual surface (since $\sim$1980) and bottom temperature (since $\sim$2010), heat content, and stronger autumn stratification, which is consistent with expected effects of climate change. Similarly, there is a general trend towards greater water clarity, consistent with re-oligotrophication. Thermocline depth and lake oxygen concentrations showed less clear patterns. For the former, observations indicate modest shifts toward shallower thermoclines in deeper lakes and towards deeper thermoclines in shallower lakes. In contrast, deepwater oxygen concentrations show no consistent trends over recent decades, potentially reflecting opposing influences of climate change and re-oligotrophication. By publishing this data, we aim to advocate for open data policies at national and international levels, facilitating its reuse in further scientific research, and contributing to evidence-based lake management and decision-making. The data presented in this work are available at https://doi.org/10.25678/000GJC (Bärenbold et al., 2026).

1 Introduction

Lake temperature, electrical conductivity, dissolved oxygen concentration, and water clarity are routinely measured in Swiss lake monitoring programs. All these variables are important drivers and indicators of water quality and ecosystem processes. Water temperature controls metabolic activity, influences chemical reactions, and regulates thermal stratification and mixing processes through its influence on density (Jones and Smol, 2023). Electrical conductivity is directly related to the concentration of dissolved ions and can therefore be used to calculate salinity (Jones and Smol, 2023), which in turn, especially in deep lakes, can influence lake overturn (Boehrer and Schultze, 2008). Dissolved oxygen controls redox conditions and thereby constrains the distribution and metabolic strategies of aquatic organisms (Jones and Smol, 2023). Finally, water clarity is strongly influenced by algal biomass and therefore is considered an indicator of lake trophic state. Furthermore, it determines the depth-distribution of incoming sunlight, thus influencing water temperature (Rose et al., 2016), and thermocline depth (Kirillin and Shatwell, 2016; Mazumder et al., 1990).

For most Swiss lakes, the main motivation behind starting and maintaining a consistent monitoring program was the eutrophication crisis caused by excessive phosphorus input into lakes. Lake phosphorus concentrations reached a maximum between 1970 and 1980 in most lakes (Swiss Federal Office for the Environment, 2026), and their most important source were agricultural fertilizers and municipal wastewater. Even though nutrients such as phosphorus and nitrate were historically the main focus of lake monitoring, physical variables were measured alongside them to provide context for the nutrient data and to assess the influence of physical processes. As a consequence, longstanding records of physical variables are available for many large lakes in Switzerland.

In Switzerland, cantonal environmental offices are responsible for monitoring and managing lakes. Lakes that cross the national boundary are monitored and managed by international lake commissions established between the late 1950s and early 1970s: the International Commission for the Protection of Lake Constance (IGKB) for Lake Constance between Germany, Austria and Switzerland (1959), the International Commission for the Protection of the Waters of Lake Geneva (CIPEL) for Lake Geneva between France and Switzerland (1963), and the International Commission for the Protection of Italian-Swiss Waters (CIPAIS) for Lake Maggiore and Lake Lugano between Italy and Switzerland (1972). In turn, these commissions mandate research institutes to perform the field and laboratory measurements of their monitoring (ISF in Langenargen for Lake Constance, INRAE in Thonon-les-Bains together with other private and institutional laboratories for Lake Geneva, SUPSI in Mendrisio for Lake Lugano, and CNR-IRSA in Verbania for Lake Maggiore).

Important considerations for lake monitoring programs include the location of sampling, as well as time and depth resolution. Although lakes are three-dimensional systems, measuring vertical profiles at the deepest point provides a cost-effective long-term monitoring approach because horizontal conditions are typically uniform due to horizontal exchange exceeding vertical exchange by several orders of magnitude (e.g. Imboden and Emerson, 1978). A monthly to seasonal sampling frequency is commonly recommended for monitoring lake trophic status (OECD, 1982), although higher frequency sampling can better capture short-term events and lake overturn timing (Marcé et al., 2016). In Swiss lakes, measurements have been recorded at the deepest location, between 4 and 24 times a year and at various depth resolutions. While initially taken at discrete depths, the introduction and adoption of multiparameter sondes has driven more and more cantons to record and store data at high vertical resolution (typically 1 m).

The decentralized organization of Swiss lake monitoring, with many involved cantons, lake commissions and research institutes, results in a heterogeneous dataset with varying sampling frequencies, depth resolutions, and instrument accuracies. While the data are technically open access, accessing them involves significant practical barriers. The process requires users to have precise knowledge of their data requirements and to submit multiple similar requests to various offices and institutes. This structure reflects the autonomy of individual monitoring programs but also means that users, including researchers, often need to perform their own data harmonization, which can lead to parallel efforts across projects. At the national level, the Swiss Federal Office for the Environment (FOEN) collects lake data periodically. However, both the datasets themselves and their metadata remain difficult to access and often do not include recent observations.

To overcome these limitations, we present here a consistent dataset of water temperature, electrical conductivity, dissolved oxygen concentration and Secchi depth for 21 large lakes and lake basins in Switzerland (Fig. 1), encompassing both Swiss and transboundary lakes (with some sampling stations located outside Swiss territory). The data of Lake Lugano and Lake Maggiore have already been published elsewhere (Capelli et al., 2024a, b; Rogora et al., 2025, 2026) and the data of Lake Constance are made available by BOWIS – Daten aus dem Bodensee-Wasserinformationssystem der Internationalen Gewässerschutzkommission für den Bodensee (IGKB). This harmonized dataset of physical lake variables represents a valuable resource to identify the ongoing consequences of reoligotrophication and climate change. In particular, it can be used to make cross-lake comparisons and draw more general conclusions across Switzerland's lakes.

The lakes included in the dataset vary in size and altitude, with surface areas between 3.3 and 580 km^2, maximum depths from 32 to 372 m, altitudes ranging from 193 to 1004 m a.s.l. (above sea level), and water residence time between less than 1 month and over 15 years (Table 1). Lakes were only included if they had at least 20 years of consistent and regular sampling because annual and seasonal averages cannot be reliably calculated with sparse measurements. We compiled information about measurement equipment and techniques, and related uncertainties in the Methods section where available. The calculation of derived variables, including surface and bottom temperature, surface and bottom dissolved oxygen concentration, thermocline depth, stratification strength (Schmidt stability) and heat content, is detailed in the Methods section and was performed consistently across lakes, with the corresponding scripts publicly available (see the "Data availability" section). Subsequently, we calculated annual and seasonal long-term trends of measured and derived variables, which are presented and discussed in the Results and Discussion section. Because many different variables (including trends for different seasons) were calculated and investigated in this work, we can only show and discuss a small subset of them. For the other variables and seasons, the reader is referred to the data repository (see the "Data availability" section).

2 Methods

2.1 Sampling and measurement methods, resolution and location

The cantonal environmental offices and the research institutes mandated by lake commissions perform long-term lake monitoring at the deepest location of the respective lake or lake basin (see Table 1 for sampling coordinates). Although earlier records are available for many lakes, consistent monitoring programs often started between the 1980s and 1990s, mostly relying on traditional field and laboratory methods like inverse mercury-filled thermometers for water temperature, various laboratory instruments for conductivity, and Winkler titration for dissolved oxygen concentration (see Table S1 in the Supplement for details). In the early 2000s, many institutions switched to multiparameter sondes, although additional conductivity and oxygen measurements are often still carried out in the laboratory using water samples (Table S1).

The temperature, conductivity and oxygen measurement methods mostly have manufacturer-specified accuracies between 0.002 and 0.2 °C, 1 and 10 $\mu S\,cm^{-1}$, and 0.1–0.2 $mg\,L^{-1}$ (or 1 %–2 %), respectively. The uncertainty of oxygen measurement using Winkler titration in the laboratory is comparably high, with 2 %–6 % according to the norm DIN EN 25813:1993-01 (DIN, 1993), although it can reach a theoretical accuracy of around 0.1 % according to Carpenter (1965). However, the measurements by multiparameter sondes can have a higher uncertainty than specified. For example, measurement uncertainty is influenced by sensor response time in relation to sonde sinking speed, and, most importantly, sensor drift, which can be controlled by good maintenance/calibration practices. However, detailed information about sensor calibration and validation is usually not consistently available for monitoring programs, especially for measurements that took place many decades ago. Some more information is available in Sects. S2 and S3 in the Supplement, including results of intercomparison tests between multiparameter sondes used by different cantons and institutes.

Details about Secchi depth measurements are not included in Table S1 because there is often no information available about this. However, it can be assumed that most cantonal offices and institutes use standard Secchi disks.

2.2 Central gathering and data curation

The data were made available by cantons and international lake commissions in various text and Excel formats. A collection of python scripts was developed and used to transform raw data into a common data format (Level 0). Subsequently, all data were quality-checked visually, and erroneous data, including obvious typing errors and sensor issues, were removed (Level 1). The resulting cleaned dataset was used in the next section to calculate physical variables (Level 2), annual and seasonal averages (Level 3) and linear and non-linear trendlines.

2.3 Calculation of surface and bottom averages and derived physical variables

We defined surface and bottom values of measured variables (e.g., temperature and oxygen) as the average between 0 and 1 m and the lowest 10 % of the water column, respec-

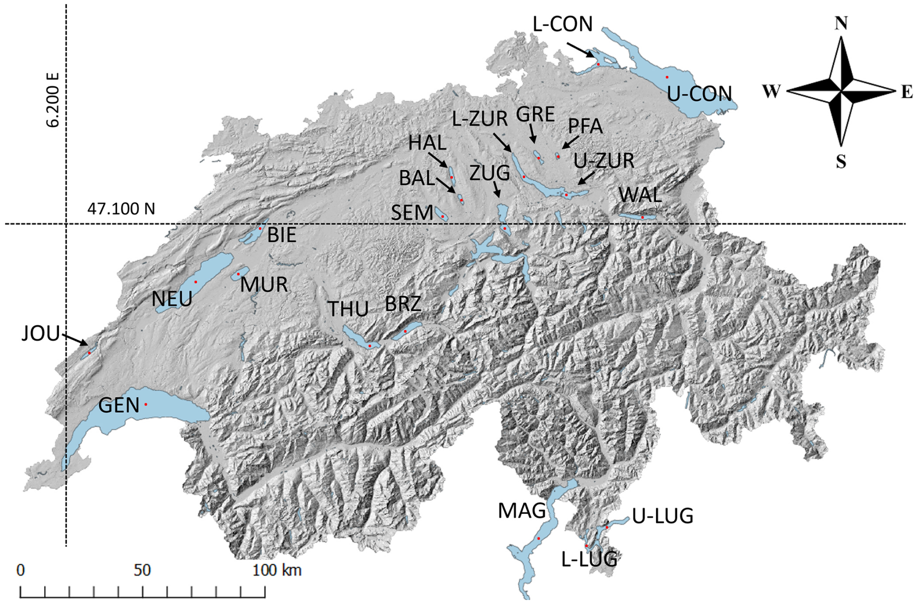

Figure 1. Map showing the 21 lakes and lake basins included in this study including the sampling points (red dots). The lake codes are explained in Table 1 (hillshade map data from Federal Office of Topography swisstopo).

Table 1. General information about the 21 lakes and lake basins included in this study. Maximum depth, area and altitude information are compiled from maps and records of cantonal offices and research institutes. Residence time is taken from Kiefer et al. (2021), sampling point location is provided by cantonal offices and research institutes, and mean conductivity is calculated as depth-average using the monitoring data between 2000 and 2023. Information about mixing and ice cover is derived from the data of this publication and from ice records of cantonal offices. For ice cover, the asterisk means that winter ice cover only occurs occasionally.

Code	Name	Max. depth m	Area km^2	Altitude m a.s.l.	Residence time yr	Sampling point N/E	Conductivity $\mu S\,cm^{-1}$ at 25 °C	Mixing	Ice cover since 2000
BAL	Lake Baldegg	66	5.2	463	4.53	47.197/8.262	382	Yearly	No
BIE	Lake Biel	74	39.4	429	0.16	47.104/7.198	364	Yearly	No
BRZ	Lake Brienz	259	29.7	564	2.60	46.718/7.952	175	Oligomictic	No
GEN	Lake Geneva	309	580.0	372	11.86	46.453/6.589	303	Oligomictic	No
GRE	Greifensee	32	8.2	439	1.19	47.350/8.678	488	Yearly	Yes*
HAL	Lake Hallwil	46	10.2	449	3.95	47.280/8.214	337	Yearly	No
JOU	Lac de Joux	32	9.5	1004	5.65	46.640/6.286	286	Yearly	Yes*
MAG	Lake Maggiore	372	213.0	193	4.10	45.964/8.645	147	Oligomictic	No
MUR	Lake Murten	45	22.6	429	1.67	46.929/7.064	458	Yearly	No
NEU	Lake Neuchatel	152	215.0	429	8.90	46.904/6.843	323	Yearly	No
PFA	Lake Pfäffikon	36	3.3	537	2.28	47.352/8.784	402	Yearly	Yes*
SEM	Lake Sempach	87	14.4	503	17.30	47.140/8.160	288	Yearly	No
THU	Lake Thun	217	47.7	558	1.90	46.673/7.763	294	Oligomictic	No
WAL	Walensee	151	24.2	419	1.58	47.123/9.223	242	Yearly	No
ZUG	Lake Zug	197	38.4	413	15.62	47.099/8.492	281	Oligomictic	No
U-CON	Upper Lake Constance	251	475.0	395	4.24	47.629/9.374	325	Oligomictic	No
L-CON	Lower Lake Constance	45	61.0	395	0.05	47.676/9.000	324	Yearly	No
U-LUG	Upper Lake Lugano	288	27.5	271	12.40	46.016/9.033	271	Oligomictic	No
L-LUG	Lower Lake Lugano	95	20.3	271	1.71	45.958/8.897	269	Oligomictic	No
U-ZUR	Upper Lake Zurich	48	20.0	408	0.20	47.205/8.823	278	Yearly	No
L-ZUR	Lower Lake Zurich	136	68.0	406	1.14	47.286/8.591	277	Oligomictic	No

tively. Because the maximum depth of a series of profiles can vary, we defined the maximum depth as the maximum depth reached by at least 80 % of the profiles. Uncertainty and potential errors of sampling depth, which is derived from pressure data for sondes and from rope length for sampling, was considered minor and not accounted for in this study. Salinity S was calculated according to Wüest et al. (1996) by multiplying specific conductivity at 20 °C with a proportionality factor:

$$S = \beta \cdot \kappa_{20} \quad (\mathrm{g\,kg^{-1}}), \tag{1}$$

where κ_{20} is specific conductivity at 20 °C and β is $0.0009\,\mathrm{g\,kg^{-1}}\,(\mathrm{\mu S\,cm^{-1}})^{-1}$ (Wüest et al., 1996). Density was calculated from temperature and salinity using a polynomial according to Chen and Millero (1986); the full polynomial is provided in Sect. S4 for completeness.

We used the python library "pylake" (Cruz, 2025) to calculate various variables derived from physical measurements. Pylake was developed and is maintained at Eawag and is based on the LakeAnalyzer software (Read et al., 2011). We used pylake to compute Schmidt stability, heat content, thermocline depth, hypolimnetic oxygen content, and hypolimnetic mean oxygen concentration for each profile that fulfills the following conditions:

- At least one measurement was taken at the surface (between 0 and 1 m)
- At least one measurement was taken at the bottom (below 90 % of maximum depth)
- A profile consists of at least 6 data points

Subsequently, the profile was interpolated (and extrapolated if needed) onto a consistent vertical grid with spacing of 1 m and used to compute the derived physical variables. Note that the integrals in the following equations were approximated by sums in our calculations.

Schmidt stability S_T (Idso, 1973) was calculated according to

$$S_\mathrm{T} = \frac{g}{A_0}\int (z-\overline{z})\rho_z A_z \mathrm{d}z \quad (\mathrm{J\,m^{-2}}), \tag{2}$$

where $g = 9.81$ is gravitational acceleration, A_0 is lake surface area, z is lake depth, $\overline{z}$ is mean lake depth, ρ_z is water density at depth z calculated according to Chen and Millero (1986), and A_z is lake area at depth z. Lake area as a function of depth is retrieved from the hypsometry database on the web platform Datalakes (https://www.datalakes-eawag.ch/lakemorphology, last access: 19 August 2026).

Lake heat content H was calculated according to

$$H = \frac{c_p}{A_0}\int \rho_z T_z A_z \mathrm{d}z \quad (\mathrm{J\,m^{-2}}), \tag{3}$$

where c_p is the heat capacity of water (assumed constant at $4.18\times10^{-3}\,\mathrm{J\,K^{-1}\,kg^{-1}}$), and T_z is water temperature at depth z. To compute thermocline depth, we used the "robust thermocline" method implemented in Pylake.

Hypolimnetic oxygen content $\mathrm{DO_{hypo}}$ was defined as the total oxygen content in the hypolimnion, whose upper boundary was defined as 5 m below the mean long-term autumn thermocline depth. It was calculated as

$$\mathrm{DO_{hypo}} = \int_{z\_\mathrm{hypo}}^{z_\mathrm{max}} [\mathrm{DO}_z] A_z \mathrm{d}z \quad (\mathrm{g}), \tag{4}$$

where V_hypo is the hypolimnion volume, z_max is maximum lake depth, and $[\mathrm{DO}_z]$ is oxygen concentration at depth z. Finally, mean hypolimnetic oxygen concentration $\overline{[\mathrm{DO}]}_\mathrm{hypo,conc}$ can be obtained by dividing $\mathrm{DO_{hypo}}$ by the hypolimnion volume V_hypo:

$$\overline{[\mathrm{DO}]}_\mathrm{hypo} = \frac{1}{V_\mathrm{hypo}}\mathrm{DO_{hypo}} \quad (\mathrm{g\,m^{-3}\ or\ mg\,L^{-1}}). \tag{5}$$

2.4 Calculation of seasonal and annual averages

The calculation of seasonal and annual averages from individual profiles is prone to uncertainty because the individual profiles might not reflect well the lake state in a certain month. To reduce uncertainty and maintain consistency over the years, we decided to apply the following minimum criteria:

- Annual averages, minima and maxima require at least 10 months with profiles per year including at least one of January and February and at least one of July and August.
- Seasonal averages need at least one profile in 2 of the 3 months in the respective season. Seasons were defined according to the meteorological terminology: winter includes December, January and February; spring includes March, April and May etc.
- Winter–spring mixing assessment required at least data from 2 of the 3 months of January, February and March.

For annual trends, the profiles were first linearly interpolated to a daily resolution before averaging to account for varying sampling frequencies. Similarly, for seasonal averages, the data were averaged on a daily basis across the available profiles. However, only the interpolated daily values of the middle month (e.g. 1 to 31 January for winter, 1 to 30 April for spring, etc.) were used to compute the seasonal mean. This approach reduced sensitivity to the exact sampling dates.

Some cantons decreased the sampling frequency of their monitoring programs over time. For example, sampling frequency was reduced from monthly sampling to 4 profiles a year in Walensee in 2001, to 6 profiles a year in Upper Lake Zurich in 2005 and to 8 profiles a year in Lakes Baldegg and

Sempach in 2015. This means that for these 4 lakes some trend calculations stop at 2000, 2004 and 2014, respectively. In contrast, vertical resolution was increased in many lakes with the introduction of multiparameter sondes. For those lakes that have an extensive data record with low vertical resolution, we downsampled the newer high-resolution profiles to maintain consistency in analysis.

2.5 Calculation of Theil-Sen and GAM trends

We computed two kinds of trends to simplify inter-lake comparisons: linear trends using Theil-Sen slopes and non-linear trends using general additive models (GAM's; Hastie, 2017). Most calculated variables do not exhibit a monotonous trend since the beginning of monitoring (usually between 1960 and 1980) and therefore GAM trends are a useful tool to capture such trends. In contrast, water temperature and some derived variables like heat content and Schmidt stability show clearly increasing trends since around 1980 and therefore, we also calculated linear regression using Theil-Sen slopes starting in 1980. GAM trends were computed with the python package "pygam" (Servén and Brummitt, 2018) with a maximum number of splines of 15 and a smoothness penalty of 10. Theil-Sen slopes were computed using the python package sklearn. For both trend calculation methods, we decided to set the minimum required number of data points (i.e., years with seasonal or annual mean) to 10, which was considered the minimum required for robust trend calculation. This means for example that no trends of annual means are calculated for Lake Pfäffikon and Lac de Joux because very often there is no data available for both January and February.

3 Results and discussion

Mean annual surface temperature consistently increased since around 1980 in all investigated lakes with a more pronounced increase since 2010 (Fig. 2). Overall, the observed trends are comparable among the investigated lakes, but mean annual temperature varies by around 4 °C between the warmest and coldest lakes. The lakes on the southern side of the Alps (Lake Maggiore and Lake Lugano) with a milder climate, but also Lake Geneva (since around 2000), are considerably warmer than the average. Conversely, Lakes Brienz and Thun (and to a lesser degree Walensee, Upper Lake Constance and Upper Lake Zurich), which are influenced by direct alpine river inflow, are clearly cooler compared to the rest of the lakes.

Similar to surface temperature, mean annual bottom temperature increased in most investigated lakes over the last few decades (Fig. 3). The increase was strongest over the last 10–15 years and for some lakes also between 1980 and 2000. There are signs of decreasing bottom temperature between 2000 and 2010, due to cold winters in 1999, 2005 and 2006, when mixing events reset bottom temperature to lower values in oligomictic lakes. The clearly highest bottom temperatures occur in two contrasting lakes: Lake Maggiore, which is the deepest investigated lake (372 m, see Table 1), and Lower Lake Constance which is shallow (45 m) and has a very short residence time (less than 1 month). The only lakes which maintain a mean annual bottom temperature below or close to 5 °C in recent years are two lakes with very high residence times (Lakes Zug and Sempach, see Table 1) as well as Upper Lake Constance and Lower Lake Zurich. It is interesting to note that even those lakes that did not experience a full overturn during the last 10–15 years (e.g., Lake Geneva, Lake Maggiore, Lake Zug, Upper Lake Lugano and Lower Lake Zurich) show significant increase of bottom temperature. In these lakes, warming during stratified periods is not caused by direct atmospheric warming, but rather by diffusive transport of heat from the lake surface water to the bottom (Livingstone, 1997). Over decades, the bottom temperature timeseries of such oligomictic lakes resembles a "sawtooth" pattern, characterized by gradual increases during stratified years followed by sudden drops during rare overturn events (Livingstone, 1997). As a consequence of this decoupling from the atmosphere for extended periods, very long time series are required for an accurate representation of the climate-driven bottom temperature warming in oligomictic lakes (Livingstone, 1993).

The mean linear warming rate of annual surface and bottom temperatures since 1980 along with the 95 % confidence interval is shown in Fig. 4. The results confirm previously reported findings (e.g., O'Reilly et al., 2015; Pilla et al., 2020) that lake surface temperature has warmed around three times faster than lake bottom temperature over the last four decades with 0.47 ± 0.11 °C per decade vs. 0.17 ± 0.10 °C per decade. A notable exception is Lake Murten where the trends of surface and bottom temperature seem comparable (Fig. 4). However, the deep-water measurements in Lake Murten before 1999 were invalidated (see Sect. S2), and the bottom temperature trend from this short timeseries is therefore prone to higher uncertainty. Although mean trends across all lakes are significantly positive, uncertainty in individual lake trends can be substantial. One source of uncertainty is sparse sampling (often monthly), which may not accurately represent the true monthly mean, particularly in summer, when short-term variability of surface temperature is high. Another source of uncertainty is the natural variability of meteorological conditions that largely drive lake temperature, especially at the surface. The latter factor is inherent and cannot be eliminated, but it can be reduced with high-frequency observations and/or longer timeseries. As a result, lakes with rather short temperature record tend to show higher trend uncertainty (e.g. Lake Brienz, Lake Sempach, Walensee and Upper Lake Zurich).

The observed increase of mean annual surface temperature of 0.47 °C per decade is comparable to the air temperature increase during the same time of around 2 °C since 1980 (MeteoSwiss and ETH Zurich, 2025). This contrasts with the prediction from heat budgets, which suggest that lake sur-

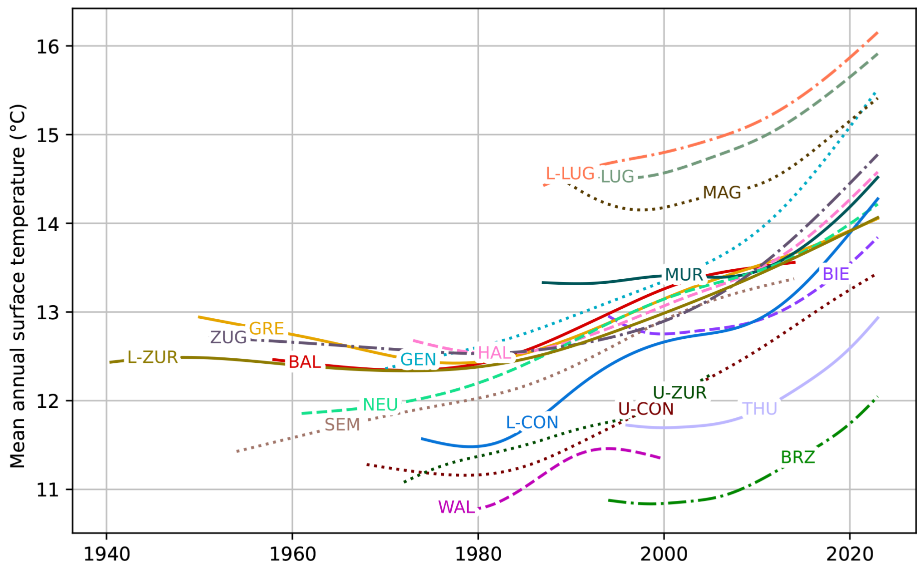

Figure 2. Mean annual surface temperature (top 1 m) of 19 Swiss lakes and lake basins calculated using GAM regression. The lake codes are explained in Table 1. Lac de Joux and Lake Pfäffikon are not shown because of insufficient sampling frequency.

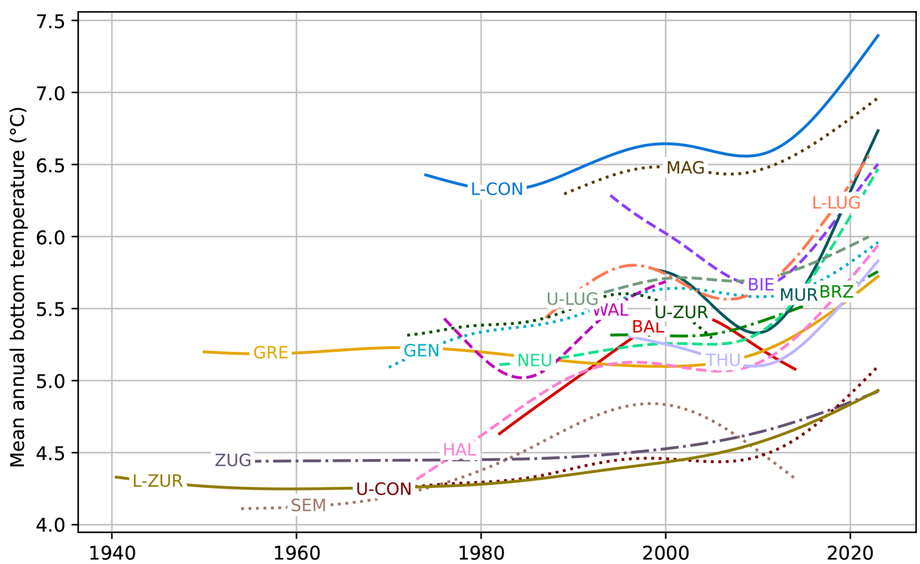

Figure 3. Mean annual bottom temperature (bottom 10 % of depth) of 19 Swiss lakes and lake basins calculated using GAM regression. The lake codes are explained in Table 1. Lac de Joux and Lake Pfàffikon are not shown because of insufficient sampling frequency.

face temperature warms by only around 75 % to 90 % of the increase in air temperature (Schmid and Köster, 2016). Schmid and Köster (2016) suggest that solar brightening (i.e., decreasing aerosol concentrations) was driving the additional warming observed in lakes up to 2013. Since then, the aerosol effect is reduced, but further solar brightening is driven by cloud effects (Schilliger et al., 2024).

Comparing lake warming rates regionally or globally is hampered by the fact that different time periods are analyzed and that data collection is heterogeneous with more observations in summer often leading to calculation of summer trends only (e.g., O'Reilly et al., 2015; Pilla et al., 2020). In addition, different data sources are used, for example in-situ measurements (e.g., O'Reilly et al., 2015; Pilla et al., 2020), model results (e.g., Stefanidis et al., 2022), or approaches using both models and satellite data (e.g., Woolway et al., 2017). Overall, the warming rates measured in the Swiss lakes are on the upper end of the spectrum in a global context. This is confirmed by Piccolroaz et al. (2020) who found that temperate lakes are especially vulnerable to climate change.

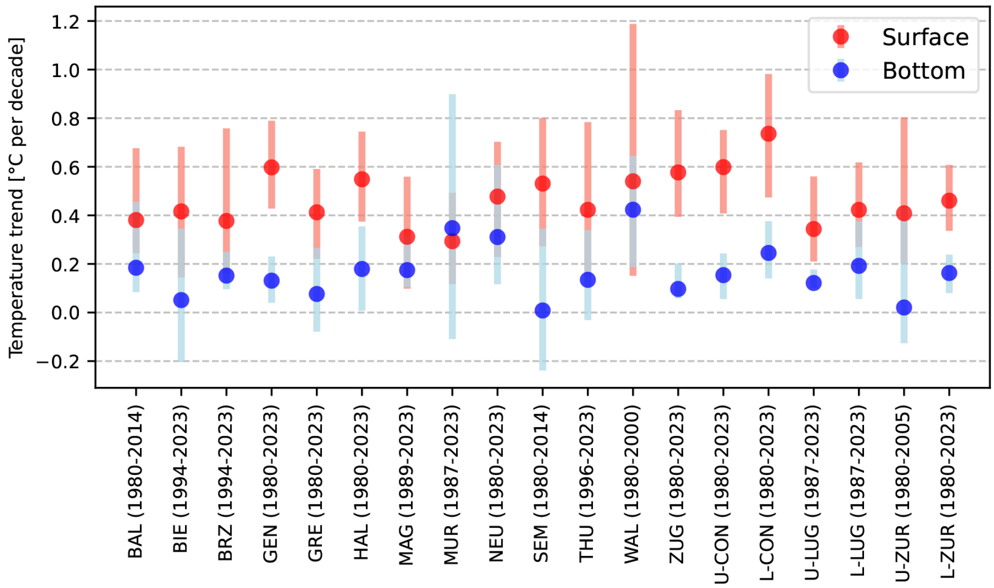

Figure 4. Theil-Sen regression slopes and 95 % confidence interval of mean annual surface (top 1 m) in red, and bottom temperatures (bottom 10 % of depth) in blue of 19 Swiss lakes and lake basins. Mean surface warming since 1980 is 0.47 ± 0.11 °C per decade and mean bottom warming is 0.17 ± 0.10 °C per decade. The time period used for regression calculation is indicated in parentheses after the lake names. Lac de Joux and Lake Pfàffikon are not shown because of insufficient sampling frequency.

The strong increase of mean surface and bottom temperatures coincides with a similar warming in the intermediate layers of lakes. Figure 5 exhibits the percentage change in total lake heat content in the 21 investigated lakes. Heat content remained relatively stable between 1940 and 1980 and increased between 10 % and 20 % since then, with the steepest increase occurring during the last 10–15 years. Note though that there was little data available between 1940 and 1980, which is not reflected in Fig. 5. Instead, these details can be found in Sect. S6 for all individual lakes.

Similar to surface and bottom temperature, the observed increase of heat content is very uniform among all observed lakes. It is interesting to note, though not well reflected in the smoothed trends in Fig. 5, that total heat content is dominated by the cold hypolimnion temperature in deep lakes because the hypolimnion often accounts for much more than half of a lake's volume. This means that total heat content drops sharply after a (rare) mixing event in deep lakes as evidenced for example by the heat content patterns of Lake Geneva (Fig. S11 in the Supplement) or Lake Maggiore (Fig. S15).

Schmidt stability expresses the amount of energy needed to completely homogenize a lake starting with the given temperature profile. Note that we neglected the influence of salinity because we did not consider the winter period here where salinity can play a major role due to weaker temperature stratification. In addition, conductivity data timeseries are often considerably shorter than temperature timeseries. Figure 6 shows that Schmidt stability has increased by 30 %–50 % on average in autumn in Swiss lakes during the last few decades (note that Walensee only has one datapoint after 2000). This means that the faster increase of surface temperature compared to bottom temperature (Fig. 4) has led to much more stably stratified lakes as they approach the winter mixing period. Due to increased autumn stability, the lake's stratification is more resistant against the disturbance by strong winds, meaning that more wind energy is required to create a lake overturn. Even in the absence of large wind events, it will take more time until the lake has cooled down enough to reach a uniform temperature profile and subsequently to overturn. In consequence, even colder winters with more negative degree days than previously would be required for lakes to freeze, further strengthening the previously observed trend of decreasing ice cover frequency on Swiss lakes (Hendricks-Franssen and Scherrer, 2008). Increased autumn stability leading to later lake overturn can be counteracted by artificial circulation and aeration systems, especially in smaller to mid-sized lakes (e.g. Fast, 1979), but its benefit is hard to assess with monthly profiles. Artificial aeration systems are currently deployed in Lake Baldegg, Lake Hallwil and Lake Sempach, where usually small bubbles of pure oxygen or air are injected in the deepwater in the stratified season and larger bubbles are injected during weak stratification to promote lake overturn.

In contrast to many other physical variables, there is no strong long-term trend for summer thermocline depth in many lakes as illustrated in Fig. 7. Several lakes with relatively shallow thermoclines exhibited a small but significant increase in thermocline depth, including Lake Baldegg, Lake Hallwil, Lower Lake Lugano and Upper Lake Zurich (see

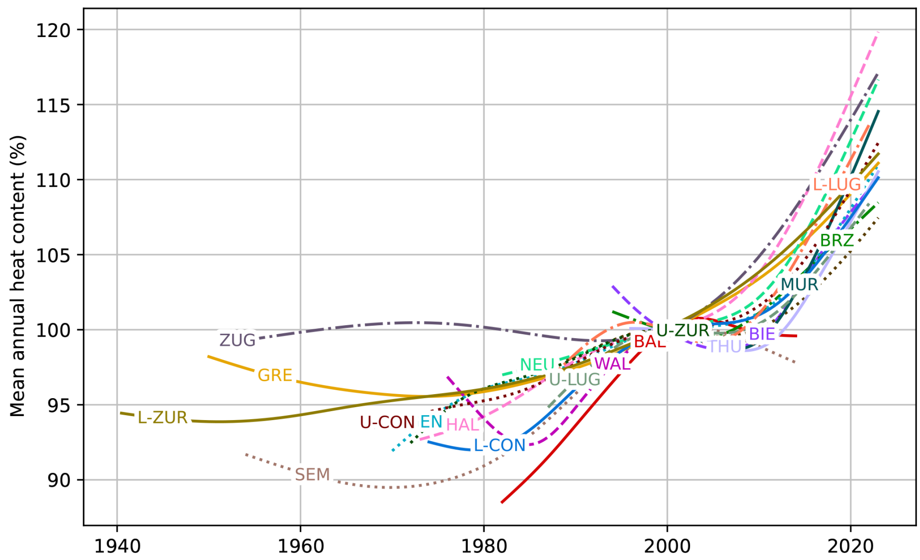

Figure 5. Mean annual heat content (relative to its value in the year 2000) of 19 Swiss lakes and lake basins calculated using GAM regression. The lake codes are explained in Table 1. Lac de Joux and Lake Pfàffikon are not shown because of insufficient sampling frequency.

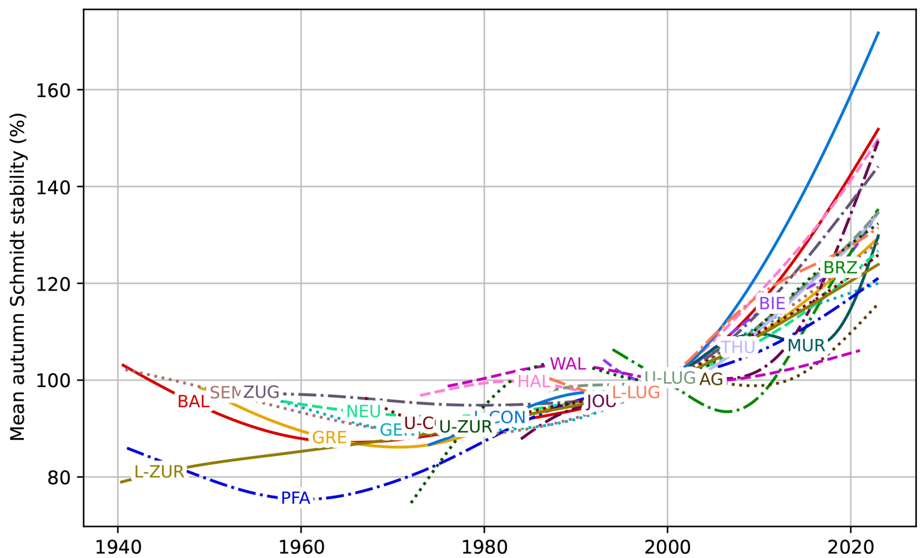

Figure 6. Mean autumn Schmidt stability (relative to its value in the year 2000) of 21 Swiss lakes and lake basins calculated using GAM regression. The lake codes are explained in Table 1.

also Fig. S5 for trend significance since 1980). In contrast, our data suggests that Lake Geneva, Lake Neuchatel and Upper Lake Constance experienced a clear trend towards a shallower summer thermocline. However, these deep lakes tend to have a more complicated thermocline structure with several steep sections. For such profiles, the thermocline computation algorithm used here is not yet fully tested and therefore the results should be interpreted with caution.

In the case of Lake Geneva, the decrease in thermocline depth, which happened mainly between 1960 and 1980, was accompanied by a decrease in summer water clarity (measured as Secchi depth; see Fig. 8). A similar correlation but with increasing thermocline depth and Secchi depth is observed for Greifensee, Lake Hallwil, Lake Brienz and Lower Lake Lugano (Figs. 7 and 8). Figure 8 shows that water clarity has been increasing in many lakes in the last 20 years, presumably as a consequence of re-oligotrophication, which often led to a shift in community structure and depth patterns of phytoplankton biomass (e.g. the expansion of *Planktothrix* spp., see Gallina et al., 2017). The only clear exception from this trend is Upper Lake Constance, where mean summer Secchi depth decreased from 5 to around 3 m during the last 20 years. Water clarity leads to deeper penetration of solar radiation and therefore to increased mixed layer depth, po-

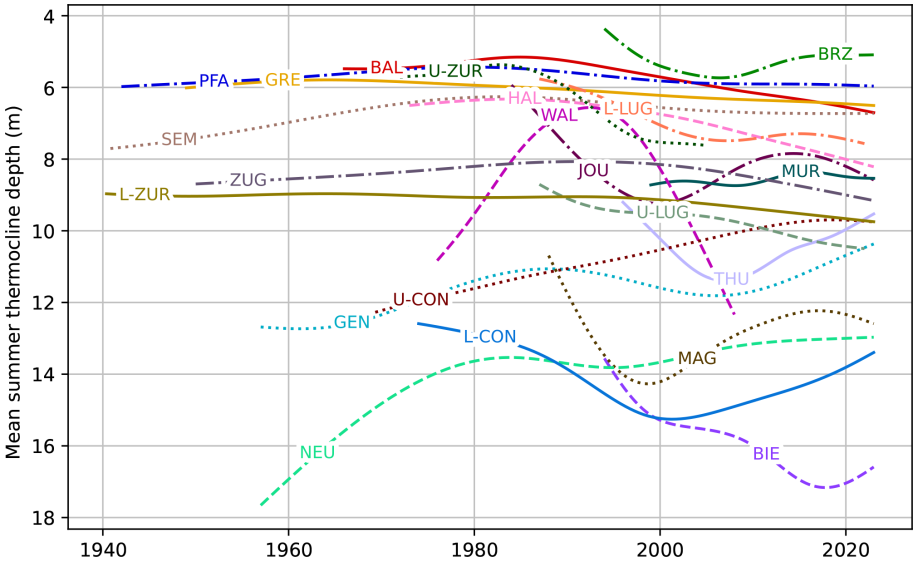

Figure 7. Mean summer thermocline depth of 21 Swiss lakes and lake basins calculated using GAM regression. The lake codes are explained in Table 1.

tentially leading to deeper mean thermocline depth (Heiskanen et al., 2015). In addition, an increase of water clarity can also attenuate surface temperature warming because incoming solar radiation is spread over a larger depth range (Rose et al., 2016). Despite this theoretical link however, most investigated lakes did not show a strong correlation between Secchi depth and thermocline depth, indicating that other processes are important, too (see also Fig. S6).

Oxygen concentrations in lakes, especially in the hypolimnion, are tightly linked to temperature-induced stratification and mixing processes. At the surface, however, oxygen levels are mainly controlled by biological activity during the stratified season (Jones and Smol, 2023). If concentrations are close to saturation levels, the influence of temperature-dependent oxygen solubility must be taken into account (Jones and Smol, 2023). In our 21 investigated lakes and lake basins, surface oxygen concentrations in summer decreased strongly from almost 12 $\mathrm{mg\,L^{-1}}$ in 1980 to less than 10 $\mathrm{mg\,L^{-1}}$ in 2020 (Fig. 9) with statistically significant linear trends in 13 out of 21 lakes (see Fig. S5). This decrease of $\sim 2\,\mathrm{mg\,L^{-1}}$ (or around 0.5 $\mathrm{mg\,L^{-1}}$ per decade) can only be partially explained by a reduction of oxygen solubility, which is $\sim 0.4\,\mathrm{mg\,L^{-1}}$ for an observed summer water temperature increase of ~ 2 °C since 1980. Thus, reduced solubility can explain at most 20 % of the observed summer oxygen decrease in the surface waters of large Swiss lakes. This apparently contrasts with the findings of a global study by Jane et al. (2021), who could explain 63 % of the observed surface oxygen decrease by solubility reduction. However, Jane et al. (2021) used annually averaged oxygen concentrations, which are presumably less related to summer primary production and more to solubility changes.

We hypothesize that the remaining 80 % of observed surface oxygen decrease are mostly due to a reduction or a vertical redistribution of primary production due to the re-oligotrophication occurring in Swiss lakes (Swiss Federal Office for the Environment, 2026). Consistently, the decreasing trend of oxygen concentration at the surface (0–1 m) and between 0 and 5 m is compensated by a steep increase in oxygen concentration between 5 and 10 m (Fig. S5), thus reflecting a shift in depth of the epilimnetic oxygen maximum.

Despite the ongoing re-oligotrophication, hypolimnetic oxygen concentrations did not significantly increase at the end of the stratification period for most lakes. Figure 10 depicts mean autumn hypolimnetic oxygen concentration, where the hypolimnion is defined to range from 5 m below the mean autumn thermocline to the lake bottom. An increase in autumn hypolimnetic oxygen is observed in Lake Baldegg, Lake Hallwil and Lake Sempach following the onset of artificial aeration in 1982, 1986 and 1984, respectively. For Lake Sempach, this increase is more apparent in Fig. S19 than in Fig. 10. Lake Pfäffikon was also aerated between 1992 and 2010, but its hypolimnetic oxygen concentration in autumn only increased slightly during this period. Besides these artificially aerated lakes, a recent increase in hypolimnetic oxygen can be observed in Lake Biel and Lake Murten. In most other lakes, there is no significant trend despite efforts to reduce phosphorus loading. There are several processes that could contribute to this observation: (i) sediment legacy effects, meaning that organic matter in the sediment from past eutrophic periods still consumes oxygen (Müller et al., 2012), (ii) more efficient utilization of phosphorus resources by phytoplankton (Müller et al., 2019), and (iii) increased water clarity leading to deeper primary production, therefore accessing additional phosphorus resources (e.g. the

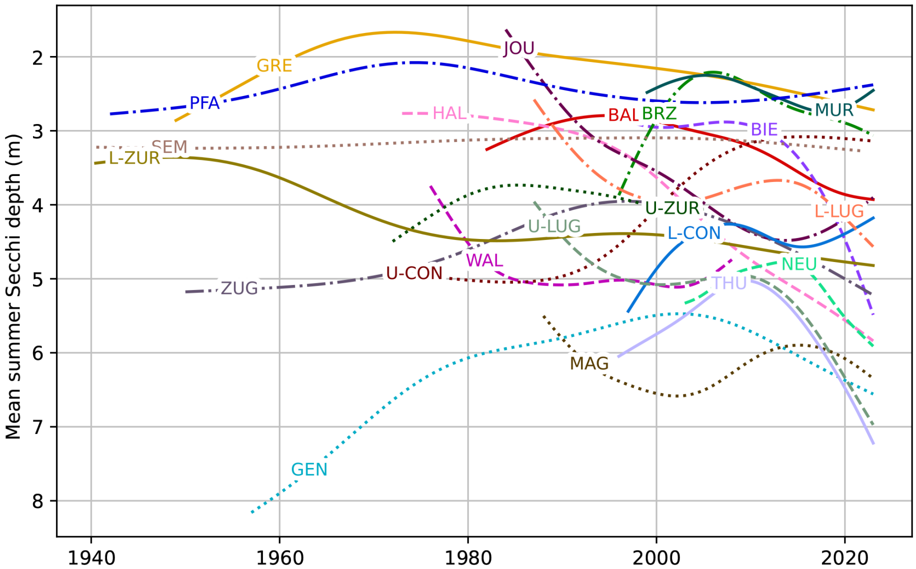

Figure 8. Mean summer Secchi depth of 21 Swiss lakes and lake basins calculated using GAM regression. The lake codes are explained in Table 1.

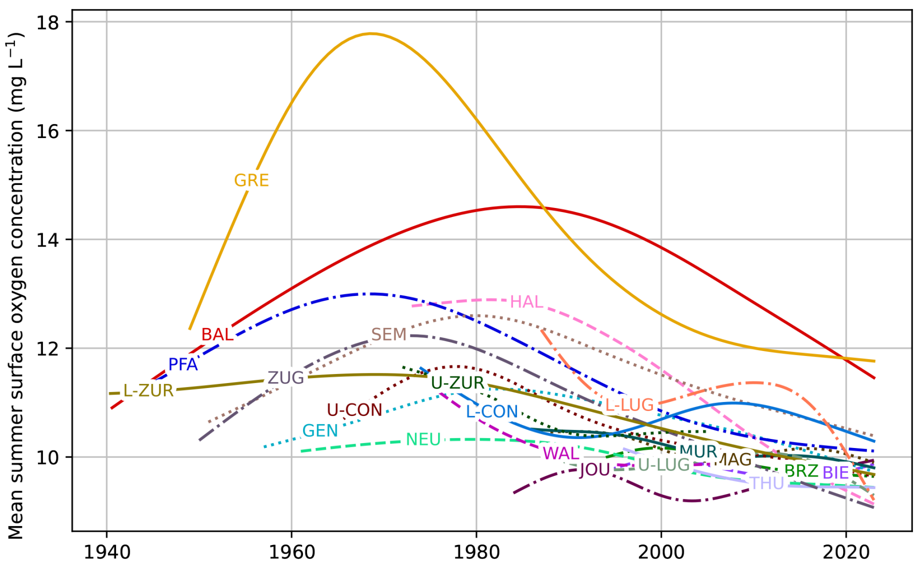

Figure 9. Mean summer surface oxygen concentration (top 1 m) of 21 Swiss lakes and lake basins calculated using GAM regression. The lake codes are explained in Table 1.

arrival of *Planktothrix* spp. in a number of lakes). Another potential reason is the earlier start of summer stratification due to climate change (e.g. Woolway et al., 2021), extending the time available for oxygen consumption until the observations in autumn. Note that oxygen trends in autumn (Fig. 10) can be driven by an earlier onset of stratification but not by delayed winter overturn.

As a result of the limited response to decreased phosphorus input and earlier onset of stratification, many lakes still have mean hypolimnetic oxygen concentrations below $4\,\mathrm{mg\,L^{-1}}$ in autumn (Fig. 10). $4\,\mathrm{mg\,L^{-1}}$ is the minimum oxygen concentration threshold prescribed in the Swiss Water Protection Ordinance (Swiss Confederation, 1998), and many lakes do not respect this threshold at all depths and all times. Deep lakes usually maintain higher mean hypolimnetic oxygen concentrations than shallower lakes throughout the stratified season because their hypolimnion volume (i.e. the oxygen reservoir available for the decomposition of settling organic matter) is large compared to the productive surface layer volume, where primary production occurs (Müller et al., 2012). In contrast, some of the deep, oligomictic lakes experienced a decrease of bottom water oxygen over the last

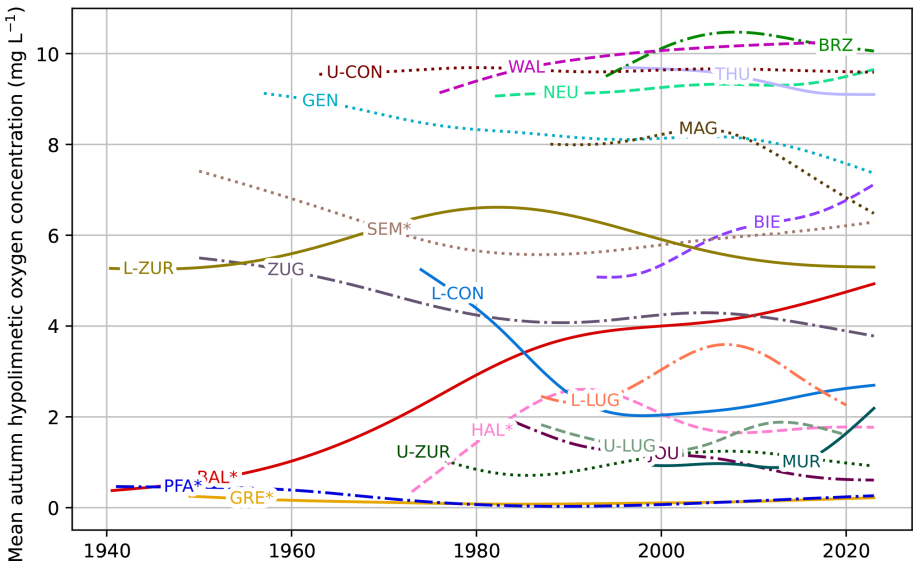

Figure 10. Mean autumn hypolimnetic oxygen concentration of 21 Swiss lakes and lake basins calculated using GAM regression. Hypolimnetic oxygen concentration is defined as mean volume-averaged oxygen concentration between 5 m below the mean autumn thermocline depth and the lake bottom. Lakes with asterisk are or were artificially aerated: BAL since 1982, SEM since 1984, HAL since 1986, GRE since 2009 (only a small aeration system) and PFA between 1992 and 2010.

2 decades (Fig. S6) presumably because of a lack of deep mixing (Fig. S7).

Besides an earlier onset of stratification, climate change is also projected to delay or even inhibit full winter overturn of lakes. During the study period, many of the investigated lakes experienced a full overturn every winter, which homogenises oxygen and nutrient concentrations vertically. However, some of the lakes are oligomictic (see Table 1), meaning that they do not mix down to the bottom annually or, in some cases, that a full winter overturn occurs only at the end of particularly cold and windy winters. Lake overturn is often a gradual process over days or weeks, which is difficult to capture using monthly profiles (Engelhardt and Kirillin, 2014). Nevertheless, monthly profiles can be used to assess whether a lake has reached a vertically mixed state during a certain winter or not. Observed inverse stratification is thereby counted as a mixing event because the lake had to cross a mixed state to reach inverse stratification. Note, however, that this classification of inverse stratification as mixed state can lead to issues if salinity is not used for density calculation. This is because in the presence of a salinity gradient, a lake can have a slight inverse temperature stratification without a full Foverturn.

A mixed state can be identified for example using temperature or density profiles (e.g. Gray et al., 2020), or by applying a threshold to Schmidt stability (Engelhardt and Kirillin, 2014). In this work, we used density profiles calculated from temperature data only, and from temperature and salinity data together, respectively. The density threshold for separating mixed from non-mixed states is often set to 0.1 kg m^{-3} (e.g. Ladwig et al., 2021; Woolway et al., 2021), although this corresponds to a temperature difference of ∼ 3.5 °C when close to the temperature of maximum density (calculated using the formula of Chen and Millero, 1986). Even at 6 °C, a typical mixing temperature for mid-sized temperate lakes, a density difference of 0.1 kg m^{-3} equals a temperature difference of ∼ 2 °C, which is still far away from allowing vertical homogenization of oxygen and nutrients. In our study, we evaluated multiple density thresholds by examining whether their predicted mixing agreed with observed deep-water oxygen recharge, which is defined as a surface–bottom oxygen saturation difference below 10 %. We used saturation rather than concentration to account for the temperature dependence of oxygen solubility.

Our analysis suggests that a better agreement between mixing and oxygen recharge can be reached if the density threshold is much lower than 0.1 kg m^{-3} and that the inclusion of salinity significantly improves agreement for deep lakes (Fig. 11). This is consistent with a study by Valerio and Pilotti (2025), who recently elucidated the influence of salinity on stratification for deep Lake Iseo. Our analysis also shows that the density threshold can be set too low with mean agreement being highest for a threshold of 0.005 kg m^{-3} (Fig. 11). This finding can be explained by the limited accuracy of measurements, but also by low temporal resolution (bi-weekly to monthly). The latter can lead to situations where the full overturn (i.e. homogeneous density) is missed by a few days or weeks but still influences oxygen in the deep water. Overall, we show that the agreement between deep mixing and oxygen recharge can be improved from ∼ 60 % to ∼ 90 % if salinity is included and an appropriate density threshold is chosen.

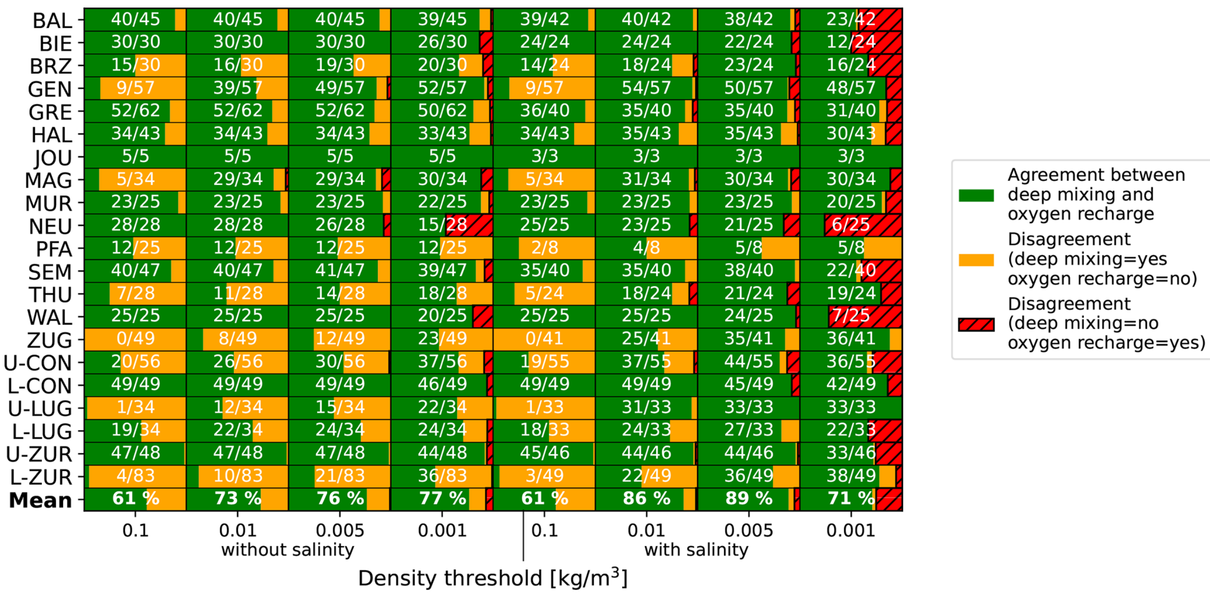

Figure 11. Prediction success of various density thresholds for the full recharge of deepwater oxygen for 21 Swiss lakes and lake basins. Oxygen recharge is defined as the occurrence of surface and bottom oxygen saturation within 10 % between January and March. A mixing event is defined as the occurrence of surface and bottom density within a certain threshold between January and March. Inverse stratification is counted as mixing event. Agreements are years when a predicted mixing event coincides with an oxygen recharge event (green); disagreements include years when mixing is predicted but no oxygen recharge is observed (yellow), and years when oxygen is recharged but no mixing predicted (red hatched).

Figure 12 shows the temporal evolution of full overturn based on density profiles, and on oxygen recharge in Swiss lakes. Our data suggest that most of the investigated lakes either overturn annually or rarely (less than every 5 years). Exceptions are Lake Brienz, Lake Thun, Upper Lake Constance, and Lower Lake Lugano, but overturns seemed to happen less frequently in recent years for some of these lakes. As noted by Livingstone (1997), lake overturns of oligomictic lakes in Switzerland tend to happen synchronously because they are triggered by regional weather, e.g., the unusually cold and windy winters 1999, 2005/2006 and 2012. Our data indicates that deep-water oxygen has not been fully recharged in Lake Geneva since 2012, and not since 2006 in Lake Maggiore, Lake Zug, Upper Lake Lugano and Lower Lake Zurich. However, in Lake Geneva, Lake Zug and Lower Lake Zurich, the two mixing indicators (oxygen recharge and density profile) disagree on when the last mixing event happened (Fig. 12). Possible causes for this disagreement are (i) short mixing duration leading to partial oxygen recharge or (ii) non-representativeness of the measured profiles with oxygen being recharged in between two stratified profiles. These reasons for disagreement between mixing indicators also apply to lakes that mix annually with, as stated, an overall agreement of close to 90 %.

The ongoing warming trend is expected to increase the duration between two complete overturns in oligomictic lakes because it leads to a greater density difference between surface and bottom through (i) the discrepancy of surface and bottom temperature warming trend (as evidenced in this study) and (ii) the (nonlinear) increase of the thermal expansion coefficient of water with increasing temperature (Imboden and Wüest, 1995). The latter leads to a larger density difference for a given temperature difference with increasing water temperature. Stratification can be further enhanced through the accumulation of solutes in isolated deep waters by mineralization, which increases hypolimnion density. Deepwater mineralization can increase as a result of increased primary production and thus gross sedimentation (e.g., Wüest et al., 1992) or bottom anoxia leading to a flux of reduced substances into the water column (Jones and Smol, 2023). Mesman et al. (2021) discuss that if the rising bottom density due to solute accumulation outpaces bottom temperature increase due to small diffusive transport from the surface (Livingstone, 1997), lakes could even become permanently meromictic. This process, known as biogenic meromixis, occurred in Upper Lake Lugano during the eutrophic phase, when the lake shifted from a mixing system to an essentially non-mixing system (Wüest et al., 1992), having turned over only once since monitoring began in the 1980s (Fig. 12, see Holzner et al., 2009). Our study confirms Upper Lake Lugano's meromictic (extremely oligomictic) character, because bottom density has remained stable since the last complete overturn in 2006, despite rising temperatures (Fig. 13). The future evolution of the lake's mixing regime will depend on the balance between gross sedimentation of primary production, carbonate sedimentation and increasing temper-

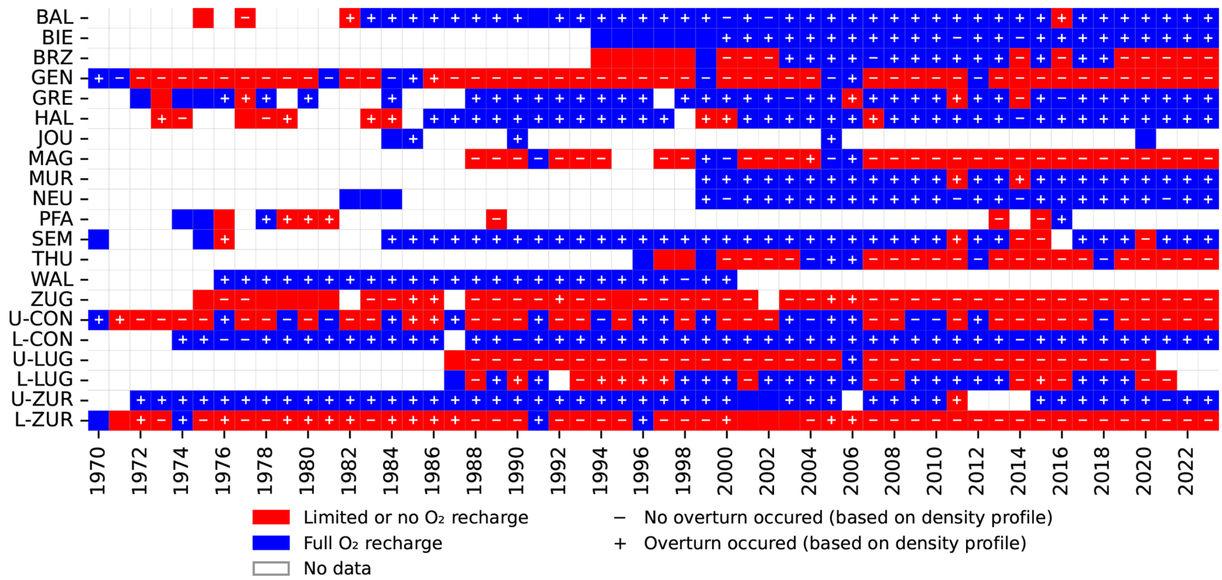

Figure 12. Full deepwater oxygen recharge in 21 Swiss lakes and lake basins since 1970 (most lakes do not have much data prior to 1970). O_2 recharge is defined as the occurrence of surface and bottom oxygen saturation within 10 % between January and March and overturn based on density profile is computed with a threshold of 0.005 $kg\,m^{-3}$ and including salinity.

ature, rendering the outcome uncertain. Among Swiss lakes, Upper Lake Lugano seems to be most prone to future long-term meromixis because of less strong decrease of bottom density compared to other deep lakes since the last mixing events in 2006 and 2012 (Fig. 13), respectively. Conversely, Lake Maggiore seems least prone to meromixis because it exhibits almost no solute accumulation.

4 Code and data availability

Data and software described in this manuscript can be accessed at repository under data DOI https://doi.org/10.25678/000GJC (Bärenbold et al., 2026).

5 Conclusions

The monitoring data analyzed in this study illustrate the profound changes of the thermal structure of Swiss lakes during the last few decades, which is largely consistent with findings in other temperate lakes. Surface and bottom temperatures of all investigated lakes show a marked increase over the last 40 years, with a mean rate of 0.47 ± 0.11 and 0.17 ± 0.10 °C per decade, respectively. These warming rates are even higher in the last 10 to 15 years. Consequently, total heat content has increased as well by around 10 % to 20 %, and autumn Schmidt stability, due to faster warming at the surface, by 30 % to 50 %. These water temperature related trends are similar among all lakes despite the variability in surface area, maximum depth and water residence time. Deep lakes, like Lake Geneva, Lake Maggiore, Upper Lake Lugano and Lake Zug, that undergo prolonged periods without overturn, thereby experience deep-water warming through both episodical equilibration with the atmosphere (during overturn), and diffusive heat transfer (during stratification). The observed increase of surface water temperature of ∼ 2 °C since 1980 is accompanied by reduced oxygen concentration in the immediate surface water in summer. However, only around 20 % of the observed decrease in summer surface oxygen concentration can be explained by decreasing saturation values due to increasing water temperature.

In addition to the warming trend, our data show consequences of the recent trend towards re-oligotrophication in Swiss lakes. The reduction of phosphorus concentrations limited phytoplankton growth near the surface and thus led to higher water clarity as illustrated by increasing Secchi depth in most lakes. In addition, we hypothesize that re-oligotrophication may explain the remaining 80 % of the observed decrease in summer surface oxygen concentration due to a relocation of phytoplankton and thus the epilimnetic oxygen maximum to greater depths. Although the increase in water clarity may lead to increased summer thermocline depth, this was not consistently observed in our data, suggesting that there are other drivers of thermocline depth in Swiss lakes.

An important consequence of the observed difference in warming rate between surface and bottom water is the decline of deep mixing in oligomictic lakes. In these lakes, we observe a tendency towards shallower maximum mixing depth in recent years with many of the lakes not experiencing a full overturn since 2006 or 2012. A general trend towards less frequent full overturns in oligomictic lakes is likely but cannot be statistically quantified at this stage because of how

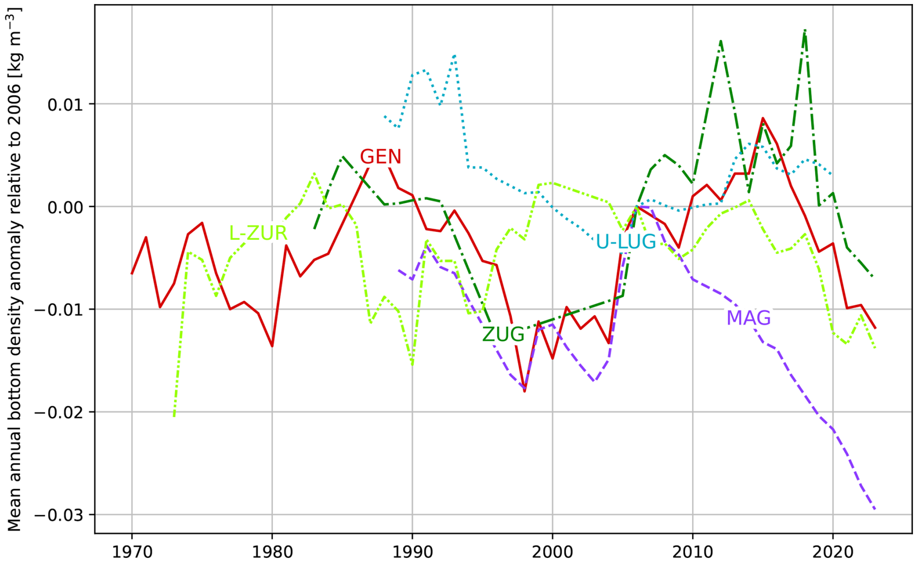

Figure 13. Mean annual bottom (bottom 10 % of depth) density anomaly relative to the year 2006 of 5 oligomictic Swiss lakes. 2006 was the last winter when all major Swiss lakes experienced a deep mixing event. The lake codes are explained in Table 1. Density is computed using the formula of Chen and Millero (1986).

rare these events are. Besides the influence of the warming trend, future lake overturn frequency could be affected by the solute concentration in the bottom water, potentially enabling meromixis if bottom water warming is offset by an increase in solute concentration. However, the recent evolution of bottom water density shows a decreasing trend in most oligomictic lakes, which positively affects the chance of overturn in the future.

The duration of stratification between annual mixing events is an important driver of hypolimnetic hypoxia in monomictic lakes but cannot reliably be calculated using monthly profiles. However, we can calculate hypolimnetic oxygen concentration in autumn, which aggregates information about how well a lake was oxygenated during the previous winter and of the strength of oxygen demand during the stratified season. Although some lakes show increasing or decreasing trends, our data show no consistent trend of autumnal hypolimnetic oxygen concentration across all lakes. This lack of general trend can be attributed to counter-acting effects of re-oligotrophication and warming trend: reduction of oxygen consumption rates can be offset by a trend towards incomplete oxygen recharge and prolonged seasonal stratification.

With this data publication, we make a first step towards open-access long-term monitoring data for Swiss lakes. The raw data provided by cantonal offices, international lake commissions and research bodies underwent consistent data processing including quality assurance. The calculation methods for derived variables and multi-decadal trends are open and can be adapted by users and updated as part of a "living data" process. Our approach allows for rigorous comparisons between lakes and provides state-of-the-art calculation methods, thus supporting local and national authorities involved in lake management. Overall, this effort will contribute to open data policy at both national and international level and to the sharing and re-use of the data for further analysis and investigations.

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Author contributions. Conceptualization and Methodology: FB, DJ, DB and MS.

Formal analysis, investigation, visualization, writing (original draft and preparation): FB.

Data curation, validation, writing (review and editing): all co-authors.

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