



# The fate of Lake Baikal: how climate change may alter deep ventilation in the largest lake on Earth

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## Abstract

Lake Baikal is the oldest, deepest, and most voluminous freshwater lake on Earth. Despite its enormous depth, episodically (almost twice a year) large amounts of surface, cold, and oxygenated water sink until the bottom of the lake due to thermobaric instability, with consequent effects on the ecology of the whole lake. A minimal one-dimensional model is used to investigate how changes in the main external forcing (i.e., wind and lake surface temperature) may affect this deep ventilation mechanism. The effect of climate change is evaluated considering the IPCC RCP8.5 and some idealized scenarios and is quantified by (i) estimating the mean annual downwelling volume and temperature and (ii) analyzing vertical temperature and dissolved oxygen profiles. The results suggest that the strongest impact is produced by alterations of wind forcing, while deep ventilation is resistant to rising lake surface temperature. In fact, the seasons when deep ventilation can occur can be shifted in time by lake warming, but not dramatically modified in their duration. Overall, the results show that Lake Baikal is sensible to climate change, to an extent that the ecosystem and water quality of this unique lacustrine system may undergo profound disturbances.

## 1 Introduction

Lake Baikal is the lake of records: it is the oldest (25 million years), deepest (max depth 1'642 m), and most voluminous (23'615 km<sup>3</sup>) freshwater lake on Earth (Fig. 1). It contains an outstanding variety of endemic species that adapted to singular conditions (e.g., large depth, several months of ice cover, high water clarity, low nutrient concentrations) during thousands

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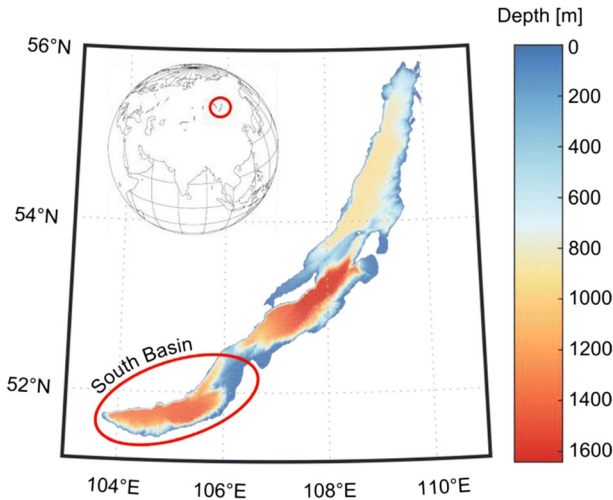
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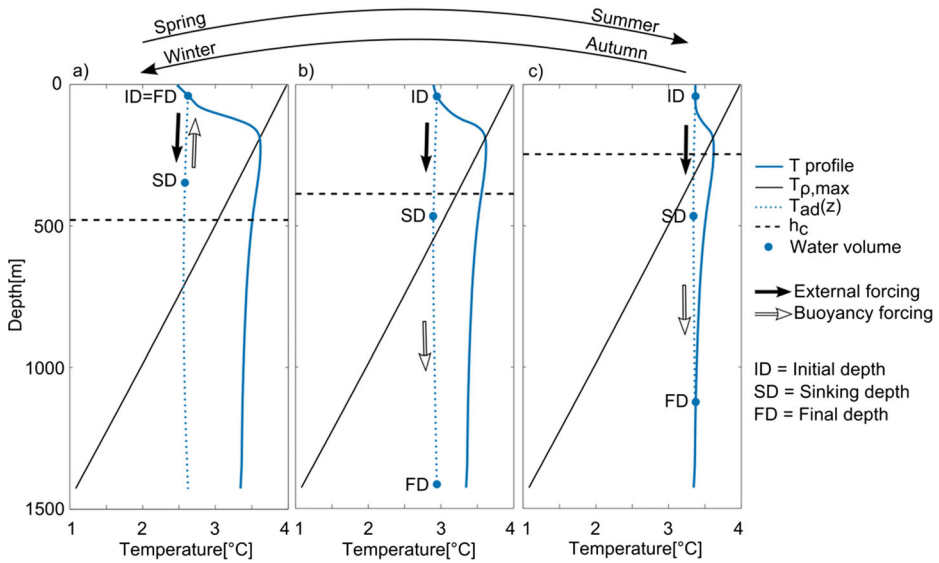
**Fig. 1** Bathymetric map of Lake Baikal and location of the lake on the Earth (inset). The South Basin of the lake is also indicated

of years (Bondarenko et al. 2006; Moore et al. 2009). This exceptional endemism earned the lake to be declared as a World Heritage site by UNESCO in 1996.

Lake Baikal is also a large freshwater system hosting a broad range of fascinating physical phenomena, which captures the attention of the scientific community. Owing to its large depth and climatic conditions, it is a fine example of thermobarically stratified lake (e.g., Boehrer and Schultze 2008), whereby thermobaricity is the combined dependence of water density ( $\rho$ ) on temperature ( $T$ ) and pressure ( $P$ ) (e.g., McDougall 1987). The thermobaric effect causes the temperature of maximum density  $T_{\rho_{\max}}$  (about 4 °C at atmospheric pressure) to decrease with depth, and the temperature profiles crossing the  $T_{\rho_{\max}}$  line to have a maximum at this intersection (Eklund 1963, 1965). Accordingly, in Lake Baikal a weak ( $10^{-4}$ – $10^{-5}$  °C/m) direct stratification, with temperatures warmer than  $T_{\rho_{\max}}$  and ranging from  $\sim 3.50$  °C to  $\sim 3.35$  °C, is permanently present below  $\sim 250$  m, while the upper layers are either directly stratified (with surface water warmer than  $T_{\rho_{\max}}$ ) or inversely stratified (surface water colder than  $T_{\rho_{\max}}$ , or ice cover), depending on the season.

Previous studies (Vereshchagin 1936; Weiss et al. 1991; Shimaraev et al. 1993) demonstrated that the mixing regime of the lake is intimately related with thermobaricity. Lake Baikal, in fact, is renowned for the occurrence of periodic large-scale recirculation triggered by thermobaric instability, causing renewal of hypolimnetic water by mixing and replacement with surface water. During inverse stratification, unstable conditions occur when relatively cold surface water ( $T < T_{\rho_{\max}}$ ) is moved beneath a threshold depth called compensation depth ( $h_c$ , i.e., the depth where the sinking water and the local water have the same density). Then, the sinking water is heavier than local water and sinks towards the bottom of the lake, stopping where its density equals that of local water (Fig. 2b) or when it reaches the bottom of the lake (Fig. 2c). Conversely, if the surface water is displaced to a depth shallower than  $h_c$ , it rises back to the surface due to buoyancy forces because it is lighter than local water (Fig. 2a).

Recent studies suggested (Wüest et al. 2005; Boehrer and Schultze 2008) and successively demonstrated (Schmid et al. 2008; Tsimitri et al. 2015) that the primary cause of thermobaric instability in Lake Baikal is coastal downwelling due to Ekman transport. The phenomenon can take place twice a year: in late spring (June, after the melting of the ice cover) and early



**Fig. 2** Downwelling driven by thermobaric instability: **a** when the external forcing is not sufficient to move the surface volume down to the compensation depth thermobaric instability does not occur, otherwise the sinking water can either **b** sink until the bottom of the lake or **c** stop where it encounters local water at the same temperature. Modified after Piccolroaz and Toffolon (2013)

winter (December/January, before the surface freezes). In these periods, the lake is stably but weakly inversely stratified in its upper part (Fig. 2b, c), and sufficiently strong winds may overcome buoyancy forces, triggering thermobaric instability. Wind forcing and lake stratification are therefore the key controls of the phenomenon, while the steep shores and elongated shape of the lake promote the occurrence of coastal downwelling (see also Toffolon (2013) for a theoretical analysis).

Since deep recirculation determines the replacement and mixing of deep water with surface water rich in dissolved gasses, some authors refer to this phenomenon as *deep ventilation* (e.g., Shimaraev et al. 1993; Moore et al. 2009), a term typically used by oceanographers (e.g., Khatiwala et al. 2012). Relevant ecological implications result from deep ventilation, among which the most evident is the high oxygen content (up to the 80% of saturation, Weiss et al. 1991) along the entire water column, which allows for the existence of aquatic fauna down to huge depths (Chapelle and Peck 1999). Deep mixing influences the recycling of carbon and nutrients, playing a key role in lakes’ biological productivity (e.g., Dokulil 2014). Therefore, any changes in the current environmental conditions able to affect deep ventilation are likely to have significant implications on the equilibrium of the lake, possibly threatening its unique ecosystem.

Relatively intense deep-mixing activity in Lake Baikal was observed and monitored especially in the South Basin (Wüest et al. 2005; Schmid et al. 2008; Tsimitri et al. 2015), where the downwelling volume was estimated ranging between 10 and 100 km<sup>3</sup> per year (Wüest et al. 2005; Schmid et al. 2008; Shimaraev et al. 2011; Piccolroaz and Toffolon 2013). For this reason and since the South Basin (maximum depth of 1461 m, volume of 6360 km<sup>3</sup>) is the region where most data are available, here we focused on the response of deep ventilation to climate change in this portion of the lake. To this aim, we used a simplified, one-dimensional model (Piccolroaz and Toffolon 2013) and considered some

scenarios constructed changing the surface boundary conditions, namely wind energy and lake surface temperature. Results obtained under these scenarios are compared to current conditions to investigate the role played by the main external forcing on deep ventilation and to quantify the impact that climate change is likely to have on deep-water oxygenation.

Although the analysis is specific for Lake Baikal, it contributes to the general understanding of how deep thermobaric convection in lakes can be affected by climate change. In fact, thermobaric stratification is a trait common to several deep temperate lakes (Boehrer and Schultze 2008) among which the most famous example is Crater Lake (USA, McManus et al. 1993; Crawford and Collier 1997, 2007; Wood et al. 2016), although other lakes can be found in Japan (Boehrer et al. 2008), Norway (Strøm 1945; Boehrer et al. 2013), and Canada (Johnson 1964; Laval et al. 2012).

## 2 Methods

### 2.1 Description of the model

The study is carried out using the minimal one-dimensional numerical model presented in Piccolroaz and Toffolon (2013) and specifically developed to investigate deep thermobaric convection in Lake Baikal, but applicable to other deep lakes. The use of a more complex three-dimensional model would be unfeasible due to data scarcity for model validation and high computational cost to run long-term climate change simulations. An exhaustive presentation of the model is provided in the [Supplementary Material](#) (we also refer the interested reader to Piccolroaz and Toffolon (2013) for all technical details about model implementation and calibration); while here, we summarize the main features. The model solves the following reaction-diffusion equation for the generic tracer  $C$  (here dissolved oxygen,  $DO$ ) in addition to the temperature  $T$ :

$$\frac{\partial C}{\partial t} = \frac{1}{S} \frac{\partial}{\partial z} \left( S D_z \frac{\partial C}{\partial z} \right) + R \quad (1)$$

where  $t$  is the time,  $z$  is the vertical direction (positive downward),  $S$  is the horizontal surface at a fixed depth,  $R$  is the source/sink term, and  $D_z$  is vertical diffusivity.

Vertical transport is simulated using two Lagrangian-based algorithms, which are at the core of the model: one for simulating wind-driven convective transport (based on wind speed  $W$  and duration  $\Delta t_{wind}$ , see Eqs. (2) and (3) below) and the other for simulating buoyancy-driven stabilization of unstable regions of the water column. Consistent with this Lagrangian approach, the water column is discretized dividing the domain into  $n$  sub-volumes having the same individual volume, which allows for an efficient and easy handling of vertical mixing. In fact, in both Lagrangian-based algorithms, the water column is simply resorted by exchanging the position of the sub-volumes affected either by wind or by buoyancy forces. While reordering the water column, mixing between each pair of exchanged volumes is accounted for through a mixing coefficient. The implementation of a similar Lagrangian algorithm proved to be successful also in different types of problem, such as the formation of double-diffusive small-scale structures in lakes (Toffolon et al. 2015).

The algorithm for wind-driven convective transport is based on the following key quantities:

$$e_w = \xi C_D^{0.5} W \quad (2)$$

$$V_{\text{down}} = \eta C_D W^2 \Delta t_{\text{wind}} \quad (3)$$

where  $e_w$  is the energy per unit volume provided by the wind,  $V_{\text{down}}$  is the surface volume of water moved by the wind forcing,  $C_D$  is the wind drag coefficient, and  $\xi$  and  $\eta$  are the main calibration parameters of the model. Equations (2) and (3) rely on wind speed  $W$  and duration  $\Delta t_{\text{wind}}$  data only. The specific energy provided by the wind is compared to the amount of energy needed to move  $V_{\text{down}}$  downwards against the buoyancy forces, thus assessing whether the energy input is sufficient to move  $V_{\text{down}}$  below the compensation depth  $h_c$  and trigger thermobaric instability (see Fig. 2 for a schematic). In all cases, the arrival depth of the sinking volume  $V_{\text{down}}$  is determined by progressively moving it down until the energy provided by the wind is sufficient to balance the change of potential energy resulting from the consecutive switch of positions between sub-volumes.

Equations (2) and (3) are derived from physical principles with reference to the Ekman transport produced by along-shore winds in elongated lakes, coherently with the primary cause of deep thermobaric convection in Lake Baikal (Schmid et al. 2008; Tsimitri et al. 2015). However, their validity can be extended to the most general case, in that the energy flux from the wind to the lake ( $E_w = e_w V_{\text{down}}$ ) is proportional to the third power of the wind speed, according to basic laws of physics (e.g., Imboden and Wüest 1995). All the other phenomenological details are implicitly accounted for by the calibration coefficients  $\xi$  and  $\eta$ .

The same model was successfully applied also to Crater Lake (Wood et al. 2016), where mechanisms other than Ekman transport drive deep thermobaric convection due to the different shape, dimension, and climate characteristics (Crawford and Collier 1997, 2007). In their work, Wood et al. (2016) compared the performance of the proposed model to that of the well-documented one-dimensional lake model DYRESM (Imerito 2014). The inadequacy of the latter model to properly simulate deep ventilation clearly showed the need to explicitly account for thermobaricity in one-dimensional models of these types of lakes. Based on these considerations and on the previous results obtained by Piccolroaz and Toffolon (2013), the proposed model is a suitable one-dimensional option for Lake Baikal.

In the present study, the domain was discretized into 159 sub-volumes having a volume of 40 km<sup>3</sup> and thickness ranging from 5 to 66 m, i.e., the same setup used in Piccolroaz and Toffolon (2013), and the model parameters were the same as in this previous study.

## 2.2 External forcing and boundary conditions

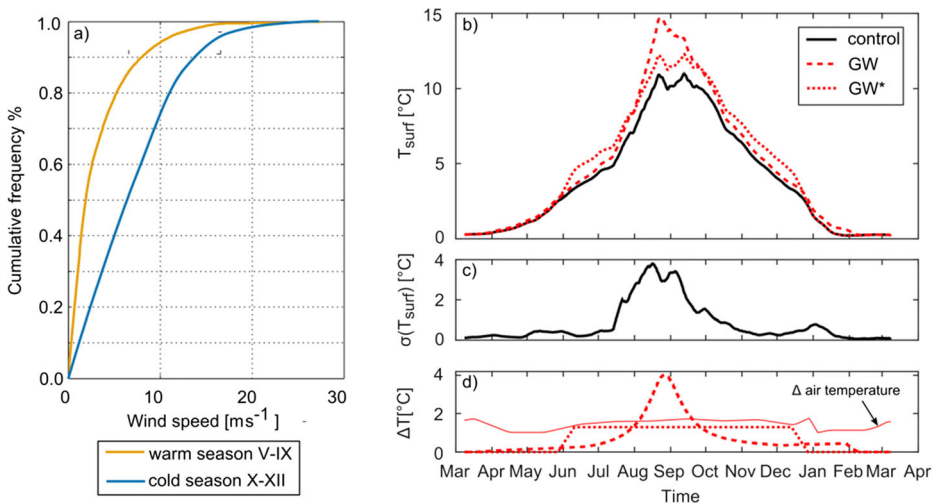
In order to address the lack of measurements available for Lake Baikal, the model was designed to require few input variables: wind speed as external forcing and lake surface temperature ( $T_{\text{surf}}$ ) as upper boundary condition. This feature makes the model particularly parsimonious, thus attractive for cases where data are scarce and the use of more complex (e.g., three-dimensional) models not possible or questionable due to the lack of information to validate the results.

Observational probabilistic distributions of wind speed were built based on the wind atlas contained in Rzheplinsky and Sorokina (1977), which collected wind data from fixed stations at the coast, on islands, and from ships along 10 years during the ice-free season (May–

December, from 1959 to 1968). This dataset is more representative of the conditions at the lake surface than data recorded at weather stations installed around the lake. In fact, the thermal inertia of the massive water volume of Lake Baikal leads to the onset of local atmospheric pressure gradients able to generate winds that are substantially different in intensity and direction compared to the surrounding region (Shimaraev et al. 1994). Owing to the strong seasonality of the wind forcing over the lake, two distinct cumulative frequency functions of wind speed were derived (Fig. 3a): one for the warm season (May–September) and the other for the cold season (October–December).

A probabilistic distribution of  $T_{\text{surf}}$  was extracted from a dataset of vertical temperature profiles covering the period 2000–2008 (courtesy of Prof. Wüest, Eawag, Switzerland), collected at a mooring station in the South Basin (see Schmid et al. (2008) for details). The 9-year series of  $T_{\text{surf}}$  was constructed based on the data of the uppermost thermistor, whose position changed slightly from year to year: mean, minimum, and maximum depth being 17 m, 9 m, and 30 m, respectively. The annual evolution of  $T_{\text{surf}}$  averaged over the 9-year measurement period is shown in Fig. 3b, and the corresponding standard deviation is shown in Fig. 3c.

In order to provide a robust description of deep ventilation statistics, we ran long-term simulations covering a 1000-year period with stationary climate conditions. We used a stochastic approach to determine the sequence of wind and  $T_{\text{surf}}$  conditions to impose as boundary conditions, combining the use of the probabilistic distributions described above and of the ECMWF ERA-40 reanalysis dataset. The ECMWF ERA-40 reanalysis dataset contains wind speed and air temperature for the period 1957–2002 with a temporal resolution of 6 h and provides a realistic chronological sequence of meteorological events (otherwise difficult to reconstruct), although not fully representative of the actual meteorological conditions at the lake due to its coarse resolution ( $\sim 125$  km). These data were statistically downscaled to local scale using the quantile-mapping approach (Panofsky and Brier 1968) and the in situ, observational statistical distribution of  $W$  and  $T_{\text{surf}}$  discussed above (see Piccolroaz and



**Fig. 3** **a** Probabilistic curves of wind speed  $W$  in the warm (May–September) and cold (October–December) seasons. **b** Mean annual evolution of lake surface temperature  $T_{\text{surf}}$ : current condition (control) and global warming scenarios (GW and GW\*). **c** Standard deviation of measured  $T_{\text{surf}}$  relative to the 9-year measurement period 2000–2008. **d** Increase in  $T_{\text{surf}}$  for the GW and GW\* scenarios and increase in air temperature (thin line) projected by the CMIP5 multi-model mean under the RCP8.5 scenario used to construct the GW scenario

Toffolon (2013) for details). Note that in the case of  $T_{\text{surf}}$ , the downscaling procedure used air temperature as predictor, which is reasonable due to the strong air–water temperature correlation (see, e.g., Piccolroaz et al. 2013; Toffolon et al. 2014a). In this way, a 1000-year long simulation was generated by randomly extracting a sequence of 1000 years from the ECMWF ERA-40 dataset.

### 2.3 Synthetic climate change scenarios

We prepared a suite of synthetic climate change scenarios varying the probabilistic distributions of  $W$  and  $T_{\text{surf}}$ . The scenarios were kept simple to easily assess the effects that changes in one or both variables are expected to have on deep ventilation. This choice was also motivated by the lack of future climate studies in the Lake Baikal region. This is particularly true for wind speed, for which ad hoc future projections do not exist. We therefore introduced two idealized yet reasonable scenarios by simply assuming that either the May–September or the October–December probabilistic distribution of wind speed (Fig. 3a) holds for the entire year, thus defining a calm wind (CW) and a strong wind (SW) scenario, respectively.

We used the CMIP5 multi-model mean projections under the IPCC AR5 RCP8.5 high emission scenario for the grid cells covering the South Basin of Lake Baikal to predict the corresponding increase in  $T_{\text{surf}}$  in the period 2041–2050, through the *air2water* model (Piccolroaz et al. 2013; Piccolroaz 2016). The *air2water* model is a simple but mechanistically based tool to predict lake surface temperature based on air temperature only, which was shown to be effective for use in climate change studies (Piccolroaz et al. 2018). The model can be classified as a hybrid model (Toffolon and Piccolroaz 2015) combining a physically based equation with a stochastic calibration of model parameters. The details of the model and of its application are provided in the [Supplementary Material](#). Based on the *air2water* results, we defined the global warming (GW) scenario for  $T_{\text{surf}}$  shown in Fig. 3b, where the curves depict the mean annual cycle. The standard deviation of  $T_{\text{surf}}$  is assumed to be the same for all scenarios and kept equal to that of measurements (Fig. 3c).

The increase in  $T_{\text{surf}}$  expected in 2041–2050 and relative to current (2000–2008) conditions is shown in Fig. 3d (scenario GW). The largest warming of  $T_{\text{surf}}$  is expected in the warm season (August–October), with mean and maximum increase of  $\sim 1.9$  °C and  $\sim 4$  °C, respectively. This is coherent with observations covering the last century, which registered the strongest warming of water temperature (measured at 25 m depth) in fall (Hampton et al. 2008). Moreover, the warm season is the one characterized by the highest variability (see the largest standard deviation of  $T_{\text{surf}}$  measurements in Fig. 3c), thus the most responsive to changes in the external forcing. The amplified warming of  $T_{\text{surf}}$  in this period compared to that of air temperature ( $\sim 1.4$  °C on average during the year, Fig. 3d) is essentially due to anticipation of strong thermal stratification, according to what reported for other deep lakes on Earth (see, e.g., Piccolroaz et al. 2015; Woolway and Merchant 2017). Conversely, due to the huge heat capacity of the lake’s surface-mixed layer when thermal stratification is weak,  $T_{\text{surf}}$  is expected to undergo minor changes during the rest of the year, including the period favorable for deep ventilation, i.e., when the lake is weakly inversely stratified and  $T_{\text{surf}}$  is close to  $T_{\rho\text{max}}$  (see Fig. 2). Wind (CW and SW) and global warming (GW) scenarios were combined together to produce the scenarios GW-CW and GW-SW.

We defined an additional warming scenario (GW\*), which is not realistic but useful to evaluate the effect that a possible shortening of the deep ventilation season due to  $T_{\text{surf}}$  warming would have on the renewal of deep layers. To this end, we described the warming



through a trapezoidal-shape function, with steep sides in correspondence of the deep ventilation season. To allow for a comparison with the more realistic scenario GW, the GW\* scenario was constructed having the same mean annual  $T_{\text{surf}}$  warming (i.e., 0.70 °C, about 50% of the mean air temperature warming).

### 3 Results

A set of 1000 years long-term simulations was run under the different climate scenarios listed in Table 1, including the current condition (control) scenario. In all simulations, the first 100 years were used as warm-up period, during which the initial (current) conditions of  $W$  and  $T_{\text{surf}}$  were gradually modified to match those prescribed by the different scenarios.

Figure 4a shows the comparison between temperature profiles on February 15 obtained for the different scenarios (all profiles are averaged over the entire simulation, excluding the first 100-year period used as warm-up). Observed profiles (period 2000–2008) are also shown for comparison. The figure clearly shows that changes in the wind dynamics have strong impacts: the deep-mixing activity is markedly enhanced under the SW scenario causing a progressive cooling of hypolimnetic waters. The opposite (warming of deep waters) occurs for the CW scenario due to reduced downwelling volumes. On the contrary, the increase of  $T_{\text{surf}}$  expected in scenario GW taken alone or in combination with the wind scenarios (GW-CW and GW-SW) does not have a relevant effect on the vertical water temperature profile, which undergoes only a slight warming compared to the counterparts control scenario, CW and SW.

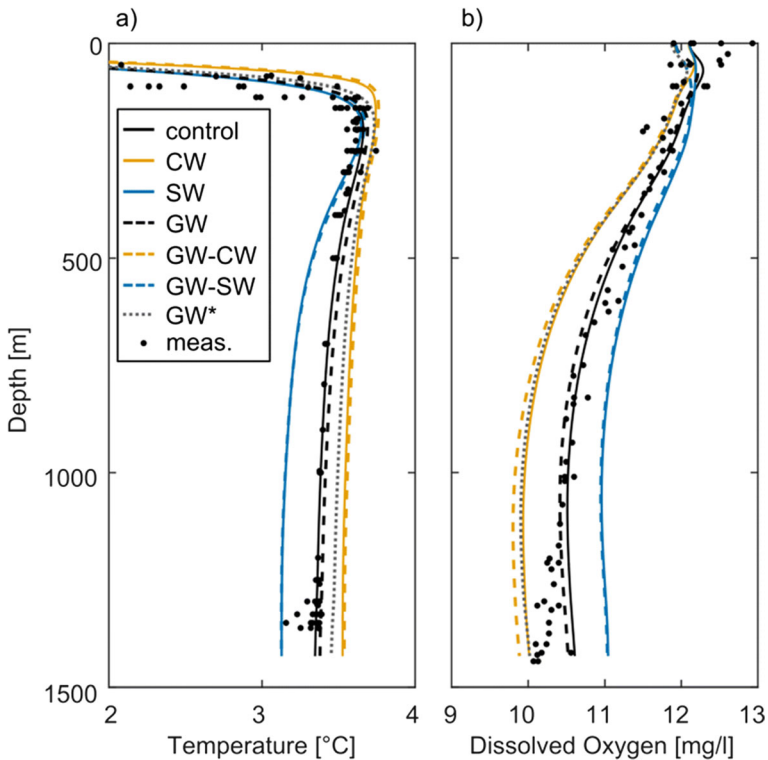
The same conclusions emerge from the analysis of the downwelling parameters listed in Table 1, where a robust statistical estimate was possible, thanks to the availability of long-term simulation results. In particular, the mean annual downwelling temperature  $T_{\text{down}}$  and downwelling volume  $V_{\text{down}}$ , both evaluated for downwelling events deeper than 1300 m depth, were taken as significant quantities characterizing deep ventilation in the lake. The different contribution of warming  $T_{\text{surf}}$  and changing wind forcing is evident: relative to the control scenario, GW does not alter  $V_{\text{down}}$  while it decreases by 26% and increases by 16% under the CW and SW scenarios, respectively. Additionally,  $T_{\text{down}}$  does not undergo significant changes under the GW scenario, while it is expected to increase by 4% and decrease by 7% under the

**Table 1** Climate change scenarios and their effect on deep ventilation. Mean downwelling temperature  $T_{\text{down}}$ , mean annual downwelling volume  $V_{\text{down}}$ , and mean  $DO$  concentration of downwelling water  $DO_{\text{down}}$  for downwelling events deeper than 1300 m depth. Statistics are evaluated excluding the first 100-year period used as warm-up. The downwelling periods are also listed. All variables are presented as mean  $\pm$  standard deviation

Scenario	Description	$T_{\text{down}}$ [°C]	$V_{\text{down}}$ [km <sup>3</sup> ]	$DO_{\text{down}}$ [mg/l]	Downwelling period	
					Spring	Winter
Control	Current condition*	3.28 $\pm$ 0.06	88 $\pm$ 71	11.56 $\pm$ 0.50	3 Jun $\pm$ 5	20 Dec $\pm$ 6
CW	Calm wind	3.42 $\pm$ 0.07	65 $\pm$ 44	11.23 $\pm$ 0.58	5 Jun $\pm$ 5	17 Dec $\pm$ 6
SW	Strong wind	3.06 $\pm$ 0.06	102 $\pm$ 82	11.82 $\pm$ 0.43	30 May $\pm$ 4	24 Dec $\pm$ 5
GW	Global warming	3.30 $\pm$ 0.06	87 $\pm$ 70	11.52 $\pm$ 0.48	31 May $\pm$ 4	24 Dec $\pm$ 6
GW-CW	Global warming + calm wind	3.41 $\pm$ 0.07	61 $\pm$ 43	11.19 $\pm$ 0.57	1 Jun $\pm$ 5	23 Dec $\pm$ 7
GW-SW	Global warming + strong wind	3.05 $\pm$ 0.07	100 $\pm$ 81	11.81 $\pm$ 0.44	27 May $\pm$ 4	28 Dec $\pm$ 7
GW*	Global warming (synthetic)	3.52 $\pm$ 0.07	67 $\pm$ 56	11.28 $\pm$ 0.47	30 May $\pm$ 3	24 Dec $\pm$ 3

\*The slight difference between  $T_{\text{down}}$  and  $V_{\text{down}}$  presented here and reported in Piccolroaz and Toffolon (2013) is due to the different randomly generated 1000-year simulation, while all calibration parameters are kept unaltered





**Fig. 4** **a** Mean temperature profiles on February 15 and **b** mean annual dissolved oxygen profiles obtained for current conditions (control) and the climate scenarios listed in Table 1. Profiles are obtained excluding the first 100 years of warm-up

CW and SW scenarios, respectively. We notice that such a relatively small difference in  $T_{\text{down}}$  is actually significant considering the small temperature gradients in the hypolimnion of Lake Baikal. The differences between the statistics of GW-CW and GW-SW compared to their counterparts CW and SW are not significant, confirming the minor impact of the GW scenario.

The influence of climate change on deep ventilation is also visible looking at the deep oxygen concentration, which eventually affects the peculiar ecosystem of Lake Baikal. *DO* profiles simulated under the different scenarios are shown in Fig. 4b, in comparison with available *DO* measurements and the simulated profile under the control scenario. Unlike temperature, the change in *DO* in the hypolimnion results from the combination of two effects: the change in  $V_{\text{down}}$  according to the results summarized in Table 1 and the dependence of *DO* saturation conditions (i.e., the upper boundary condition for *DO*) on  $T_{\text{surf}}$ . The latter factor influences deep oxygenation altering both the diffusive flux of *DO* from the atmosphere to the lake throughout the year, and the *DO* concentration of the downwelling water according to its temperature (i.e.,  $T_{\text{down}}$ , see Table 1). According to Fig. 4a, CW and SW scenarios show a stronger effect than GW alone (compared to the control scenario, mean *DO* concentration below 1300 m depth is  $-0.6$  mg/l and  $+0.5$  mg/l in the first two cases and  $-0.1$  mg/l in the last case).

The secondary importance of  $T_{\text{surf}}$  warming on deep temperature and *DO* profiles is attributable to the fact that only a small temporal shift in the deep ventilation period is expected for GW compared to the control scenario, while its duration does not undergo significant changes (Table 1). In fact,  $T_{\text{surf}}$  warming is likely to affect deep ventilation only if the periods when  $T_{\text{surf}}$  is

close to  $T_{\text{pmax}}$  are significantly shortened or extended. It is therefore interesting to analyze also the synthetic (and unrealistic) GW\* scenario, specifically constructed to evaluate this effect. Results suggest that in response to almost halving of the downwelling period (Table 1) due to a marked steepening of  $T_{\text{surf}}$  (Fig. 3b, d), the warming effect would become relevant and clearly visible in the temperature and, due to the combination of effects discussed above, even more in the  $DO$  profiles. Relative to the control scenario,  $V_{\text{down}}$  decreases by 24%,  $T_{\text{down}}$  increases by 7%, and mean  $DO$  concentration below 1300 m depth decreases by 0.6 mg/l.

## 4 Discussion

The analysis of deep-water renewal described in the previous sections indicates a complex but predictable response of Lake Baikal. The results show that the main mechanisms affecting deep ventilation under a changing climate are well identifiable and that the role played by the main external variables can be assessed and quantified. Overall, changes in the wind forcing have been shown to alter deep ventilation significantly more than rising lake surface water temperature, the latter factor playing a secondary role also when considering a severe climate change scenario (the GW scenario has been constructed based on the most severe IPCC AR5 emission scenario, i.e., the RCP8.5). In fact, it is not just the intensity of  $T_{\text{surf}}$  warming that dictates the impact on deep ventilation, but more importantly its timing. This clearly emerged by comparing the response of the lake under two different  $T_{\text{surf}}$  scenarios characterized by the same mean annual warming, but with two different warming distribution during the year (Fig. 3d): realistic in one case (GW) and artificial in the other case (GW\*). In the first case (GW), the main  $T_{\text{surf}}$  warming occurs far from the downwelling periods, and the duration of the periods favorable to downwelling occurrence is not significantly altered, thus determining a negligible impact on deep ventilation. Contrarily, in the second case, the warming scenario was deliberately shaped to shorten the favorable periods, thus obtaining a marked reduction of thermobaric-driven deep ventilation. Such a completely unrealistic scenario (GW\*) can be seen as an artificial experiment to demonstrate the importance of the duration of the ventilation periods.

The high resistance of deep thermobaric convection to global warming is an important result for Lake Baikal, but can be reasonably extended to other deep thermobarically stratified lakes. This complements the conclusions of Boehrer et al. (2008, 2013) that deep-water temperature in thermobarically stratified lakes is much less susceptible to changes in surface temperature than in lakes where deep-water temperature is chiefly controlled by winter thermal conditions at the surface. Recent studies have shown that global warming is expected to inhibit the intensity and duration of deep mixing in many of these lakes, with consequent deep-water warming and deoxygenation. Some examples are lakes Tahoe (USA, Sahoo et al. 2013), Iseo (Italy, Valerio et al. 2015), Geneva (Switzerland/France, Schwefel et al. 2016), and Garda (Italy, Salmaso et al. 2017). Another evocative example is Crater Lake, for which Wood et al. (2016) showed that, under the RCP8.5 scenario, the lake will undergo a thermal regime shift progressively transitioning from dimictic to warm monomictic or to oligomictic, decreasing the frequency of episodic deep downwelling events. This is not likely to occur in Lake Baikal, for which projected air temperature in winter will still remain well below 0 °C even under the RCP8.5 scenario, at least in the near future.

A catastrophic shift occurred in Lake Tanganyika, the second deepest lake in the world, where the warming of lake surface temperature combined with the weakening of winds progressively reduced the mixing depth, causing a significant decline in oxygen concentrations

and in primary productivity rates (O'Reilly et al. 2003). Despite the inherent differences between the two lakes (Lake Tanganyika is a tropical, meromictic lake), we can speculate that a scenario GW-CW would likely affect the primary productivity also in Lake Baikal, where the internal recycling of nutrients from deep to shallow depths was evaluated of the same order of magnitude as all external inputs (Müller et al. 2005; Moore et al. 2009).

We remark that the present analysis was based on idealized (yet realistic) scenarios of wind forcing. Possibly, a more complex behavior could be expected if, besides the seasonal distribution of the wind speed, also the time distribution of wind events will be affected by climate change. However, the definition of reliable wind speed scenarios is typically associated to large uncertainties (Chen et al. 2012; Carvalho et al. 2017) and is likely hampered in Lake Baikal, where local pressure gradients and strong lake-atmosphere interactions may challenge the use of climate models. Contrasting scenarios have been formulated for the lake area: Shimaraev et al. (1994) suggested that it is likely that warming will generate greater wind activity, while Potemkina et al. (2018) observed that winds are weakening in the last decades. Further efforts are therefore required in this direction, provided the importance of winds in controlling stratification and mixing dynamics in deep lakes, as clearly demonstrated in some recent works (e.g., Austin and Allen 2011; Butcher et al. 2015; Valerio et al. 2015; Wood et al. 2016), including the present one.

Despite results certainly depend on the choice of the climate change scenario, here we propose a meaningful description of the fundamental response of Lake Baikal to changing external forcing. These results respond to a major research need raised by Moore et al. (2009), concerning the importance of understanding how deep ventilation and mixing processes are likely to change in the future, due to their major effect on the oxygenation of deep layers and transport of nutrients from deep to shallow depths. In fact, previous climate change studies on Lake Baikal were mainly aimed at assessing the consequences on the lake ecosystem through the use of multivariate relationships between biotic and abiotic (e.g., physical, chemical, climatic) variables, but without the support of any hydrodynamic model of the lake (see, e.g., Mackay et al. 2006; Hampton et al. 2008).

## 5 Conclusions

In the present work, we presented the first detailed sensitivity analysis of the response of Lake Baikal to climate change, showing that this lake is sensible to climate change to an extent that its ecosystem and water quality may undergo profound disturbances. We showed that deep ventilation is sensitive to changes in wind speed, but resistant to changes in lake surface water temperature. This suggests that improving the definition of future wind scenarios is a main research need and that more attention should be paid to properly include these scenarios in climate change studies of deep lakes, an aspect that is often overlooked. The self-resistance of thermobaric instability to global warming is inherent in the system as it is ensured by the large thermal inertia of the lake during the downwelling periods (when the lake is nearly homothermal) which mitigates changes in lake surface water temperature in these periods of the year. This is a trait that can be reasonably extended also to other deep thermobarically stratified lakes, and introduces an interesting difference relative to monomictic or oligomictic lakes in warmer climates which, on the contrary, are particularly sensitive to a warming climate. Further research is needed to assess how changes in climate drivers are expected to affect the lake ecosystem, directly and through their influence on lake's physical processes. To this aim, we believe that additional efforts should be put in a deeper collaboration between physicists and

biologists, trying to overcome the actual fragmentation of the limnological community into expert, specialized fields with limited interaction among each other (Lewis 1995; Salmaso and Mosello 2010; Toffolon et al. 2014b).

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