Effects of climate change on deepwater oxygen and winter mixing in a deep lake (Lake Geneva): Comparing observational findings and modeling

Robert Schwefel1, Adrien Gaudard2, Alfred Wüest1,2, and Damien Bouffard1

1Physics of Aquatic Systems Laboratory, Margaretha Kamprad Chair, École Polytechnique Fédérale de Lausanne, Institute of Environmental Engineering, Lausanne, Switzerland, 2Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters – Research and Management, Kastanienbaum, Switzerland

Abstract Low concentrations of dissolved oxygen remain a global concern regarding the ecological health of lakes and reservoirs. In addition to high nutrient loads, climate-induced changes in lake stratification and mixing represent additional anthropogenic menace resulting in decreased deepwater oxygen levels. The analysis of 43 years of monitoring data from Lake Geneva shows no decreasing trend neither in the areal hypolimnetic mineralization rate nor in the extent of hypoxia. Instead, hypoxic conditions are predominantly controlled by deep mixing in winter and much less by the trophic variations over the past decades. To reproduce winter mixing, the one-dimensional hydrodynamic model SIMSTRAT was specially adapted to deep lakes and run for several climate scenarios. The simulations predicted a decrease in the maximum winter mixing depth from an average of ~172 m for 1981–2012 to ~136 m and ~127 m in response to predicted atmospheric temperatures between 2045–2076 and 2070–2101 according to Intergovernmental Panel on Climate Change scenarios. Concurrently, events with complete homogenization of temperature and oxygen in winter will decrease by ~50%. Consequently, the hypolimnetic oxygen concentrations will significantly decrease. These results demonstrate that changes in deep mixing can have stronger impact than eutrophication on the deepwater oxygen levels of oligomictic lakes.

1. Introduction

Among the various parameters used to monitor the health of lake ecosystems, dissolved oxygen remains of utmost importance. During the twentieth century, hypoxia in lakes and oceans increased significantly due to eutrophication caused by anthropogenic nutrient inputs [e.g., Diaz, 2001; Farley, 2012; Friedrich et al., 2014]. Thus, initial lake management efforts focused on reducing nutrients and in turn, many empirical models were proposed to quantify oxygen depletion utilizing nutrient loading and lake morphometry [e.g., Comet and Rigler, 1979; Matthews and Effler, 2006; Müller et al., 2012]. Although the use of these models often facilitated meaningful solutions in the form of nutrient load reduction and often led to an increase in water quality, the relation between phosphorus and oxygen depletion in lakes is still not completely understood [Gächter and Müller, 2003].

The effect of global warming on water quality of lakes and reservoirs and on oxygen renewal, in particular, is currently a critical concern [Fang and Stefan, 2009; Foley et al., 2012; Zhang et al., 2015]. Average lake surface temperature increases of 0.01–0.1°C yr−1 have been observed in the recent past [Schneider and Hook, 2010; Shimoda et al., 2011; O’Reilly et al., 2015] and a further increase is predicted [Schmid et al., 2014]. A major effect of global warming is to increase the duration of summer stratification. Foley et al. [2012] analyzed four decades of data from a small temperate lake in England and observed an average increase of 38 days in the duration of summer stratification. This change led to an increase in hypolimnetic anoxia, despite the fact that the rate of oxygen depletion decreased during the assessed four decades. Besides the extent of the stratified season, the maximal depth of convective mixing in winter (i.e., “winter mixing”) also plays a key role for oxygen renewal in deep lakes. Therefore, climate-induced reductions in the intensity of winter mixing directly affect the oxygen budget. Livingstone [2003] and North et al. [2014] found an increase in stratification and hypoxia in Lake Zurich based on data dating back to 1949. Furthermore, Straile et al. [2003] reported a decrease in deepwater oxygen renewal due to reduced winter mixing in Lake Constance. Zhang et al. [2015] observed similar trends in a deep reservoir in China. Jankowski et al. [2006] and Straile...
et al. [2010] investigated the effect of extraordinary warm periods and concluded that increased thermal stratification will have an impact on the deepwater oxygen content. Few studies, so far, have modeled the impact of climate change on winter mixing and deepwater oxygen budget. Fang and Stefan [2009] simulated the oxygen dynamics of 27 generically designed types of lakes at 209 different hypothetical locations in the U.S. meant to be representative for typical temperate lakes. For the expected conditions, the authors also predicted the effects of a twofold increase in CO₂ concentration in the atmosphere. Their study focused on rather shallow lakes (depth < 24 m), with annually occurring complete winter mixing. Fink et al. [2014] and Perroud and Goyette [2012] used horizontally averaged one-dimensional k-ε turbulence models [Goudsmit et al., 2002] to predict the impact of climate change on the deep waters of Lakes Constance and Geneva. These studies, however, focused on heat budget and lake-atmosphere coupling. Matzinger et al. [2007] assessed the combined effects of atmospheric warming and different nutrient loads on the oxygen budget and temperature structure of Lake Ohrid. The authors concluded that even under decreasing nutrient inputs, hypoxic conditions in the deep water would drastically expand if the air temperature increases at the current rate during the next decades as the lake would become meromictic with a permanently anoxic deep layer. Sahoo et al. [2012] predicted the same for Lake Tahoe where deep mixing and deepwater oxygen concentration will decrease drastically according to numerical simulations based on different IPCC emission scenarios.

We consider Lake Geneva as an ideal water body to investigate the impact of deep winter mixing on hypoxia. Lake Geneva is warm monomictic with irregularly occurring complete winter mixing, thereby leading to hypolimnetic oxygen levels which are highly sensitive to mixing. The extent of hypoxia as well as deepwater oxygen levels showed strong fluctuations over the last 40 years (Figures 1a and 1b). Nevertheless, the...
measured oxygen depletion remained high, despite a drastic reduction in phosphorus concentration from \(90\) to \(20\) \(\mu\)g L\(^{-1}\) between 1980 and 2010 [Savoye et al., 2015; Müller et al., 2014]. In response to the decreasing nutrient input, a subsequent decrease in the areal hypolimnetic mineralization rate (AHM) of organic matter in the hypolimnion was expected. The AHM describes the mineralization of organic matter in the hypolimnion and is identical to the areal hypolimnetic oxygen depletion rate under oxic conditions [Matzinger et al., 2010]. However, the AHM oscillated around a mean of \(1.34 \pm 0.34\) g O\(_2\) m\(^{-2}\) d\(^{-1}\) (calculated as oxygen depletion during summer stagnation below a constant depth of 15 m) without any significant trend over the last 40 years (Figure 1c). We therefore hypothesize that the amount of oxygen resupply during winter mixing events is the governing factor controlling the extent and strength of hypoxia in deep hypolimnia.

To verify this hypothesis, we analyzed 43 years of temperature and oxygen data with focus on (i) water column stability, (ii) deep mixing, and (iii) the occurrence and severity of hypoxia. We also assess possible future changes by numerical modeling based on regional climate predictions [CH2011, 2011] and varying water clarity. The calibrated model provides essential information for investigating the effect of future climate changes on deepwater mixing and oxygen budgets.

2. Methods

2.1. Study Site

Lake Geneva is a deep perialpine lake situated between France and Switzerland (46.45°N, 6.52°E, supporting information Figure S1) at an altitude of 372 m. With a volume of 89 km\(^3\) and a surface area of 580 km\(^2\), it is the largest freshwater lake in Western Europe. Lake Geneva is a warm monomictic lake with deepest seasonal mixing in late February/early March. Due to its maximum depth of 309 m and mild temperatures, the lake never freezes in winter, and complete winter overturns occur irregularly (every fifth year on average). Between 1983 and 2000, the mean annual surface temperature increased by \(18\) C with seasonally increases of up to \(28\) C in summer [Gillet and Quétin, 2006; Molinero et al., 2007]. The length of the stratification period consequently increased [Anneville et al., 2013].

Lake Geneva is still recovering from its eutrophic past. Once considered as an oxygen-rich oligotrophic lake [Forel, 1895; Vivier, 1944], the trophic state turned to eutrophic due to high phosphorus input after 1950 [Lachavanne, 1980]. Until 1980, phosphorus concentration increased by a factor of seven and caused decreasing water transparency, changes in phytoplankton and zooplankton composition and low oxygen concentrations in the deep hypolimnion [Loizeau and Dominik, 2005]. Oxygen measurements were only occasionally performed before 1957, but all measurements showed consistently high oxygen concentrations even in the deepest layers [Forel, 1895; Delebecque, 1898; Vivier, 1944]. Despite a reduction in phosphorus, hypoxic conditions still appear occasionally in the deep layers and AHM remained high.

2.2. Measurements and Analysis of Lake Profiles

Oxygen and temperature profiles are measured regularly since 1957 at point SHL2 (46.45°N; 6.59°E; supporting information Figure S1) by the Commission Internationale pour la Protection des Eaux du Léman (CIPEL). Sampling frequencies were 6–8 times per year before 1970, monthly between 1970 and 1980 and 18–20 times per year after 1980. The number of sample depths per profile varied between 12 and 20. The vertical resolution was 2.5–10 m down to 30 m depth, followed by 50 m between 50 and 250 m depth and again finer below 250 m (mostly at 275, 290, 300, 305, and 309 m). Details concerning the sampling methodology are annually published in the scientific reports of CIPEL, the most recent one is Savoye et al. [2015].

Temperature and oxygen profiles were interpolated vertically and temporally to 1 m and 1 day resolution using cubic spline interpolation. Afterward, water density (\(\rho\)) was estimated from temperature data; and the Schmidt stability (\(S\)), a measure of the stability of the overall stratification, was calculated:

\[
S = \frac{1}{A_0} \sum_{z=0}^{z_{\text{max}}} (z-z_0)(\rho(z) - \rho_0) A(z) \Delta z, \tag{1}
\]

where \(A_0\) is the lake surface area, \(\rho(z)\) and \(A(z)\) are the density and area at depth \(z\), varying from 0 (lake surface) to \(z_{\text{max}}\) (maximal depth) by \(\Delta z = 1\) m and \(z_0\) is the volumetric mean depth defined as...


\[ Z = \frac{1}{V} \sum_{z=0}^{z_{\text{max}}} z A(z) \Delta z \]  

\[ N = \frac{1}{1 \text{ year}} \sum_{t=0}^{t_{\text{max}}} \left( \frac{A_t}{A_0} \right) \Delta t, \]  

with the lake volume \( V \). \( \rho_a \) is the mean density (defined equivalent to \( z \)).

In this study, we use Nürnberg’s hypoxic factor HF [Nürnberg, 2002] to quantify hypoxia. It combines information about the annual temporal and spatial extent of hypoxia based on measured oxygen profiles and lake geometry and is defined as

\[ HF = \frac{1}{1 \text{ year}} \sum_{t=0}^{t_{\text{max}}} \left( \frac{A_t}{A_0} \right) \Delta t, \]  

where \( A_t \) denotes the area under which the oxygen concentration falls below a predefined critical value during the time \( \Delta t \). Accordingly, HF (d yr\(^{-1}\)) describes the relative lake area, under which hypoxic conditions are observed multiplied by the duration of the hypoxic conditions in the year considered. An HF of 365 d yr\(^{-1}\) means that the complete lake volume is hypoxic throughout the year. A value of 100 d yr\(^{-1}\) could mean either that the lake was hypoxic the entire year below an area equal to 27% (100/365) of the surface area or that the complete lake was hypoxic for 100 d yr\(^{-1}\) (or any combination of the two). To distinguish hypoxic from oxic water, a threshold oxygen level needs to be defined. Here we chose 4 mg L\(^{-1}\) justified by local water quality regulations, based on minimally tolerable oxygen concentration for fish egg survival [Müller et al., 2012; Savoye et al., 2015]. Using other thresholds [Nürnberg, 2002; North et al., 2014] would not significantly change our findings.

The maximal depth of deep convective winter mixing (hereafter called mixing depth) was determined based on the vertical structure of the oxygen and temperature profiles during the winters 1970–2012. Data before 1970 were omitted since the temporal resolution was considered as too coarse. Uncertainty in the mixing depth estimation depends on the vertical resolution of the profiles and is usually large for mixing depth shallower than 250 m, where the vertical resolution reaches 50 m between 50 and 250 m depth. Independent from this study, mixing depth is calculated since 1978 by CIPEL and published in the annual reports [e.g., Savoye et al., 2015, for 2014]. A comparison shows only minor differences.

### 2.3. One-Dimensional Model

#### 2.3.1. The Numerical Model SIMSTRAT

In the present study, the one-dimensional (1-D) model SIMSTRAT [Goudsmit et al., 2002] was used (Version 2015). It combines a buoyancy-extended \( k-e \) model with an internal seiche model to estimate the vertical diffusivity as function of time and depth. SIMSTRAT was already applied to medium-sized to large-sized lakes for different purposes [Peeters et al., 2002; Matzinger et al., 2007; Fink et al., 2014].

In the past decades, several 1-D model approaches have been developed and were able to reproduce thermal structures of lakes with high accuracy [e.g., Imberger et al., 1978; Burchard et al., 1999]. Perroud et al. [2009] compared the performance of four such 1-D models in predicting the temperature structure of Lake Geneva. Among them, SIMSTRAT performed best and showed a satisfactory reproduction of temperature profiles and thermocline variability. However, the 2009 version of SIMSTRAT tends to overestimate deepwater mixing and temperatures in the deep layers. Perroud and Goyette [2012] found a systematic deviation of +0.5°C for the deeper hypolimnion of Lake Geneva throughout the year. This is caused by systematic overestimation of the turbulent kinetic energy transferred by the internal seiche, which results in too large downward fluxes of heat during winter. The model transfers a constant fraction of the wind energy into internal seiching. In reality, the efficiency of this transfer is dependent on the internal wave period and, in turn, on the density stratification [Patterson et al., 1984]. To force internal seiching efficiently, the wind has to blow in a consistent direction for a time of ideally one-quarter of the seiching period. The longer the period, the more unlikely this condition is met. In turn, this period is a function of geometry and stratification [Bouffard and Boegman, 2012]. In Lake Geneva, the period of the most dominant Kelvin wave varies from 70 h in midsummer to 110 h in early spring and much larger values during weakly stratified winter periods [Bouffard and Lemmin, 2013]. A more realistic parameterization of the internal seiching of the 1-D model has to take the strength of the stratification into account. The easiest approach, used in this study, is to use two different parameters \( z \) for the energy transfer depending on the season. Values of \( z \) used in this study for winter (November–March), and summer (April–October) are listed in Table 1.
2.3.2. Model Forcing
Meteorological Data
Air temperature, cloud cover, solar radiation, vapor pressure, and wind speed and direction were obtained from the meteorological station Pully (46.52°N, 6.67°E, MeteoSwiss). The data are available from 1981 to 2013 on 10 min and hourly time increments. A comparison between model runs with 10 min and hourly resolution reveals only minor differences because internal waves dominate the hypolimnion dynamics and time scales of several hours are necessary to generate them. Subsequently, hourly forcing was chosen.

Light Absorption
The absorption of shortwave-radiation in SIMSTRAT is calculated by Lambert-Beer law:

\[ H_s(z) = G(1 - r_s) \exp(-\varepsilon_{abs} z) \]  

(4)

where \( G \) is the ground solar radiation (W m\(^{-2}\)) and \( r_s \) its reflection. We estimated \( \varepsilon_{abs} \) (m\(^{-1}\)) by daily interpolation of monthly to bimonthly measured Secchi depth data (\( z_{SD} \)) provided by CIPEL and by using the empirical relation:

\[ \varepsilon_{abs} = k z_{SD}^{-1} \]  

(5)

During model calibration, \( k = 1.4 \) turned out to be the best value for Lake Geneva.

Inflow and Outflow
The primary inflow to Lake Geneva is the Rhône River with a mean discharge of 185 m\(^3\) s\(^{-1}\) which is responsible for 70–75% of total inflow. Other contributors include Dranse, Aubonne, Venoge, and several other small rivers. Recent multibeam survey confirms the existence of groundwater inflows but their role remains marginal as recently shown with a giant (100 m diameter) pockmark in the nearby Lake Neuchâtel [Reusch et al., 2015]. The mean residence time is \( \sim 11.6 \) years and therefore, the inflows and outflows were neglected, after testing that the thermal structure of Lake Geneva was only little affected by this assumption. Since Pilotti et al. [2014] showed that water residence time is expected to increase with changing climate, this assumption is also justified for model runs with increased air temperature. However, the Rhône inflow still acts as a small additional source of deepwater oxygen during periods of flood-induced turbidity underflows [Loizeau and Dominik, 2000; Fink et al., 2016].

Model Calibration
Using CIPEL temperature monitoring data from 1981 to 2012, we optimized the model parameters \( p_1, p_2, C_{10}, a, \) and \( q \) (Table 1) by minimizing the root-mean-square error (RMSE):

\[ \text{RMSE} = \sqrt{\frac{1}{M} \sum_{i=1}^{M} (T^m_i - T^o_i)^2} \]  

(6)

between measurements and model results (\( M \) is the total number of measurements, \( T^m \) is the modeled temperature at time \( t \), and \( T^o \) is the observed temperature for measurement \( i \)). The calibration was repeated for varying absorption coefficients \( k \) (equation (5)). The lowest RMSE were found for \( k = 1.4 \), which was close to \( k = 1.3 \) used by Fink et al. [2014] for Lake Constance. A detailed description of the function of the calibrated parameters is provided in the supporting information Text S1. To achieve the most realistic reproduction, the parameter \( a \) was set different for summer and winter and the value for winter (Table 1) was further adapted to reproduce the temperatures of the deepest layers accurately.

2.3.3. Climate Change
Potential future local atmospheric temperatures were estimated from CH2011 [2011] according to the A1B emission scenario (balanced use of fossil and renewable energy) of the Intergovernmental Panel on Climate Change [IPCC, 2013]. To address the local impact of global climate change, different regional downscaling algorithms of the global model were applied in CH2011 [2011]. The most probable air temperature change

| Table 1. Parameters Used in SIMSTRAT Model (Details in Goudsmit et al. [2002]) |
|-----------------------------|-------------------|-----------------|
| Parameter | Value Used in This Study | Description |
| \( p_1 \) | 1.09 | Correction for absorption of infrared radiation |
| \( p_2 \) | 0.90 | Correction for sensible heat flux |
| \( C_{10} \) | 0.0017 | Wind drag coefficient 10 m above water |
| \( a \) | Summer: 0.035, Winter: 0.009 | Fraction of wind energy transferred to seiche energy |
| \( Q \) | 1.25 | Distribution coefficient for seiche energy |

SCHWEFEL ET AL. CLIMATE CHANGE EFFECTS IN A DEEP LAKE 8815
at Lake Geneva was estimated by averaging the predicted changes of four meteorological stations around the lake (Pully, 46.52°N, 6.67°E; Montreux-Clarens, 46.45°N, 6.90°E; Genève-Cointrin 46.25°N, 6.13°E; Nyon-Changins 46.4°N, 6.23°E). For each station, the mean of five different global climate models using ten different regional downsampling chains was determined (details in CH2011 [2011]).

In total, we investigated nine different model simulations. The comparable reference "A0" uses the meteorological forcing for the years 1981–2012. Model runs B0 and C0 simulate the lake stratification for the 2045–2076 and 2070–2101 predicted conditions. B0 and C0 are constructed by adding the mean temperature changes predicted by CH2011 [2011] to the reference temperature (supporting information Figure S2). As for cloud cover and wind speed, no clear trends are predicted, only the change of air temperature is considered. The temperature additions differed depending on the season and were higher in summer with a maximum around August. Because the lake model uses local meteorological data, the temperatures given by regional climate models are not necessarily representative for the location of the lake. Since we add the average temperature increases between present conditions and future climate scenarios (supporting information Figure S2), we assume that the variability in temperatures and the bias between regionally modeled and local temperatures do not change significantly in the future.

In addition to temperature changes, we also investigated the effect of altered light absorption on the thermal structure of the lake (Table 2). In the model runs A+, B+, and C+, we investigated the combined effect of increased light absorption (+10% increase) and changing air temperatures (which were identical to the scenarios A0, B0, and C0, respectively). In scenarios A−, B−, and C−, the absorption was decreased by the same amount. The supporting information contains further details on the absorption scenarios (supporting information Text S3).

### 2.4. Oxygen Model

The oxygen concentration was reproduced based on the results of the hydrodynamic model SIMSTRAT. Oxygen was simulated in the mixed (upper) and stratified (lower) layers of the lake. To estimate the impact on the deep part of the lake, the deepest 50 m were simulated as third (deep) layer. The depth of the upper end of the thermocline defined the base of the upper layer. To ensure that all the primary production occurs in the upper layer we also defined a minimum thickness of 30 m for this layer.

In the upper layer, the change of oxygen \( \text{d}C_{\text{ul}} / \text{d}t \) was modeled as

\[
\frac{dC_{\text{ul}}}{dt} = c_1 k [C_{\text{sat}}(T, t) - C_{\text{ul}}] + c_2 \text{Min}(t) \times 1.036^{(T-20)} C^{	ext{max}}(t) - c_3 \text{VOD}(z, t),
\]

where the first term on the right-hand side describes the gas exchange with the atmosphere, followed by the oxygen production, and the oxygen depletion by respiration and organic matter decomposition. \( c_1, c_2, \) and \( c_3 \) are calibration parameters (\( c_1 = 1.85, c_2 = 0.08, c_3 = 0.72 \). \( k \) describes the wind-dependent gas exchange velocity according to Cole and Caraco [1998], \( C_{\text{sat}}(T) \) the saturation concentration. The oxygen production was calculated according to Fang and Stefan [2009] based on measured chlorophyll \( a \) (Chl in g m\(^{-3}\)) profiles. \( P_{\text{max}} \) (9.6 g O\(_2\) per g Chl and per h) describes the maximal oxygen production as given in Fang and Stefan [2009]; \( \text{Min}(t) \) is the light limitation. The light limitation was considered proportional to the day length and modified by the calibration parameter \( c_2 \) (see supporting information Text S2). The factor 1.036\(^{(T-20)} \) accounts for the temperature dependency of oxygen production. Since Chl data were not available for the whole measurement period, we used the years 2007–2012 to get averaged Chl concentration with a representative annual variation and used these averaged data for the period before 2007. For the model runs representing the future climate, we used the same Chl concentrations as in model run A0. This assumption is probably an oversimplification, since increasing temperatures as well as decreasing nutrient loads lead to a change in biomass production. However, the maximal oxygen production takes place in summer and leads to an oversaturation

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<tr>
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<tr>
<td>Increased light absorption</td>
<td>A+</td>
<td>B+</td>
<td>C+</td>
</tr>
<tr>
<td>Measured light absorption</td>
<td>A0</td>
<td>B0</td>
<td>C0</td>
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<tr>
<td>Decreased light absorption</td>
<td>A−</td>
<td>B−</td>
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### Table 2. Summary of the Model Runs Employed in This Study

Temperature

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Technique</th>
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<tbody>
<tr>
<td>A0</td>
<td>Recent Past 1981–2012</td>
</tr>
<tr>
<td>B0</td>
<td>Predicted 2045–2076</td>
</tr>
<tr>
<td>C0</td>
<td>Predicted 2070–2101</td>
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in the surface layer. Therefore, an increasing production leads directly to an increased loss to the atmosphere. The oxygen concentration in the deep layer is less affected. One should even expect a decrease in the deepwater oxygen, since increased biomass production leads to an increase in oxygen depletion in the hypolimnion. However, the oxygen depletion in the hypolimnion (Figure 1c) showed no significant trend in the last 40 years despite important changes in nutrient loads and temperature.

The time and depth dependent oxygen depletion rate (VOD in g O₂ m⁻³ d⁻¹) is based on the oxygen decrease in the hypolimnion during the summers 1970–2012 estimated from the CIPEL monitoring data. In winter, the oxygen depletion is expected to be lower than in summer. During model calibration, a reduction by 50% gave reasonable results and was used during all model runs. Unfortunately, no simple method is available to determine winter depletion based only on monthly CTD-data.

In the lower and deep layers, no oxygen production takes place and water is isolated from the atmosphere. Therefore, oxygen depletion remains the only relevant process:

\[ \frac{dC_{ll}}{dt} = -C_{3} \cdot \text{VOD}(z, t). \]  

(8)

The output of SIMSTRAT was daily averaged and allowed the thickness of the upper and lower layer to be calculated. For each day, the oxygen concentrations of the three layers were determined based on the oxygen levels of the previous day and the changes in the layer volumes. Finally, the changes in concentration during the day were calculated according to equations (7) and (8). The model includes exchange between upper and lower layer implicitly due to the change of the layer thicknesses, the diffusion between lower and deep layer was explicitly calculated with an optimized exchange coefficient of $2 \times 10^{-7}$ m s⁻¹.

If the upper layer increases by a volume $\Delta V$ between the time steps $n - 1$ and $n$, the new concentration at time step $n$ ($C_{ul}^{n}$) is calculated as

\[ C_{ul}^{n} = \frac{1}{V_{ul}^{n}} \left( V_{ul}^{n-1} \cdot C_{ul}^{n-1} + V_{ul}^{n} \cdot C_{ul}^{n} + \Delta V \right), \]  

(9)

where $C_{ul}^{n}$ and $C_{ll}^{n}$ are the concentrations of the upper and lower layer and $V_{ul}^{n}$ the volume of the upper layer at time step $n$. If the mixing reaches below 260 m, the lower layer disappears and the oxygen is distributed between the deep layer and the upper layer. If the mixing reaches to maximum depth, the whole lake is considered as one mixed layer.

The change in oxygen concentration caused by river inflows or outflows is neglected. The supporting information contains more details about the parametrization of oxygen sinks and sources in the proposed model (supporting information Text S2 and supporting information Figures S3 and S4).

3. Results

3.1. Field Observations

3.1.1. Stability and Deepwater Mixing

The thermal structure of Lake Geneva is depicted by seasonal stratification with a thermocline depth of ~15 m in spring, which continually deepens during summer and autumn. Seasonal water-temperature fluctuations are high at the thermocline and only gradual, around ~5.7°C, in the deep hypolimnion. Winter mixing varied between complete mixing (309 m) and mixing depths of only ~50 m with an average of 179 ± 20 m. During February and March, winter mixing reached deepest and the maximum mixing depth correlated strongly with the Schmidt stability during this season (Figure 2). Winter mixing depth was strongly correlated ($r^2 = 0.73$) with the mean air temperature (Figure 3 and supporting information Figure S5). In contrary, mixing depth is only weakly correlated with winter wind speed ($r^2 = 0.29$). No full mixing event occurred when the Schmidt stability was larger than 50 kg m⁻¹ (Figure 2) during February and March. Over 43 years of observations, complete winter mixing occurred during 10 winters (dotted lines in Figure 1b), seven of them during 1981–2012, which is the period numerically modeled in this study.

3.1.2. Hypoxia

Since 1970, the oxygen concentrations in the deep layers of Lake Geneva decline regularly below the threshold of 4 mg L⁻¹ (Figure 1). Hypoxic conditions were also observed between 1960 and 1970, most pronounced 1969 [Loizeau and Dominik, 2005]. Before 1960, hypoxic conditions were detected neither with
direct field observations [Forel, 1895; Delebecque, 1898; Vivier, 1944] nor via analysis of sediment cores [Jenny et al., 2014]. During the last 40 years, HF varied from 0 to more than 100 d yr\(^{-1}\), with a mean of 34 d yr\(^{-1}\).

The estimated HF corresponds to a hypoxic volume between 0 and 12 km\(^3\) or up to 12% of the total volume. As expected, HF strongly decreased during winters with complete mixing. During two periods (1971–1979 and 1986–1999), no complete winter mixing occurred and HF prolonged to 104 d yr\(^{-1}\) in 1977 and 95 d yr\(^{-1}\) in 1996 (Figure 1b).

### 3.2. Model Results

#### 3.2.1. Thermal Structure and Deepwater Mixing

The optimized version of SIMSTRAT reproduced mean temperatures and the thermal structure of Lake Geneva well. The modeled volume-averaged mean temperature was 6.68°C and very close to the measured value of 6.74°C. Time series of the modeled and measured lake temperatures are shown in Figures 4a and 4b, and a contour plot is given in the supporting information Figure S6. The seasonal evolution of the thermal structure is reproduced with a RMSE of ~2°C in the thermocline region, and better than 0.5°C in the deeper layers. While the RMSE is low in the deep layers and no systematic bias is observed (Figures 4c and 4d), the larger differences in the thermocline are caused by baroclinic displacements, such as by internal seiches or gyres [Lemmin and D'Adamo, 1997], which are apparent in the in situ measurements but cannot be reproduced with a 1-D model. The small RMSE demonstrates the success of our internal seiche parameterization using two seasonal wind energy transfer parameters (Table 1). Note that not only the bottom temperature but also Schmidt stability (Figure 5) and deepwater mixing are very well reproduced. The average modeled mixing depth of 172 m was in excellent agreement with the observed mixing depth of 179±20 m. However, the model shows still an overestimation during very cold winters (9 years with complete winter mixing instead of seven). In winters without complete overturn, the mixing was underestimated (113 m instead of 143 m). The original code using a single value for wind energy transfer ($\alpha = 0.025$) resulted in a 10% higher RMSE. While there was almost no improvement in the upper layers, the RMSE below 300 m improved by almost 30%.

#### 3.2.2. Effects of Atmospheric Warming on Lake Temperatures

In the model runs B0 and C0 (Table 2), the previously validated model is now forced with increased air temperatures according to the predictions by CH2011 [2011] for the period 2045–2076 (B0) and 2070–2101 (C0). The change in the seasonally modeled lake temperatures relative to the reference is shown in Figures 6b and 6c. We observe a temperature increase over the entire water column. However, the surface water
temperature increases faster than the hypolimnion water (1.5°C warming in the top layer compared to 0.7°C in the deepest layer for B0; as well as ~2°C and ~1°C for C0), leading to an overall stronger temperature stratification. The temperature increase had a comparable pattern in the past (Figure 6a), although the absolute observed temperature increase between 1957 and 2012 was less than the model prediction for the end of the century.

3.2.3. Effects of Atmospheric Warming on Stratification and Mixing
To quantify the stability in winter, we estimated the average Schmidt stability during February and March \( (S_{\text{Winter}}) \) as well as the depth of deepest convective mixing (Table 3) based on the modeled temperatures. Relative to the reference A0, the mean \( S_{\text{Winter}} \) doubled for B0, from 71 to 146 kg m\(^{-1}\), and increased further to 179 kg m\(^{-1}\) for C0 (Table 3). Consequently, the mean mixing depth was reduced from 172 to 136 m and 127 m for B0 and C0, respectively, which corresponds to reductions of ~21% and ~26% in mixing depth. The number of winters with complete mixing decreased with increasing temperatures from nine (A0) to four (C0) (Table 3; Figure 7).

3.2.4. Effects of Water Transparency
Besides the effect of increasing atmospheric temperature, we investigated the effect of variable transparency on the thermal structure of Lake Geneva (Table 2). The relevant model parameter is the short wave absorption coefficient, which depends on Secchi depth and in turn on particle concentration. With increased light absorption, the thermocline becomes more stable and mean

![Figure 4](image-url) Modeled (blue) and measured (black) temperatures 1981–2012 at (a) 15 m depth and (b) 250 m depth. (c) Root-mean-square error of modeled temperature output. While there are considerable differences in the thermocline (as baroclinic dislocations are considered in the observations but not in the model), the modeled deepwater temperature is in good agreement with measurements. (d) Deviation of the mean annual modeled temperatures from the measured mean values (1981–2012).

![Figure 5](image-url) Mean Schmidt stability in February and March: measurements (black, dashed) 1981–2012 compared to simulation results for the reference scenario A0 (blue). Dotted lines indicate the winter mixing events reaching below 270 m depth (Table 3).

![Figure 6](image-url)
Lake temperature and mixing depth decrease (Table 4). In turn, less absorption leads to a slightly warmer lake with a less stable thermocline. The largest temperature changes are discovered below the thermocline with up to $0.5^\circ C$ at the end of autumn (supporting information Figures S7a and S7b). In total, the mean temperature differences between changed absorption ($A_-$ and $A_+$) and reference ($A_0$) were only $0.1^\circ C$. In $B_+$ and $C_+$, where increased absorption was combined with higher air temperature, the suppression of lake warming below the thermocline was amplified (supporting information Figure S7d). In turn, reduced absorption ($B_-$ and $C_-$) leads to an enhanced warming in this region (supporting information Figure S7c). The differences in mean temperature were about $0.1^\circ C$ between $B_/B_-$ versus $B_0$ and $C_/C_-$ versus $C_0$, respectively. Overall, we suggest that lower transparency cools the lake and strengthens the thermocline while higher transparency has the opposite effect.

3.2.5. Effects of Atmospheric Warming on Oxygen Concentrations

The oxygen model coupled to SIMSTRAT allows for estimating the impact of climate change on the oxygen budget. The comparison of the model results with the oxygen concentrations measured between 1981 and 2012 showed that the general trend in oxygen is very well reproduced (Figure 8). The variability between summer and winter is slightly lower in the model compared to the measurements. Particularly in 2007, the model predicts a too little oxygen gain in spring. This disagreement can be partially explained by the hydrodynamic model, which tends to underestimate the mixing in warm winters. In the following analysis, year 2007 is excluded, and additional oxygen was added, to match the measured concentrations in January 2008 for the model run $A_0$. The same amount of oxygen was added in $B_0$ and $C_0$.

The RMSE of the modeled oxygen concentration was 0.51 mg L$^{-1}$ in model run $A_0$. The simulations $B_0$ and $C_0$ revealed a general decrease in oxygen. The annual mean oxygen concentration of the entire lake fell from 8.99 to 8.48 mg L$^{-1}$ for $B_0$ and 8.30 mg L$^{-1}$ for $C_0$ (Figure 9a). While the decrease in the mean concentration was minor, the impact on the deepest layer was much stronger. Here the model...
run A0 predicts a mean value of 6.02 mg L\(^{-1}\) (measured value: 5.59 mg L\(^{-1}\)), which to 5.01 mg L\(^{-1}\) in model run B0 and 4.60 mg L\(^{-1}\) in run C0. Consequently, the fraction of values lower than 4 mg L\(^{-1}\) increased by more than 25% in model run C0, indicating longer periods of hypoxic conditions (Figure 9b).

### 4. Discussion

#### 4.1. Modeling Deep Winter Mixing

The modified SIMSTRAT model provides a good estimate of deep mixing during winter (Table 3). The previous model version with constant wind-to-seiche energy transfer overestimated the mixing depth and predicted complete mixing in more than 50% of all winters. With the newly adapted parameterization, the simulated stability \(S_{\text{Winter}}\) is remarkably close to the observations (Figure 5). Consequently, the simulated mean winter mixing depth, of 172 m is close to the observed value of 179 m (Table 3). The number of complete winter mixing events is overestimated (9 versus 7) although some of these events were very short. In contrast, the model underestimates the mixing during winters with shallow mixing depth. We explain this deviation with the temperature dependence of the energy transfer to internal waves. The transfer is more effective during warmer winters, when the internal seiche period remains shorter. Using the same parameterization for every winter thus leads to a mixing depth overestimation during cold winters and an underestimation during warm winters. Nevertheless, our simple approach reproduces the temperature pattern and mixing behavior without bias and with a low RMSE especially in the deep layers as shown in Figure 4d.

#### 4.2. Effect of Climate Change on Lake Warming and Stratification

Lake warming under higher atmospheric temperature was clearly apparent in all simulations (Figures 6b and 6c). The simulated lake warming is even stronger in the future than the previously observed trends based on systematic temperature measurements since 1957 (Figure 6a). Consequently, lake stratification becomes stronger. The annual mean Schmidt stability increases from 1250 kg m\(^{-1}\) (A0) to 1490 kg m\(^{-1}\) (B0) and 1590 kg m\(^{-1}\) (C0). Not only the increased temperature gradient between epilimnion and metalimnion but also increased mean temperatures lead to this stability increase. The volumetric averaged lake temperature over the reference period was 6.7°C. This value increased to 7.5°C for B0 and 7.9°C for C0. The Schmidt stability (equation (1)) is dependent on the density difference due to temperature gradients and temperature change per se, as expressed by

\[
\frac{\partial \rho}{\partial T} = -\rho \alpha (T),
\]

as the thermal expansivity \(\alpha\) increases with temperature. Therefore, increasing temperatures cause higher stability even when gradients do not change. For Lake Geneva, the predicted increase in temperature between 1997 and 2035 is typically 1.5°C in the upper part of the thermocline and 0.5°C in the deep water. For typical summer conditions (22.5°C at 7 m depth and 8.5°C at 25 m), this results in an increase of the temperature gradient from 0.78 to 0.83°C m\(^{-1}\) (6.4%), whereas the mean thermal expansivity increases from 1.52 \times 10^{-4} to 1.62 \times 10^{-4}°C\(^{-1}\) (6.6%). Both effects thus have a comparable impact on the increase in stability.
With increased air temperatures, warming is less pronounced between 25 and 75 m depth during the second half of the stratification period. This minimum in warming is caused by the stronger summer stratification, which reduces the warming just below the thermocline. Since this phenomenon occurs mainly in late summer and autumn, it is irrelevant during the period of deep winter mixing.

Compared to climate warming the effects of transparency on the hypolimnion temperature are small. The biggest effect is visible in the thermocline, which deepened with decreasing absorption. The effect on the mixing depth was only marginal (Table 4). This is fundamentally different in shallow lakes with smaller hypolimnia. There, water quality was found to be a significant factor affecting the thermal structure [Mazumder and Taylor, 1994; Snucins and John, 2000; Persson and Jones, 2008]. Details about the effect of water transparency are given in the supporting information Text S3.

### 4.3. Implication for Deepwater Mixing and Oxygen Budget

The Schmidt stability in late winter (February and March) is strongly correlated with the mixing depth, both for the observations as well as for the model simulations (Figure 2). The shape of the curve in Figure 2 is similar for all investigated model runs. For B0 and C0, model results are shifted to shallower mixing depths and higher stabilities. The mean Schmidt stability increased for B0 and C0 and, in turn, winter mixing depth decreased (Figures 2 and 7).

The model predicts a decrease of the mean mixing depth from 172 m (reference A0) to 136 m (B0) and 127 m (C0), respectively. Seven full overturns were observed in the simulation period which corresponds to 22% of all winters (e.g., one every four to five winters, Figure 7). This value decreased to six (19%) for the period 2045–2076, although the model seems to overestimate extreme mixing events. For 2070–2101, the number was further reduced to four (i.e., one every eight winters, 13%). Hence, the frequency of deepwater reoxygenation will be reduced by a factor of two by the end of the century according to our model results.

Furthermore, the duration of unstratified winter periods will be shorter in the future (defined as the period in which the temperature difference in the top 50 m is less than 3°C). From 125 days for the period 1981–2012, the duration decreased to 118 days (−6%) for 2045–2076 and to 115 days (−8%) for 2070–2101.

Our study predicts complete winter mixing events even for the warmest scenario while Matzinger et al. [2007] and Sahoo et al. [2012] predicted both a complete halt of winter mixing in their studies. While the deep hypolimnion shows a constant temperature increase during periods without complete mixing, the epilimnion experiences strong seasonal fluctuations (Figures 4a and 4b). Although a warmer lake tends to be more stable (thermal expansivity $\alpha_\text{th}$; equation (10)), the hypolimnion continuously warms in the absence of mixing and becomes susceptible for deep mixing in extraordinary cold winters. While Matzinger et al.

### Table 4. Modeled Mixing Depth (m) for Increased (+) and Reduced (−) Light Absorption

<table>
<thead>
<tr>
<th>Period</th>
<th>Mixing Depth Reference (m)</th>
<th>Mixing Depth Stronger Absorption (m)</th>
<th>Mixing Depth Weaker Absorption (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981–2012</td>
<td>172 (A0)</td>
<td>167 (A+)</td>
<td>177 (A−)</td>
</tr>
<tr>
<td>2045–2076</td>
<td>136 (B0)</td>
<td>128 (B+)</td>
<td>138 (B−)</td>
</tr>
<tr>
<td>2070–2101</td>
<td>127 (C0)</td>
<td>119 (C+)</td>
<td>130 (C−)</td>
</tr>
</tbody>
</table>

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[2007] use a constant temperature ramp-up to predict future air temperature, our study kept the observed temperature fluctuations between 1981 and 2012 in addition to the warming trend. With this realistic temperature variability, extraordinary cold winters and complete deep mixing still occur. Local climate conditions, which dictate a stronger temperature increase in summer compared to winter [CH2011, 2011] (supporting information Figure S2), also favor occasional winter mixing.

A comparison of the model results of the runs (A, B, and C) with (A, B, and C) demonstrates that the effect of sunlight absorption on mixing depth is marginal. The higher absorption has the strongest effect at the end of the stratification period in autumn. At the end of winter, when deep mixing occurs, the temperature difference between the different absorption scenarios was not more than ±0.1°C. The predicted difference in mixing depth of ~5 m between A0 and A+/A−, respectively (Table 4), was seven times smaller than the differences due to air temperature increase (from A0 to B0). The beginning of the unstratified winter period was later by negligible degree. Similar to the mixing depth, this effect was marginal (change of 1 day only) and caused no relevance for the oxygen budget.

To estimate the impact of deep mixing on oxygen concentration, we set up a simplified three-box oxygen model. Despite its substantial simplifications, the proposed model was able to reproduce the trends in oxygen concentration between 1981 and 2012 (Figure 8). The difference between oxygen production and consumption was about 0.28 × 10^5 t yr⁻¹, which directly relates to the net O₂ flux to the atmosphere and the net carbon burial in the sediment. Assuming the Redfield ratio [Redfield, 1958] of 138 mol of O₂ per 106 mol of carbon (C), this corresponds to a net burial of 14 g C m⁻² yr⁻¹, which is produced in the upper layer but not consumed and accumulates in the sediments without contribution to the oxygen depletion. This flux is in good agreement with core-based estimates of net sediment accumulation of 11 g C m⁻² yr⁻¹ in Lake Geneva [Span et al., 1990; Loizeau et al., 2012]. In addition, the net oxygen system production of 1.57 × 10^5 t yr⁻¹ corresponds to carbon gross sedimentation, i.e., a total biomass production of 79 g C m⁻² yr⁻¹, which is fully consistent with the estimate of Graham et al. [2016]. The oxygen depletion of ~1.29 × 10^5 t yr⁻¹ corresponds to a stagnation duration of 180 days (only slightly lower than the estimate of 1.34 g O₂ m⁻² d⁻¹ based on CIPEL measurements; Figure 1c). The oxygen budget terms are in excellent agreement with independent observations in Lake Geneva and confirm that the model realistically reproduces the relevant processes.

To estimate the effects of changing climatic conditions, we focused on the simulations without considering the negligible effect of light absorption (Table 4). The mean deepwater oxygen concentration decreases by 6% for B0 and by 8% for C0. However, the variability of oxygen content in the lake will be larger, especially in winter. While there will be still large amounts of oxygen after complete mixing events, the concentrations will be lower during episodes without deep mixing (Figure 9a). For this reason, the variations in the deep layers are much larger than the changes of the average oxygen level. For the layer of the lowest 50 m above maximum depth, the model predicted concentrations below 4 mg L⁻¹ in 31% of the simulation period in

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**Figure 9.** (a) Probability distribution of oxygen content of Lake Geneva for simulations A0 (blue), B0 (green), and C0 (red). The numbers show the annual mean concentration. There is a trend to lower concentrations for the simulations with higher air temperatures. (b) Cumulative sum of the oxygen concentration in the deep layer (lowest 50 m) for the model runs A0 (blue) and C0 (red). Values below the dotted lines (4 mg L⁻¹) show hypoxic conditions.
5. Conclusions

The analysis of 43 years of combined oxygen and temperature data in the deepest part of Lake Geneva demonstrated that hypoxic conditions occur regularly in its deep layers. As no decreasing trend in hypolimnetic oxygen depletion (currently at $1.34 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$) nor in the hypoxic factor (average $34 \text{ d yr}^{-1}$, varying between 0 and 120 d yr$^{-1}$) were observed, hypoxia was found to depend on winter air temperatures and subsequent deep winter mixing.

Deepwater temperatures of Lake Geneva were realistically simulated using an improved version of a one-dimensional $k-c$ model specially adapted to deep lakes. The model successfully reproduces the observed trends in deep convective winter mixing in the lake. Using the proposed model, future changes in the lake thermal structure were predicted for various locally downscaled IPCC A1B climate scenarios. The results show a strong decrease in the mean winter mixing depth from 172 to 136 m (for 2045–2076) and 127 m (for 2075–2101). At the end of the century, complete deep homogenization in winter will decrease by ~50% but will not cease completely. After long periods of stratification, extraordinary cold winters still lead to a homogenization of the lake. In additional model simulations, the effect of light absorption was investigated. The results confirmed that stronger light absorption results in cooler hypolimnia, however, with minor effects on lake stratification and winter mixing.

As a consequence of the reduced mixing, our model predictions show that average oxygen concentrations in the hypolimnion will decrease by the end of the century by ~8%. Moreover, the deepest layers are expected to experience an increase in hypoxic conditions by more than 25% due to reduced winter mixing and fewer complete mixing events. Since independent simulations of other deep lakes indicated a regime shift from oligomictic to meromictic, with even more severe consequences for the oxygen budget, predicting the mixing behavior under climate-induced forcing remains an important challenge for lake modeling.

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