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Influence of atmospheric modes of variability on a deep lake south of the Alps

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ABSTRACT: Limnological measurements and winter air temperatures recorded in a deep lake south of the Alps (Lake Garda) have been analysed and related to temporal variations in 5 teleconnection patterns, i.e. the East Atlantic pattern (EA), the Eastern Mediterranean Pattern (EMP), the North Atlantic Oscillation (NAO), the Scandinavia pattern (SCAND) and the East Atlantic/West Russia Pattern (EA/WR). The EA and EMP played a significant role in winter in the large-scale atmospheric circulation over the Mediterranean region. Positive and negative EA, and negative and positive EMP phases were closely connected with the development of mild and harsh winters, respectively. In turn, harsh winters had a strong positive impact on the development of diatoms in spring and cyanobacteria in summer and autumn. These modifications were controlled through a linked chain of factors, which included lower winter lake water temperatures, deep lake circulation episodes, and higher replenishment of epilimnetic phosphorus at spring overturn. This work demonstrates the existence of a strong connection between large-scale climatic fluctuations over the Mediterranean area and the temporal variations in the limnological characteristics of the large lakes located between the Alps and the northern border of the Mediterranean region. Conversely, the NAO, SCAND and EA/WR did not show any relationship with the winter climate and the limnological characteristics of Lake Garda.

KEY WORDS: Climatic fluctuations · Deep lakes · Lake overturn · Climate–nutrient interactions · East Atlantic pattern · Eastern Mediterranean Pattern · North Atlantic Oscillation

1. INTRODUCTION

The past 2 decades have shown an increasing use of climate indices based on several climatic patterns in an attempt to understand the mechanisms linking weather at different time scales with freshwater ecosystem variability (e.g. Straile & Stenseth 2007). In this context, large-scale climate patterns provide a conceptual framework and a broader understanding of observed changes in the local physical environment (Stenseth et al. 2003).

Among the indices defined by the synoptic analyses carried out by NOAA Climate Prediction Centre (NOAA-CPC), the North Atlantic Oscillation (NAO) represents the first leading mode of low frequency variability over the North Atlantic. The NAO influences the atmospheric behaviour in the North Atlantic region, controlling air temperature and precipitation over large areas of the northern hemisphere in winter (Blenckner & Chen 2003, Hurrell et al. 2003, Lehmann et al. 2011). Many studies have confirmed a causal connection between the NAO and atmospheric precipitation in southern Europe (e.g. Trigo et al. 2004), whereas the relationships between the NAO and temperatures appeared inconclusive. Analysing the connections between climate and interannual variability in the limnological characteristics of a deep lake south of the Alpine chain (Lake Garda), Salmaso (2005) found that the winter NAO had only a slight, insignificant influ-

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ence on the winter climate and water temperatures at maximum spring overturn.

Besides the NAO, other NOAA-CPC modes potentially important for interannual climate variability over the Mediterranean region and southern Europe are the East Atlantic pattern (EA), the Scandinavia pattern (SCAND) and the East Atlantic/West Russia Pattern (EA/WR). The EA represents, after the NAO, the second leading mode of low frequency variability over the North Atlantic. However, the EA is less well known than the NAO. It is structurally similar to the NAO, and it is defined by a north–south dipole of anomaly centres spanning the North Atlantic from east to west. Compared with the nodal lines of the NAO pattern, the anomaly centres of the EA are displaced south-eastward. The EA defined by NOAA-CPC is similar to that described by Barnston & Livezey (1987), who characterised this atmospheric mode by a centre located near 55° N, 20°–35° W and an opposite one over North Africa and the Mediterranean Sea (25°–35° N, 0°–10° W). A few recent works have recognised the importance of this atmospheric pattern for the Mediterranean area and at larger scales (e.g. Josey & Marsh 2005). Josey et al. (2011) showed that the EA, in its negative state, gives rise to strong cyclonic wind forcing of the North Atlantic. In the western Mediterranean, in winter, it produces a strong pressure gradient which generates a cold northerly airflow and general cooling. The SCAND and EA/WR were previously referred to as the Eurasia-1 and Eurasia-2 patterns by Barnston & Livezey (1987). A few studies have investigated their relationships with climate dynamics in the Mediterranean regions (e.g. Krichak & Alpert 2005, Hatzaki et al. 2010, Josey et al. 2011). Nevertheless, the extent of their impact remains to be fully determined.

Hatzaki et al. (2007) detected a specific mode of variability (named the Eastern Mediterranean Pattern, EMP) due to an opposed oscillation between the north-eastern North Atlantic (52.5° N, 25° W) and the eastern Mediterranean (32.5° N, 22.5° E) in winter at the 300 and 500 hPa levels. This pattern appears weak in spring and summer, weakens at lower levels and does not exist at 1000 hPa. The negative phase of the EMP is characterised by an increased zonal flow over Europe, whereas the positive phase shows an intensification of the Atlantic anticyclone resulting in an increased northerly flow toward the central Mediterranean. The EMP has been demonstrated to affect the winter patterns of temperature and precipitation in the eastern Mediterranean, with inverse impacts between the 2 phases (Hatzaki et al. 2009).

In deep and large lakes, such as those on the northern and southern flanks of the Alps, replenishment of phosphorus from the hypolimnion to the surface layers during maximum winter and spring overturn is important to secure a pool of nutrients to be utilised by phytoplankton communities during the growing period. In this regard, a linked chain of causal factors — including winter climate, water temperature, extent of the spring lake overturn, and extent of nutrient replenishment — has been shown to have significant effects on the development of phytoplankton biomass in Lake Garda and other deep southern subalpine lakes (Salmaso 2005, Salmaso et al. 2007). The specific objective of this work is to evaluate the relationships between the large-scale climatic fluctuations influencing the European and Italian climate (here represented by NAO, EA, SCAND, EA/WR and EMP) during the winter months and the limnological variables directly connected with winter climate, spring lake mixing and surface nutrient replenishment in the lake district south of the Alps. This geographic area is located in the zone of influence of the 2 north-west to south-east EA and EMP dipoles. Therefore it could be hypothesised that these 2 teleconnection indices may be more suitable, compared with the other indices, for exploring the relationships between interannual variability of limnological variables and the large-scale climatic fluctuations in the southern subalpine region.

2. MATERIALS AND METHODS

Lake Garda is the largest Italian lake. It is located in the eastern part of the southern subalpine region. It has a surface of 368 km^2, a volume of 49×10^9 m^3, and a maximum depth of 350 m. Sampling and field measurements were carried out every 4 wk (13 per year) between 1991 and 2009 at the deepest zone of the western basin (out of the village of Brenzone; 45° 41′ 51″ N, 10° 43′ 15″ E). In 1991 and 1992, additional samples were collected every 2 weeks during late spring and summer. Data were not available in December 2009. To allow comparison of the data in the different years, the analyses were carried out on a starting matrix of monthly averages (12 cases per year from 1991 to 2008; 11 in 2009) of both environmental and biological data. Environmental variables in the water column were recorded using underwater multiparametric probes (Idronaut and Seacat-Seabird probes). The determination of the extent of maximum spring mixing was estimated by analysing the sequences of depth profiles of temperature, oxygen, pH and conductivity. Mean values of environmental variables in the water column were obtained by computing volume-weighted average values in selected lake strata. In the surface layer (0 to 20 m), chemical analyses and phytoplankton data are available since 1995 and 1993, respectively. Nutrients were analysed following standard methods (APHA 1995). Phytoplankton samples were fixed with acetic Lugol's solution and counting was performed with inverted microscopes (Wetzel & Likens 1991). Algal biovolumes were calculated from abundances and specific biovolumes (Rott et al. 2007). Limnological methods and laboratory procedures have been described in detail by Salmaso (2005).

Mean daily air temperatures were measured by the Istituto Agrario di S. Michele all'Adige at the meteorological station of Arco (91 m above sea level), which is approximately 5 km away from the northern border of the lake.

The local climatic conditions and limnological characteristics were related to the mean values of the single teleconnection indices computed for the winter period (December, January and February): NAO_{DJF}, EA_{DJF}, $SCAND_{DJF}$, EA/WR_{DJF} and EMP_{DJF}.

There is no single way to numerically characterise the atmospheric modes of variability. One approach is to utilise rotated principal components analysis (RPCA). This method has been widely employed at the NOAA-CPC, where RPCA is applied to monthly mean standardised 500 hPa height anomalies in the region 20° to 90° N (Barnston & Livezey 1987), allowing the provision of regularly updated monthly index values for each leading mode. Mean winter NAO, EA, SCAND, EA/WR and EMP values were computed from monthly indices calculated by the NOAA-CPC (www.cpc.ncep.noaa.gov). In this work, I have used the new indices, which are standardised by the 1981 to 2010 climatology.

Another technique to identify different atmospheric modes of variability is through the computation of one-point correlation matrices of geopotential heights, investigating the existence of teleconnection patterns by regions of maximum negative correlations (e.g. Portis et al. 2001). Following this approach, the EMP index was defined at 500 hPa in this work following the methodology described by Hatzaki et al. (2007), as follows:

$$EMP = gpm(52.5° N, 25° W) - gpm(32.5° N, 22.5° E)$$

where gpm is the mean daily geopotential height of the grid point representing each pole. Mean EMP values were calculated for the winter (from December through February) of each year and then standardised for the period 1981 to 2010. Mean monthly geopotential heights were obtained from the website of the NCEP Reanalysis-1 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA. Reanalysis projects use a state-of-the-art analysis/forecast system to perform data assimilation using past data from 1948 to the present (Kalnay et al. 1996; www.esrl.noaa.gov/psd/data/gridded/reanalysis/). Updated winter EMP_{DJF} values may be obtained from the website www.limno.eu/archives/.

Correlations between variables were calculated using the Spearman's rank correlation coefficient (ρ). The use of this coefficient does not require specific assumptions, and also provides consistent results with non-linear relationships (Sokal & Rohlf 1995). Before correlation analyses, the physical, chemical, and biological variables were linearly detrended for the corresponding sub periods under examination. This transformation makes it possible to avoid spurious correlations originating from the presence of temporal trends (George 2004). To highlight the relationships among the different years and variables, the single cases were ordered by principal components analysis (PCA) calculated from the correlation matrix obtained from selected climatic, environmental and biotic variables. As for phytoplankton, PCA computations were made on log-transformed biovolumes. PCA was computed including only the period for which full environmental and biological data were available (1995 to 2009). Statistical analyses were carried out with R 12.12.1 (R Development Core Team 2010) and Statistica 6.1.

3. RESULTS

Table 1 reports the Spearman's rank correlation coefficients between the descriptors of winter climatic conditions and a few selected limnological variables computed for the period 1991 to 2009. For total phosphorus (TP) and phytoplankton, the table reports the correlations calculated for the period 1995 to 2003, when these variables were available concurrently. Among the indices analysed in this work, only the EA and the EMP showed a clear relationship with the variables directly connected with winter climate, spring lake mixing and surface nutrient replenishment.

The EA_{DJF} showed a decrease at the beginning of the 1990s and in the middle of the 2000s. Compared with the whole temporal series, lower values were also recorded at the end of the 1990s (Fig. 1a). The EMP_{DJF} showed a specular temporal development compared with EA_{DJF} (Fig. 1a, Table 1, $\rho = -0.86$). Overall, EA_{DJF} and EMP_{DJF} showed highly significant

Table 1. Spearman's rank correlation coefficients, ρ, between the descriptors of winter climatic conditions and the limnological variables. EA_{DJF} and EMP_{DJF}: mean winter (December to February) values of the East Atlantic pattern and Eastern Mediterranean Pattern, respectively. T_{airDJF}: mean winter air temperatures from December to February; T_{0-50S}: minimum mean values of water temperature in the 0 to 50 m layer at spring overturn; $MixVol_{\%}$: extent of spring water mixing, as percent of the total lake volume; TP_{epiS}: maximum concentrations of total phosphorus at spring overturn (between February and March). $Cyan_{JD}$ and $Diat_{MA}$: mean biovolumes of cyanobacteria and diatoms in summer and autumn (June to December), and in spring (March to April), respectively. The correlations refer to the years from 1991 to 2009 (n = 19), with the exception of TP and algal groups, which refer to the period 1995 to 2009 (n = 15). All calculations are based on linearly detrended data. Significance: ***p ≤ 0.001, **p ≤ 0.01, *p ≤ 0.05; not significant: (+) p ≤ 0.1; (–) p > 0.1

	EA_{DJF}	EMP_{DJF}	T_{airDJF}	T_{0-50S}	$MixVol_{\%}$	TP_{epiS}	$Cyan_{JD}$	$Diat_{MA}$
EA_{DJF}	1.00	***	**	***	***	***	**	+
EMP_{DJF}	–0.86	1.00	***	***	***	***	**	–
T_{airDJF}	0.61	–0.74	1.00	***	***	***	**	*
T_{0-50S}	0.84	–0.84	0.81	1.00	***	***	**	*
$MixVol_{\%}$	–0.70	0.86	–0.82	–0.80	1.00	***	**	–
TP_{epiS}	–0.76	0.96	–0.89	–0.84	0.92	1.00	**	*
$Cyan_{JD}$	–0.77	0.69	–0.70	–0.69	0.68	0.68	1.00	*
$Diat_{MA}$	–0.45	0.40	–0.51	–0.56	0.34	0.51	0.52	1.00

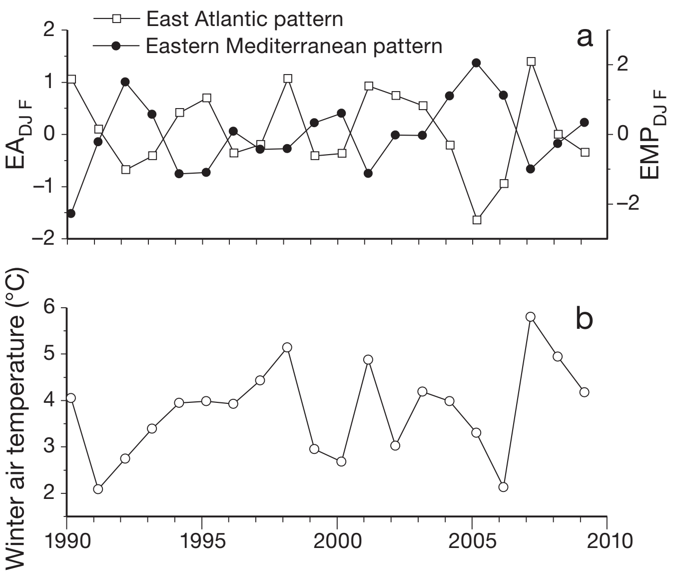

Fig. 1. Temporal variations of climatic variables. (a) Average winter (December to February) East Atlantic pattern (EA_{DJF}) and Eastern Mediterranean Pattern (EMP_{DJF}), from 1990 to 2009. (b) Average winter (December to February) air temperatures, from 1990 to 2009. In both graphs, the years refer to the months of January and February, e.g. the 1990 value contains the average of December 1989, and January and February 1990

and opposite correlations with the mean values in the winter air temperatures recorded from December to February (T_{airDJF}; Table 1; Fig. 1b). As a practical observation, strong cooling episodes were always associated with EA_{DJF} values below or close to zero (and vice versa for EMP_{DJF}). Considering the whole series, a discrepancy could be represented by the winter 1991 data. The strong cooling was not associated with low EA_{DJF} and high EMP_{DJF} values. However, even in this case, the values of the 2 indices were close to zero (and definitely not approaching high EA_{DJF} and low EMP_{DJF} values, which are typical of mild winters).

Large-scale climatic fluctuations and winter air temperatures had a significant impact on the long-term development of hypolimnetic water temperatures (Fig. 2a). Episodes of cooling of the deepest waters were identified between the winter and the spring months in 3 periods, i.e. in 1991, between 1999 and 2000, and between 2004 and 2006. Annual minimum water temperatures recorded between 0 and 50 m (T_{0-50S}) were strongly correlated with EA_{DJF}, EMP_{DJF} and T_{airDJF} (Table 1). The 0 to 50 m layer showed homogeneous cooling every year, thus representing the part of the lake most affected by the climatic events during the winter months. In the periods between the cooling episodes, the hypolimnion showed a progressive warming, of the order of 0.1°C yr^{-1} in the layer below 200 m.

The 3 larger hypolimnetic cooling episodes coincided with the complete circulation of the lake, and complete vertical homogenisation of the physical and chemical characteristics of the water column. In the intervals between the 3 periods of complete overturn, the spring mixing depths ranged from 80 to 200 m, which corresponded to mixed lake volumes ranging from 44 to 83% of the total lake volume (Fig. 2b). Even in this case, the temporal correspondence between the extent of the spring mixing lake volumes ($MixVol_{\%}$) and EA_{DJF}, EMP_{DJF}, T_{airDJF} and T_{0-50S} was rather clear (Table 1).

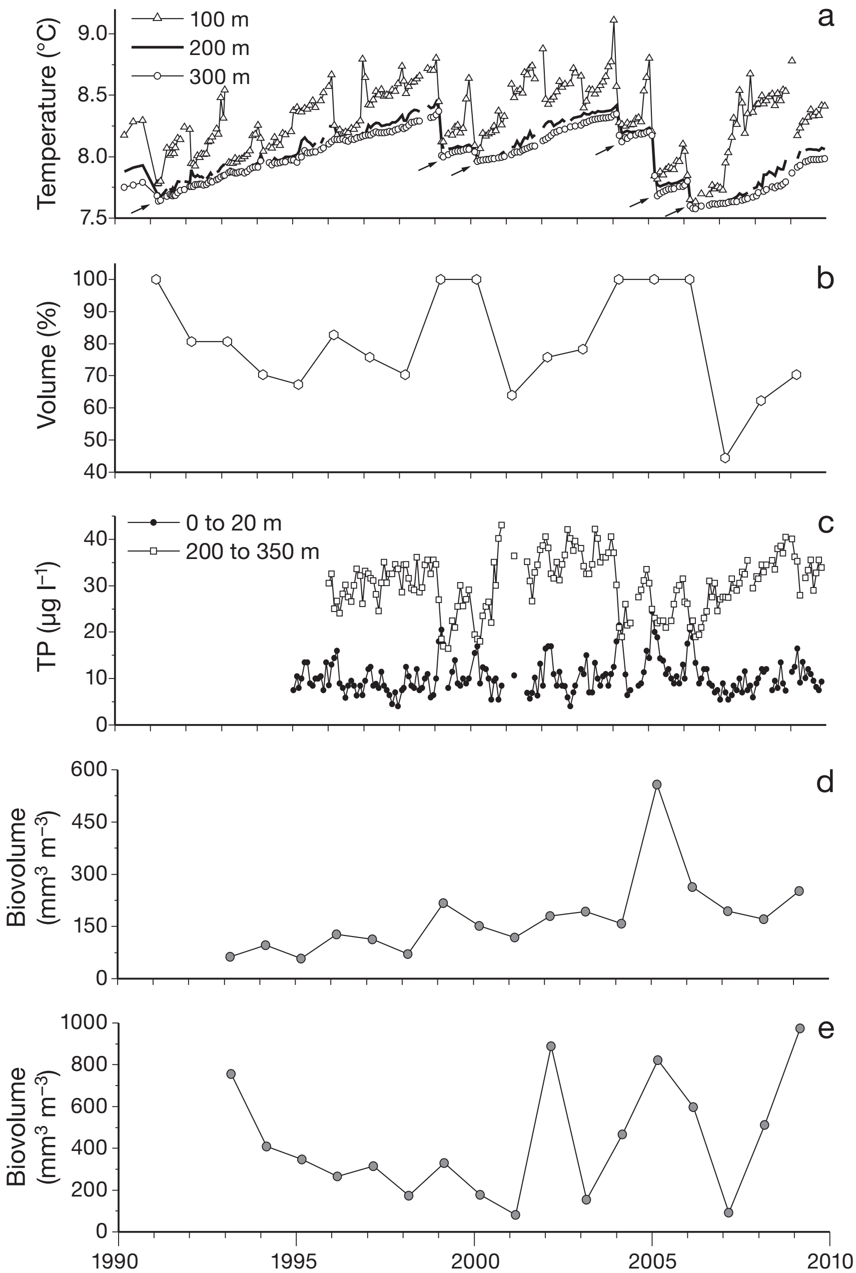

Fig. 2. Temporal variations of limnological variables and phytoplankton. (a) Hypolimnetic temperatures from April 1990 to December 2009; arrows: complete cooling and mixing. (b) Spring mixing volumes, from 1991 to 2009. (c) Concentrations of total phosphorus (TP) from January 1995 to December 2009 in the trophogenic (0 to 20 m) and hypolimnetic (200 to 350 m) layers. Annual average biovolume values of (d) cyanobacteria in summer and autumn (June to December), and (e) diatoms in spring (March to April) from 1993 to 2009

The effects of the harshest winters were particularly evident on the vertical distribution of nutrients. During the episodes of complete circulation in 1999 to 2000 and between 2004 and 2006, the lake underwent a complete replenishment of TP from the hypolimnion to the trophogenic layers (Fig. 2c). In the remaining years, concentrations were generally much lower, especially when mixed lake volumes were <70 to 75%. Overall, epilimnetic TP concentrations at spring overturn showed a strong and significant dependence on mixing depth, water and air temperature, and EA_{DJF} and EMP_{DJF} (Table 1).

The chain of effects controlled by large-scale winter climatic fluctuations had a strong impact on the development of major phytoplankton groups in the periods of their maximum seasonal development (Fig. 2d,e). In Lake Garda, cyanobacteria and diatoms represent 2 principal algal groups which mainly develop in summer and autumn, and during the spring months, respectively (Salmaso 2011). In the study period, cyanobacteria were almost exclusively dominated by *Planktothrix rubescens*, a filamentous species with toxic strains (Messineo et al. 2009). Diatoms consisted mainly of large species, mostly *Fragilaria crotonensis*, *Asterionella formosa*, *Tabellaria fenestrata* and *Diatoma tenuis*. These 2 algal groups showed a positive correlation. In the periods of their larger seasonal growth, the development of cyanobacteria and, to a lesser extent, diatoms was strongly correlated with the whole group of variables connected with EA_{DJF} and EMP_{DJF} (Table 1). In particular, diatoms showed only a marginal negative correlation with EA_{DJF}, and a positive ($\rho = 0.40$), though not significant, relationship with EMP_{DJF} (Table 1). Extending the computations to the period 1993 to 2009, the values of the Spearman's rank correlations between the 2 algal groups and EA_{DJF}, EMP_{DJF}, T_{airDJF}, T_{0-50S} and $MixVol_{\%}$ provided practically the same results reported in Table 1, with the same significance levels. The only exceptions were the relationships between cyanobacteria biovolumes ($Cyan_{JD}$) and EMP_{DJF} ($p < 0.05$), and $Cyan_{JD}$ and diatom biovolumes ($Diat_{MA}$) ($p < 0.1$).

The PCA results summarise clearly the relationships among the climatic (EA_{DJF}, EMP_{DJF} and T_{airDJF}), environmental (T_{0-50S}, $MixVol_{\%}$ and maximum TP concentration at spring overturn, TP_{epiS}) and phytoplankton ($Cyan_{JD}$ and $Diat_{MA}$) variables (Fig. 3). The graph shows the first 2 axes, which explain 86% of the total variance (77% and 9%, respectively). The first axis has the highest positive loadings for EMP_{DJF}, spring TP concentrations, spring lake mixed volumes, cyanobacteria and, partly, diatoms, and highest negative loadings for EA_{DJF}, and the winter air and water temperatures. The second axis has positive and negative loadings contributed by diatoms and, partly, cyanobacteria, respectively. The first axis separates the years characterised by complete or more extended overturn (see Fig. 2b) from the remaining years.

NAO_{DJF}, $SCAND_{DJF}$ and EA/WR_{DJF} did not show any significant correlation with EA_{DJF} and EMP_{DJF} ($-0.19 < \rho < 0.16$, n = 19, p > 0.1). Similarly, NAO_{DJF}, $SCAND_{DJF}$ and EA/WR_{DJF} were uncorrelated with T_{airDJF}, T_{0-50S}, $MixVol_{\%}$ ($-0.32 < \rho < 0.34$, n = 19, p > 0.1), TP_{epiS} ($-0.29 < \rho < 0.17$, n = 15, p > 0.1) and the biovolumes of cyanobacteria and Bacillariophyta (1993 to 2009: $-0.40 < \rho < 0.30$, n = 17, p > 0.1; 1995 to 2009: $-0.37 < \rho < 0.06$, n = 15, p > 0.1).

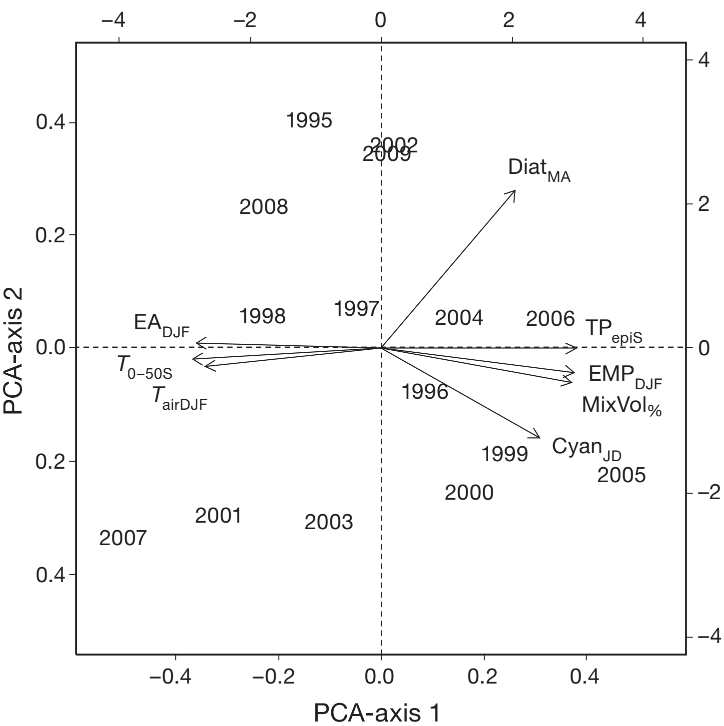

Fig. 3. Principal components analysis (PCA). Ordination of the limnological years from 1995 to 2009. Arrows: the relative loadings of the climatic and limnological variables on the first and second principal components. See Table 1 legend for variable abbreviations

4. DISCUSSION

This work confirms previous analyses made on Lake Garda (Salmaso 2005), highlighting the weak connection between the limnological variables and the NAO. Similar uncertainties have also been found in Lake Maggiore, which is located in the western part of the southern subalpine region (Morabito 2007, Manca & De Mott 2009).

Contrary to the well known NAO, the effects of the EA and EMP on Mediterranean temperatures and atmospheric precipitation have been less studied, whereas no investigations have been carried out so far on the impact of EMP dynamics on aquatic and terrestrial ecosystems. A few recent papers have demonstrated a strong influence of the EA on the air–sea heat exchange and temperature over the Mediterranean regions (deCastro et al. 2008, Schroeder et al. 2010, Josey et al. 2011), whereas Toreti et al. (2010) found a strong relationship between air temperatures and the EA all over Italy. The impact of the EMP on precipitation extremes over Cyprus has been studied by Hatzaki et al. (2008). In addition, Hatzaki et al. (2009) confirmed previous observations, showing how the EMP affected the mean winter patterns of temperature, precipitation, and their extreme events in the Eastern Mediterranean. The results reported in the present study show how the influence of the EMP can broaden over a more extended area, at the border between the Alps and the Mediterranean region.

Statistically, and in the considered period, EA_{DJF} and EMP_{DJF} were strictly correlated. The strict connection between these 2 indices is further substantiated if one extends the data analysis from 1958 to 2009 ($\rho = -0.70$, p < 0.001). Hatzaki et al. (2007, 2010) were able to identify and confirm the spatial pattern associated with the EMP by applying multidimensional exploratory statistical methods (RPCA and RCCA, regularized canonical correlation analysis). Nevertheless, in both studies, the EA was recognised as an important atmospheric mode. As underlined by Josey et al. (2011), further research is needed to identify how the EMP fits with the synoptic picture provided by the NOAA-CPC mode framework. At this stage, the results in this paper evidence an association between the EA and EMP, at least in the winter period. These results are of interest because both indices appear to be effective candidates for exploring the relationships between atmospheric modes of variability and the temporal variations in the limnological characteristics of water bodies in the Mediterranean and surrounding regions (including the subalpine zone). A disadvantage of station-based indices is that they are fixed in space, so that they cannot take into account the fraction of variability in the position of the action centres (Hurrell et al. 2003).

The data reported in this work update and confirm previous analyses made on Lake Garda, which demonstrated a strong connection between physical, chemical and biological factors (Salmaso 2005, 2011). Similar results have also been obtained in other deep southern subalpine lakes (Simona 2003, Salmaso 2005). In addition, the present study demonstrates the existence of a strong link between the temporal development of limnological variables in Lake Garda and specific modes of variability due to opposed oscillations between the north-eastern North Atlantic and eastern Mediterranean in winter. The mechanism of how the atmospheric circulation patterns affect the limnological variables includes a long chain of interconnected causal factors, from EA_{DJF} and EMP_{DJF} to the development of the dominant algal groups.

The mechanism proposed here will take into consideration processes favouring complete spring overturn and fertilisation. (1) In its negative state, the EA_{DJF} mode is characterised by intense high pressure over the West Atlantic, causing a north-easterly airflow, which brings cold air from continental Europe over the full Mediterranean basin (Josey et al. 2011). A similar pattern characterises the positive phase of EMP_{DJF}, with an intensification of the Atlantic anticyclone, the formation of a cyclonic anomaly over the eastern Mediterranean, and a northerly anomaly cold flow toward the central Mediterranean (Hatzaki et al. 2007). (2) Air temperatures strongly affect the thermal structure of the lake acting on the heat-exchange processes between water and atmosphere (Lerman et al. 1995). At this stage, colder air temperatures enable stronger heat losses from the lake surface, and water cooling. (3) During cold winters, convective mixing due to heat loss and wind shear are strong enough to destroy density stratification. In this case, the lake undergoes complete mixing, with a vertical homogenisation of the water column, and (4) complete nutrient fertilisation of the surface layers. (5) The increase in nutrient availability promotes the growth of 2 dominant algal groups in the periods of their maximum seasonal development, namely cyanobacteria in summer and autumn and, partly, diatoms in spring. The above processes will be progressively attenuated and reversed with a progressive change of the EA_{DJF} and EMP_{DJF} towards positive and negative values, respectively.

These processes are centred on deeply penetrative mixing events that, in turn, result in the upward transport of phosphorus from the hypolimnion to the trophogenic zone. Salmaso (2005) estimated that in 1998, with intermediate overturn (around 70% of the total lake volume; Fig. 2b), the input of TP to the productive layers of Lake Garda (0 to 20 m) was $<40 \times 10^3$ kg. The successive year, as a consequence of complete circulation (Fig. 2), the transport of TP to the trophogenic zone increased to 80×10^3 kg. The estimated epilimnetic supply of TP during the spring months constitutes a high input of nutrients, readily utilisable for phytoplankton growth.

The clearest effect of nutrient fertilisation is represented by the significant increase in cyanobacteria in summer and autumn. These organisms are generally strongly and positively linked to gradients of phosphorus concentrations (e.g. Istvánovics 2009). The development of the dominant species in this group (*Planktothrix rubescens*) requires strict, specific conditions (D'Alelio et al. 2011). In summer and early autumn, this species develops in the metalimnion, in stable conditions and in dim light, near the photosynthetic compensation point, entraining successively into the surface mixed layer at the beginning of the late autumn cooling. Compared to cyanobacteria, the impact of the spring fertilisation on the development of diatoms appears less marked. The large and heavy organisms composing this group require high water turbulence to avoid sinking and losses (Padisák et al. 2003). Therefore the maximum net growth of the large diatoms is generally observed before the maximum seasonal warming of the lake.

At the multi-decadal scale, cyanobacteria showed a significant increase, due to a parallel increase in nutrients and trophic status since the beginning of the 1970s (Salmaso et al. 2007; Fig. 2d). Nevertheless, the fine tuning in the year-to year development of this group is under the strict control of atmospheric forcings and deep mixing lake dynamics.

Considering the high coherence in the long-term development of spring water temperatures measured at maximum spring overturn in the deep southern subalpine lakes (Salmaso & Mosello 2010), it can be speculated that the effects of the EA and EMP could also be detected in other water bodies south of the Alps. As a matter of fact, the interruption of meromixis in Lake Lugano was observed after 2 consecutive cold and windy winters (2004 to 2005 and 2005 to 2006), which destabilised the water column, leading to 2 strong mixing events (Holzner et al. 2009). These episodes were associated with a period of high negative (positive) phase in the winter EA (EMP) values.

Both indices comply with the criteria depicted by Straile & Stenseth (2007) for the identification of indices useful for explaining interannual variability in time series: The EA and EMP are strongly related with the meteorological conditions in winter; winter conditions, and especially temperatures, have a significant impact on environmental conditions; and finally, this variability is of paramount importance for the temporal dynamics of species.

5. CONCLUSIONS

This study has demonstrated the existence of a strong link between the temporal development of limnological variables in Lake Garda and specific atmospheric modes of variability. Enhanced development of dominant algal groups was strongly connected with negative (positive) phases of the winter EA (EMP), through a linked chain of causal factors, which included higher replenishment of phosphorus at spring overturn, higher extent of deep circulation episodes, lower lake water temperature, and lower winter temperatures associated with harsh winter conditions. EA and EMP winter dynamics could represent important tools for understanding the link between large-scale climatic fluctuations and local climatic patterns, and their impact on freshwater ecosystems in the Mediterranean and the southern subalpine area. At the same time, this opens new and important perspectives in the interpretation of the impact of climate and eutrophication on lakes. Nevertheless, the contribution of these 2 teleconnection patterns to the temperature variations and temporal dynamics of freshwater ecosystems in the area between the Alps and Mediterranean need to be thoroughly investigated, extending the periods under examination and the number of freshwater ecosystems. These elements are also important for the evaluation of the degree of stationarity over longer periods of time. Moreover, the relationships between teleconnection indices relevant for the Mediterranean area and the variability of limnological variables in the other seasons were not explored (see, for example, the analyses made utilising summer data by Molinero et al. 2007 in Lake Geneva, at the northern border of the Alps). Improvement of the knowledge of the mechanisms governing the relationships between atmosphere and lakes is also important considering the forecasted impact of climate change. As demonstrated by Josey et al. (2011), a shift in the strength and spatial extent of the major atmospheric modes of variability — in particular the EA — will have a significant impact on the heat budget in the Mediterranean region. Finally, further research is needed to evaluate the identity and singularity of the station-based index (EMP) compared with the results obtained through synoptic analyses by NOAA-CPC.

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