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Sensitivity of the multiannual thermal dynamics of a deep pre-alpine lake to climatic change

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Abstract:

The study of the multiannual thermal dynamics of Lake Iseo, a deep lake in the Italian pre-alpine area, is presented. Interflow was found to be the dominant river entrance mode, suggesting future susceptibility of the lake thermal structure to the overall effects of climate change expected in the upstream alpine watershed. A lake model employed the results of a long-term hydrologic model to simulate the effects of a climate change scenario on the lake's thermal evolution for the period 2012–2050. The model predicts an overall average increase in the lake water temperature of 0.012 °C/year and a reinforced Schmidt thermal stability of the water column in the winter up to 800 J/m^2. Both these effects may further hinder the deep circulation process, which is vital for the oxygenation of deep water.

KEY WORDS Lake Iseo; pre-alpine lake; climate change; deep circulation; glacier; inflows

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INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), lakes are considered as one of the ecosystems most threatened by climate change, so it is important to investigate the fate of lakes functioning in a changing environment (IPCC, 2007).

In the deep, large, pre-alpine lakes, several investigators showed that global warming is expected to increase water temperature at all depths and to intensify the thermal stratification, leading to longer stratified periods, stronger thermal gradients across the thermocline and altered mixing conditions characterized by less frequent overturns (Peeters *et al*., 2002; Livingstone, 2003; Danis *et al*., 2004). This would potentially have an enormous impact on the deep-water dynamics, which would become more susceptible to interannual variations in meteorological conditions (Livingstone, 1997) and more isolated from above, with modified mechanisms of epilimnetic nutrient replenishment, possible lack of deep-water oxygenation (Peeters *et al*., 2002; Danis *et al*., 2004) and consequent delay in the recovery after eutrophication (Matzinger *et al*., 2007; Blenckner *et al*., 2010; Trolle *et al*., 2011).

In this context, the response of individual lakes to climate change can be very different because of different physical lake features (Danis *et al*., 2004) or local climatic conditions at the catchment scale (Blenckner *et al*., 2010). In this paper, we investigate the response of the thermal structure of Lake Iseo, a 256 m deep basin located in the northern part of Italy, to the climatic change scenario foreseen in its catchment area for the period 2012–2050. To the knowledge of the authors, this paper is the first work aimed at providing quantitative forecasting of the impact of climate warming on the deep pre-alpine lakes located south of the Alps. Because of the great depth of these oligomictic lakes ($122 < z < 410$ m), vertical mixing plays a key role in controlling the interannual variations of their trophic status (Garibaldi *et al*., 1999; Salmaso *et al*., 2003). Accordingly, it is crucial to be aware of the long-term effects on the circulation pattern in lakes that are in a recovery phase from eutrophication.

Among deep Italian pre-alpine lakes, Lake Iseo is an ideal candidate to study the consequences of climate change. The outlet of Lake Iseo drains a watershed of 1781 km^2, which shares the largest glacierized Italian area (Adamello glacier, with a surface of 17.53 km^2). It has been reckoned (Ranzi *et al*., 2009; Grossi *et al*., 2013) that this glacier underwent an average loss of 1290 mm/year of water equivalent over the last decade. Additionally, there is evidence that in this lake, the hypolimnetic temperature has increased in the last 50 years. The first scientific survey of bottom temperature in May and

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November 1967 (Bonomi and Gerletti, 1967) showed a value of 5.75 °C, which is considerably lower than the average temperature of about 6.4 °C, measured during the period 1995–2011. This increase is mostly related to the reduction in the frequency of full winter circulation episodes in the lake, which might be linked both to the increased chemical stability of the water column (Ambrosetti and Barbanti, 2005) and to climatic change. As a matter of fact, from 1987 to 2004, the increased occurrence of milder winters reduced the cooling of deeper waters in most of the deep lakes of the alpine area. Examples of periods of reduced winter mixing are 1987–1990 in Lake Geneva (Livingstone, 2003), 1987–1991 and 1992–1995 in Lake Constance (Straile *et al*., 2003) and 1992–1998 and 2001–2003 in Lake Garda (Salmaso, 2005).

The impact of climate change on lakes has been investigated through field observations (e.g. Livingstone, 1997) or lake-specific numerical models, which use as input either long-term historical time series (e.g. Coats *et al*., 2006) or perturbed meteorological data aimed at representing idealized climate changes (e.g. Matzinger *et al*., 2007; Bueche and Vetter, 2013) or boundary conditions derived by the output of regional climate models run under IPCC scenarios (e.g. Perroud and Goyette, 2010). In order to explore how Lake Iseo might be affected by future climate change, we drove the one-dimensional (1D) Dynamic Reservoir Simulation Model (DYRESM) with the output of a hydrologic model (Barontini *et al*., 2009), which was calibrated for the alpine catchment of Lake Iseo on the basis of a global circulation model for the period 2012–2050.

When three-dimensional (3D) effects do not have a dominant role (Imberger and Patterson, 1981), the 1D modelling approach is widely shared for this type of application because it provides a compromise between the actual physics and the computational load, which otherwise would be overwhelming and might suffer from an accumulation of numerical errors over long simulation periods (Yeates and Imberger, 2003). On the other hand, many challenges still exist about the capability of 1D models to reproduce the physics of the hypolimnetic zone in deep lakes (e.g. Gal *et al*., 2003; Yeates and Imberger, 2003; Perroud *et al*., 2009); this study provides an enrichment of the record of these applications. The choice of a catchment-wide approach, which accounts also for climate-induced variations in the hydrological flow regime, makes this approach innovative. To the knowledge of the authors, previous analysis about climate-related conditions of pre-alpine lakes (e.g. Bueche and Vetter, 2013) did not investigate the effects of the modified discharge and temperature of the inflows, although it has been recognized that there is the need for an approach that integrates lakes within their watersheds (Shimoda *et al*., 2011).

FIELD SITE

Lake Iseo, located at an average elevation of 185.15 m a.s.l. in the pre-alpine area of central–eastern Lombardy (Figure 1a), is the fifth largest Italian lake in terms of volume (7.9 km^3). As shown in Figure 1b, the lake is characterized by the presence of a large island and by a large flat plateau, 256 m deep, which covers a relevant percentage of the lake area (refer to the dimensionless depth-area curve within Figure 1b). Lake Iseo is 61 km^2 wide and drains the alpine catchment of the Oglio River (average altitude: 1400 m a.s.l., area: 1781 km^2) where the largest Italian glacier (Adamello) is located. The lake has two main inflows, the Oglio River (RL1 in Figure 1b) and the so-called Industrial Canal (RL2 in Figure 1b), entering the lake at the northern end of the basin. Whilst RL1 originates around the area of the Adamello glacier, RL2 is diverted from the Oglio River 10 km from its mouth, and it is used for hydropower generation. In average yearly terms, these two tributaries contribute almost equally to the overall average inflow of 58 m^3/s to the lake, which corresponds to a 4.3-year theoretical water renewal time. Under ordinary flow conditions, their path is significantly affected by the Earth's rotation (Pilotti *et al*., 2014). The outflow is located at the dam at Sarnico (RL3 in Figure 1b), which regulates the water level fluctuations within −30 and +110 cm with respect to the average level of the lake, mostly for agricultural purposes.

The area surrounding the lake is subjected to a temperate climate and to periodic winds, characterized by a daily inversion as a result of katabatic effects; their predominant directions are aligned with the north–south lake axis, and their average speed is 3.9 m/s, when measured 2m above the lake surface. The wind structure induces basin-scale internal waves characterized by a regular daily periodicity, amplitudes around 5 m in the stratified period (Valerio *et al*., 2012) and epilimnetic speed in the order of a few cm/s. As is typical of the sub-alpine lakes, a pronounced thermal stratification is present in Lake Iseo during most of the year. A well mixed and warm surface layer, which reaches maximum temperature (~23 °C) in July, is separated from the cold (~6.4 °C) hypolimnion by an intermediate metalimnion, which progressively deepens from May to October (Figure 2b). Even though the lake may be classified as warm monomictic according to its climatic area, a complete overturn over the last 20 years has happened only twice, so anoxic conditions have been established below 200 m (Figure 2a).

METHODS

Numerical model

DYRESM is a 1D hydrodynamic model developed by the Centre for Water Research (CWR) of the University

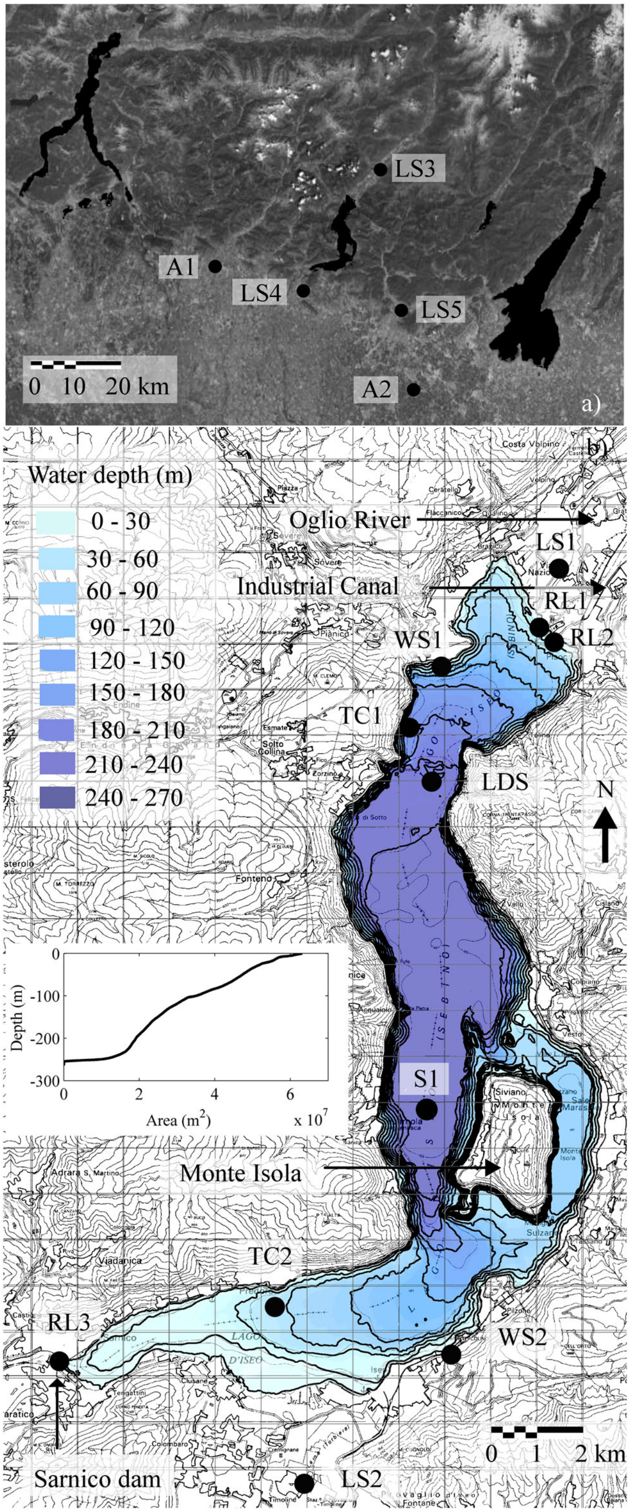

Figure 1. Geographical setting of Lake Iseo (a) and location (b) of the measurement stations, thermistor chains (TC), wind stations (WS), land stations (LS), Lake Diagnostic System (LDS), river logger (RL), sampling location (S1) and airports (A) where cloud cover was monitored. The bathymetry (b) of Lake Iseo is here represented with isodepth lines at 30-m spacing, while in the white panel, it is synthetically described through the depth-area curve

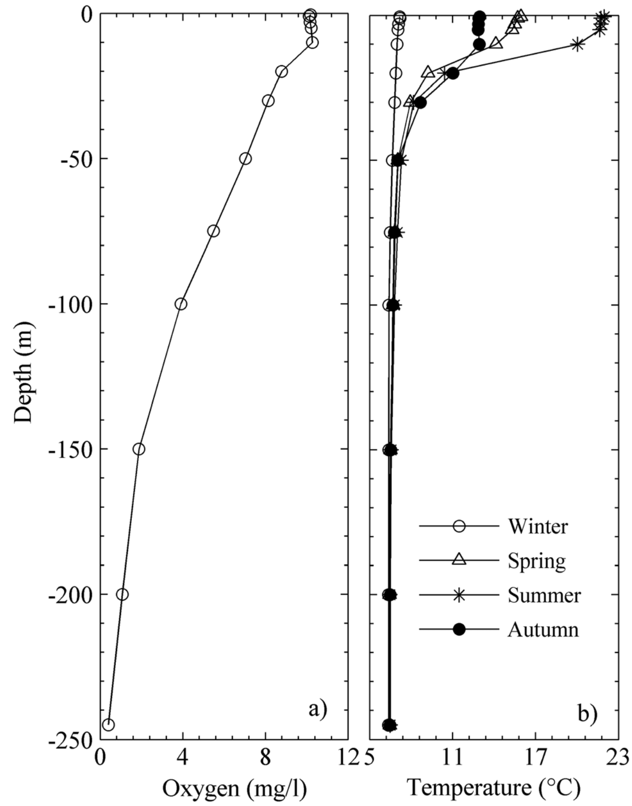

Figure 2. Average vertical profiles of (a) oxygen and (b) temperature in Lake Iseo computed on the basis of the 1993–2010 time series

of Western Australia, which simulates the distribution of temperature and salinity with depth and time in lakes and reservoirs (Imberger and Patterson, 1981).

DYRESM uses a Lagrangian layer subdivision of the lake volume in a series of horizontally averaged layers of uniform properties but variable thickness. The heat transfer equation is solved with the use of a mixing parameterization based on an energy-budget approach. Heat is transferred within the water column by wind stirring, convective overturn and shear mixing. These processes are regarded as a source of turbulent kinetic energy by means of efficiency coefficients; when this energy, stored in the topmost layers, exceeds a potential energy threshold, layer mixing occurs and adjacent layers are combined (Imberger and Patterson, 1981). Additionally, the hypolimnetic mixing is parameterized through a vertical eddy diffusion coefficient K_z, which accounts for turbulence created by the damping of the motion of basin-scale internal waves on the bottom boundary and in the interior of the lake (Yeates and Imberger, 2003). The entrance of the river inflow into the lake is modelled by the insertion of a volume into a number of existing layers at the level of neutral buoyancy; the affected layers expand or contract, and those above move up or down to accommodate the volume change.

In order to evaluate the multiannual thermal dynamics of Lake Iseo, a period of 16 years was considered; the model was calibrated for a 1 year long period and then used in validation for the remaining period. Temperature and meteorological data described in the following sections were used to assign the initial and boundary conditions to the model.

Field data: calibration period

Starting from 2009, a network of gauging stations has been set up on Lake Iseo, providing water temperature and meteorological data measured on the lake surface and hence optimal for model calibration. Details of the deployment of the measurement stations are described in Pilotti *et al.* (2013).

A Lake Diagnostic System (LDS) is located in the northern part of the lake (Figure 1b), measuring the main thermal, radiative and mechanical fluxes on the lake surface since December 2009. This floating station consisted of meteorological sensors [wind speed and direction, net total radiation, incoming shortwave radiation (SWR), air temperature and relative humidity] located 2.5 m above the water level. The temperature of the first 50 m of the water column data was monitored with accuracy ±0.01 °C by two submerged thermistor chains. One was located under the LDS and equipped with 21 nodes whose depth ranges from 0.25 to 49.75 m, while another consisted of 16 sensors over the first 30 m of the water column, located in the northern part of the lake from October 2009 to February 2010 (TC1) and later moved in the southern part (TC2). Two additional wind stations are present in Castro (WS1 in Figure 1b) on the lake shore close to the LDS location and in Iseo (WS2 in Figure 1b), also measuring atmospheric pressure variations.

Outflow water level, discharge and temperature, as well as the daily-averaged discharge of the two main tributaries, were available. Regarding the inflow temperature, since February 2009, two temperature loggers have been placed at the mouth of the two main tributaries (RL1 and RL2 in Figure 1b) to measure the water temperature fluctuations every 1 min.

Field data: validation period

Measurements provided by the station network described previously were integrated with the other parameters monitored by the stations in the area surrounding the lake (Figure 1), providing a data set suitable for the validation of the numerical model (Pilotti *et al.*, 2013).

With regard to the meteorological parameters, LS1 provided rain, SWR, air temperature and relative humidity; LS2 measurements were used to complete the series when data were not available. SWR was obtained mainly from the LS1 station and completed with the data measured by LS2, LS3 and LS5, while long wave radiation was calculated for cloud cover factor data measured at the Orio al Serio airport (A1 in Figure 1a), integrated with the Ghedi airport (A2 in Figure 1a) when data were not available. As for the calibration period, inflowing and outflowing discharges were available. Lake temperature and dissolved oxygen were measured monthly in the area of maximum depth (S1 in Figure 1). Samples were collected through a Van Dorn bottle at depths 0, 10, 20, 30, 50, 75, 100, 150, 200 and 245 m, and measurements were taken using an automatic probe (refer to details in Pilotti *et al.*, 2013).

For wind and river temperature, it was necessary to supplement the available historical data with some correlations. Before 2009, the temperature of the tributaries was measured only during occasional samplings. Several studies showed that river temperature can be evaluated from some meteorological variables (e.g. Tanentzap *et al.*, 2007). Following the approach proposed by Smith (1981), air temperature at the LS1 land station (Figure 1) was found to be the variable that has the strongest correlation with the mean daily Oglio and Industrial Canal temperatures. Accordingly, we determined the coefficients of the linear equations to predict the RL1 Oglio temperature from the LS1 air temperature and then the RL2 Industrial Canal temperature from the RL1 Oglio temperature in 2009 (Table I). This procedure was then used to compute the time series of the mean daily temperatures for the two tributaries during the whole validation period; as shown in Figure 3, it allows a successful prediction of the temperature series at RL1 and RL2 in 2010.

With regard to the wind, which is the primary force acting on the lake surface, care is needed when using land measurements to generate values over open water for hydrodynamic modelling, as already observed in similar mountain lakes (e.g. Hornung, 2002). When wind data are taken from land stations only, a correction factor must be applied, e.g. on the basis of a weather numerical model (Perroud *et al.*, 2009). In Lake Iseo, LDS data provide a clear picture of the on-lake wind conditions, which significantly differ from the ones provided by the other land stations because of the considerable spatial variability of the on-lake

Table I. Results of the linear regression between the time series of the daily mean air temperature (LS1) and Oglio temperature (RL1) in the periods 1 March 2009–22 June 2009 (I) and 23 June 2009–28 February 2010 (II) and between the daily mean Oglio temperature (RL1) and Industrial Canal temperature (RL2) from 1 March 2009 to 28 February 2010

	RL1 *versus* LS1		RL2 *versus* RL1
	I	II	
Intercept	6.291	5.900	−2.921
Slope coefficient	0.263	0.357	1.073
R^2	0.905	0.937	0.973

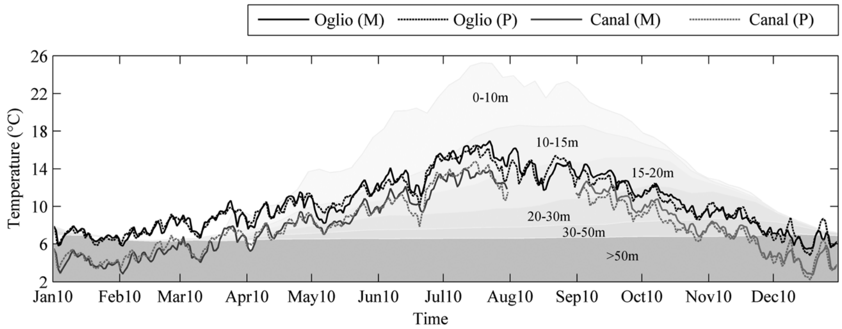

Figure 3. Comparison between the water temperature of the inflows measured (M) and predicted (P) from air temperature. The shaded areas mark the temperature range of water lying between assigned depth levels in the lake. The temperature of the Industrial Canal in August has been excluded because no volume is diverted in the Canal in this period of the year

wind field induced by the surrounding topography (Valerio *et al*., 2012). Accordingly, an equivalent 1995–2011 wind series has been produced by integrating LS2 and LS1 data and by applying wind multiplication factors to derive a reasonable indication of the on-lake speeds (refer to details in Pilotti *et al*., 2013).

RESULTS

Calibration

DYRESM was calibrated over the period 25 October 2009–25 October 2010, when meteorological forcing variables were measured on the lake, and high-resolution water temperature data were available for a detailed evaluation of the model performance.

On the basis of a sensitivity analysis, two calibration parameters were identified: the maximum permissible layer thickness H_{max}, used to discretize the vertical extent of the lake, and the mixing coefficient *CLN*, which controls the vertical amount of turbulent diffusion. As a final result of an extensive calibration, we concluded that the best fit was achieved with $H_{max} = 3$ m and $CLN = 5000$ (Figures 4 and 5). The values of the other parameters are listed in Table II. Even though this set of parameters allows the best reproduction of the average temperature trend over time, there are still some discrepancies between the measured and simulated temperature during the summer months in the layer between 10 and 20 m (Figure 4). The contour lines in Figure 5 clarify that these discrepancies are due to an underrated heat transfer to the metalimnion, which leads to a stronger and shallower thermocline. Finally, during the winter period when the column is homogeneous, water temperature is underestimated by the model of about 0.4 °C.

Validation

After calibration, DYRESM was run at a 1-h time step, with a daily output, to provide the continuous simulation of the thermal structure of Lake Iseo from 1995 to 2011. For validation purposes, the output of the model was compared with the field temperature data collected at S1 and with the continuous temperature series measured at RL3. Regarding the S1 series, we considered the volume-weighed temperatures over the depth ranges 0–10 m, 10–50 m and 50 m–bottom, which correspond to the average location of epilimnion, metalimnion and hypolimnion during the summer (Figure 2b).

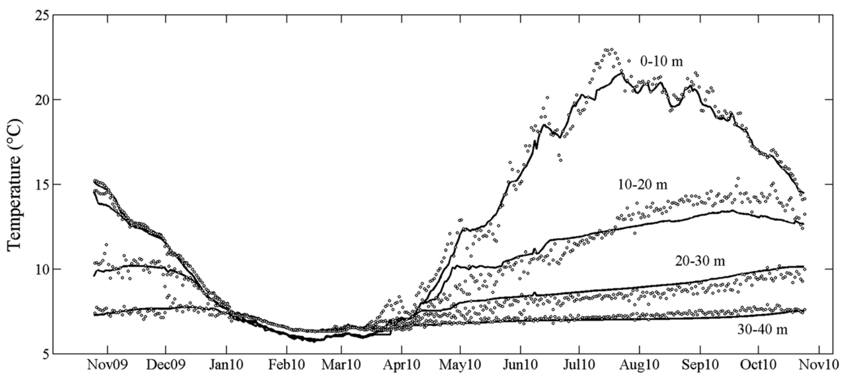

Figure 4. Comparison between the time series of the observed (dots) and simulated (continuous line) temperature, averaged over the first four layers of the water column ($CLN = 5000$ and $H_{max} = 3$ m)

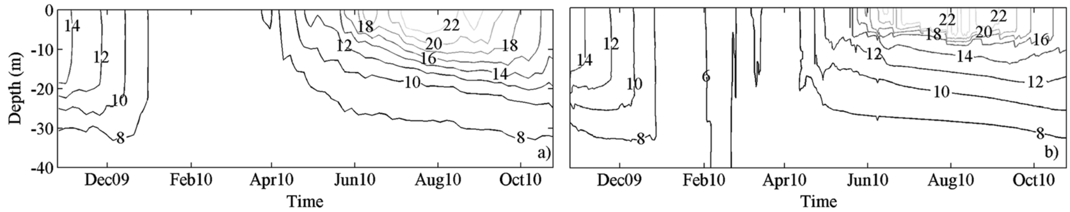

Figure 5. Contours of (a) the measured (5 days averaged) and (b) the simulated temperature field ($CLN = 5000$ and $H_{max} = 3$ m)

Table II. Value of the DYRESM parameters used for the simulations during the calibration period

Parameter	Value
Light extinction coefficient $m^{(-1)}$	0.35
Mean albedo of water (—)	0.08
Water surface emissivity (—)	0.96
Bulk aerodynamic transport coefficients for momentum, sensible and latent heat (—)	$1.3 \cdot 10^{-3}$
Critical wind speed (m/s)	3
Shear production efficiency (—)	0.08
Potential energy mixing efficiency (—)	0.2
Wind stirring efficiency (—)	0.8
Effective surface area coefficient (m^2)	10^7
Benthic boundary layer dissipation coefficient (—)	$1.4 \cdot 10^5$
Vertical mixing coefficient (—)	Calibration
Minimum layer thickness (m)	0.5
Maximum layer thickness (m)	Calibration

As shown in Figure 6, DYRESM correctly captured the thermal structure of the lake over the entire 16-year time period, which is characterized by a periodic annual trend with an average maximum epilimnetic temperature of 21.8 ± 1.2 °C recorded between July and August and by a nearly uniform profile between February and March. This seasonal trend progressively dampens with depth, becoming almost indistinguishable under 150 m, where water reacts to long-term trends rather than to short-term meteorological variability.

DYRESM successfully reproduced the strong seasonal variability in the upper layer temperatures, with a mean absolute error of 0.6 °C (5%) in the epilimnion and of 0.6 °C (7%) in the metalimnion. In particular, it is interesting to observe the good fit between the surface (0–1 m) temperature simulated by the model and the high temporal resolution data measured at the RL3 location (Figure 7). DYRESM did not capture the weak seasonal variability that affects the water between 50 and 150 m. However, the difference between simulated and observed hypolimnetic temperature is always less than 0.8 °C, and with regard to the longer term trend, the model succeeded in simulating the deep-water cooling that occurred in 2005 and 2006. During these events, the observed (simulated) averaged hypolimnetic temperature lowered from 6.7 (6.4), as an average in the period 1995–2004, to 6.4 (6.0), as an average in the period 2007–2010. This phenomenon is ascribable to the exceptionally strong and quick decrease of the deep-water temperature observed in March 2005 and 2006, which dropped from 6.5 to 6.1 °C and from 6.3 to 5.7 °C respectively. In correspondence to these events, the model simulated comparable drops in temperature at 250 m, which decreased from 6.1 to 5.7 °C in 2005 and from 5.7 to 5.5 °C in 2006. It is also interesting to notice (Figure 8) that in March 2005 and 2006, the oxygen concentration exceptionally overcame 4 mg/l, as a result of the mixing between the colder and oxygenized water at the surface and the deep anoxic water. Accordingly, the model was capable of reproducing the occurrence of circulation events that penetrate

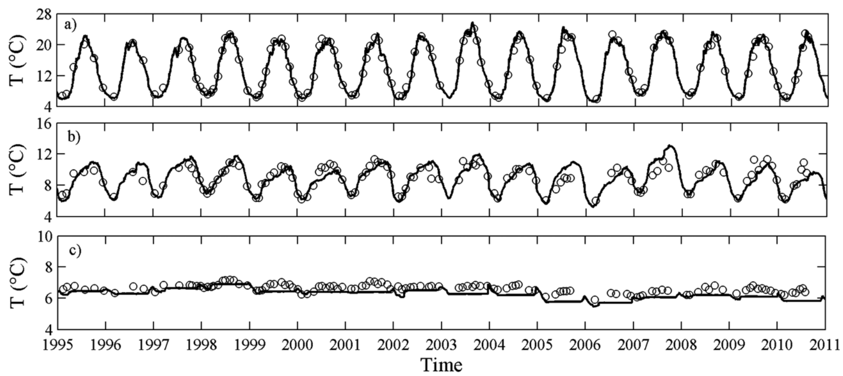

Figure 6. Comparison between measured (dots) and simulated (continuous line) temperature (T) averaged in the (a) epilimnion (0–10 m), (b) metalimnion (10–50 m) and (c) hypolimnion (50 m–bottom)

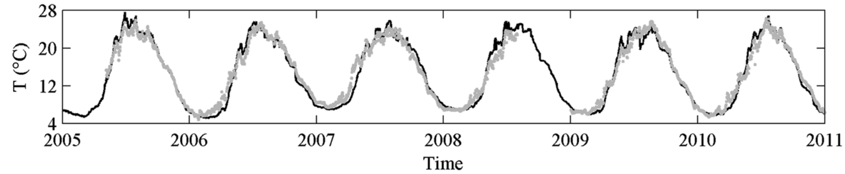

Figure 7. Comparison between simulated (black solid line) and observed (gray dots) surface (0–1 m) temperature (T) at the exit of the Oglio River from 2005, when the monitoring of outflow temperature started

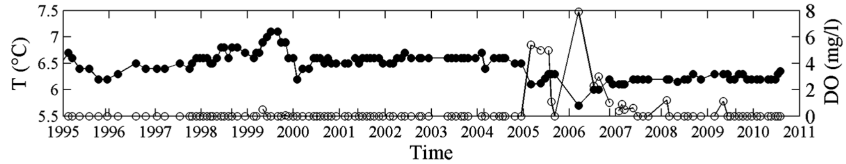

Figure 8. Temperature (black dots) and oxygen concentration (white dots) measured at 250 m

more deeply compared with the other years. On the contrary, the model could not reproduce the rapid increase of the deep-water temperature that occurred in the months following the 2005 and 2006 circulation events, leading to a slight underestimation of the hypolimnetic temperature at the end of the simulation period.

Sensitivity analysis of main factors influencing the thermal evolution of Lake Iseo

As presented in the previous section, DYRESM proved effective in simulating the Iseo temperature distribution over the last 16 years. The validated model was used to perform a sensitivity analysis of the role played by the main forcing terms on the evolution of the lake thermal structure. This analysis prepares the ground for the discussion about the reliability of the results of climate change simulations that will be presented in the following text.

To determine the relative importance of the two main mechanical forcings, we first ran DYRESM without inflows and outflows (s1), and then, we performed two simulations where the wind speed was increased (s2) and decreased (s3) by 25%. Model predictions were compared with the results obtained in unperturbed conditions (s0).

In the s1 scenario (Figure 9a), an overall average warming of 0.65 °C occurs in the lake compared with the s0 simulation. The warming effect is particularly amplified in the upper 50 m and during the summer months. In this period, the absence of inflows and outflows makes epilimnetic and metalimnetic water up to 3 °C warmer compared with the validation results. During the weakly stratified periods, the absence of cold plunging flows and the convective mixing of deep waters with warmer water above causes a rise in the temperature of hypolimnetic waters up to 0.6 °C. Accordingly, a reduction in the discharge of the tributaries would increase the average temperature of Lake Iseo.

With regard to scenarios s2 and s3, they highlight the key role played by wind in distributing heat along the water column. The wind has a direct role on the heat balance of the epilimnetic water, acting on latent and sensible heat fluxes (e.g. Henderson-Sellers, 1984). Whilst the former is an energy loss associated with the latent energy removed by the evaporation process, the latter may sometimes be an energy gain to the lake. In any case, usually, the former term prevails over the latter, so, from this perspective, the 25% increase in the wind intensity should imply a cooling of the lake surface. On the other hand, increasing wind enhances the heat transfer

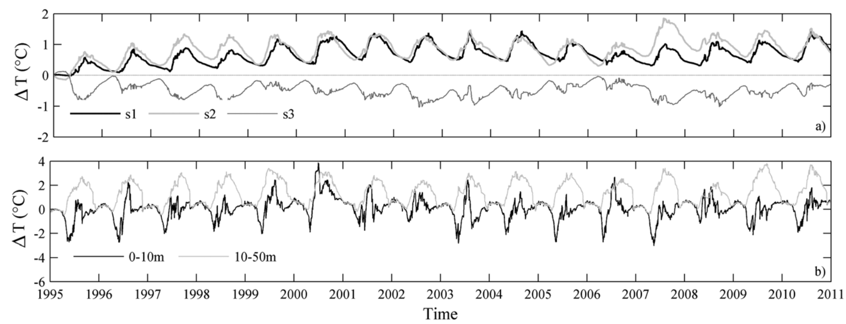

Figure 9. (a) Difference ΔT between the volume-averaged temperature of Lake Iseo obtained from simulations without inflows and outflows (s1), with wind speed increased by 25% (s2) and decreased by 25% (s3) and the unperturbed simulation (s0). (b) Difference ΔT between the epilimnetic (0–10 m) and mesolimnetic (10–50 m) temperature obtained from simulations with wind speed increased by 25% (s2) and the unperturbed simulation (s0)

from the lake surface to the layers below in the periods of weaker stratification. This is the reason why the mesolimnetic (epilimnetic) temperature increases (decreases) during the spring up to 3.5 °C compared with s0 (Figure 9b). During the following warmer months, the decreased epilimnetic temperature reduces the long-wave flux from the lake surface (which depends on the fourth power of surface lake temperature), fostering the warming of the lake. Accordingly, the long-term effect of the increased wind is that of an overall warming of the water column around 1 °C at the end of the simulation period (Figure 9a). The reverse processes characterize the case s3, where wind is reduced (Figure 9).

Thermal evolution of Lake Iseo under a climate change scenario

The potential impact of climate change scenarios on the run-off regime of the watershed drained by Lake Iseo was investigated by Barontini *et al*. (2009), who considered the precipitation and temperature scenarios produced for the 2000–2099 period by three global climate models [GCM; Parallel Climate Model (PCM), Hadley Centre Coupled Model HadCM3 and ECHAM4], eventually selecting PCM on the basis of its effectiveness in reproducing the observed rainfall and temperature regimes of the last 20 years in the Oglio basin. The PCM results were downscaled to adapt the coarse and biased GCM's daily precipitation and temperature output to the scale of the watershed, by using a modified version of the multiplicative cascade β-model, originally proposed by Novikov and Stewart (1964). Considering the so-called business-as-usual IPCC Special Report on Emissions Scenarios A2 scenario (IPCC, 2000; Beniston, 2004), an increase of about 3% in the annual precipitation and of 1.1 °C in the air temperature is expected for 2050 in the Oglio watershed drained by Lake Iseo. In addition, because of a decrease in the glaciated areas and an increase in the tree-line altitude, evapotranspiration will be affected. Accordingly, using the semi-distributed WATFLOOD hydrological model (e.g. Kouwen, 1988), Barontini *et al*. (2009) estimated an increase in the spring melt and a decrease in the summer and autumn run-off, which lead to an overall decrease of about 7% in the annual run-off volume for the 2050 scenario, with no clear variations in the fraction of rainy days.

In order to evaluate the consequences of these changes on the thermal structure of Lake Iseo, we ran the model DYRESM for the period 2011–2050 under different climatic forcings. As a reference scenario (s4), we assumed that the meteorological conditions observed in the period 1995–2010 would cyclically repeat till 2050. It is here relevant to observe that it would not be suitable to use an average year obtained from the original 1995–2010 series of meteorological data because the average would filter the extreme events that play a dominant role in the deep circulation of the lake. In order to set up a simulation (s5) consistent with the climatic scenario described previously, to be compared with the results of s4, the inflowing and outflowing discharges were modified by applying the monthly coefficients derived by Barontini *et al*. (2009) and reported in Table III. These coefficients comply with the 7% reduction of the annual run-off and with the modified monthly run-off regime during the year. Air temperature was increased by 0.0275 °C/year, corresponding to the overall increase of 1.1 °C in 2050; this value is consistent with the air temperature projections obtained by the regional climate model CLM for the investigated area (Grossi *et al*., 2013). The temperature of the inflows was computed from the 2011 to 2050 air temperature on the basis of the correlations reported in Table I, leading to an overall increase of 0.3–0.4 °C at the end of the simulation period.

The overall effect of the modified boundary conditions is the warming of the water column at an average rate of 0.012 °C/year. Decreases in temperature compared with the undisturbed scenario s4 may be observed only occasionally, e.g. for the increased discharge of the tributaries that may trigger stronger interflows or plunging flows. Figure 10 shows the temperature difference between the simulations s5 and s4 in the three layers of the lake, highlighting that in the last 5 years of simulation (2045–2050), the epilimnetic, metalimnetic and hypolimnetic temperature has reached an average increase of 0.79, 0.62 and 0.37 °C respectively. As known in the literature, the overall heating will have effects on ecological processes (e.g. Shimoda *et al*., 2011) such as algal bloom, decrease of dissolved oxygen content, reduction of thermal habitat for cold water fish and increased reaction kinetics at the water–sediment interface. Moreover, the fundamental hydrodynamic implication of the differential warming of the water column is in terms of stability. Figure 11 shows that the climate change progressively strengthens the thermal stability of Lake

Table III. Ratios between predicted and present monthly run-off at the entrance of Lake Iseo applied in the climate change scenario (s5) according to the forecast of Barontini *et al*. (2009)

January	February	March	April	May	June	July	August	September	October	November	December
0.79	1.29	1.26	1.09	0.91	0.95	0.74	0.78	0.84	0.62	1.17	0.98

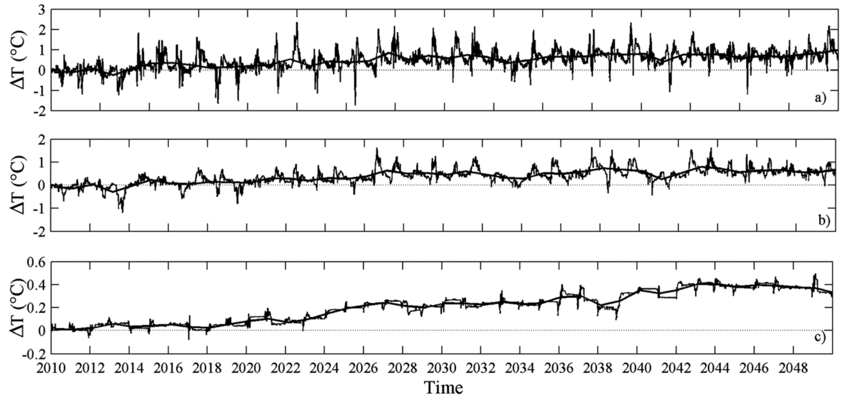

Figure 10. Difference ΔT between the temperature simulated with climate change scenario s5 and the reference undisturbed condition s4. Temperature values have been averaged in the (a) epilimnion (0–10 m), (b) metalimnion (10–50 m) and (c) hypolimnion (50 m–bottom). A running average over 365 days has been superimposed to the daily values

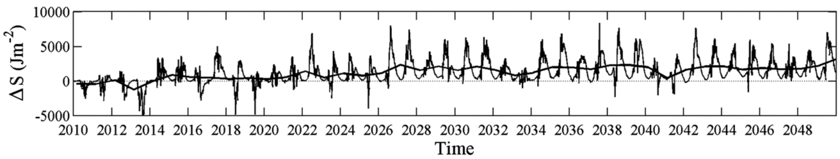

Figure 11. Difference ΔS between the Schmidt stability of the water column simulated in the climate change scenario s5 and the reference undisturbed condition s4. A running average over 365 days has been superimposed to the daily values

Iseo, quantified through the Schmidt parameter S (Schmidt, 1928), defined as

$$S = \frac{g}{A_0} \int_0^{z_0} (z - z_v) \rho_z A_z dz \tag{1}$$

where g is the acceleration as a result of gravity, z_v the depth of the centre of volume, A_0 the area and A_z and ρ_z the area and the water density at the depth z, which was evaluated according to the Chen and Millero (1986) freshwater equation of state. This parameter reflects the resistance of a lake to mechanical mixing, in terms of potential energy inherent to stratification of the water column. During the stratified period, S increases up to 15% compared with the s4 results, with maximum growth around 8000 J/m^2 in the summer. With regard to the winter period (January to March), it is possible to observe a weaker but gradual increase in thermal stability, which grows from 0 up to 800 J/m^2 at the end of the simulation period.

In the s5 simulation, we investigated the role played by the modified run-off and air and river temperature on the thermal structure of Lake Iseo, with no modification of the wind field. Accordingly, one could wonder how relevant the contribution related to run-off and temperature changes would be compared with the ones related to wind speed. To provide an answer, we ran two simulations that kept the same boundary conditions as s5 but with a 25% reduced (s6) and increased (s7) wind speed during the winter months (January–March) when deep mixing typically occurs. In this period of the year, wind mainly affects the extent of deep mixing, which, in turn, may lead to abrupt variations of the hypolimnetic temperature (Livingstone, 1997). Figure 12 shows a comparison between the s5, s6 and s7 simulations in terms of temperature variations in the 50 m–bottom layer compared with the reference undisturbed condition s4. Depending on the epilimnetic temperature in the winter time, a wind increase can have a warming or cooling effect. With relatively warm epilimnetic water, the

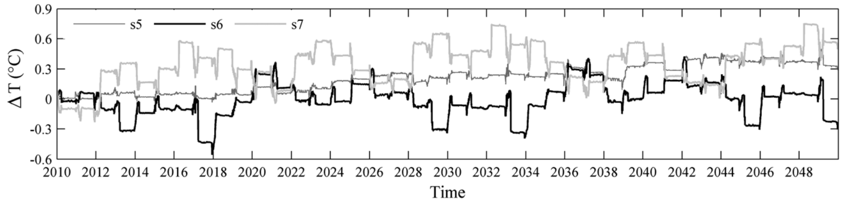

Figure 12. Difference ΔT between the hypolimnetic (50 m–bottom) volume-averaged temperature simulated in the climate change scenarios s5–s7 and the reference undisturbed condition s4

increase of the wind forces a deeper mixing with an increase of the hypolimnetic temperature compared with the s5 scenario (e.g. the period between 2028 and 2036). The opposite occurs during cold winters (e.g. from 2036 to 2038). Accordingly, if one expects a future dominance of warm winters, an increased wind (s7) is likely to reinforce the action of the increasing air temperature, while the reduced winter wind speed (s6) is expected to shelter the hypolimnion from the upper water, reducing vertical mixing that, on average, will warm the intermediate-deep waters of the lake.

DISCUSSION

In this paper, the long-term evolution of the thermal structure of a deep lake obtained by means of a 1D model is presented. Even though DYRESM was originally devised as a calibration-free process-based model, the complexities of 3D mixing processes that characterize this basin implied some degree of calibration to improve model fit to observed data, as already observed in other case studies (e.g. Tanentzap *et al*., 2008; Bueche and Vetter, 2013). In particular, we observed a lack of heat penetration under the thermocline before calibration, partially compensated by choosing high *CLN* values that enhance internal vertical mixing, as already reported for Lake Constance (Hornung, 2002) and Lake Geneva (Perroud *et al*., 2009). The strong internal wave activity that has been observed in Lake Iseo (Valerio *et al*., 2012) may physically justify the need for this increase of the *CLN* parameter. After calibration, DYRESM well reproduced the temperature of the upper layers (0–50 m) and was capable in capturing some of the strongest variations in the thermal hypolimnetic conditions that occurred during the investigated period.

The discrepancies between the observed and simulated temperatures may arise from the insufficient modelling of internal mixing, which conceptualizes seiching motions and benthic boundary layer dynamics, and by the approximation of the wind forcing as uniform over the lake surface. In this direction, there is space for a more sophisticated modelling approach. In particular, the occurrence of 3D phenomena in such a complex bathymetry likely explains the incorrect simulation of the fast increase of the deep-water temperature that occurred after the 2005–2006 overturns and the weaker dynamic resulted under 50 m. Finally, an intrinsic reason for some occasional discrepancies between model results and field data in the metalimnion during the stratified period could be ascribed to the fact that the measured data are affected by the temperature fluctuations at the sampling location because of vertical seiching, which at the S1 location range within a few degrees under ordinary summer conditions (Valerio *et al*., 2012).

The validated model was used to test the effects on the lake thermal structure of a possible climate change scenario. To the knowledge of the authors, this is the first work aimed at providing quantitative forecasting of the impact of local warming for a deep pre-alpine lake located south of the Alps. The predicted overall warming of the water column (0.012 °C/year), characterized by stronger increases in the upper layers and by an increase in thermal stability, is in agreement with observed trends and predictions in other lakes of the alpine area. For example, Livingstone (2003) reports for Lake Zurich warming rates observed in the period 1950–1990 of about 0.24 and 0.13 °C per decade for the upper (0–20 m) and lower layer (20–136 m) respectively. Additionally, the increase in thermal stability is coherent with other predictions in basins such as Lake Zurich (Peeters *et al*., 2002), Lake Geneva (Perroud and Goyette, 2010) or Lake Ammersee (Danis *et al*., 2004). The increase in thermal stability predicted for 2050 in Lake Iseo in the winter time (~800 J/m^2) is comparable with the contribution deriving from the current chemical stability, which, on the basis of the measured conductivity profiles, we reckon to be 1200 J/m^2. According to Ambrosetti and Barbanti (2005), this contribution of salinity on vertical density distribution is able to explain in itself the reduction of complete overturn events that started from the mid 1990s and the consequent deoxygenation of the deep water. From this point of view, climate change in Lake Iseo is likely to strongly reduce deep mixing, affecting its trophic status (Garibaldi *et al*., 1999; Salmaso *et al*., 2003) and preventing the restoration of a good ecological quality status, as dictated by the EU Water Framework Directive.

In the paper, we followed a catchment-wide approach that takes into account the variations in the hydrological flow regime because the simulations that we accomplished without inflows and outflows (Figure 9) showed the importance of their contribution to the heating of the lake. The observation of the prevailing interflow regime of the two main tributaries may help to explain this result. As shown in Figure 3, after the onset of thermal stratification, both the inflows intrude below the lake surface, potentially in the depth range $10 < z < 15$ m from early April to August, $15 < z < 20$ m from August to the middle of September and at $20 < z < 50$ m in the three following months. In the homothermal period, the waters of the Industrial Canal intrude below 50 m. These depths are occasionally larger during major floods when turbidity increases the water density. Because the outflowing water comes only from the epilimnic layers close to the lake surface, the heat flux related to the cold water entering the lake is significantly lower than the one flowing out, with a difference of -1.23 GW, as an average in the 1995–2011 period. This means that the inflow–outflow process induces an average yearly overall removal of heat from the lake of $3.6 \cdot 10^{16}$ J (Table IV). On the basis of these considerations, we believe that in a climate change

Table IV. Mass and energy balance of the inflowing and outflowing water in the validation (1995–2011) and projection (2012–2050, scenario s5) period

	1995–2011			2012–2050		
	Oglio	Canal	Outflow	Oglio	Canal	Outflow
Q (m^3/s)	26.45	27.41	53.61	25.85	25.71	51.15
T (°C)	10.71	8.57	14.41	10.73	8.59	14.86
net F (GW)	−1.23			−1.16		

Q, T and net F refers to the average discharge, temperature and net thermal energy flux from the tributaries (i.e. inflow–outflow) respectively.

scenario, it is important to take into account, in addition to the air temperature increase, also the variation in the inflow regime, temperature and discharge.

In Lake Iseo, the modified forcings operate differently: the simulated air temperature increase, with its effects on the rates of exchange of latent and sensible heat, causes maximum temperature increase of the epilimnetic water, mostly between February and May. In this period, the warming effect can be easily transferred also to the deeper layers because of minimum resistance to vertical mixing. On the other hand, a modified inflow–outflow regime gives rise to a warming in the first 50 m of the water column, particularly evident between July and October. As shown in Table IV, in the climate change scenario, one can expect an attenuation of the lake cooling operated by inflows in the order of $7 \cdot 10^7$ W. This phenomenon is mainly attributable to the reduction of the discharges in the summer period. The effect of the increased inflow temperature that would also contribute to increase the net heat flux is instead compensated by the warming of epilimnetic waters (Table IV).

Additional simulations with only the air temperature variation show that the epilimnetic, metalimnetic and hypolimnetic temperatures would reach, at the end of the simulation period, an average increase of 0.35, 0.38 and 0.28 °C instead of 0.79, 0.62 and 0.37 °C observed with the full climate change scenario. Accordingly, the increase in the hypolimnetic heat content observed in s5 is mainly attributable to the increase in air temperature (~80%, by comparing the temperature variations with and without the modified discharges). This result is coherent with what was already observed and modelled in the deep lakes of the alpine area, where deep-water warming has been interpreted as a response to longer-term air temperature trends (e.g. Livingstone, 1997). However, the air temperature increase is responsible only for ~60 and ~40% of the overall temperature rise in the metalimnion and in the epilimnion, where a role of comparable importance is played in this lake also by the modified heat fluxes of the rivers.

A reason for additional uncertainty on the effects of climate change on the thermal structure of a deep lake arises from the absence of definite information regarding the future evolution of the local wind field. This information plays a major and non-trivial role in lake dynamics but is not provided by hydrological modelling. For instance, Tanentzap *et al.* (2008) demonstrated that a 28-year decrease in the whole lake average temperature of a Canadian lake, despite signatures of climate change, was attributable to a 35% reduction in surface wind speeds. This result is confirmed by our sensitivity analysis on the role played by the wind on the average lake temperature (Figure 9, case s3). A similar effect is obtained when the reduction in wind speed is applied in the colder season only (Figure 12, case s6); in this period of the year, the wind reduction shelters the hypolimnion from the warming effects operated by the other meteorological variables. However, it may be worth noting that in deep lakes like Lake Iseo, the oxygenation of the hypolimnion heavily relies on the mixing process triggered by wind. From this point of view, one might argue that a wind reduction in the winter period would be almost inevitably related to a worsening of the hypolimnetic oxygenation that already besets this lake, while a wind increase could eventually enhance the transfer of oxygen in the deeper waters.

CONCLUSION

Lake Iseo, a mid-size deep pre-alpine lake located in northern Italy, is the outlet of a strongly populated alpine valley, whose highest part is dominated by the largest Italian glacier. Accordingly, it is a natural integrator of the effects of climate change and of anthropic pressure. The present contribution studies the reaction of the lake's thermal structure to a future climate change scenario, using a catchment-wide approach, which accounts for climate-induced variations in the hydrological regime of the drained watershed.

The hydrodynamics of the lake were simulated by a 1D model (DYRESM). During the 1 year long calibration period, the model proved effective in reproducing the strong seasonal variability in the upper layer temperatures, with a mean absolute error of 0.6 °C (5%) in the epilimnion and of 0.6 °C (7%) in the metalimnion. It was also reasonably effective in reproducing the strongest variations in the thermal hypolimnetic conditions during a 16 years long validation period, without being able to capture the weak seasonal variability that affects the water between 50 and 150 m and the increase in the deeper water temperature after full circulation events.

The climatic prediction presented in this paper is based on the hydrological results obtained by Barontini *et al.* (2009)

and Ranzi *et al.* (2009), who discussed the effects of climate change scenarios on the run-off regime of the alpine Oglio basin for this century, providing daily run-off over the 2000–2099 period. The simulation of the thermal regime of Lake Iseo from 2011 to 2050 shows an overall warming of the water column (0.012 °C/year), which is not distributed uniformly at the different depths within the lake: the temperature in the epilimnion, metalimnion and hypolimnion increases at an average rate of 0.02, 0.015 and 0.009 °C/year respectively. This differential heating leads to a general reinforcement in the thermal stability of the lake: in particular, during the winter period, the simulation shows a raise up to 800 J/m^2 at the end of the investigated period. Accordingly, the expected modifications of the thermal structure could have relevant ecological implications for the water quality of Lake Iseo, where hypolimnetic dissolved oxygen is strongly controlled by the occurrence of occasional deep convection.

The separate analysis of the role played by the different forcings shows that the predicted increase in the hypolimnetic heat content is mainly attributable to the increase in air temperature (~80%), while in the metalimnion and in the epilimnion, a role of comparable importance (~50%) is played by the heat fluxes conveyed by the tributaries and effluents of the lake. In particular, the reduction of discharges in the summer period is expected to give rise to an overall warming of the lake water, reinforcing the action of the increasing air temperature. This confirms the relevance of a climatic change scenario that takes into account the variation in the hydrological regime of the drained catchment.

Finally, the obtained results also show that there is a need for an increase in modelling efforts to reproduce both the space distribution of wind field on large lakes and to prospect future scenarios of local wind evolution. Without this information, the exact extent of climate change effects on deep lakes will remain uncertain.

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