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Past and future warming of a deep European lake (Lake Lugano): What are the climatic drivers?

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ABSTRACT

We used four decades (1972–2013) of temperature data from Lake Lugano, Switzerland and Italy, to address the hypotheses that: [i] the lake has been warming; [ii] part of the warming reflects global trends and is independent from climatic oscillations and [iii] the lake will continue to warm until the end of the 21st century. During the time spanned by our data, the surface waters of the lake (0–5 m) warmed at rates of 0.2–0.9 °C per decade, depending on season. The temperature of the deep waters (50-m bottom) displayed a rising trend in a meromictic basin of the lake and a sawtooth pattern in the other basin, which is holomictic. Long-term variation in surface-water temperature correlated to global warming and multidecadal variation in two climatic oscillations, the Atlantic Multidecadal Oscillation (AMO) and the East Atlantic Pattern (EA). However, we did not detect an influence of the EA on the lake's temperature (as separate from the effect of global warming). Moreover, the effect of the AMO, estimated to a maximum of +1 °C, was not sufficient to explain the observed temperature increase (+2–3 °C in summer). Based on regional climate projections, we predicted that the lake will continue to warm at least until the end of the 21st century. Our results strongly suggest that the warming of Lake Lugano is tied to global climate change. To sustain current ecosystem conditions in Lake Lugano, we suggest that management plans that curtail eutrophication and (or) mitigation of global warming be pursued.

Introduction

During the last few decades, lakes worldwide have become warmer (Ambrosetti et al., 2003; Livingstone, 2003; Schneider et al., 2009; Dokulil et al., 2010; Schneider and Hook, 2010; Mishra et al., 2011). Lakes in mid- to high latitudes of the Northern Hemisphere are warming particularly fast. For example, from 1985 to 2009, the summer surface temperature of lakes across northern and central Europe has increased at rates of 0.6–0.8 °C per decade (Schneider and Hook, 2010). Although the evidence supporting these warming trends is compelling, at present, knowledge of the underlying drivers remains speculative. Global climate change (IPCC, 2013) is probably an important factor, but lake temperatures track other medium-term (decadal time scale) climatic variation, including climatic oscillations such as the North Atlantic Oscillation or the East Atlantic Pattern (e.g., Dokulil et al., 2010; Salmaso, 2012). Therefore, any attributions of lake warming to global warming would be uncertain without an assessment of the relative contribution by climatic oscillations. Surprisingly, few studies have attempted to separate the effects of these climatic drivers (global change and climatic oscillations) on fresh waters, and all have focused on streams, which may respond to climate change differently than lakes (Durance and Ormerod, 2007; Lepori et al., 2014).

Better insight into the climatic drivers of the warming trends in lakes would be important not only for our understanding, but also for our ability to predict future lake temperatures and evaluate appropriate mitigation strategies. Climatic oscillations are largely, although not exclusively, natural phenomena (Visbeck et al., 2001; Hurrell et al., 2003; Knudsen et al., 2011). The oscillation periods do not usually exceed 60–80 years (Knudsen et al., 2011). Therefore, if climatic oscillations have been (and will continue to be) the main drivers, the warming trends may revert spontaneously in the future (Livingstone, 2003). By comparison, global climate change arises to a greater extent from a human-induced accumulation of greenhouse gases in the atmosphere (IPCC, 2013). Therefore, if global climate change has influenced (or will influence) lake temperatures, the warming trends may not revert until the emission of these gases is reduced. Regardless of when such reduction might be achieved, the influence would be long-lasting because, globally, temperature is expected to rise for at least another century (IPCC, 2013).

In this study we explored the temperature trends and the climatic drivers of these trends of Lake Lugano, a deep (288 m) central European lake whose temperature has been monitored since 1972. Like many other European lakes, Lake Lugano lies in a densely populated area and supports services that are important to the regional economy,

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including tourism, recreation and fisheries (Dokulil, 2014a). Because most of these services are climate-sensitive and may be threatened by continued warming, we were interested in examining the past and future influences of global warming on the temperature of the lake. We tested the hypotheses that: [i] the water of the lake has warmed from 1972 to 2013, [ii] part of the warming reflects global warming and is independent from the influence of climatic oscillations and, therefore, [iii] the lake will continue to warm at least until the end of the 21st century.

Methods

Study lake

Lake Lugano (E 9° 0′ 56.35″ N 46° 0′ 23.77″, altitude 271 m) is a natural glacial lake situated at the southern fringe of the Central Alps, spanning the border between Switzerland and Italy (Fig. 1). The lake is divided by a causeway (built on a natural moraine) into two main basins, the north basin and the south basin. The north basin is deep (288 m) and meromictic, i.e. almost permanently stratified due to a salinity difference between deep and surface waters. During the study period (1972–2013), this basin turned over only once, during the winter of 2005–2006 (Simona and Veronesi, 2009). However, partial vertical mixing, to a depth of approximately 100 m, occurs yearly between the end of winter and early spring (February–March). The south basin is shallower (95 m) and holomictic, turning over almost every year at the end of the winter, usually in February or March.

The climate of the lake's catchment is influenced by regional factors, including the presence of mountains and, at larger scales, influxes of air masses from continental, polar, Atlantic or Mediterranean regions (MeteoSwiss, 2012). Overall, the local climate is mild and wet, with a year-round average air temperature of 11–12 °C and approximately 1600 mm of total precipitation. Because of the relatively mild climate, the lake remains ice-free.

During the last century, the climate of our study region has become warmer (MeteoSwiss, 2012). Since the 1960s, spring and summer air temperatures have increased at a rate of 0.5 °C per decade, whereas autumn and winter temperatures have increased more slowly, at a rate of 0.2–0.3 °C per decade. Model-based projections indicate that the regional climate will continue to warm at least until the end of the 21st century, at rates that will depend on season and the global emission of greenhouse gases (IPCC, 2013).

Data compilation

Long-term (1972–2013) data of Lake Lugano's temperature were obtained from the Institute of Earth Science of the University of Applied Sciences and Arts of Southern Switzerland. We used data collected from research vessels at two sampling stations, one located in the north basin (Gandria) and the other in the south basin (Figino; Fig. 1). Data from 1982 onwards were collected monthly, whereas earlier data were collected less regularly. Measurements were taken at discrete depths from the surface to the bottom to the lake. Temperature was measured using reversing thermometers (accuracy ±0.1 °C) from 1972 to 1979, and resistance thermometers (accuracy ±0.003–0.05 °C) from 1980 to 2013. In this study, for consistency across the database, all temperature values were reported to the nearest 0.1 °C.

Local air temperature data from 1973 to 2013 (measured in the town of Lugano, adjacent to the lake) were obtained from MeteoSwiss, the Swiss Federal Office of Meteorology and Climatology (available online at www.meteoswiss.admin.ch).

To assess the influence of climatic oscillations on the lake's temperature, we considered five oscillations known or suspected to influence fresh waters in Central Europe: the NAO (Barnston and Livezey, 1987), the Summer NAO (Folland et al., 2009), the Atlantic Multidecadal Oscillation (AMO; Schlesinger and Ramankutty, 1994), the Mediterranean Oscillation (MO; Conte et al., 1989), and the East Atlantic Pattern (EA; Barnston and Livezey, 1987) (for the effects on European fresh waters, see e.g. Dokulil et al., 2006, 2010; Salmaso, 2012; Lepori et al., 2014). These oscillations were parameterized using indices available from various climatic research institutes, as specified in Table 1. The AMO index used in this study is detrended, to remove the influence of global warming.

We used monthly global temperature anomalies as an index of global climate change. This anomaly is closely correlated ($r = 0.9$, $P < 0.001$) to an index of the radiative forcing due to atmospheric CO_2 (the CO_2 component of the NOAA annual greenhouse gas index of Butler and Montzka, 2014). Therefore, our index of global climate change accurately tracks the global increase in CO_2 emissions, the major agent of industrial-era anthropogenic climate forcing (IPCC, 2013). Global temperature data were obtained from the National Climatic Data Center of the National Oceanic and Atmospheric Administration (available online at www.ncdc.noaa.gov).

Projections for air temperature in 2081–2100, the anomalies expected relative to the reference period 1986–2005, were obtained from the

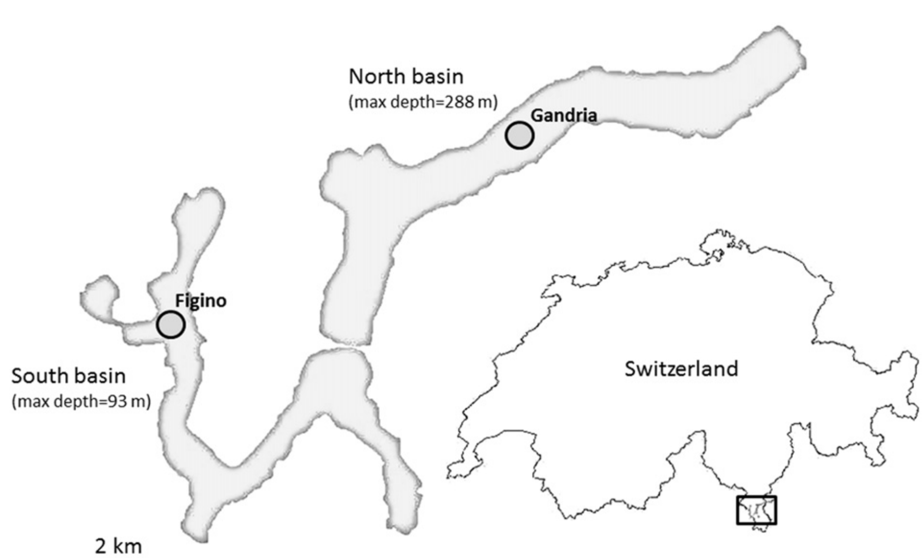

Fig. 1. Location of Lake Lugano and the sampling stations (Gandria, north basin and Figino, south basin) where lake temperature was measured.

Table 1
Indices of the five climatic oscillations considered in this study and their sources. NAO = North Atlantic Oscillation; Su_NAO = Summer NAO; AMO = Atlantic Multidecadal Oscillation; MO = Mediterranean Oscillation; EA = East Atlantic Pattern.

Climatic oscillation	Index	Source
NAO	NAO index, a measure of the pressure anomaly over the North Atlantic between Greenland and a pole spanning central latitudes (35°N and 40°N), calculated using rotated principal component analysis.	http://www.cpc.ncep.noaa.gov//products/precip/CWlink/pna/nao.shtml
Su_NAO	Summer NAO index, a measure of summertime pressure anomalies over the North Atlantic (40–70N, 90W–30E), calculated using an empirical orthogonal function covariance analysis.	http://climexp.knmi.nl//getindices.cgi?WMO=NCEPNCAR40/snao_ncepncar&STATION=SNAO_ncepncar&TYPE=i&id=someone@somewhere
AMO	AMO index, essentially a detrended index of the North Atlantic surface temperature.	http://www.esrl.noaa.gov/psd/data/timeseries/AMO/
MO	MOI1, the normalized pressure difference between Algiers and Cairo.	http://www.cru.uea.ac.uk/cru/data/moi
EA	EA index, the second prominent mode of variability over the North Atlantic, similar to the NAO but with a dipole shifted southward. Calculated from a rotated principal component analysis (RPCA) of normalized 500-hPa height anomalies from the period 1950–2000.	http://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml

Atlas of Global and Regional Climate Projections supplied by the IPCC's Fifth Assessment Report (IPCC, 2013). Each projection is provided as a likely value (the 50th percentile from a probability distribution) and an associated uncertainty envelope, defined as the interquantile range (Q1 to Q3). This range accounts for two sources of uncertainty, model spread and natural variation. To account for future changes in greenhouse gas emissions, a third source of uncertainty, we used the four scenarios proposed by the IPCC (2013): a low-emission scenario (RCP2.6), two medium-emission scenarios (RCP4.5 and RCO6.0) and a high-emission scenario (RCP8.5). The scenario RCP2.6 assumes a rapid reduction of emissions starting from 2020, the scenario RCP4.5 a gradual reduction after 2040, the scenario RCP6.0 a gradual reduction after 2060 and the scenario RCP8.5 a continuous increase until 2100. Projections are supplied as intervals (e.g. +0.0–0.5 °C). To simplify our analyses we represented each interval using its midpoint (e.g. +0.25 °C).

Spatial and temporal units

During most of the year, Lake Lugano is stratified into an epilimnion and a hypolimnion, separated by a sharp temperature gradient (thermocline), whose depth varies seasonally. Trends in epi- and hypolimnetic temperatures should be studied separately (Livingstone, 2003). Because a portion of our data lacks the resolution necessary to locate the depth of the thermocline, we did not attempt to estimate the thickness of these layers throughout the study period. Instead, we focused on two fixed-depth layers of the water column, the layer extending between the surface and 5 m of depth, representative of the epilimnion, and the layer extending from 50 m of depth to the bottom, representative of the hypolimnion (Livingstone, 2003). Hereafter we will refer to these layers as "surface waters" and "deep waters", respectively. In most cases, temperature was measured at several depths within each layer; these values were averaged to provide a single layer temperature.

In the analyses concerning surface-water temperature (SWT) we focused on seasonal temperature. Therefore, the data obtained, which were supplied either as monthly averages (climatic data) or "spot" values (water temperature) were averaged within seasons (defined as: winter = DJF; spring = MAM; summer = JJA; autumn = SON; capital letters denote months of the year) to obtain seasonal values. Our rationale was that at finer temporal scales (monthly or daily) the signal of large-scale climatic oscillations may be overshadowed by the influence of local weather phenomena (E. Barnes, Department of Atmospheric Science, Colorado State University, *personal communication*). Coarser time units (yearly) would also buffer the signals of climatic oscillations, because oscillations, except the AMO, vary mostly within shorter time scales (Hurrell et al., 2003).

For the deep waters (50 m-bottom), a season-by-season analysis was not warranted because seasonal temperatures were temporally autocorrelated (*not shown*). This was expected because, in Lake Lugano, the deep-water temperature (DWT) is set during the late-winter/early-spring vertical mixing event, and changes little until the following winter. Because the February temperature anomaly is strongly correlated with the anomalies of any of the following 11 months (*not shown*), we used it as an indicator of the year-round DWT.

Statistical analysis

Before averaging within seasons, we transformed water temperature data into temperature anomalies, defined as the difference between the spot temperature measured in any one month and a typical temperature for that same month. We obtained typical temperatures by fitting a sinusoidal regression through the temperature data (Model 1, Table 2) and using the resulting equation to predict the temperature of each month of the year (Lepori et al., 2014). This conversion was intended to reduce bias and error in our analysis of water temperatures, which was based on an incomplete series of data. We assumed that monthly anomalies are unbiased indicators of average seasonal anomalies.

We used linear regression equations (Model 2, Table 2; Durance and Ormerod, 2007; Kaushal et al., 2010; Lepori et al., 2014) to assess whether lake temperatures increased from 1972 to 2013 (hypothesis [i]). For the surface waters, we performed a separate analysis for each season. For the deep waters, we focused on the February anomalies. A similar analysis was performed on the indices of the climatic oscillations, to identify which oscillations displayed apparent trends (indicating multidecadal variation) during the study period.

Table 2
Regression models used to detect trends, identify drivers and project future values of lake-water temperature. The rate of change, β_0, was multiplied by 10 to obtain the decadal rate of change (°C per decade).

Model 1	$T_w = \beta_0 + \text{seasonal influence} + \varepsilon$ Where: ■ T_w = "spot" water temperature [°C] ■ seasonal influence = $\beta_1 \times \sin(2 \times \pi \times t) + \beta_2 \times \cos(2 \times \pi \times t)$ ■ $\beta_{0\rightarrow 2}$: constants ■ t: time [months] ■ ε: error
Model 2	$T(a)_{w,\ seasonal} = \beta_0 + \beta_1 \times t + \varepsilon$ Where: ■ $T(a)_{w,\ seasonal}$: average seasonal water temperature anomaly [°C]. The anomaly is the spot temperature minus the predicted month temperature (from Model 1). ■ $\beta_{0\rightarrow 1}$: constants ■ t: time in years
Model 3	$T_{w,\ seasonal} = \beta_0 + \beta_1 \times T_{air} + \varepsilon$ Where: ■ $T_{w,\ seasonal}$: average seasonal water temperature [°C] ■ T_{air} = average seasonal temperature[°C]

The drivers of the temperature trends were explored using correlation, partial correlation and multiple-regression analysis (hypothesis [ii]). For the surface waters, we tested for correlation between water-temperature anomalies and the indices of the climatic oscillations and for partial correlation (after accounting for the effect of climatic oscillations) between water and global temperature anomalies. For the deep waters, we used a similar approach, except that we focused, as for the trend analysis, on the February anomaly. Multiple regressions were used to separate the individual effects of climatic oscillations and global warming on lake temperature, except where these drivers showed high collinearity (defined as $r \geq 0.8$).

To project the temperature of Lake Lugano at the end of the 21st century (hypothesis [iii]), we predicted local (city of Lugano) air temperatures in 2081–2100 by adding the projected increases supplied by the IPCC's Fifth Assessment Report (IPCC, 2013) to benchmark 1986–2005 averages (winter: 4.2 °C, summer: 21.1 °C). We then modeled lake temperature as a function of air temperature (Model 3, Table 2), using separate regression models for each season (McCombie, 1959; Dokulil, 2014b). Finally, we fed the 2081–2100 projected air temperatures into these models to predict the corresponding lake temperatures (Lepori et al., 2014). To illustrate the change predicted between the present and the end of the century, these projections were compared to the average lake temperatures observed during 2003–2013. We reported the uncertainty of our regression models, quantified as the standard error of the estimate (S), along with the statistical significance. This approach, while inadequate to predict short-term (e.g. daily) variation in temperature, is useful to predict changes at coarser temporal scales in non-glaciated catchments (FOEN, 2012). We present projections only for the seasonal temperature of surface waters, which is directly influenced by climate. Changes in DWT will depend to a larger extent on the effects of future climate on the timing, strength and frequency of the seasonal turnover of the lake, which were not addressed in this study.

Results

Trends in lake temperature and climatic oscillations

From 1972 to 2013, the SWT of Lake Lugano displayed significant trends toward higher values in all seasons, with the exception of autumn temperature in the north basin (Table 3a, Fig. 2). Spring and summer temperatures increased faster (0.6–0.9 °C per decade) than winter and autumn temperatures (0.2–0.3 °C per decade). Trends in DWT differed between basins (Table 3b, Fig. 2). In the north basin, the DWT displayed a slow (0.1 °C per decade) rising trend. In the south basin, the DWT displayed alternating warming and cooling phases, but no overall trend.

During the same period, all climatic oscillations considered in this study and global temperature displayed significant increasing or decreasing trends, suggesting multidecadal variation, at least during one season (Table 4). The AMO and the global temperature showed strong increasing trends in all seasons. Trends in other oscillations were limited to certain seasons and were statistically weaker.

Drivers of lake temperature trends

Variation in seasonal lake temperature, except for variation in SWT in the north basin in winter, was significantly correlated to the AMO index (at least one significant correlation in any one season, across basins), the EA index (winter and summer) and the global temperature (all seasons; Table 5). The climatic oscillations NAO, Summer NAO and MOI had no apparent influence.

During the study period, global temperature was correlated to the AMO index ($r = 0.8$–0.9 across seasons) and the EA index ($r = 0.4$–0.6 in winter and summer). However, in several cases (4 of 8 at alpha = 0.05, or 7 of 8 at alpha = 0.1, Table 5), global temperature had a significant effect on SWT even after the influences of the AMO and EA were accounted for. Furthermore, multiple-regression analysis indicated that the EA had no individual effects (above the effects of global temperature) on lake temperature (Table 6). Owing to collinearity, the individual effects of the AMO on lake temperature could not be assessed using the same regression approach.

Lake temperature projections

We derived significant regression models to predict SWT from air temperature for both lake basins and all seasons, except for winter in the north basin (Table 7). Predictions of lake temperature obtained by entering projected increases in air temperature into these models (Fig. 3) suggest that Lake Lugano will continue to warm between the present (2003–2013) and the end of the 21st century (2081–2100), at least under medium- or high-emission scenarios. The predicted temperature increases depended on season, greenhouse gas emission scenario and lake basin (Fig. 3). Compared to the temperatures observed during 2003–2013 (average ± SE, north basin: 6.9 ± 0.1 °C in winter and 23.1 ± 0.3 °C in summer, south basin: 6.5 ± 0.1 °C in winter and 23.1 ± 0.4 °C in summer) these projections suggest that, by the end of the century, the temperature of the lake will rise by further 0.1–1.6 °C in winter and 0.1–5.1 °C in summer. Uncertainty in these predictions

Table 3
Warming rates (from 1972 to 2013) and associated *P*-values of Lake Lugano, by basin (north or south), season and water layer (a, surface waters; b, deep waters). Linear trends were estimated as the slope of the regression lines of temperature anomalies versus time. In b, the February temperature anomaly was used as an index of year-round deep-water temperature. D–W: Durbin–Watson statistics. Wi = winter; Sp = spring; Su = summer; Au = autumn.

a) Surface waters (0–5 m)

Basin	Season	Warming rate ± SE (°C decade^{-1})	df	*P*-value	D–W
North	Wi	0.2 ± 0.1	1,37	.048	2.05
	Sp	0.6 ± 0.2	1,40	<0.001	2.04
	Su	0.6 ± 0.1	1,36	<0.001	2.00
	Au	0.2 ± 0.1	1,40	.15	2.13
South	Wi	0.2 ± 0.1	1,37	.003	1.74
	Sp	0.8 ± 0.2	1,39	<0.001	2.15
	Su	0.9 ± 0.2	1,36	<0.001	1.88
	Au	0.3 ± 0.1	1,40	.031	1.42

b) Deep waters (50 m-bottom)

Basin	Season	Warming rate ± SE (°C decade^{-1})	df	*P*-value	D–W
North	February	0.1 ± 0.0	1,32	<0.001	0.92
South	February	–	1,32	.14	1.07

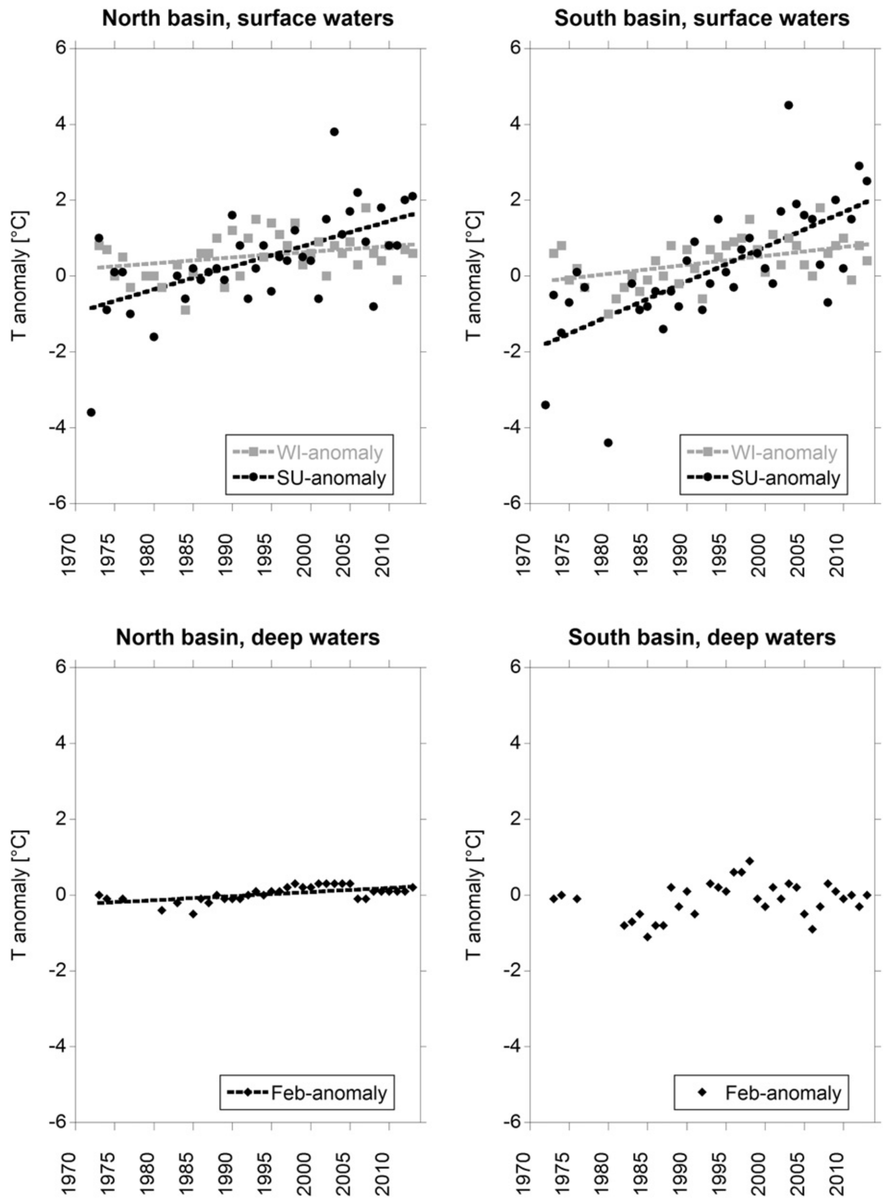

Fig. 2. Trends in the water temperature of Lake Lugano between 1972 and 2013, by water layer (surface waters and deep waters), season (winter and summer) and sampling station (north basin and south basin). See Table 3 for warming rates in other seasons.

has two main components, the uncertainty in the IPCC's projections (0.1–2.1 °C, Fig. 3), and uncertainty in the models converting air to water temperature (S = 0.4–0.8 °C, Table 7). The temperature rises predicted under the scenario RCP2.6 fell within the combined envelope of uncertainty, the rises predicted under the scenarios RCP4.5–6.0 appeared likely (≥ than the combined uncertainty) in summer, and the rises predicted under the scenario RCP8.5 appeared likely in both winter and summer.

Table 4
Linear trends in the indices of five climatic oscillations (Table 1) and global temperature (G.T.) from 1972 to 2013, by season. Linear trends were estimated as the slope of the regression line of the oscillation indices versus time. For simplicity, we report only the direction of the trend (increasing, ↑; decreasing, ↓; no trend, =) and its statistical significance (? = $P < 0.1$, * = $P < 0.05$; ** $P < 0.01$, *** $P < 0.001$). Other conventions as in Table 3.

Oscillation	Wi	Sp	Su	Au
NAO	=	=	↓*	=
Su_NAO	=	=	↓*	=
AMO	↑***	↑***	↑***	↑***
MOI1	=	=	=	↓*
EA	=	↑**	↑***	↑*
G.T.	↑***	↑***	↑***	↑***

Discussion

Long-term trends in lake temperature

The warming rate of Lake Lugano's surface waters during 1972–2013 (+0.6–0.9 °C per decade in spring and summer) accords with patterns observed elsewhere in the Northern Hemisphere (+0.6–0.8 °C per decade; Dokulil et al., 2010; Schneider and Hook, 2010). The faster rates observed in spring and summer were also expected, for two reasons. First, in our study region, climate has warmed faster in these seasons than in autumn and winter (MeteoSwiss, 2012). Second, in winter and autumn atmospheric conditions have a weaker influence on the SWT because the epilimnion exchanges heat not only with the atmosphere, but also with deeper waters, as a result of vertical water mixing.

Table 5
Coefficients of the correlation between lake temperature, the indices of five climatic oscillations (Table 1) and global temperature (G.T.) by lake basin, season and water layer (a, surface waters; b, deep waters). † correlation coefficients (r), ‡ partial correlation after accounting for the combined AMO + EA effect (where the EA had significant effects) or the AMO effect (other cases). Other conventions as in Tables 3 and 4.

a) Surface waters (0–5 m)

	North basin				South basin			
	Wi	Sp	Su	Au	Wi	Sp	Su	Au
NAO†	0.08	0.01	−0.08	0.19	−0.08	0.04	−0.05	0.10
Su_NAO†	−0.06	0.01	−0.10	0.00	−0.28	0.02	−0.08	0.05
AMO†	0.20	0.36*	0.54***	0.12	0.35*	0.44**	0.49**	0.34*
MOI1†	0.00	0.11	0.25	−0.03	−0.24	0.10	0.17	0.15
EA†	0.30	0.17	0.40*	0.17	0.44**	0.18	0.40*	0.19
G.T. †	0.39*	0.38*	0.61***	0.25	0.45**	0.50**	0.66***	0.42**
G.T.‡	0.40*	0.16	0.28?	0.36*	0.34*	0.27?	0.51**	0.30?

b) Deep waters (50 m-bottom)

	North basin	South basin
	Feb-anomaly	Feb-anomaly
NAO†	−0.03	−0.08
Su_NAO†	−0.21	−0.23
AMO†	0.64***	0.26
MOI1†	−0.24	−0.12
EA†	0.29	0.31
G.T.†	0.58***	0.27
G.T.‡	0.12	0.10

In these seasons, therefore, heat losses due to vertical mixing can buffer the SWT against the effects of climate warming (Livingstone, 2003).

The DWT displayed an apparent long-term increasing trend in the north basin, but not in the south basin. In all probability, this difference stems from the turnover regime. In the south basin, which turns over every year, the DWT showed a typical 'sawtooth' pattern of alternating warming and cooling phases (Livingstone, 1997). Warming phases are caused by milder-than-usual winters, which lead to incomplete vertical mixing, and allow heat to accumulate from one year to the next. Cooling phases are prompted by cold winters, which reset water temperature to a base value of approximately 4.5–5.0 °C, and thus preempt the development of long-term trends. Similar sawtooth patterns in DWT occurred simultaneously in other deep lakes situated south of the Alps, including e.g. Lake Garda (Salmaso, 2012), suggesting that resetting winters were triggered by the same regional climatic events.

The apparent long-term warming trend in the north basin is explained by the meromixis. In meromictic basins, cold winters, alone, cannot reset the DWT. Resets occur only when the DWT has increased sufficiently to counterweigh the effect of meromixis (the density difference between surface and deep waters) and trigger a full turnover (Livingstone, 1997). This is probably what happened in the winter of 2005–2006, when this basin turned over for the first time since records began in 1972 (Simona and Veronesi, 2009). However, because of the infrequency of these events, warming phases can last several decades, rather than few years, and may give the impression of continuous warming during the medium term, as in this study. Similar multidecadal trends in DWT have occurred in other deep lakes located south of the Alps (e.g. lakes Maggiore and Como, Ambrosetti and Barbanti, 1999). These neighboring lakes are not meromictic but, because of their great depth, they rarely experience full turnovers, and therefore permit heat to accumulate in the hypolimnion over several decades.

Drivers of the trends

Between 1972 and 2013, two climatic oscillations, the AMO and EA, displayed increasing trends, indicating multidecadal variation. The AMO shifted from a negative phase in the early 1970s to a positive phase since the mid-1990s (Arguez et al., 2009; Knudsen et al., 2011). The EA shifted from a negative phase during 1950–1976 to a positive phase during 1977–2004. Because positive AMO and EA phases are associated with above-average air temperatures in central Europe (Arguez et al., 2009; Salmaso, 2012), these shifts probably contributed to the warming of the regional climate and, consequently, to the warming of the lake. However, an independent influence of the EA on the lake, as separate from global warming, was not detected in this study. This does not mean that this oscillation had no influences on Lake Lugano. Across the southern fringe of the Alps, including our study region, negative spells of the EA in winter cause unusually cold weather, which, in turn, result in deeper-than-usual vertical mixing in spring (Salmaso, 2012). It is probably not coincidental that the exceptional turnover of the north basin of Lake Lugano occurred after two such winters (the winter EA index was −1.6 in 2005 and −0.9 in 2006). However, the main influence of the EA is probably confined to these events. Our results indicate that this oscillation played no discernible role in driving the monotonic trends toward higher seasonal temperatures observed in this study.

The influence of the NAO on the temperature of lakes across Europe is well known (e.g. Dokulil et al., 2006, 2010). The NAO is essentially a winter and spring phenomenon. Positive phases of this oscillation result

Table 6
Regression coefficients (± SE) from multiple regressions between lake temperature, the EA index and global temperature (G.T.), and by lake basin and season. Regressions were applied only where the EA was significantly correlated to lake temperature (see Table 5). n/a = not applicable. Other conventions as in Tables 3 and 4.

	North basin				South basin			
	Wi	Sp	Su	Au	Wi	Sp	Su	Au
EA	n/a	n/a	0.0 ± 0.3	n/a	0.2 ± 0.1	n/a	−0.1 ± 0.3	n/a
G.T.	n/a	n/a	3.6 ± 1.0**	n/a	0.9 ± 0.5*	n/a	5.3 ± 1.3***	n/a

Table 7
Equation, significance (P-value) and uncertainty (standard error of the estimate, S) of the regression models used to predict surface-water temperature (SWT) from air temperature (T_{air}), by lake basin and season. Other conventions as in Table 3.

Basin	Season	Model equation	df	P-value	S
North	Wi	$SWT = 6.2 + 0.2 \times T_{air}$	1,27	0.13	0.4
	Su	$SWT = 3.8 + 0.9 \times T_{air}$	1,26	<0.001	0.6
South	Wi	$SWT = 4.8 + 0.4 \times T_{air}$	1,37	0.006	0.6
	Su	$SWT = 0.0 + 1.0 \times T_{air}$	1,34	<0.001	0.8

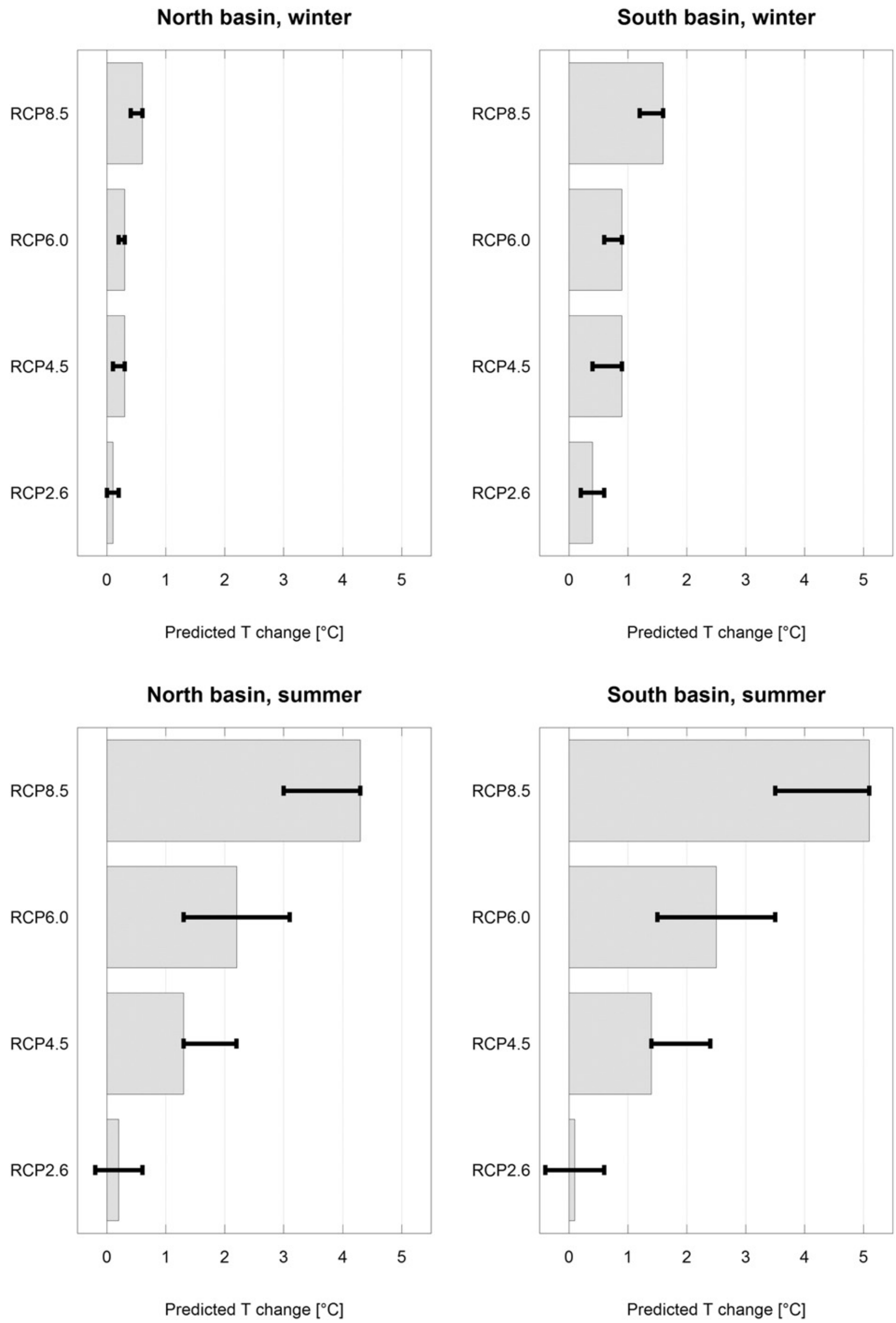

Fig. 3. Predicted changes in the surface-water temperature of Lake Lugano between 2003–2013 and 2081–2100, by basin (north and south), season (Wi and Su), and emission scenario (RCP2.6–8.5, see IPCC, 2013). Predictions were obtained by feeding projected regional air temperatures (IPCC, 2013) into regression models (Table 5). The bars represent the changes predicted under the most likely (50th percentile) projected air temperatures. The error bars represent the changes predicted under low (25th percentile) and high (75th percentile) projected air temperatures.

in higher SWTs during these seasons. Furthermore, since the SWT during spring turnover influences the DWT during the subsequent stratification period, the NAO phase in winter–spring indirectly influences the DWT (Dokulil et al., 2006). However, the lack of an apparent effect of the NAO on Lake Lugano might have been expected, because in the southern European Alpine region the NAO signal appears to be much weaker than in other European regions (Salmaso, 2012).

Unfortunately, owing to collinearity, we could not separate the influence of the AMO from the influence of global warming using multiple-regression or partial-correlation analysis. Nonetheless, we propose that an approximate notion of the effects of the AMO and global warming on SWT might be inferred from known relationships between these climatic drivers and air temperature, and between air temperature and SWT. We focus on summer, because we could not quantify the effects of the AMO on the climate of other seasons. First, in our study area, positive phases of the AMO are associated with summer air temperature anomalies of +0.3 to +0.6 °C and negative phases with anomalies of −0.3 to −0.6 °C (Sutton and Hodson, 2005; Arguez et al., 2009). Therefore, the shift from a negative to a positive phase during the study period could have led to an increase in air temperature of approximately 1 °C. Second, from the 1970s to the present, the global summer temperature has increased at a rate of 0.2 °C decade^{-1} (this study). Because in the Alpine region air temperature appears to be increasing twice as fast as the global average (Dokulil et al., 2010), the summer warming rate of our study area due to global warming was probably constrained between 0.2 °C and 0.4 °C decade^{-1}. During the study period, the resultant increase in air temperature would amount to 0.8–1.6 °C. Third, according to our study, summer air temperature and SWT are related by linear functions with slopes of 0.9 (north basin) and 1.0 (south basin). As a result, the increase in summer SWT due to the AMO influence is estimated to approximately 0.9–1.0 °C (max 1.2 °C). Likewise, the increase due to the influence of global warming is estimated to 0.7–1.6 °C, depending on basin and warming rate. Combined, these estimated influences explain a rise in SWT of 1.6–2.6 °C, which is within 1 °C of the observed increases of 2.4 °C (north basin) and 3.6 °C (south basin). Although probably simplistic, these estimates suggest that the warming trend observed in the surface waters of the lake from 1972 to 2013 was driven by both multidecadal variation in the AMO and global warming, with each driver contributing an increase of 1–2 °C.

Lake temperature predictions, effects on the ecosystem and conclusions

The influence of global warming on the SWT of Lake Lugano suggests that future temperature trends will be tied to patterns in global emissions of greenhouse gases. This possibility was supported by our predictions, which suggest that, between 2003 and 2013 and the end of the 21st century (2081–2100), the summer SWT of Lake Lugano would remain essentially stable under the emission scenario RCP2.6, increase by 1–2 °C under the scenarios RCP4.5–6.0 or increase by 4–5 °C under the scenario RCP8.5. The predictions arising from the intermediate scenarios RCP4.6 and 6.0 agree with the outcome of other predictive efforts concerning European lakes. For example, Dokulil (2014b) predicted that in Austrian lakes the summer SWT will increase by 2 °C between 2000-2009 to 2050. One implication of these predictions is that the relative importance of the natural and anthropogenic drivers of lake temperature will also change. In Lake Lugano, if the AMO causes fluctuations in lake temperature not greater than 1 °C, climate forcing will become the dominant driver of decadal changes in temperature within a few decades, whereas at present natural and anthropogenic influences appear to be more balanced (Lepori et al., 2014).

Continuing warming would affect most aspects of the lake ecosystem. Predicted physical effects will include not only a rise in temperature, but also changes in thermal stability and turnover regime (Livingstone, 2003). Paradoxically, the effects on the turnover regime of Lake Lugano might have contrasting characteristics in the two basins of the lake. In the north basin, where warming works against the existing meromixis (by warming the deep waters and thus reducing their density), warming should increase the frequency of turnovers. In the south basin, by comparison, warming should increase thermal stability and lead to weaker turnovers (Livingstone, 2003). Here, during exceptionally mild winters, turnovers might be suppressed altogether, as we observed for the first time since 1972 during the winter of 2013–2014. In turn, these physical changes will influence key biochemical processes. Turnovers in the meromictic north basin reduce oxygen concentrations across the water column and transport large amounts of phosphorus to the epilimnion (Simona and Veronesi, 2009). Suppressed turnovers in the south basin can increase the duration of anoxic conditions in the hypolimnion and, as a result, cause increased internal phosphorus loading. In both cases, the effects amount to severe ecological disturbances.

In addition, warming could change the biological community of the lake. In lakes across the Northern Hemisphere, increasing water temperature is altering the phenology, abundance and species composition of phyto- and zooplankton (Weyhenmeyer et al., 1999; Peeters et al., 2007; Parker et al., 2008; Domis et al., 2013; Gauthier et al., 2014). Interactions between warming and changes in land use have been associated with blooms of undesired cyanobacteria (Markensten et al., 2010; Scavia et al., 2014; Rigosi et al., 2014). Rising water temperatures also affect higher trophic levels. For example, an increase in the number of ice-free days in lakes of the northern U.S.A. is predicted to favor warm-water fish species, but be detrimental to cold-water fishes (Sharma et al., 2007). Likewise, contractions of cold-water fish populations have been observed or are predicted to occur in European lakes (Jeppesen et al., 2012; Comte et al., 2013). Moreover, warming trends in lake tributaries and outlets (van Vliet et al., 2011; Lepori et al., 2014) are altering the timing of spawning migrations by adfluvial fish populations, including the European Grayling (*Thymallus thymallus*) (Wedekind and Küng, 2010).

Viewed from an applied perspective, the predicted increases in internal phosphorus loading, losses of cold-water fish habitat and stimulation of cyanobacterial blooms suggest that warming will weaken some of the services provided by the lake. Furthermore, as these effects appear to mimic or reinforce the impacts of high nutrient loadings, they might negate the benefits of the ongoing restoration from eutrophication (Simona and Veronesi, 2009). Our study suggests that if the present lake services are to be maintained, global warming should be mitigated and (or) the lake ecosystem should be made less vulnerable to warming, for example through a further reduction of eutrophication.

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