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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

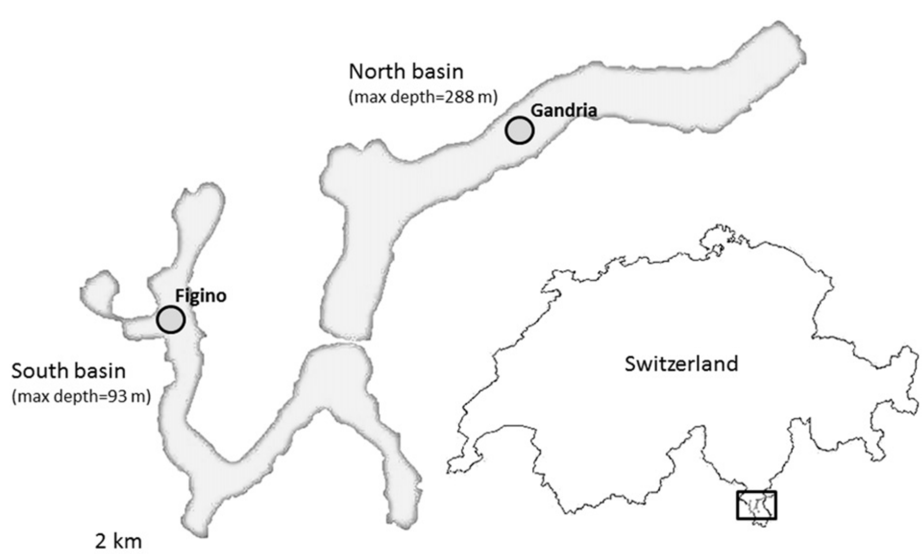

Fig. 1. Location of Lake Lugano and the sampling stations (Gandria, north basin and Figino, south basin) where lake temperature was measured.