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EUROPEAN LARGE LAKES III

Influence of atmospheric modes of variability on the limnological characteristics of large lakes south of the Alps: a new emerging paradigm

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Abstract Winter air and spring surface water temperatures, spring epilimnetic phosphorus, and hypolimnetic oxygen in the deep lakes south of the Alps (Garda, Iseo, Como, Lugano, and Maggiore) showed a high degree of temporal coherence. The common temporal patterns were originating from the effects caused by winter climate, and from corresponding synchronisms in the interannual variations in the extent of the spring water renewal and replenishment of nutrients. In turn, the sequence of linked causal events was triggered by two atmospheric modes of variability relevant for the Mediterranean region, i.e. the East Atlantic pattern (EA) and the Eastern Mediterranean Pattern (EMP). In contrast, there were no significant relationships of air and water temperatures with the North Atlantic Oscillation. In oligotrophic lakes, which were characterised by weak vertical nutrient gradients, the spring replenishment of P was negligible and difficult to detect (Maggiore), or detectable but of minor importance (Garda and Como) compared to that measured in more enriched lakes (Iseo and Lugano). The applicability of EA and EMP in the study of the impact of climate on aquatic ecosystems will require to be tested by expanding the number, typology, and geographical location of water bodies in the Alpine and Mediterranean regions.

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Introduction

Climate strongly affects lake ecosystems and communities. Nevertheless, what seems a simple statement actually needs a more articulated examination depending on the temporal scales, and lake typology. Meteorological fluctuations at the weekly and monthly scales affect the short-term dynamics of living organisms, with profound changes that can be observed cyclically every year. A paradigmatic example is the appearance of surface cyanobacterial blooms (sensu Reynolds and Walsby, 1975) in warm and calm summers. Often considered a sign of eutrophication, the manifestation of such episodes is mostly driven by changes in local weather (Reynolds, 1987; George, 2010). With long-term temporal scales, climate change causes influential alterations in the physics, chemistry and biology of lakes, affecting ecological processes and life cycles, and with the potential of causing the disappearance of autochthonous and introduction of new exotic species (Blenckner, 2005; EEA, 2010).

Across the whole temporal spectrum, differences in lake physiography, climatic location (including latitude and altitude), and other site specificities filter and modulate the relative effect of climate change on ecosystem variables (Mooij et al., 2005; Nõges, 2009; Arvola et al., 2010). Life cycles and seasonal dynamics in lakes located at higher latitudes and/or altitudes are strongly affected by the timing and duration of ice cover (Salmaso & Decet, 1997; Ohlendorf et al., 2000; Wang et al., 2010), whereas shallow lakes are more sensitive to changes triggered by local and transient weather fluctuations (Naselli-Flores & Barone, 2012). In large and deep lakes, warming is caused by the downward transport of heat by turbulent diffusion within the hypolimnion during stratification. Therefore deep waters retain a “climatic memory”, which records information about past climatic fluctuations (Ambrosetti & Barbanti, 1999; Salmaso et al., 2003). These few examples confirm how different can be the effects of climate fluctuations on different typologies of lakes.

During the last 20 years the relationships between weather at different time scales and the physical, chemical, and biological variability in freshwater ecosystems were studied also making use of climate indices indicative of different climatic patterns (Stenseth et al., 2003). Among the most well-known indices, the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO) provided conceptual tools to understand the impact of climatic fluctuations on aquatic and terrestrial ecosystems at different levels of complexity, from the life cycles of individual species to changes in complex trophic webs (Hurrell et al., 2001; Straile, 2002; Poveda et al., 2011). The NAO was shown to influence climate from the eastern coast of the United States to Siberia and from the Arctic to the subtropical Atlantic (Hurrell et al., 2003). It was efficiently used to explain, among the others, the number of days of total ice cover, the winter lake surface temperatures, the timing of the phytoplankton biomass spring peaks, the timing of *Daphnia* growth and grazing (Straile et al., 2003; George, 2010, and references herein).

In this paper, we will study the effects of large scale atmospheric circulation patterns and climatic fluctuations on the limnology of the large and deep lakes south of the Alps (from E to W, lakes Garda, Iseo, Como, Lugano, and Maggiore). In this group of lakes, algal nutrient loads and climate (both at short and decadal scales) still represent the two most important factors controlling the interannual and long-term fluctuations in the basic limnological variables and trophic status (Mosello et al., 2010; Morabito et al., 2012). Though at various degrees in the different water bodies, interannual changes of climate during the winter months are a key factor controlling deep mixing dynamics, hypolimnetic oxygenation, and the fraction of nutrients recyclable from the deeper hypolimnetic layers (Manca et al., 2000; Simona, 2003; Salmaso et al., 2003).

In a recent paper, Salmaso (2012) analysed the effects of several teleconnection indices potentially relevant for the Mediterranean area on the thermal structure and deep mixing dynamics of Lake Garda. Among the five indices analysed (North Atlantic Oscillation, NAO; East Atlantic pattern, EA; Scandinavia pattern, SCAND; East Atlantic/West Russia Pattern, EA/WR; Eastern Mediterranean Pattern, EMP), the EA and EMP showed a strong and significant link with the winter air and lake temperatures, spring deep mixing dynamics, replenishment of phosphorus in the epilimnetic layers and development of phytoplankton during the spring and summer months. In discussing the results, it was speculated that the effects of the EA and EMP could also be detected in other water bodies south of the Alps. Therefore the specific objectives of this work are: (i) to evaluate the influence of the winter EA and EMP on the winter air temperatures and the limnological variables directly connected with winter climate, i.e. spring water temperatures, the extent of the spring lake mixing, the surface nutrient replenishment at spring overturn and the hypolimnetic oxygenation in the large and deep lakes south of the Alps; (ii) to verify the degree of coherence in the response of the different lakes to the impact of the two teleconnection patterns.

Materials and methods

Study sites

The five lakes considered in this study have maximum depths and volumes ranging between 251 and 410 m, and 4.7 and 49 billions of m^3, respectively (Fig. 1). They are located within the River Po catchment area, contributing water for about 40% of its discharge. Theoretical renewal times are around 4–5 years (lakes Maggiore, Como and Iseo), 12 years (Lake Lugano), and 27 years (Lake Garda). Considering the climatic location, this group of lakes should be classified as warm monomictic, with complete circulation once a year in the winter at or above 4°C, and stable stratification from spring to early autumn (Wetzel, 2001). Nevertheless, owing to their large depth, these lakes are actually mero-oligomictic, showing long periods of incomplete spring mixing, interrupted by occasional and irregular complete overturns following harsh and windy winters (cf. Ambrosetti & Barbanti, 1999).

Phosphorus concentrations of Lake Lugano and of the other lakes showed a consistent increase since the 1960s and 1970s, respectively (Mosello et al., 1997). At the end of the 1980s trophic status ranged between the oligo-mesotrophy of Lake Garda and the eutrophy–hypereutrophy of Lake Lugano. Lake Maggiore and lakes Como and Iseo were meso-eutrophic and eutrophic, respectively. Since the early 1990s, the remedial measures produced positive effects in lakes Maggiore (now oligotrophic; average TP concentrations in the water column, around 10 μg P l^{-1}), Como (oligo-mesotrophic; around 25 μg P l^{-1}) and Lugano (meso-eutrophic; around 60–80 μg P l^{-1}). Lakes Iseo (meso-eutrophic) and Garda (oligo-mesotrophic) showed a stabilisation of the P concentrations in the whole water column around 50–60 and 18 μg P l^{-1}, respectively (Mosello et al., 2010).

Teleconnection indices

A selection of environmental variables representative of the climatic fluctuations and limnological characteristics of the five deep lakes were related to the mean values of the East Atlantic pattern and of the Eastern Mediterranean Pattern computed for the winter period (December, January and February, EA_{DJF} and EMP_{DJF}); at the same time, the influence of the winter North Atlantic Oscillation (NAO_{DJF}) was tested on the same set of environmental variables. The winter period (December–January) considered in the analysis was completely adequate to describe the impact of the climatic fluctuations on the limnological variables measured during the spring months (Salmaso, 2012). The use of other winter sub-periods or monthly values was much less effective or uninformative and did not improve the interpretation of the data set. The mean monthly EA and NAO values were calculated by the NOAA-CPC (www.cpc.ncep.noaa.gov), using Rotated Principal Components Analysis (RPCA) applied to standardized 500 hPa height anomalies. EMP values (www.limno.eu/archives/) were obtained computing the differences in the mean daily geopotential height between two fixed centres located at 52.5°N, 25°W, and 32.5°N, 22.5°E (Hatzaki et al., 2007). The EA and EMP essentially describe a dipole of anomaly centres located in the North Atlantic and in North Africa. They have opposite sign due to the different approach used in their estimation. Negative (positive) values of the EA_{DJF} (EMP_{DJF}) are linked with the occurrence of cold winters over the Mediterranean area. This condition is reversed with a progressive change of the EA_{DJF} (EMP_{DJF}) towards positive (negative) values. A review of the spatial and seasonal influence of the EA and EMP was undertaken by Salmaso (2012).

Sampling, field measurements, and laboratory analyses

In the five lakes the data used in the analyses include measurements recorded in the periods between (depending on the availability of data in the single variables) 1991–1996 and 2011 (Garda), 1994 and 2011 (Iseo), 2004 and 2011 (Como), and 1991 and

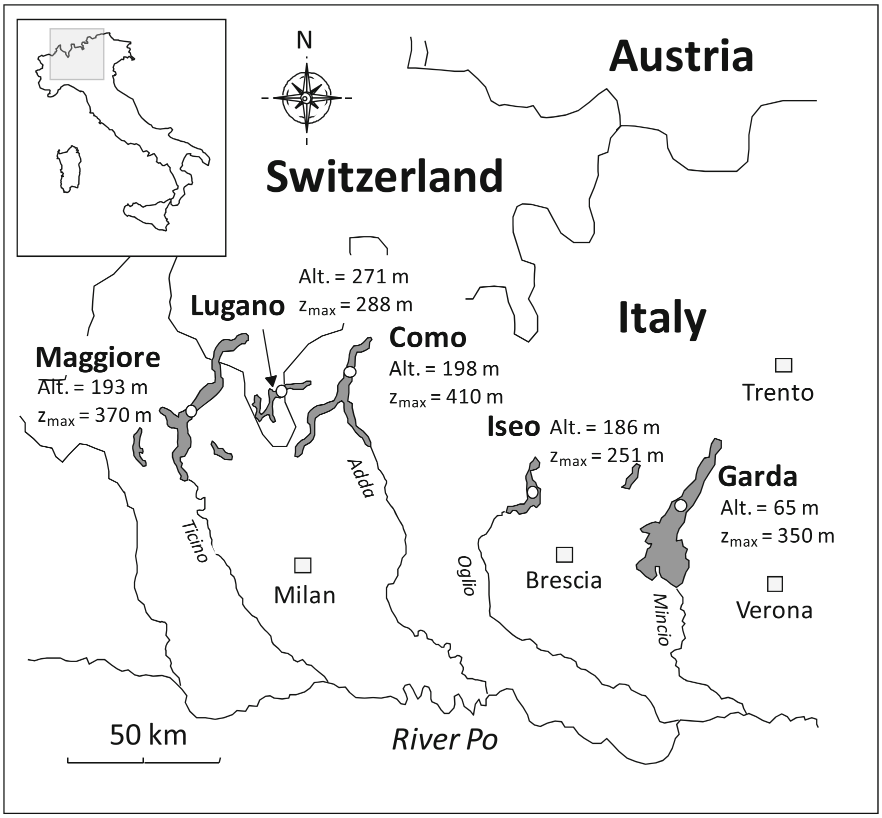

Fig. 1 Geographical location of the deep lakes south of the Alps. Alt., lake altitude; z_{max}, maximum depth. The *hollow circles* indicate the location of the sampling stations

2011 (Lugano and Maggiore). The sampling frequency varied between 15 days and 1 month, with a few gaps which, however, did not influence the specific database used in this work (see below).

In lakes Garda, Iseo and Maggiore, and in the northern basin of Lake Lugano, the sampling stations were located at the deepest point of the basins. Monthly samplings in Lake Como were carried out at the station of Dervio, in the northern basin ($z_{max} = 270$ m); similarly to the other lakes (see below), estimation of the maximum mixing depths in Lake Como were, however, based on measurements made at the time of maximum overturn (usually March) in the deepest zone of the basin (Mosello et al., 2010). In the epilimnetic layers of the five lakes samples were collected between 0 and 20 m. Additional samples were collected, every 50 m or less, in the hypolimnetic layers. Chemical analyses followed comparable and standardised protocols, and the results were checked by intercalibration exercises among the laboratories (e.g., Mosello et al., 1995).

Besides collection of discrete samples, measurements of temperature, oxygen, pH, and conductivity in the water column of the lakes Garda, Lugano and Como were carried out using underwater multiparameter probes (Idronaut and Seacat-Seabird probes). In Lakes Iseo and Maggiore the use of multiparameter probes was less frequent or began only very recently.

As for lakes Garda, Como and Lugano, the archives used for data analysis included water temperatures measured with the underwater probes. In lakes Iseo and Maggiore data included measurements made with mercury-filled Celsius thermometers. Dissolved oxygen values were recorded using the Winkler titration method (Wetzel & Likens, 1991), with the exclusion of Lake Como and, partly, Lake Iseo, for which the oxygen data used in the computations included measurements collected with the underwater probe, checked regularly with determinations (Winkler method) made in the laboratory.

The determination of the extent of the deep water mixing events during the spring months was estimated by analysing the sequences of depth profiles of the physical and chemical data recorded with the underwater probes, supplemented, and confirmed with the data obtained with the analysis of the discrete samples (pH, conductivity, dissolved oxygen, major ions, and nutrients). In Lake Iseo the extent of deep water renewal was evaluated using the profiles based on the analysis of the discrete samples and, when available, the profiles of the submersible probe. The same approach, based exclusively on discrete samples, was applied to Lake Maggiore, but the weak gradients which characterised most of the physical and chemical data made it difficult to obtain reliable estimates of the extent of water renewal. For this reason, in the following analysis this variable was not considered in the case of Lake Maggiore. Deep overturn episodes were identified by a complete vertical homogenisation in the physical and chemical variables (Salmaso, 2012). In oligomictic and oligo-mesotrophic lakes—such as Lake Garda—complete mixing causes also a complete replenishment of oxygen (up to 80–85%) to the deepest layers (e.g., Salmaso, 2012). In meromictic lakes—such as Iseo and Lugano—complete cooling and vertical homogenisation can result only in a modest re-oxygenation of the deep hypolimnion, with low O_2 concentrations over the whole water column (Holzner et al., 2009). Therefore, deep water renewal events in lakes Iseo and Lugano do not necessarily imply absolute and high oxygen replenishment in the deep hypolimnion.

Mean daily air temperatures were recorded in the vicinity of the lakes. Meteorological variables in Lake Garda were measured by the Istituto Agrario di S. Michele all'Adige at the station of Arco (91 m a.s.l.), which is approximately 5 km away from the northern border of the lake. Mean daily air temperatures in Lake Iseo were provided by ARPA Lombardia with measurements made at the meteorological station of Costa Volpino (186 m a.s.l.), ca. 1 km away from the northern border of the lake. The meteorological station in Lake Como was located at Colico, ca. 2 km from the north-east shores. Meteorological data in Lake Lugano were supplied by the Federal Office of Meteorology and Climatology (METEOSWISS); measurements were made at the Biblioteca Cantonale di Lugano, along the lake shore. Continuous air temperatures in Lake Maggiore were recorded at the CNR-ISE meteorological station, located in Pallanza, on the lake shore.

Data analysis

The numerical analyses were principally based on the data collected in lakes Garda, Iseo, Lugano and Maggiore, whereas Lake Como, which was characterised by a shorter temporal data set (8 years), was analysed separately. For every lake, the periods analysed in the regression analyses (Figs. 3, 4, 5, 6, 7, 8) were identified including only the years for which full environmental and biological data were available, i.e. 1996–2011 (Garda), 1994–2011 (Iseo), 2004–2011 (Como), and 1991–2011 (Lugano and Maggiore).

Different climatic and limnological variables were related to EA_{DJF} and EMP_{DJF} (Figs. 2, 3, 4, 5, 6, 7). These include: (1) the mean winter air temperatures measured from December to February ($Tair_{DJF}$). (2) The minimum water temperatures in the upper hypolimnion and epilimnion (0–50 m; T_{0-50S}), between the second half of February and March. The layer 0–50 m underwent homogeneous cooling every year, thus representing the part of the lake most affected by the winter climate. (3) The extent of the maximum spring water mixing ($MixD_S$), estimated in the period coinciding with the minimum values of the water temperatures. (4) The maximum concentrations of the spring epilimnetic (0–20 m) soluble reactive phosphorus (SRP_{epiS}); in the considered lakes, the maximum epilimnetic replenishment of nutrients was observed in the period of maximum spring water mixing (usually between the end of February and March). (5) The mean concentrations of hypolimnetic dissolved oxygen between two spring circulation events, i.e. between May and December (Oxy_{hypo}). In the three deeper lakes (Como, Maggiore, and Garda), Oxy_{hypo} was estimated in the layer between 200 m and the bottom, whereas the computations in lakes Iseo and Lugano were made between 150 m and the bottom, and 100 m and the bottom, respectively. To better evaluate quantitatively the differences and analogies in the five lakes, the regressions were computed on the original variables. The possible existence of spurious correlations originating from the presence of temporal trends in the lakes with the longer datasets (Garda, Iseo, Lugano, and Maggiore) was evaluated with a parallel set of regressions computed on linearly de-trended data. However, the comparison of the regressions obtained with the de-trended and non de-trended series gave equivalent results, with the exception of a few relationships involving the winter NAO index (see the section 'Results'). In a few cases, relationships showing abrupt changes in the response variables over varying range of values of the teleconnection indices were analysed by piecewise regressions. The selection of break-points was guided by computing the residual standard error of several two-segment piecewise models. Residuals were graphically examined for evidence of departures from normality, homogeneity, and dependence (Zuur et al., 2009). Before analysis the values of the mixing depths were transformed by decimal logarithm.

The remaining relationships (Table 2, and the temporal coherence of variables between lakes) were calculated using the Spearman's rank correlation coefficient (ρ). The use of ρ does not require particular assumptions, providing consistent results with non-linear relationships (Sokal & Rohlf, 1995).

The differential response of lakes to the impact of the teleconnection indices (TC) was evaluated by mean of generalised least squares models (GLS; Pinheiro & Bates, 2000). GLS models were applied including: selected limnological variables (LV) as response variables (in turn, $T_{0\text{-}50\mathrm{S}}$, $\mathrm{SRP}_{\mathrm{epiS}}$, and $\mathrm{Oxy}_{\mathrm{hypo}}$); TC as a continuous explanatory variable; lake as a categorical variable; and a TC-lake interaction term:

$$LV_{ij} = \alpha_j + \beta_j \times TC_{ij} + \varepsilon_{ij}$$

where i and j are indices for the observations and the lakes, respectively, and ε the residuals. In the different models, different intercepts and/or slopes were included only if significant. The spread of the residuals was very different in the lakes included in the models, e.g. for $\mathrm{SRP}_{\mathrm{epiS}}$ (see also Fig. 2c). Therefore models were also allowed to include different residual variations for the different lakes, taking into account the heterogeneity of variances. Selection of models was evaluated based on the AIC (Akaike Information Criterion) values and ANOVA tests (Zuur et al., 2009).

The assumption of independence of residuals in regression analyses was evaluated computing the Breusch–Godfrey test (5% level) and inspecting autocorrelation function (ACF) plots. Autocorrelation in the residuals was verified in two regressions

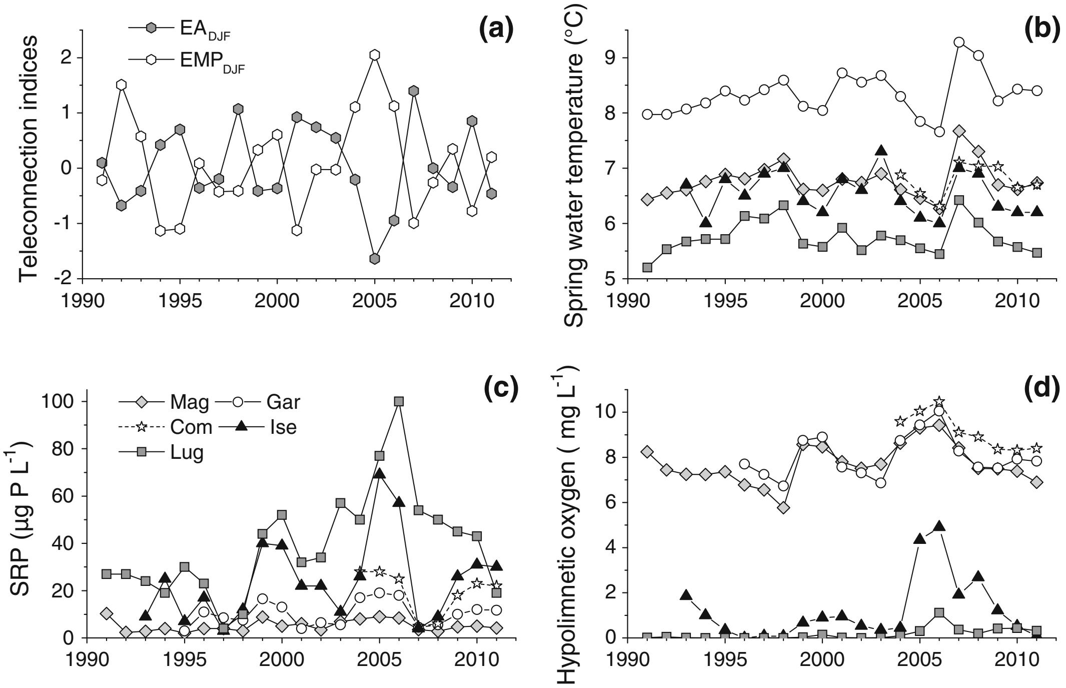

Fig. 2 **a** Temporal fluctuations of the winter East Atlantic pattern ($\mathrm{EA}_{\mathrm{DJF}}$) and the Eastern Mediterranean Pattern ($\mathrm{EMP}_{\mathrm{DJF}}$); the years refer to the months of January and February, e.g. the 1991 value contains the average of December 1990, and January and February 1991. Temporal development of **b** water temperatures (0–50 m) at the time of maximum spring overturn ($T_{0\text{–}50\mathrm{S}}$), **c** spring epilimnetic soluble reactive phosphorus ($\mathrm{SRP}_{\mathrm{epiS}}$), and **d** hypolimnetic dissolved oxygen ($\mathrm{Oxy}_{\mathrm{hypo}}$) in the large lakes south of the Alps between May and December. In the legend of **c**, the lakes were ranked according to their trophic status, following the increasing concentrations of SRP

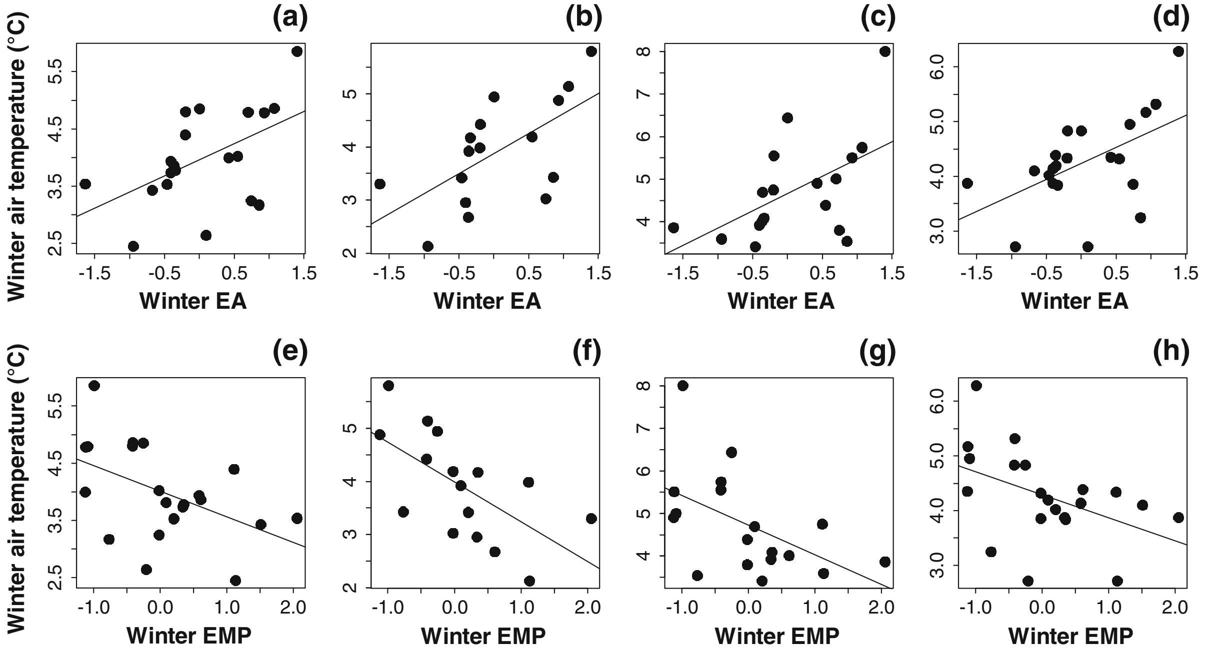

Fig. 3 Effects of the winter values of the East Atlantic pattern (EA_{DJF}) (*upper graphs*) and Eastern Mediterranean Pattern (EMP_{DJF}) (*lower graphs*) on the winter air temperatures in lakes: **a**, **e** Maggiore, **b**, **f** Garda, **c**, **g** Iseo, and **d**, **h** Lugano. The relationships are significant at least at $P < 0.05$

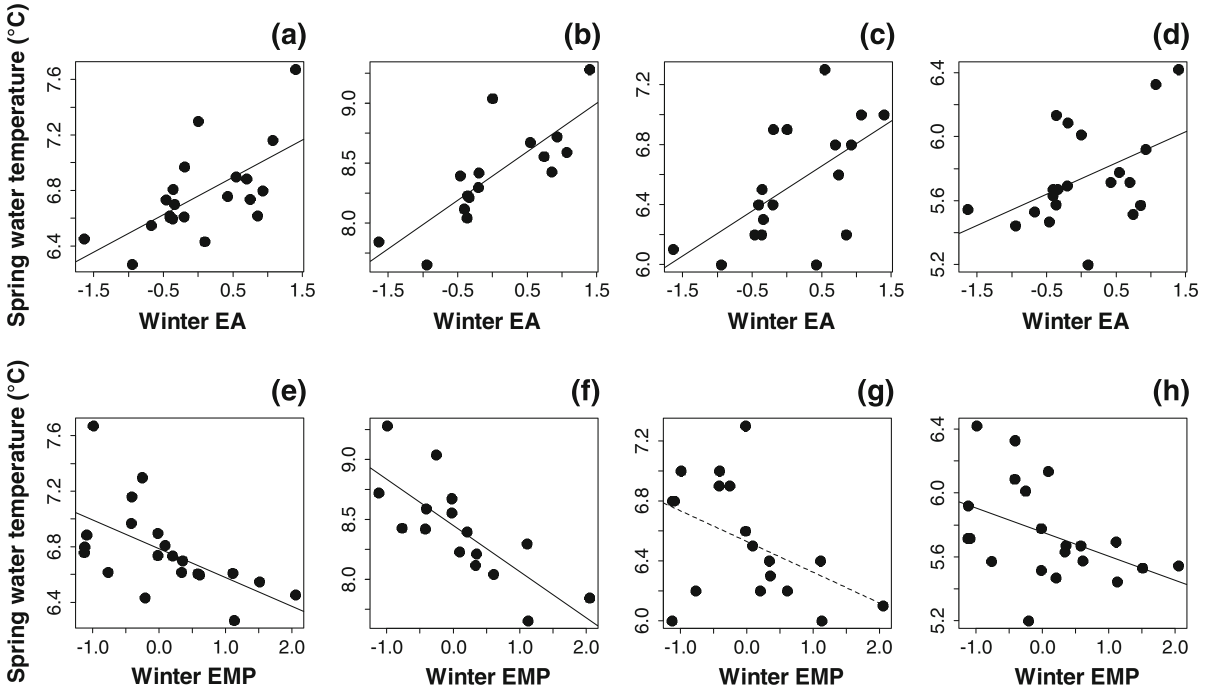

Fig. 4 Effects of EA_{DJF} (*upper graphs*) and EMP_{DJF} (*lower graphs*) on the spring water temperatures between 0 and 50 m in lakes: **a**, **e** Maggiore, **b**, **f** Garda, **c**, **g** Iseo, and **d**, **h** Lugano. The relationships are significant at least at $P < 0.05$ (*continuous lines*) and $P < 0.10$ (*dotted lines*)

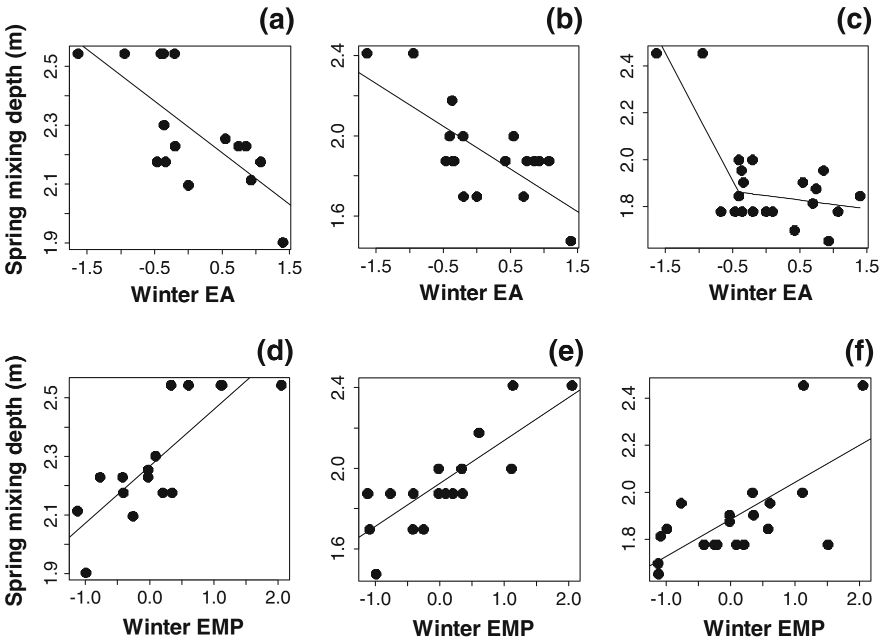

Fig. 5 Effects of EA_{DJF} (*upper graphs*) and EMP_{DJF} (*lower graphs*) on the deep water renewal estimates in lakes: **a**, **d** Garda, **b**, **e** Iseo, and **c**, **f** Lugano. Mixing depths were previously transformed by $\log_{10}$. The relationships are significant at $P < 0.01$

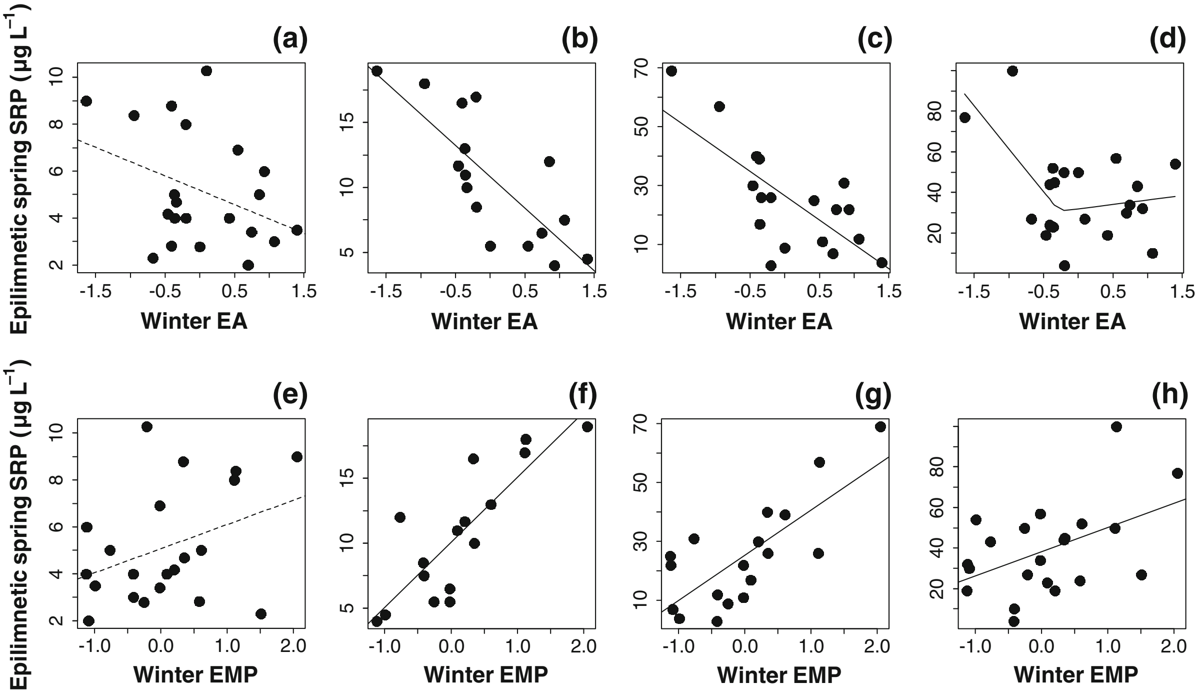

Fig. 6 Effects of EA_{DJF} (*upper graphs*) and EMP_{DJF} (*lower graphs*) on the concentrations of soluble reactive phosphorus between 0 and 20 m in lakes: **a**, **e** Maggiore, **b**, **f** Garda, **c**, **g** Iseo, and **d**, **h** Lugano. The relationships are significant at least at $P < 0.05$ (*continuous lines*) and $P < 0.10$ (*dotted lines*)

(Figs. 6h, 7a). The inclusion of an auto-regressive process of order 1 (AR1) in these models (Pinheiro & Bates, 2000) did decrease the significance of the relationship in Fig. 6h ($P = 0.10$; see "Results" section). Statistical analyses and statistical graphs were calculated in R 3.0.0 (R Core Team, 2013).

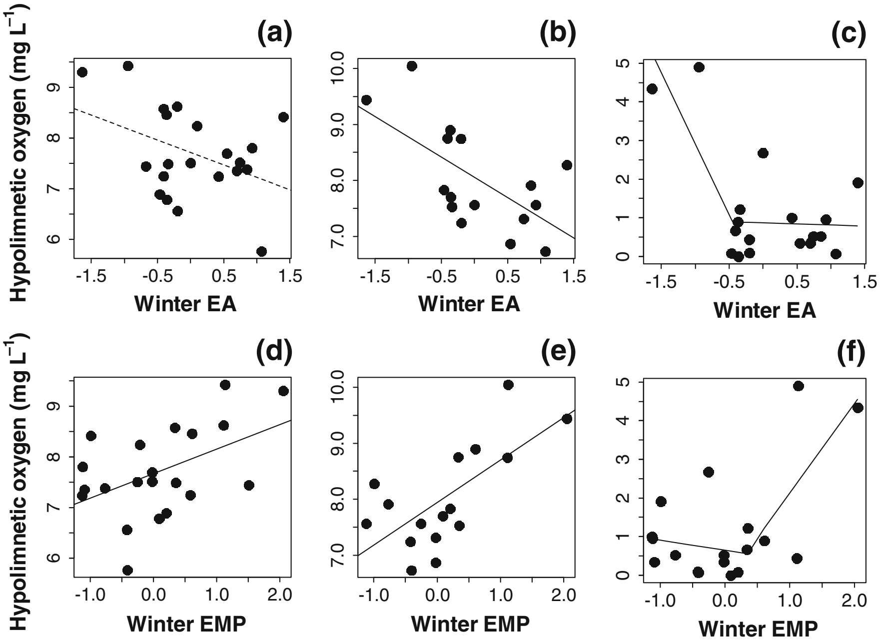

Fig. 7 Effects of EA_{DJF} (*upper graphs*) and EMP_{DJF} (*lower graphs*) on the hypolimnetic concentrations of dissolved oxygen in lakes: **a**, **d** Maggiore, **b**, **e** Garda, and **c**, **f** Iseo. The relationships are significant at least at $P < 0.05$ (*continuous lines*) and $P < 0.10$ (*dotted lines*). Lake Lugano was not included in the analyses because of the hypoxia conditions during most of the study period (Fig. 2d)

Results

Variables connected with the climatic fluctuations

In the whole analysed period (1991–2011), EA_{DJF} and EMP_{DJF} showed an opposite temporal pattern (Fig. 2a; $\rho = -0.84$, $P < 0.01$). A detailed description of the temporal development of the two indices was reported in Salmaso (2012) and Salmaso & Cerasino (2012).

In lakes Garda, Iseo, Lugano and Maggiore, mean air temperatures between December and February were between 2 and 8°C. In Lake Como winter air temperatures were lower (ca. 0.5–5°C) due to the localisation of the meteorological station in a northern near-mountainous area, and local climate. Overall, winter air temperatures were strongly correlated over the whole southern sub-alpine lake district ($0.76 < \rho < 0.96$, $P < 0.01$; and $0.59 < \rho < 0.97$, $0.01 < P \leq 0.1$ including Lake Como; pairwise deletion of missing values).

The averages of minimum spring water temperatures between 0 and 50 m were ranked according to the altitudes of the water bodies (Fig. 2b) with values, over the whole temporal series, around 8.3°C (Garda), 6.5–6.8°C (Iseo, Como and Maggiore), and 5.7°C (Lugano). Overall averages of the $T_{0\text{–}50S}$ values of the 5 lakes between 2004 and 2011 (when the data were concurrently available) showed a negative, highly significant and linear dependence on the lake altitudes ($r^2 = 0.95$, $P < 0.01$, $n = 5$), with a mean slope (decrease) of 0.013°C m^{-1}. The $T_{0\text{–}50S}$ values in lakes Garda, Iseo, Lugano and Maggiore showed a highly significant temporal coherence ($0.65 < \rho < 0.88$, $P < 0.01$), with common cooling of the water column in 1999 and 2000, 2004–2006, and after 2008. These results did change little ($P < 0.05$) including in the computations Lake Como.

The effects of the cooling episodes were studied in detail in Lakes Garda and Lugano. Lake Garda showed a complete homogenisation in the physical and chemical characteristics of the water column in 1991, 1999–2000, and 2004–2006. In the intervals between these three cooling periods, the spring mixing depths ranged between 80 and 200 m (Salmaso, 2012, and references herein). As underlined by Holzner et al. (2009), in Lake Lugano the Schmidt stability values observed in the winters of 2004–2005 and 2005–2006 were virtually zero. The tracer data (helium isotopes, tritium, sulphur hexafluoride, and chlorofluorocarbons), along with changes in the physical characteristics of the water column, demonstrated a considerable deepwater renewal and gas exchange with the atmosphere. Based on the analyses of the vertical physical and chemical profiles, deep water renewal in the springs 2004 and 2005 were observed also in lakes Iseo and Como. More in general, the estimates in the extent of the deep water renewal in lakes Garda, Iseo and Lugano were closely correlated ($0.69 < \rho < 0.85$, $P < 0.01$). Though limited to a short period, similar results were found comparing the $\mathrm{MixD_S}$ values in Lake Como with the other lakes (P at least ≤ 0.1).

The effects due to the alternation between warmer and cooler winters were quite apparent on the replenishment of SRP in the epilimnetic layers and on the supply of oxygen in the hypolimnetic layers (Fig. 2c, d).

Soluble epilimnetic reactive phosphorus at spring overturn was characterised by ample fluctuations (Fig. 2c). Similarly to $\mathrm{Tair_{DJF}}$ and $T_{0\text{–}50\mathrm{S}}$, $\mathrm{SRP_{epiS}}$ showed a strong correlation in lakes Garda, Iseo and Maggiore ($0.70 < \rho < 0.83$, $P < 0.01$). Correlations with Lake Lugano were lower ($0.33 < \rho < 0.44$, $0.05 < P < 0.2$). Despite the low number of observations, $\mathrm{SRP_{epiS}}$ in Lake Como showed coherent temporal pattern with the other lakes ($P < 0.05$), with the exclusion of Lake Lugano.

Dissolved oxygen concentrations below 200 m in lakes Garda and Maggiore practically showed the same pattern ($\rho = 0.76$, $P < 0.01$), with values ranging between 5 and 10 mg $\mathrm{l^{-1}}$ (Fig. 2d). These characteristics were confirmed including into the computations the meromictic lakes Iseo and Lugano ($0.53 < \rho < 0.76$, P at least <0.05). With the exclusion of the relationship with Lake Lugano ($P > 0.1$), the temporal pattern of $\mathrm{Oxy_{hypo}}$ in Lake Como was almost undistinguishable from the other lakes (Fig. 2d; $0.62 < r < 0.93$, $0.01 < P \leq 0.1$). Excluding the deep water renewal events, hypolimnetic oxygen concentrations in lakes Iseo and Lugano were around or below 1–1.5 mg $\mathrm{l^{-1}}$. In the three larger, deeper and less eutrophic lakes the hypolimnetic concentrations were much higher (5.5–10 mg $\mathrm{l^{-1}}$). Hypolimnetic O_2 concentrations in Lake Como were a little higher compared with the other oligomictic lakes (Garda and Maggiore) due to the position of the sampling station (270 m), which did not include the deepest zone of the lake (410 m).

In general, strong cooling episodes and mixing were always associated to winter EA (EMP) values below (above) or close to zero. As previously discussed (Salmaso, 2012), a possible discrepancy could be represented by the data recorded in 1991. Nevertheless, even in this case, the values of $\mathrm{EA_{DJF}}$ and $\mathrm{EMP_{DJF}}$ were close to zero (and definitely not towards values typical of mild winters, i.e. high $\mathrm{EA_{DJF}}$ and low $\mathrm{EMP_{DJF}}$). Cooler winters were followed by a greater replenishment of SRP in the epilimnetic layers, and by a larger supply of oxygen to the deep hypolimnetic layers.

Impact of $\mathrm{EA_{DJF}}$ and $\mathrm{EMP_{DJF}}$

Relationships in Figs. 3, 4, 5, 6, 7, 8 were computed based on data measured in the periods for which full environmental data ($\mathrm{EA_{DJF}}$, $\mathrm{EMP_{DJF}}$, $\mathrm{Tair_{DJF}}$, $T_{0\text{–}50\mathrm{S}}$, $\mathrm{MixD_S}$, $\mathrm{SRP_{epiS}}$, and $\mathrm{Oxy_{hypo}}$) were concurrently available in lakes Garda (1996–2011), Iseo (1994–2011), Lugano and Maggiore (1991–2011).

The two teleconnection indices affected significantly the winter air temperatures, with a significant positive ($\mathrm{EA_{DJF}}$) and negative ($\mathrm{EMP_{DJF}}$) impact on the annual $\mathrm{Tair_{DJF}}$ values (Fig. 3), and with slopes ranging between 0.6 and 0.8 ($\mathrm{EA_{DJF}}$) and −0.5 and −0.8 ($\mathrm{EMP_{DJF}}$). $\mathrm{EA_{DJF}}$ and $\mathrm{EMP_{DJF}}$ had a similar impact on the spring water temperatures between 0 and 50 m (Fig. 4), with slopes between 0.2 and 0.4 ($\mathrm{EA_{DJF}}$) and −0.2 and −0.4 ($\mathrm{EMP_{DJF}}$).

The two teleconnection indices showed a strong control on the deep-water renewal of lakes Garda, Iseo and Lugano (Fig. 5). In lake Lugano the linear regressions linking $\mathrm{MixD_S}$ with $\mathrm{EA_{DJF}}$, though significant ($P < 0.01$), did not adequately represent the relationship, which was instead better described by a piecewise regression (Fig. 5c). The piecewise model was significantly different (ANOVA, $P < 0.01$) and better (AIC: −19 vs. −11) than the linear model. The threshold limit of the winter EA value in Fig. 5c was around −0.5.

$\mathrm{EA_{DJF}}$ and $\mathrm{EMP_{DJF}}$ had strong effects on the epilimnetic concentrations of SRP measured at spring overturn (Fig. 6). However, for Lake Maggiore, the linear relationships were only barely significant ($P < 0.1$; Figs. 6a, e); the uncertainty in these two relationships is confirmed by non-significant δ correlation values. In Lake Lugano the relationship between $\mathrm{EA_{DJF}}$ and $\mathrm{SRP_{epiS}}$ was better represented ($P = 0.09$) by a piecewise regression compared with a linear model, which was not significant (Fig. 6d; AIC: 190 vs. 192). Based on the linear models, the increase of $\mathrm{SRP_{epiS}}$ per unit change of $\mathrm{EMP_{DJF}}$ (lower panel in Fig. 6) were much higher in lakes Iseo and Lugano (15, 12) than in lakes Garda (5) and Maggiore (1). Likewise the relationship between $\mathrm{SRP_{epiS}}$ and $\mathrm{EA_{DJF}}$ was steeper for Lake Iseo (slope: −17) than for lakes

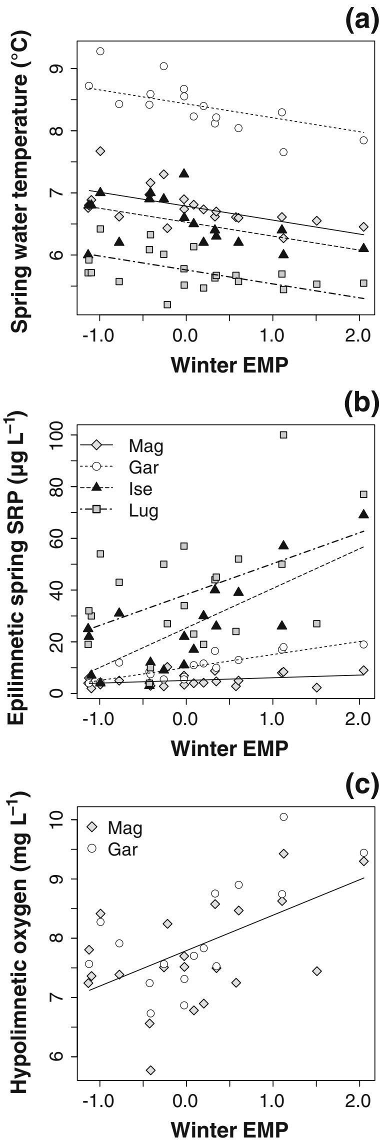

Fig. 8 Graphical representation of the results obtained by the application of GLS models (Table 1). The models include a selection of key variables linked with linear relationships with EMP_{DJF} (Figs. 4, 6, 7)

Garda (−5) and Maggiore (−1). The significance of the relationship in Fig. 6h ($P = 0.03$) should be considered with care, due to a significant Breusch–Godfrey test. This uncertainty appears confirmed by a barely significant δ correlation value ($P = 0.09$).

In the hypolimnetic layers, the oxygen concentrations showed a strong connection with the two teleconnection indices (Fig. 7). However, similar to SRP_{epiS}, the weak linear relationship between EA_{DJF} and Oxy_{hypo} in Lake Maggiore (Fig. 6a) was confirmed by non-significant δ correlation values. As for Lake Iseo, the relationships with Oxy_{hypo} were better described by piecewise models, which were significantly different (EA_{DJF} vs. Oxy_{hypo}, ANOVA, $P = 0.01$; AIC, 56 vs. 64) or slightly better (EMP_{DJF} vs. Oxy_{hypo}, ANOVA, $P = 0.07$; AIC, 61 vs. 64) than the linear models. It is worth to observe that, in the two oligomictic lakes Garda and Maggiore the slopes of the relationships showed comparable values (Fig. 7, between −0.7 and −0.5, upper panel; and between 0.5 and 0.8, lower panel).

The comparison of the regression slopes and intercepts by GLS models is reported in Fig. 8. The models were computed for a selection of key variables ($T_{0\text{–}50S}$, SRP_{epiS} and Oxy_{hypo}), linked with linear relationships with EMP_{DJF}. A summary of the models (full and nested models) is reported in Table 1. Based on the AIC values and ANOVA tests, the spring water temperatures (Fig. 8a) showed significant different intercepts, whereas the epilimnetic spring SRP concentrations (Fig. 8b) were characterised by both different intercepts and slopes. As for the relationship between EMP_{DJF} and Oxy_{hypo}, the analysis in Fig. 8c did not include the lakes Iseo (better represented by a piecewise model) and Lake Lugano (hypoxic during most of the study period). The hypolimnetic oxygen concentrations in lakes Maggiore and Garda were better represented by a unique regression line (Fig. 8c).

In Lake Como, the relationships between EA_{DJF} and EMP_{DJF} and the limnological variables were very similar to those described in Figs. 3, 4, 5, 6, 7 for the oligomictic and meso-oligotrophic lakes (Garda and Maggiore), and with practically the same slopes, i.e. 0.84 and −0.69 ($Tair_{DJF}$ vs. EA_{DJF} and EMP_{DJF}, respectively); 0.18 and −0.15 ($T_{0\text{–}50S}$, vs. EA_{DJF} and EMP_{DJF}); −6.1 and 6.5 (SRP_{epiS} vs. EA_{DJF} and EMP_{DJF}) and −0.5 and 0.5 (Oxy_{hypo} vs. EA_{DJF} and EMP_{DJF}) (see also Tables 1, 2). Nevertheless, owing to the low number of available data, the relationships were significant or at the limit of significance (at least $P \leq 0.10$) only in a few cases (EA_{DJF} vs. $T_{0\text{–}50S}$ and SRP_{epiS}; EMP_{DJF} vs. $T_{0\text{–}50S}$, SRP_{epiS} and Oxy_{hypo}).

The average winter (December–February) NAO values (NAO_{DJF}) did not show any significant correlation with the whole set of variables considered in Figs. 3, 4, 5, 6, 7, with the exception of a few positive correlations (ρ) based on untransformed data in Lake Iseo (NAO_{DJF} vs. Oxy_{hypo}, $\rho = 0.54$, $P < 0.05$) and

Table 1 Relationships between the winter Eastern Mediterranean Pattern (EMP_{DJF}) and $T_{0\text{-}50S}$, SRP_{epiS} and Oxy_{hypo} in lakes Maggiore (Mag), Garda (Gar), Iseo (Ise), and Lugano (Lug)

EMP_{DJF} vs.	F values; slopes	Lake effect	Lake: EMP_{DJF} interaction
Spring water temperature, $T_{0\text{-}50S}$	$F_{1,71} = 23.8^{**}$; Mag, Gar, Ise, Lug, −0.22	$F_{3,71} = 252.6^{**}$	n.s.
Epilimnetic spring SRP, SRP_{epiS}	$F_{1,68} = 29.9^{**}$; Mag, 1.0+ Gar, 5.0** Ise, 15.3** Lug, 11.9*	$F_{3,68} = 43.0^{**}$	$F_{3,68} = 10.7^{**}$
Hypolimnetic oxygen, Oxy_{hypo}	$F_{1,35} = 15.9^{**}$; Mag, Gar, 0.60	n.s.	n.s.

In the case of significant different slopes SRP_{epiS}, additional P values in column 2 indicate whether the slopes were significantly different from the "baseline" level, i.e. Maggiore. The graphical solutions of the models are reported in Fig. 8. Significance codes: ** $P < 0.01$, * $P < 0.05$, $^{+}$ $P < 0.1$

Table 2 Spearman's rank correlation coefficients, ρ, between the descriptors of winter climatic conditions and the limnological variables

	Maggiore ($n = 21$)	Garda ($n = 16$)	Como ($n = 8$)	Iseo ($n = 18$)	Lugano ($n = 21$)
EA_{DJF} vs. $Tair_{DJF}$	0.50*	0.74**	0.55	0.56**	0.50*
EMP_{DJF} vs. $Tair_{DJF}$	−0.50*	−0.71**	−0.55	−0.56*	−0.51*
$Tair_{DJF}$ vs. $T_{0\text{-}50S}$	0.80**	0.81**	0.73*	0.69**	0.84**
$T_{0–50S}$ vs. $MixD_S$		−0.81**	−0.57	−0.55*	−0.37+
$MixD_S$ vs. SRP_{epiS}		0.82**	0.60	0.82**	0.75**
$MixD_S$ vs. Oxy_{hypo}		0.56*	0.85**	0.22	0.49*

Significance codes as in Table 1. The correlations refer to the periods 1996–2011 (Garda), 1994–2011 (Iseo), 2004–2011 (Como), and 1991–2011 (Lugano and Maggiore)

linearly de-trended data, including the relationships between NAO_{DJF} and Oxy_{hypo} in lakes Maggiore ($\rho = 0.55$, $P < 0.05$) and Iseo ($\rho = 0.72$, $P < 0.01$), and the relationship between NAO_{DJF} and SRP_{epiS} in Lake Lugano ($\rho = 0.57$, $P < 0.01$).

Functioning mechanisms in the deep lakes south of the Alps

Previous works made in Lake Garda (e.g. Salmaso, 2012; Salmaso & Cerasino, 2012) demonstrated the existence of a long chain of linked causal factors controlling the spring concentrations of nutrients and algal development. These included the large-scale atmospheric circulation patterns relevant for the Mediterranean area during the winter months (EA_{DJF} and EMP_{DJF}), the winter air temperatures, the cooling of hypolimnetic waters and deep water renewal, and the epilimnetic replenishment of P at spring overturn. These relationships, for the five lakes included in this study, have been quantitatively and synthetically evaluated in Table 2. Excluding a few cases in Lake Como (due to the lower number of observations) and two values in lakes Iseo and Lugano, the relationships were always significant, at least at $P < 0.05$, therefore describing a sequence of linked events related to each other. In the case of Lake Lugano, though the relationship between $T_{0–50S}$ and $MixD_S$ showed a threshold limit (figure not shown), the computation of piecewise regressions did not provide reliable models. The results obtained so far have been summarised in Fig. 9.

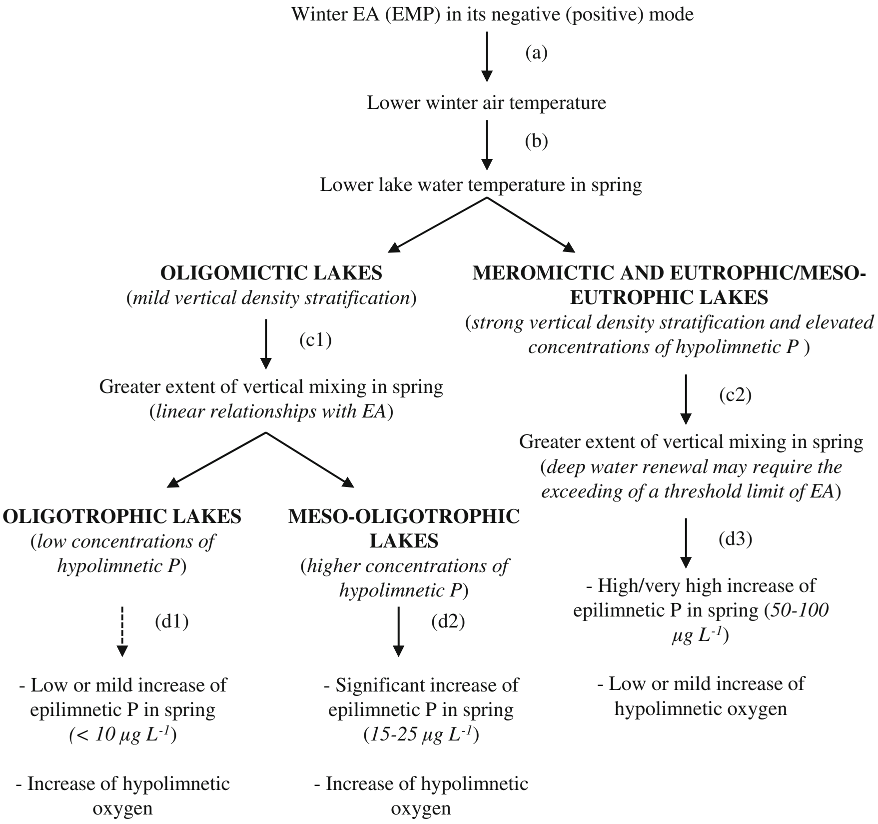

Fig. 9 Diagram reporting the cascading effects on the limnological characteristics of the largest lakes south of the Alps triggered by the interannual fluctuations of the EA_{DJF} and EMP_{DJF}. Oligomictic lakes include lakes Maggiore (oligotrophic), and Garda and Como (meso-oligotropic). Meromictic lakes include lakes Iseo and Lugano. The strength of the relationships (*continuous* and *dotted lines*) is based on the results reported in Figs. 3, 4, 5, 6, 7, and 8; and Tables 1 and 2

Discussion

The synoptic analysis performed on data spanning over 15–20 years demonstrated and confirmed undetectable impacts of the NAO on the winter air temperatures and minimum spring water temperatures in the large and deep lakes south of the Alps. Studying the climate of the Mediterranean area, Luterbacher & Xoplaki (2003) showed that the low relationships between the winter NAO and the winter temperatures could be interpreted in terms of compensatory effects between the areas with negative correlations with the NAO (Eastern Mediterranean), areas with non-significant correlations (Western and Central Mediterranean), and other areas which showed positive correlations for parts of the last century. These authors concluded that the NAO could not be considered the most important signal of atmospheric variability concerning temperature over the Mediterranean region. This picture is further complicated by other studies showing the existence of low, but significant correlations between the NAO and air temperatures in Northern Italy (Toreti et al., 2010). On the other side, many investigations documented the existence of a negative highly significant correlation between the winter NAO and winter Mediterranean precipitations (Luterbacher & Xoplaki, 2003; Zanchettin et al., 2008).

As hypothesised in previous works made in Lake Garda (Salmaso, 2012), the winter climate, the thermal structure, the mixing regime and the vertical redistribution of oxygen and nutrients in the largest lakes of the southern sub-alpine lake district were controlled by two modes of atmospheric circulation relevant for the Mediterranean area, i.e. the East Atlantic pattern and the Eastern Mediterranean Pattern. Though computed with two conceptual different approaches, EA_{DJF} and EMP_{DJF} were equally able to catch a significant fraction of climate variability in winter in the southern region south of the Alps. The strong statistical connection between the two indices was already highligted (Salmaso, 2012), but the functional relationship between these two representations of variability of winter climate in southern Europe will deserve more attention, in order to evaluate the degree of overlap and differences. However, the spatial pattern associated with the EMP was further verified by applying multidimensional exploratory statistical methods (RPCA and RCCA, regularized canonical correlation analysis) (Hatzaki et al., 2007, 2010). In these studies, the EA, along with the EMP, was recognised as an important and distinct atmospheric mode. Nevertheless, further reasearch is needed to discover the connection of the EMP with the synoptic picture identified by the NOAA-CPC mode framework (Josey et al., 2011). Besides these considerations, taking into account the results obtained in this work, and the results which demonstrated a strong impact of EA (Toreti et al., 2010; Josey et al., 2011) and EMP (Hatzaki et al., 2009) over the Mediterranean area, it could be hypothesised a strong connection between these two indices and the limnological variables also in other water bodies of the Italian peninsula (including the southern Alpine regions) and other countries around the Mediterranean sea.

The temporal development in the limnological variables analysed in lakes Garda, Iseo, Como, Lugano and Maggiore showed a coherent pattern. As for temperature, this finding was not surprising, and widely expected. Despite the large distance separating the two regions, Livingstone & Padisák (2007) demonstrated that the daily mean lake surface water temperatures in Switzerland and Hungary exhibited a coherent and significant response to synoptic-scale meteorological forcing expressed as air temperatures. The authors concluded that large-scale climatic forcing in lakes is far more important than hitherto thought. Similar results were previously found in a larger synoptic investigation based on a multidecadal analysis of annual mean hypolimnetic temperatures in 12 deep lakes located between the central-northern Alps and northern Europe (Dokulil et al., 2006). The coherent temporal pattern in hypolimnetic temperatures was explained by the effects, at a continental scale, of the NAO index in winter and spring.

The high temporal coherence in the development of epilimnetic SRP and hypolimnetic oxygen is far less expected, especially considering the differences in the trophic status and mixing characteristics of the oligomictic and meromictic lakes. Nevertheless, the common temporal patterns were originating from the common effects caused by winter climate (Fig. 9a, b) in the region south of the Alps, and from corresponding synchronisms in the interannual variations in the extent of the spring water renewal (Fig. 9c1–c2). These mechanisms controlled, on a regional scale, the interannual variations in trophic status around different baseline levels (Fig. 9d1–d3), in their turn dependent from the overall amount of nutrients and dissolved oxygen stored in the epilimnetic and hypolimnetic waters. Put in other terms, the extent of mixing vertically redistributed nutrients and oxygen along the water column. In oligotrophic lakes, which are characterised by weaker vertical chemical gradients, the spring replenishment of P was negligible and difficult to detect (Maggiore), or detectable but of minor importance (Garda and Como) compared to that measured in meso-eutrophic and eutrophic lakes (Iseo and Lugano).

This last point deserves specific attention, because indicative of a significant interaction between climate and trophic status, well represented statistically by the interaction term between $\mathrm{EMP_{DJF}}$ and lakes (Table 1). Low (high) values of $\mathrm{EA_{DJF}}$ ($\mathrm{EMP_{DJF}}$) and cooler winters caused a progressive greater increase of epilimnetic P in the more eutrophic water bodies (Figs. 2, 6, 8b). Therefore, significant interannual variations in the large scale atmospheric modes of variability over the North Atlantic and North Africa were able to cause dramatic changes in the trophic status of surface waters in the deep lakes south of the Alps. The link between cool winters and eutrophication seems at odd if interpreted in the light of the current view which states that the effects of global warming on water bodies mimic those of eutrophication (Porter et al., 1996; Mooij et al., 2005; Winder & Sommer, 2012). These counterintuitive links must be interpreted as typical of deep lakes, and mediated through mechanisms in which the physiographic features of the water bodies and mixing depths in a limited spring period play a pivotal role.

It should be underlined that the variations in the content of P in the trophogenic layers can also be due to the direct input of nutrients from the inflows. The theoretical water renewal times of lakes Maggiore, Como and Iseo are quite short, signifying that episodic inputs of nutrients from the rivers should not be disregarded. On the contrary, Lake Garda has a much longer theoretical water renewal time, due to a much lower inputs from rivers, which are practically confined to the northern side (River Sarca). Nevertheless, also taking into account the external sources of P, the effects of climate and deep water renewal on SRP are quite clear (Fig. 6; Table 2), underlining that the vertical redistribution of nutrients in the water column represents an important source of recycled nutrients to the epilimnetic layers in this group of lakes. In late spring and summer, during and after the formation of a stable and isolated epilimnion, nutrients coming from the deep hypolimnion become progressively less important.

The resistance to mixing has two different facets well represented in lakes Lugano and Iseo. Continuous meromictic conditions, which cause detrimental effects to the deeper layers, could have apparent beneficial effects to the surface waters. On the other hand, in the long-term, this increases the probability to experience high spring epilimnetic pulses of nutrients due to the effects of colder winters, and to the progressive increase of P in the isolated hypolimnion due to the mineralisation of the sinking organic particles (Salmaso & Decet, 1998). The deep water renewal event documented in Lake Lugano was quite exceptional. After the 1960s this lake showed a persistent meromixis, with the complete disappearance of oxygen and an increase of the concentrations of nutrients and reducing chemical compounds in the deeper layers (Barbieri & Simona, 1997). The transient interruption of meromixis documented in 2005 and 2006 had impressive consequences (Aeschbach-Hertig et al., 2007; Holzner et al., 2009). In 2005 the strong gradient in the concentrations of dissolved solids which stabilised the water column disappeared, while traces of O_2 occurred at the bottom of the lake for the first time during the last 40 years (Holzner et al., 2009). In 2006, with the successive, second deep water renewal event, the entire water column showed practically uniform oxygen concentrations of 1.5–2.0 mg l^{-1}, i.e. with levels harmful for the life of sensitive fishes, many of which were found dead soon after the deep-mixing event (CIPAIS, 2006). The insusceptibility of meromictic lakes to mix is further highlighted by the existence, in Lake Lugano, of threshold limits in EA_{DJF} that need to be overcome in order to trigger the mixing.

The transport mechanisms controlling deep water renewal of hypolimnetic waters are not depending exclusively on convective mixing. Ambrosetti et al. (2010) showed that, in Lake Maggiore, other three processes different from convective mixing could favour turnover in deep waters, i.e. conveyor belt currents, the inflow of colder and denser fluvial water sliding down to the lake bottom, and higher cooling of littoral waters which sink down the lake's slopes. These three mechanisms—which are linked, besides to air temperature, to wind and atmospheric precipitations—could contribute significantly to strengthen the penetration of surface waters at depth, as demonstrated, besides Lake Maggiore (see also Ambrosetti & Barbanti, 1992), in Lake Garda (Salmaso et al., 1999: Figs. 3, 4). The above mechanisms could result in the formation of deep water masses, with lower temperatures and higher oxygen content than the column layers above, rendering not trivial the estimation of the mixing layer based on profiles obtained from the analysis of only discrete depths. Because of these reasons, the mixing layer depth in Lake Maggiore has been always referred as depth of convective mixing (Ambrosetti & Barbanti, 1999; Ambrosetti et al., 2010) and estimated using an equation taking into account the wind run, the difference between water and air temperatures, and the solar radiation. Due to this different calculation approach, which takes into consideration only one component in the mixing processes, a direct comparison of the mixing depth data in Lake Maggiore and in the other deep subalpine lakes can be misleading and was avoided in this analysis.

Taking into account the above considerations, considering that climate does not affect ecosystems through a single weather variable but rather through a combination of weather features (Stenseth et al., 2003), teleconnection indices, which are proxies describing overall climate conditions, in principle should carry more information when analysing the relationships with mixing dynamics in deep lakes.

Conclusions

The winter air temperatures, and the winter lake thermal structure, spring mixing regime, and vertical distribution of phosphorus and oxygen in the largest lakes south of the Alps were significantly influenced by two atmospheric modes of variability relevant for the Mediterranean region, namely the East Atlantic pattern and the Eastern Mediterranean Pattern. The usefulness of indices integrating different facets of climate is demonstrated by the large number of papers published on the NAO in the scientific literature (with a nearly constant maximum between 300 and 350 papers per year since 2004; Thomson WoS). The range of applicability of EA and EMP, and the usefulness, efficiency and quality in explaining year-to-year fluctuations in the limnological characteristics of water bodies represent a wide and promising field of research. A better understanding of the direct and indirect influence of climate on the fluctuations in the thermal regime and spring nutrient fertilisation may aid also to interpret the underlying causes of changes in the trophic status, and in the phenology and structure of phytoplankton and zooplankton assemblages. These aspects and links with EA and EMP will require to be analysed more in detail seeking analogies and differences especially in lakes—such as Lake Maggiore—showing only a moderate input of epilimnetic nutrients in response to the impact of colder winters. In perspective, the East Atlantic pattern and the Eastern Mediterranean Pattern could represent two suitable climatic indices for the analysis of the interannual changes and degree of temporal coherence in the limnological variables of many water bodies located in the Mediterranean region and the southern Alpine area.

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