Insights into the dynamics of the deep hypolimnion of Lake Geneva as revealed by long-term temperature, oxygen, and current measurements

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Abstract

In order to identify or shed light on dominant long-term processes of the deep hypolimnion of Lake Geneva (309 m depth), time series of temperature and horizontal currents and profiles of temperature and oxygen, taken for over a decade in the deepest part of the lake, were analyzed. The focus was on the summer stratification period (May to October). During that period, temperatures near the bottom always increased quasi-linearly with the same gradient and small amplitude variability. Vertical mean temperature gradients in the lowest 60 m of the water column remained nearly constant over the years and were comparable to those of the deep ocean. Mean current velocity at the deepest point was 3.0 ± 0.5 cm s⁻¹ and ever-present inertial motions clearly dominated currents. Oxygen decreased quasi-linearly and eutrophication appeared not to affect this rate of decrease. It is suggested that as in the deep ocean, breaking internal waves and friction from decaying inertial motion occurring in the deep hypolimnion strongly contribute to turbulent mixing in that layer. The climate change-induced long-term warming trend seen in the upper layers of the lake was not detected in the deep hypolimnion. Instead, year-to-year climate change-induced variability strongly affected the deep hypolimnion. During cooling in cold winters, lateral advection contributed more to temperature decrease and oxygen renewal in the deep hypolimnion than vertical convection. The present analysis has shown that the dynamics of this layer are highly three-dimensional and that the processes occurring therein cannot be correctly described by traditional one-dimensional concepts.

Lakes are ecosystems wherein diverse bio-geo-chemical and physical processes interact. In the past, the long-term balance between these processes in most lakes was fairly stable, because it was mainly controlled by atmospheric forcing, whose strength and seasonal variability changed little or only gradually over time. However, in recent decades, anthropogenic activities have intensified and have significantly disturbed this fragile balance in lakes, causing for example, rapid system changes due to eutrophication, and surface water warming due to climate change. Since lakes have high economic and societal value and are often important drinking water reservoirs, lake management concepts have to be constantly adapted and effective new strategies have to be developed that take these processes into consideration. In order to achieve this, a good understanding of these processes in the whole-water column of a lake is essential. Unfortunately, at present, knowledge about the response of the deep hypolimnion layer of deep lakes to these processes is still scarce, mainly due to the lack of high-resolution, long-term measurements. This study, carried out for Lake Geneva, Western Europe's largest lake, aims to help narrow that knowledge gap.

The effects of climate change on lakes have been summarized by Goldman et al. (2013). The most obvious effect is the trend of mean lake near-surface water temperature warming following the trend of climate change-induced rising mean air temperature (O’Reilly et al. 2015). O’Reilly et al. (2015) stressed that due to the important influence of local parameters, for example, lake surface area, depth, and surrounding topography, no general trend in lake response to climate change effects can be drawn. Therefore, the processes that determine the response of a specific lake system to climate change, in particular, the effect that climate change may have on the different layers of the water column of a lake have to be investigated individually for each lake. The warming of surface waters may intensify the gradient of thermal stratification (Rempfer et al. 2010), often by forming a stronger and deeper thermocline. This may lead to reduced mixing at depths below

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the thermocline (Coates et al. 2006). At present, the climate change response dynamics of the lowest layers of the hypolimnion of deep lakes is not well understood. Some insight may be gained by using surface layer warming as a "tracer," that is, investigate the downward diffusion of these warm water masses into the deeper layers of the lake and thereby establish the long-term effects, if any, on these layers. For deep lakes, it is important to determine whether the whole-water column responds in a similar way to climate change or not.

Studies in Swiss lakes, which are located in the Central European climate belt, have shown that surface forcing typically affects water column processes down to depths of approximately 100–150 m; for example, in Lake Zürich (maximum depth 130 m) near isothermal conditions down to the lake bottom have occurred almost every winter, and have thus allowed continuous one-dimensional (1D) modeling of the lake’s stratification for many decades (Peeters et al. 2002). However, in deep Swiss lakes, defined in this study as being deeper than 150 m, there are indications that the dynamics of the hypolimnion layer below that depth are only weakly coupled to surface forcing, especially during the stratified season (May to October). Multiannual series of regularly taken temperature profiles in these deep lakes often show a sawtooth pattern with continuous gradual warming taking place in the deep hypolimnion over several consecutive years, but cooling at the bottom only occurring occasionally during severely cold winters (Livingstone 1997; Ambrosetti et al. 2010). Ambrosetti and Barbanti (1999) linked deep-water warming to climate change. Livingstone (1997) suggested that the primary cause for deep layer warming is the downward transport of heat by vertical turbulent diffusion during stratification.

In order to study vertical diffusion in Lake Geneva (maximum depth 309 m), Zhang 1994 and Zhang et al. (1994) carried out a Thorpe scale analysis (Thorpe 1977) and determined vertical diffusion coefficients \( K_z \) that were nearly constant below 80 m depth. Michalski and Lemmin (1995) observed that the vertical diffusion coefficient \( K_z \) obtained with the flux gradient method decreases from the surface down to approximately 100 m depth. In the layer between approximately 30 m depth and 100 m depth, the relation between the mixing coefficient \( K_z \) and the buoyancy frequency implied that turbulence in this layer is generated by local shear flows and internal waves (Welander 1968). From 100 to 300 m depth, the mixing coefficients remain nearly constant (Michalski and Lemmin 1995) and are similar to those reported by Zhang (1994). The source of the turbulent mixing in the deep hypolimnion, however, is still unknown.

The \( K_z \) values that were obtained in the lower hypolimnion layer of Lake Geneva (Zhang 1994; Michalski and Lemmin 1995) are comparable to those that have been reported for the deep ocean layer where the breaking of progressive internal waves in that layer is considered to be one of the most important mechanisms for turbulent mixing (Gregg 1987; Garrett and St. Laurent 2002; Garrett 2003). In lakes, progressive internal waves were first observed by Mortimer (1974), and were later detected in other lakes (Antenucci and Imberger 2001; Lorke et al. 2006), as well as in the upper layers of Lake Geneva (Thorpe and Lemmin 1999). One source for these progressive waves is the passage of standing nonlinear internal Kelvin wave fronts (Thorpe et al. 1996). Progressive waves are known to break over the lateral slopes of lakes (Lemmin et al. 1998; Lorke et al. 2006) and thus contribute to mixing. They may also break in the lake interior (Thorpe et al. 1999). However, nothing is known about progressive internal wave dynamics in the deep hypolimnion layers of Lake Geneva.

Another source of turbulent mixing in the deep ocean is the frictional decay of inertial motions (van Haren and Millot 2005). Bauer et al. (1981) reported occasional inertial motions in Lake Geneva, sometimes in a sequence of five to six circles, primarily in the stratified upper layers. These motions completed full circles in the local inertial period of 16.5 h and occurred after a suddenly imposed or suddenly changed wind stress. The authors emphasized that this was the first observation of inertial motion in such a small water body (lake width \( O(10 \text{ km}) \)). Inertial oscillations were also detected in the upper layers in the Great Lakes (Mortimer 2004, 2006; Rao et al. 2008). No inertial motion observations in the deep hypolimnion layers of deep lakes seem to exist.

In the present study, aspects of the long-term dynamics of the deep hypolimnion (below 150 m depth) of Lake Geneva during the summer stratification period (May to October) are investigated. Time series of temperature and horizontal current data obtained from moored instruments and full-depth profiles of temperature and oxygen taken at approximately monthly intervals, all recorded for over a decade at a location in the center (deepest part) of the lake are analyzed. The following questions are addressed: (1) Is the deep hypolimnion directly affected by surface layer dynamics during stratification? (2) Do processes take place in the deep hypolimnion that act year-after-year in the same manner and intensity, and yet are independent of climate change, but may be comparable to those observed in the deep ocean? (3) How are deep layer dynamics during the stratification period affected by processes occurring during the rest of the year? and (4) Can these processes be explained by traditional 1D concepts, or are they three-dimensional (3D)?

**Materials and methods**

**Study site**

Located between Switzerland and France, Lake Geneva, also referred to as Lac Léman in the literature, is Western Europe’s largest lake. It is a crescent shaped, deep, warm, monomictic, perialpine lake with a mean surface elevation of 372 m and is approximately 70 km long, with a maximum width of 14 km. It has a surface area of 582 km\(^2\) and a volume of approximately 89 km\(^3\). The lake is composed of two basins: an eastern
deep, wide basin called the Grand Lac (maximum depth 309 m), and a western shallow, narrow basin, the Petit Lac (maximum depth approximately 70 m) (Fig. 1). The lake is flanked by the Jura Mountains in the northwest, and by the Alps in the south and, to a lesser extent, the northeast (Fig. 1). This topography creates a wide “corridor” through which two strong dominant winds, namely the Bise coming from the northeast, and the Vent from the southwest pass over most of the lake surface (Lemmin and D’Adamo 1996).

The width of Lake Geneva corresponds to approximately 2.4 Rossby radii during mean summer stratification, and Coriolis force plays a role in the lake’s dynamics. The main inflow, the Rhône River (Rhône-in) at the eastern end of the lake and the main outflow (Rhône-out) at the western end of the lake are marked in Fig. 1. The theoretical (water) residence time (also called flushing time in the literature) is 11.3 yr (CIPEL 2018). Most years, Lake Geneva remains stratified year-round. Occasionally, during severely cold winters, the water column may become nearly isothermal in late March. In May, a thermocline is well developed at approximately 15–20 m depth and continues to strengthen until September when it starts to sharpen and move downwards.

**Time series**

In 2001, a mooring, hereinafter called Midlake Mooring (for location, see MM on Fig. 1), was installed and operated by the author on the central 300 m deep plateau (~ 12 km x ~ 6 km), which is also the deepest part of the lake (maximum depth 309 m); it was maintained during most of the period from 2001 to 2015. Water temperatures were taken every 10 min year-round at depths of 120, 180, 240, and 305 m using Seabird temperature nodes (resolution 0.001 K; drift 0.001 K yr\(^{-1}\)). Currents, and at times, oxygen, were measured with an Aanderaa RCM9 acoustic current meter (hereinafter referred to as RCM9). The RCM9 measures the horizontal current components at a single level. Initially, it recorded every 10 min, then later on in
the study, every hour, in order to extend the recording period. Depending on the day the instrument was put into the lake, it did not always provide full stratification (May to October) coverage in all years due to battery capacity limitations. However, most data files analyzed start on 1 May. In 2001, three RCM9 current meters were deployed at 246, 299, and 304 m depth.

In addition to Midlake Mooring data, the analysis included time series data of air temperature taken at 10 m height and lake near-surface temperature at 1 m depth that were recorded every hour for the years 2002–2016 at the near-shore EPFL station, Buchillon Mast (Fig. 1; Graf et al. 1984), as well as oxygen data collected using an optode in the deep hypolimnion of Lake Geneva by the Russian MIR submarines in summer 2011 during the international Project element (Lemmin 2016). These data were combined with temperature and pressure in order to determine oxygen saturation.

**Full-depth profiles**

The Commission Internationale pour la Protection des Eaux du Léman (CIPEL) (https://www.cipel.org/en/; last accessed 15 September 2019) is a Swiss–French intergovernmental organization that monitors Lake Geneva water quality. Since 1957, CIPEL has regularly measured water temperature and oxygen profiles at locations SHL2 (309 m depth) and GE3 (70 m depth) in the Grand Lac and Petit Lac, respectively, at a frequency of 1–2 profiles per month and reported them at selected depths. The focus here will be on CIPEL data from station SHL2 (Fig. 1), and mainly profiles taken between 1980 and 2015 will be analyzed. SHL2 is located in proximity to the Midlake Mooring site and both are sufficiently far from the Rhône River, the main inflow into the lake, (Fig. 1). Thus, effects of river-induced through flow on temperature profile dynamics can be neglected during summer stratification (Rahaghi et al. 2018).

In order to identify the data sources, the figures have headings: “CIPEL” for data collected by CIPEL at the SHL2 monitoring station; “Midlake Mooring” and “Buchillon Mast” for field data collected by the author at these two sites; “MIR” for data recorded by the MIR submarines.

**Results**

**Temperatures**

When studying the long-term temperature dynamics of the deep hypolimnion layers of a lake, in particular when investigating the potential consequences of climate change on these layers, it is important to first quantify climate change effects in the near-surface layers. In Lake Geneva, annual mean values of CIPEL profile data show a trend of increasing air temperature around the lake and a comparable increase in the surface water temperature (Fig. 2a). For the period 1980–2016, a mean increase in air temperature of 0.39°C decade⁻¹ and of 0.41°C decade⁻¹ in surface water temperature is indicated by the linear trend lines (Fig. 2a). Gillet and Quetin (2006) suggested a water temperature increase of 0.056°C yr⁻¹ for the period 1983–2001. O’Reilly et al. (2015) reported for Lake Geneva a water temperature increase of 0.11°C decade⁻¹ from in situ measurements taken over a 23-yr period, and a decrease of −0.49°C decade⁻¹ from satellite images, over a 13-yr period. However, the correlation coefficient for the linear trend in Fig. 2a is low and the standard error is high and comparable to the weather-induced year-to-year annual mean temperature change. Furthermore, if only the period 2000–2013 is considered, the mean air temperature increase is smaller than the long-term trend, in agreement with worldwide observations, and yet, the range of the year-to-year variability did not decrease during that period in Lake Geneva.

In order to determine the statistical significance of the CIPEL data, a full year (2014) of hourly data of the near-surface temperature at 1 m depth and the air temperature at 10 m above the lake surface that were recorded at Buchillon Mast were analyzed (Fig. 2b; for location, see Fig. 1). The actual extent and shape of this data cloud changes from year-to-year and reflects the weather pattern of that particular year. A hysteresis loop with a wide extent is observed. Three distinct regimes can be distinguished in this loop: (1) Winter cooling occurs at the beginning of the year from January to late March under mainly unstable atmospheric boundary layer (ABL) conditions when air temperatures fluctuate over a wider range than the corresponding water temperatures; (2) From late March to July, the lake warms under predominantly stable ABL conditions. However, unstable conditions are also seen during this period, mainly due to nighttime cooling; and (3) From August to the end of the year, the lake cools under unstable ABL conditions causing convective mixing. From this data set, annual mean values of air temperature and near-surface water temperatures for 2014 are 10.8°C and 12.9°C, respectively, whereas CIPEL reports 11.7°C and 13.1°C, respectively, for the same period. The two mean surface water temperatures are close to each other. The greater difference in the mean air temperature is mainly due to the fact that CIPEL air data are measured over land, not in the ABL over the lake, as is the case at Buchillon Mast.

A strong interannual scatter of the annual mean temperature is still evident at 50 m depth (Fig. 2a), and the linear multidecadal trend increases much slower than near the surface. The annual mean temperature time series trends at greater depths show similar patterns (Fig. 2c). The amplitudes of the interannual fluctuations decrease with increasing depth. A nonsignificant linear trend with a comparable slope and large standard error is seen at all four depths in Fig. 2c. At 309 m depth, an increase of 0.062°C decade⁻¹ is found. This is much lower than the weakly significant trend of approximately 0.4°C decade⁻¹ in the near-surface layer and in the atmosphere (Fig. 2a).

A saw-tooth pattern of multiannual continuous warming and more abrupt cooling is apparent at all layers and becomes increasingly evident when approaching the lake bottom (309 m depth; Fig. 2c). The slope of the increase in all the multiannual warming phases of the saw-tooth pattern at
309 m depth is similar (Supporting Information Fig. S1), indicating that the same processes were active during all these multiannual warming phases. It should be noted that from 2004 to 2012, the annual mean temperature at 309 m depth decreased by 0.8°C. This is the longest and strongest cooling period in the near-bottom layer of Lake Geneva, since CIPEL started taking measurements in 1957.

In order to study in more detail deep hypolimnion temperature dynamics, Seabird data that were recorded every 10 min at the Midlake Mooring (Fig. 1), were analyzed. Several features of the deep-water dynamics become apparent from the example for the 3-yr period 2001-2003 (Fig. 3). The amplitude of the temperature fluctuations changes from year-to-year, as is most evident at 120 m depth, and strongly decreases with depth. A linear increase in temperature occurs during stratification at 180 m depth and below. Cooling in winter 2001-2002 descends only down to approximately 240 m and does not reach the lake bottom. This cooling does not change the

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**Fig. 2.** (a) Annual mean temperatures at different depths taken at the CIPEL monitoring station SHL2 (for location, see Fig. 1) and air temperatures around the lake. The corresponding linear regression lines are shown, (b) scatter plot of hourly values of water temperature at 1 m depth and air temperature at 10 m height measured in 2014 at Buchillon Mast (for location, see Fig. 1). The year was divided into three periods, as indicated in the legend. Stable and unstable refer to atmospheric boundary layer stability. Separate running means over a 30-day period were calculated for the stable and unstable period. The black cross marks the mean value of the whole year for water and air temperature, and (c) annual mean temperatures at SHL2 for different depths. The legend gives the depths and indicates the corresponding linear regression coefficients r and standard errors S.
mean temperatures at the different depths and the increasing trend seen in 2001 continues into 2002.

During winter 2002-2003, cooling reaches the lake bottom (Fig. 3). Cooling occurs as a sequence of individual events. Temperatures below 180 m, in particular, below 240 m depth, significantly fall below any values seen in the water column above, thus indicating that the cold water in these deep hypolimnion layers cannot come by way of vertical convection. Other processes, such as laterally advected density currents, have contributed to cooling in the deep layers more than vertical mixing, making deep hypolimnion cooling a highly 3D process. After the 2002-2003 cooling period, the whole-water column temperature pattern is shifted downwards, but the vertical gradient is maintained, and temperatures below 120 m increase again quasi-linearly at the same rate as that in the previous 2 years.

The long-term significance of the quasi-linear warming trend in the deep layers, evident in the above example for 2001-2003, was further investigated by comparing Seabird data taken at 304 m depth during the stratification period (May to October) for all the years when measurements were made. Close to the lake bottom, the rate of this seasonal increase varies very little from year-to-year (Fig. 4a). The linear regression correlation coefficient in all years is above 0.9. No major events significantly disturbed this trend at that depth. However, smaller fluctuations vary in intensity in different years. For each year, the temperature at the beginning of the recording is determined by the intensity of cooling during the preceding winter. Note that the seasonal mean temperature decreased from 2002 to 2012. From these data, the temperatures at the deepest part of the lake increased by approximately 0.03°C over the 6-month period for all years. This is a significantly greater increase in temperature compared to the multidecadal mean trend in this layer (Fig. 2c; ~ 0.006°C yr⁻¹) and is also a greater increase than the climate change-induced trend in the near-surface layer (Fig. 2a; ~ 0.04°C yr⁻¹).

For most years, the vertical temperature differences between 240 m and 305 m depth do not significantly change with time over the whole summer stratification period and are of comparable magnitude in different years (Supporting Information Fig. S2). A similar pattern can be seen for the annual mean temperatures for the period 1980–2015 (Supporting Information Fig. S3). In the box plots of the temperature differences between 240 m and 305 m depth (Fig. 4b), a narrow interquartile range of 0.01–0.03°C is found, signaling a near constant gradient. These temperature differences correspond to a mean vertical temperature gradient of approximately 0.0005°C m⁻¹ which is a value comparable to those reported in the deep ocean.

For the years 2012–2014, vertical temperature differences are higher than in the other years (Fig. 4b), suggesting that a major change in the deep hypolimnion temperature gradient occurred in 2012. Its amplitude then progressively decreased in 2013 and 2014. During the first 3 months of 2012, a significant drop in lake heat content was observed (Rahaghi et al. 2018). CIPEL profile data from January to February 2012 show that temperatures in the whole-water column decreased, except at 250 m depth (Fig. 5a), indicating that above 250 m, convective cooling from the surface down dominated, whereas cooling was most likely due to lateral advection in
the layers below 250 m. This cooling pattern is similar to the one in winter 2002-2003 (Fig. 3). From February to March 2012, the temperatures down to 200 m changed little (Fig. 5a). However, the layer below 200 m depth cooled further and in the process, eliminated the warm layer at approximately 250 m and maintained a strong gradient from 200 m depth down to the bottom. This pattern again emphasizes the importance of lateral cold-water advection in the deep hypolimnion layers. During summer, until October, temperatures between 150 m and 250 m remained nearly constant, while temperatures below 250 m increased (Fig. 5a). Thus, this strong winter cooling event in 2012 changed the rate of deep-water warming (Fig. 4a), as well as the vertical temperature gradient in the stratification period of 2012 (Fig. 4b).

Fig. 4. (a) Temperature time series at 304 m depth at the Midlake Mooring for the summer stratification period (May to Oct) during different years. The year is indicated for each curve, and (b) box plots for the temperature differences between 240 m and 309 m depth for the same years. The red horizontal lines and the blue rectangles indicate the median and the interquartile range (25–75 percentiles), respectively. The length of the whiskers is specified as 1.5 times the interquartile range.
Oxygen

Oxygen concentration is a major parameter for determining the water quality of an ecosystem. Therefore, CIPEL has always simultaneously taken full-depth profiles of temperature and oxygen at station SHL2 (Fig. 1). In the present study, no detailed analysis of oxygen dynamics was carried out. Instead, oxygen data are used here as “tracers” in conjunction with the study of the physical parameters. Oxygen concentration in the near-bottom layer not only changes strongly over time during the stratification period, but also over longer time scales (Supporting Information Fig. S4). In most years, during the stratification period, oxygen data at 309 m depth decreased quasi-linearly with time (Fig. 6), while temperature increased quasi-linearly during the same period (Fig. 4a). Between 1957 and 2012, the slope of the linear fall-off is comparable in all years investigated (Fig. 6). During that period, the trophic status changed from oligotrophic in 1957 to a eutrophic peak in the late 1970’s, and then returned to near oligotrophic conditions after the implementation of effective eutrophication control measures (CIPEL 2018). The eutrophication level seems to have no effect on the fall-off slope of the linear trend of oxygen during stratification.

![Fig. 5. Selected CIPEL profiles measured at SHL2 for the year 2012 for: (a) temperature, and (b) oxygen. See legends for the dates the profiles were taken.](image)

![Fig. 6. Oxygen gradients at 309 m depth at SHL2 over the summer stratification period for different years. Years are given in the legends with their corresponding linear regression coefficients r and the standard errors S.](image)
Superimposed on this linear trend, temporal, lateral and vertical oxygen concentration variability is found. Noticeable short-term time variability is seen in the time series of the oxygen data recorded by the RCM9 current meter at the Midlake Mooring (Fig. 7a; for details, see Discussion section). In summer 2011, the oxygen concentration near the bottom of Lake Geneva was recorded along the dive trajectories of the Russian submarines MIR and the percentage (%) oxygen saturation was then calculated. An example is given in Fig. 8 from a straight-line MIR 1 trajectory that diagonally crossed the central 300 m deep plateau from the northwest to the southeast (see Fig. 1). Along each of the three near-bottom legs of the trajectory, the submarine remained nearly stationary, collecting sediment cores, water samples and taking measurements. Oxygen saturation values shown in Fig. 8 for each of the three legs are the mean of 20–40 samples measured after the sensor had adjusted. The range of variability between different samples of each leg is less than 3%. Over a total distance of approximately 8 km, however, oxygen saturation changes substantially (Fig. 8). Furthermore, in many instances, a significant difference was observed between oxygen depth profiles taken by the MIRs during their straight vertical descent at one location, and during their straight vertical ascent at another location. This large spatial variability in the near-bottom layer, which apparently has not been reported before, indicates that care has to be taken when extrapolating measurements from single position profiles to the whole lake, as is often done, for example, when the oxygen stock of the lake is calculated.

Near-saturation oxygen levels close to the bed (Fig. 6) are generally considered to be the result of full-water column convective overturning due to severely cold winter conditions. According to this concept, oxygen is brought from the surface down to the lake bottom by vertical convective deep mixing. However, oxygen profiles taken by CIPEL during those cold winter years do not always support this concept. An example from 2012 shows a strong oxygen minimum at 275 m depth (Fig. 5b) in February, with oxygen concentration near
the bed having increased to above 8 mg L\(^{-1}\) from approximately 3 mg L\(^{-1}\) in January. In March, oxygen saturation is reached at the lake bottom and the minimum has moved up to 200 m depth. This minimum is maintained well into the stratification period. Vertical mixing cannot produce such profiles and the corresponding temperature profiles that have been discussed above (Fig. 5a), likewise, do not support vertical, whole-water column cooling. Similar profiles and time development are found for other years when near-bottom oxygen saturation was reached. These profiles indicate that oxygen concentrations in the lowest layers of the hypolimnion, that is, below 275 m depth, were not the result of convective vertical mixing, or at least, not of vertical mixing alone. Lateral advection of oxygen must have occurred in these lowest layers.

### Currents

Little was known about the current dynamics in the deep hypolimnion layer of Lake Geneva prior to the year 2000, because no long-term current measurements had been carried out. The author therefore installed in 2001 an Aanderaa RCM9 acoustic current meter, hereinafter referred to as RCM9, at the Midlake Mooring at approximately 5 m above the lake bottom (304 m depth). There are currents close to the bottom most of the time, and a wave-like pattern is often evident in the current structure (Fig. 7b), as detailed below. Seasonal mean current speeds in all years are 3.0 ± 0.5 cm s\(^{-1}\). Current speeds above 5 cm s\(^{-1}\) are most often observed at the beginning and at the end of the stratification period when the thermocline is weakest and winds are stronger than during the peak of stratification, and these speeds may reach up to 12 cm s\(^{-1}\) (Supporting Information Fig. S5).

**Fig. 9.** Progressive vector diagram at 304 m depth at the Midlake Mooring for: (a) May 2008, and (b) the summer stratification period of 2015.

**Fig. 10.** Spectra of: (a) the two horizontal velocity components, and (b) oxygen from the RCM9 recording at the Midlake Mooring, for summer 2003. In both spectra, a peak is seen near the inertial frequency of Lake Geneva (marked f).
The direction histogram is generally flat, and may display a “hump” for a certain sector; both change from year-to-year.

When a short excerpt of the current-direction time history is plotted (Supporting Information Fig. S6), a nearly continuous steady clockwise rotation of the direction can be observed for several days. Similar segments occur at other times during the recording and are found in all current recordings for all years. The period of a rotation is approximately 16 h (Supporting Information Fig. S6); this is close to the inertial period for the latitude of Lake Geneva (16.5 h). A progressive vector diagram for the same period is characterized by a sequence of circles that slowly decrease in diameter with time (Fig. 9a). A diameter of 1 km corresponds to a mean velocity of approximately 5 cm s⁻¹ under steady conditions. With time, this rotation may die out and the period becomes shorter. However, soon after, a new sequence of rotation is initiated.

The progressive vector diagram for summer 2015 highlights the quasi-permanent inertial circling observed during the whole summer stratification period (Fig. 9b). The summary of progressive vector diagrams for all summers when current data were recorded (Supporting Information Fig. S7) indicates that in all years, a nearly continuous circular motion is superimposed on unidirectional currents whose direction and intensity changed from year-to-year. A spectral analysis carried out for summer 2003 shows a significant peak at the inertial frequency for Lake Geneva for both current components (Fig. 10a; Supporting Information Fig. S8). Spectra for all other years provide comparable results, always with only one significant peak located at the inertial frequency, thus indicating the strong presence of inertial motion in all years (Supporting Information Fig. S7).

Aspects of the depth structure of currents were investigated by comparing recordings taken by three RCM9 current meters at the Midlake Mooring in 2001. The instruments were placed at 236 m, 299 m, and 305 m depth and recorded from June to the end of September. At all three depths, the overall structure of the currents is similar, with inertial motions clearly dominating (Fig. 11); this excerpt is representative for the whole record. It appears that the current amplitudes at 236 m depth are at times slightly smaller than those of the deeper instruments. This would suggest that inertial motion is reflected from the lake bottom.

**Discussion**

**Temperature**

During the stratification period for all years when data were available, deep hypolimnion water layers warmed at almost the same linear rate (Fig. 4a), while at the same time, the vertical temperature gradient in the lowest 60 m of the water column (240 m to 304 m depth) did not change significantly with time (Fig. 4b). This continuity indicates that deep hypolimnion dynamics are not directly affected by atmospheric forcing events whose effects were evident higher in the water column (e.g., strong temperature fluctuations at 120 m depth; Fig. 3). Deep-water warming may be caused by turbulent mixing, advection of warm water or geothermal heat flux. The latter varies from 0.07 to 0.13 W m⁻² in several Swiss lakes (Finckh 1981; no measurements exist for Lake Geneva) and is too small to produce any measurable deep-water warming. In an ongoing Ecological Engineering Laboratory (ECOL) investigation, it was observed that the turbidity currents generated by the Rhône River plume might occasionally carry warm waters through the Rhône River canyon into the deeper layers of the lake (K. Blanckaert pers. comm.). However, these events are rare and have too short a duration to produce the observed linear warming trend in the deep hypolimnion layers.

The vertical diffusion coefficient profiles reported by Michalski and Lemmin (1995) and those that can be estimated by combining the rate of temperature increase and the vertical temperature gradients in the deep layers observed in the present study, suggest that turbulent diffusion can explain this temporal temperature increase during stratification. Turbulent diffusion in the interior of the deep hypolimnion can result from (1) the downward penetration of turbulence produced in the near-surface layers, (2) the horizontal penetration of shear produced over the lateral slopes of the lake, or (3) processes occurring within the deep hypolimnion.

For case (1) above, the profile of the vertical diffusion coefficient $K_z$ (Michalski and Lemmin 1995) suggests that downward penetration is not a dominant process. For case (2) above, studies over the lateral slopes of Lake Geneva (Thorpe and Lemmin 1999; Fer et al. 2002b; Cimatoribus et al. 2018) have shown that shear is produced there. This shear, therefore, may contribute to turbulent diffusion in the interior of the lake. And finally, for case (3) above, it should be noted that vertical temperature gradients in the deep hypolimnion
of Lake Geneva observed in the present study, and vertical diffusion coefficients are comparable to those that have been reported for the deep layers of oceans where turbulent mixing is mainly attributed to the breaking of progressive internal waves in those layers (Gregg 1987; Garrett and St. Laurent 2002; Garret 2003) and to the frictional decay of inertial motion (van Haren and Millot 2005; Alford et al. 2016). Progressive internal waves that have been observed in the upper layers of Lake Geneva (Thorpe et al. 1996, 1999) occur at all times, and as the present investigation shows, also in the deep hypolimnion (Supporting Information Fig. S9). Spectra calculated for the temperature data of different depths have a broad peak in the range between the inertial frequency and the buoyancy frequency and no peak at the inertial frequency.

In the present study, inertial motions were found to be quasi-permanently excited in the deep layers during summer stratification for all years when data were available (Figs. 7, 9; Supporting Information Fig. S7), and thus are an important contributor to deep-water dynamics. Inertial motions regularly decayed due to friction before a new set was activated. Therefore, analogous to the deep ocean, shear produced locally within the deep hypolimnion by breaking internal waves and decaying inertial motion can be expected to be significant contributors to turbulent mixing in the lake’s deep hypolimnion layers. Friction resulting from the variability of the nearly permanent unidirectional currents observed in the deep hypolimnion in this study are another source of locally produced turbulent mixing. These processes are not affected by climate change.

Although several years with annual mean air temperatures well above the long-term average were recorded over the past decade in Central Europe, the seasonal mean temperatures close to the lake bottom actually decreased, starting in 2002 (Fig. 4a), mainly due to several colder than average winters during that period. This winter cooling determines what the temperature will be at the beginning of the next stratification period, but it does not affect the near-constant warming rate of that stratification season, except after severe winters such as the one in 2012 (Figs. 4, 5). Winter cooling can be caused by vertical convection, plunging inflows, and density currents (resulting from differential cooling). Convective cooling is often considered to be the dominant process for deep-water cooling, particularly in shallower lakes. However, evidence provided here for Lake Geneva indicates that in a deep lake, other processes (e.g., lateral advection) may be equally or more important. This study has made evident that during colder than average winters, lateral advection in the deepest layers contributes strongly to the cooling and the reoxygenation in those layers. An oxygen concentration increase at 309 m depth was documented for all years (Supporting Information Fig. S4), even in those years with relatively warm winters when convective cooling barely went below 100 m depth; this can only be the result of lateral advection.

Lateral advection in the bottom layers of a lake can result from diverse processes. As an ongoing ECOL Rhône River plume study confirms, some deep-water cooling in Lake Geneva may result from occasional, dense, sediment-laden turbidity currents (Giovanoli 1990). However, they are not sufficiently frequent or intense enough to be the dominant contributor to cooling. In another ongoing ECOL investigation dealing with the water exchange between the shallow Petit Lac basin (maximum depth 75 m) and the deep Grand Lac basin (maximum depth 309 m), a thick cold bottom boundary layer at the junction of the two basins (red line in Fig. 1) was frequently observed during winter which then plunges into the Grand Lac, affected by the Coriolis force. Previously reported density currents generated over the lateral slopes of Lake Geneva by differential cooling may further contribute to deep-water cooling by lateral advection (Fer et al. 2002a). Ambrosetti et al. (2010) suggested that cold-water density currents contributed to deep-water oxygen renewal in Lago Maggiore (370 m depth), as well as in other deep lakes on the southern slope of the Alpine mountains. The possibility that such density currents could exist in Lake Geneva was already hypothesized by Forel (1895).

### Currents

During stratification, the current dynamics of the deepest layers in Lake Geneva are dominated by quasi-permanently occurring circular inertial motions (Figs. 7, 9, 11; Supporting Information Fig. S7). It has been shown that inertial motions are most often generated by strong wind stress impulses in the ocean (e.g., D’Asaro et al. 1995; Alford et al. 2016) and in lakes (Bauer et al. 1981; Mortimer 2006; Rao et al. 2008). The wind field over Lake Geneva during summer is characterized by weak winds, with diurnal winds being a prominent component, and by occasional thunderstorm impulses (Lemmin and D’Adamo 1996). This wind field, however, appears not to be strong enough to generate the quasi-permanent inertial motions in the near-bottom region. Unfortunately, the origin of the inertial motions cannot be determined with the presently available data.

In the conceptual model applied most often to inertial motions on the scale of lakes, it is assumed that the vertical component of the velocity field can be ignored, because stratification, expressed by the buoyancy frequency $N$, is sufficiently strong in the layers where these motions have been previously observed (Bauer et al. 1981; Mortimer 2006; Rao et al. 2008). Therefore, only the component of the Coriolis term that is aligned with the local vertical is considered. However, Gerkema et al. (2008) pointed out that this concept, which they termed “traditional approximation,” might not be universally valid. They concluded that under weak stratification, the meridional component of the Coriolis force (the cosine term) can no longer be neglected. In the cosine term, the motion field in the vertical is always involved. For very small buoyancy frequencies in the deep layers of the Mediterranean Sea, the inertial periodicity of the vertical velocity component was well documented for a 200 m thick layer...
where it was also seen in the horizontal velocity component (van Haren and Millot 2005). According to Gerkema et al. (2008), this indicates that for weakly stratified layers, the concept of the traditional approximation may not hold.

In the near-bottom layers of Lake Geneva, the Midlake Mooring measurements show a vertical temperature difference of 0.03°C or less between the Seabird temperature nodes at 240 m and at 304 m (Fig. 7b), resulting in a mean vertical temperature gradient of approximately 0.0005°C m⁻¹ and thus in \( \frac{N}{2} \Omega \approx 3 \), with \( \Omega \) being the Earth’s angular velocity. This value falls into the range where Gerkema et al. (2008) suggest that nontraditional effects can be significant for the dynamics. Lacking the vertical velocity component in the current measurements to test this concept, oxygen was used as a tracer instead in the present study. When oxygen and the horizontal velocity components, which are both measured simultaneously by the RCM9 current meter, are plotted for summer 2003, it can be seen that the oxygen concentration changes regularly with a periodicity, matching that of the velocity components (Fig. 12). The long stability of this pattern can occur if there is a steady vertical oxygen concentration gradient in this layer, as is often evident in CIPPE profiles (cf. Fig. 5), and if the inertial motion is not horizontal. Noteworthy is that oxygen spectra only have one peak located at the inertial frequency (Fig. 10b), matching the peak frequency of the velocity components (Fig. 10a). Such a match between currents and oxygen has apparently not been previously observed. Similar results, and in particular, the peak in the oxygen spectra were also found in 2002. Unfortunately, oxygen time series using the RCM9 were not measured in the remaining years.

Other concepts for inclined inertial motions have been proposed for stratified (Friedlander and Siegmann 1982; Maas 2001) and nonstratified conditions (Maas 2003). However, as Alford et al. (2016) pointed out, discrete current measurements at a single depth, as were made in the present study, cannot define the spatial structure of inertial motions. Current profilers would be needed to provide the phase structure in the vertical, and the horizontal structure can be investigated with multiple moorings.

**Conclusions**

This analysis of high resolution long-term temperature and horizontal current time series and full-depth profiles of temperature and oxygen has allowed identifying or shedding some light on dominant long-term processes in the deep hypolimnion of Lake Geneva that appear to have not yet been documented or with such detail. These measurements have made evident for the first time the following for:

**Temperature**
- During summer stratification, a quasi-linear warming trend with the same slope was found close to the bottom of Lake Geneva for over 10 yr (2001–2014).
- From 2001 to 2014, temperatures close to the lake bottom increased at a faster rate than the climate change-induced trend of rising temperatures in the lake’s near-surface layers.
- The vertical temperature differences over the lowest 60 m (240 m to 304 m depth) of the water column also remained nearly constant for over 10 yr (2001-2014) and were comparable to those of the deep ocean.
- Year-to-year weather variability provided for winter cooling of different intensity in different years and no continuous long-term warming occurred in the deep hypolimnion; in fact, mean stratification seasonal temperatures actually dropped from 2002 to 2012.
- Progressive internal waves were observed at all times in the deep hypolimnion.

**Oxygen**
- During summer stratification, oxygen concentration close to the lake bottom decreased linearly at approximately the same rate in different years and appeared not to be affected by the eutrophication level.
- Important spatial and temporal oxygen concentration variations were superimposed on that linear trend.

**Currents**
- In the deep hypolimnion of Lake Geneva, water masses are rarely stagnant. Mean current velocity at the deepest point was 3.0 ± 0.5 cm s⁻¹.
- The dominant feature of the current field is the quasi-continuous excitation of inertial motion, which, it seems,
has never been observed before in the hypolimnion of a deep lake.

- Due to the weak temperature gradient in the deep hypolimnion, the axis of the inertial motion may be inclined.

The analysis of this data suggests that:

- During summer stratification, turbulent diffusion in the deep hypolimnion of Lake Geneva is mainly generated locally by breaking internal waves and by frictional decay of inertial motion within that layer, as is the case for the deep ocean, where similar temperature gradients and diffusion coefficients have been reported. These processes are not affected by the climate change-induced warming trend.

- During winter, year-to-year weather variability determines whether warming will be continuous or cooling will occur in the deep hypolimnion. The observed climate change-induced trend of warming of the near-surface layers of the lake has no direct effect on deep hypolimnion dynamics. In fact, historically, it appears that there has hardly been any change over the past 240 yr: In 1777, de Saussure recorded 5.4°C at the lake bottom (309 m) and Forel reported comparable values for several years (5.2°C in 1879; 5.0°C in 1883; 5.4°C in 1884; 5.6°C in 1885; 5.3°C in 1886). These measurements have a precision of 0.1°C (FitzGerald 1895).

- Winter cooling is a highly 3D process where every year lateral advection of cold waters increases the oxygen concentration near the lake bottom and may reduce the temperature of the deep hypolimnion.

- During cold winters, lateral advection appears to be more important to deep hypolimnion water renewal than convective vertical downward diffusion.

- Traditional 1D concepts that propose winter cooling only by vertical convection from the surface down to the lake bottom and which also transports at the same time, oxygen to these deepest layers, cannot realistically describe the deep hypolimnion processes in Lake Geneva.

In this investigation, the observed year-to-year variability in temperature and oxygen concentration in the deep hypolimnion is clearly linked to winter cooling due to climate change-induced variability, rather than to the climate change-induced warming trend. In a recent climate change study on Switzerland (CH2018 2018), it was predicted that despite a general warming climate trend, “cold winter periods will continue to occur for several more decades due to the very high variability of winter temperatures.” Furthermore, that report also specified that the source regions of the cold air advected toward Switzerland (mainly as a Bise wind; see Fig. 1) in winter are located in the continental high latitudes. Kretschmer et al. (2018) demonstrated that cold spells observed in those regions during winter are due to weak stratospheric polar vortex states and may be linked to Arctic amplification (Cohen et al. 2014). Francis and Vavrus (2012) and Vavrus et al. (2006) hypothesized that such cold spells in those regions would continue into the future, in agreement with the CH2018 (2018) predictions. This suggests that the probability of strong winter cooling in the deep hypolimnion of Lake Geneva will be maintained. Indeed, if this scenario actually does play out, then the water quality in the deep hypolimnion of Lake Geneva will change little or may even improve in the future, at the same time that its near-surface waters suffer from the consequences of the climate change-induced warming trend.

From the insights obtained in this analysis, it is evident that further in-depth whole-water column investigations are needed. For example, current profilers can provide the phase structure in the vertical, and multiple simultaneously recording moorings can be used to define the horizontal structure. Only then can effective management strategies be drawn up that can properly monitor, maintain and improve the “health,” that is, the water quality, of deep lake systems.

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Conflict of Interest

None.