Author's response to reviewers

W. Thiery, A. Martynov, F. Darchambeau, J.-P. Descy, P.-D. Plisnier, L. Sushama, N.P.M. Van Lipzig

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The authors would like to thank reviewers #1 and #2, for the time devoted to review the manuscript and for the useful and constructive suggestions. Their contribution is acknowledged in the manuscript. All comments by the referee were carefully addressed and the manuscript has substantially benefited from the proposed changes. Here below, we would like to clarify our changes regarding each of the 39 comments.

This response letter contains numbered illustrations and references to these illustrations. Except when indicated explicitly, reference is given to page and line numbers and figures in the originally submitted manuscript, and not to the new, re-submitted manuscript. To prevent confusion, the figures embedded within this response letter are called *illustrations*. Finally, the following convention is applied to denote modification in the original manuscript: ~~deleted words~~; **added words.**

Reviewer #1

> ***Comment 1*: "Observational data have been processed and this was clearly described, but representativity of the data is a weak point. The driving data was measured at other locations than where the lake observations were collected. How representative are the meteorological variables as a forcing term for the lake parameterization and how representative are the lake measurements?"**

Indeed this is an important point, and we will address each aspect of this comment. First, regarding the representativity of the Ishungu water temperature measurements for the whole of Lake Kivu, this is discussed extensively in a new study in Tellus A (Thiery et al., accepted). In this study, where we apply seven one-dimensional lake models to Lake Kivu to investigate the surface energy balance and deep water stratification, we argue that Ishungu is representative for the whole Lake Kivu, except for Bukavu and Kabuno Bay. This is done based on the analysis of a set of 60 temperature profiles collected during five cruises from March 2007 to October 2010 (Illustration 1):

> *"The temperature recordings show that, although limited spatial differences exist, this variability is clearly less important than seasonal variations. Maximum horizontal temperature variations during a single cruise range from 0.3 °C to 0.6 °C (0.5 °C on average) at 5 m depth, while maximum temporal temperature fluctuations at one location range from 0.3 to 1.5 °C (1.1 °C on average) at 5 m. Towards 60 m, vertical temperature profiles converge, both in space and time. There below, in the permanently stratified monimolimnion, horizontal homogeneity can be expected as water residence times are two to three orders of magnitude larger than time scales of horizontal mixing (Pasche et al., 2011). In agreement, Schmid and Wüest (2012) argue that temperature and conductivity are nearly homogenous throughout the main basin, and very similar in Kalehe, Ishungu and main basins. Notable exceptions are the vertical profiles from both Bukavu and Kabuno bay (not shown); while the 100 m deep Bukavu bay regularly mixes down to the bottom, Kabuno bay has a permanent chemocline at 12m and is isolated from the rest of the lake. The findings from the temperature profiles are confirmed by the horizontal homogeneity for chemical and biological lake characteristics reported across all sub basins except Bukavu and Kabuno bay (Sarmento et al., 2006; Pasche et al., 2009), although the deep water sources and riverine outflow prevent that the chemistry of the* CO_2*- and* CH_4*-rich layers in these three subbasins can be considered completely homogeneous (Tassi et al., 2009)." (from Thiery et al., in press)*

For Lake Tanganyika, in contrast, horizontal homogeneity cannot be assumed, and in-situ measurements at Kigoma and Mpulungu cannot be considered representative for the whole lake (or a large part of it). For instance, as shown in illustration 2 and argued in Plisnier et al. (1999), the dry season increase in wind velocity over the lake causes a sinking of the thermocline in the north after April, in turn leading to internal wave motions (see also P5155L17-28). These differences are also clearly visible when comparing Fig. 6 to Fig. 8 and Fig. 7 to Fig. 9.

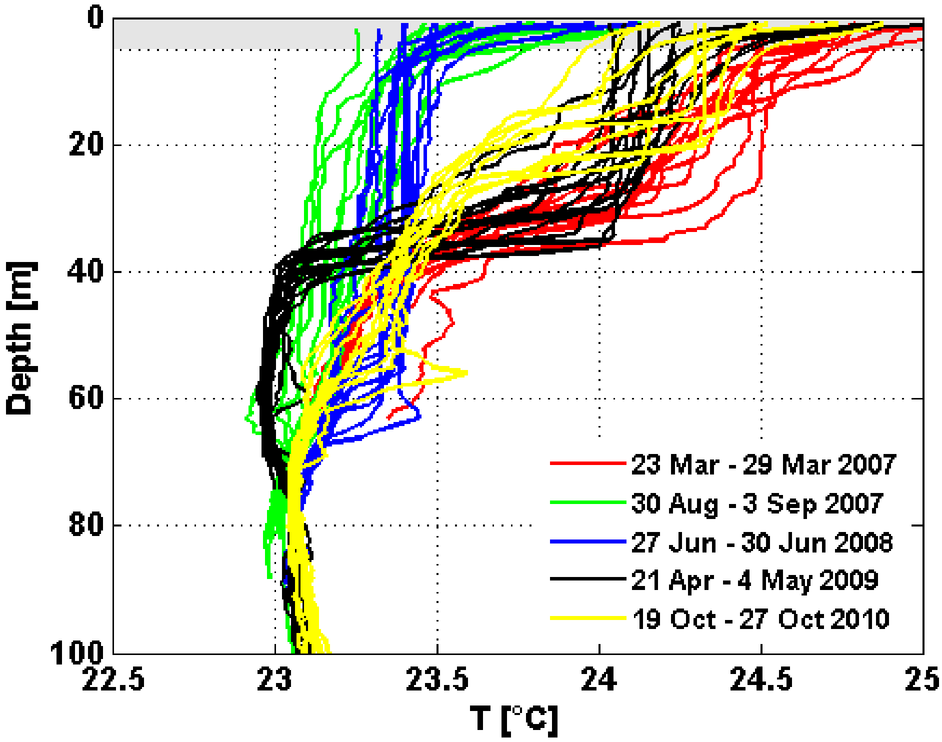

Illustration 1. Temperature profiles collected at 14 different locations in Lake Kivu during 5 cruises. Profiles collected at Bukavu and Kabuno bay are omitted due to their clear deviation from profiles of the main basin. Differences in the top 5m (grey shade area) are partly due to daily variations (Thiery et al., under review).

Second, concerning the representativity of the meteorological observations for the respective measurement sites, we note that such a discussion is already present in the manuscript for one variable, namely the wind velocity (P51549L25-P5150L21). For the other variables, it is however much more difficult to assess the representativity of e.g. AWS 1 for Ishungu. In case of wind velocity, the comparison of AWS 1 to AWS Kivu provided a clear upper bound for wind velocities at Ishungu (P5150L10-13). Such a comparison is however not useful for other variables, since one cannot argue that the state-of-the-art AWS Kivu, located 73 km northeast from Ishungu, is more representative for the Ishungu evaluation site than AWS 1, and since no other meteorological data is available over the lake surface during the measurement period.

Therefore in the text, the following sentences have been added to clarify the representativity of the data:

- <u>P5145L24-26</u>: "Unfortunately, for this station only 13 months of data (Feb. 2002 – Apr. 2003) were available. **With all three AWSs located on land, one can expect some differences between the measured values and actual meteorological conditions at the sites they aim to represent. However, given the lack of meteorological observations at these locations, it is difficult to assess the degree to which these stations represent their respective evaluation site, except probably for wind speed measurements (Sect. 2.4). Possibly AWS 3, the most exposed station and located on the lake shore, succeeds best at representing the meteorological conditions of the evaluation site.** AWS topographic characteristics and meteorological averages are listed in Table 1."

- P5148L22-23: "At each of these locations, they provide a clear image of the surface lake's thermal structure and hence mixing regime. **While it can be argued that temperature recordings at Ishungu are representative for the whole Lake Kivu, except Bukavu Bay and Kabuno Bay (Thiery et al., 2014), the same cannot be claimed for Lake Tanganyika, where seasonal variations in wind velocity and internal wave motions cause spatially variant mixing dynamics (Plisnier et al., 1999). This is also apparent from the comparison of the CTD casts of Kigoma and Mpulungu (Sect. 3.2, 3.3). Consequently, the results of the FLake simulations for Ishungu can be used to study the mixing physics of Lake Kivu (Sect. 3.6), whereas the mixing processes within the whole Lake Tanganyika cannot be captured by single-column simulations at two sites only.**

  To ease ~~their~~ **the** intercomparison **of the different CTD casts**, first …"
- P5164L12-15: "Slight differences in external parameters, and uncertainties associated with the meteorological forcing data **(for instance related to measurement or atmospheric model uncertainty, or to the representativity of the data for over-lake conditions)** may already lead to a switch from the observed regime of seasonal mixed layer deepening to either the permanently stratified or the fully mixed regime."

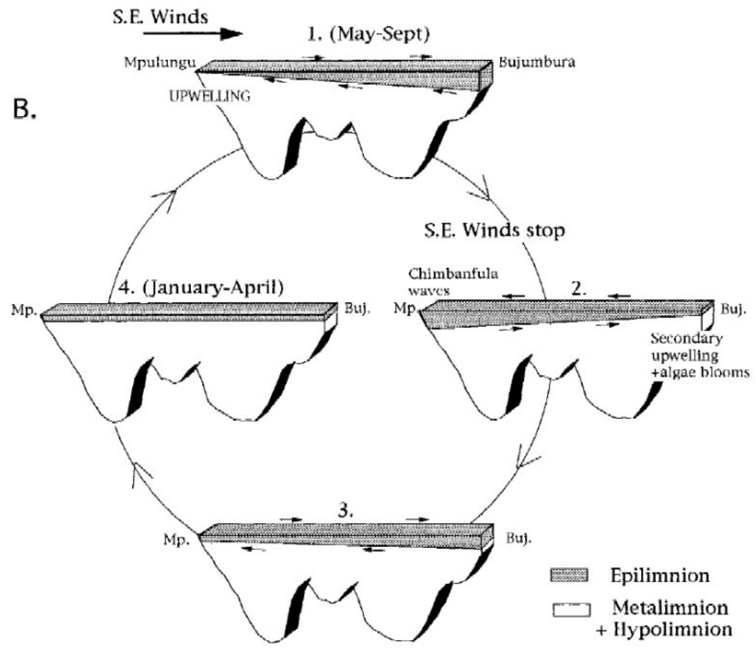

Illustration 2. Schematic profile of water layers in Lake Tanganyika during an annual cycle (Plisnier et al., 1999).

<u>Comment 2</u>: "My major point of criticism focuses on the neglect of the fetch which is an important set-up parameter. To run FLake successfully the fetch has to be specified. What kind of value did you use and why did you not investigate the sensitivity of the fetch?"

Indeed this was not mentioned in the manuscript. For the fetch, we used a value of 1 x 10^4 m in all simulations. This value was based on the distance between the Ishungu evaluation site and the southeastern shore of the Ishungu basin, given the predominant southeasterly wind direction at this site. This value is thought to be representative as well for Mpulungu (located 8.5 km north of the lake shore) and Kigoma (in the center of the lake but partly sheltered by its location within the Kigoma bay). There is no default value for the fetch, but for the official FLake test cases, values of 2 km, 4 km and 4 km are used for Lake Heiligen, Lake Mueggel and Lake Stechlin, respectively (www.lakemodel.org).

Following the suggestion by Reviewer #1, we tested the sensitivity of FLake to different values for the fetch. In particular, we used values 100 km, 50 km, 5 km and 1 km in addition to the control simulation (10 km), therewith testing a wide range of possible fetch values. It was found that for Lake

Kivu, FLake is rather insensitive to strong modifications in the fetch (Illustration 3, 4). In particular, the mixing regime is not modified by changes in the fetch, and both 5 m and 60 m temperatures are only slightly affected (with in general lower temperatures with increasing fetch). Note that, consequently, the fetch is not an appropriate tuning parameter for FLake over large tropical lakes. Based on these findings, we included the following sentences in the manuscript:

- P5158L21: "**Furthermore, note that we also investigated the sensitivity of FLake to changes in the fetch, by conducting a set of simulations with the fetch varying between 1 and 100 km, respectively (the value in all other simulations is 10 km). It was however found that for Lake Kivu, FLake exhibits only little sensitivity to modifications in this parameter**."

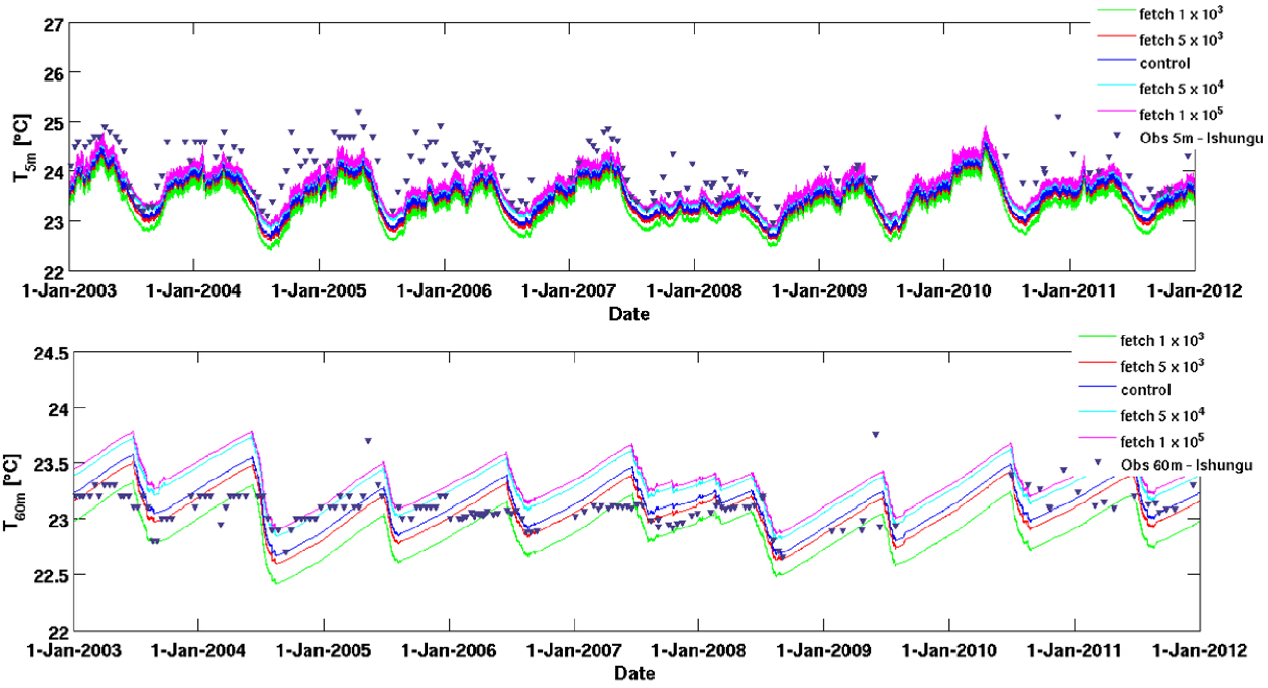

Illustration 3. Effect on 5 m and 60 m water temperatures of varying the wind fetch at Ishungu. The legend shows the different values of the fetch [m].

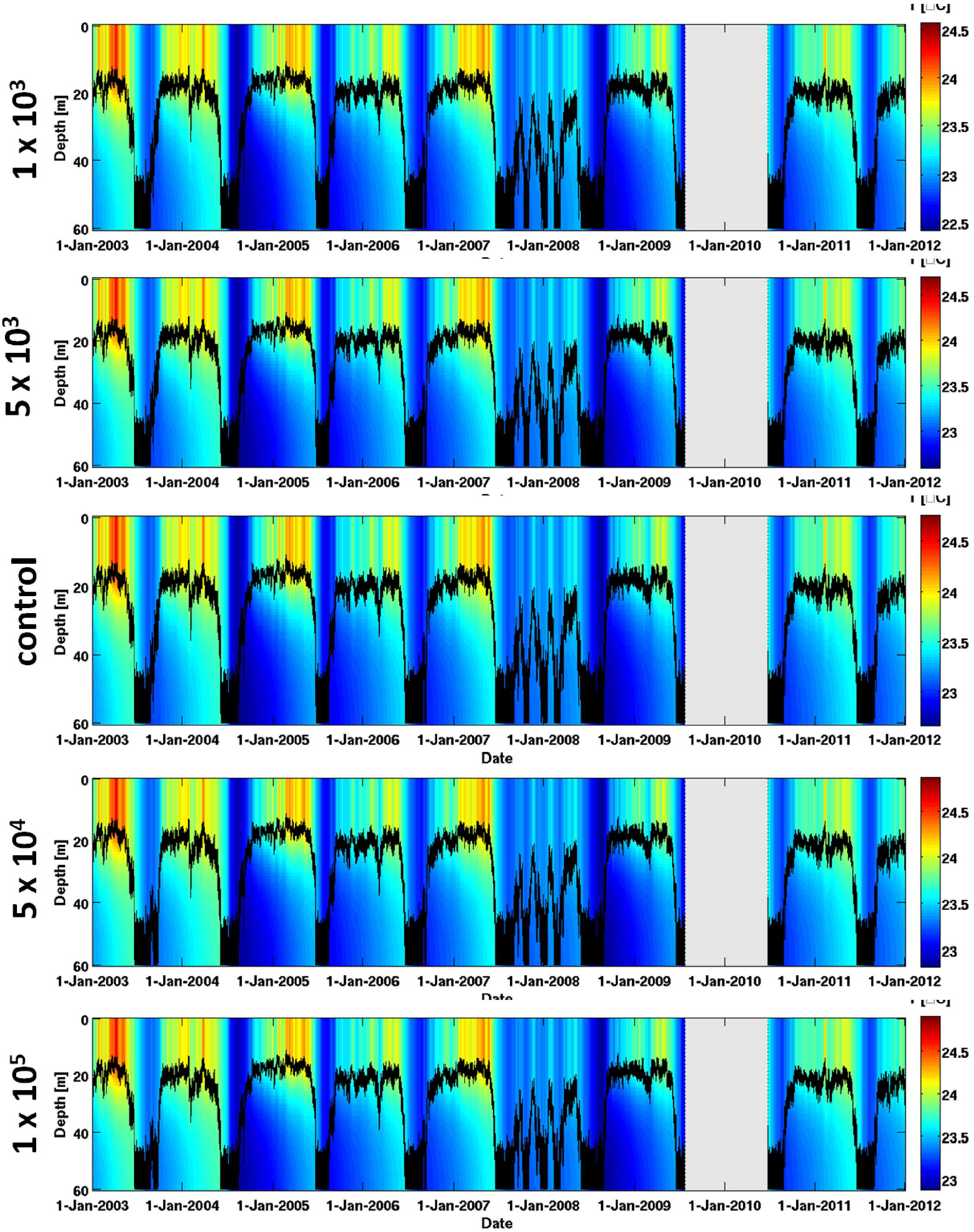

Illustration 4. Effect on water column temperatures of varying the wind fetch (values [m] shown on the left) at Ishungu. Note that the actual mixed layer depth is shown here instead of the weekly mean mixed layer depth.

<u>Comment 3:</u> "Another point is that the incoming SW radiation was not considered in the sensitivity study. The reason for this was the poor quality of the data. However, it is a well known fact that the incoming SW radiation is an important variable in the surface energy balance of lakes. Was it is not possible to apply ERA-Interim data instead?"

As correctly noted, SW_{in} certainly is an important term in the lake surface energy balance, and therefore a crucial input variable for FLake. In particular, it is the most important source of energy for the African Great Lakes. The reason why SW_{in} was not considered in the original sensitivity study is not its poor quality, but the very high standard deviation of SW_{in} caused by the large diurnal cycle of this variable (P5159L18-20). When adding e.g. 2 standard deviations (i.e. 504 W m^{-2}) to the average observed SW_{in}, of course this change dominates over every other possible perturbation.

We now adopted a new approach to allow including SW_{in} in the sensitivity study. We conducted an additional sensitivity experiment wherein SW_{in} and LW_{in} were perturbed by the standard deviation of daily means (σ_{dm}) instead of the standard deviation of the original time series (σ; note that we cannot apply such an approach for the other variables, as this would lead to strong decreases in the respective σ). The σ_{dm} of SW_{in} and LW_{in} are 35 W m^{-2} and 12 W m^{-2}, respectively. The results shows that both SW_{in} and LW_{in} require fairly large perturbations before these variables provoke a regime switch, but that the model is generally more sensitive to changes in SW_{in} than changes in LW_{in} (Illustration 5). Again compensating effects can be noted: a negative perturbation of one variable may be compensated by a positive perturbation of the other. This experiment also allows computing the uncertainty range for which FLake predicts the correct mixing regime. This value (42 W m^{-2}) is similar to the LW_{in} uncertainty range and shows that collecting in-situ measurements within these uncertainty bounds is feasible.

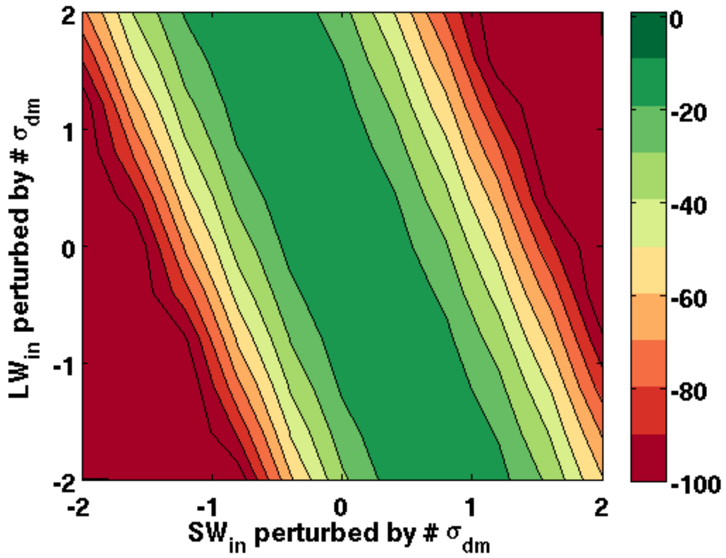

Illustration 5. Vertically averaged Brier Skill Scores (BSS) of water temperature profiles (0 – 60 m; 1 m vertical increment) at Ishungu from a sensitivity experiment wherein SW_{in} and LW_{in} were perturbed by proportions of their respective standard deviations σ of daily average values.

On the other hand, SW_{in} has only very little influence on the seasonal changes in mixing, even though this variable is the main source of energy for the African Great Lakes and FLake is found sensitive to perturbations in this variable. In Sect 3.6 (mixing physics), we describe the interplay between the seasonal variability of meteorological forcing fields and mixed layer depth seasonality. As can be inferred from Fig. 14, the monthly mean SW_{net} (and thus SW_{in}, since the lake surface albedo is assumed constant in FLake) hardly varies between the different months. This is already explained in the manuscript (P5163L11-18).

According to this additional sensitivity experiment, we included Illustration 5 and updated the references to figures throughout the manuscript. We also made the following changes in the manuscript:

- P5159L19-23: "Sensitivity experiments for p and SW_{in} are not shown, the former since FLake was found to be not sensitive to this variable, the latter since its high standard deviation (252 W m^{-2}) led to unrealistic perturbations. ~~For the other variables, standard deviations of the respective observed variable are small enough to ensure that FLake was tested within bounds representative for tropical conditions.~~ **To overcome this issue, an additional experiment was conducted**

wherein the SW_{in} and LW_{in} time series were perturbed by the respective standard deviations of their daily means (σ_{dm}, with values of 35 W m^{-2} and 12 W m^{-2}, respectively; Fig. 12)."

- P5160L8-10: "**When comparing SW_{in} and LW_{in} for perturbations of the order of their respective σ_{dm} (Fig. 12), it can be noted that fairly large perturbations are needed to provoke a regime switch, and that such a switch is provoked more easily by modifying SW_{in} than LW_{in} by their respective σ_{dm}.**"
- P5160L18-19: "For RH , T **,** ~~and~~ LW_{in} **and** SW_{in}, this range is 17 %, 2.0 °C**,** ~~and~~ 50 W m^{-2} **and 42 W m^{-2}**, respectively. While for the latter ~~three~~ **four** variables, …"
- Figure 12: "**Vertically averaged Brier Skill Scores (BSS) of water temperature profiles (0 – 60 m; 1 m vertical increment) at Ishungu from a set of simulations with SW_{in} and LW_{in} perturbed by proportions of their respective standard deviations of daily mean values (σ_{dm}).**"

Comment 4: ***"In the description of the lakes nothing is said about the in- and outflow of the lakes. Both lakes provide water to the Congo river system and this affects the circulation in the lakes and thus the temperature. This should at least be mentioned in the Discussion."***

The small watershed (4400 km^2) of Lake Kivu is drained by over 100 small rivers, resulting in an estimated riverine inflow of 2.0 +/- 0.4 km^3 year^{-1} (Schmid and Wüest, 2012). The Ruzizi river is the only outflow from Lake Kivu, removing 3.0 +/- 0.4 km^3 year^{-1} southward towards Lake Tanganyika (Schmid and Wüest, 2012). For Lake Tanganyika, the inflow from its watershed and outflow towards the Congo Basin amount up to 14 km^3 year^{-1} and 2.7 km^3 year^{-1}, respectively (Coulter and Spigel, 1991).

However, considering that both lakes are characterized by very long water retention times (~100 years and ~800 years for Lake Kivu and Lake Tanganyika, respectively (Schmid and Wüest, 2012; Coulter and Spigel, 1991), the impact of riverine in- and outflow is of little impact to the circulation within these lakes:

- <u>P5144L24</u>: "... its salt content is lower compared to Lake Kivu (Spigel and Coulter, 1996). **Lake Kivu and Lake Tanganyika are both characterised by long lake water retention times (~100 years and ~800 years, respectively; Schmid and Wüest, 2012; Coulter, 1991), hence the impact of riverine in- and outflow is of little importance to the circulation within these lakes**."

<u>Comment 5</u>: "The title suggests that all African Great lakes are investigated. In fact there are six great lakes namely Victoria, Tanganyika, Malawi, Albert, Kivu and Edward. In the study only lake Tanganyika and Kiva are considered. So I would like to rephrase the title to something like "Understanding the performance of the Flake model in two large African lakes""

Indeed not all African Great Lakes are considered in this study. Therefore, we modified the manuscript title to:

- <u>P5141L1-2</u>: "Understanding the performance of the FLake model over ~~the~~ **two** African Great Lakes.**"**

<u>Comment 6</u>: "Page 5143 line 6, "enhanced winds due to higher fetch" Wind is not enhanced by a higher fetch, but indeed waves are. Fetch is used in relation to waves."

We agree with this remark and made the following changes in the manuscript:

- <u>P5143L6-7</u>: "…(ii) enhanced winds due to the ~~higher fetch~~ **lower surface roughness**, …"
- <u>P5143L6-7</u>: "Since ~~the wind fetch at~~ **the location of** AWS Kivu is much ~~higher than the one encountered in~~ **more exposed than** the Ishungu basin – especially given the predominance of southeasterlies over the lake – ~~AWS Kivu~~ wind velocities **measured by AWS Kivu** provide a definite upper bound for wind velocities in the Ishungu Basin."

<u>Comment 7</u>: "Page 5145 line 2, ERA-Interim also suffers from sparse

observations in Africa. Or is additional data apart from remote-sensing data included in the analysis? What is the grid-box size? Can you comment on this?"

Yes, relatively few observations are assimilated into ERA-Interim over tropical Africa. Additional information in ERA-Interim was added to the manuscript:

- P5151L1-2: "…Finally, FLake was integrated using ERA-Interim data from the nearest grid cell as forcing. **ERA-Interim is a global reanalysis product produced by the European Centre for Medium-Range Weather Forecasts (ECMWF; Simmons et al., 2007). It consists of a long-term atmospheric model simulation in which historical meteorological observations are consistently assimilated. Note however that the horizontal resolution of this product is T255 (0.703125° or about 80 km), hence a large fraction each nearest pixel represents land instead of lake. Moreover, only few observations are assimilated into ERA-Interim over tropical Africa, adding to the uncertainty of this product as a source of meteorological input to FLake.**"

Comment 8: "Page 5145 line 16, What does DRC mean?"

- P5145L16: "… in Bulavu, ~~DRC~~ **Democratic Republic of the Congo**, approximately …**"**

Comment 9: "Page 5146 line 1, You are using confusing abbreviations for wind speed and wind direction. Please use the WMO standard abbreviations, e.g. ff and dd."

We implemented the WMO standard abbreviations for wind speed (ff) and wind direction (dd) everywhere in the manuscript (P5146L1, P5146L2, P5150L1, P5150L3, P5150L17, P5150L18, P5153L18, P5154L21, P5155L13, P5159L11, P5159L14, P5160L3, P5160L4, P5160L12, P5162L8, P5162L9, P5162L12, P5162L13, P5162L18, table1, Fig. 11, Fig. 13).

Comment 10: "Page 5146 line 1, AWS data, what is the observation

(instrumental) error?"

AWS1, 2 and 3 are all Davis Instruments weather stations. The accuracy of the T, RH, p, ff, dd, and SW_{in} sensors are +/- 0.5 °C, +/- 3%, +/- 1 hPa, +/- 5%, +/- 3°, and +/- 5% (Davis Instruments, 2013). This is now included in the text:

- <u>P5146L3</u>: "... at a single level above the surface**, and at an estimated accuracy of ±0.5 °C, ±1 hPa, ±5%, ±3 °, ±3% and ±5%, respectively**. The measurement frequency …"

<u>Comment 11</u>: "Page 5146 line 21, How can ONE single point be representative for such a large lake? Rephrase please."

See also our reply to comment 1. We made the following modifications in the manuscript:

- <u>P5146L19-21</u>: "… The one-dimensional FLake model is designed to represent the evolution of ~~the lake's~~ **a lake column** temperature profile and the integral energy budgets of its different layers (Mironov, 2008; Mironov et al; 2010). In particular, the model consists of two **vertical** water layers: …"

<u>Comment 12</u>: "Page 5147 line 5, There are also two layers in the bottom sediment."

Indeed, the bottom sediment routine of FLake consists of a two-layer parametric representation of the temperature profile in the bottom sediments based on Golosov and Kreitman (1992) and Golosov et al. (1998):

- <u>P5147L5</u>: "…Additionally, FLake includes the representation of the thermal structure of lake ice and snow cover and (optionally) also of **the temperature of two layers in the bottom sediments** ~~an upper layer of bottom sediments~~, …"

<u>Comment 13</u>: "Page 5147 line 10, Here you explain that incoming SW really

matters. In the results the impact of incoming SW radiation is almost neglected."

For an answer to this comment we refer to comment 3.

<u>Comment 14</u>: "Page 5148 line 1, oligotrophic refers to environments that offer little (nourishment) to sustain life, for example in caves, so in this context I believe it is the wrong word."

As correctly suggested by the reviewer, oligotrophic refers to environments with only little nutrient input to the ecological system. Usually, the trophic state of a Lake is defined following the classification of lakes by e.g. Wetzel (2001). Based on this classification, both lakes can be considered as oligotrophic, as they have very low nutrient concentrations in the mixolimnion. In their literature overview of Phytoplankton ecology of Lake Kivu, Sarmiento et al. (2012) report annual average Chlorophyll a concentrations of 2.16 mg m^{-3} for the mixed layer and low nutrient levels in the euphotic zone, and conclude that Lake Kivu is an oligotrophic Lake. In Lake Tanganyika, primary production is even lower (Sarmento et al., 2012).

<u>Comment 15</u>: "Page 5148 line 3, after "chorophyll" "a" should be erased"

The "a" behind "chlorophyll" is not a typo. When discussing chlorophyll concentrations, it is advised to consider "chlorophyll a", as this pigment is present in all phytoplankton, whereas other chlorophylls are found in some classes only. Hence chlorophyll a can be considered a good estimate of the total phytoplankton biomass.

<u>Comment 16</u>: "Page 5148 lines 14-18, In Fig. 3 you reveal interesting results, but you do not explain the differences of k in the text. Could you comment on the fact that probability curves of k are so different?"

The difference in water transparency is a consequence of differences in ecosystem productivity between the two lakes. The lower water transparency in Lake Kivu is a consequence of higher local primary production at Ishungu relative to Kigoma and Mpulungu. A slightly higher primary production for Lake Kivu compared to Lake Tanganyika was already reported by Beadle (1981), and is confirmed by comparison of measurements of phytoplankton production rates at Ishungu (241 g C m^{-2} $year^{-1}$ for 2002-2003; Sarmento et al., 2012) to Kigoma (127 g C m^{-2} $year^{-1}$ for 2002-2008; Descy et al., 2005) and Mpulungu (190 g C m^{-2} $year^{-1}$ for 2002-2003; Descy et al., 2005). But more important than variations the production rates is the strong difference in total phytoplankton biomass (Chlorophyll a concentrations) between Lake Kivu (2.02 $\pm$0.78 mg m^{-3}; Sarmento et al., 2012) and Lake Tanganyika (0.67 $\pm$0.25 mg m^{-3}; Stenuite et al., 2007).

- P5148L14-18: "…For each dataset of k, a gamma probability density function was fitted (Fig. 3), from which subsequently average $\bar{k}$ and standard deviation σ_k were calculated (Table 2). **The higher $\bar{k}$ observed at Ishungu relative to Kigoma and Mpulungu is caused by the higher phytoplankton biomass (represented by Chlorophyll a concentrations) in Lake Kivu (2.02 $\pm$0.78 mg m^{-3}; Sarmento et al., 2012) compared to Lake Tanganyika (0.67 $\pm$0.25 mg m^{-3}; Stenuite et al., 2007).** Note that, since an uncertainty remains associated with the exact value of k, its value was allowed to vary within given bounds in the different simulations (see Sect. 2.4)."
- P5170L1: "**Sarmento, H., Darchambeau, F., and Descy, J.-P.: Phytoplankton of Lake Kivu, in: Lake Kivu: Limnology and biogeochemistry of a tropical great lake, Descy, J.-P., Darchambeau, F., Schmid, M. (Eds.), Springer, Dordrecht, 67-83, 2012.**"
- P5170L20: "**Stenuite, S., Pirlot, S., Hardy, M. A., Sarmento, H., Tarbe, A. L., Leporcq, B., and Descy, J.-P.: Phytoplankton production and growth rate in Lake Tanganyika: evidence of a decline in primary productivity in recent decades, Freshwater Biol., 52, 2226–2239, doi: 10.1111/j.1365-2427.2007.01829.x, 2007.**"

> ***Comment 17**: "Page 5150 lines 10-20 Wind data was corrected to obtain the right mixing regime. But why did you not consider another value for the fetch, an important set-up parameter of FLake (see Mironov 2008)."*

As FLake is found insensitive to changes in a realistic range for the fetch (see Comment 2), the fetch is not a suitable parameter to use for correction.

<u>Comment 18</u>**: "Page 5152 line 6-7, The sentence "The former three calculated scores........" is in the wrong place. It should be mentioned earlier, because it belongs to the text of the Taylor diagram."***

We moved the sentence to P5151L23:

- <u>P5151L23</u>: "...and the Brier Skill Score BSS (Nash and Sutcliffe, 1970; Taylor, 2001; Wilks, 2005). **The former three calculated scores are visualised together in a Taylor diagram (Taylor, 2001), enabling the performance assessment of FLake.** The $RMSE_c$ is ..."
- <u>P5152L6-7</u>: "... to +1 (perfect prediction). ~~The former three calculated scores are visualised together in a Taylor diagram (Taylor, 2001), enabling the performance assessment of FLake.~~"

<u>Comment 19</u>**: "Page 5154 line 4, not only the radiosonde data, but also other observations (SYNOP, PILOT) are sparse in Africa."***

Yes, this is a correct remark:

- <u>P5154L4</u>: "... (ii) the higher uncertainty of this product in central Africa owing to the sparse ~~radiosonde~~ **observational data** coverage in this region (Dee et al., 2011)**."**

<u>Comment 20</u>**: "Page 5160 3.5.2 Forcing data In this section the incoming SW radiation is completely ignored, in section 2.1 you describe that SW radiation penetrates in the water and is being absorbed. Why do not you study this important forcing? If data is missing you can use ERA-Interim data, see my previous comment."***

For our answer to this question, we refer to comment 2. Note that we used the values of SW_{in} observed at AWS 1 (after correction) in the sensitivity study, as these are the time series used for the raw and control simulations at Ishungu.

<u>Comment 21</u>*: "General comment: figures are too small, you need a magnifying glass to interpret them properly. The line spacing is also small."

We enhanced the readability of Figs. 2, 4, 5, 6, 7, 8, and 9 (where possible) in the revised manuscript. Note that we ensure readability of all figures during the typesetting, in case the manuscript would be retained for publication.

<u>Comment 22</u>*: "Fig. 2: What are mixolimnion and monolimnion in terms of FLake variables"

Mixolimnion is that part of the lake which is seasonally mixed. In case of Lake Kivu, this is the top ~60 m of the water column. The monimolimnion is the permanently stratified layer thereunder. In term of FLake variables, the mixolimnion corresponds to the lake depth (60 m), the monimolimnion has no counterpart since the lake bottom is artificially set to 60 m. The relationship between FLake variables and limnological strata is already discussed in Sect. 2.4, but we also included a clarification in the caption to Figure 2:

- <u>P5149L11-13</u>: "However, for most of the deep African Great Lakes, their actual lake depth cannot be used, since FLake only describes the ~~mixolimnion~~ **mixed layer** and thermocline, whereas in reality a monimolimnion is found below the thermocline of these meromictic lakes."
- <u>Fig.2</u>: "…as reported by Schmid et al. (2005). **For Lake Kivu, the artificial lake depth set in FLake corresponds to the mixolimnion depth, hence the monimolimnion has no counterpart in FLake.** Note the strong increase in salinity from 60-70 m downwards, i.e. below the mixolimnion."

<u>Comment 23</u>*: "Fig. 3 Why is the probability of k so different from Ishungu?"

For an answer to this question, we refer to comment 16.

<u>Comment 24</u>*: "Fig. 10 Taylor diagrams are nice, but nothing is said about the

bias"

We choose to represent the skill of the model in terms of Taylor diagrams as they give a clear picture of the model's ability to represent the observed variability. Nevertheless, we also take into account systematic bias through the application of brier skill score (BSS). For instance, in the ERA-Interim simulation for Ishungu, where the water temperature bias quickly increases for the deeper layers, this leads to very low Brier Skill Scores towards the artificial lake bottom.

- P5152L6: "**Note that, compared to the variables displayed in a Taylor diagram, the *BSS* has the advantage of accounting for the model bias**."

Comment 25: "Fig. 11 Why does the legend begin at 0?"

It was chosen to begin the legend at 0 since there are no BSS higher than 0 calculated for the considered model simulation. Moreover, starting at zero allows to use intuitive colour scheme increments, with a colour change every 10 units. Hence, the legend represents only a part (-100 to 0) of the potential BSS range (-∞ to 1), but covers the whole computed range.

Comment 26: "Fig. 13/14 Mention in the caption also the averaging period, this makes the figs more self-contained."

- Figure13: "Monthly averages **for 2003-2011** of (a) wind velocity ff (m s-1) and air temperature."
- Figure14: "Deviation of the monthly average of the surface energy balance components from its long-term mean (W m^{-2}) at Ishungu**, 2003-2011,** calculated by FLake's surface flux routines."

References

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Reviewer #2

> ***<u>Comment 1</u>*: "I totally agree with the first reviewer concerning the title. It should be modified to clearly state that the paper does not deal with all the African Great Lakes."**

We refer to our answer to comment 5 (Reviewer #1).

> ***<u>Comment 2</u>*: "A lot of acronyms and variables are used in the manuscript. Most of the time they are defined once and for all (some acronyms are never defined), but it is not so obvious to find the definition back when it occurs later in the text. I suggest to add a table with all acronyms, simulation names et variables."**

To enhance the readability of our manuscript, we included a table in the appendix at the end of the manuscript, explaining all acronyms, simulations and variables. Additionally, we made the following changes in the manuscript:

- <u>P5143L18-21</u>: "...a correct representation of lakes within Regional Climate Models (RCMs) and General Circulation Models (GCMs) is essential (Stepanenko et al., 2012**; see appendix for a list of all acronyms, variables and simulation names**)."
- <u>P5145L2</u>: "At each location, FLake was also driven by **the re-analysis product** ERA-Interim ~~re-analysis data~~ (Simmons et al., 2007)."
- <u>P5147L14</u>: "…atmospheric model COSMO (**Consortium for Small-scale Modeling;** Doms and Schättler, 2002), …"
- <u>P5162L25</u>: "This, in turn, causes a higher upward **net long-wave radiation flux** (LW_{net}) ~~flux~~ from May to July (Fig. 14)."
- <u>P5163L13-14</u>: "Overall, monthly variations in **downward short-wave radiation (** SW_{in} **)** seem to have only little effect on the mixed layer seasonality."
- <u>P5163L14-18</u>: "Possibly, the interplay of astronomic **short-wave radiation** ~~*SW*~~ variability~~,~~ **(**with less **short-wave** ~~*SW*~~ radiation reaching the top of the atmosphere during the dry seasons) and balances out the amount of **short-wave** ~~solar~~ radiation reaching the surface…"

<u>Comment 3</u>: "Page 5145, line 2: ERA-Interim is not defined. Maybe it is obvious for climate modelers. It is not for everyone (at least me)."

In response to comment 7 by reviewer #1 and this comment, we have included a description of ERA-Interim and a short, qualitative assessment of its uncertainty over the African Great Lakes in Sect. 2.4.

<u>Comment 4</u>: "Page 5146, line 4: The authors say that the AWS record have a frequency of 15 or 30 minutes, but they are using hourly values to force the model. Did they take means or instantaneous values?"

Since the original measurement frequency (15 and 30 min) is composed of instantaneous values, and since we have only have 2 or 4 measurements available per hour, we thought it most appropriate to use the hourly instantaneous values. Note that this also choice also avoids the dampening out of extreme wind speeds.

- <u>P5146L4</u>: "…but for the integrations only hourly **instantaneous** values were retained"

<u>Comment 5</u>: "Page 5148, line 6: Flake –> FLake"

- <u>P5148L6</u>: "… In ~~Flake~~ **FLake**, however,…"

<u>Comment 6</u>: "Page 5150, line 9: "By linearly increasing wind velocities at AWS 1 by 2.0 m/s". Do the authors mean that they have increase each wind velocity measuremnt by 2.0 m/s? If yes, it is not a linear increase but a constant increase. If not, I don't really understand what they did. Please clarify."

The modification of ff indeed consists of a constant increase of 2.0 m s-1:

- P5150L9: "~~By linearly increasing wind velocities at AWS 1 by 2.0 m s^{-1},~~ **By applying a constant increase of 2.0 m s^{-1} to the wind velocities observed at AWS 1,** the $RMSE$ between wind velocities from both AWSs reduced to 1.8 m s^{-1}."

<u>Comment 7</u>: "Page 5150, line 25: "Note however that this second correction (...) had little to no impact upon the final model modern outcome". Why not limiting the adjustment to wind velocity then?"

The choice to allow both ff and k to vary was made at the beginning of this study, since, for these lakes, these were the input variables which were considered most uncertain. Moreover, as the sensitivity tests have demonstrated, FLake may react very nonlinear to changes in k (Sect. 3.5.1). Hence it was certainly worth including this second correction, even if, after conducting the different experiments, it was found that this second correction is of little influence for the control experiment. Finally, excluding this second correction would also have no influence upon the results conveyed in this study. Hence we believe the second correction may stay in the manuscript.

<u>Comment 8</u>: "Page 5157: Sensitivity study. Why limiting to Kivu? Please clarify."

But the same experiments have been conducted for Kigoma and Mpulungu as well, and revealed very similar, nonlinear responses to the imposed changes. However, for illustrative purposes it was chosen not to include these results in the final manuscript.

- P5158L12-13: "Note that each set of the following tests was conducted starting from the Lake Kivu control simulation (Sect. 3.1). **However, the same experiments have been conducted for Kigoma and Mpulungu as well, and revealed very similar responses to the imposed changes.**"

<u>Comment 9</u>: "Page 5159: FLake seems very sensitive to wind. As I said, I am not a climate modeler. However, I guess it should no be so easy to obtain very accurate winds in a climate model. It will have an influence on the

behavior of FLake, as the authors mentioned several times in the manuscript. However, I would like the authors to discuss the feedback on the climate model. If Flake does not reproduce the appropriate temperature regime of the lake (as it is not so unlikely to happen due to high sensitivity to wind forcing), how much the complete climate model will be affected?"

Indeed, based on our findings it is possible to make some statements about the potential applicability of FLake to study lake-climate interactions when interactively coupled to an atmospheric model. First, it is very well possible that e.g. wind velocities predicted by an RCM will not fall within the narrow range for which FLake predicts a correct mixing regime. FLake might therefore erroneously predict permanently mixed or stratified conditions over the African Great Lakes. Second, however, the only FLake variable which directly influences the atmospheric boundary layer is the lake water surface temperature ($LWST$, note that in case of FLake this is equal to T_{ML}). This is the variable based on which the different terms of the surface energy balance are computed, and hence the exchange of water and energy between the lake and the atmosphere. Consequently, if this variable is correctly reproduced, the influence of the lake on the regional climate will be correctly reproduced.

It is notably one of the main outcomes of this study that the (in our case exemplified by the 5 m water temperature) are mostly correctly captured by FLake, even when the mixing regime is not reproduced and depicts a strong bias. In short: even though bottom temperatures may be wrong, the predictions for the near-surface water temperatures are robust (e.g. P5142L16-19, P5158L22-25, P5160L24-29, P5164L7-10). We may therefore suppose that the complete climate model system is likely to be not very much affected by strong sensitivity of FLake to wind speed values.

In preliminary model simulations during 2002 over the African Great Lakes (using horizontal resolution of 0.0625°) using Flake interactively coupled to the regional climate model CCLM (Thiery et al., in prep.), this hypothesis is confirmed. In particular, lake surface temperature biases generally seem to stay below 1-2°C for Lake Victoria, Lake Tanganyika, Lake Kivu and Lake Albert. This is a major improvement compared to standard CCLM configuration, wherein lake water surface temperatures are parameterized based on a interpolation of sea surface temperatures taken from the lateral boundary conditions. Hence, also coupled model simulations confirm that FLake is a suitable tool to study lake-climate interactions. It is however too early to include these preliminary results of this lake feedback to the RCM in this manuscript.

- P5160L30: "**This has implications for the applicability of FLake to the study of tropical lake-climate interactions. When FLake is interactively coupled to an atmospheric model, it may very well be that e.g. the near-surface wind velocities serving as input to FLake will not fall within the narrow range for which it predicts a correct mixing regime. However, the only FLake variable which directly influences the atmospheric boundary layer is T_{ML}, the variable from which the exchange of water and energy between the lake and the atmosphere are computed. In this study, T_{ML} predictions were found to be robust, even when modelled T_{BOT} values are biased. We may therefore suppose that for tropical conditions, a coupled model system will not be much affected by the strong sensitivity of FLake's deepwater temperatures to, for instance, wind speed values.**"
- P5164L7-10: "The near-surface water temperatures were found to be quite robust to changes in the model configuration. If the observed mixing regime is not reproduced, 5 m temperature predictions deteriorate compared to the control integration, but are relatively little affected. **Hence, FLake can be considered an appropriate tool to study the climatic impact of lakes in the region of the African Great Lakes.** In ..."

> ***Comment 10*: "Page 5161, line 9: "By setting the intial mixed layer depth (...)". Those initial conditions seem relatively arbitrary. Is it possible that we would arrive to other conclusions with other arbitrary values?"**

Although it may not appear so, these initials conditions have been chosen with great care. First, in order to impose full mixing, the mixed depth is set to the lake depth, after which an initial temperature needs to be chosen. Here, we opted for a warm initialisation, since a lake can release heat more efficiently than it can take up heat. Of course, in case of a fully mixed initialisation excluding spin-up (MES), other initial temperature would certainly lead to another result, but as explained in the manuscript (P5161L23-25), this is exactly why this approach to spin-up is to be avoided. But if we use this initialisation and allow for spin-up (MIS), the result would be the same irrespective of the initial water column temperature.

Second, for the case of a stratified initialisation excluding spin-up (SES), the initial conditions were so as to mimic the set-up used for the CORDEX-Africa simulations conducted with the Canadian Regional

Climate Model version 5 (CRCM5). These simulations are analysed by Hernández-Díaz et al. (2012) and Martynov et al. (2012). Due to the strong decoupling of the thermocline and the mixed layer in this cold bottom initialisation, again the choice of the initial mixed layer temperature is of little impact to the final result, apart probably from the first year wherein the mixed layer temperature adjusts to the meteorological forcing fields.

- P5161L21-24: "Within 9 spin-up years, the complete mixing allows for an efficient heat release until the regime switches to the expected pattern. **Since the model is allowed to spin-up until convergence is reached, the selection of the initial water column temperature does not influence the model performance, as long as it is chosen artificially warm.** However, without spin-up (MES), this advantage vanishes …"
- P5161L27-28: "... (SES) becomes an option, given the acceptable results near the lake surface even though the thermal structure is not reproduced. **Note that this was the approach adopted for the CORDEX-Africa simulations conducted with the Canadian Regional Climate Model version 5 (Hernández-Díaz et al., 2012; Martynov et al., 2012).** Hence, ..."

> ***Comment 11*: "Page 5162, line 9: "(...) neither u nor T significantly differ from one season to another, since in both cases seasonal differences are never more than 25% and 10%, respectively, of the observed standard deviation (...), RH and LWin both show a clear seasonality (...)" Maybe I missed something, but regarding Figures 13a and b, it seems to me that if RH and LWin are considered to present a "clear seasonality", so does u."**

The considered text in the manuscript was inspired by a comparison of the standard deviation of hourly, instantaneous values of the considered meteorological forcing variables to the maximum range of three-monthly averages (consistent with Fig. 13a, b, see Table 1).

Variable	Standard deviation of hourly values	maximum range of seasonal means
ff (m s^{-1})	**1.23**	**0.29**
T (°C)	**2.61**	**0.15**

Table 1: standard deviation of hourly instantaneous values (before filling data gaps) and maximum range of seasonal means (DJF, MAM, JJA, SON), 2003-2011 at Ishungu, lake Kivu.

However, following this comment we opted for a new approach. We conducted an additional FLake simulation, using the same set-up as the Ishungu control simulation, but removing the seasonality from the wind speed. This was achieved by subtracting the monthly mean wind speed anomaly from the wind speed time series, therewith removing the seasonality but maintaining the variance of the original time series (Illustration 6). Since this simulation is extremely similar to the Ishungu control simulation (Illustration 7), it can be concluded that, although the wind velocity depicts some seasonality, this is absolutely of no influence to the mixing cycle within Lake Kivu.

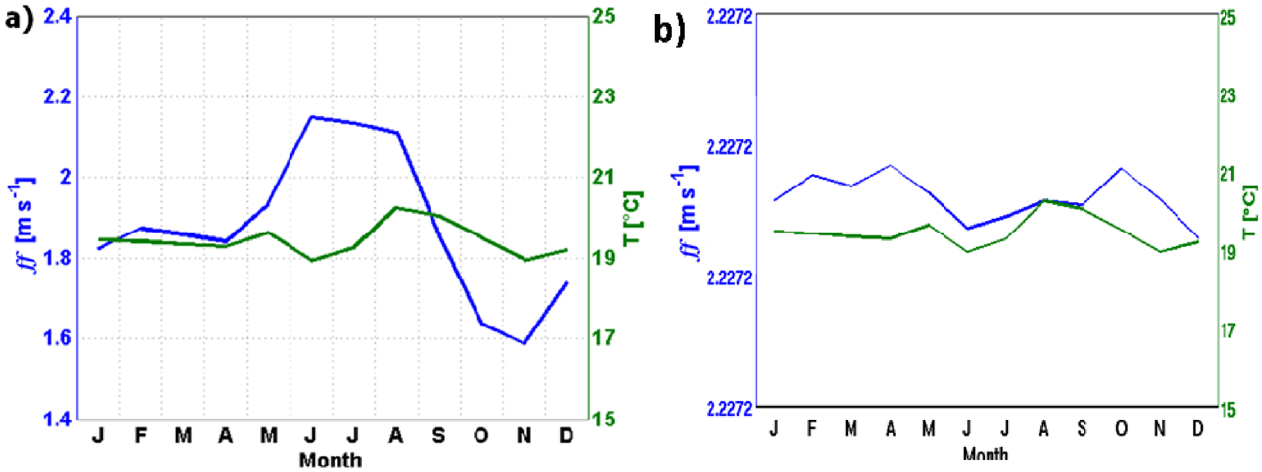

Illustration 6. Monthly averages for 2003-2011 of wind speed *ff* ($m\ s^{-1}$) and air temperature *T* (°C) (a) before and (b) after removal of the wind speed seasonality.

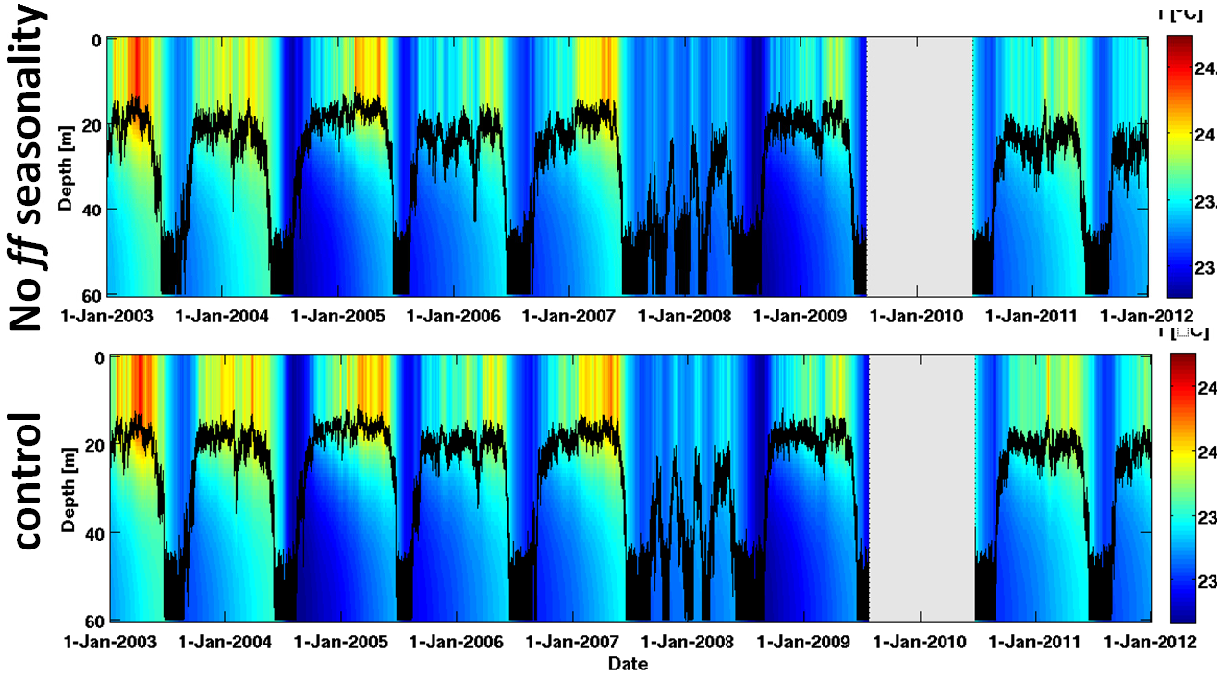

Illustration 7. Effect on water column temperatures of removing the wind speed seasonality at Ishungu. Note that the actual mixed layer depth is shown here instead of the weekly mean mixed layer depth.

We modified the manuscript to convey this new approach, and corrected for a typo:

- P5162L9-11: "~~On the one hand, even though ff slightly increases during the dry season, neither ff nor T significantly differ from one season to another, since in both cases seasonal differences are never more than 25% and 10%, respectively, of the observed standard deviation (Fig. 13a).~~ **On the one hand, even though ff depicts some seasonality (Fig. 13a), neither ff nor T influence the seasonality of the mixed layer depth at Ishungu**. ~~Moreover,~~ **First,** a comparative histogram of corrected ff binned per month (1 m s^{-1} bin width; not shown) reveals that the probability of occurrence of stronger winds ($ff > 5$ m s^{-1}) is lower from April to July, adding to the hypothesis that higher wind velocities are not responsible for the deepening mixed layer depth during the dry season. This is confirmed by FLake, who attributes the mixed layer deepening at the start of the dry season to convection rather than wind-driven mixing. **Moreover, when conducting the Ishungu control simulation with the seasonality removed from ff, the predicted water temperatures are almost identical to the control simulation. This indicates that the ff seasonality also has no major influence on the convective**

driven mixing."

On the other hand, in contrast to ...

- P5162L18-19: "... with three-monthly averages 13% and ~~26~~ **11** W m^{-2}, respectively, lower ..."

***Comment 12*: "Figures 5, 7 and 9: Why not showing RAW simulations? I understand that they do not provide the best results, but ERA-Interim simulations neither and they are presented. For the control simulations, it would be nice to display the error in addition."**

We have opted not to show the raw simulations, as the results look very much like the ERA-Interim simulations (see also Fig. 4, 6, 8). For illustrative purposes it was therefore decided not to show these panels. For this reason, we included the following sentence in the manuscript:

- Fig. 5: "Note the different colour scaling in (c). **The Lake water temperatures for the raw simulation are not shown as they strongly resemble the predictions of the ERA-Interim simulation**."

***Comment 13*: "Figures 10 and 12: I really like Taylor diagrams. I think those figures deserve to be displayed larger."**

We thank the reviewer for this suggestion, and will make sure that the Taylor diagrams are shown in the proper size when typesetting the manuscript.

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