

## Author's response

*NB: the mentioned pages and lines refer to the marked-up manuscript.*

### Referee #1

1. The parametrisation of energy is introduced out of context of the original model. By reading the preceding paper I am able to see where these parameters fit in, and I understand the desire by the authors to be concise and not to repeat previously published work, however the paper should also stand on its own. I suggest that a more appropriate balance in this case would be to write out the full equation set being solved (which is not long) and then point readers at the previous paper for the details of the discretisation. This would make understanding the parametrisation presented much easier.

*We agree with Referee #1 that the context of the new parametrisation was insufficiently explained in the manuscript, and that it is important that the present paper stands on its own. However, we think that presenting the full set of equations, which would then also require explaining the full set of parameters used in these equations, would distract too much from the main focus of the manuscript. Both are fully developed in Goudsmit et al. 2002. Instead, we added a more detailed explanation about the meaning and relevance of the modified parameter ( $P_{\text{seiche}}$ ) in the Simstrat model, as follows: "Within the standard system of equations of a  $k$ - $\epsilon$  model, where  $k$  is the turbulent kinetic energy and  $\epsilon$  its dissipation,  $P_{\text{seiche}}$  is used as a source term in the differential equation for  $k$  and, multiplied by  $\epsilon/k$  and a constant, as a source term in the differential equation for  $\epsilon$ ." on page 5, lines 15-17.*

1.a. As a minor point, it is conventional to typeset subscripts and superscripts which are English words in upright text.  $f_{\text{stab}}$  conventionally means  $f_{s^*t^*a^*b}$  while  $f_{\text{\texttrm{stab}}}$  means what the authors intend here.

*We agree and changed the syntax accordingly throughout the manuscript.*

2. Verification. There is no verification of the model: the manuscript jumps straight from explaining the parametrisation to validation (ie testing the model's effectiveness on a real problem). Given that the validation exercise involves significant calibration, it is not really possible for the reader to conclude from the paper that the implementation presented is actually correct. One would usually expect as an intermediate step, some very idealised cases where the model error is demonstrated to converge at the predicted rate. In the absence of such evidence, how is the reader supposed to conclude that the implementation is correct? Admittedly, the validation exercise provides evidence that the implementation is not disastrously wrong, but minor bugs which nonetheless affect solution quality are very common.

*We agree with Referee #1 that model verification would be useful to prevent the occurrence of bugs. We propose adding an idealized case where wind is a periodic rectangular function of variable frequency affecting a two-layer basin. We can then show that, depending on the frequency of the wind function, filtering is correctly performed and transmitted to the model and that BSIW excitation occurs as expected. There is however to our knowledge no analytical solution or other method that could predict the exact output of the model running such an idealized case.*

*We added such an idealized case on the GitHub (folder: "Simstrat\_WindFiltering/", parameter file: "kepsilon\_IdealizedCase.par", input files: "IdealizedCase/", results:*

*“IdealizedCase\_Results/” and “IdealizedCase\_Results\_wfilt/”*). The central features of the setup are:

- *Basin with a depth of 100 m and a surface area of 100 km<sup>2</sup> (from surface to bottom).*
- *Temperature of 15°C from 0 to 25 m depth, temperature of 5°C below 25 m depth.*
- *No inflows and outflows and no heat flux at the surface, therefore there are only internal water and heat exchanges.*
- *Wind forcing (5 m s<sup>-1</sup> in both directions) as a rectangular function with period of either 1 hour (hereafter W1; file “Forcing\_period1.dat3”) or 24 hours (hereafter W24; file “Forcing\_period24.dat3”).*
- *Default set of parameters used for all model runs.*

*The seiching period of the first mode of the basin is around 27 hours (Equation (1) of the manuscript). Although the overall wind average is the same, W24 would result in a stronger response of BSIWs within the idealized basin than W1, as the wind period is much closer to the seiching period of the basin.*

*This idealized case allows to verify the following aspects of our algorithms:*

- *If there is no wind forcing, the temperature evolution in the idealized basin is governed solely by molecular diffusion. Wind promotes faster mixing between the layers and progressively drives the “thermocline” deeper.*
- *W24 induces an increased excitation of the basin when compared to W1 (e.g., clear temperature oscillations at the interface at 25 m depth).*
- *Wind filtering (script “Simstrat\_WindFiltering.R”) reduces the average intensity of W1 by ~37 % and of W24 by ~1 %. As a result, the filtered W24 excites the idealized basin significantly more efficiently than the filtered W1.*

*After thorough discussion, we decided not to add this test case to the manuscript. We feel that the information that can be gained by including it does not outweigh the length and complexity that it adds to the manuscript. We then prefer to keep the manuscript focused on real systems.*

3. Independence of calibration and validation. If I understand the last paragraph of page 9 correctly, the same data period was used to calibrate the models as is then used to assess the model performance. If I am mistaken in this, then the relationship between the data used for the two phases should be made much more explicit. If it is indeed the case that the same data was used for calibration and assessment, this would appear to significantly undermine the results in the paper. Using disjoint data sets for this purpose is surely necessary to demonstrate the predictive power of the model.

*Our work aims at explaining the importance of an overlooked physical process and including it into the model. In our case, we propose external processing of the wind time series to improve BSIW parametrisation. We therefore want to highlight the improvement that the proposed modification brings in comparison to the original parametrisation, rather than demonstrate the performance and predictive power of a new model. The single difference between the models is that the “modified version” takes a different time series of wind as input into Equation (3). As a measure of the improvement, we compare the results for the new model version with those for the original model version. Both model versions are calibrated in exactly the same way. Because the revised model does not include any additional calibration parameters compared to the original version, we don't think that separating the data in a calibration and a validation*

*period would yield additional information concerning the usefulness of the new parametrisation.*

#### 4. Model code availability and reproducibility.

I set out to attempt to reproduce the results in this paper using the code provided. I failed completely. There is a litany of issues:

a. Plain GitHub URL. This is not a safe archive for model code. This is for two reasons. First, the code might disappear from GitHub tomorrow, second, it is not at all clear which version of the repository was used to create the results in this paper - and as the model is developed into the future, the current version of the code at any given time will no longer be the version in this paper. Please use the GitHub Zenodo integration, or similar, to archive the precise version of the code used in this paper in a permanent location with a DOI. See: <https://guides.github.com/activities/citable-code/>

*We agree that there must be a safe archive for model code and related files. Simstrat was only recently transferred to version control. As suggested, we archived the code in a permanent location with a DOI. The link to this archive is given in the "Code and data availability" Section of the manuscript, on page 18, lines 18-19.*

b. Code does not build. The provided .exe file is clearly not going to be of any use on my Linux workstation, so I set out to build the code. The user manual provides no information on how to do this. The developer manual is clearly incomplete but does at least say something.

i. The first surprise is that I need FABM. This rather important dependency isn't cited in the paper. One would rather think it would be and that what FABM provides to the model would be documented somewhere. FABM did not build for me, this may be my fault although the amount of manual intervention in the build process which the instructions appear to require makes this inherently error-prone.

*We address this comment in the next answer.*

ii. Apparently there is a dependency on NetCDF and HDF5, however since this section is only a header, with a single sentence body indicating that the author failed at this point, I have no indication of what I am supposed to do.

*The manual provided on the GitHub, although it is not a final version, covers a larger scope than required for the model used in the manuscript. Neither FABM, nor NetCDF nor HDF5 are required to compile the code provided on the GitHub or run the simulations presented in the manuscript. We are sorry if this was not clear and clarified the manual accordingly. We updated the Readme file on the GitHub with simple instructions on how to run the model and visualize the results.*

iii. I then attempted to compile kepsmodel\_2016.F90 using gfortran 5.4.0, knowing that there would probably be a linker problem due to the missing libraries. However, the code does not compile due to missing keps\_utilities\_clean.f90. Presumably this means that keps\_utilities.f90 needs to be preprocessed in some way, but no instructions to end are provided.

*Using gfortran, compilation of the source code should work independently of the platform, as no extra library is required. However, as Referee #1 rightly highlighted, a typo prevented compilation: at the end of the main file kepsmodel\_2016.f90, the suffix "\_clean" should be removed from the two include filenames. We corrected the code accordingly.*

c. Scripts are not provided. None of the namelists, parameter files or Matlab scripts referred to in the user manual are actually present in the repository. This despite the manuscript explicitly claiming they are there. In particular, all the code required to drive PEST appears to be absent.

*For the sake of simplicity, we decided not to provide the files that were not strictly needed to compile the model. However, we agree that the parameter files and the processing scripts should be provided, and we added them to the repository. We also provided the code used to run calibration through PEST, and updated the Readme file on the GitHub with simple instructions on how to calibrate the model.*

d. Data is not identifiable. Neither the paper nor the repository provides enough information for the user to obtain the data used from the original sources, since no identification is provided for the datasets. The fact that the data is not publicly available further underlines the need for verification tests based on ideal synthetic data, so that a future user can establish that the code works without depending on data to which he or she may never have access. In short, the model code does not appear to have been published in a usable way, and the information required to reproduce the results in this paper (even assuming access to data) does not appear to be present. Indeed, the GitHub commit record appears to suggest that some code was just thrown together and committed on one day in November. It seems unlikely that the code in the repository was actually used in its current form to produce the paper. This does not conform with either the spirit or the letter of GMDs guidance on code and data availability and needs to be fixed.

*We agree and provided information allowing better identification of the data. For clearness, we removed the incomplete references from page 9, lines 4, 11 and 12-13. We added full identification of the datasets in the “Code and data availability” Section, on page 18, lines 11-15 and in Table 5. In addition, in order to facilitate independent testing of the model, we provided an excerpt of the data we used on the GitHub. As the authors are not the data owners, we don’t have the right to make the complete datasets used in the model freely available. These are available upon request from the data owners listed in the “Code and data availability” Section of the manuscript, on page 18, lines 11-15.*

## Referee #2

### Specific Comments

1. The Abstract is provides clear information of a general nature, but it could be developed to provide specific, quantitative information on the extent of improvements in accuracy of model temperatures and mixed layer depths

*We agree and added the main quantitative results, i.e. up to 40 % reduction in RMSE for the near-bottom temperature and a significantly better reproduction of the vertical extent of the seasonal deep convective mixing, on page 1, lines 16-18.*

2. p.5, l.15: gamma depends on bottom friction and basin geometry – please add some detail on this

*We replaced gamma by its equation, based on Goudsmit et al. (2002), on page 5, lines 21-23:*

$$\gamma = A_{lake} V_{lake}^{-3/2} \rho_{water}^{-1/2} C_{Def}f$$

*where  $A_{lake}$  and  $V_{lake}$  are the lake surface area and volume, respectively,  $\rho_{water}$  the density of water and  $C_{Def}f$  the bottom drag coefficient.*

3. p.9, l.24: The PEST software is used to calibrate the model; beyond the reference to Doherty (2005), please define the acronym and briefly explain how PEST works

*We defined the acronym of PEST (“Model-Independent Parameter Estimation and Uncertainty Analysis”) and added the following sentence: “PEST searches for the optimal value of chosen parameters which ensure the best match between model results and available observations (here, temperature measurements over the simulation period).” on page 10, lines 4-7. In addition, the code to run calibration through PEST is provided on the GitHub repository.*

4. p.9, l.26: Two of the three parameters used in model tuning are only mentioned here; please provide details (equations?) to explain the “fit parameter for absorption of solar radiation” and the “fit parameter for the fluxes of sensible and latent heat”

*We added more details about these two parameters as follows, based on Goudsmit et al. (2002), on page 10, lines 9-11:*

- *$p_1$  (fit parameter for absorption of longwave radiation) linearly scales the amount of heat that is absorbed in the lake water from the incoming longwave radiation from the atmosphere.*
- *$p_2$  (fit parameter for the fluxes of sensible and latent heat) linearly scales the exchange of sensible and latent heat between the lake surface and the atmosphere.*

*We explained the significance of these two parameters as follows: “ $p_1$  and  $p_2$  account for the fact that, in specific cases, there is always a difference between the heat flux formulas and the effective fluxes, as the formulas are empirical and the meteorological data is not always fully representative for the lake surface.” on page 10, lines 11-13.*

5. pp. 15-16: Sect.4 provides brief conclusions; there is no explicit discussion, although brief reference to applications (p.16, lines 1-2); a more developed Discussion section would be more appropriate

*We agree, however we purposely kept the manuscript as concise as possible. We developed the following items in more detail:*

- *We further commented Figure 7, as follows: “Fig. 7 shows that the original version of the model largely overestimated deep convective mixing, as full lake mixing was being predicted almost every winter. Using wind filtering, deep seasonal mixing is more finely reproduced, which also helps towards modelling of lake-scale circulation of water, oxygen and nutrients.” on page 16, lines 6-9.*
- *We added a discussion about our calibrated values for the  $\alpha$  parameter for the deep lakes, which tend to be higher than the ones found by previous studies, on page 14, lines 1-13.*
- *We added a concluding sentence about possible further research on page 18, lines 6-9.*

1. p.3, l.20: rather than “aquatic systems”, why not say “lakes”?

*We replaced the expression by “lakes and reservoirs” on page 4, line 3.*

2. p.7, l.8: “in order to smooth the cut-off effect”

*Corrected on page 7, line 16.*

3. p.7, l.14: “both oppose excitation of BSIWs”

*Corrected on page 7, line 22.*

4. p.11, l.5: “and rather briefly”

*Corrected on page 11, line 18.*

5. p.11, lines 5-6: the sentence “A comparison of the filtering for all four lakes is shown in Fig. 3” should be moved to the start of Sect. 3.1

*Moved accordingly to page 11, line 7.*

6. p.11, l.13: Equation (12) is hardly an equation – why is it necessary to use two different symbols for the same factor?

*We removed Equation (12).*

7. p.12, l.1: How is “average wind direction” defined?

*We defined how average wind direction can be calculated on page 12, lines 8-10.*

8. p.15, l.2: “which then remains denser”

*Corrected on page 16, line 6.*

9. p.15, l.19: “In winter, however, filtering strongly ...”

*Corrected on page 17, line 17.*

#### **Other changes**

- *It is inexact to compare the calibrated  $\alpha$  values of the initial and improved models. The global filtering  $f$  multiplies the wind speed used in Equation (3), where it is then raised to the cube. Therefore, the overall filtering can be expressed as follows:*

$$\text{Initial model} \quad P_{seiche} = \alpha A_{lake} \rho_{air} C_{10} U_{10}^3$$

$$\text{Improved model} \quad P_{seiche} = \alpha f^3 A_{lake} \rho_{air} C_{10} U_{10}^3$$

*A more relevant comparison is then  $\alpha$  of the initial model with  $\alpha f^3$  of the improved model. We adapted Tables 3 and 4 accordingly on page 13 and briefly described and discussed this expression and this new comparison on page 13, lines 8-10 and 17-18.*

- *We added references to four recent relevant studies: Schwefel et al. (2016), Woolway and Simpson (2017), Fink et al. (2016), Valerio et al. (2017).*
- *We added more references to Table 1 and to the “Code and data availability” Section on page 8, line 22 and page 9, lines 19 and 26.*
- *We made several other minor corrections, clarifications and referencing changes.*

# Optimizing the parameterization of deep mixing and internal seiches in one-dimensional hydrodynamic models: a case study with Simstrat v1.3

Adrien Gaudard<sup>1</sup>, Robert Schwefel<sup>2</sup>, Love Råman Vinnå<sup>2</sup>, Martin Schmid<sup>1</sup>, Alfred Wüest<sup>1,2</sup> and Damien Bouffard<sup>1,2</sup>

<sup>1</sup>Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters – Research and Management, Seestrasse 79, CH-6047 Kastanienbaum, Switzerland

<sup>2</sup>École Polytechnique Fédérale de Lausanne, Physics of Aquatic Systems Laboratory – Margaretha Kamprad Chair, EPFL-ENAC-IIIE-APHYS, CH-1015 Lausanne, Switzerland

*Correspondence to:* Adrien Gaudard (adrien.gaudard@eawag.ch) or Damien Bouffard (damien.bouffard@eawag.ch)

**Abstract.** This paper presents an improvement of a one-dimensional lake hydrodynamic model (Simstrat) to characterize the vertical thermal structure of deep lakes. Using physically based arguments, we refine the transfer of wind energy to basin-scale internal waves (BSIW<sub>s</sub>). Namely, we consider the properties of the basin, the characteristics of the wind time series and the stability of the water column to filter and thereby optimize the magnitude of wind energy transferred to BSIW<sub>s</sub>. We show that this filtering procedure can significantly improve the accuracy of modelled temperatures, especially in the deep water of lakes such as Lake Geneva, for which the root mean square error between observed and simulated temperatures was reduced by up to 40 %. ~~This~~The modification, tested on four different lakes, increases model accuracy and contributes to a significantly better reproduction of seasonal deep convective mixing, a fundamental parameter for biogeochemical processes such as oxygen depletion. It also improves modelling over long time series for the purpose of climate change studies.

## 1 Introduction

### 1.1 Hydrodynamics of vertical mixing in lakes

Lakes are recognized as sentinels of changes in climate change and catchment processes (Shimoda et al., 2011; Adrian et al., 2009). They have multiple intricate interactions with their environment, simultaneously reacting to external forces and acting on their surroundings. The complex hydrodynamic processes occurring in stratified lakes are mainly governed by the combination of surface heat flux and wind stress (Bouffard and Boegman, 2012). The former sets up a density stratification by warming the near-surface water, which floats on top of the cold deep water. This stratification pattern isolates the lower parts of the lake (hypolimnion) from the surface layer (epilimnion) and acts as a physical barrier reducing vertical fluxes. The latter, wind stress, brings momentum into the system and thereby contributes to mixing. Notably, the action of wind stress on a stratified basin leads to internal waves (seiches), rerouting the energy at various spatial and temporal scales (Wüest and Lorke, 2003; Wiegand and Carmack, 1986). Basin-scale internal waves (hereafter BSIW<sub>s</sub>) play a crucial role in

the transport of mass and momentum in the lake, driving horizontal dispersion and vertical mixing with ~~great-important~~ implications for biogeochemical processes (Bouffard et al., 2013; Umlauf and Lemmin, 2005).

In situ measurements, laboratory experiments and theoretical considerations have shown that the response of a stratified basin to wind depends on the strength, duration and homogeneity of the wind field as well as the geometry of the basin and the stratification of the water column (Valerio et al., 2017; Valipour et al., 2015; Stevens and Imberger, 1996; Mortimer, 1974)(Valipour et al., 2015; Stevens and Imberger, 1996; Mortimer, 1974). The typical assumption consists in considering the stratified water body as a two-layer system with different densities and thicknesses. The ~~re~~after, ~~the~~ wave period of longitudinal or transversal standing waves ( $T_{BSIW}$  [s]) can then be estimated with the Merian formula (Bäuerle, 1994; Merian, 1828):

$$T_{BSIW} = 2L \left( n^2 g \frac{\rho_2 - \rho_1}{\rho_2} \frac{h_1 h_2}{h_1 + h_2} \right)^{-1/2} \quad (1)$$

10 where  $L$  [m] is the length of the basin at the interface depth (in the direction of the excitation),  $g$  [ $\text{m s}^{-2}$ ] is the acceleration of gravity,  $\rho_1$  and  $\rho_2$  [ $\text{kg m}^{-3}$ ] are the densities of the upper and lower layers,  $h_1$  and  $h_2$  [m] are the layer thicknesses and  $n$  is the number of wave nodes.

In most lakes, the zone of abrupt temperature change, commonly referred to as thermocline or metalimnion, progressively deepens ~~after the warm season~~from spring to autumn. ~~Simultaneously, t~~The temperature difference between the two layers, determining the stratification strength, decreases, from mid-summer to autumn. The net result of both a deepening of the thermocline and a reduced stratification strength resulting in is an strong increasing in  $T_{BSIW}$  (Eq. (1)). This effect is remarkably strong in meromictic and oligomictic lakes, which can maintain stratification throughout the whole year. Lake Geneva can be categorized as ~~an~~ oligomictic ~~lake~~ with a period of the dominant first-mode longitudinal BSIW ranging from ~60 to ~600 h, as shown in Fig. 1. ~~This figure was constructed from more than 50 years of monitoring data at the location of the deepest point of the lake. As expected, t~~The wave period greatly increases from late autumn to early spring due to weakening of the stratification.



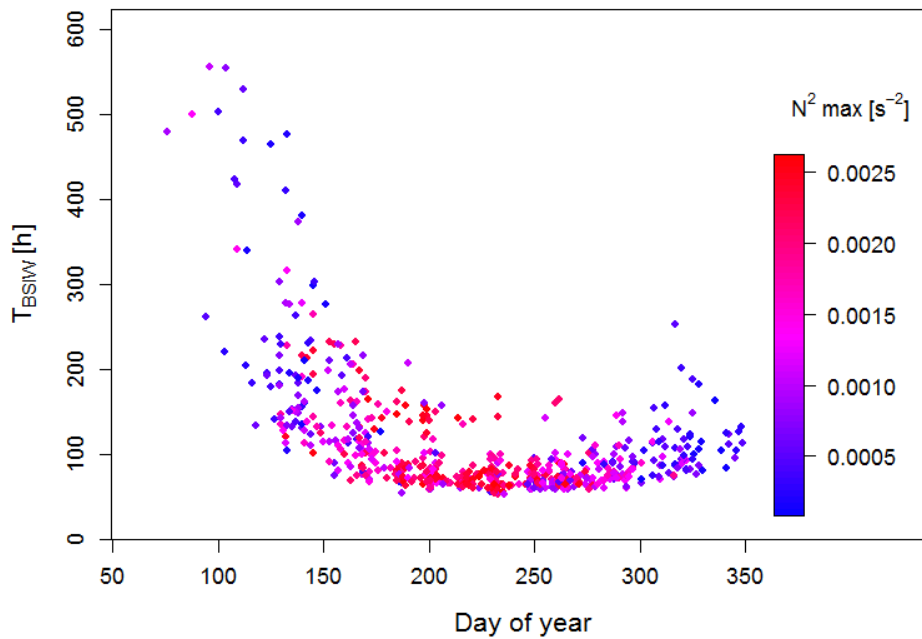


Figure 1 – Period of the first longitudinal mode BSIW as a function of the day of year in Lake Geneva. Points are coloured based on the observed maximum water column stability  $N^2$ . Values of  $N^2 < 10^{-4} \text{ s}^{-2}$  correspond to rare instances of complete lake overturn, i.e. unstratified water column, and are consequently not shown. The figure was constructed from more than 50 years of monitoring data at the deepest location of the lake.

Besides wind-induced BSIWs, convection is a subtle although important vertical energetic pathway in lakes (Read et al., 2012; Wüest et al., 2000)(Read et al., 2012). This process may be triggered by surface cooling or density currents (Thorpe et al., 1999). The generally weak winds over perialpine lakes increase the relative importance of convective processes in these systems. Notably, cooling during winter is responsible for temperature and thus density homogenization in mid-latitude water bodies.

In deep lakes however, the vertical mixing caused by convective and wind-induced turbulent processes (Imboden and Wüest, 1995) may be insufficient to mix the water column down to the bottom deepest layers. In this case, the deepest part of the lake remains separated from the homogenized upper part (Jankowski et al., 2006; Straile et al., 2003). The extent of deep mixing is of critical importance for reoxygenation of the deep water, and therefore for water quality. Insufficient oxygen supply often affects lake ecosystems and can trigger the release of harmful compounds and reduced substances as iron or manganese (Friedrich et al., 2014; Beutel and Horne, 1999). Comprehension and accurate prediction of the extent of deep mixing are thus vital for proper management of water resources, especially in deep lakes. Moreover deep mixing, as a key process of heat transfer to the hypolimnion, partly governs its response to climate change (Ambrosetti and Barbanti, 1999). However, the complex vertical pathway of kinetic energy makes modelling of the thermal structure challenging.

## 1.2 Numerical modelling

Over the past decades, many numerical models have been developed to allow for prediction and understanding of hydrodynamics in ~~aquatic systems~~ lakes and reservoirs. The algorithms and assumptions applied by these models vary greatly, as does their complexity, which ranges from simple box models to intricate three-dimensional models (Stepanenko et al., 2016; Wang et al., 2016; Ji, 2008; Hodges et al., 2000). For climate change studies, long-time lake simulations are needed, often utilizing vertical one-dimensional (1D) models (Wood et al., 2016; Butcher et al., 2015; Komatsu et al., 2007; Hostetler and Small, 1999). These models are computationally inexpensive (Goyette and Perroud, 2012), permitting long-term simulations (several decades or longer) and facilitating parameter estimation and sensitivity analyses.

Common 1D lake models have been extensively studied, validated and compared with different sets of observational data (Thiery et al., 2014; Perroud et al., 2009; Boyce et al., 1993). They have been proven to satisfactorily simulate the seasonality of surface temperature. Still, problems arise in reproducing the vertical mixing through the thermocline and the evolution of the deep water temperature (Schwefel et al., 2016; Stepanenko et al., 2010)(~~Stepanenko et al., 2010~~). Lake models have often been developed for specific applications and do not explicitly include all relevant physical processes and interactions. For instance, while processes like shear-induced turbulent mixing and solar radiation are usually modelled, the effect of internal waves is commonly not parameterized (Stepanenko et al., 2010). As a result, the estimation of bottom temperature appears to be significantly less accurate than that of surface temperature (Goyette and Perroud, 2012). This leads to large discrepancies between different models under similar running conditions (Stepanenko et al., 2013). Model accuracy can be improved by including BSIW parameterization and subsequent mixing (Schwefel et al., 2016). The problem has been partly tackled for small basins (Stepanenko et al., 2014), but not for large, deep lakes.

An inherent weakness of 1D models is the neglect of horizontal processes. These models may be able to reproduce fine vertical structures but generally perform calculations that are horizontally averaged over the whole simulation domain (Komatsu et al., 2007). Beside the classical problem of spatial heterogeneity, the ratio between vertical and horizontal turbulent viscosity, recognized to impact the response of lakes to wind forcing (Toffolon and Rizzi, 2009), cannot be accounted for. When vertical and horizontal viscosity are on the same order of magnitude (typically in winter), horizontal circulation is favoured and wind energy will give rise to large horizontal gyres rather than vertical motion (Straile et al., 2010). The stratified situation, associated with smaller vertical viscosity in comparison to horizontal viscosity, will favour BSIWs as well as up- and downwelling, the energy being absorbed by thermocline displacement and subsequently dissipated (Woolway and Simpson, 2017). We hypothesize that in 1D models resolving BSIWs, too much wind energy is introduced and converted into BSIW in winter, incorrectly impacting deep convection patterns (Fink et al., 2014b).

Here, we propose physically motivated modifications of the BSIW parameterization of a well-established 1D numerical model for better reproduction of deep mixing and hence improved prediction of deep water temperature. In Section 2, we present the model, describe our modifications and introduce the sites for which we test the model. In Section 3, we discuss

some aspects of our modifications and compare both calibration and results of the initial and modified models. Finally, we discuss the implications of our improvements.

## 2 Methods

In this study, we use the one-dimensional numerical model Simstrat v1.3, a modified version of the model developed by Goudsmit et al. (2002). ~~The model~~ Simstrat is a finite-difference buoyancy-extended reservoir model with k-ε turbulence closure. It has been extensively used to simulate water column temperature development under different conditions and over periods ranging from days to decades (Schwefel et al., 2016; Fink et al., 2014b; Stepanenko et al., 2014; Straile et al., 2010; Peeters et al., 2007, 2002)(~~Peeters et al., 2002, 2007; Straile et al., 2010; Stepanenko et al., 2014; Fink et al., 2014b~~). The model ~~has been shown to~~ performs equally good and in many aspects even better than other models, as shown in a comparison study for simulating Lake Geneva (Perroud et al., 2009). A possible reason for that is the implemented explicit parameterization of turbulence caused by BSIWs through the partitioning of wind energy.

### 2.1 Parameterization of internal waves

Simstrat parameterizes the total BSIW energy  $E_{\text{seiche}}$  [J] as a balance between production  $P_{\text{seiche}}$  [W] and loss  $L_{\text{seiche}}$  [W] of seiche energy (Goudsmit et al., 2002):

$$\frac{dE_{\text{seiche}}}{dt} = P_{\text{seiche}} - L_{\text{seiche}} \quad (2)$$

Within the standard system of equations of a k-ε model, where k is the turbulent kinetic energy and ε its dissipation,  $P_{\text{seiche}}$  is used as a source term in the differential equation for k and, multiplied by ε/k and a constant, as a source term in the differential equation for ε.  $P_{\text{seiche}}$  is parameterized as a function of the energy introduced by wind forcing at the lake surface:

$$P_{\text{seiche}} = \alpha A_{\text{lake}} \rho_{\text{air}} C_{10} U_{10}^3 \quad (3)$$

where  $\alpha$  [-] is the efficiency of energy conversion from wind to seiches,  $A_{\text{lake}}$  [m<sup>2</sup>] the surface area of the lake,  $\rho_{\text{air}}$  [kg m<sup>-3</sup>] the density of air,  $C_{10}$  [-] the wind drag coefficient and  $U_{10}$  [m s<sup>-1</sup>] the wind speed 10 m above the water surface. The following power law is used to calculate  $L_{\text{seiche}}$  is exponentially proportional to/from the total seiche energy  $E_{\text{seiche}}$ , as follows:

$$L_{\text{seiche}} = \gamma A_{\text{lake}} V_{\text{lake}}^{-3/2} \rho_{\text{water}}^{-1/2} C_{\text{Def}} E_{\text{seiche}}^{3/2} \quad (4)$$

where  $\gamma$  [m<sup>-1</sup> kg<sup>-1/2</sup>] is a constant of proportionality depending on the bottom friction and basin geometry.  $V_{\text{lake}}$  [m<sup>3</sup>] is the volume of the lake,  $\rho_{\text{water}}$  [kg m<sup>-3</sup>] the density of water and  $C_{\text{Def}}$  [-] the bottom drag coefficient.

The wind drag coefficient is calculated according to an empirical relation based on Wüest and Lorke (2003) – which is not the original formulation of Goudsmit et al. (2002):

$$C_{10} = \begin{cases} 6.215 \times 10^{-2} & ; U_{10} \leq 0.10 \text{ m s}^{-1} \\ 4.4 \times 10^{-2} U_{10}^{-1.15} & ; 0.10 < U_{10} \leq 3.85 \text{ m s}^{-1} \\ -7.12 \times 10^{-7} U_{10}^2 + 7.387 \times 10^{-5} U_{10} + 6.605 \times 10^{-4} & ; U_{10} > 3.85 \text{ m s}^{-1} \end{cases} \quad (5)$$

The modelling choices of Simstrat have been proven to yield very good estimates of water column temperature during the strongly stratified summer conditions in Lake Geneva (Perroud et al., 2009). However, the model was shown to invariably overestimate the intensity of winter deep mixing in Lake Geneva. Therefore, it was unable to follow lake-deep water temperature evolution over long timescales. The turnover of the lake is significantly exaggerated by the model, yielding more unstable deep water temperature than observed. An arguable solution to this problem would be prioritizing the deep water temperature during model calibration. While doing so, however, the wind-driven mixing observed in the thermocline region is then insufficiently represented (Stepanenko et al., 2010). For Lake Geneva, this disequilibrium is exemplified in Fig. 2 (upper frame) comparing observed and modelled temperature at 50 and 250 m depth. Mixing is clearly underestimated at a depth of 50 m and overestimated at a depth of 250 m. As a result, every-in most winters the simulated mixing depth strongly exceeds the observed value (Fig. 2, lower frame).

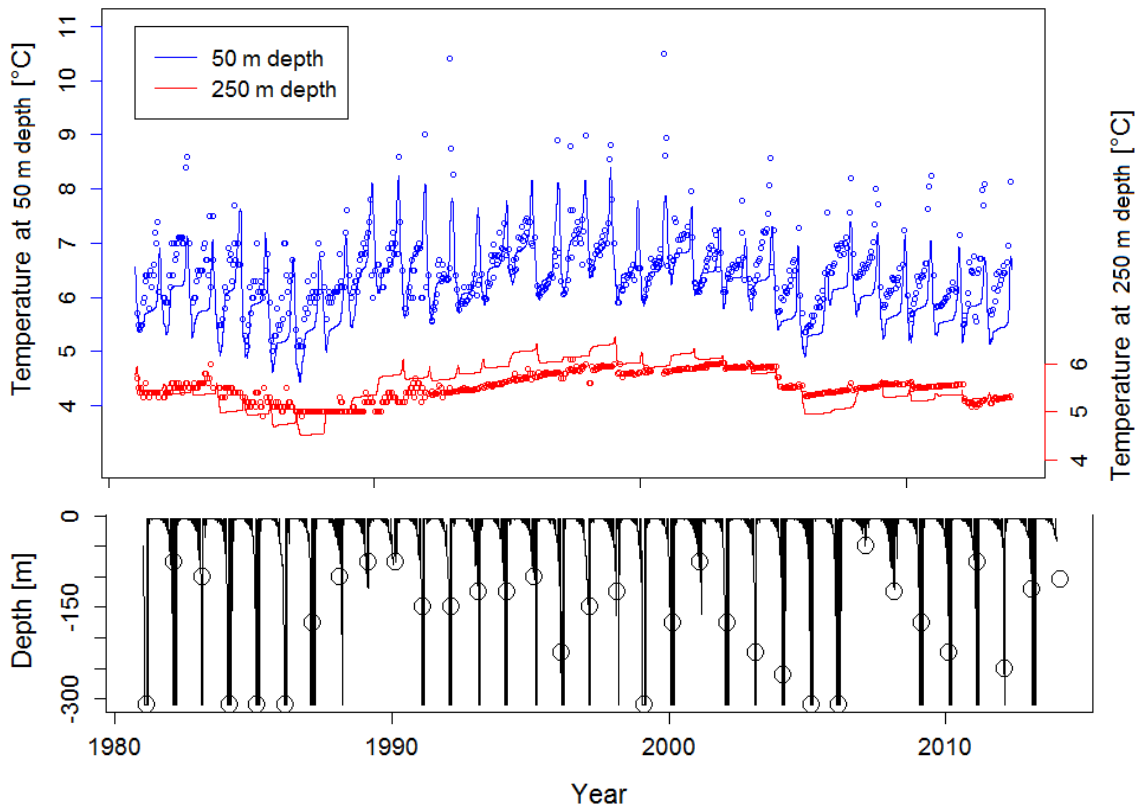


Figure 2 – Upper frame: evolution of observed and modelled temperature for Lake Geneva. Lower frame: evolution of observed and modelled mixing depth for Lake Geneva. Circles represent observations, lines represent Simstrat model-results obtained with the unmodified Simstrat model. The mixing depth is defined as the uppermost depth at which the absolute temperature gradient exceeds  $0.005 \text{ } ^\circ\text{C m}^{-1}$ , using time-averaged temperature time series over 60 days.

## 2.2 Proposed improvements

Our approach consists in parameterizing the energy pathway from wind to BSIWs with ~~three-two parameters-factors~~ representing different controlling processes. Those ~~parameters-factors~~ are used to calculate a filtered wind speed  $U_{10}^{\text{filtered}}$  for subsequent ~~calculation-estimation~~ of the BSIW energy production in Simstrat with Eq. (3). ~~The focus here is not a global reduction of wind strength, but rather filtering at the event-scale as a function of the present state of the lake and of wind forcing.~~ The standard wind speed  $U_{10}$  is still used for all other calculations, i.e. shear stress and heat flux.

$$U_{10}^{\text{filtered}} = f_{\text{dur}} f_{\text{stab}} U_{10} \quad (6)$$

All factors  $f_{\text{dur}}$  and  $f_{\text{stab}}$  range from zero to one and consequently induce a reduction of the effective wind speed available for BSIW energy production. We filter the wind based on the duration of wind events with  $f_{\text{dur}}$  [-] and based on lake stability with  $f_{\text{stab}}$  [-]. ~~The focus here is not a global reduction of wind strength, but rather filtering at the event-scale as a function of the present state of the lake and of wind forcing.~~

Regardless of their intensity, wind events much shorter than the BSIW period (from Eq. (1)) will inefficiently excite the oscillation modes of the internal waves. Specifically, wind stress lasting less than one fourth of the wave period should be filtered out (Schwefel et al., 2016; Stevens and Imberger, 1996)~~(Stevens and Imberger, 1996)~~. This limitation is parameterized in  $f_{\text{dur}}$  and is computed as follows ~~(one being the upper bound)~~:

$$f_{\text{dur}} = \min \left\{ \left( \frac{T_{\text{wind}}}{T_{\text{BSIW}}/4} \right)^{1/2}, 1 \right\} \left( \frac{T_{\text{wind}}}{T_{\text{BSIW}}/4} \right)^{1/2} \quad (7)$$

Here  $T_{\text{wind}}$  [s] is the duration of a wind event and  $T_{\text{BSIW}}$  [s] is the period of the first horizontal mode of BSIWs given in Eq. (1). The ratio is raised to the power of one half in order to smoothen the cut-off effect induced by the chosen criterion (one-fourth of the BSIW period). Wind events are defined as the periods with mean wind speed at least equal to ~~one-and-a-half~~ 1.5-times the overall average. Their duration is then the longest interval such that this condition is satisfied. The filter is applied at all times during the whole duration of the corresponding wind events. This filter is ~~naive-simplified~~ since it considers neither the resonance effects nor the other oscillation modes of a given basin. However, we hypothesize that despite its simplicity, the filter covers most of the BSIW excitation range for large lakes.

The stability of the water column ~~as well as and~~ the depth of the mixed layer both oppose ~~to~~-excitation of BSIWs. We incorporate this in  $f_{\text{stab}}$  by utilizing the Wedderburn number  $W$  [-] (Imberger and Hamblin, 1982).  $W$  ~~measures the ratio between buoyancy force and wind stress, and~~ scales inversely to the magnitude of vertical mixing in stratified basins (Shintani et al., 2010). ~~and~~  $W$  is defined as:

$$W = g \frac{\rho_2 - \rho_1}{\rho_1} \frac{h_1^2}{u_*^2 L_{\text{max}}} \quad (8)$$

Here  $g$  [ $\text{m s}^{-2}$ ] is the acceleration of gravity,  $\rho_1, \rho_2$  [ $\text{kg m}^{-3}$ ] the densities of the upper and lower layers,  $h_1$  [m] the thickness of the upper layer,  $L_{\text{max}}$  [m] the length of the basin at the surface and  $u_*$  [ $\text{m s}^{-1}$ ] is the water-side shear velocity:

$$u_*^2 \approx \frac{C_{10} U_{10}^2 \rho_{\text{air}}}{\rho_{\text{surf}}} \quad (9)$$

Here  $\rho_{\text{surf}} \sim \rho_1$  [ $\text{kg m}^{-3}$ ] is the density of the water at the surface.

The reduction factor based on the stability of the water column is then computed as:

$$f_{\text{stab}} = \frac{1}{1 + \frac{W}{L/(4h_1)}} \quad (10)$$

5 Here  $L$  [m] is the approximate length of the basin at the interface depth (see Eq. (11)) and  $h_1$  [m] is the thickness of the upper layer. The normalizing factor  $L/(4h_1)$  was discussed as an appropriate threshold for the amplitude of BSIWs (Adams and Charles, 2000). Both  $L$  and  $W$  is are bounded from below to its their respective minimal non-zero value. This avoids computation errors and total filtering of the wind time series when the lake is well mixed (therefore consisting in a single layer of thickness  $h_1$ , with  $L = 0$  and  $W = 0$ ; in this case the lower layer is defined using the bottom temperature).

10 Arguably,  $f_{\text{dur}}$  and  $f_{\text{stab}}$  build on similar principles. However, they incorporate different and complementary filtering of the wind field.  $f_{\text{dur}}$  takes explicitly takes the duration of wind events into account, and therefore the physical resonance effects inherent to wind excitation of a water body.  $f_{\text{stab}}$  compares the actual wind stress at the water surface to the overall stability of the water column.

15 The construction of the filtered wind requires knowledge of the wind characteristics before and after the present time, as well as of the corresponding state of the lake at each time step. Therefore, the model should be run with the unfiltered wind speed in a first step. Afterwards, the filter can be applied using the output of the first model run to calculate the filter parameters and determine  $U_{10}^{\text{filtered}}$  from Eq. (6) for a second run. An improvement would be to calculate wind filtering at runtime (i.e. during model execution).

### 2.3 Sites presentation and in situ data

20 The proposed change to the modelling scheme is applied and tested on four perialpine lakes in Switzerland. The chosen lakes range in volume from 1.1 to 89  $\text{km}^3$ , representing the general conditions for medium to large-sized lakes. Information for each lake is provided hereunder. Information about the data sources is provided in the “Code and data availability” Section.

25 **Lake Geneva** (46.452° N, 6.620° E) is the largest lake of western Europe, located between France and Switzerland. Overall, the lake has a maximum length of ~75 km, a maximum width of ~13 km and a surface area of 580  $\text{km}^2$ . The maximum depth is 309 m and the average hydraulic residence time is about 11 years. The Rhône River is both the main inflow and outflow. The lake is heavily affected by wind-induced currents, mixing and internal waves (Bouffard and Lemmin, 2013). Concurrently, the mild climate and its size makes it rather thermally stable, and the mild climate maintains a relatively high

hypolimnion temperature (above 5 °C) (Michalski and Lemmin, 1995). Full mixing occurs irregularly in Lake Geneva (every 7 years on average).

Sixty years of vertical temperature profiles, obtained with a conductivity-temperature-depth probe (CTD), are available at the deepest point. This combined dataset is used for model initialization and calibration. The ~~MeteoSwiss~~ weather station in Pully (46.512° N, 6.667° E) provides meteorological data necessary for model forcing since 1981: air temperature, humidity, wind speed and direction, solar radiation and cloudiness. Given the large retention time of the basin, we neglect river inflow and outflow.

**Lake Constance** (47.629° N, 9.374° E) is a deep perialpine lake with a maximum depth of 254 m. The Rhine River acts as its main tributary, resulting in a hydraulic residence time of about 4.5 years. The maximum length is ~50 km and the width ~12 km, for a surface area of 536 km<sup>2</sup>. Seasonal mixing reaches the lake bottom every few years (Fink et al., 2014a).

Surface forcing data is provided by the ~~MeteoSwiss~~ weather station in Güttingen (47.602°N, 9.279°E) since 1981, while CTD profiles and hydrological data about the inflow rate and temperature are available ~~from the Federal Office for the Environment (FOEN)~~ since 1984. Both inflow and outflow are assumed to take place near the lake surface. Monthly CTD measurements at the deepest point cover the complete time period.

**Lake Neuchâtel** (46.904° N, 6.843° E) is a medium-sized lake located in western Switzerland. Although relatively deep (maximum 152 m), Lake Neuchâtel is monomictic. It is therefore a good test case for our numerical model scheme to assess the correct reproduction of deep mixing. Its surface area is 218 km<sup>2</sup> and the average hydraulic residence time is slightly more than 8 years.

Meteorological data are available since more than 35 years ~~from the stations listed in Table 1~~, but regular CTD profiling started only in 1994. Given the long residence time, inflows and outflows are neglected.

**Lake Biel** (47.104° N, 7.798° E) is the smallest and shallowest of the lakes analysed in this study. With a surface area of ~40 km<sup>2</sup> and a maximum depth of 74 m, it is located directly downstream (i.e. to the North-East) of Lake Neuchâtel. It is also monomictic. Since the correction of the Aare River in the 19th century, Lake Biel has a very short average retention time of only 60 days (Albrecht et al., 1999). Inflows thus play a primary role in the hydrodynamic behaviour of the lake.

As for Lake Neuchâtel, the CTD measurement program started in 1994. ~~The f~~Forcing time series for Lake Biel was likewise computed based on several meteorological stations around the lake, ~~listed in Table 1~~. For the inflows, a gravity-driven intrusion algorithm adapted from Hipsey et al. (2013) is applied, with an inflow plunging in the lake, entraining water and stabilizing when density equilibrium is reached. The inflow corresponds to the sum of the Hagneck River, the Suze River and the Zihl channel, and density effects ~~due to of~~ salinity and suspended matter are neglected.

The most important aspects of these four lakes are summarized in Table 1. For Lake Neuchâtel and Lake Biel, several weather stations are used to fill data gaps in the prioritized measurement station. In this case, missing data were completed with data from ~~other nearby weather~~ stations, ~~which were linearly and~~ adjusted to have the same signal amplitude mean as the priority station.

	Max. depth	Area	Grid layers	Simulation period	Weather station(s) (first is prioritized)
Lake Geneva	309 m	580 km <sup>2</sup>	600	01.01.1981 - 01.01.2014	Pully
Lake Constance	254 m	536 km <sup>2</sup>	600	01.01.1984 - 01.01.2012	Güttingen
Lake Neuchâtel	152 m	218 km <sup>2</sup>	450	01.01.1994 - 01.01.2015	Neuchâtel, Bullet / <u>La Frétez</u> , Chaumont, Cressier, Method, Mühleberg, Payerne
Lake Biel	74 m	40 km <sup>2</sup>	300	01.03.1994 - 01.01.2015	Cressier, Biel/ <u>Bienne</u> , Mühleberg, Chasseral, Neuchâtel

**Table 1 – Main properties of the study sites.**

## 2.4 Model configuration and calibration

The model is set to use a time\_step of 300 seconds. Both the initial model and the improved version are calibrated with the PEST (Model-Independent Parameter Estimation and Uncertainty Analysis) software package (Doherty, 2005), using its default setup, using the available temperature measurements over the corresponding simulation period. PEST searches for the optimal value of chosen parameters which ensure the best match between model results and available observations (here, temperature measurements over the simulation period). Only three parameters are chosen for calibration: the fraction of wind energy converted to seiche energy ( $\alpha$ , see Eq. (3)), the fit parameter for absorption of ~~solar~~ longwave radiation ( $p_1$ ) and the fit parameter for the fluxes of sensible and latent heat ( $p_2$ ).  $p_1$  linearly scales the amount of heat that is absorbed in the lake water from the incoming longwave radiation from the atmosphere, and  $p_2$  linearly scales the exchange of sensible and latent heat between the lake surface and the atmosphere (Goudsmit et al., 2002).  $p_1$  and  $p_2$  account for the fact that, in specific cases, there is generally a bias between the calculated and the effective heat fluxes, as empirical formulas are used and the meteorological data is not always fully representative for the lake surface. All the other parameters are set to standard values (see Table 2), which makes the optimization procedure more solid and more trustworthy. Latitude is set according the above description of the sites, and the geothermal heat flux is set as follows: 0.50 W m<sup>-2</sup> for Lake Geneva, 0.00 W m<sup>-2</sup> for Lake Constance, 0.15 W m<sup>-2</sup> for Lake Neuchâtel and 0.08 W m<sup>-2</sup> for Lake Biel. These values match the temperature slopes found in the deep water over summer and autumn (when heat input from above is negligible). Deep river inflows are not modelled, although they can bring heat to the hypolimnion in summer (Fink et al., 2016).

As mentioned above, the focus of the wind filter is not a global reduction of the energy input to BSIWs. Instead, it should act at the event-scale, depending on the current state of the lake and wind forcing. The parameter  $\alpha$  then allows to adjust the absolute magnitude of the energy input.



Parameter description and units	Parameter in Goudsmit et al. (2002)	Value
Geographical latitude [°]	–	Lake-dependent
Air pressure [mbar]	$p_a$	990
Fractionation coefficient for seiche energy [-] (parameter $q$ in (Goudsmit et al., 2002))	$q$	1.25
Bottom drag coefficient [-]	$C_{D\text{eff}}$	0.002
Geothermal heat flux [ $\text{W m}^{-2}$ ]	$H_{\text{geo}}$	Lake-dependent
Fraction of short-wave radiation absorbed as heat in the uppermost layer [-]	–	0.30

**Table 2 – Fixed (non-calibrated) physical parameters of the model.**

The length of each lake, used to compute BSIW period, was calculated with the surface area of the lake  $A_{\text{lake}}$  according to:

$$L = 2\sqrt{A_{\text{lake}}} \quad (11)$$

This rather simplistic formula assumes a rectangular shape with aspect ratio equal to four, but limits the number of input parameters needed by the model.  $L$  is then the fetch along the longest dimension of the basin.

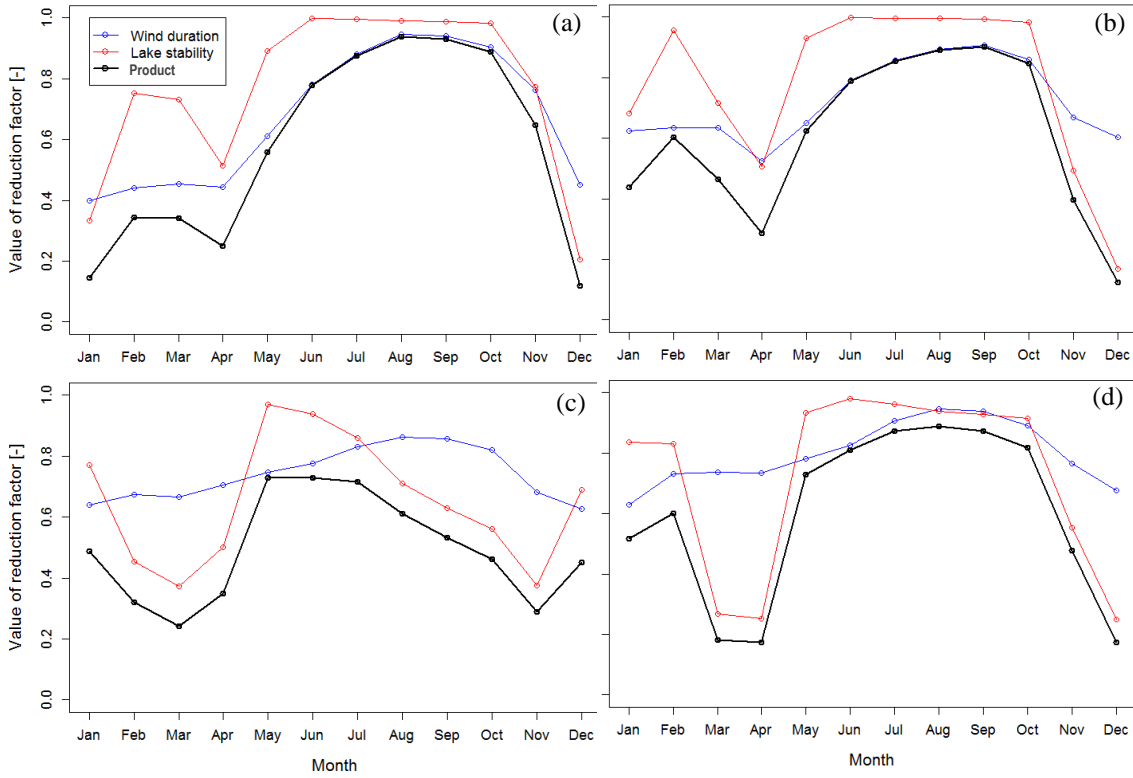
## 5 3 Results and discussion

### 3.1 Wind filtering

A comparison of the filtering for all four lakes is shown in Fig. 3. The reduction factors result in a seasonal filtering of the wind, with a clear tendency to curb the transfer of wind speed energy to BSIWs during the winter time, while the time series during the stratified period remains almost unchanged. Figure 3a shows the monthly averaged value of the reduction factors over the whole time series for Lake Geneva (33 years). On such average basis, both reduction factors behave similarly, however, at the event timescale, they have clearly different patterns (not shown).

Applied on the observed hourly wind speed according to Eq. (6), the filtering scheme displays a seasonal reduction of the observed values. In winter, wind intensity is reduced, whereas in summer, the time series remains rather unchanged.

Results are essentially the same for Lake Constance, although filtering was globally weaker in the first months of the year. In Lake Biel, the overall filtering ratio is a smoother curve with minimal reduction occurring as early as May. In Lake Biel and Lake Neuchâtel, filtering in winter and spring is mostly driven by high lake stability, and much less by the wind duration. In particular, repeated unstratified periods, characterized by high Wedderburn numbers, lead to sharp wind filtering. In deep lakes, homogeneity occurs very infrequently and rather ~~shortly/briefly~~. ~~A comparison of the filtering for all four lakes is shown in Fig. 3.~~ Especially for Lake Biel, unstable water columns appear during summer already, which leads to stronger stability-driven filtering.



**Figure 3 – Monthly averaged reduction factors for Lake Geneva (a), Lake Constance (b), Lake Biel (c), Lake Neuchâtel (d). Shown factors: wind duration (Eq. (7):  $f_{dur}$ , blue), lake stability (Eq. (10):  $f_{stab}$ , red) and overall resulting filtering factor ( $f_{dur} f_{stab}$ , black).**

- 5 Wind with heterogeneous direction may overall prove incapable of causing BSIWs. As a further improvement, this limitation could be parameterized with an additional factor  $f_{dir}$  [-], which could be included into Eq. (6).

$$f_{dir} = \theta_{wind} \quad (12)$$

~~Here  $\theta_{wind} f_{dir}$  [-] would can be estimated as the fraction of the time that wind direction is in the same half-circle (i.e. within  $\pm\pi/2$  radians) as the average wind direction (i.e. within  $\pi/2$  radians). The average wind direction is computed for during each every determined wind event identified with the method described in Section 2.2.~~ Such filtering is expected to particularly

10 impact systems with pronounced diurnal or seasonal wind forcing.

### 3.2 Calibration results

Parameter calibration of the initial model for Lake Geneva yielded unrealistic parameter sets. While trying to match the observed temperatures, PEST raised  $p_2$ , the correction factor for the flux of latent and sensible heat, to a value exceeding 1.5. Such strong correction factors suggest that lake processes are not correctly accounted for. Hence, for all subsequent

15 calibration procedures, the range of calibration of  $p_1$  and  $p_2$  was bound between 0.80 and 1.25. The calibration results under

this constraint are shown in Table 3. Forcing the lake with the filtered wind time series results in a notable improvement of  $p_2$  (i.e. getting closer to 1.00). We also notice an increase of  $\alpha$ , which amplifies the overall magnitude of energy transfer to seiche-induced mixing. This compensates the reduction due to the filtered wind magnitude, but increases further the impact of the long wind events (which went through the filter), in contrast to the ones that were filtered out.

5 These results were confirmed by applying the same procedure for Lake Constance. Notably,  $p_2$ , was reduced for both lakes, while  $p_1$ , the fit parameter controlling infrared radiation from sky, remained almost constant. One may also note that  $\alpha$  is considerably higher for Lake Geneva than for Lake Constance, illustrating a strong impact of the regional wind field on BSIWs. However, the global energy transfer ratio, expressed by the expression  $\alpha(f_{dur}f_{stab})^3$  (see Eq. (3)) remains rather similar in the deep lakes, pointing towards a globally efficient energy transfer: the total amount of energy transferred to  
 10 BSIW's isn't much reduced by wind filtering.

Parameter and units	Lake Geneva			Lake Constance		
	Initial model	Improved model	Relative change	Initial model	Improved model	Relative change
$\alpha$ [-]	0.0709	0.1761	+148 %	0.0295	0.0515	+74.6 %
<u><math>\alpha \cdot (f_{dur} \cdot f_{stab})^3</math> [-]</u>	<u>0.0709</u>	<u>0.0699</u>	<u>-1.40%</u>	<u>0.0295</u>	<u>0.0215</u>	<u>-27.1%</u>
$p_1$ [-]	1.089	1.065	-2.20 %	1.208	1.177	-2.60 %
$p_2$ [-]	1.250	1.087	-13.0 %	1.064	0.898	-15.6 %
Near-bottom RMSE [°C]	0.32	0.20	-37.5 %	0.29	0.24	-17.2 %

**Table 3 – Calibration results and near-bottom RMSE for the “deep” lakes.**

Concerning Lake Neuchâtel and Lake Biel, which are both less deep with yearly overturn, we did not expect the wind filtering to affect the results significantly. Indeed, calibration showed extremely similar results (Table 4). Expectably, there was a slight increase of the  $\alpha$  parameter, which compensates for the reduced wind intensity. The increase is much slighter  
 15 than for the large, deep lakes, the reason of which is understood to be the lower influence of BSIWs. For Lake Neuchâtel, the value of the  $p_2$  parameter dropped below the chosen upper bound, meaning that the model was not anymore forced to converge. In these shallow lakes, the global energy transfer ratio, expressed by the expression  $\alpha(f_{dur}f_{stab})^3$  (see Eq. (3)), gets significantly reduced, which once more reveals that seiches are less efficiently excited there.

Parameter and units	Lake Neuchâtel			Lake Biel		
	Initial model	Improved model	Relative change	Initial model	Improved model	Relative change
$\alpha$ [-]	0.0099	0.0111	+12.10 %	0.0043	0.0049	+14.0 %
<u><math>\alpha \cdot (f_{dur} \cdot f_{stab})^3</math> [-]</u>	<u>0.0099</u>	<u>0.0050</u>	<u>-49.5 %</u>	<u>0.0043</u>	<u>0.0016</u>	<u>-62.8 %</u>
$p_1$ [-]	1.205	1.204	-0.10 %	1.095	1.095	0.00 %
$p_2$ [-]	1.250	1.249	-0.10 %	1.250	1.250	0.00 %
Near-bottom RMSE [°C]	0.48	0.47	-2.20 %	0.94	0.91	-3.20 %

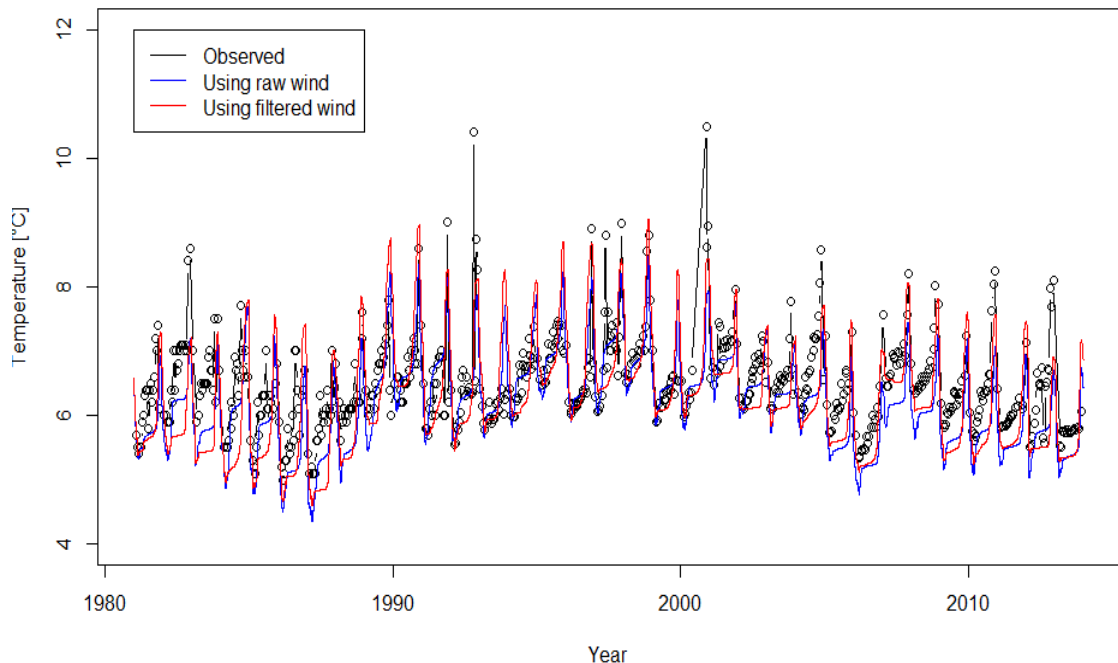
**Table 4 – Calibration results and near-bottom RMSE for the “shallow” lakes.**

For the deep lakes (especially for Lake Geneva), the calibrated values of the  $\alpha$  parameter tend to be higher than the ones found by previous studies, which ranged from 0.001 to 0.03 for large basins (Schmid and Köster, 2016; Fink et al., 2014b; Finger et al., 2007). There are several reasons that can explain this deviation:

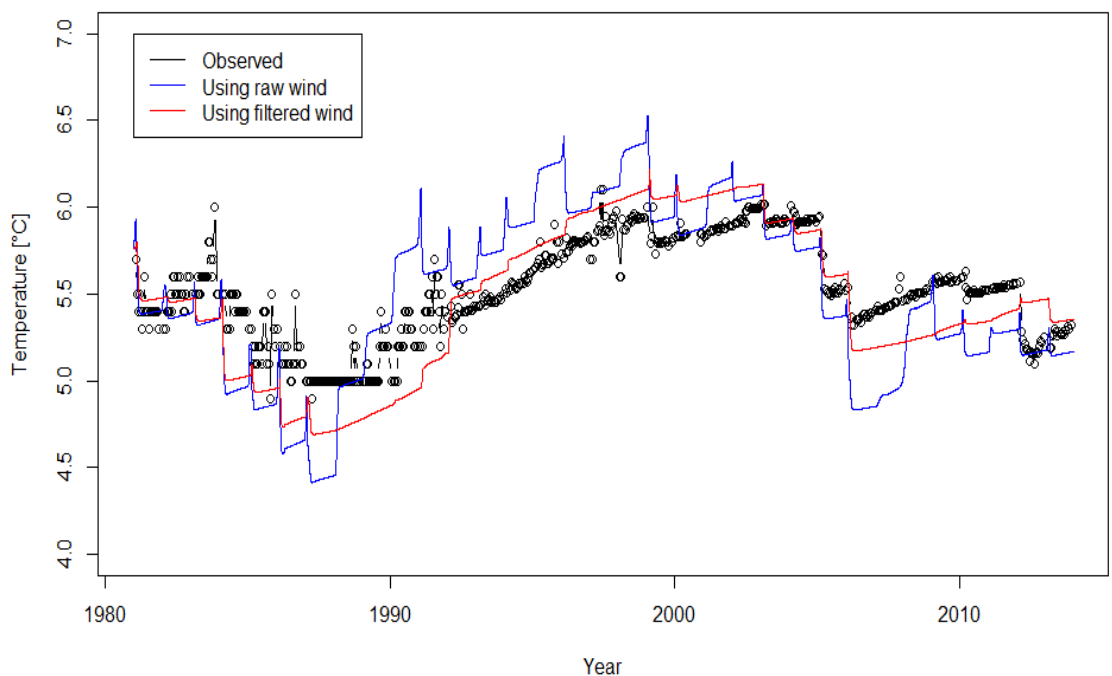
- If the wind observed at the onshore meteorological station(s) underestimates the wind intensity over the lake, PEST is likely to compensate with a larger  $\alpha$  value (and a larger  $p_2$  value). For Lake Geneva, it has been reported that the wind in Pully may be weaker than the global wind over the lake (Lemmin and D'Adamo, 1997). The surrounding topography greatly influences the wind field over the lake and its impact on BSIWs (Valerio et al., 2017).
- The wind drag coefficient for Simstrat is given by an empirical expression (Eq. (5)) instead of a constant, in contrast to most previous studies. This leads to an overall lower drag and therefore also to a larger  $\alpha$  value (see Eq. (3)): in our case for Lake Geneva,  $\alpha$  increased by ~25 %.
- This is also one of the first studies where the parameter defining the fraction of short-wave radiation absorbed as heat in the uppermost layer (see Table 2) is set to a non-zero value (which was physically incorrect). This change also appears to lead to an increased  $\alpha$  value: in our case for Lake Geneva,  $\alpha$  increased by ~18 %.

### 3.3 Simulation results

For the following model ~~runs~~ results, the optimized set of parameters found by PEST was used. Results with filtered wind data for Lake Geneva do not improve significantly at mid-depth, even though greater variability is reproduced (Fig. 4). However, the accuracy in deep layers temperature improved greatly (Fig. 5). In accordance with Lake Geneva, the model performance improved in the deep water of Lake Constance. Reduction in root-mean-square error (RMSE) in deep water temperature substantiates these statements (see Table 3). As expected, for shallower lakes with yearly turnover, the extended model did neither improve nor worsen the results (see Table 4). Figure 6 shows the change in RMSE between the improved model and the version using unfiltered wind. In this case, positive values express a reduction of RMSE, i.e. an improvement of the model. In the deepest part of Lake Geneva, the improvement was nearly 40 %, which supports our approach.



**Figure 4 – Temperature time series at 50 m depth in Lake Geneva: observations, initial model and improved model.**



**Figure 5 – Temperature time series at 250 m depth in Lake Geneva: observations, initial model and improved model.**

- 5 For the shallower Lake Neuchâtel and Lake Biel, there is very little change in the results. Correcting the remaining offset, which is surely caused by other inaccuracies in the modelling schemes and in the forcing input, would require further work.

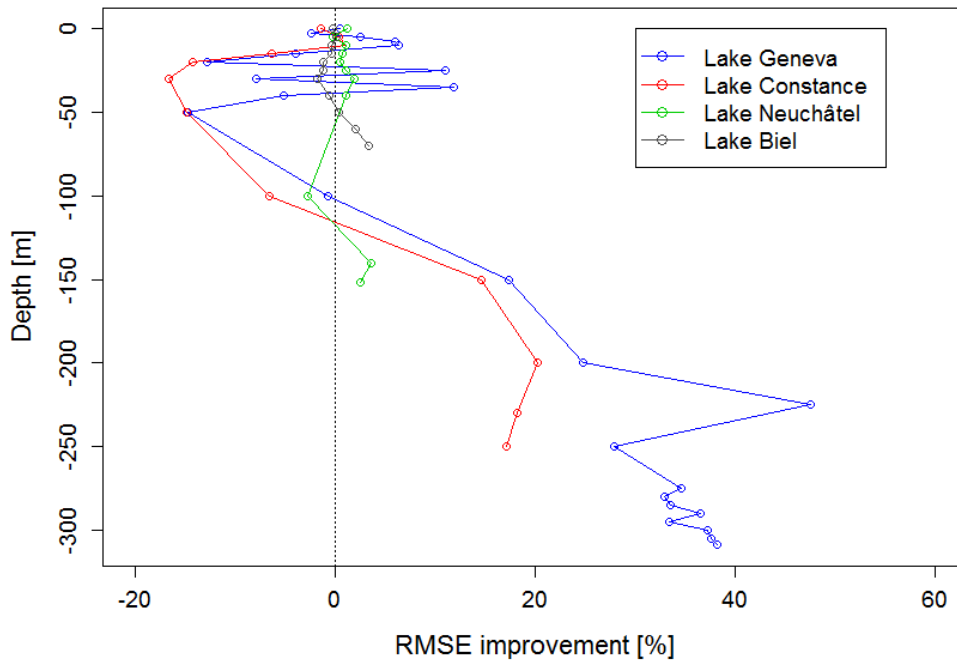


Figure 6 – RMSE change between initial and improved model, as a function of depth. RMSE values are calculated with the temperature time series at the observations depths.

As shown in Fig. 7 (which is an overlap of the lower pane of Fig. 2), the modelled yearly mixing depths are in much better accordance to the observed values. This is due to reduced wind-induced mixing in the hypolimnion, which then remains heavier-denser than the upper layers through the winters that are not cold enough to trigger complete mixing. Fig. 7 shows that the original version of the model largely overestimated deep convective mixing, as full lake mixing was predicted almost every year. Using wind filtering, deep seasonal mixing is more finely reproduced, which also helps towards modelling of lake-scale circulation of water, oxygen and nutrients.

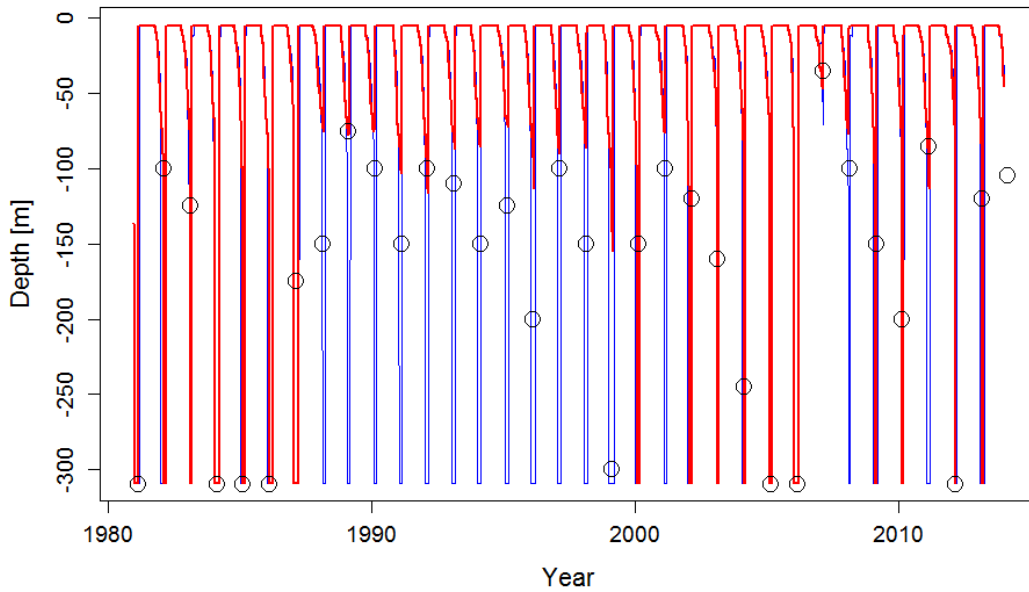


Figure 7 – Deep mixing extent in Lake Geneva, illustrated as the mixing depth as a function of time. Circles represent observations, the curves represent corresponding model results: the original version (blue) and the version using filtered wind (red). The mixing depth is defined as the first depth at which the absolute temperature gradient exceeds  $0.005 \text{ }^{\circ}\text{C m}^{-1}$ , using time-averaged temperature time series over 60 days.

#### 4 Conclusions

The difficulty of 1D lake models to reproduce deep water temperatures is ~~to a large amount~~ mainly caused by the unrealistic transport of wind energy to the deeper layers of the lake. Especially in large lakes, turbulent kinetic energy produced by the dissipation of internal waves plays a major role. Our study showed that the internal wave parameterization of Simstrat can be remarkably improved for deep lakes by using filtering techniques taking into account the physical processes necessary for internal wave generation. In turn, the filters had only minor effects on shallower lakes as they fully mix over winter. However, it is very likely that our filter can be optimized for each specific case.

By considering the signal properties of the wind speed time series (notably the duration of wind events), as well as the stability ~~state~~ of the water column, we were able to parameterize deep mixing in the basin better than with the simple parameterization provided by the original Simstrat model. This supports our assumption that BSIW processes are a key factor for the inaccuracy of 1D models in the deep hypolimnion of large lakes. Not surprisingly, the filtering had almost no effect in summer, when the Wedderburn number and the BSIW period remain small. In winter, however, ~~they~~ filtering strongly reduced the energy transport into internal seiches. These results lead to better prediction of mixing depth and thermal structure in the deep water and open the door to a finer understanding of the process and, altogether, to a better management of lakes. Indeed, prediction of deep water reoxygenation, nutrient cycle and sediment interactions would greatly benefit from accurate modelling of deep mixing. In addition, the latter is also essential for long-term climate change studies.

Our findings emphasize the fact that the properties of complex three-dimensional processes such as BSIW formation must be better parameterized in 1D models. If such mechanisms are overly simplified, significant inaccuracies may arise. Our method has the advantages of remaining rather simple and of requiring very little computation time and very few additional parameters. In our opinion, ~~its~~ the main drawback is the difficulty to link wind and internal water motion using only direct approximations, especially for lakes with complicated shapes, bathymetry and wind field. For instance, we ~~overlook~~ neglect the oscillatory character of BSIW, resonance and damping effects and the several possible oscillation modes. In general, there is very little research about the temporal variability of wind-induced mixing (Woolway and Simpson, 2017) and the modelling of deepwater temperature evolution could still benefit much from better understanding and parameterization of the underlying processes.

## 10 Code and data availability

The authors are grateful to the different ~~organisms~~ institutions that provided the data used in this paper: ~~the CIPEL for Lake Geneva, the 10 IGKB for Lake Constance and the BAFU for Lake Neuchâtel and Lake Biel~~ the cantonal laboratories for the CTD profiles, the Federal Office for the Environment (FOEN) for hydrological data, the Federal Office of Meteorology and Climatology (MeteoSwiss) for meteorological data, the CIPEL for additional data on Lake Geneva and the IGKB for additional data on Lake Constance. Identification of the data is given in Table 5. The source code and documentation of the numerical model and data processing, as well as the parameter and input files can be accessed through ~~a GIT repository (GIT clone: <https://github.com/adrien-ga/Simstrat-BSIW.git>, direct link: <https://github.com/adrien-ga/Simstrat-BSIW/archive/master.zip>)~~ an archived GIT repository (link: <https://github.com/adrien-ga/Simstrat-BSIW/tree/v1.3>, DOI: [10.5281/zenodo.820785](https://doi.org/10.5281/zenodo.820785), direct download link: <https://github.com/adrien-ga/Simstrat-BSIW/archive/v1.3.zip>). As previously discussed, this version of Simstrat implements the possibility to use a separate time series of wind speed for computing seiche energy, a gravity-driven intrusion algorithm for inflows and wind drag coefficient varying with wind speed.

	<u>CTD profiles: location ID and coordinates (CH1903)</u>	<u>Hydrological data: station ID(s)</u>	<u>Meteorological data: station short name(s)</u>
<u>Lake Geneva</u>	<u>1696 (534700, 144950)</u>	<u>=</u>	<u>PUY</u>
<u>Lake Constance</u>	<u>1644 (745450, 277120)</u>	<u>2473</u>	<u>GUT</u>
<u>Lake Neuchâtel</u>	<u>1674 (554610, 194980)</u>	<u>=</u>	<u>NEU, FRE, CHM, CRM, MAH, MUB, PAY</u>
<u>Lake Biel</u>	<u>1607 (581700, 217060)</u>	<u>2085, 2307, 2446</u>	<u>CRM, BIL, MUB, CHA, NEU</u>
<u>Data providers</u>	<u>Cantonal laboratories</u>	<u>FOEN <a href="https://hydrodaten.admin.ch/en">hydrodaten.admin.ch/en</a></u>	<u>MeteoSwiss <a href="https://meteoswiss.admin.ch">meteoswiss.admin.ch</a></u>

Table 5 – Identification of the data used.



## References

- Adams, H. E., Charles, R. M.: A Preliminary Investigation of Lake Stability and Chemical Analysis of Deep Waters of the Kigoma Sub-basin (Northern Basin) and the Kalemie Sub-basin (Southern Basin) of Lake Tanganyika, 2000.
- 5 Adrian, R., O'Reilly, C. M., Zagarese, H., Baines, S. B., Hessen, D. O., Keller, W., Livingstone, D. M., Sommaruga, R., Straile, D., Van Donk, E., Weyhenmeyer, G. A., Winder, M.: Lakes as sentinels of climate change, *Limnol. Oceanogr.* 54, 6, 2283–2297, 2009.
- Albrecht, A., Goudsmit, G., Zeh, M.: Importance of lacustrine physical factors for the distribution of anthropogenic <sup>60</sup>Co in Lake Biel, *Limnol. Oceanogr.* 44, 196–206, 1999.
- 10 Ambrosetti, W., Barbanti, L.: Deep water warming in lakes: an indicator of climatic change, *J. Limnol.* 58, 1, 1–9, 1999.
- Bäuerle, E.: Transverse baroclinic oscillations in Lake Überlingen, *Aquat. Sci.* 56, 2, 145–160, 1994.
- Beutel, M. W., Horne, A. J.: A Review of the Effects of Hypolimnetic Oxygenation on Lake and Reservoir Water Quality, *Lake Reserv. Manag.* 15, 4, 285–297, 1999.
- 15 Bouffard, D., Ackerman, J. D., Boegman, L.: Factors affecting the development and dynamics of hypoxia in a large shallow stratified lake: Hourly to seasonal patterns, *Water Resour. Res.* 49, 5, 2380–2394, 2013.
- Bouffard, D., Boegman, L.: Basin-scale internal waves, in: *Encyclopedia of Lakes and Reservoirs*. Springer, pp. 102–107, 2012.
- Bouffard, D., Lemmin, U.: Kelvin waves in Lake Geneva, *J. Gt. Lakes Res.* 39, 4, 637–645, 2013.
- 20 Boyce, F. M., Hamblin, P. F., Harvey, L. D., Schertzer, W. M., McCrimmon, R. C.: Response of the thermal structure of Lake Ontario to deep cooling water withdrawals and to global warming, *J. Gt. Lakes Res.* 19, 3, 603–616, 1993.
- Butcher, J. B., Nover, D., Johnson, T. E., Clark, C. M.: Sensitivity of lake thermal and mixing dynamics to climate change, *Clim. Change* 129, 1–2, 295–305, 2015.
- 25 Doherty, J.: PEST: Software for Model-Independent Parameter Estimation. Watermark Numerical Computing, Australia, 2005.
- Finger, D., Schmid, M., Wüest, A.: Comparing effects of oligotrophication and upstream hydropower dams on plankton and productivity in perialpine lakes, *Water Resour. Res.* 43, 12, W12404, 2007.
- Fink, G., Schmid, M., Wahl, B., Wolf, T., Wüest, A.: Heat flux modifications related to climate-induced warming of large European lakes, *Water Resour. Res.* 50, 3, 2072–2085, 2014a.
- 30 Fink, G., Schmid, M., Wüest, A.: Large lakes as sources and sinks of anthropogenic heat: Capacities and limits, *Water Resour. Res.* 50, 9, 7285–7301, 2014b.
- Fink, G., Wessels, M., Wüest, A.: Flood frequency matters: Why climate change degrades deep-water quality of peri-alpine lakes, *J. Hydrol.* 540, 457–468, 2016.
- 35 Friedrich, J., Janssen, F., Aleynik, D., Bange, H. W., Boltacheva, N., Çagatay, M. N., Dale, A. W., Etioppe, G., Erdem, Z., Geraga, M., Gilli, A., Gomoiu, M. T., Hall, P. O. J., Hansson, D., He, Y., Holtappels, M., Kirf, M. K., Kononets, M., Konovalov, S., Lichtschlag, A., Livingstone, D. M., Marinaro, G., Mazlumyan, S., Naehner, S., North, R. P., Papatheodorou, G., Pfannkuche, O., Prien, R., Rehder, G., Schubert, C. J., Soltwedel, T., Sommer, S., Stahl, H., Stanev, E. V., Teaca, A., Tengberg, A., Waldmann, C., Wehrli, B., Wenzhöfer, F.: Investigating hypoxia in aquatic environments: Diverse approaches to addressing a complex phenomenon, *Biogeosciences* 11, 4, 1215–1259, 2014.
- 40

- 5 Goudsmit, G.-H., Burchard, H., Peeters, F., Wüest, A.: Application of k- $\epsilon$  turbulence models to enclosed basins: The role of internal seiches, *J. Geophys. Res. Oceans* 107, C12, 3230, 2002.
- Goyette, S., Perroud, M.: Interfacing a one-dimensional lake model with a single-column atmospheric model: Application to the deep Lake Geneva, Switzerland, *Water Resour. Res.* 48, 4, W04507, 2012.
- 5 Hipsey, M. R., Bruce, L. C., Hamilton, D. P.: GLM: General Lake Model. Model overview and user information, *Univ. West. Aust. Tech. Man. Perth Aust.*, 2013.
- Hodges, B. R., Imberger, J., Saggio, A., Winters, K. B.: Modeling basin-scale internal waves in a stratified lake, *Limnol. Oceanogr.* 45, 7, 1603–1620, 2000.
- 10 Hostetler, S. W., Small, E. E.: Response of North American freshwater lakes to simulated future climates. *Wiley Online Library*, 1999.
- Imberger, J., Hamblin, P. F.: Dynamics of lakes, reservoirs, and cooling ponds, *Annu. Rev. Fluid Mech.* 14, 1, 153–187, 1982.
- Imboden, D. M., Wüest, A.: Mixing mechanisms in lakes, *Phys. Chem. Lakes* 83–138, 1995.
- 15 Jankowski, T., Livingstone, D. M., Bührer, H., Forster, R., Niederhauser, P.: Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: Implications for a warmer world, *Limnol. Oceanogr.* 51, 2, 815–819, 2006.
- Ji, Z.-G.: *Hydrodynamics and water quality: Modeling rivers, lakes, and estuaries*. John Wiley & Sons, 2008.
- Komatsu, E., Fukushima, T., Harasawa, H.: A modeling approach to forecast the effect of long-term climate change on lake water quality, *Ecol. Model.* 209, 2, 351–366, 2007.
- 20 Lemmin, U., D’Adamo, N.: Summertime winds and direct cyclonic circulation: observations from Lake Geneva, *Ann. Geophys.* 14, 11, 1207–1220, 1997.
- Merian, J. R.: *Über die Bewegung tropfbarer Flüssigkeiten in Gefässen*, *Math Ann.*, Ser. Basel, Schweighauser. Reproduced by Vonder-Mühl, K., 1886, 27, 575, 1828.
- 25 Michalski, J., Lemmin, U.: Dynamics of vertical mixing in the hypolimnion of a deep lake: Lake Geneva, *Limnol. Oceanogr.* 40, 4, 809–816, 1995.
- Mortimer, C. H.: Lake hydrodynamics, *Mitt Int Ver Limnol* 20, 124–197, 1974.
- Peeters, F., Livingstone, D. M., Goudsmit, G.-H., Kipfer, R., Forster, R.: Modeling 50 years of historical temperature profiles in a large central European lake, *Limnol. Oceanogr.* 47, 1, 186–197, 2002.
- 30 Peeters, F., Straile, D., Lorke, A., Ollinger, D.: Turbulent mixing and phytoplankton spring bloom development in a deep lake, *Limnol. Oceanogr.* 52, 1, 286–298, 2007.
- Perroud, M., Goyette, S., Martynov, A., Beniston, M., Annevillec, O.: Simulation of multiannual thermal profiles in deep Lake Geneva: A comparison of one-dimensional lake models, *Limnol. Oceanogr.* 54, 5, 1574–1594, 2009.
- 35 Read, J. S., Hamilton, D. P., Desai, A. R., Rose, K. C., MacIntyre, S., Lenters, J. D., Smyth, R. L., Hanson, P. C., Cole, J. J., Staehr, P. A., Rusak, J. A., Pierson, D. C., Brookes, J. D., Laas, A., Wu, C. H.: Lake-size dependency of wind shear and convection as controls on gas exchange, *Geophys. Res. Lett.* 39, 9, L09405, 2012.
- Schmid, M., Köster, O.: Excess warming of a Central European lake driven by solar brightening, *Water Resour. Res.* 52, 10, 8103–8116, 2016.
- 40 Schwefel, R., Gaudard, A., Wüest, A., Bouffard, D.: Effects of climate change on deep-water oxygen and winter mixing in a deep lake (Lake Geneva)—Comparing observational findings and modeling, *Water Resour. Res.* 52, 11, 8811–8826, 2016.

- Shimoda, Y., Azim, M. E., Perhar, G., Ramin, M., Kenney, M. A., Sadraddini, S., Gudimov, A., Arhonditsis, G. B.: Our current understanding of lake ecosystem response to climate change: What have we really learned from the north temperate deep lakes?, *J. Gt. Lakes Res.* 37, 1, 173–193, 2011.
- 5 Shintani, T., de la Fuente, A., Niño, Y., Imberger, J.: Generalizations of the Wedderburn number: Parameterizing upwelling in stratified lakes, *Limnol. Oceanogr.* 55, 3, 1377–1389, 2010.
- Stepanenko, V. M., Goyette, S., Martynov, A., Perroud, M., Fang, X., Mironov, D.: First steps of a lake model intercomparison Project: LakemiP, *Boreal Environ. Res.* 15, 191–202, 2010.
- Stepanenko, V. M., Jöhnk, K. D., Machulskaya, E., Perroud, M., Subin, Z., Nordbo, A., Mammarella, I., Mironov, D.: Simulation of surface energy fluxes and stratification of a small boreal lake by a set of one-dimensional models, *Tellus A* 66, 1, 21389, 2014.
- 10 Stepanenko, V. M., Mammarella, I., Ojala, A., Miettinen, H., Lykosov, V., Vesala, T.: LAKE 2.0: a model for temperature, methane, carbon dioxide and oxygen dynamics in lakes, *Geosci. Model Dev.* 9, 5, 1977–2006, 2016.
- Stepanenko, V. M., Martynov, A., Jöhnk, K. D., Subin, Z. M., Perroud, M., Fang, X., Beyrich, F., Mironov, D., Goyette, S.: A one-dimensional model intercomparison study of thermal regime of a shallow, turbid midlatitude lake, *Geosci. Model Dev.* 6, 4, 1337–1352, 2013.
- 15 Stevens, C., Imberger, J.: The initial response of a stratified lake to a surface shear stress, *J. Fluid Mech.* 312, 39–66, 1996.
- Straille, D., Kerimoglu, O., Peeters, F., Jochimsen, M. C., Kümmerlin, R., Rinke, K., Rothhaupt, K.-O.: Effects of a half a millennium winter on a deep lake – a shape of things to come?, *Glob. Change Biol.* 16, 10, 2844–2856, 2010.
- 20 Straille, D., Livingstone, D. M., Weyhenmeyer, G. A., George, D. G.: The response of freshwater ecosystems to climate variability associated with the North Atlantic Oscillation. Wiley Online Library, 2003.
- Thiery, W., Stepanenko, V. M., Fang, X., Jöhnk, K. D., Li, Z., Martynov, A., Perroud, M., Subin, Z. M., Darchambeau, F., Mironov, D., Van Lipzig, N. P. M.: LakeMIP Kivu: evaluating the representation of a large, deep tropical lake by a set of one-dimensional lake models, *Tellus, Ser. A*, 66, 21390, 2014.
- 25 Thorpe, S. A., Lemmin, U., Perrinjaquet, C., Fer, I.: Observations of the thermal structure of a lake using a submarine, *Limnol. Oceanogr.* 44, 1575–1582, 1999.
- Toffolon, M., Rizzi, G.: Effects of spatial wind inhomogeneity and turbulence anisotropy on circulation in an elongated basin: A simplified analytical solution, *Adv. Water Resour.* 32, 10, 1554–1566, 2009.
- 30 Umlauf, L., Lemmin, U.: Interbasin exchange and mixing in the hypolimnion of a large lake: The role of long internal waves, *Limnol. Oceanogr.* 50, 5, 1601–1611, 2005.
- Valerio, G., Cantelli, A., Monti, P., Leuzzi, G.: A modeling approach to identify the effective forcing exerted by wind on a prealpine lake surrounded by a complex topography, *Water Resour. Res.* 53, 4036–4052, 2017.
- 35 Valipour, R., Bouffard, D., Boegman, L., Rao, Y. R.: Near-inertial waves in Lake Erie, *Limnol. Oceanogr.* 60, 1522–1535, 2015.
- Wang, W., Roulet, N. T., Strachan, I. B., Tremblay, A.: Modeling surface energy fluxes and thermal dynamics of a seasonally ice-covered hydroelectric reservoir, *Sci. Total Environ.* 550, 793–805, 2016.
- 40 Wiegand, R. C., Carmack, E. C.: The climatology of internal waves in a deep temperate lake, *J. Geophys. Res. Oceans* 91, C3, 3951–3958, 1986.
- Wood, T. M., Wherry, S. A., Piccolroaz, S., Girdner, S. F.: Simulation of deep ventilation in Crater Lake, Oregon, 1951–2009. US Geological Survey, 2016.

- Woolway, R. I., Simpson, J. H.: Energy input and dissipation in a temperate lake during the spring transition, *Ocean Dyn.* 1–13, 2017.
- Wüest, A., Lorke, A.: Small-scale hydrodynamics in lakes, *Annu. Rev. Fluid Mech.* 35, 1, 373–412, 2003.
- 5 Adams, H. E., Charles, R. M.: A Preliminary Investigation of Lake Stability and Chemical Analysis of Deep Waters of the Kigoma Sub-basin (Northern Basin) and the Kalemie Sub-basin (Southern Basin) of Lake Tanganyika, 2000.
- Adrian, R., O'Reilly, C. M., Zagarese, H., Baines, S. B., Hessen, D. O., Keller, W., Livingstone, D. M., Sommaruga, R., Straile, D., Van Donk, E., Weyhenmeyer, G. A., Winder, M.: Lakes as sentinels of climate change, *Limnol. Oceanogr.* 54, 6, 2283–2297, 2009.
- 10 Albrecht, A., Goudsmit, G., Zeh, M.: Importance of lacustrine physical factors for the distribution of anthropogenic <sup>60</sup>Co in Lake Biel, *Limnol. Oceanogr.* 44, 196–206, 1999.
- Ambrosetti, W., Barbanti, L.: Deep water warming in lakes: an indicator of climatic change, *J. Limnol.* 58, 1, 1–9, 1999.
- Bäuerle, E.: Transverse baroclinic oscillations in Lake Überlingen, *Aquat. Sci.* 56, 2, 145–160, 1994.
- 15 Beutel, M. W., Horne, A. J.: A Review of the Effects of Hypolimnetic Oxygenation on Lake and Reservoir Water Quality, *Lake Reserv. Manag.* 15, 4, 285–297, 1999.
- Bouffard, D., Ackerman, J. D., Boegman, L.: Factors affecting the development and dynamics of hypoxia in a large shallow stratified lake: Hourly to seasonal patterns, *Water Resour. Res.* 49, 5, 2380–2394, 2013.
- Bouffard, D., Boegman, L.: Basin-scale internal waves, in: *Encyclopedia of Lakes and Reservoirs*. Springer, pp. 102–107, 2012.
- 20 Bouffard, D., Lemmin, U.: Kelvin waves in Lake Geneva, *J. Gt. Lakes Res.* 39, 4, 637–645, 2013.
- Boyce, F. M., Hamblin, P. F., Harvey, L. D., Schertzer, W. M., McCrimmon, R. C.: Response of the thermal structure of Lake Ontario to deep-cooling water withdrawals and to global warming, *J. Gt. Lakes Res.* 19, 3, 603–616, 1993.
- 25 Butcher, J. B., Nover, D., Johnson, T. E., Clark, C. M.: Sensitivity of lake thermal and mixing dynamics to climate change, *Clim. Change* 129, 1–2, 295–305, 2015.
- Doherty, J.: PEST: Software for Model-Independent Parameter Estimation. Watermark Numerical Computing, Australia, 2005.
- Finger, D., Schmid, M., Wüest, A.: Comparing effects of oligotrophication and upstream hydropower dams on plankton and productivity in perialpine lakes, *Water Resour. Res.* 43, 12, W12404, 2007.
- 30 Fink, G., Schmid, M., Wahl, B., Wolf, T., Wüest, A.: Heat flux modifications related to climate-induced warming of large European lakes, *Water Resour. Res.* 50, 3, 2072–2085, 2014a.
- Fink, G., Schmid, M., Wüest, A.: Large lakes as sources and sinks of anthropogenic heat: Capacities and limits, *Water Resour. Res.* 50, 9, 7285–7301, 2014b.
- 35 Friedrich, J., Janssen, F., Aleynik, D., Bange, H. W., Boltacheva, N., Çagatay, M. N., Dale, A. W., Etiope, G., Erdem, Z., Geraga, M., Gilli, A., Gomoiu, M. T., Hall, P. O. J., Hansson, D., He, Y., Holtappels, M., Kirf, M. K., Kononets, M., Konovalov, S., Lichtschlag, A., Livingstone, D. M., Marinaro, G., Mazlumyan, S., Naeher, S., North, R. P., Papatheodorou, G., Pfannkuche, O., Prien, R., Rehder, G., Schubert, C. J., Soltwedel, T., Sommer, S., Stahl, H., Stanev, E. V., Teaca, A., Tengberg, A., Waldmann, C., Wehrli, B., Wenzhöfer, F.:
- 40 Investigating hypoxia in aquatic environments: Diverse approaches to addressing a complex phenomenon, *Biogeosciences* 11, 4, 1215–1259, 2014.
- Goudsmit, G. H., Burchard, H., Peeters, F., Wüest, A.: Application of  $k-\epsilon$  turbulence models to enclosed basins: The role of internal seiches, *J. Geophys. Res. Oceans* 107, C12, 3230, 2002.

- Goyette, S., Perroud, M.: Interfacing a one-dimensional lake model with a single-column atmospheric model: Application to the deep Lake Geneva, Switzerland, *Water Resour. Res.* 48, 4, W04507, 2012.
- Hipsey, M. R., Bruce, L. C., Hamilton, D. P.: GLM: General Lake Model. Model overview and user information, Univ. West. Aust. Tech. Man. Perth Aust., 2013.
- 5 Hodges, B. R., Imberger, J., Saggio, A., Winters, K. B.: Modeling basin-scale internal waves in a stratified lake, *Limnol. Oceanogr.* 45, 7, 1603–1620, 2000.
- Hostetler, S. W., Small, E. E.: Response of North American freshwater lakes to simulated future climates. Wiley Online Library, 1999.
- 10 Imberger, J., Hamblin, P. F.: Dynamics of lakes, reservoirs, and cooling ponds, *Annu. Rev. Fluid Mech.* 14, 1, 153–187, 1982.
- Imboden, D. M., Wüest, A.: Mixing mechanisms in lakes, *Phys. Chem. Lakes* 83–138, 1995.
- Jankowski, T., Livingstone, D. M., Bühner, H., Forster, R., Niederhauser, P.: Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: Implications for a warmer world, *Limnol. Oceanogr.* 51, 2, 815–819, 2006.
- 15 Ji, Z.-G.: Hydrodynamics and water quality: Modeling rivers, lakes, and estuaries. John Wiley & Sons, 2008.
- Komatsu, E., Fukushima, T., Harasawa, H.: A modeling approach to forecast the effect of long term climate change on lake water quality, *Ecol. Model.* 209, 2, 351–366, 2007.
- Lemmin, U., D'Adamo, N.: Summertime winds and direct cyclonic circulation: observations from Lake Geneva, *Ann. Geophys.* 14, 11, 1207–1220, 1997.
- 20 Merian, J. R.: Über die Bewegung tropfbarer Flüssigkeiten in Gefässen, *Math Ann., Ser. Basel*, Schweighauser. Reproduced by Vonder Mühl, K., 1886, 27, 575, 1828.
- Michalski, J., Lemmin, U.: Dynamics of vertical mixing in the hypolimnion of a deep lake: Lake Geneva, *Limnol. Oceanogr.* 40, 4, 809–816, 1995.
- Mortimer, C. H.: Lake hydrodynamics, *Mitt Int Ver Limnol* 20, 124–197, 1974.
- 25 Peeters, F., Livingstone, D. M., Goudsmit, G. H., Kipfer, R., Forster, R.: Modeling 50 years of historical temperature profiles in a large central European lake, *Limnol. Oceanogr.* 47, 1, 186–197, 2002.
- Peeters, F., Straile, D., Lorke, A., Ollinger, D.: Turbulent mixing and phytoplankton spring bloom development in a deep lake, *Limnol. Oceanogr.* 52, 1, 286–298, 2007.
- Perroud, M., Goyette, S., Martynov, A., Beniston, M., Annevillec, O.: Simulation of multiannual thermal profiles in deep Lake Geneva: A comparison of one-dimensional lake models, *Limnol. Oceanogr.* 54, 5, 1574–1594, 2009.
- 30 Råman Vinnå, L., Wüest, A., Bouffard, D.: Physical effects of thermal pollution in lakes, *Water Resour. Res.* 53, 3968–3987, 2017.
- Read, J. S., Hamilton, D. P., Desai, A. R., Rose, K. C., MacIntyre, S., Lenters, J. D., Smyth, R. L., Hanson, P. C., Cole, J. J., Staehr, P. A., Rusak, J. A., Pierson, D. C., Brookes, J. D., Laas, A., Wu, C. H.: Lake-size dependency of wind shear and convection as controls on gas exchange, *Geophys. Res. Lett.* 39, 9, L09405, 2012.
- 35 Schmid, M., Köster, O.: Excess warming of a Central European lake driven by solar brightening, *Water Resour. Res.* 52, 10, 8103–8116, 2016.
- Schwefel, R., Gaudard, A., Wüest, A., Bouffard, D.: Effects of climate change on deep-water oxygen and winter mixing in a deep lake (Lake Geneva)–Comparing observational findings and modeling, *Water Resour. Res.* 52, 11, 8811–8826, 2016.
- 40

- Shimoda, Y., Azim, M. E., Perhar, G., Ramin, M., Kenney, M. A., Sadraddini, S., Gudimov, A., Arhonditsis, G. B.: Our current understanding of lake ecosystem response to climate change: What have we really learned from the north temperate deep lakes?, *J. Gt. Lakes Res.* 37, 1, 173–193, 2011.
- 5 Shintani, T., de la Fuente, A., Niño, Y., Imberger, J.: Generalizations of the Wedderburn number: Parameterizing upwelling in stratified lakes, *Limnol. Oceanogr.* 55, 3, 1377–1389, 2010.
- Stepanenko, V. M., Goyette, S., Martynov, A., Perroud, M., Fang, X., Mironov, D.: First steps of a lake model intercomparison Project: LakemIP, *Boreal Environ. Res.* 15, 191–202, 2010.
- Stepanenko, V. M., Jöhnk, K. D., Machulskaya, E., Perroud, M., Subin, Z., Nordbo, A., Mammarella, I., Mironov, D.: Simulation of surface energy fluxes and stratification of a small boreal lake by a set of one-dimensional models, *Tellus A* 66, 1, 21389, 2014.
- 10 Stepanenko, V. M., Mammarella, I., Ojala, A., Miettinen, H., Lykosov, V., Vesala, T.: LAKE 2.0: a model for temperature, methane, carbon dioxide and oxygen dynamics in lakes, *Geosci. Model Dev.* 9, 5, 1977–2006, 2016.
- Stepanenko, V. M., Martynov, A., Jöhnk, K. D., Subin, Z. M., Perroud, M., Fang, X., Beyrich, F., Mironov, D., Goyette, S.: A one dimensional model intercomparison study of thermal regime of a shallow, turbid midlatitude lake, *Geosci. Model Dev.* 6, 4, 1337–1352, 2013.
- 15 Stevens, C., Imberger, J.: The initial response of a stratified lake to a surface shear stress, *J. Fluid Mech.* 312, 39–66, 1996.
- Straile, D., Kerimoglu, O., Peeters, F., Jochimsen, M. C., Kümmerlin, R., Rinke, K., Rothhaupt, K. O.: Effects of a half a millennium winter on a deep lake—a shape of things to come?, *Glob. Change Biol.* 16, 10, 2844–2856, 2010.
- 20 Straile, D., Livingstone, D. M., Weyhenmeyer, G. A., George, D. G.: The response of freshwater ecosystems to climate variability associated with the North Atlantic Oscillation. Wiley Online Library, 2003.
- Thiery, W., Stepanenko, V. M., Fang, X., Jöhnk, K. D., Li, Z., Martynov, A., Perroud, M., Subin, Z. M., Darchambeau, F., Mironov, D., Van Lipzig, N. P. M.: LakeMIP Kivu: evaluating the representation of a large, deep tropical lake by a set of one dimensional lake models, *Tellus, Ser. A*, 66, 21390, 2014.
- 25 Thorpe, S. A., Lemmin, U., Perrinjaquet, C., Fer, I.: Observations of the thermal structure of a lake using a submarine, *Limnol. Oceanogr.* 44, 1575–1582, 1999.
- Toffolon, M., Rizzi, G.: Effects of spatial wind inhomogeneity and turbulence anisotropy on circulation in an elongated basin: A simplified analytical solution, *Adv. Water Resour.* 32, 10, 1554–1566, 2009.
- 30 Umlauf, L., Lemmin, U.: Interbasin exchange and mixing in the hypolimnion of a large lake: The role of long internal waves, *Limnol. Oceanogr.* 50, 5, 1601–1611, 2005.
- Valipour, R., Bouffard, D., Boegman, L., Rao, Y. R.: Near inertial waves in Lake Erie, *Limnol. Oceanogr.* 60, 1522–1535, 2015.
- 35 Wang, W., Roulet, N. T., Strachan, I. B., Tremblay, A.: Modeling surface energy fluxes and thermal dynamics of a seasonally ice-covered hydroelectric reservoir, *Sci. Total Environ.* 550, 793–805, 2016.
- Wiegand, R. C., Carmack, E. C.: The climatology of internal waves in a deep temperate lake, *J. Geophys. Res. Oceans* 91, C3, 3951–3958, 1986.
- 40 Wood, T. M., Wherry, S. A., Piccolroaz, S., Girdner, S. F.: Simulation of deep ventilation in Crater Lake, Oregon, 1951–2099. US Geological Survey, 2016.
- Woolway, R. I., Simpson, J. H.: Energy input and dissipation in a temperate lake during the spring transition, *Ocean Dyn.* 1–13, 2017.
- Wüest, A., Lorke, A.: Small scale hydrodynamics in lakes, *Annu. Rev. Fluid Mech.* 35, 1, 373–412, 2003.