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# PRESENT CLIMATE OF LAKE MONTCORTÈS (CENTRAL PYRENEES): PALEOCLIMATIC RELEVANCE AND INSIGHTS ON FUTURE WARMING

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**ABSTRACT.** The varved sediments of the Pyrenean Lake Montcortès (Pallars Sobirà, Lleida) embody a unique continuous high-resolution (annual) paleoarchive of the last 3000 years for the circum-Mediterranean region. A variety of paleoclimatic and paleoecological records have been retrieved from these uncommon sediments that have turned the lake into a regional reference. Present-day geographical, geological, ecological and limnological features of the lake and its surroundings are reasonably well known but the lack of a local weather station has prevented characterization of current climate, which is important to develop modern-analog studies for paleoclimatic reconstruction and to forecast the potential impacts of future global warming. Here, the local climate of the Montcortès area for the period 1955-2020 is characterized using a network of nearby stations situated along an elevational transect in the same river basin of the lake. The finding of statistically significant elevational gradients for average temperature and precipitation (-0.59 °C and 82 mm per 100 m elevation, respectively) has enabled to estimate these parameters and their seasonal regime for the lake site. The estimated average annual temperature is 9.7±0.8 °C and the estimated total annual precipitation is 1031±34 mm, in average. A representative climograph has been shaped with these data that can serve as a synthetic descriptive and comparative climatic tool. The same analysis has provided climatic data for modern-analog studies useful to improve the interpretation of sedimentary records in climatic and ecological terms. In addition, the seasonal slope shifting of the climatic elevational gradients has been useful to gain insights about possible future climatic trends under a warming scenario.

## *Clima actual del lago Montcortès (Pirineos centrales): relevancia paleoclimática y perspectivas sobre el calentamiento futuro*

**RESUMEN.** Los sedimentos varvados del lago pirenaico de Montcortès (Pallars Sobirà, Lleida) constituyen un paleoarchivo continuo de alta resolución para los últimos 3000 años que es único a nivel de la región mediterránea. Gracias a la variedad de registros paleoclimáticos y paleoecológicos que se han obtenido en estos sedimentos tan poco comunes, el lago se ha convertido en una referencia para la región. Las características geográficas, ecológicas y limnológicas del lago y sus alrededores son razonablemente bien conocidas, pero la falta de una estación meteorológica ha impedido caracterizar adecuadamente el clima actual, lo cual es necesario para desarrollar estudios de análogos modernos orientados a la reconstrucción paleoclimática, así como para predecir el impacto potencial del calentamiento global. En este artículo se caracteriza el clima local del área de Montcortès para el período 1955-2020, utilizando una red de estaciones meteorológicas cercanas situadas en un transecto altitudinal a lo largo de la misma cuenca fluvial en la que se encuentra el lago. La existencia de gradientes altitudinales estadísticamente significativos para la temperatura y la precipitación (-0.59 °C y 82 mm por cada 100 m de altitud, respectivamente) ha permitido estimar estos parámetros y su régimen estacional para el área del lago. La temperatura media anual estimada es 9.7±0.8 °C y la precipitación total anual estimada es 1031±34 mm, en promedio. También se ha construido un climograma que se puede utilizar como una síntesis climática descriptiva y una herramienta de comparación. El mismo análisis ha proporcionado datos climáticos para aplicar a estudios de análogos modernos orientados a optimizar la interpretación de registros sedimentarios en términos climáticos y ecológicos. Además, los cambios estacionales observados en la intensidad de los gradientes altitudinales han resultado útiles para sugerir posibles tendencias climáticas futuras en un escenario de calentamiento general.

**Keywords:** climatology, paleoclimatology, temperature, precipitation, climographs, elevational gradients, global warming, Lake Montcortès, central Pyrenees.

**Palabras clave:** climatología, paleoclimatología, temperatura, precipitación, climograma, gradientes altitudinales, calentamiento global, Lago de Montcortès, Pirineos centrales.

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## 1. Introduction

Lake Montcortès (thereafter LM) has become a keystone paleoecological site due to its annually-laminated sediments containing a continuous varved record of the last 3000 years, which is unparalleled across the whole Mediterranean region (Corella *et al.,* 2016; Rull *et al.,* 2021). During the last decade, these unique sediments have been intensively studied and have provided high-resolution paleoclimatic and paleoecological records that can be considered as a reference for the western Mediterranean region. These studies include, among others, varve formation and chronology, sediment yield history, past temperature and precipitation reconstructions (including heavy rainfall events), hypoxia and oxygenation events in lake waters, paleolimnological reconstructions (diatoms, pigments and other algae remains), vegetation and landscape dynamics, anthropization timing and patterns, human-impact history (burning, deforestation, cultivation, grazing), comparisons between paleoecological and historical records, and modern-analog studies for paleoclimatic and paleoecological reconstruction using physico-chemical and biological proxies, including biomolecular markers (Cao *et al.,* 2020; Corella *et al.,* 2011, 2012, 2014, 2016, 2019; Montoya *et al.,* 2018; Rull and Vegas-Vilarrúbia, 2014, 2015, 2021; Rull *et al.,* 2011, 2017, 2021a, b; Scussolini *et al.,* 2011; Trapote *et al.,* 2018a, b; Vegas-Vilarrúbia *et al.,* 2018, 2020, 2022).

Detailed knowledge on modern environmental features (notably geology, climate, vegetation and limnology, in the case of a lake) of paleoecological sites is important for past reconstructions, not only as a present-day reference but also as a potential source of modern-analog studies and also for calibrating sedimentary proxies in climatic and ecological terms (Overpeck *et al.,* 1985; Jackson and Williams, 2004; Birks *et al.,* 2012; Bradley, 2015). The geological, vegetational and limnological features of LM and its catchment are well known (Camps *et al.,* 1976; Modamio *et al.,* 1988; Carreras *et al.,* 2005-2006; Gutiérrez *et al.,* 2012; Mercadé *et al.,* 2013; Trapote *et al.,* 2018a) but this is not the case for climatology, due to the lack of a local weather station. To date, modern-analog and calibration studies requiring present-day climatic information have used different strategies to circumvent the lack of local climatic data.

For example, Vegas-Vilarrúbia *et al.* (2022) used regional Pyrenean-wide datasets to obtain transfer functions that allowed estimation of regional paleoprecipitation from varve thickness. Rull *et al.* (2017) used multiparameter (temperature, precipitation, relative humidity, wind direction and velocity) anomalies measured on a nearby weather station to establish climate-pollen relationships that could be used as modern analogs to infer the main climatic drivers of past vegetation change. Trapote *et al.* (2018) used short-term (~2 years) temperature series measured in lake waters to study the formation of modern varves in terms of climatic seasonality, and to extrapolate these relationships to the past. The same short-term climatic data were used to assess the responses of present-day photosynthetic algae to environmental drivers, as a tool for paleoclimatic inference using the same proxies preserved in lake sediments (Vegas-Vilarrúbia *et al.,* 2020). Cao *et al.* (2020) used similar short-term climatic data to calibrate molecular biomarkers (GDGTs) in terms of temperature, to obtain a molecular paleothermometer.

These and other approaches have demonstrated to be robust enough for characterizing past paleoenvironmental trends, but the availability of in situ climatic information could contribute to improve future developments. Installing a weather station on LM seems urgent (Rull, 2014) but, according to the current standards (WMO, 2017), three decades of data gathering would be necessary for a reliable climatic characterization. Meanwhile, we could explore other possibilities to palliate the lack of local climatic information. This paper presents one of the alternative options consisting of a study of temperature and precipitation trends measured in a local network of representative (>30-year measurements) weather stations situated along an elevational gradient in the same river basin of LM, aimed at estimating these climatic parameters for the lake by statistical interpolation.

The ultimate objective is to shape a hypothetical but statistically reliable climatic diagram (climogram or climograph) for LM. As is well known, a climograph is a statistical model of an average year, in terms of temperature and precipitation and their seasonal distribution, which provides a quick synthetic overview of the main climatic features of a particular site and facilitates comparison with other localities. Beyond this general climatic characterization, the results obtained in this study can also be used in modern-analog and calibration studies to improve past reconstructions using the varved LM sediments. In addition, some of these results may provide insights on future climatic trends that are discussed at the end.

## 2. Study area

Lake Montcortès (42°19’50” N - 0°59’41” E; 1027 m elevation) is situated in the southern-central Pyrenean flank, in the Catalan *comarca* of Pallars Sobirà (Lleida) (Fig. 1). The lake is kidney-shaped and small, with a diameter of 400-500 m, a total surface of 0.14 $km^2$ and a maximum depth of 32 m. The watershed is also small (1.4 $km^2$), with a few intermittent small creeks and scattered springs, and the lake is fed primarily by groundwater. The lake lies in karstic terrain characterized mainly by Triassic limestones, marls and evaporites, and Oligocene carbonatic conglomerates. Triassic ophytes outcrop mainly at the south and Quaternary lacustrine sediments surround the present-day water body (Corella et al., 2011). LM lies near the altitudinal boundary between submontane and montane bioclimatic belts, which coincides with the upper boundary of Mediterranean influence, in terms of both climatic and vegetation features. Indeed, above this boundary the characteristic Mediterranean summer aridity attenuates and the evergreen sclerophylous *Quercus rotundifolia* forests are replaced by forests dominated by deciduous *Quercus* (*Q. faginea* and *Q. pubescens*) and montane conifers, notably *Pinus nigra* and *P. sylvestris* (Mercadé *et al.,* 2013). The lake is situated in the upper-middle course of the Noguera Pallaresa river, a tributary of the Segre river, which flows to the south, as part of the Ebro basin. The area selected for this study is between approximately 42°15’-42°30’ N and 0°50’-1°15’ E, and ranges from ~500-1300 m elevation (Fig. 1). This area includes two valleys, the main Noguera Pallaresa valley and the valley of its tributary, the Flamisell river.

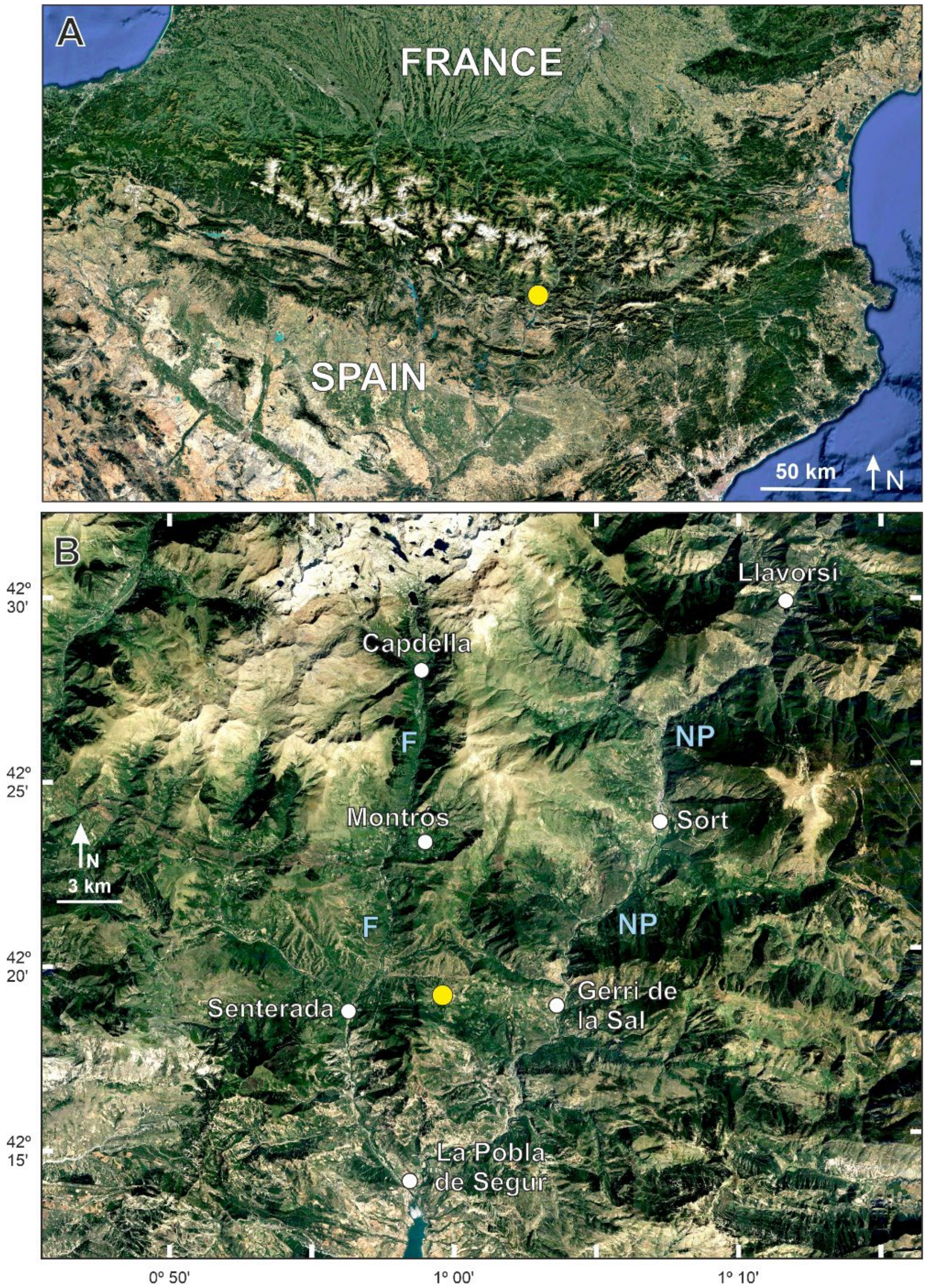


*Figure 1. Location map. A) General view of the Pyrenean range with the location of LM marked by a yellow dot. B) Study area indicating the weather stations (white dots) situated around LM (yellow dot), along the Noguera Pallaresa (NP) and Flamisell (F) valleys. Base images from Google Earth.*

## 3. Material and methods

### *3.1. Raw data*

Seven weather stations are available in the study area, which are situated at different elevations and have different time periods of measurement (Fig. 2). There are more stations along the Noguera Pallaresa and adjacent valleys but they are beyond the scope of this study, as they correspond to elevations and bioclimatic conditions that do not represent LM and its surrounding area. The stations of the study area underwent historical changes in location and instrumentation that produced homogeneity breaks in the climatic series. The manual stations of the Agencia Estatal de Meteorologia (AEMET) stopped reporting data in the 1980s-1990s, resuming continuity in some through automatic stations of the Servei Meteorològic de Catalunya (SMC) (Pérez-Zanón *et al.,* 2017).

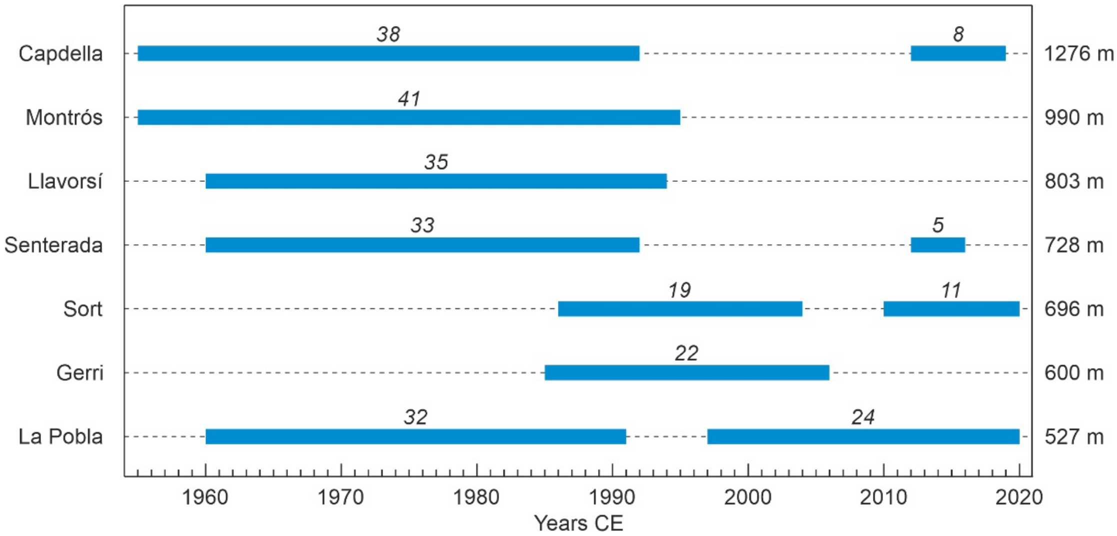


*Figure 2. Time periods with measurements (blue bands) in the weather stations of the Montcortès area (see Fig. 1 for location). The elevation in meters is provided at right and the number of years of each time series is indicated (in italics) above the blues bands.*

To circumvent the inhomogeneity of data derived from these circumstances, the Spanish High-Mountain Climate Database (SHMCDv1) has been used (Sigró *et al.,* 2022). This database consists of quality-controlled and homogenized daily records of temperature and precipitation for high elevations from Spain and its area of influence. To validate/reject doubtful data, the Rclimex-extraQC quality control software has been used, whereas homogeneity has been verified and adjusted by means of the Standard Normal Homogeneity Test (Alexanderson and Moberg, 1997), using the CLIMATOL software (Guijarro, 2006; Domonkos *et al.,* 2021).

The climatic conditions of a particular site are usually derived from a minimum of 30-year measurements, especially during the 1961-1990 interval, which has been considered an international reference (WMO, 2017). In the study area, five of the available stations fit with these requirements (La Pobla, Senterada, Llavorsí, Montrós and Capdella), whereas the other two (Gerri and Sort) began measurements in the 1980s. Four stations (La Pobla, Sort, Senterada and Capdella) hold two measurement periods, although the second period uses to be too short (5-11 years) for reliable statistical inference, except in the case of La Pobla, which possess the longest post-1990 series of the area with 24 years (1997-2020).

### *3.2. Data management*

These data have allowed reconstruction of temperature and precipitation trends in the study area for the period 1955-2020, using annual averages. The general climatic features of the study area have been characterized by assembling climographs for each weather station. In addition, point temperature and precipitation values for Lake Montcortès have been interpolated using regression analysis, after defining statistically significant linear relationships between these parameters and elevation within the study area. These significant relationships have been established for annual and monthly averages, which has enabled to build up a climograph for the lake site on the basis of its elevation. The LM climograph has been compared with the climographs of the available weather stations.

Regression analyses were performed using the ordinary least squares (OLS) method (Stigler, 1982), which requires normal distribution of residuals, homogeneity of variances (homoscedasticity) and lack of positive autocorrelation of residuals. The Shapiro-Wilk test was used to check for normal distribution of residuals and the Breusch-Pagan test was used to check for homoscedasticity or homogeneity of variance. In both cases, the test is positive for normality and homoscedasticity if p-values are above 0.05 (Shapiro and Wilk, 1965; Breusch and Pagan, 1979). Autocorrelation was checked using the Durbin-Watson test, which statistic (DW) ranges from 0 (positive autocorrelation) to 4 (negative autocorrelation); no autocorrelation occurs at values around 2 (Durbin and Watson, 1950, 1951). For n = 7 (which is our case) and α = 0.05, positive autocorrelation occurs at DW values below 0.70 and the range 0.70-1.36 is inconclusive, whereas negative autocorrelation occurs above WD = 3.30 and the range 2.64-3.30 is inconclusive. The prediction errors of the obtained linear regressions were calculated as the root mean square errors (RMSE) (Hyndman and Koehler, 2006). The software PAST 4.09 (Hammer *et al.,* 2001) was used to perform these statistical analyses.

## 4. Results

### *4.1. General temperature and precipitation trends*

The general mean anomalies of temperature and precipitation obtained from the available stations are shown in Figure 3. A general temperature decrease is observed during the 1960s leading to a phase of lower temperatures (up to ~1 °C below the average) in the 1970s. A sudden increase in 1980 initiated a general warming trend that is still ongoing. At the end of the measurement period (2020), the temperature was ~2 °C above the 1965-1980 phase of lower temperatures. Precipitation was maximum at the beginning (1960), but immediately initiated a long descent that continued during the 1965-1980 cold phase and attained minimal values (~200 mm below the average) coinciding with the 1980 warming. This drier phase extended up to 1990 and, after a decade of slow precipitation increase, a new drier interval began by 2004 that lasted until 2017, when a short recovery was observed until 2020. Interestingly, precipitation values remained mostly below or around the average during the 1980-2020 warming.

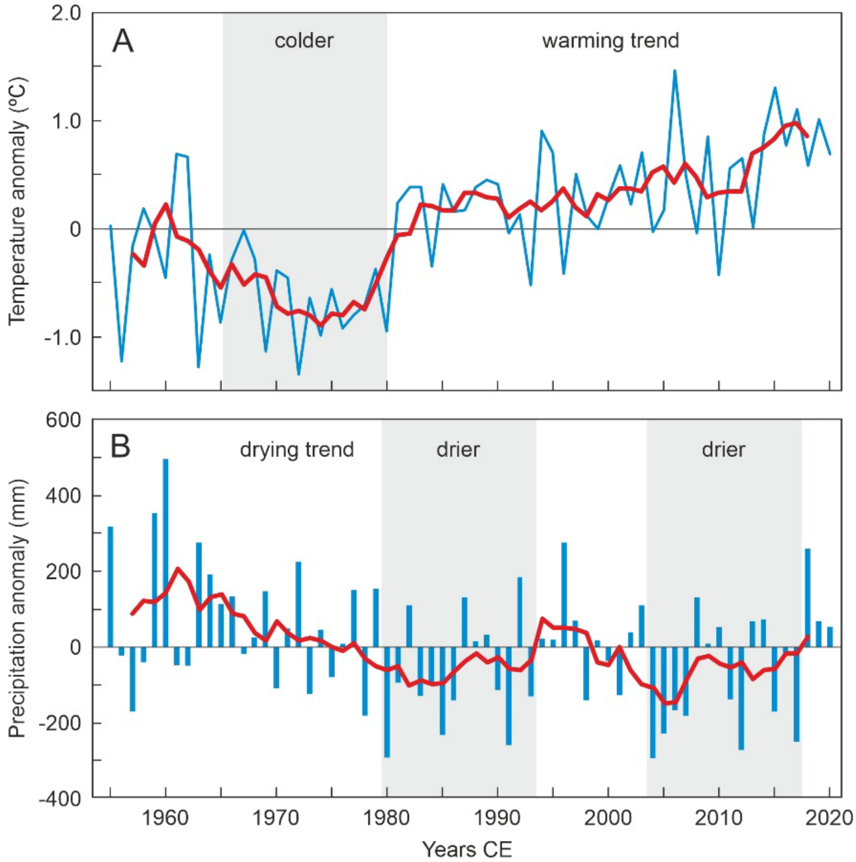


*Figure 3. Temperature (A) and precipitation (B) trends of the last 65 years in the study area, using the averaged anomalies of the seven weather stations used in this work (Fig. 1). Blue lines/bars are actual measures and red lines are 5-yr moving averages.*

*Table 1. Temperature and precipitation differences in stations with two measurement periods (Fig. 2)*

| Station | Period (years) | T (°C) | P (mm) | Period (years) | T (°C) | P (mm) | ΔT (°C) | ΔP (mm) |
|---|---|---|---|---|---|---|---|---|
| Capdella | 1955-1992 (38) | 8.85 | 1250 | 2012-2019 (8) | 10.60 | 1119 | 1.75 | -131 |
| Senterada | 1960-1992 (33) | 10.46 | 865 | 2012-2016 (5) | 11.28 | 748 | 0.82 | -118 |
| Sort | 1986-2004 (19) | 12.08 | 766 | 2010-2020 (11) | 12.34 | 759 | 0.26 | -7 |
| La Pobla | 1960-1991 (32) | 12.48 | 658 | 1997-2020 (24) | 13.68 | 582 | 1.20 | -76 |

## *4.2. Site climographs*

Considering the above results, the stations of Capdella, Montrós, Llavorsí, Senterada and La Pobla possess a representative period (>30 years) in the range around 1960-1990, which fit with the usual requirements for a climograph. In the case of Capdella and Senterada, the most recent measurement periods are too short (5-8 years) and far from the representative range (20 years apart) to be included in the respective climographs. In the La Pobla station, the situation is different because both measurement periods can be considered representative and the significant differences in temperature and precipitation for these two periods prevents to include both in the same climograph. Therefore, two climographs have been assembled for comparison, one for each period, although only the one corresponding to 1960-1991 will be used for further statistical treatment. In Gerri, there is no option, only the available measurement period of 22 years can be used. In the case of Sort, the small differences in temperature and precipitation between the available measurement periods (Table 1), along with the short delay between them (only 6 years), make possible to merge both series in a single representative series of 30 years.

The resulting climographs are depicted in Figure 4. In all of them, maximum temperatures occur in summer (July-August) and minimum values in winter (January and December), with an evident difference with elevation that will be further analyzed in more detail. Precipitation patterns are less homogeneous, although maximum values are usually recorded in spring and autumn while summers are drier, which indicates some Mediterranean influence. However, in contrast with typically Mediterranean climates, the summer dryness is shorter and less intense than in winter (January-March and December), with February as the driest month. The wettest month is May. There is also an elevational dependence of precipitation that will be further addressed.

The annual average temperature shows a decreasing pattern with elevation (temperature lapse rate) that follows a linear trend with a slope of -0.0059±0.0013 (Fig. 5), which implies a decreasing rate of 0.59±0.13 °C per 100 m elevation. Contrastingly, annual average precipitation increases with elevation at a rate of 81.92±9.8 mm per 100 m elevation (slope = 0.8192±0.098) (Fig. 5). In both cases, the residuals were normally distributed ($p_T = 0.7138$; $p_P = 0.6326$), the variances were homogeneous ($p_T = 0.8481$; $p_P = 0.8292$) and the residuals were not positively autocorrelated ($WD_T = 2.210$; $WD_P = 2.930$). Therefore, the obtained regression equations (Fig. 5) allow reliable estimations of intermediate average temperature and precipitation values from elevation. For LM, situated at 1027 m, the estimated annual average temperature is 9.70 °C, with a prediction error of 0.80 °C, and the estimated annual average precipitation is 1031 mm, with a prediction error of 34.45 mm.

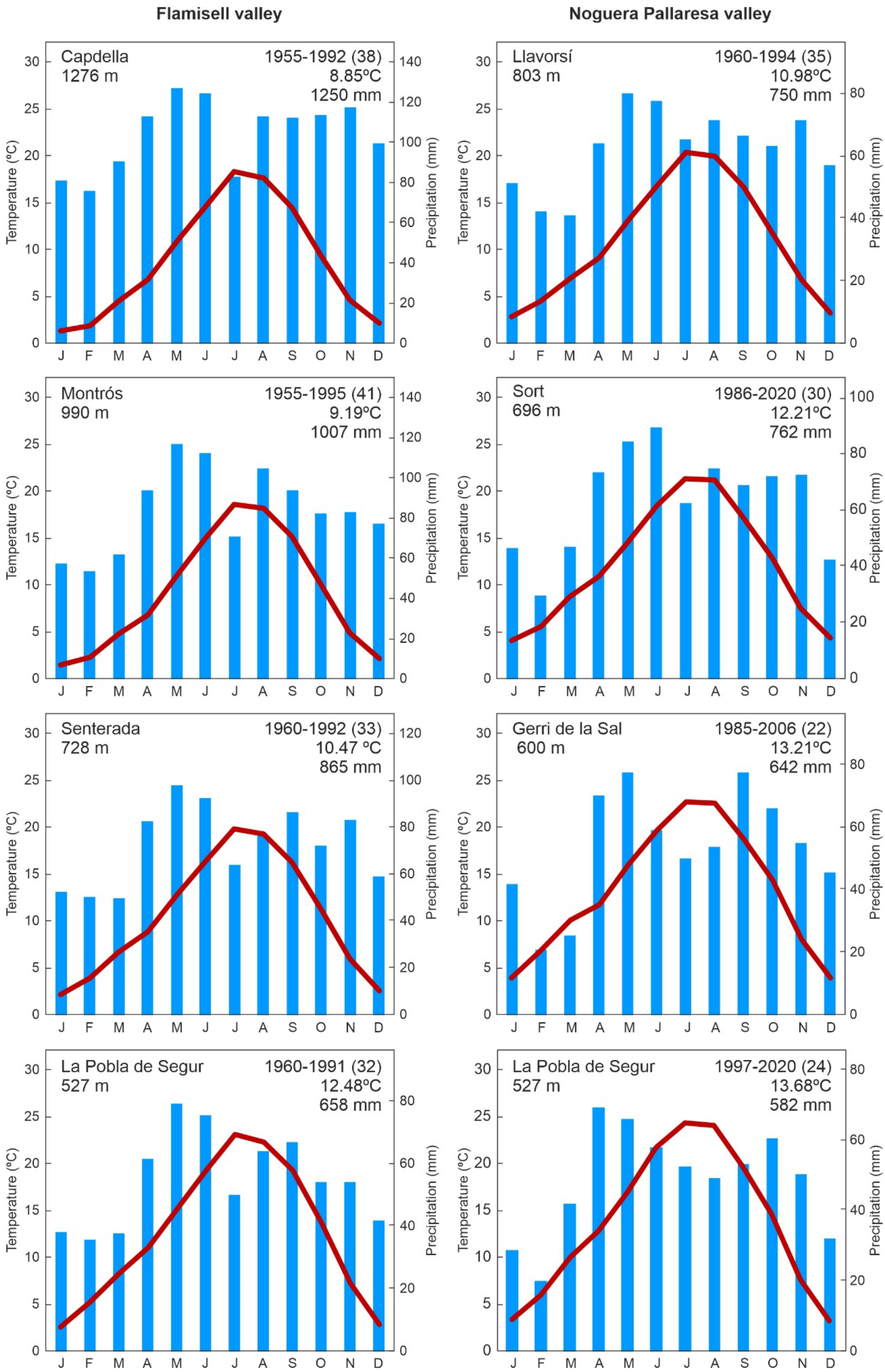


*Figure 4. Climographs for the seven weather stations of the study area. Note that two diagrams are shown for the La Pobla station (see text). The climographs are organized by elevation, according to the valley to which they belong, with the Flamisell valley at left and the Nogera Pallaresa valley at right (Fig. 1).*

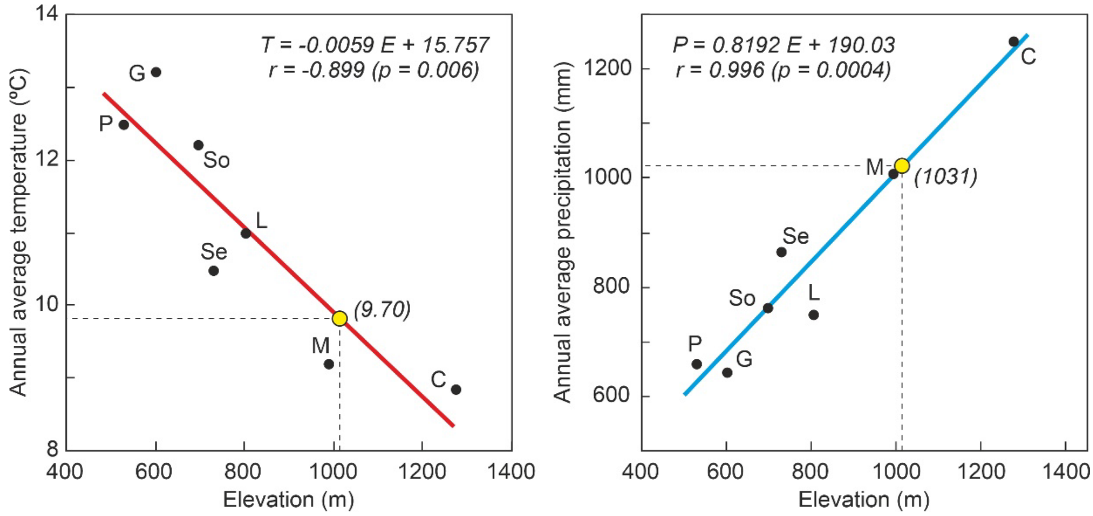


*Figure 5. Temperature (T) decrease and precipitation (P) increase with elevation (E) in the area around LM, using raw data from the surrounding weather stations (Fig. 1). The position of LM along the obtained regression lines is represented as a yellow dot. C, Capdella; G, Gerri de la Sal; L, Llavorsí; M, Montrós; P, La Pobla de Segur; Se, Senterada; So, Sort.*

## 4.3. The Montcortès climograph

Linear relationship of temperature and precipitation with elevation are also statistically significant using monthly averages, which enables to reliably estimate these parameters on a monthly basis, thus providing the raw data for assembling a climograph for any intermediate point of the altitudinal transect. Tables 2 and 3 show the parameters of the linear regression equations for each month and the corresponding estimates for LM. The estimated climograph for the lake using these values is shown in Figure 6. The overall reliability of these estimates is demonstrated by comparing all the observed (measured) and estimated monthly values obtained using the seven weather stations of the study area. As shown in Figure 7, all values are situated along the 1:1 line with little dispersion, and the regression parameters are very close to a perfect fit (slope = 1; intercept = 0; r = 1). It can be concluded that the climograph depicted in Figure 6 reliably represents the temperature and precipitation trends of LM on a monthly basis and, therefore, can be used to describe the present climatic features of the lake in those terms.

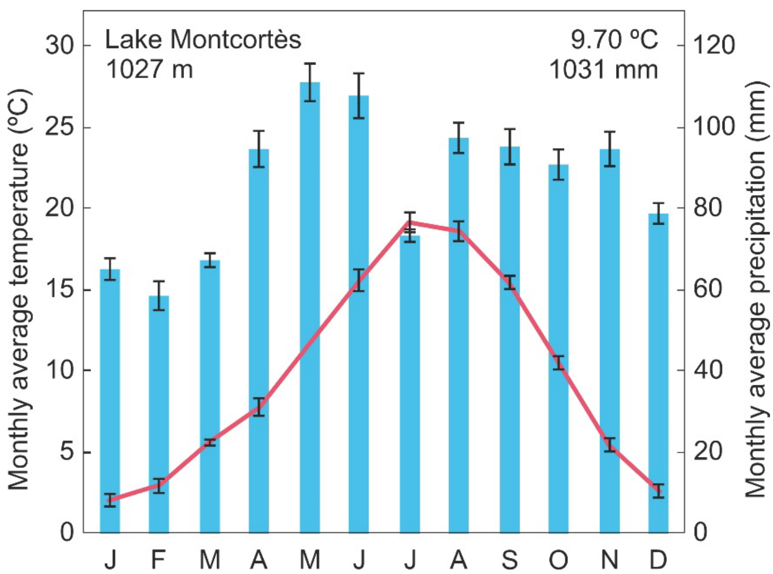


*Figure 6. Estimated climograpgh for LM using the values obtained by linear regression analysis on a monthly basis (Tables 2 and 3). Prediction errors are indicated by vertical segments.*

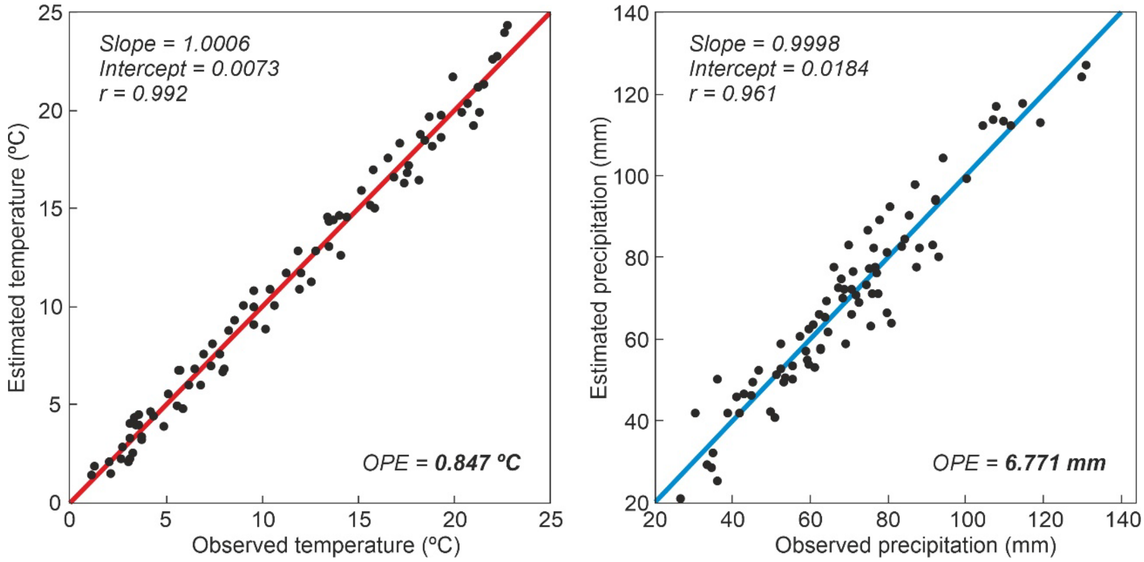


*Figure 7. Statistical performance of linear equations from tables 2 and 3 tested by comparing monthly average temperature (left) and precipitation (values) values measured in all weather stations with the same parameters estimated from linear equations. OPE, Overall prediction error.*

According to the estimated climograph for LM, the maximum average temperatures (~19 °C) correspond to July and August and the minima (2-2.5 °C) to January and February. Precipitation peaks in May-June (~110 mm) and, after a July drop to ~70 mm, it recovers to values above 90 mm between August and November. The lowest values correspond to January-March, with February as the driest month (58 mm) (Fig. 6, Tables 2 and 3). Considering the annual average temperature and precipitation, this estimated climograph is intermediate between those of Montrós and Capdella but more similar to the first (Fig. 4). The temperature follows the same seasonal pattern as all other diagrams, whereas the precipitation trends follow the same seasonal patterns as the Capdella station but with slightly higher temperatures and lower precipitation values, due to the elevational difference. The whole picture indicates that, despite its intermediate position between the Flamisell and the Noguera Pallaresa valleys (Fig. 1), the climate of LM is more similar to the stations from the first, especially in seasonal terms. This suggests that the Mediterranean influence on the Montcortès climate is lower than in the stations from the Noguera Pallaresa valley, which are situated at lower elevations and more oriented to the Mediterranean side.

***Table 2.*** *Main parameters of the regression equations between elevation and monthly average temperature. SE, Standard errors (95%); r, correlation coefficient; p(u), probability of non-significant correlation; p(n), probability for normality of residuals (Shapiro-Wilk test); p(h), probability for homoscedasticity (Breusch-Pagan test); DW, parameter of the Durwin-Watson test for autocorrelation; LM-T, annual average temperature predictions for LM (°C); PE, Prediction error (RMSE).*

| Month | Slope | SE | Intercept | SE | r | p(u) | p(n) | p(h) | DW | LM-T | PE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | -0.0035 | 0.0011 | 5.5513 | 0.9482 | -0.811 | 0.0270 | 0.9516 | 0.5311 | 2.210 | 1.9568 | 0.7103 |
| Feb | -0.0066 | 0.0013 | 9.6809 | 1.1126 | -0.912 | 0.0042 | 0.6896 | 0.9682 | 2.347 | 2.9027 | 0.8334 |
| Mar | -0.0081 | 0.0016 | 13.8770 | 1.3941 | -0.905 | 0.0011 | 0.3584 | 0.5215 | 1.746 | 5.5583 | 0.3148 |
| Apr | -0.0083 | 0.0017 | 16.2170 | 1.4587 | -0.905 | 0.0016 | 0.2818 | 0.2759 | 1.634 | 7.6929 | 1.0923 |
| May | -0.0083 | 0.0019 | 20.1880 | 1.5818 | -0.891 | 0.0043 | 0.4698 | 0.5887 | 1.403 | 11.6639 | 1.1851 |
| Jun | -0.0088 | 0.0021 | 24.6090 | 1.7964 | -0.879 | 0.0075 | 0.9425 | 0.7787 | 1.184 | 15.5714 | 1.3458 |
| Jul | -0.0075 | 0.0018 | 26.7680 | 1.5325 | -0.877 | 0.0086 | 0.8892 | 0.7259 | 1.127 | 19.0655 | 1.1488 |
| Aug | -0.0081 | 0.0018 | 26.8870 | 1.5783 | -0.887 | 0.0070 | 0.9262 | 0.7195 | 1.234 | 18.5683 | 1.1822 |
| Sep | -0.0067 | 0.0013 | 22.2780 | 1.1073 | -0.915 | 0.0033 | 0.5875 | 0.6171 | 1.103 | 15.3971 | 0.8299 |
| Oct | -0.0073 | 0.0014 | 17.8650 | 1.1724 | -0.919 | 0.0014 | 0.5151 | 0.9081 | 1.443 | 10.3679 | 0.8783 |
| Nov | -0.0048 | 0.0011 | 10.3360 | 0.8936 | -0.894 | 0.0029 | 0.2121 | 0.8964 | 2.830 | 5.4064 | 0.6698 |
| Dec | -0.0023 | 0.0010 | 4.9464 | 0.8789 | -0.707 | 0.0681 | 0.6478 | 0.2806 | 2.595 | 2.5843 | 0.6598 |

*Table 3. Main parameters of the regression equations between elevation and monthly average precipitation. SE, Standard errors (95%); r, correlation coefficient; p(u), probability of non-significant correlation; p(n), probability for normality of residuals (Shapiro-Wilk test); p(h), probability for homoscedasticity (Breusch-Pagan test); DW, parameter of the Durwin-Watson test for autocorrelation; LM-P, annual average precipitation predictions for LM (mm); PE, Prediction error (RMSE). Asterisks indicate the cases in which some OLS conditions are not fulfilled. Note that only in two cases (February and April) residual normality is not accomplished and in other two (May and December) the residuals are negatively autocorrelated (although this does not violate the OLS requirements).*

| Month | Slope | SE | Intercept | SE | r | p(u) | p(n) | p(h) | DW | LM-P | PE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 0.0606 | 0.0074 | 2.5578 | 0.1840 | 0.965 | 0.0004 | 0.4400 | 0.3861 | 2.930 | 64.794 | 4.6321 |
| Feb | 0.0747 | 0.0114 | -18.3490 | 3.5364 | 0.947 | 0.0012 | *0.0152 | 0.5934 | 2.182 | 58.3679 | 7.1432 |
| Mar | 0.0735 | 0.0143 | -8.1476 | 11.963 | 0.917 | 0.0070 | 0.3872 | 0.1164 | 2.469 | 67.3369 | 2.7019 |
| Apr | 0.0608 | 0.0138 | 32.0700 | 11.527 | 0.892 | 0.0069 | *0.0087 | 0.9531 | 2.581 | 94.5116 | 8.6344 |
| May | 0.0804 | 0.0145 | 28.3070 | 12.1150 | 0.928 | 0.0026 | 0.7792 | 0.8353 | *3.368 | 110.8778 | 9.0748 |
| Jun | 0.0901 | 0.0173 | 15.0730 | 14.5030 | 0.919 | 0.0013 | 0.0733 | 0.3634 | 2.505 | 107.6057 | 10.8632 |
| Jul | 0.0415 | 0.0050 | 30.5980 | 4.1817 | 0.966 | 0.0009 | 0.2601 | 0.2532 | 2.178 | 73.2185 | 3.1323 |
| Aug | 0.0884 | 0.0124 | 6.5923 | 10.4950 | 0.953 | 0.0017 | 0.0723 | 0.1905 | 2.771 | 97.3791 | 7.8614 |
| Sep | 0.0672 | 0.0164 | 25.9310 | 13.7570 | 0.877 | 0.0750 | 0.6431 | 0.1944 | 3.214 | 94.9454 | 10.3044 |
| Oct | 0.0664 | 0.0117 | 22.4380 | 9.7880 | 0.930 | 0.0059 | 0.1011 | 0.5145 | 1.465 | 90.6308 | 7.3317 |
| Nov | 0.0820 | 0.0130 | 10.2490 | 10.8910 | 0.942 | 0.0023 | 0.5039 | 0.8751 | 1.880 | 94.463 | 8.1581 |
| Dec | 0.0875 | 0.0081 | -11.2790 | 6.8253 | 0.979 | 0.0013 | 0.9331 | 0.2594 | *3.608 | 78.5835 | 5.1126 |

## *4.4. Shifting elevational gradients*

In addition to provide the data for the Montcortès climograph, tables 2 and 3 show that the slope of temperature and precipitation elevational gradients vary across the year. In the case of temperature, the rate of decline with elevation shifts from low values in January (-0.35 °C per 100 m) to maximum values in June (-0.88 °C per 100 m) and low values again in December (-0.23 °C per 100 m) (Table 2, Fig. 8). In the case of precipitation, gradient rates are more fluctuating (Fig. 8) and no clear relationships with monthly average precipitation values are observed. However, it is worth noting that the lowest gradient values (~4 mm per 100 m) occur in July, the driest and hottest month (Table 3, Fig. 8).

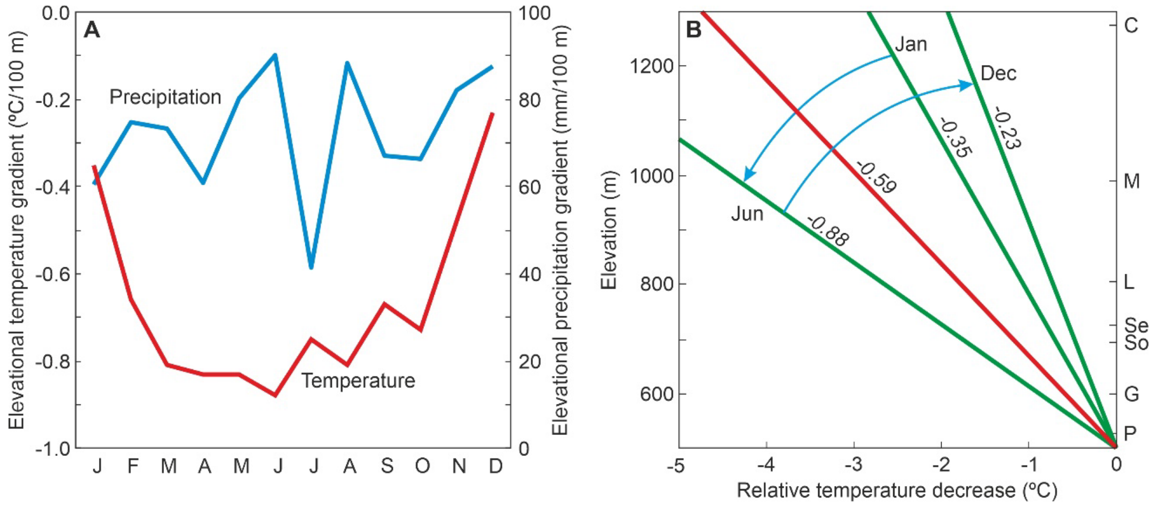


*Figure 8. Shifting temperature and precipitation elevational gradients in the study area. A) Monthly average values of temperature (red line) and precipitation (blues line) gradients. B) Shifting temperature elevational gradients (green lines) throughout the year. Numbers on gradient lines (in italics) are in °C per 100 m elevation. The red line is the annual average gradient. Blue arrows indicate the seasonal gradient shifts. C, Capdella; G, Gerri de la Sal; L, Llavorsí; M, Montrós; P, La Pobla de Segur; Se, Senterada; So, Sort.*

## 5. Conclusions and discussion

The main climatic features of the area around Lake Montcortès, including a climograph for the lake site, have been obtained by linear interpolation after defining statistically significant temperature and precipitation elevational gradients, using a network of nearby weather stations. The obtained regression equations can be used to estimate average annual and monthly temperature and precipitation values for any site within the study area. Although these particular equations are of local utility, similar studies may be conducted on different montane areas to estimate the representative climatic parameters and their seasonal regime, in sites devoid of weather stations. This would be helpful not only in paleoecological research, as already mentioned in the introduction, but also in modern ecological studies where the potential influence of climate on ecosystem and landscape dynamics is a relevant feature.

The approach developed here cannot replace the availability of actual data from weather stations but can enable to develop climatically-related ecological and paleoecological studies until the stations are installed. Otherwise, the lack of climatic data would inhibit research. In the case of LM, the installation of a weather station is strongly recommended, as the varved lake sediments would make possible to merge past and present climatic and ecological records into single time series of similar resolution, thus leading to truly long-term series, which are required for increasing prediction accuracy (Rull, 2014).

Another contribution of this work is the development of new climatic series useful for modern-analog studies and proxy calibration, specifically for LM and its surrounding area. Indeed, the temperature/precipitation anomalies of Figure 3 can be used to develop reliable transfer functions based on representative training sets ($n = 66$) useful to estimate paleotemperature and paleoprecipitation series from a variety of physico-chemical and biological proxies of the LM varved record. If necessary, the climatic data series of Figure 3 could be decomposed in seasonal data series or complemented with maxima and minima series to test whether climate-proxy correlations improve thus increasing the reliability of reconstructions. For example, Vegas-Vilarrúbia *et al.* (2022), using a regional climatic training set, found a significant correlation between the thickness of the calcite layer of each varve and autumn precipitation, which allowed to develop a transfer function leading to an autumn paleoprecipitation record for the last 500 years. It would be interesting to repeat the same analysis using the LM dataset provided here to check whether this relationship is maintained or different patterns emerge at more local level.

Temperature lapse rates are comparable to those measured in other areas of the Pyrenees and other mountain ranges of the Iberian Peninsula, as well as in the Alps (e.g., Rolland, 2003; Navarro-Serrano *et al.,* 2018). In the Iberian Peninsula, however, significant spatial and seasonal variability has been recorded due to local climatic particularities linked to synoptic atmospheric circulation (Navarro-Serrano *et al.,* 2018). In the LM area, shifts in elevational gradients throughout the year can provide insights on future climate change. For example, the steeper temperature gradient recorded at higher summer temperatures may suggest that, as global warming progresses, elevational temperature gradients may become stronger, which could lead to a positive feedback that exacerbates high-elevation warming. As a result, highlands could be overheated, in comparison to the lowlands of the same valley. This phenomenon is known as elevation-dependent warming (EDW) and has been recorded in other mountains around the world (Pepin *et al.,* 2015, 2020). Several mechanisms have been invoked to explain the EDW (You *et al.,* 2020) but changes in albedo and downward thermal radiation have been considered the most important drivers (Palazzi *et al.,* 2019). The EDW can influence hydrological regime, snow cover, high-mountain biodiversity, ecosystem dynamics and human activities and is therefore worth to be monitored for a more consistent appraisal and to improve conservation actions.

On the other hand, the observed summer minimum in the precipitation gradient means that, under warmer conditions, highlands receive less precipitation than expected. Such a reduction in precipitation combined with an increase in evaporation, as a consequence of overheating, could amplify highland dryness. A similar phenomenon has been observed in the Iberian Peninsula, where drought severity has increased in the last five decades as a consequence of enhanced atmospheric evaporative demand resulting from temperature rise, which could compromise future water supplies (Vicente-Serrano *et al.,* 2014). As a consequence, future warming could lead to overheated and overdried highlands, in comparison with the lowlands of the same valley, which could deeply affect spatiotemporal ecological and biodiversity patterns and, as a consequence, natural resource availability for human populations.

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