

Sensitivity of two Iberian lakes to North Atlantic atmospheric circulation modes

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Abstract The North Atlantic Oscillation (NAO) exerts a major influence on the climate of the North Atlantic region. However, other atmospheric circulation modes (ACMs), such as the East Atlantic (EA) and Scandinavian (SCAND) patterns, also play significant roles. The dynamics of lakes on the Iberian Peninsula are greatly controlled by climatic parameters, but their relationship with these various ACMs has not been investigated in detail. In this paper, we analyze monthly meteorological and limnological long-term datasets (1950–2011 and 1992–2011, respectively) from two lakes on the northern and central Iberian Peninsula (Sanabria and Las Madres) to develop an understanding of the seasonal sensitivity of these freshwater systems to the NAO, EA and SCAND circulation modes. The limnological variability within Lake Sanabria is primarily controlled

by fluctuations in the seasonal precipitation and wind, and the primary ACMs associated with the winter limnological processes are the NAO and the SCAND modes, whereas only the EA mode appears to weakly influence processes during the summer. However, Lake Las Madres is affected by precipitation, wind and, to a lesser extent, temperature, whereas the ACMs have less influence. Therefore, we aim to show that the lakes of the Iberian Peninsula are sensitive to these ACMs. The results presented here indicate that the lake dynamics, in some cases, have a higher sensitivity to variations in the ACMs than single local meteorological variables. However, certain local features, such as geography, lake morphology and anthropic influences, are crucial to properly record the signals of these ACMs.

Keywords Atmospheric circulation modes · Limnology · North Atlantic · Climate · Iberian Peninsula

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1 Introduction

Climate variability in Europe is highly affected by large-scale patterns of atmospheric circulation (Trenberth et al. 2007), which primarily occur as fluctuations in sea level pressure (SLP) over the European sector of the North Atlantic region and are associated with high- and low-pressure systems spanning various locations. It is well known that the North Atlantic Oscillation (NAO) exerts a strong effect on air temperatures, precipitation and wind patterns over south-western Europe during boreal winter (Hurrell 1995; Trigo et al. 2002; Hurrell et al. 2003). However, in addition to the NAO, other atmospheric circulation modes (ACMs) may better explain the climate variability. For example, the East Atlantic (EA) and Scandinavian (SCAND) patterns have been shown to significantly contribute to European climate dynamics, including the western Mediterranean region (e.g., Trigo et al. 2008; Casado and Pastor 2012; Comas-Bru and McDermott 2014).

The NAO is the most important circulation mode in this area and is characterized by large-scale fluctuations in air pressure differences between the Azores High and the Iceland Low (e.g., Hurrell and van Loon 1997). The EA mode is structurally similar to the NAO and defined by a north–south dipole involving the SLP anomaly centers, which spans the entire North Atlantic Ocean. Compared with the nodal lines of the NAO pattern, the anomaly centers of the EA mode are displaced in the southeast direction (Barnston and Livezey 1987). The SCAND pattern is associated with positive SLP anomalies over Scandinavia, which are characterized by weaker centers of the opposite sign over Western Europe and eastern Russia–western Mongolia (Bueh and Nakamura 2007).

Attempts to determine how ecosystems will adapt to recent climate change have prompted intense research of ecosystem functioning, biodiversity and their relationships with climate dynamics (e.g., Hampe and Petit 2005; Butchart et al. 2010). In particular, lakes are widely affected by climate variables, such as air temperature, wind speeds and precipitation (Margalef 1983), and observations have demonstrated that many physical and biological lake properties are controlled by these parameters on seasonal to decadal scales (Catalan et al. 2013). Interestingly, authors have gone a step further and stressed the relevance of ACMs to European lake ecosystem dynamics (e.g., Livingstone and Dokulil 2001; Weyhenmeyer 2004; Salmaso 2012), and additional authors (e.g., Stenseth et al. 2003; Hallett et al. 2004; Stenseth and Mysterud 2005) have noted that ACMs and other ‘weather packages’ often outperform local weather variables in terms of explaining climate-related variations in ecosystem evolution, ultimately defining the ‘weather package’ concept (Stenseth and Mysterud 2005). These authors assumed (as an empirical fact) that ACMs

may explain more ecological variations than single weather components and suggested that the reason is because the ACMs combine the temporal and spatial features of several weather components (e.g., temperature, precipitation and wind speed). Similarly, internal lake dynamics might be understood as a consequence of interactions between these spatio-temporal climate features, which shape limnological, biological and geochemical processes. Therefore, the lake might also act as a ‘signal blender’ by responding to the climate signal of multiple weather variables, which would better capture the ACMs compared with single local weather records.

Therefore, the objective of this study is to assess the sensitivity of two Iberian freshwater systems to the seasonal effects of interannual variations in the NAO, EA and SCAND modes by inferring relationships between the climate patterns and lake dynamics caused by the ACMs, limnological variations and meteorological variables (MVs). For this purpose, we have chosen the Sanabria and Las Madres lacustrine systems because their limnological datasets (1991–2011) are, to our knowledge, the longest spanning available datasets from lakes on the Iberian Peninsula.

Section 2 describes the data and the methodology employed. Section 3.1 presents the limnological variability according to the status of the water column as mixed (winter) or stratified (summer), which in turn is divided in hypolimnion and epilimnion. Sections 3.2, 3.3 and 3.4 present the influence of ACMs over MVs; MVs over limnological variability; and ACMs over limnological variability, respectively. This influence was assessed according to Spearman’s rank correlation coefficients and multi-linear regression models (MLRMs), which allowed us to determine when and how this influence is transmitted to the lake. Finally, Sect. 4 presents the concluding remarks.

2 Data and methods

2.1 Study sites

Lake Sanabria (Zamora) is the largest natural freshwater ecosystem on the Iberian Peninsula (Vega et al. 1992). This lake is 3160 m long and up to 1530 m wide and has a volume of $9.6 \times 10^7 \text{ m}^3$ (Vega et al. 2005) (Table 1). It is located on the northwestern Iberian Peninsula at $42^\circ 07' \text{N}$ – $06^\circ 43' \text{W}$ at an elevation of 1000 m a.s.l. It is a hydrologically open system, with the Tera River as its main inlet and outlet. The lake has two sub-basins (Fig. 1a): the western sub-basin reaches a depth of 46 m, and the eastern sub-basin is 51 m deep (Vega et al. 2005). Based on its physical and chemical characteristics, this lake is oligotrophic and monomictic temperate, exhibits winter

Table 1 Monthly mean ranges of the main physical, chemical and biological features of the two studied lakes

	Lake Sanabria	Lake Madres
Geographical coordinates	42°07'N–06°43'W	40°18'N–3°31'W
Altitude (m a.s.l.)	1000	530
Area (ha)	368	3.58
Volume (m ³)	9.6 × 10 ⁷	2.83 × 10 ⁵
Maximum depth (m)	51	19
Trophic state	Oligotrophic	Mesotrophic
Thermal state	Monomictic	Monomictic
Water Temperature (°C)	4.9–10.2	7.8–23.3
Transparency (m)	6.6–8.2	1.9–3.9
Dissolved oxygen (mg/l)	7.1–10.8	6.7–9.7
pH	6.1–6.5	6.9–7.6
Conductivity (μs/cm)	12.5–13.4	2029–2383
Nitrates (μg/l)	39.5–65.0	6000–8200
Total phosphorous (μg/l)	5.4–7.2	40.8–85.8

Sources Lake Sanabria (Vega et al. 2005) and Lake Las Madres (<http://www.redote.org/estacion-laguna-madres.htm>)

mixing and is thermally stratified from March/April to mid-November (Vega et al. 1992). The lake is located on the boundary between the relatively humid maritime regime of the Iberian north coast and the semi-arid central Iberian plain. The local climate is of the wet Mediterranean mountain type with an annual mean temperature of 9 °C and mean annual rainfall of 1510 mm (Fig. 1b).

Lake Las Madres (Madrid) is a gravel-pit seepage lake located 20 km southeast of Madrid. It is underlain by Quaternary sediments of the Jarama River in the central Iberian Peninsula (40°18'N–3°31'W; 530 m a.s.l.). The lake is sited in an ellipsoidal basin with its long axis oriented east–west and is sheltered from the wind. There is no upstream surface drainage network, and its water inputs consist of rainfall and seepage from the underlying aquifer (Alvarez-Cobelas et al. 2005). It is a small (3.58 ha), shallow (mean 7.9 m) lake with a maximum water depth of 19 m (Fig. 1a). The lake is monomictic, with complete mixing beginning in mid-December that disrupts the strong summer pycnocline. It is mesotrophic and phosphorous limited (Alvarez-Cobelas et al. 2006) (Table 1). Lake Las Madres experiences the semi-arid Mediterranean continental climate of the central Iberian Peninsula, with an annual mean temperature of 14 °C and mean annual rainfall of 425 mm (Fig. 1b). The lake does not experience snowfall or exhibit ice (Alvarez-Cobelas et al. 2005).

2.2 Instrumental and simulated data

Monthly mean air temperature and precipitation records from the areas of lakes Sanabria and Las Madres were

obtained from nearby meteorological stations. The most relevant station to Lake Sanabria is the Ribadelago Station (42°07'N–06°45'W), which is located 1 km west of the lake, and to Lake Las Madres is the Getafe Station (40°18'N–03°43'W), which is located 16.8 km west of the lake. Both stations belong to the Spanish Meteorological Agency (AEMET) network, and the data span the period from 1950 to 2011. The temperature and precipitation records were checked for inconsistencies and quality control following the procedure recommended by Brunet et al. (2006). In addition to the local recorded data, we used MVs retrieved from a hindcast climate simulation to fill any gaps of precipitation and temperature and develop a complete record of wind speed. This simulation was performed with the widely used MM5 Mesoscale Model (Grell et al. 1994), which is driven by ERA-40 reanalysis (Uppala et al. 2005) at a relatively high resolution (10 km) over the entire Iberian Peninsula. This analysis spans the period of 1959–2007, and its outputs were recorded every hour. However, for this work, the monthly mean times series obtained from the average of the hourly values for a particular month were employed. Additional details regarding this simulation and a validation exercise can be found in Jerez et al. (2013).

The lakes have been monitored on a monthly basis for various limnological variables (see database description in Alvarez-Cobelas et al. 2005, 2006; Giralt et al. 2011). In this study, the monthly average water temperature, Secchi depth, conductivity, pH, dissolved oxygen, nitrates and total phosphorus (total P) from 1992 to 2011 were selected as the parameters for analysis (Fig. 2) because they are common to both lakes and their corresponding series do not contain significant temporal gaps (see Giralt et al. 2011 and <http://www.redote.org/estacion-laguna-madres.htm> for additional details). These limnological variables were measured at 21 and 12 different water depths for Lake Sanabria and Lake Las Madres, respectively. However, to investigate the relationship between climate and limnological variables, we calculated the mean value of the entire water column (using these 21 and 12 measures for Lake Sanabria and Lake Las Madres, respectively) for mixing periods and mean value of the epilimnion (N = 6 for Lake Sanabria, and N = 5 for water temperature and dissolved O₂ and N = 1 for the other variables for Lake Las Madres) and hypolimnion (N = 15 for Lake Sanabria) for periods that presented water column stratification. Data for all of the studied variables from the hypolimnion of Lake Las Madres were not available; therefore, this zone was not analyzed in this work. Table 1 and Fig. 2 show the range of values for the variables during the study period.

The monthly values of the NAO, EA and SCAND indices spanning the period of 1950–2011 were obtained from the Climate Prediction Center (CPC) of the U.S. National

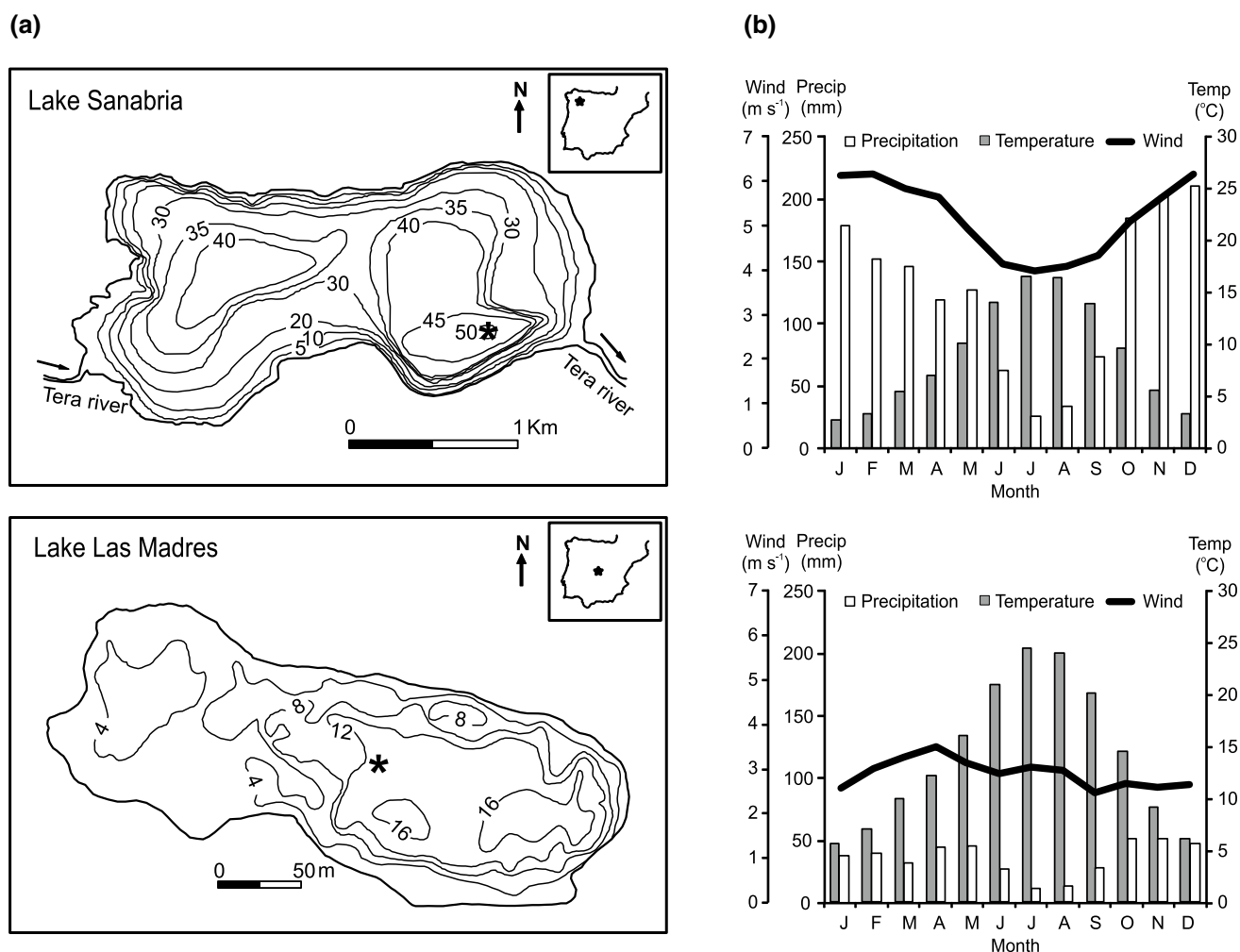


Fig. 1 **a** Bathymetric maps of Lake Sanabria (modified from Vega et al. (1992), top) and Lake Las Madres (modified from Alvarez-Cobelas et al. (2005), bottom). Depths are in meters. Asterisks denote the water sampling points. Stars denote the locations of lakes Sanabria and Las Madres on the Iberian Peninsula. **b** Climatograms from lakes Sanabria (top) and Las Madres (bottom) showing precipita-

tion (black bars), temperature (empty bars) and wind speed (gray lines). Precipitation and temperature data are from the Ribadelago Station (42°07'N–06°45'W) for Lake Sanabria and Getafe Station (40°18'N–03°43'W) for Lake Las Madres and span the period from 1950 to 2011. The wind speeds were obtained using the MM5 high-resolution simulation (10 km) spanning the period from 1959 to 2007

Oceanic and Atmospheric Administration (NOAA) (<http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>).

2.3 Statistical analyses

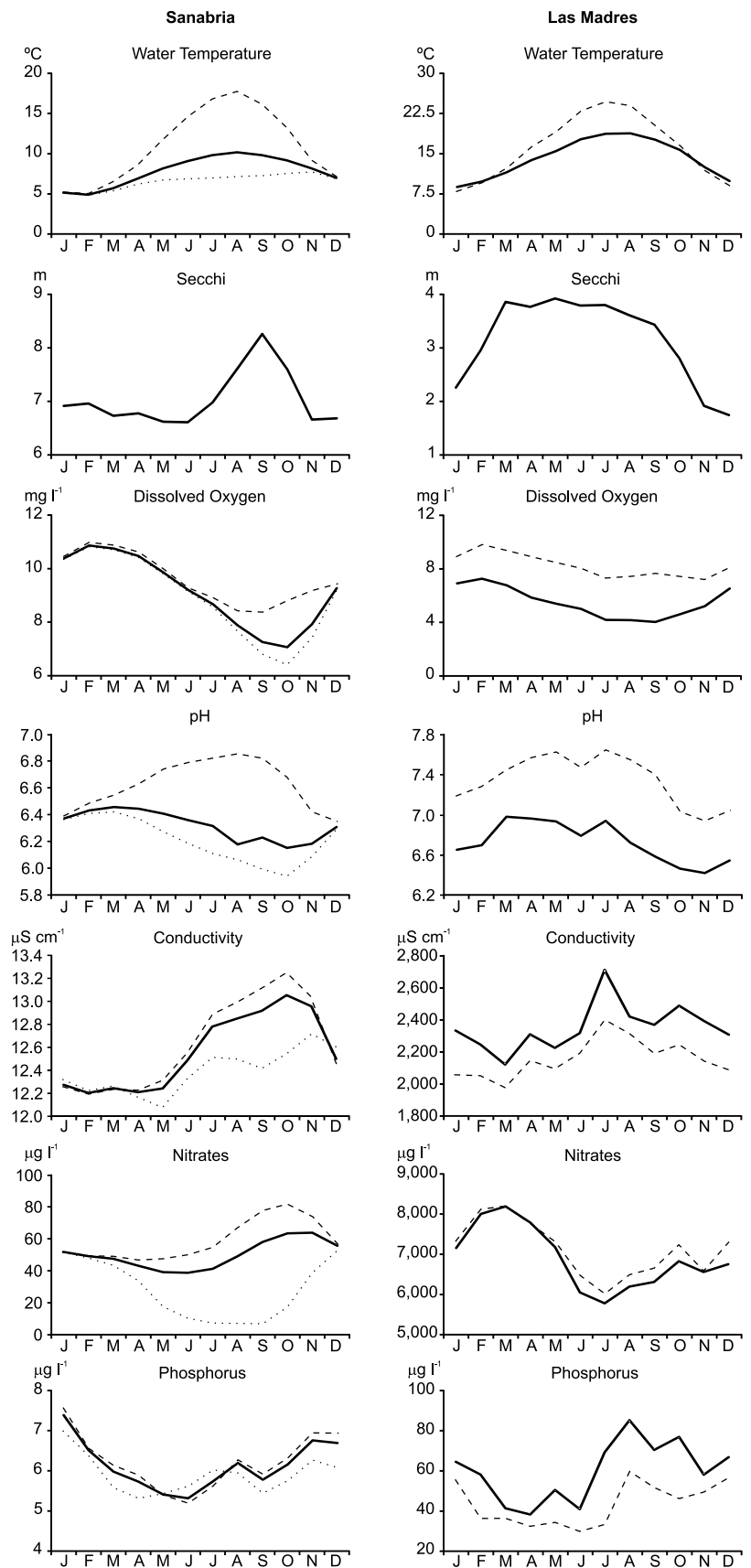
Principal component analyses (PCAs) of the normalized mean monthly limnological variables (water temperature, Secchi depth, conductivity, pH, dissolved oxygen, nitrates and total P) were used to characterize the primary underlying processes that control the limnological variability in winter (for entire water column) and summer (for epilimnion and hypolimnion separately). These primary underlying processes were established using the first and second principal components ($PC1_{lim}$ and $PC2_{lim}$ for the entire water column, $PC1_{epilim}$ and $PC2_{epilim}$ for the epilimnion,

and $PC1_{hypolim}$ and $PC2_{hypolim}$ for the hypolimnion). The magnitude of the relationships between each ACM, MV and PC were obtained according to Spearman's rank correlation coefficients (ρ) and associated p values. Unless otherwise stated, significance (p value) is always discussed at $p < 0.01$. Moreover, to investigate extent to which combined ACMs (NAO, EA and SCAND) and MVs (precipitation, temperature and wind) are able to explain the temporal evolution of the PCs series, MLRMs were employed (Eq. 1):

$$x(t) = c1 \cdot y1(t) + c2 \cdot y2(t) + c3 \cdot y3(t) + c0(t) \quad (1)$$

where x is the diagnostic variable; $y1$, $y2$ and $y3$ are the predictors, such as the NAO, EA and SCAND or MVs (precipitation, temperature and wind); and $c1$, $c2$, $c3$ and

Fig. 2 Monthly mean water temperatures, Secchi disk depth, conductivity, pH, dissolved oxygen, nitrates and total P values in lakes Sanabria (*left*) and Las Madres (*right*) from 1992 to 2011. The *solid line* indicates the average of the entire water column, *dashed line* indicates the average of the samples from the epilimnion and *pointed line* indicates the average of the samples from the hypolimnion



c_0 are the coefficients and residual coefficients obtained by fitting the MLRM to the recorded or measured x time series using the minimum mean square error method. With this method, the ACMs or MVs are used as predictors and the corresponding MLRMs are fit to the MV or PC time-series to obtain the values of the coefficients c_1 , c_2 , c_3 and c_0 . These derived coefficient values are then inserted into Eq. 1 to reproduce the MV and PC series according to the variations of either the NAO, EA and SCAND or precipitation, temperature and wind. The accuracy of these modeled series is then evaluated by comparison with the original values. Thus, two scores were employed: a) temporal Spearman's rank correlation coefficients between the original and modeled series and b) standard deviation ratio, which is defined as the ratio between the standard deviation of the modeled series and standard deviation of the original series. Finally, the relative contributions of each predictor included in the MLRM were also computed. Equation 2 shows an example of how this relative contribution was computed; in this case, the y_1 predictor is used to perform the reconstruction.

$$|c_1|/(|c_1| + |c_2| + |c_3|) \times 100 \quad (2)$$

However, although ACMs are independent modes of variability, different MVs are known to be partially correlated. Hence, partial MLRMs were obtained by removing one of the MV predictors to determine the possible co-linearity between MVs when interpreting the results (see Table S1).

2.4 Data selection

A lake's resilience to environmental forcings depends on its lacustrine features (e.g., morphology and catchment) and forcing time span, which indicates that the correct temporal scale must be considered to obtain valid comparisons and reconstructions of the temporal impacts of ACMs on lake dynamics (see Table S2). Thus, we used seasonally (instead of monthly) averaged climate and limnological data to overcome the observed high-frequency variability on a monthly scale and the likely corresponding variability in the lake's resilience (Figs. 1b, 2). The averaged values for the entire water column during mixing (winter) and for the hypolimnion and epilimnion separately during stratified (summer) periods were employed. The seasonal subsets for both lakes were selected based on the seasonal mixing and stratified periods of the lakes as indicated by their monthly limnological variables (Fig. 2). Accordingly, the seasonal averages of the PCs were calculated for the winter (DJFM) and summer (MJJAS) seasons for both lakes. However, the response of lakes to external forcings (i.e., MVs) differed depending on whether the lake water column was stratified or completely mixed. Furthermore, the transmission

Table 2 Selection of the limnological seasons and their corresponding climatological seasons with the applied time lags according to the seasonal limnological behavior (mixing and stratified periods) of each lake

Season	Layer	Lake Sanabria		Lake Las Madres	
		MVs/ACMs	PCs	MVs/ACMs	PCs
Winter	Average	NDJF	DJFM	NDJF	DJFM
Summer	Epilimnion	AMJJA	MJJAS	MJJAS	MJJAS
	Hypolimnion	MAMJJ	MJJAS	–	–

of climate signals to the lake water masses commonly does not occur instantaneously, and a time lag might occur (Straile et al. 2003a). This was evaluated between the seasonal averages of the MVs and ACMs and calculated using Spearman's rank correlation coefficients (see Table S2 for further details). The means of the MVs and ACMs for November, December, January, and February (NDJF) were selected for both lakes in winter, whereas in summer, the means for April, May, June, July and August (AMJJA) and March, April, May, June and July (MAMJJ) were selected for the epilimnion and hypolimnion, respectively, in Lake Sanabria, and the means for May, June, July, August and September (MJJAS) were selected for the epilimnion in Lake Las Madres (Table 2).

3 Results and discussion

3.1 Limnological variability

3.1.1 Mixing period (winter)

The first two eigenvectors of the PCAs conducted for the winter limnological variables of lakes Sanabria and Las Madres explain 57 and 51 % of the total variance, respectively. The first eigenvectors account for 33.6 and 31.4 % of the total variance, whereas the second set accounts for 23.2 and 19.1 % (Fig. 3).

The first eigenvector characterizing only the water column ($PC1_{lim}$) winter period (DJFM) for Lake Sanabria is associated with dissolved oxygen (24 %) at the positive end and water temperature (23 %), nitrates (16 %), conductivity (15 %) and Secchi disk depth (14 %) at the negative end (Fig. 3a; Table S3). The variation of dissolved oxygen with respect to water temperature indicates that this first axis captured a seasonal limnological displacement between years. The second eigenvector ($PC2_{lim}$) of winter limnological variables on Lake Sanabria is mainly related to pH (20 %), total P (20 %), nitrates (20 %) and conductivity (19 %) at the negative end of the vector (Fig. 3a; Table S3); these variables are strongly related to the

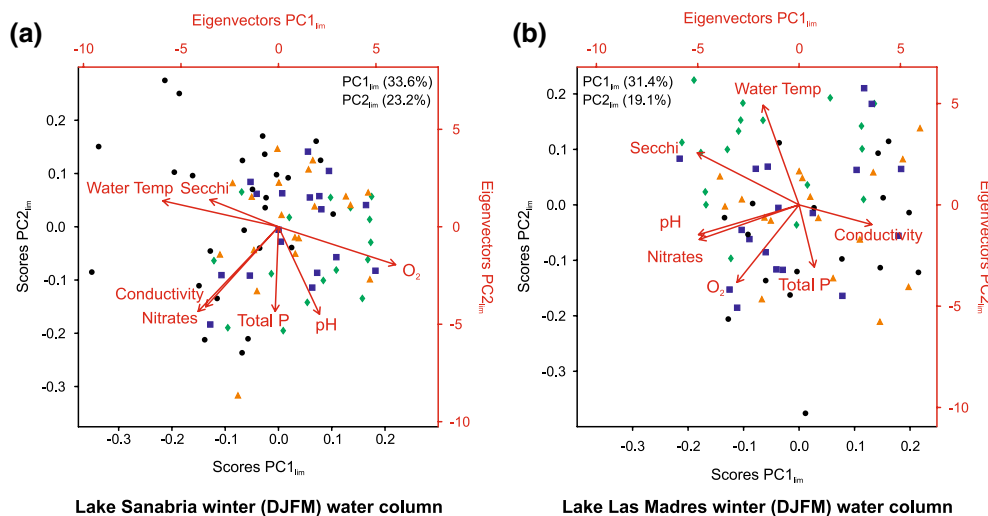


Fig. 3 Plots of the plane defined by the first two eigenvectors (PC1_{lim} and PC2_{lim}) obtained via principal component analysis (PCA) of the normalized monthly instrumental limnological datasets of the water column averages from Lake Sanabria (a) and Lake Las Madres (b)

for the period from 1992 to 2011. *Dots, squares, diamonds and triangles* correspond to December, January, February and March, respectively

variability of December (Figs. 2, 3) and importance of the date of mixing as a driver of changes on the in-lake cycling of resources (e.g., by enhancing the release of total P from the sediment).

The PC1_{lim} of Lake Las Madres is positively correlated with conductivity (15 %) and negatively correlated with Secchi disk depth (21 %), pH (21 %), nitrates (20 %) and dissolved oxygen (13 %) (Fig. 3b; Table S3). Lower conductivity indicates higher dilution by external inputs of water and consequently higher inputs of nitrate from the surrounding crop fields (Alvarez-Cobelas et al. 2005). The PC2_{lim} from Lake Las Madres is related to water temperature (27 %) and Secchi disk depth (14 %) at the positive end and dissolved oxygen (21 %) and total P (16 %) at the negative end (Fig. 3b; Table S3). This variability indicates a mixing process that should enhance the release of P from the deep sediment as the lake chemocline erodes. The occurrence (or not) and date of complete mixing (between December and January) might impose large changes in the sequestration of P when monolimnetic waters become oxygenated (Fig. 2).

3.1.2 Stratification period (summer)

Stratification in both lakes usually occurs in summer. During this period, the thermocline causes a strong and effective barrier to water-column mixing, isolating the hypolimnion from epilimnion exchanges and the atmosphere. Thus, analyses have been performed to differentiate between the epilimnion and hypolimnion samples.

The first two eigenvectors of the PCAs for lakes Sanabria and Las Madres summer epilimnion limnological variables explain 57 and 46 % of the total variance, respectively. The first eigenvectors account for 33 and 28.2 % of the variance, whereas the second set accounts for 23.7 and 17.4 % (Fig. 4a, b).

The first eigenvector characterizing the summer (MJJAS) epilimnion (PC1_{epilim}) of Lake Sanabria is associated with dissolved oxygen (28 %) and nitrates (20 %) at the positive end and water temperature (28 %) and Secchi disk depth (15 %) at the negative end (Fig. 4a; Table S3). This axis has a clear seasonal component from lower May temperatures to higher August–September temperatures (Fig. 2) that could explain the higher correlation of nitrate according to nitrate consumption during summer, which produces increased lake transparency (Secchi disk). The second eigenvector characterizing the summer epilimnion (PC2_{epilim}) of Lake Sanabria is mainly related to conductivity (28 %), pH (23 %) and, to a lesser extent, total P (13 %) and nitrates (11 %) at the negative end, whereas Secchi disk depth (17 %) is associated with the positive end (Fig. 4a; Table S3). This axis does not show a clear seasonal pattern and should capture the interannual variability of epilimnetic parameters (pH and conductivity; Fig. 2), which should be related to the variability of Tera river inputs. In Lake Las Madres, the PC1_{epilim} component is negatively correlated with nitrates (26 %), pH (25 %), conductivity (21 %) and dissolved oxygen (14 %) and positively correlated with total P (9 %) (Fig. 4b; Table S3). Higher conductivity would increase throughout the summer season because of the low input

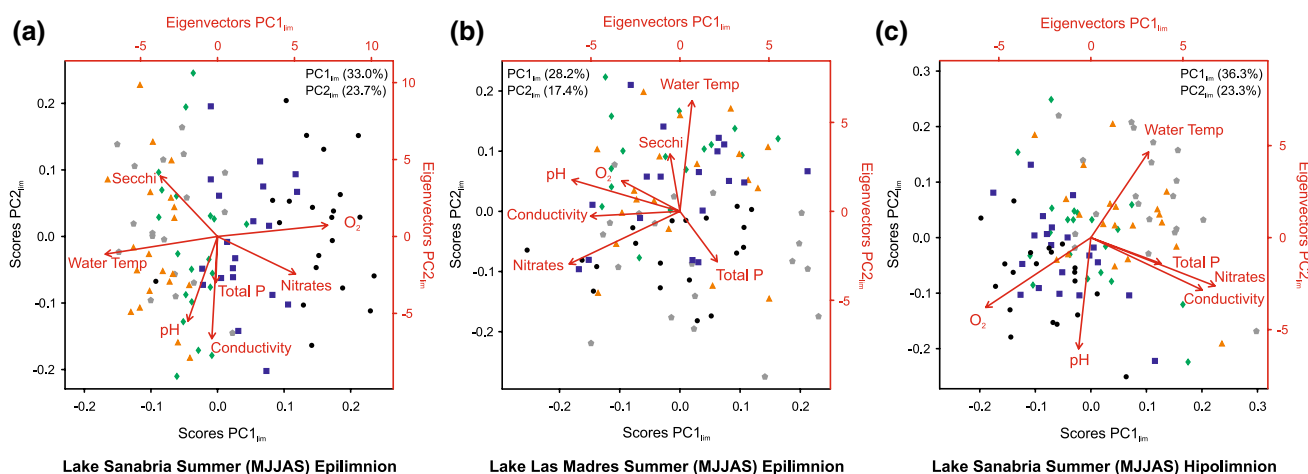


Fig. 4 Plots of the plane defined by the first two eigenvectors ($PC1_{lim}$ and $PC2_{lim}$) obtained via principal component analysis (PCA) of the normalized monthly instrumental limnological datasets of Lake Sanabria's epilimnion averages (a), Lake Las Madres' epilimnion averages

(b) and Lake Sanabria's hypolimnion averages (c) for the period from 1992 to 2011. Dots, squares, diamonds, triangles and pentagons correspond to May, June, July, August and September, respectively

of water and higher evaporation processes. The $PC2_{epilim}$ of Lake Las Madres is related to water temperature (33 %) and Secchi disk depth (17 %) at the positive end and nitrates (16 %) and total P (15 %) at the negative end (Fig. 4b; Table S3). The high correlation of this axis with water temperature suggests a clear seasonal component; therefore, the large increase of P throughout the summer season is related to a higher release of P from the sediment because of a decreasing potential redox throughout the summer (anoxia; Alvarez-Cobelas et al. 2005).

As previously stated, only the PCA of the Lake Sanabria hypolimnion was performed. The first two eigenvectors of the PCA explain 60 % of the total variance, with the first eigenvector accounting for 36.3 % and the second accounting for 23.3 % (Fig. 4c).

The first eigenvector characterizing the summer hypolimnion ($PC1_{hypolim}$) of Lake Sanabria is associated with nitrates (26 %), conductivity (23 %), total P (14 %) and water temperature (12 %) at the positive end and dissolved oxygen (22 %) at the negative end. These results suggest the enhanced release of P and nitrates from the sediment because of a decreasing potential redox on the sediment water interphase throughout summer. The second eigenvector characterizing the summer hypolimnion ($PC2_{hypolim}$) is mainly related to water temperature (22 %) at the positive end of the plot and pH (28 %), dissolved oxygen (18 %), conductivity (13 %), nitrates (12 %) and total P (7 %) at the negative end of this vector (Fig. 4c; Table S3). This axis has a clear seasonal component caused by the lower temperatures, higher oxygen content and pH in May to the lower pH and oxygen and higher temperatures in September. The increasing dominance of lake

respiration processes in the hypolimnetic waters throughout the summer would increase the CO_2 content (lowering pH).

3.2 Atmospheric circulation modes and local meteorological variables

On a seasonal scale, both study areas exhibit the same signs and a similar magnitude of correlation between the ACMs and MVs (Fig. 5; Table 3). The NAO mode has the greatest effect on precipitation and wind speed in winter at both sites, although the NAO impact decreases drastically during the summer. The effect of EA mode is prominent on the temperatures in winter and summer in both areas. Finally, the effect of the SCAND mode is variable and displays a less clear pattern, with the most significant relationships consisting of positive correlations between the SCAND mode and precipitation and wind speed during winter and negative correlations between SCAND mode and temperatures during summer at both lakes (Fig. 5; Table 3).

The correlations between the MLRMs of NAO+EA+SCAND modes and MVs as well as the relative contribution of each ACM for lakes Sanabria and Las Madres are shown in Tables 3 and 4. In Lake Sanabria, the combined influence of the three ACMs displays high and significant correlations of 0.57, 0.67 and 0.50 with winter precipitation, temperature and wind speed, respectively; whereas the corresponding ρ -values for Lake Las Madres are 0.74, 0.61 and 0.67, respectively. In summer, only temperature shows correlations higher than 0.50 with the MLRM built on the NAO, EA and SCAND modes, with values of 0.66 and 0.56 for AMJJA and MAMJJ in Lake Sanabria, respectively, and 0.68 for MJJAS in Lake Las Madres.

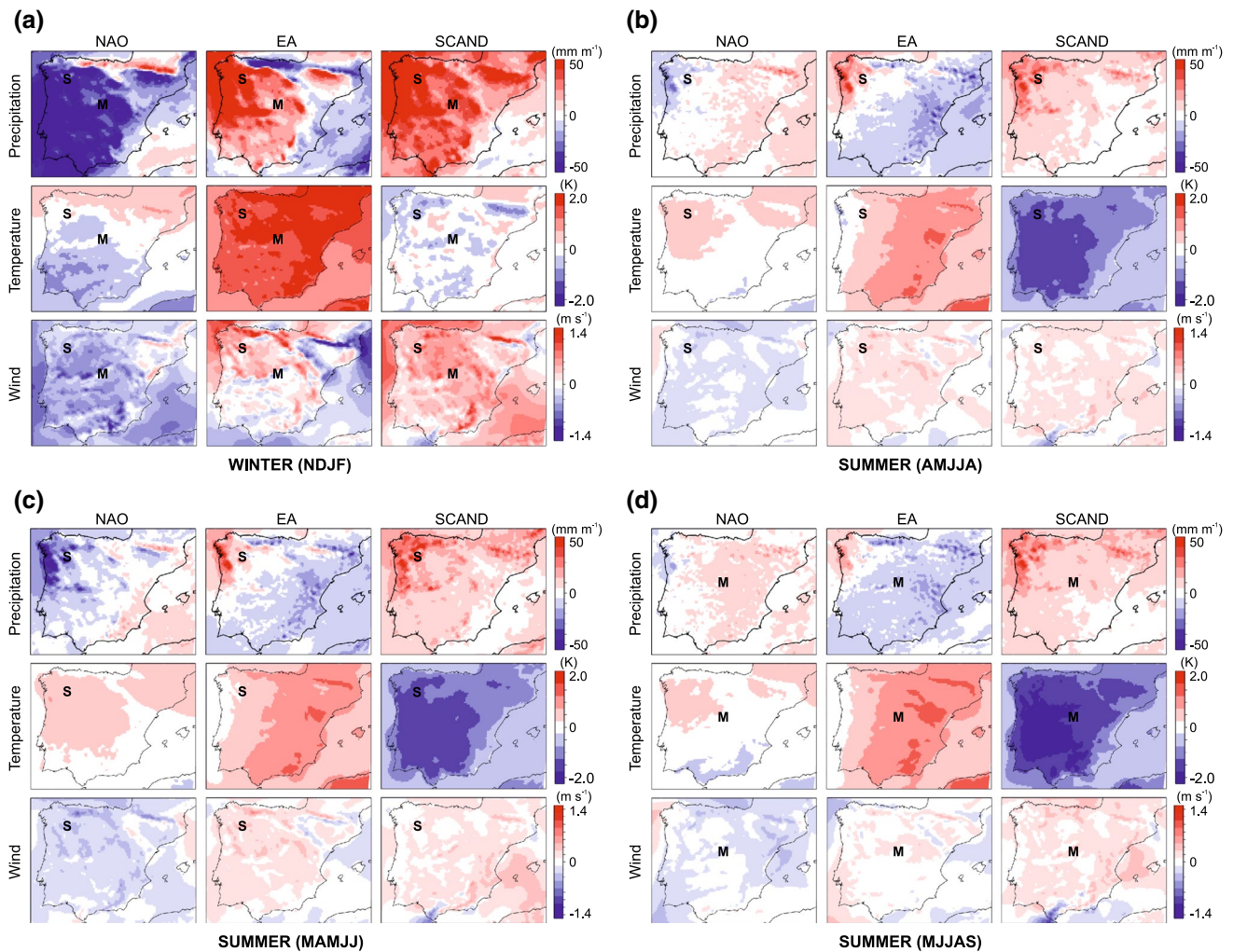


Fig. 5 Composites showing the impact of the NAO (1st column), EA (2nd column) and SCAND modes (3rd column) on the mean precipitation (1st row), temperature (2nd row), and wind speed (3rd row) with a **a** 1 month lag time (NDJF average) over the selected limnological winter months (DJFM) for both lakes; **b**, **c** 1 and 2 month times lags (AMJJA and MAMJJ averages) over the selected limnological summer months (MJJAS) for Lake Sanabria; and **d** no time lag (MJJAS average) over the selected limnological summer months

(MJJAS) for Lake Las Madres. These composites show the differences in the mean values of each variable between the positive and the negative phases of the various modes. Note the locations of the lacustrine systems as denoted using the letters S (Lake Sanabria) and M (Lake Las Madres). Units are as follows: mm month⁻¹ for precipitation, K for temperature and m s⁻¹ for wind speed. The time period was 1959–2007. Data source: MM5 simulation

Our analysis indicates that the impacts of the ACMs on MVs are usually of higher amplitude in winter than summer (Fig. 5; Table 3), which is similar to the results of previous works (e.g., Trigo et al. 2008; Comas-Bru and McDermott 2014). Nonetheless, the effect of the ACMs is not restricted to winter. Several recent studies have characterized the dynamics of the summer NAO (e.g., Folland et al. 2009) and its corresponding impact on European climate (e.g., Chronis et al. 2011; Bladé et al. 2012). The summer conditions do not follow a simple pattern, particularly in Mediterranean regions, where the NAO along with

other ACMs may provide better explanations of climate variability. For example, the effect of the EA and SCAND patterns on summer temperatures should not be overlooked because the influence of the SCAND is higher in summer than in winter (Fig. 5; Table 3).

Further evaluations of the relationships between each of these ACMs and meteorological fields over the Iberian Peninsula are beyond the scope of this work; however, a complete assessment of the impact of these ACMs over Iberia has been evaluated in other studies (Jerez and Trigo 2013).

Table 3 Spearman's rank correlation coefficients associated with seasonal series of MVs and atmospheric circulation modes (ACMs) for Lake Sanabria (top) and Lake Las Madres (bottom)

Winter (NDJF)	NAO	EA	SCAND	MLRM (NAO+EA+SCAND)
LAKE SANABRIA				
Precipitation	-0.55	<i>0.28</i>	<i>0.27</i>	0.57
Temperature	<i>0.15</i>	0.53	<i>-0.20</i>	0.67
Wind	<i>-0.46</i>	<i>0.23</i>	0.44	0.50
Summer (AMJJA)				
LAKE SANABRIA				
Precipitation	<i>0.17</i>	<i>-0.17</i>	<i>0.34</i>	<i>0.33</i>
Temperature	<i>0.12</i>	0.57	-0.42	0.66
Wind	<i>0.17</i>	<i>-0.14</i>	<i>-0.17</i>	<i>0.23</i>
Summer (MAMJJ)				
LAKE SANABRIA				
Precipitation	<i>-0.19</i>	<i>0.06</i>	<i>0.31</i>	<i>0.33</i>
Temperature	<i>0.09</i>	0.46	<i>-0.37</i>	0.56
Wind	<i>0.10</i>	<i>-0.09</i>	<i>-0.06</i>	<i>0.12</i>
Winter (NDJF)				
LAKE LAS MADRES				
Precipitation	-0.70	<i>0.24</i>	<i>0.31</i>	0.74
Temperature	<i>-0.12</i>	0.61	<i>-0.08</i>	0.61
Wind	-0.66	<i>0.05</i>	0.44	0.67
Summer (MJJAS)				
LAKE LAS MADRES				
Precipitation	<i>0.18</i>	<i>-0.37</i>	<i>0.27</i>	<i>0.36</i>
Temperature	<i>-0.10</i>	0.55	-0.47	0.68
Wind	<i>-0.17</i>	<i>0.23</i>	<i>-0.07</i>	<i>0.26</i>

Italic, regular and bold numbers indicate values at $p > 0.05$, $p < 0.05$ and $p < 0.01$, respectively

3.3 Influence of local meteorological variables on limnological variability

The correlations between the MVs and PCs are shown in Table 5. Rather than assessing the impact of each MV on every limnological variable individually, we assessed the influence of the MVs on the limnological variability represented by the first two principal components presented in Sect. 3.1 because (1) these two limnological main components explain more than 50 % of the total variance and (2) the lake response to changes in the MVs will affect several limnological parameters, not just each one individually.

Lake Sanabria's $PC1_{lim}$ values during the winter season (DJFM) correlate with winter (NDJF) precipitation ($\rho = 0.72$) and wind speed ($\rho = 0.67$). In Lake Sanabria, the winter limnological season begins after the breakdown of the thermocline. This collapse occurs because of a combination of wind shear over the low heat content water column and large discharge of cold water from the Tera River

during the rainy season (Fig. 1) and, consequently, December shows the highest variability on the $PC1_{lim}$ axis (water temperature gradient). In addition, Lake Sanabria's $PC1_{epilim}$ values during the summer season (MJJAS) correlate with summer (AMJJA) precipitation ($\rho = 0.63$). Therefore, summer precipitation also plays a key role, indicating that the discharge of the Tera River in spring (May is the month with highest variability on $PC1_{epilim}$ axis; Fig. 4) is a key factor to explain the epilimnion variability of Lake Sanabria. MLRMs were constructed to assess the combined and proportional effects of precipitation/temperature/wind speed on the PCs. These MLRMs display a higher correlation with the winter $PC1_{lim}$ ($\rho = 0.78$) and summer $PC1_{epilim}$ ($\rho = 0.68$) than the single MVs (Tables 4, 5), indicating the combined effects ('weather packages') of these MVs on the $PC1_{lim}$ and $PC1_{epilim}$ components. This combined effect of local weather on the $PC1_{lim}$ and $PC1_{epilim}$ components is clearly dominated (>60 %) by precipitation which controls the Tera River discharge (Giralt et al. 2011) in both cases (Table 4).

Table 4 MLRMs information (from left to right): diagnostic variables, predictors, coefficients, Spearman’s rank correlation coefficients between the measured and modeled diagnostic variables, standard deviation ratio between the measured and modeled diagnostic variables and relative contribution (%) of each predictor to the modeled diagnostic variable

Diagnostic variable (X)	Predictors			Coefficients			SCCs X/MLRM	SD ratio	Contribution of predictors (%)		
	Y1	Y2	Y3	C1	C2	C3			Y1	Y2	Y3
LAKE SANABRIA											
Winter (NDJF) precipitation	NAO	EA	SCAND	-56.91	41.8	10.86	0.57	0.55	52	38	10
Winter (NDJF) temperature	NAO	EA	SCAND	0.96	1.2	-0.27	0.67	0.70	40	49	11
Winter (NDJF) wind	NAO	EA	SCAND	-0.15	0.14	0.36	0.50	0.44	23	22	55
Winter (DJFM) PC1 _{lim}	Precip	Temp	Wind	0.59	-0.08	0.22	0.78	0.65	66	9	25
Winter (DJFM) PC1 _{lim}	NAO	EA	SCAND	0.29	0.15	0.16	0.72	0.54	48	25	27
Summer (AMJJA) temperature	NAO	EA	SCAND	-0.24	1.60	-1.85	0.66	0.60	7	43	50
Summer (MAMJJ) temperature	NAO	EA	SCAND	0.45	1.25	-2.19	0.56	0.51	12	32	56
Summer (MJJAS) PC1 _{epilim}	Precip	Temp	Wind	-0.18	0.11	0.00	0.68	0.52	62	38	0
LAKE LAS MADRES											
Winter (NDJF) precipitation	NAO	EA	SCAND	-195.06	79.53	6.89	0.74	0.72	69	28	3
Winter (NDJF) temperature	NAO	EA	SCAND	1.57	6.32	-2.34	0.61	0.57	15	62	23
Winter (NDJF) wind	NAO	EA	SCAND	-0.19	0.04	0.11	0.67	0.60	56	12	32
Winter (DJFM) PC2 _{lim}	Precip	Temp	Wind	0.24	0.08	-0.36	0.59	0.26	35	12	53
Summer (MJJAS) temperature	NAO	EA	SCAND	1.04	8.42	-7.17	0.68	0.60	6	51	43
Summer (MJJAS) PC1 _{epilim}	Precip	Temp	Wind	-0.12	0.10	0.56	0.65	0.50	15	13	72
Summer (MJJAS) PC1 _{epilim}	NAO	EA	SCAND	-1.43	0.88	0.17	0.52	0.70	58	35	7

Table 5 Spearman’s rank correlation coefficients associated with seasonal series of MVs, PCs and ACMs

LAKE SANABRIA (Winter)	Precip	Temp	Wind	NAO	EA	SCAND	MLRM (Temp + Precip + Wind)	MLRM (NAO + EA + SCAND)
PC1 _{lim}	0.72	-0.07	0.67	-0.64	0.37	0.62	0.78	0.72
PC2 _{lim}	0.10	0.32	-0.12	0.11	0.09	-0.32	0.15	0.29
LAKE SANABRIA (Summer)	Precip	Temp	Wind	NAO	EA	SCAND	MLRM (Temp + Precip + Wind)	MLRM (NAO + EA + SCAND)
PC1 _{epilim}	0.63	0.39	0.37	-0.16	0.51	-0.06	0.68	0.32
PC2 _{epilim}	-0.31	-0.01	0.21	-0.09	-0.12	0.25	0.24	0.17
PC1 _{hypolim}	-0.14	-0.19	0.12	0.14	-0.13	0.23	0.28	0.22
PC2 _{hypolim}	0.41	-0.15	0.17	-0.03	0.03	0.03	0.48	-0.05
LAKE LAS MADRES (Winter)	Precip	Temp	Wind	NAO	EA	SCAND	LRM (Temp + Precip + Wind)	LRM (NAO + EA + SCAND)
PC1 _{lim}	-0.23	-0.18	-0.32	0.05	-0.20	-0.16	0.49	0.30
PC2 _{lim}	-0.05	0.53	-0.47	0.15	0.15	-0.39	0.59	0.19
LAKE LAS MADRES (Summer)	Precip	Temp	Wind	NAO	EA	SCAND	LRM (Temp + Precip + Wind)	LRM (NAO + EA + SCAND)
PC1 _{epilim}	-0.62	0.26	0.56	-0.38	0.41	0.11	0.65	0.52
PC2 _{epilim}	-0.31	0.45	-0.09	-0.16	0.28	-0.27	0.36	0.28

Italic, regular and bold numbers indicate values at $p > 0.05$, $p < 0.05$ and $p < 0.01$, respectively

In Lake Las Madres, the winter (DJFM) $PC1_{lim}$ component does not exhibit a significant correlation with single MVs in winter. Consequently, the $PC1_{lim}$ of Lake Las Madres is not clearly influenced by the seasonal climatic variation probably as a result of nitrate inputs from the crop fields. However, the winter $PC2_{lim}$ component exhibits significant correlations ($\rho = 0.53$, $p < 0.05$) with temperature. The MLRMs also highlight the climatic influence over the $PC2_{lim}$ ($\rho = 0.59$, $p < 0.05$). This $PC2_{lim}$ is related to a lower P content at higher lake water temperatures that could be influenced by the release of P from the anoxic metalimnion when the chemocline disappears during cold winter periods. This trend may be related to the role of temperature (and other MVs) on the occurrence (or not) of mixing and thus the date of lake overturn. The summer (MJJAS) precipitation and wind speed varies negatively and positively ($\rho = -0.62$; $\rho = 0.56$, $p < 0.05$; respectively) with the $PC1_{epilim}$ component. Additionally, the MLRMs also indicate that the combined effects of local summer weather only affect the variability of the $PC1_{epilim}$ component ($\rho = 0.65$). These summer effects of precipitation and wind speed over the $PC1_{epilim}$ component should be related to the external inputs of solutes from the surrounding crop fields (high conductivity and high nitrate contents).

The lack of correlation between the MVs and PCs from the hypolimnion in both lakes indicates that the summer thermocline isolated this bottom water mass from any direct climate influence at a seasonal scale.

3.4 Sensitivity of limnological variability to the atmospheric circulation modes

In northern Europe, the relationship between the NAO index and lake dynamics has been carefully explored in other studies (e.g., Livingstone and Dokulil 2001; Gerten and Adrian 2002; Zahrer et al. 2013). For example, Straile et al. (2003b) found that the impact of the NAO on freshwater ecosystems affects the physics, hydrology, chemistry and biology, and therefore the food-web structure of lakes. The effects of the NAO on the water chemistry in lakes in Sweden were analyzed (Weyhenmeyer 2004) and indicated an impact of the NAO on variables linked to surface-water temperatures. A study by Salmaso (2012) went a step further by verifying the effects of several ACMs (e.g., the NAO, EA, and SCAND modes) on limnological variables in a subalpine lake, thus revealing a strong connection between the dominant algal groups and EA and eastern Mediterranean patterns, whereas the limnological variables exhibited much weaker correlations with other ACMs. Here, we are interested in determining the direct effects of the ACMs on the limnological variability of lakes Sanabria and Las Madres. Both studied lakes are located in areas that present a similar climatic impact of ACMs on MVs

(Fig. 5; Table 3); therefore, their limnological variability is expected to be similarly influenced by the ACMs.

In Lake Sanabria, the correlation between the winter $PC1_{lim}$ component and NAO mode is negative ($\rho = -0.64$), whereas the correlation with SCAND is positive ($\rho = 0.62$). Additionally, the combined effect of the NAO+EA+SCAND modes is highly correlated ($\rho = 0.72$) with the winter $PC1_{lim}$ variations (48 % NAO, 25 % EA and 27 % SCAND) (Table 4). These results are consistent with the impact of the ACMs on MVs (Fig. 5; Table 3) because the NAO is negatively correlated with precipitation and the SCAND is positively correlated with wind speed. Therefore, the NAO and SCAND should influence the date of thermocline breakdown ($PC1_{lim}$) via precipitation and wind speed. The summer $PC1_{epilim}$ values show a weak positive correlation with the EA pattern ($\rho = 0.51$, $p < 0.05$); however, the MLRM results do not exhibit significant correlations with the summer $PC1_{epilim}$. Thus, the reduced impact of the ACMs on the summer climate and non-significant correlation between the EA mode and precipitation precludes providing an accurate and proper interpretation of the influence of this weak EA pattern over $PC1_{epilim}$.

The principal components corresponding to Lake Las Madres only exhibit a statistically significant correlation in the MLRM that includes the summer $PC1_{epilim}$ component ($\rho = 0.52$, $p < 0.05$), with 58 % of the effect attributable to the NAO mode, 35 % to the EA mode and only 7 % to the SCAND mode. Similar to Lake Sanabria, the weak correlation between the ACMs and $PC1_{epilim}$, reduced impact of ACMs on the summer climate (Fig. 5; Table 3) and high influence of local human activities (field crops, summer leisure and industrial exploitation; Alvarez-Cobelas et al. 2005) reduce the likelihood of properly interpreting the transmission of summer ACMs on limnological processes.

These results show that the impacts of the ACMs on limnological processes of Lake Las Madres are much more subtle and difficult to discern than for Lake Sanabria. Authors have noted that the effect of the NAO signal varies among lake types according to morphological properties and mixing behavior (Gerten and Adrian 2002). Lake Sanabria is the largest natural freshwater ecosystem on the Iberian Peninsula and occupies a glacial depression, with the Tera River as the only tributary and emissary (Fig. 1), and it lies on an acid rock substrate (gneiss and granodiorites) that has low solubility and is poor in salts. The population residing in the drainage basin is small (hundreds of people) and distributed between two villages, and the area shows negative demographic, agricultural and socio-economic trends (Vega et al. 1992, 2005). In contrast, Lake Las Madres is a small (3.58 ha) seepage lake in a Quaternary valley that is close (20 km) to Madrid (>3 million people). The lake is situated in an ellipsoidal basin sheltered from the wind that does not have an upstream surface drainage network,

and its water inputs consist of rainfall and seepage from the underlying aquifer (Alvarez-Cobelas et al. 2005). Deposits in the vicinity of Lake Las Madres are typically sand and gravel. The area has been subject to agricultural practice for more than two centuries, which has resulted in high concentrations of nitrogen and phosphorus in the groundwater close to Lake Las Madres. Land use changed to pit mining in the early seventies, and gravel-pits are still in operation close to the lake. Hence, differences in the impacts of the ACMs on lakes Sanabria and Las Madres can be ascribed to these differences in altitude, orientation, catchment, lake morphology and anthropic influence (Fig. 1a).

Moreover, because the ACMs affect the limnological variations of these two lakes due to their impact on the meteorological conditions, a stronger relationship should occur between the local climatic variables and ACMs than between the lake limnology and ACMs (Quadrelli et al. 2001; Pokrovsky 2009). However, this assumption is not always true because the ACMs may exhibit an even stronger correlation with other environmental variables than with the local meteorological data (Straile et al. 2003b; Stenseth et al. 2003; Trigo et al. 2004; Hallett et al. 2004). In at least one previous study (Straile et al. 2003b), the NAO produced a stronger signal on the lake surface temperature than on the air temperature in certain parts of Austria, and another study (Trigo et al. 2004) revealed that the impact of the NAO on stream flows in Iberia can exceed the corresponding impact on precipitation. This trend may have been caused by the integrated effects of landscape and internal lake/river filtration (Blenckner 2005) and stochastic climate noise related to the specific microtopographic conditions at particular study sites.

Our results demonstrate that certain lakes may be better indicators of ACM variations than single discrete MVs as follows: (1) the winter NAO and SCAND influence over the winter limnological variability ($PC1_{lim}$) of Lake Sanabria is higher ($\rho = -0.62$ and $\rho = 0.64$, respectively) than the influence of these ACMs over any local MV ($|\rho| < 0.55$) (Tables 3, 5); (2) the winter dynamics ($PC1_{lim}$) of Lake Sanabria displays a stronger correlation with the combination of all of the ACMs ($\rho = 0.72$) than any of the discrete local MVs with the combination of all of the studied ACMs (precipitation, $\rho = 0.57$; temperature, $\rho = 0.67$; and wind speed, $\rho = 0.50$) (Tables 3, 5); and (3) the summer $PC1_{epilim}$ component of Lake Las Madres shows a better correlation with all of the ACMs ($\rho = 0.52$, $p < 0.05$) than with precipitation ($\rho = 0.36$) or wind speed ($\rho = 0.26$, $p < 0.05$) (Tables 3, 5). The true climate conditions are a blend of all relevant atmospheric conditions, which are difficult to assess without considering the internal lake filter (Magnuson et al. 2006). Hence, the lake “signal blender” effect enables to record the impact of all the ACMs in terms of limnological variability reflecting the overall effect of a weather package (e.g., NAO+EA+SCAND) simultaneously.

4 Conclusions

In this study, we characterized the influence of the NAO, EA and SCAND modes on the local climate and limnological variations using long-term monitoring datasets for lakes on the Iberian Peninsula (1992–2011). This work provides a proper understanding of the influence of single or combined (‘weather packages’ via MLRMs) MVs and ACMs on the lake dynamics, which is required to determine if they can be used as sensors of climate variability. Although Lake Sanabria and Lake Las Madres are located in similar climate zones (in terms of the impacts of ACMs on MVs) and their respective limnological variations are governed by relatively similar limnological processes defined by the PCAs, the ACMs have a different influence on each lacustrine system.

Lake Sanabria’s limnological variability is primarily controlled by precipitation and wind, whereas the limnological processes of Lake Las Madres tend to be linked to temperature in winter and precipitation and wind in summer. The influence of the Tera River and small size seepage lake conditions of lakes Sanabria and Las Madres, respectively, may control the influence of precipitation in both lakes, which highlights the usefulness of these two lakes in reconstructing the temporal evolution of precipitation rather than temperature.

The primary ACMs associated with the interannual winter variability of Lake Sanabria are the NAO and SCAND modes, whereas the EA mode is prevalent in summer. Lake Sanabria better reflects the effects of ACMs than Lake Las Madres. This difference may be caused by factors that include geography, limnological complexity and morphology because (1) Lake Sanabria is located in an area of less anthropic influence; (2) the limnological processes of Lake Las Madres appear to be more complex; and (3) the larger size and greater depth of Lake Sanabria may be a key factor in smoothing out any non-climatic signals.

Interestingly (although not necessarily obvious), the inferred relationships between the ACMs and lake dynamics determined primarily by applying the MLRMs as “weather packages” were often stronger than those between the ACMs and local climatic variables. This result is attributable to the “signal blender” effect and further emphasizes the great potential of certain lakes (e.g., Lake Sanabria) to act as sensors of ACMs.

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