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Lake Surface Water Temperature in high altitude lakes in the Pyrenees: Combining satellite with monitoring data to assess recent trends

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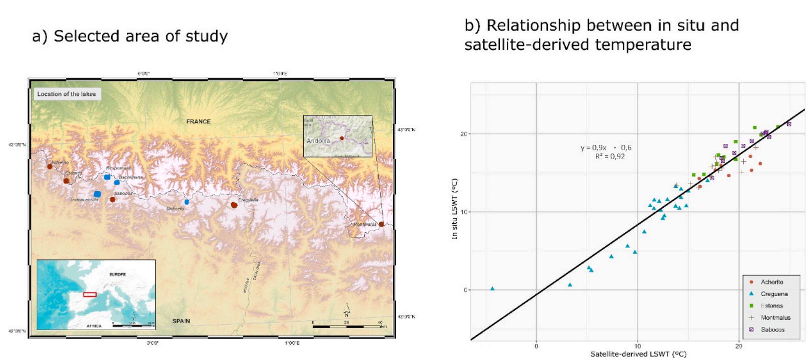
HIGHLIGHTS

- *In situ* and satellite-derived LSWT in Pyrenean lakes are highly correlated ($r = 0.94$).
- LSWT has been reconstructed in 9 small alpine lakes.
- Average LSWT has increased since 1985 in all studied lakes.
- This combined methodology can be applied in absence of *in situ* monitoring programs.

GRAPHICAL ABSTRACT



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ABSTRACT

Lake Surface Water Temperature (LSWT) influences critical bio-geological processes in lake ecosystems, and there is growing evidence of rising LSWT over recent decades worldwide and future shifts in thermal patterns are expected to be a major consequence of global warming.

At a regional scale, assessing recent trends and anticipating impacts requires data from a number of lakes, but long term *in situ* monitoring programs are scarce, particularly in mountain areas. In this work, we propose the combined use of satellite-derived temperature with *in situ* data for a five-year period (2017–2022) from 5 small (<0.5km^2) high altitude (1880–2680 masl) Pyrenean lakes. The comparison of *in situ* and satellite-derived data in a common period (2017–2022) during the summer season showed a notably high ($r = 0.94$, $p < 0.01$) correlation coefficient, indicative of a robust relationship between the two data sources. The root mean square errors ranged from 1.8 °C to 3.9 °C, while the mean absolute errors ranged from 1.6 °C to 3.6 °C.

We applied the obtained *in situ*-satellite eq. (2017–2022) to Landsat 5, 7 and 8/9 data since 1985 to reconstruct the summer surface temperature of the five studied lakes with *in situ* data and to four additional lakes with no *in situ* monitoring data. Reconstructed LSWT for the 1985–2022 showed an upward trend in all lakes. Moreover, paleolimnological reconstructions based on sediment cores studies demonstrate large changes in the last decades in organic carbon accumulation, sediment fluxes and bioproductivity in the Pyrenean lakes.

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Our research represents the first comprehensive investigation conducted on high mountain lakes in the Pyrenees that compares field monitoring data with satellite-derived temperature records. The results demonstrate the reliability of satellite-derived LSWT for surface temperatures in small lakes, and provide a tool to improve the LSWT in lakes with no monitoring surveys.

1. Introduction

The change in lake water temperature has been one of the most studied issues regarding the recent dynamics of lakes and the global warming impacts in these ecosystems (Beniston, 2005, 2003; Diaz and Bradley, 1997; Hock et al., 2019; Moser et al., 2019; Piccolroaz et al., 2021; Sabás et al., 2021; Woolway, 2023; Woolway et al., 2019). As the rate of warming is amplified with elevation, it is also expected that high-mountain lakes will experience more rapid changes than those located in lower altitude environments (Pepin et al., 2015; Rangwala and Miller, 2012). Besides, high mountain lakes are ecosystems exposed to extreme climatic conditions and as they are generally located far from direct human activities the climate forcing could be easier disentangled from the human factor (Čiamporová-Zaťovičová, 2011; Pastorino and Prearo, 2020). As temperature is a key environmental variable in lakes controlling biogeochemical processes (Sabás et al., 2021; Woolway et al., 2022; Woolway and Merchant, 2019), the knowledge of how lake temperatures are changing is critical in order to provide the scientific basis for the appropriate decisions by managers and policymakers.

The Pyrenees are a complex mountain range with high topographic gradients, Atlantic and Mediterranean climate influences and a long history of intense human impact. These mountains are home to the largest glaciers remaining in southern Europe (Grunewald and Scheithauer, 2010; López-Moreno et al., 2016; Vidaller et al., 2021) and also to a large number of high altitude lakes originated after the last deglaciation. Many lakes and their catchment areas have been used over the centuries by human societies (Bal et al., 2011; García-Ruiz and Valero-Garcés, 1998), and their sedimentary sequences have provided climatic, environmental and anthropogenic reconstructions at millennial, centennial and decadal scales (see for example Corella et al., 2021; Leunda et al., 2017; Oliva-Urcia et al., 2013; Vicente De Vera-García et al., 2023).

Monitoring surveys have demonstrated a rapid retreat of the remaining Pyrenean glaciers during the last decades (Vidaller et al., 2023) and also rapid changes in the lake dynamics since the 1950s (Vicente De Vera-García et al., 2023). A number of studies have shown that the high altitude ecosystems are experiencing rapid changes due to the combining effects of climate change and increasing human pressures (Catalan et al., 2013; Oliva-Urcia et al., 2018; OPCC, 2021; Sabás et al., 2021; Vicente De Vera-García et al., 2023).

Measuring the recent changes in Lake Surface Water Temperature (LSWT) is a powerful tool to assess the impact of global warming in alpine environments. Monitoring studies on temperature changes in small high altitude lakes are scarce, and most of them are focused on ice phenology (Heinilä et al., 2021; Hernández et al., 2015; Kropáček et al., 2013; Latifovic and Pouliot, 2007; Viel et al., 2022). Most studies on small lakes (<2km^2), as Pedreros-Guarda et al. (2021), are located in temperate zones. In the Pyrenees the longer temperature time series spanning several decades are from Redó Lake (Aranda et al., 2016; Catalan et al., 2013, 2002; https://www.ceab.csic.es/en/facilities/limnological-observatory-pyrinees/) and they showed a clear trend of increasing temperatures during the last century especially higher during the last decades. A recent survey of surface temperatures in >70 Pyrenean lakes (Sabás, 2020; Sabás et al., 2021) have found a direct correlation with altitude and secondarily with other geographic variables. Available *in situ* data from lakes included in the REPLIM network and the Pyrenean Observatory of Climate Change (https://www.opcc-ctp.org/es/replim) showed also a clear increase in lake surface water temperature, especially during summer and autumn, a reflection of higher air temperatures. Changes in thermal regimes may have contributed to the documented changes in diatom communities during the last decades in some Pyrenean lakes (Vicente De Vera-García et al., 2023).

Lake Water Surface Temperature (LWST) is considered as an essential climate variable (ECV) by the World Meteorological Organization (WMO). Epilimnetic (surface) water temperature is highly correlated with regional air temperature (Adrian et al., 2009; Heddam et al., 2020; Zhu et al., 2023), and can affect a number of physical processes, such as turbidity or transparency, which in turn can accelerate ice melting processes on the surface of the water, generate changes in the radiative balance, *etc.* (Smith, 1978; Williamson et al., 1999). On the other hand, land surface temperature (LST) is a critical variable that plays an important role in determining the radiative energy budget of the Earth's surface (Hulley et al., 2019). The use of LST for Global Change studies is no novelty (Debnath et al., 2018; Zhou and Wang, 2016), nor is obtaining LSWT from satellite data (Czernecki and Ptak, 2018; Layden et al., 2015; Piccolroaz et al., 2024; Yang et al., 2019; Yu et al., 2020). Regarding the latter, many papers have been published comparing buoy-derived (*in situ* LSWT) and satellite-derived water temperature primarily in large lakes (Duan et al., 2021; Li et al., 2022; Liu et al., 2015) or open saltwater areas (Merchant et al., 2014; Sobrino et al., 2020a). Several studies have focused on large perialpine and subalpine lakes (Pareeth et al., 2017, 2016; Riffler et al., 2015), and they used a lower spatial resolution and a higher temporal resolution. Recently, UAVs have been utilized in glacial geomorphology research, such as those studying glacier lake outburst floods (GLOFs) (Tomczyk et al., 2020; Tomczyk and Ewertowski, 2020). Thermal cameras are also embedded in drones (Śledź et al., 2021) in glaciers (Kraaijenbrink et al., 2018), and in particular, for agro-ecological applications (Awais et al., 2022; Heinemann et al., 2020), although they have not yet been used for the study of water surface temperature. Regarding LSWT modeling, an extensive and detailed review has recently been published (Piccolroaz et al., 2024).

In this contribution, we compared the lake water surface temperature (LWST) measured *in situ* since 2017 at five lakes in the Pyrenees (the largest lake has a surface area of 0.44km^2), located at high altitude (between 1880 and 2680 masl) with those derived from satellite data. The lake temperatures have been monitored with an hourly time resolution scale by the REPLIM network coordinated by the Pyrenean Institute of Ecology (IPE-CSIC) since 2017. The main aim of the work is to assess the potential of satellite-derived data for temperature analysis in small high altitude lakes, by comparing the temperature recorded *in situ* with those obtained from the satellite, and then use the satellite data to reconstruct past surface temperatures when monitoring data are not available. Based on the correlation between both measurements, we reconstructed the summer (June–July-August-September) surface water temperature for the selected five lakes since 1985 and applied the same methodology to four lakes of similar features but without *in situ* monitoring data.

The significant correlation between *in situ* and satellite data sets allowed us to reconstruct more accurately past LSWT since 1985 and compared the reconstructed temperature trends with some of the documented recent changes in the lakes. As many lakes in this mountain range are not monitored, the use of remote sensing can greatly contribute to the diagnostic studies of climate change in Pyrenean lakes (Li et al., 2023; Reiners et al., 2023; Sobrino et al., 2020b; Woolway, 2023). The methodology allowed validation of satellite measurements and its application to a larger suite of small lakes to obtain a more accurate regional picture of global change impacts in high mountain lakes.

2. Materials and methods

2.1. Study sites

The nine lakes are located in the southern Pyrenees, eight of them are in Spanish territory, within the region of Aragon, and one of them in Andorra (Fig. 1 and Table 1). The lakes originated after the ice retreated from over-excavated cirques by the glaciers at the end of the last glaciation (Pardo et al., 2014). They are located in granitic (Cregüeña, Bachimaña, Respomuso, Montmalús) and mixed carbonate and silicate watersheds. No weather stations are located near any of the monitored lakes.

The selected lakes are very small in size, ranging from 0.05 km^2 in area (Acherito) to 0.44 km^2 (Cregüeña) The maximum depth of these glacial lakes varies from 27 m (Estanés) to almost 100 m (Cregüeña). The average summer surface temperature of each lake (2017–2022) ranges from 8.71 °C in Cregüeña to 18.56 °C in Sabocos.

The local climate at higher elevation in the Pyrenees is controlled by location (northern *versus* southern slopes and Atlantic *versus* Mediterranean influences), the local topography and exposures (López-Martín et al., 2007). The high mountain climate is characterised by abundant rainfall (>1200 mm/year) and mean annual temperature (MAT) between 8 and 4 °C (López-Martín et al., 2007). The high mountain lakes remain ice-covered between November and June, although those at higher altitudes can accelerate their freezing and delay their thawing by up to a month. Therefore, our study period focuses on the analysis of surface temperatures in the ice-free summer months from June to September.

Table 1
Basic characteristics of the lakes under study. *Maximum depth and area may vary due to its impoundment conditions. These lakes are devoid of *in situ* thermometers.

	Altitude (masl)	Area (km^2)	Max. depth (m)	Thermistor depth (m)	Summer avg. temp. at surface (°C)
Acherito	1880	0.05	29	1	15.28
Estanés	1757	0.19	27	0.5	17.74
Sabocos	1892	0.09	32	1	18.56
Cregüeña	2680	0.44	98	1.5	8.71
Montmalús	2432	0.06	20	0.5	15.48
*Tramacastilla	1680	0.08	10	No monitoring	–
*Respomuso	2102	0.40	30	No monitoring	–
*Bachimaña	2191	0.33	Unknown	No monitoring	–
*Urdiceto	2370	0.24	22	No monitoring	–

2.2. In situ temperature

The temperature data for Acherito, Estanés, Sabocos, Cregüeña and Montmalús were obtained from the REPLIM network (https://www.opcc-ctp.org/es/replim). HOBO thermistors had been installed at several depths in the deepest part of the lake. The depths at which the thermistors were installed vary in each lake, depending on different

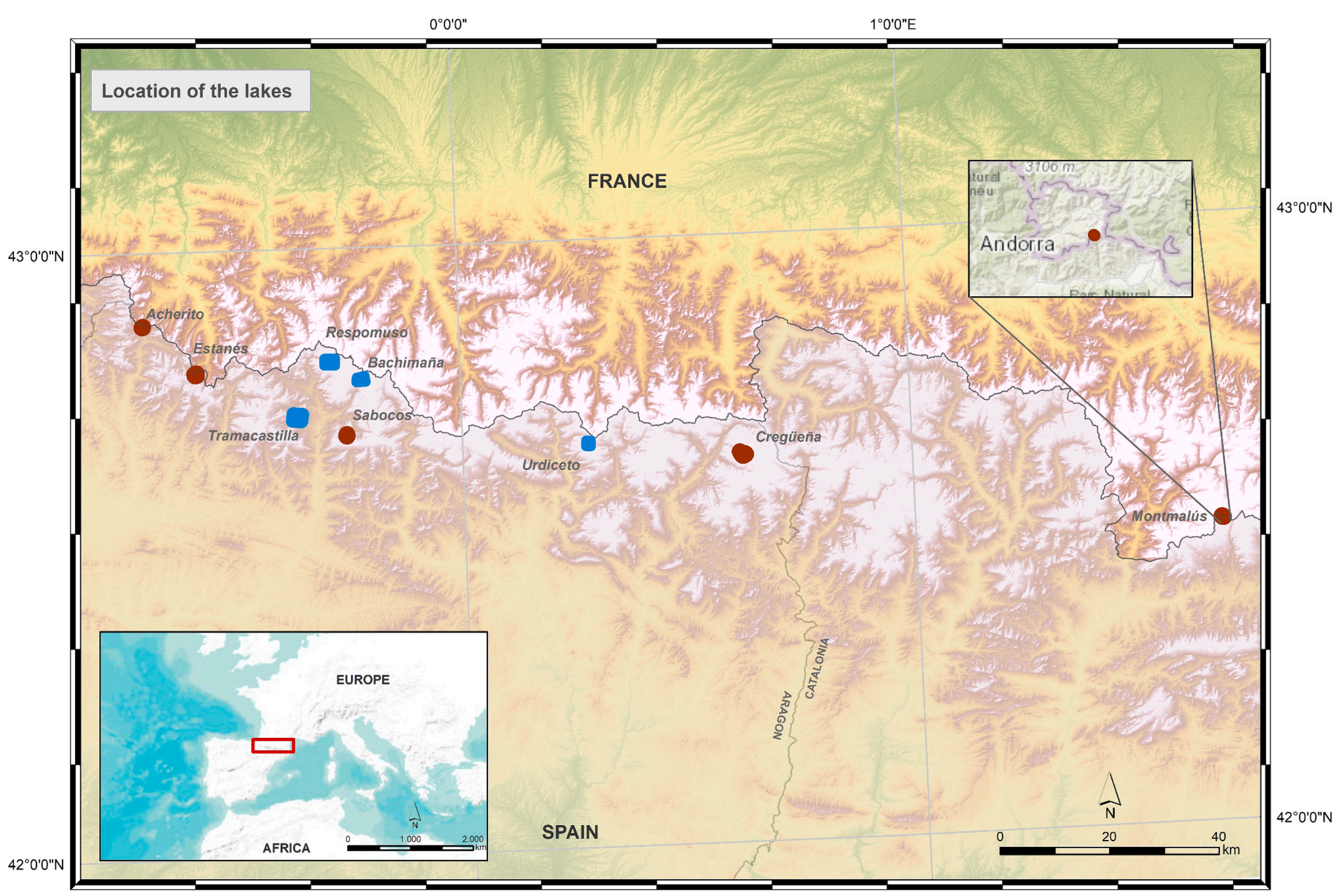

Fig. 1. Location of the lakes. Eight of them are located in Aragón, Spain (Acherito, Estanés, Sabocos,Cregüeña, Tramacastilla. Bachimaña, Respomuso and Urdiceto), and one of them is in Andorra (Montmalús). Red dots refer to the lakes used for *in situ*-satellite comparison. Blue dots are the location of the lakes currently without *in situ* monitoring.

characteristics such as the ice phenology and the maximum depth of the lake. In this work we use the uppermost thermistor in order to compare the data from the satellite's thermal sensor. In Cregüeña, the shallowest thermistor is installed at 1.5 m, to avoid that the ice in winter does affect the sensor. In other lakes such as Estanés and Montmalús, the uppermost thermistor is located at 0.5 m, while in Acherito and Sabocos is located at 1 m. The sensor registers the temperature once a day, at 11 UTC, although in some lakes the frequency is hourly. In those lakes with hourly measurements, the value of 12 UTC has been selected, which is the approximate time at which Landsat overpasses.

2.3. Landsat-derived lake surface water temperature

The small surface area of the lakes under study requires the use of thermal channels with high spatial resolution. That was the reason to choose Landsat-8/9, as it offered a high spatial resolution in the thermal band in addition to the great temporal continuity since the early 1980s.

The lake surface water temperature (LSWT) was obtained using Google Earth Engine (GEE), an online platform with access to catalogues of satellite imagery (Gorelick et al., 2017). The spatial resolution of the thermal infrared band in Landsat series data was resampled to 30 m. Land surface temperature (LST) values were retrieved from the USGS EROS Archive - Landsat Archives - Collection 2 Level-2 Science Products, through GEE, providing a robust mass data processing capability (Wulder et al., 2008). LST is derived from the USGS LST provisional product according to Cook et al. (2014). Schaeffer et al. (2018) provided a broad-scale validation of the USGS LST provisional product, concluding that the stability of the Landsat algorithm is sufficient to evaluate the interannual variability of lakes and other aquatic ecosystems (absolute errors <2 °C).

The selected images of the lakes since 2017 (69 in total) were used for comparison with the thermistor data during the summer periods. The images chosen were free of shadows and clouds, and a visual inspection (>100 images since 1985) was made to avoid possible outliers. In order to ensure that the chosen class corresponds to the category "water", the central pixels of the lake, which are outside the influence of the ground or other land covers, were selected (see S1 in "Supplementary material"). The presence of remaining ice during the summer in some lakes available in the REPLIM network greatly reduced the number of high quality images and they were not included in this study. For example, Marboré Lake, despite being located at a lower altitude than Cregüeña, had an average duration of snow cover longer than the latter (https://labo.obs-mip.fr/multitemp/snow-cover-duration-at-lakes-in-the-pyrenees/; Vicente De Vera-García, 2023). For this reason, Marboré lake was not included in this study, although it has one of the longest *in situ* monitoring series (2013–2023). The images have undergone a manual filtering process, removing outliers resulting from cloud intrusions or shadows. Although the number of years is only 5, given the small size of the lakes, the time series is considered to be adequate (Piccolroaz et al., 2016).

2.4. Statistical methods

Prior to the statistical analyses, the normality of the data was checked using the Chi2 test ($n = 69$), and it turned out not to conform to a normal distribution in the case of the *in situ* LSWT, so non-parametric statistics were used. The root mean square error (RMSE), mean absolute error (MAE) and coefficient of determination (r^2) between *in situ* and satellite measurements were used to assess the degree of agreement between both data sources.

To examine the accuracy of the LSWT, we calculated the RMSE

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (\widehat{T}_i - T_i)}{N}} \quad (1)$$

and the MAE

$$MAE = \sum_{i=1}^{N} \frac{\sum_{i=1}^{N} |x_i - \widehat{x}_i|}{N} \quad (2)$$

where $\widehat{T}_i$ and T_i are *in situ* and satellite-derived daily temperature at the time *i*.

The Kruskal-Wallis test was used as a non-parametric alternative to ANOVA to test for significant differences between lakes and months. Significant differences were identified at $p < 0.05$.

Spearman's R-value was also used as a non-parametric alternative to Pearson's coefficient. In order to check for trends, the Mann-Kendall test has been used for the reconstructed temperature data series since 1985.

2.5. Recent lake evolution data

Lake temperatures were reconstructed since 1985 for the five *in situ* monitored lakes using the data from Landsat 5, 7, 8 and 9 and the correlation between the satellite-thermistor data obtained for the last 5 years. In addition, we have applied the function derived from the relationship between both data sources to obtain the summer surface temperature since 1985 in four additional lakes: Respomuso, Bachimaña, Tramacastilla and Urdiceto (Fig. 1). The similar results demonstrate the applicability of our approach to other small water bodies in the Pyrenees not included in monitoring programs.

Although there are no data of measured changes in the lakes comparable to the temperature reconstructions (1985–2022), paleolimnological reconstructions based on short core analyses for Acherito, Sabocos and Cregüeña have provided time series of recent changes in lithogenic and organic carbon fluxes since the mid 1950s (Vicente De Vera-García et al., 2023). Similar time series were obtained following the same methodology for Estanés and Montmalús.

3. Results and discussion

3.1. Comparison of satellite and in situ LSWT (2017–2022)

The average summer lake surface temperature of each lake (2017–2022) measured *in situ* ranges from 8.71 °C in Cregüeña to 18.56 °C in Sabocos.

Comparison between *in situ* and satellite data shows a high coefficient of determination ($r^2 = 0.92$) (Fig. 2). Spearman's R-value is 0.94 with a confidence interval above 99 % ($p < 0.01$), indicating that the relationship between the two temperature values is significant.

The average value for RMSE for all the lakes is 2.7 °C (Table 2). Estanés has the lowest error (1.8 °C) and Acherito the highest (3.9 °C). As for the MAE, the average error is 2.4 °C, with values ranging from 1.6 °C to 3.6 °C in the lakes mentioned. The standard deviation of each lake is between 2 and 3 °C, except for Cregüeña, with a value close to 5 °C, suggesting a greater variability in the data recorded by the satellite.

The distribution of satellite and *in situ* LSWT data by month (Fig. 3), show the highest variability of temperatures in the month of June, when ice and snow may still remain in some lakes, and the lowest variability in September and August.

Fig. 4 shows the distribution of satellite and *in situ* temperature values in each lake. Cregüeña is the lake with the lowest temperature values in both LSWT, followed by Montmalús, Acherito, Estanés and Sabocos. Cregüeña is also the lake with the greatest temperature variability, which could be related both to its higher altitude and its location on the north face of the mountain. Kruskall-Wallis test identified significant differences in LSWT between lakes.

Numerous studies have investigated the relationship between surface temperature recorded by the lake thermistors with the satellite-inferred in large lakes (Read et al., 2014; Schneider and Hook, 2010). Our data demonstrate that similar methodologies are applicable to small lakes at

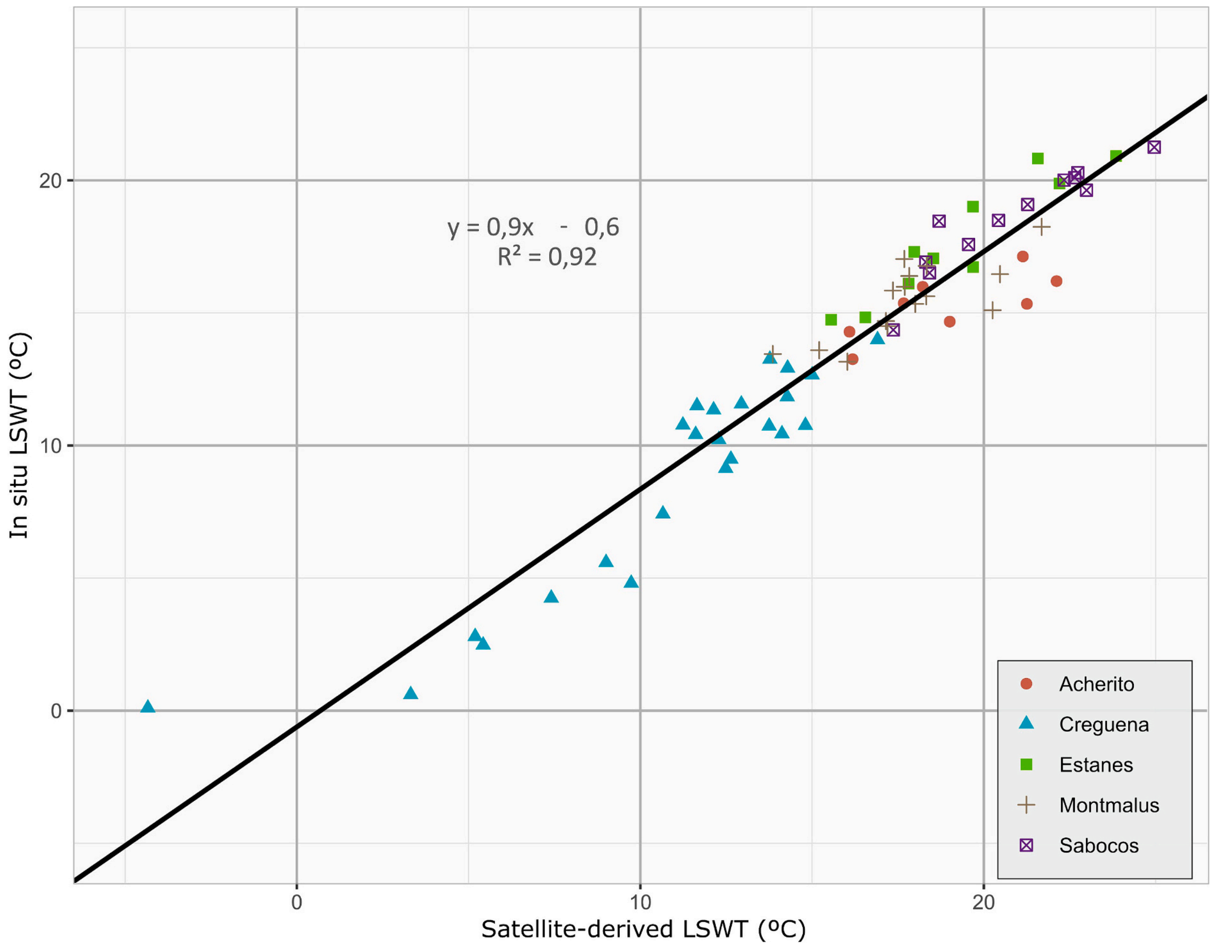

Fig. 2. Relationship between satellite-derived and ground temperature monitoring (2017–2022).

Table 2
Average, standard deviation, RMSE and MAE for satellite-derived LSWT (°C) (2017–2022).

	Satellite-derived LSWT (°C) - average	Satellite-derived LSWT (°C) - standard deviation	RMSE (°C)	MAE (°C)
Acherito	19.0	2.3	3.9	3.6
Estanés	19.3	2.6	1.8	1.6
Sabocos	20.8	2.4	2.4	2.2
Cregüeña	10.8	4.6	2.8	2.5
Montmalús	17.8	2.0	2.6	2.3
All 5 sites	16.2	4.8	2.7	2.4

high altitude mountain environments, and that the satellite-derived LSWT was consistently higher than *in situ* measurements.

Despite the small surface area of the lakes, we found a high ($r = 0.94$) and significant ($p < 0.01$) overall correlation coefficient, which coincides with the results obtained in similar studies of larger lakes (Czernecki and Ptak, 2018; Yang et al., 2019; Zhu et al., 2020). As for the quantified error between the simulated and observed temperature, we found RMSE values ranging from 1.8 °C in Estanés to 3.9 °C in Acherito, with an average error for all lakes of 2.7 °C. Our average error is higher than those reported from other studies likely due to their longer time series of *in situ* data for validation (Pareeth et al., 2017; Schneider et al., 2009) or the larger surface area of the lakes (Lazhu et al., 2022; Li et al., 2022) resulting in RMSE values of <1 °C, given that there may be a higher number of pixels absent from cloud presence.

The differences in the RMSE of each lake in our survey can be partly explained by three main reasons: 1) the variable depth of the thermistors, as we could expect larger discrepancies when the thermistors are deeper; 2) the number of data pairs in each lake, which is controlled by the short length of monitoring period and the ice-free season; 3) the emissivity, given that it can change and lead to an uncertainty of 1 %, resulting in errors of 1 K. Although the emissivity of liquid water is high, ranging from 0.95 to 0.99, values can vary based on specific conditions such as the water composition and turbidity.

Acherito has the highest RMSE, which may be related to both the thermistor depth (1 m) and the relatively lower number of data pairs used (8), as this is the lake with the lowest number of records. Sabocos thermistor is also located at a depth of 1 m, and the lake has very similar characteristics to Acherito (altitude and depth) but Sabocos lake is somewhat larger, which could explain its lower RMSE.

Cregüeña is the lake with the second highest RMSE. Although it has 24 pairs of data between 2018 and 2022, the shallowest thermometer is at a depth of 1.5 m. A negative satellite-derived value (Fig. 2) does not correspond to an outlier but to a temperature value that the satellite has captured when the lake was partially frozen (24/06/2018). The *in situ* value that we found for that particular date was 0.1 °C. Thus, the concordance between the two data sources is also contingent upon the time of year, owing to the heightened sensitivity of LST to surface ice presence and the deeper location of the thermometers.

The surface thermometers at Montmalús and Estanés are at 0.5 m. However, the latter has a smaller error even though it also has a smaller number of data pairs (15 *vs.* 10 data pairs). Perhaps these differences found in both lakes have to do with the fact that Estanés is a relatively larger lake, so there is no spectral confusion with non-water pixels.

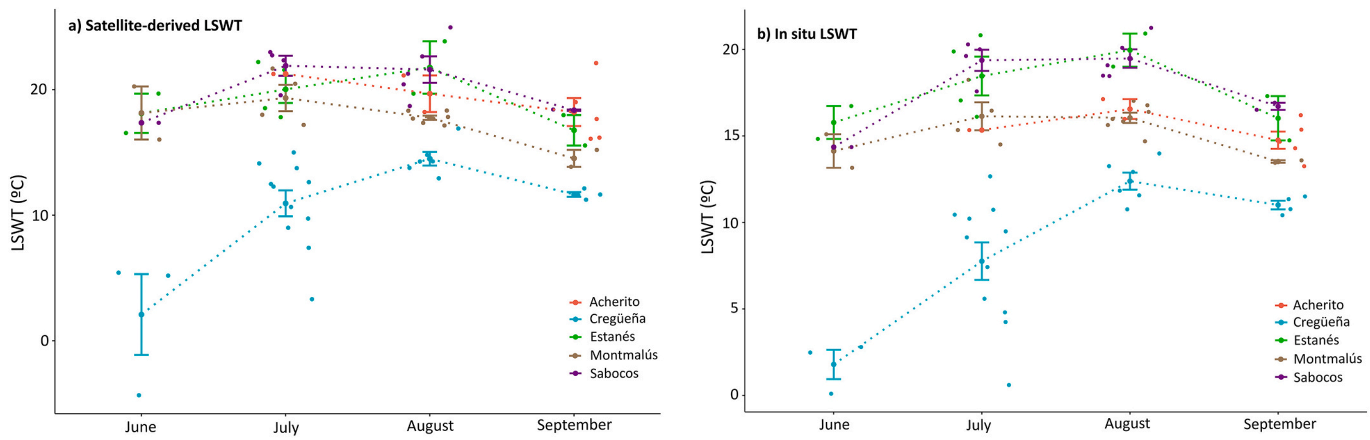

Fig. 3. Distribution of satellite-derived (a) and *in situ* LSWT values (b) by month.

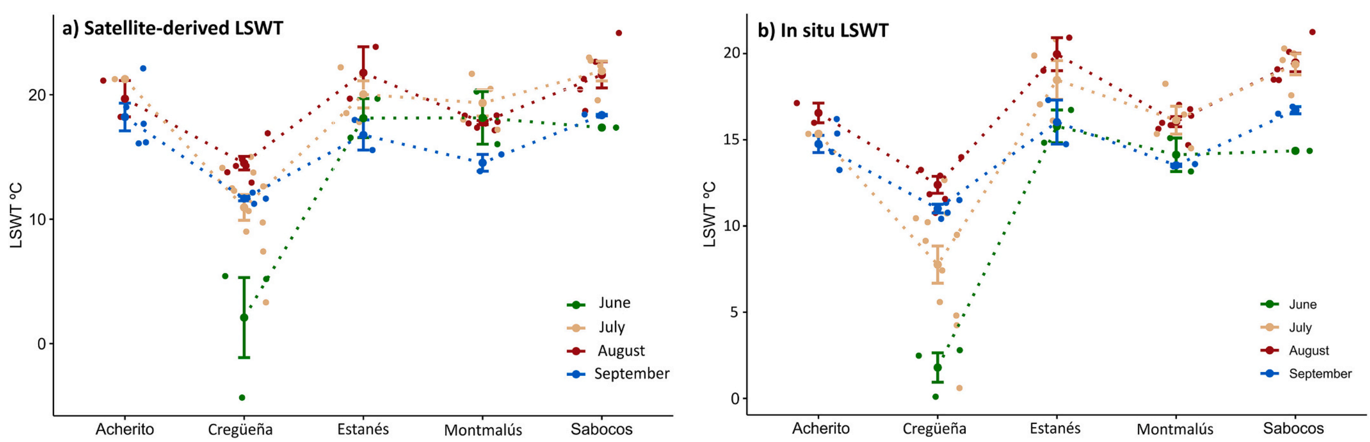

Fig. 4. Distribution of satellite-derived (a) and *in situ* LSWT values (b) by lake.

3.2. Reconstruction of past lake surface temperature since 1985

The comparison between satellite and thermistor temperature for the 2017–2022 period allowed us to obtain a correlation between both variables (Fig. 2.):

$$y = 0.9x - 0.6 \tag{3}$$

where y is the output for the estimated surface temperature and x is the retrieved value from satellite temperature.

Applying that equation to the 1985–2022 Landsat satellite data, we estimated the *in situ* surface temperatures for the five lakes during the ice-free season (Fig. 5). Overall, the distribution of lake surface temperatures shows an upward trend. This positive trend is evident across all lakes, (Table 3). The computed p-value is below the designated α significance level, which supports the acceptance of the alternative hypothesis (*Ha*).

Fig. 5 highlights a notable degree of coherence across the majority of the lakes when comparing the predicted temperatures to those measured *in situ* during the common study period. For the sites with no good quality images for early summer (Montmalús), the distribution of predicted temperature has a smaller range compared with the variability observed in the field-collected temperature data. The maximum summer temperatures show a good agreement between satellite and *in situ* data, but the minimum summer temperatures show a larger discrepancy (*e.g.* Montmalús, Fig. 5). The minimum summer temperatures measured *in situ* correspond to the month of June, when low temperatures are expected. However, there were not good quality images for June in Montmalús and the satellite data correspond mostly to July and August.

Table 4 presents an analysis of errors between the average predicted temperatures derived from the former Eq. (3) and the actual *in situ* temperatures recorded during the period spanning from 2017 to 2022. This analysis offers valuable insights into the accuracy of temperature reconstructions for the lakes under study dating back to 1985. The error ranges between 0.9 and 1.7 °C with the reconstructed temperatures following closely the *in situ* measurements (Table 4). Sabocos exhibits the most favourable outcome with the lowest error (0.9 °C), closely followed by Estanés (1.1 °C), Montmalús (1.6 °C), Cregüeña, and Acherito (1.7 °C). This outcome suggests that the equation's fit is stronger for Sabocos and Estanés, although the model does not replicate well the more extreme temperature values measured *in situ*.

On the contrary, Cregüeña and Acherito display the highest errors, as previously documented in Table 2. It's noteworthy that these two lakes also exhibit greater variations in LSWT as indicated by their higher standard deviations. This variability in LSWT likely contributes to the elevated Root Mean Square Error (RMSE) observed in these lakes.

The comparison between the two data sources illustrates how the lack of images during some periods (early summer) increases the uncertainty of the reconstructions and particularly the prediction of the temperatures during these periods. A higher number of good quality images and a more regular distribution during the summer months would enable adjustment of the relationship between predicted and observed LSWT.

In order to test the use of this methodology in other lakes with no monitoring programs, we have selected four additional lakes with similar surface area, depths and location in the Pyrenees (Fig. 6).

The temperature reconstruction for the four lakes (Fig. 6) also shows

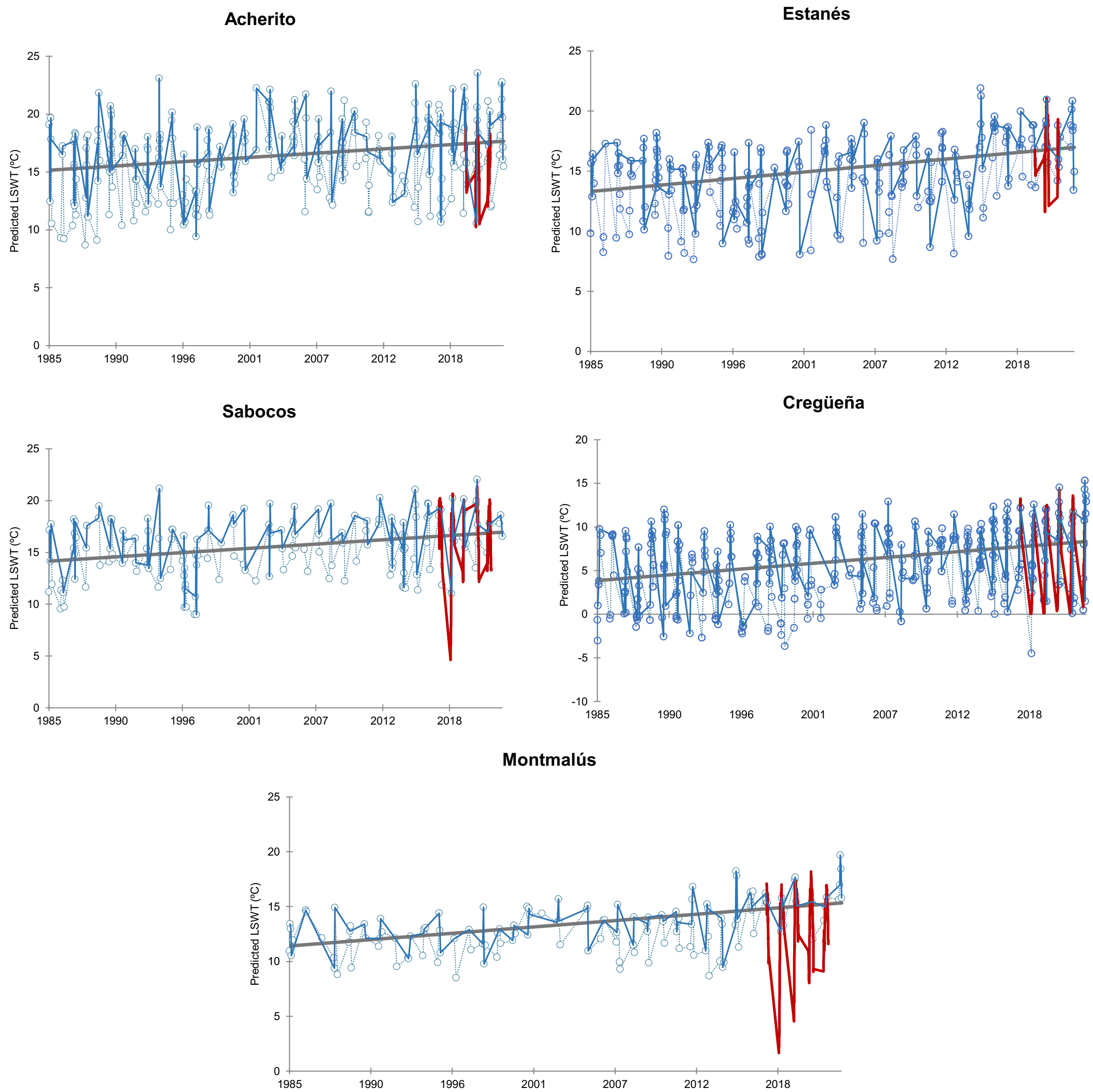

Fig. 5. Summer surface water temperature reconstruction for the five lakes since 1985. Solid blue line refers to the reconstructed temperature for July and August. Dotted blue line refers to the temperature for all summer (Jun-Jul-Aug-Sep). Red line represents available summer *in situ* temperature data (2017–2022) and grey line represents Sen's slope.

Table 3
Results of the two-tailed Mann-Kendall test. H0: there is no trend in the series; *Ha*: there is a trend in the series.

	Kendall's Tau	p-Value	Hypothesis accepted at α = 0.05
Acherito	0.16	<0.001	*Ha*
Estanés	0.24	<0.001	*Ha*
Sabocos	0.19	<0.001	*Ha*
Cregüeña	0.22	<0.001	*Ha*
Montmalús	0.34	<0.001	*Ha*

an upward, significant trend (Table 5). Bachimaña and Respomuso are located in the same valley and relatively close to each other, and they have similar temperature values and trends (Kendall's Tau = 0.27 and 0.24, respectively). The common response of these lakes to the general global warming trend is apparent, yet we do not have *in situ* temperature values to validate the predicted temperature. In the case of Tramacastilla, the reconstructed temperatures show a smaller range and a greater degree of homogeneity, possibly due to its location at a lower altitude, and its smaller size and depth. On the contrary, Urdiceto,

Table 4
Comparison of the predicted and *in situ* LSWT (°C) in the common period 2017–2022. Average and standard deviation refers to the predicted LSWT (1985–2022).

	Predicted LSWT (°C) - average	Predicted LSWT (°C) - standard deviation	RMSE (°C)	MAE (°C)
Acherito	16.2	3.2	1.7	1.3
Estanés	14.5	3.1	1.1	0.9
Sabocos	15.6	2.7	0.9	0.7
Cregüeña	5.7	4.0	1.7	1.4
Montmalús	13.1	2.5	1.6	1.0
All 5 sites	13.9	4.8	1.4	1.1

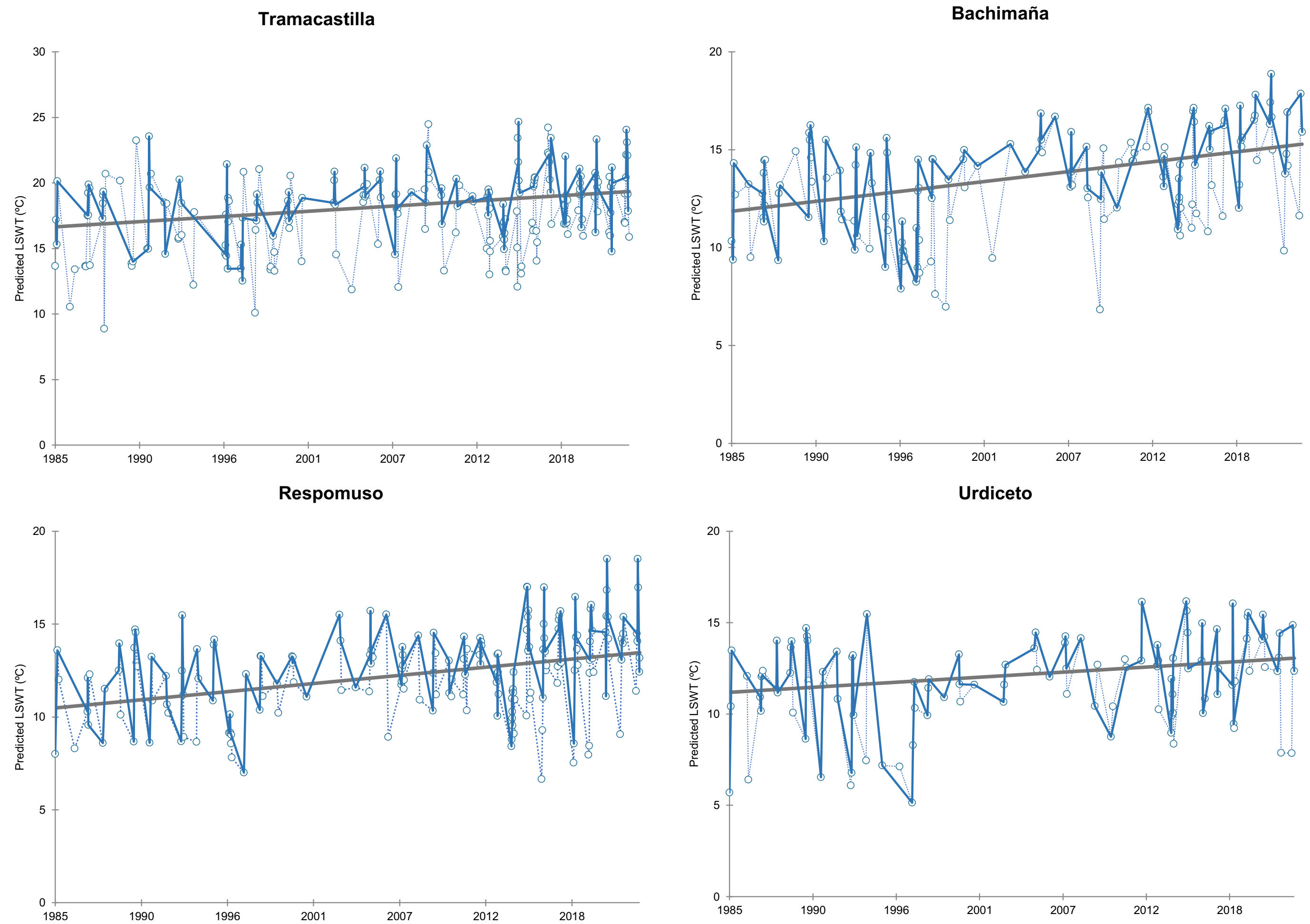

Fig. 6. Summer surface water temperature reconstruction for the four lakes since 1985. Solid blue line refers to the reconstructed temperature for July and August. Dotted blue line refers to the temperature for all summer (Jun-Jul-Aug-Sep). Grey line represents Sen's slope.

Table 5
Results of the two-tailed Mann-Kendall test for the four lakes. H0: there is no trend in the series; *Ha*: there is a trend in the series.

	Kendall's Tau	p-Value	Hypothesis accepted at $\alpha = 0.05$
Tramacastilla	0.18	<0.001	*Ha*
Bachimaña	0.27	<0.001	*Ha*
Respomuso	0.24	<0.001	*Ha*
Urdiceto	0.17	0.007	*Ha*

located at a higher altitude, had lower temperature values and a greater variation, especially during the first 12 years (as can also be seen in Bachimaña).

Overall, the equation's reconstructed values using the regional dataset refined the satellite temperature data, enhancing its accuracy and reliability. As shown in Fig. 2, the satellite temperature values are in all cases (except for one) higher than the *in situ* sensor values, which help to explain the smoothing effect of LSWT after applying the equation (see graphs in S2 in "Supplementary material"). These differences in satellite-derived LSWT before and after applying the equation results into an average absolute value of 2.2 °C for all the lakes.

This approach contributes to a more precise depiction of temperatures, likely by mitigating discrepancies arising from variations in emissivity that can cause gaps in the measurement values. Reconstructed temperatures using the regional equation improves the reliability of the raw values from the satellite.

Finally, we have checked whether there are observable and significant trends in the maximum temperature values for all 9 lakes (S3 in the "Supplementary material"). We have selected the maximum value of the month of August, in order to avoid greater variations among lakes and the effect of remaining ice. The trends are similar to those on Figs. 5 and 6, although in some lakes there were non-significant, possibly due to the lack of values (good quality images) in some years. Regarding this matter, it is worth noting that maximum temperature values cannot accurately represent the annual trends, as the number of images is very variable per year and per lake. For example, we were able to obtain a unique value for August 1992 in Cregüeña (see S3). Table of the Mann-Kendall test results can be also found in "Supplementary material" (Table 1).

3.3. Temperature and lake dynamics changes

The review of surface temperature of 59 Pyrenean lakes (Sabás et al., 2021) and the thermal profiles changes during the last few years (OPCC, 2021; Vicente De Vera-García et al., 2023) indicated that altitude was the main driving factor explaining regional LSWT variability of the Pyrenean lakes.

Considering a temporal scale, Redó Lake is the lake with the longest monitoring record in the Pyrenees (Aranda et al., 2016; Catalan et al., 2002). The time series shows a clear trend of increasing temperatures during the last decades. A trend to increase summer temperatures during the last decades in the Pyrenees at higher elevations has been recently shown by tree ring analyses (Büntgen et al., 2024). Available data from the REPLIM network shows a clear increase in lakes' surface water temperature, especially during the summer and autumn (Vicente De Vera-García et al., 2023). Seasonal changes in temperature have already had an impact on biodiversity in the Pyrenean lakes. For example, the temperature increase during summer and autumn have favoured the proliferation of short-lived planktonic diatom species, such as *Fragilaria nanana* and *Cyclotella pseudostelligera*, as well as chrysophyte algae that form cysts in spring and the length of the ice-covered period has a direct influence on the composition of planktonic crustacean communities (Catalan et al., 2009; Vicente De Vera-García et al., 2023). A comparison between LSWT and local air temperature is not possible as there are no weather stations located close to the lakes or at high altitude. However, the correlation between LSWT with the air temperature from Góriz weather station located near Marboré lake (at 2.200 masl), showed a good correlation (see S4 in "Supplementary material"): the year with the lowest average and maximum temperature in Góriz was 2018 (5 and 18.4 °C respectively), and that was reflected *in situ* lower LSWT of Cregüeña and Marboré lake (2.600 masl), as the average (2.9 and 2.1 °C) and maximum (11.4 and 11.6 °C) temperatures were also the lowest on the time series (Vicente De Vera-García, 2023).

No significant changes in water chemistry have been found in these lakes during the last years. Water samples have been collected from the lakes since 2017 by the REPLIM network at different depths and several analyses have been performed including main anions and cations, chlorophyll concentration, organic matter concentration, alkalinity and phosphorus, and $\delta^{18}O$ and δD in water samples. A continuous measurement along the water column of various physicochemical properties (temperature, pH, Dissolved Oxygen, conductivity) was also conducted the same day of water sampling with the use of a multiparametric probe (Vicente De Vera-García, 2023). Results show differences among the lakes, varying from more alkaline waters in Sabocos and Acherito to more acidic and less concentrated waters in Cregüeña. Montmalús and Estanés lakes were not included in the REPLIM network analysis. In general, no significant trend in changes in water composition has been identified during the last five years.

Paleolimnological studies have been able to produce longer time series of lake dynamics changes. High resolution sedimentary records demonstrated unique patterns of sediment and organic carbon fluxes since 1850 CE and particularly during the last decades (Vicente De Vera-García, 2023). Fig. 7 illustrates the coherence between higher – although variable – lithogenic and TOC (total organic carbon) fluxes from all lakes since 1850 CE and regional temperatures (top graph Fig. 7 and OPCC report). A rapid increase on the planktonic component documented in Acherito and Cregüeña during the last decades (Vicente De Vera-García et al., 2023) is likely correlated with higher air temperatures, similarly to Redó lake (Catalan et al., 2002) and many other sites in mountain and polar regions (Rühland et al., 2015). In the case of the Pyrenees, an increase in nutrient availability could also play a determinant role in higher algal bioproductivity and changes in diatom assemblages (Catalan et al., 2013, 2002; Pla et al., 2009; Vicente De Vera-García et al., 2023).

Due to the limited time overlap between LSWT dataset and lithogenic and TOC fluxes dataset and the different time resolution, comparing them poses a challenge: while the age models show multi-year time scales, the temporal resolution of the LSWT data is almost weekly. Moreover, certain lakes, such as Cregüeña, exhibit only three comparable data pairs during this shared timeframe. Conversely, the availability of a greater number of data pairs for Estanés could explain the good ($r = 0.57$) and significant ($p < 0.05$) relationship between temperature and organic carbon in this lake. In broad terms, the relationship between these variables may exhibit a degree of consistency, with temperature being one influential factor among others, rather than the sole determinant. LSWT, TOC and lithogenic fluxes graphs for Estanés and Sabocos are available in "Supplementary material" (S5), as these are the lakes with more accurate age models than the others.

Higher atmospheric deposition of Saharan dust in the Pyrenees could also be a main forcing in recent changes in lake dynamics, as most African dust input occurred as wet deposition and the highest deposition rates in the Iberian Peninsula were found in the Pyrenees (data from the DONAIRE network of atmospheric deposition sites in the Iberian Peninsula, Pey et al., 2020a; Pey et al., 2020b). More frequent atmospheric patterns conducive to higher dust delivery towards the Iberian Peninsula since the mid-20th century have also been documented (Salvador et al., 2022). On the other hand, several studies on lakes in Central Pyrenees have also found an increase in atmospheric phosphorus and nitrogen during the last decades (Camarero and Catalan, 2012). Higher CO_2, temperatures, nitrogen and phosphorus deposition all could have a positive synergistic effect leading to higher lake primary productivity (Catalan et al., 2013; Peñuelas et al., 2013).

The trend to increasing average lake surface water temperatures during the last decades is coherent with the increase in air temperature throughout the Pyrenees shown by various studies (Büntgen et al., 2024; El Kenawy et al., 2011; López-Moreno et al., 2011a; Spagnoli et al., 2002), the shorter duration of the ice-covered period in lakes and the decrease in snow accumulation in watersheds (López-Moreno et al., 2011b; López-Moreno et al., 2016). Recent changes in air temperature have been widely demonstrated to be the main driver for changes on lake surface temperatures at a global scale (Adrian et al., 2009; Butcher et al., 2015; Heddam et al., 2020; Schmid et al., 2014; Schneider and Hook, 2010; Woolway, 2023; Woolway et al., 2020; Zhu et al., 2023). Ice and snow cover insulate the water below and reflect solar radiation, leading to later spring warm up and lower water temperatures persisting into the summer (Butcher et al., 2015). The ice-covered period on high mountain lakes is projected to decrease in the context of ongoing global warming (Gobiet et al., 2014; Stefanidis et al., 2022; Woolway, 2023). Relatively smaller variability in surface temperatures may introduce drastic changes in the seasonal thermal regime of some lakes and increase thermal resistance to vertical mixing (Butcher et al., 2015). Long-term changes in thermal structure might have severe consequences for nutrient and oxygen concentrations (Adrian et al., 2009).

4. Conclusions

We evaluated the use of combined remote sensing and *in situ* measurements to obtain longer and more accurate time lake surface temperature in nine small high altitude lakes in the Pyrenees. The reconstructed surface temperature in all lakes has been increasing since 1985. This combined approach of *in situ* and satellite data could be used for other locations with no monitoring data. Remotely-sensed temperatures were slightly higher than *in situ* measurements. Nonetheless, this study endeavors to enhance the quality of the data by providing a more accurate dataset of reconstructed temperature.

However, it is important to note that the effectiveness of this approach may be limited in certain cases, particularly for lakes where topographical and environmental factors could pose challenges for accurate satellite imaging. A larger number of satellite images would help to improve the quality of temperature data reconstructions in high mountain lakes.

Monitoring studies along the Pyrenees and sediment core-based reconstructions have demonstrated large changes in organic accumulation, bioproductivity, sediment delivery and diatom assemblages in high altitude Pyrenean lakes since the mid-20th century, likely due to the synergistic effects of higher temperatures and increasing atmospheric nutrient deposition. Detailed comparison with our LSWT analysis is hindered by the different time resolution of paleolimnological and satellite-*in situ* temperature data.

The reconstructed recent temperature and biogeochemical changes in high altitude lakes will help to better define the regional trends and impacts, to communicate to the stakeholders, citizens and to better implement restoration policies.

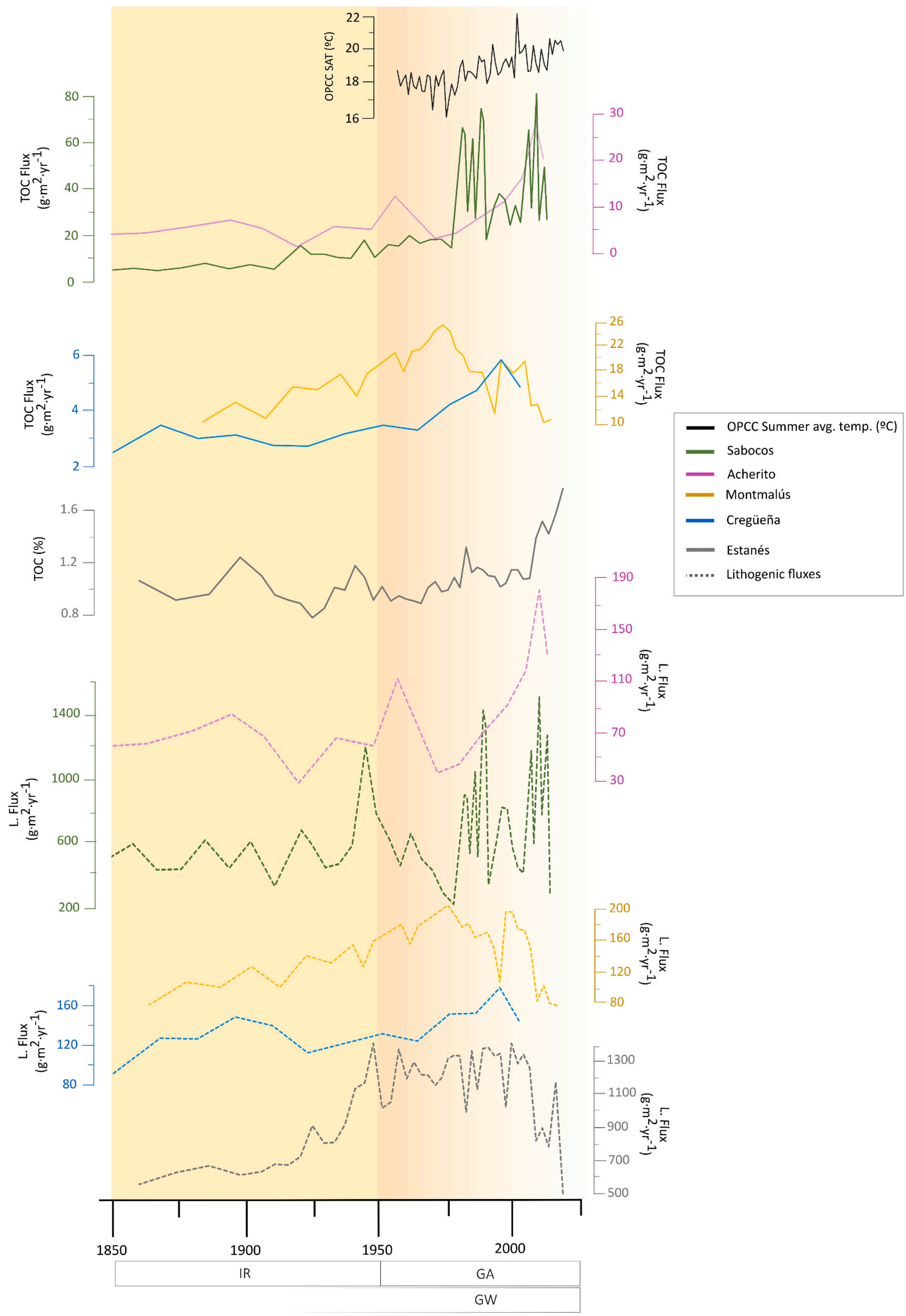

Fig. 7. Recent changes in some high altitude lakes in the Pyrenees: Organic carbon and sediment fluxes (data for Acherito, Sabocos and Cregüeña from Vicente De Vera-García et al., 2023). Summer average temperature (SAT) in the Pyrenees obtained by OPCC (https://www.opcc-ctp.org/sites/default/files/documentacion/en_informe_opcc_adapyr.pdf).

CRediT authorship contribution statement

Kilian Jungkeit-Milla: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Fernando Pérez-Cabello:** Writing – review & editing, Validation, Supervision, Software, Methodology. **Alejandra Vicente de Vera-García:** Writing – review & editing, Visualization, Resources. **Marcel Galofré:** Visualization, Software, Resources, Conceptualization. **Blas Valero-Garcés:** Writing – review & editing, Writing – original draft, Supervision, Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.173181.

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