Author's response to reviewers

Kevin Sterckx[1], Philippe Delandmeter[2], Jonathan Lambrechts[3], Eric Deleersnijder[4], Piet Verburg[5], Wim Thiery[1,6]

[1] Vrije Universiteit Brussel, Department of Hydrology and Hydraulic Engineering, 1050 Brussels, Belgium

[2] Institute for Marine and Atmospheric Research, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands

[3] Université Catholique de Louvain, Institute of Mechanics, Materials and Civil Engineering (IMMC), 1348 Louvain-la-Neuve, Belgium

[4] Université Catholique de Louvain, Institute of Mechanics, Materials and Civil Engineering (IMMC) & Earth and Life Institute (ELI), 1348 Louvain-la-Neuve, Belgium

[5] National Institute of Water and Atmospheric Research, 3216 Hamilton, New Zealand

[6] ETH Zurich, Institute for Atmospheric and Climate Science, 8092 Zurich, Switzerland

Correspondence to: **Kevin Sterckx (Sterckx.Kevin@outlook.com)**

The authors would like to thank referee #1 and #2 for the time devoted to review the manuscript and for their useful and constructive suggestions. All comments by the referees were carefully addressed and the manuscript has substantially benefited from the proposed changes. Here below, we would like to clarify our changes regarding all comments, except the small comments on word usage, spacing,... as suggested by referee #2, as these were all justified and have been incorporated in the revised manuscript.

The following convention is applied in this response letter to denote modification in the original manuscript: *response to the referee*; ~~deleted words~~; **added words**.

Anonymous Referee #1

GENERAL COMMENTS: This manuscript discusses the warming of Lake Tanganyika with future climate change as per the RCP8.5 scenario, as assessed through 3D numerical simulations. Though both the topic and the study case are of high relevance, this manuscript provides a too small contribution to be published on its own. As a matter of fact, despite the use of a 3D model, the study of "lake hydrodynamics", as introduced in the title, is reduced to only epilimnetic temperature variations, mostly addressing the surface only, without any detail on water circulations. Temperature variations in the hypolimnion are neglected: while they are increasingly slow with increasing depth, they nevertheless do occur. The study should have dealt with the growing inertia of deep waters through proper long-term simulations of thermal structure evolution, especially given the exceptional depth of Lake Tanganyika. Furthermore, while SLIM 3D works great for assessing present day hydrodynamics as regards both the stratification dynamics and circulations, I have several concerns as regards its application to climate change studies, due to its incomplete modelling of lake surface heat budget. The comparison of SLIM 3D with the 1D model FLake is not correctly developed, as explained in the specific comments below. The manuscript also implicitly relies too much on the

Delandmeter et al. (2017) paper: no details about the model are given herein, which puzzles the general reader. The most relevant ones, e.g. mesh resolution, should at least be provided. Methods are not clearly explained and I have some concerns over the results, some model blemishes being overly evident. The Introduction and the very small Discussion sections lack an actual insight and a comparison against the wide literature available on lake warming with climate change and the related modelling efforts. The organisation of the paper is poor and makes me think that it is an incomplete rearrangement of a M.Sc. thesis. Several language errors are also present. Because of these general reasons, in addition to the specific comments below, I must suggest the rejection of the manuscript by the journal. I hope my comments would stimulate the Authors to expand and review their work and try to publish it again soon.

Thank you for this feedback. In this response letter we address each of the comments raised. Based on the reviewer suggestions, we have made substantial changes to the initial manuscript. In short, these changes include: (i) a substantial extension of the introduction and discussion sections including reference to key recent studies on lake warming, (ii) a careful revision of the spelling in the manuscript, (iii) an update and rearrangement of most of the figures, (iv) a more detailed description of the SLIM 3D model including the surface heat flux representation and an argumentation for its applicability to future projections, (v) a clarification of the FLake simulation set-up and motivation for the comparison of both simulation tools, and (vi) the discovery of the model blemishes as a postprocessing artefact which we now removed. More details on each of these changes are provided in the step-by-step replies. To expand the discussion and interpretation of the results, Piet Verburg, an expert on Lake Tanganyika, joined the author team.

We would also like to note that, as the reviewer points out, the topic of this study is of high relevance. Our study is the first to investigate projected climate change impacts on the hydrothermal characteristics of Lake Tanganyika. Our results show dramatic projected changes in the temperature and mixing regime of this lake, which were hitherto not known. In light of the anticipated impacts of these drastic changes on ecosystem functioning and local communities, we believe that this information represents a relevant contribution to the peer-reviewed literature, despite the possible improvements to the study design and analysis which can be taken into account in follow-up studies.

We would like to start by showing the revised introduction:

> In recent decades, climate change has caused impacts on ecosystems and societies on all continents and in the global ocean, highlighting their sensitivity to a changing climate. Climate change also affects the functioning of inland water bodies. In this study, we focus on the impact of climate change on the hydrodynamics of Lake Tanganyika, a meromictic lake located between Burundi, DR Congo, Tanzania and Zambia (Fig. 1a). With the countries surrounding Lake Tanganyika being relatively poor, their inhabitants are strongly dependent on local resources for their basic needs, such as food and water. The lake fulfils an essential role in this supply, mainly because of the intensive fishery (Sarvala et al., 1999). There are around 100,000 people directly involved in the fisheries, operating from almost 800 sites, and by estimation, 25 to 40% of the protein diet of approximately 1,000,000 people living around the lake comes from these fisheries (O'Reilly et al., 2003). The main fishery is on pelagic clupeids (sardines), and together with many other fish species in the lake, their food supply is strongly dependent on the vertical mixing between deeper and shallower water layers. Clupeids strongly depend on algal productivity and an efficient carbon transfer from the algae to fish (Tierney et al., 2010; Yvon-Durocher et al., 2012). However, stratification of the water column reduces mixing between the nutrient-poor epilimnion and the nutrient-enriched hypolimnion (De Wever et al., 2005; Paerl et al., 1975), limiting primary productivity (Verburg et al. 2003).

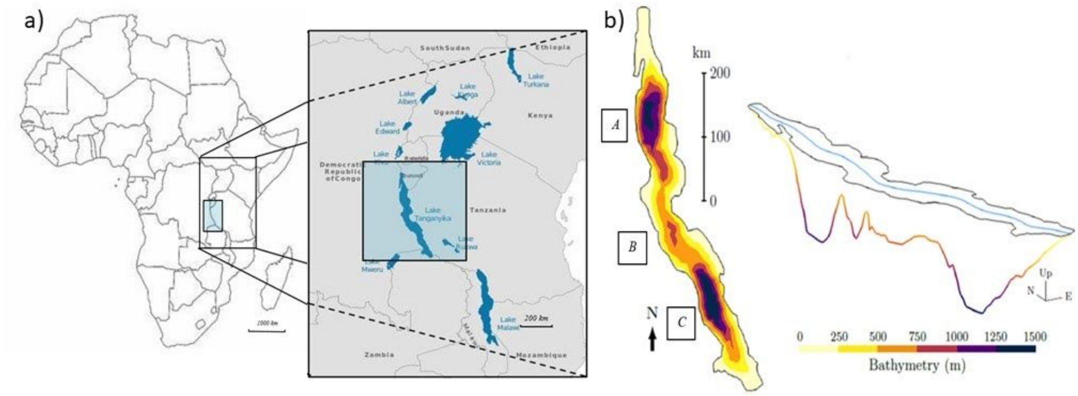

Fig. 1: (a) Location of Lake Tanganyika (3°20'S - 8°48'S; 29°12'E - 31°12'E), surrounded by Burundi, Tanzania, Zambia and DR Congo; (b) Cross section Lake Tanganyika with basins A: Kigoma, B: Kungwe, C: Kipili (Delandmeter et al., 2018)

Past climate change has already influenced the functioning of Lake Tanganyika. This is visible through a rise in water level, in surface water temperature and in stability of the water column, which in turn decreases the mixing of the layers (Kraemer et al., 2019). Future climate change is further affecting the lake system in various ways. First, atmospheric warming induces a change of the mixed layer depth and the mixing properties, which enhances stratification, leading to significant changes in terms of nutrient supply to the epilimnion (Verburg et al. 2003; Kraemer et al., 2015; Woolway and Merchant, 2019; Woolway et al., 2020; Maberly et al., 2020). Primary productivity has decreased as indicated by increased water transparency, reduced uptake of dissolved silica by diatoms and decreased phytoplankton biomass (Verburg et al., 2003). Historical records suggest a 30% decrease in fish production due to climate change and its effects (O'Reilly et al., 2003). Also, reduced vertical mixing may result in a shallower oxycline with anoxic water closer to the surface which could result in more frequent fish kills (Coulter, 1963) by nearshore upwelling of anoxic hypolimnetic water. Upwelling may occur less frequent in the future but may have greater impact when it does happen (Lau et al. 2020). Besides, by atmospheric temperature, mixing is also influenced by wind velocity, with decreasing wind velocity resulting in reduced mixing (Naithani et al., 2011). A third influence comes from near-surface atmospheric humidity, which is inversely linked to the mixing (Verbur and Antenucci 2010; Thiery et al., 2014). A dryer atmospheric boundary layer enhances evaporation from the surface water, and since this is an endothermic reaction, the water surface temperature decreases, which drives the natural convection. This means that the different temperatures in the water cause density variations, leading to buoyancy forces. In this case, it will lead to upwelling of the underlying warmer water, driving the mixing mechanism. Effects on the lake surface temperature are translated into impacts on hydrodynamics.

However, to date very little is known about how Lake Tanganyika will respond to projected future climate change. The extent of the feedback from future changes in the lake to changes in the atmosphere is also not known. A key parameter influencing the lake is atmospheric temperature, as it directly influences the lake surface water temperature. A second parameter is wind speed, as this acts as a catalyser for evaporation and upwelling. Third, changes in atmospheric humidity may affect the evaporation potential and thereby the surface temperature. Finally, changes in shortwave and longwave radiation may further affect the surface energy budget. The outcomes of this paper represent a starting point for further research on projected ecological changes.

> In this study, we therefore aim to assess the present-day variability and potential future changes in the hydrodynamics of Lake Tanganyika. Specifically, this work aims to (i) assess the added value of a 3D hydrodynamic lake model compared to a 1D lake model, (ii) uncover the impact of present-day seasonal atmospheric variability on the lake hydrodynamics by analysing a short-term simulation, and (iii) uncover climate change effects on the lake hydrodynamics by analysing two long-term simulations representing in present-day and future climate conditions. To this end, we use high-resolution dynamical downscalings of a reanalysis product and a global climate model (GCM) as input for the 3D version of the Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM 3D, https://www.slim-ocean.be/).

L. 54. What is the meaning of the expression "more anoxic"? It does not make sense.

Thank you for your comment. We corrected the manuscript as follows:

> ~~Stratification also affects the properties of the hypolimnion, since this layer will become more anoxic, which means the organisms that require oxygen will be threatened.~~ **Also, reduced vertical mixing may result in a shallower oxycline with anoxic water closer to the surface which could result in more frequent fish kills (Coulter, 1963) by nearshore upwelling of anoxic hypolimnetic water. Upwelling may occur less frequent in the future but may have greater impact when it does happen (Lau et al., 2020).**

L59. The expression "rotate upwards" should be replaced with something more technical.

Thank you for your comment. We have corrected the manuscript as follows:

> A dryer atmospheric boundary layer favours evaporation from the surface water, and since this is an endothermic reaction, the water surface temperature decreases, which ~~allows warmer water from below to rotate upwards, increasing the mixing.~~ **drives the natural convection. This means that the different temperatures in the water cause density variations, leading to buoyancy forces. In this case, it will lead to upwelling of the underlying warmer water, driving the mixing mechanism.**

L60-65. This whole passage is unclear.

Thank you for your comment. We have corrected the manuscript as follows:

> However, to date very little is known about how Lake Tanganyika will respond to projected future climate change. **The extent of the feedback from future changes in the lake to changes in the atmosphere is also not known. A key parameter influencing the lake is atmospheric temperature, as it directly influences the lake surface water temperature. A second parameter is wind speed, as this acts as a catalyser for evaporation and upwelling. Third, changes in atmospheric humidity may affect the evaporation potential and thereby the surface temperature. Finally, changes in shortwave and longwave radiation may further affect the surface energy budget.**

> ~~As the atmospheric temperature is in close interaction with the lake, the atmosphere will first influence the lake temperature, which is, together with the wind driving the hydrodynamics. The extent of the feedback from the lake changes to the atmosphere is also not known. In the lake itself, the influence of hydrodynamic evolution has not been assessed. regarding the chemical and biological consequences~~, ~~the input parameters for the latter research can be based on the outcomes of this paper.~~ **The outcomes of this paper represent a starting point for further research on projected ecological changes**.

<u>L73-76.</u> **If a paper follows a standard structure, there is no need to present a recap of its content.**

Thank you for this suggestion. We have removed the paragraph:

> ~~This paper is organised as follows: in Section 2 we introduce the background information regarding the Lake and the current dynamics; in Section 3, the different tools and datasets are discussed; in Section 4, the methods, including an overview with the different runs are given; in Section 5, we show all results; in Section 6, these results are discussed; in Section 7, we formulate the final conclusions.~~

<u>L101-106.</u> **This whole passage is contradictory. Which is the trophic state of the lake? What is the anthropogenic influence on it? It is not clear.**

Thank you for your comment. To elaborate, according to Van Meel, L. I. J., & Kufferath, J. (1987), the lake is pseudo-eutrophic. According to the concentrations of chlorophyll a and nutrients the lake can be classified as oligotrophic. On the other hand, the lake's productivity is relatively high for such an oligotrophic lake, in part as a result of rapid recycling within the epilimnion. We have edited the paragraph as follows:

> Early biological research concluded that high water transparency, low nutrient concentrations in the epilimnion and low phytoplankton densities ~~led to~~ **suggest the lake is** oligotrophic ~~pelagic environment, which means the water body offers very little to sustain life~~ (Beauchamp, 1939). Lake Tanganyika has been classified as pseudo-eutrophic (i.e. holding both eutrophic and oligotrophic characteristics) due to ~~the local~~ **the relatively high** productivity of the lake ~~by dense phytoplankton blooms and diurnal vertical movements of zooplankton and fish. Being a eutrophic lake implies high levels of biological productivity, supported by the rich nutrient constitution~~ (Van Meel & Kufferath, 1987). A modelling study showed that the lake is not eutrophic~~ated~~ (Naithani et al., 2007).

<u>L130-131.</u> **Wind accelerates also because the drag coefficient of water is much lower than that of land cover.**

Thank you for this input, we suggest to add it as follows:

> In the centre of the lake, a major speed-up occurs, which can be explained by a channelling effect along the mountain valleys **and the decrease of the drag coefficient over water compared to land.**

L131-135. **This discussion on the Froude number of wind is unclear.**

Thank you for this comment, as per suggestion of referee #2, we removed the passage:

> ~~The Froude number~~ represents ~~the ratio of inertia forces to gravity forces, which leads to , where and In the south and north of the lake, the Froude number is mainly < 1, which implies orographic blocking, while the central parts of the lake allow overflow of the near-surface (south)easterlies (Docquier et al., 2016).~~

L146-148. **This sentence is in contradiction with those above, in which it is stated that the Lake Tanganyika area experiences a single rainfall season.**

Thank you for pointing this out, we have rephrased this sentence as follows:

> At Lake Tanganyika, **the beginning of the rain season is driven by the southward migration of the ITCZ, which starts around September/October and lasts until December. This period is characterized by short rains, whereas, after a short period of decreased rainfall (January - February), a longer rains occur** ~~the long rains generally occur every year~~ around the boreal spring (March-May), **which are driven by the northward migration of the ITCZ.** ~~where the secondary rainfall event contains shorter rains in autumn (September-December) as those are the seasons when These periods are the effect of the ITCZ travels over the region.~~

L154. **What is the meaning of "poor vegetation conditions"?**

Poor vegetation conditions refer to the limited blooming of the vegetation during warm ENSO events. Plisnier et al., 2000 states: "For example, during warm ENSO phases, the Lake Victoria area showed warmer and more humid conditions with an increased vegetation activity while the central and southern part of the study area showed warmer, but drier conditions with a decreased vegetation activity. The area west of Lake Tanganyika is characterized by poor vegetation conditions during warm ENSO events."

This is confirmed by an analysis using satellite-based NDVI data and multiple gridded precipitation data sets (Hawinkel et al., 2016). The results notably show a negative correlation between ENSO index and monthly precipitation west of Lake Tanganyika (Illustration 1), with lower precipitation leading to lower vegetation activity in the region (i.e. positive correlation between precipitation and ENSO; Illustration 2).

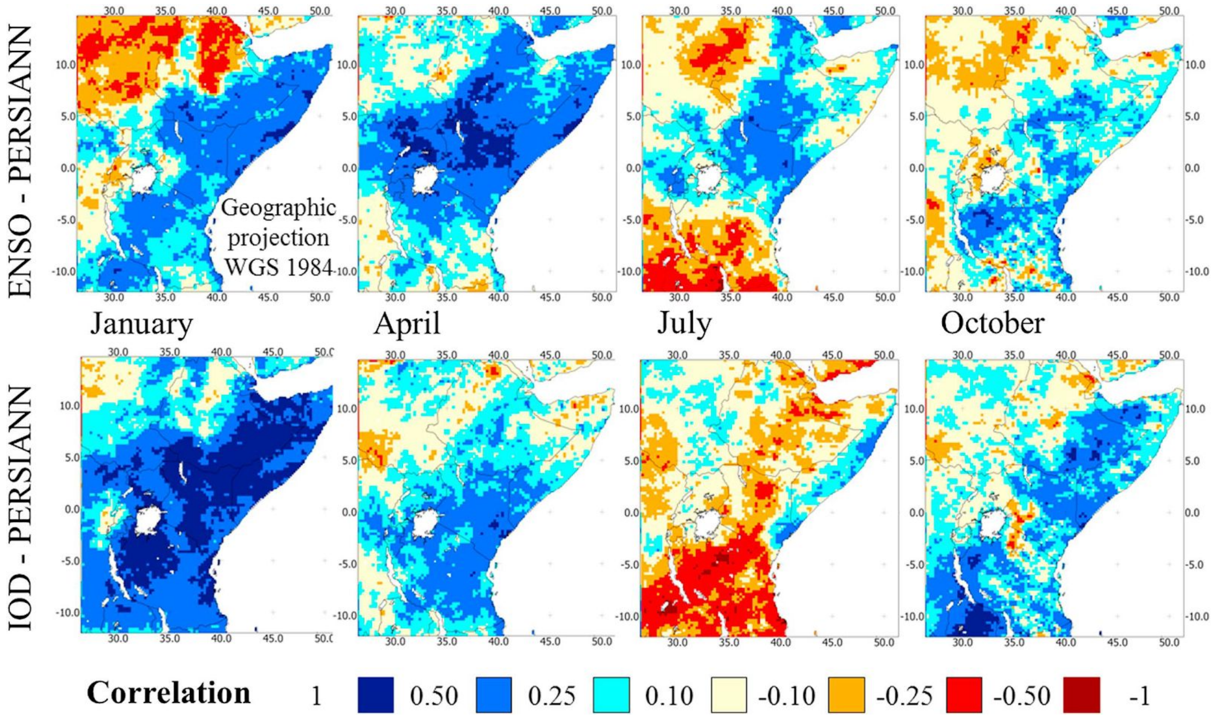

Illustration 1: A positive ENSO phase leads to drier conditions West of Lake Tanganyika (top row), especially in July. Illustration from Hawinkel et al. (2016).

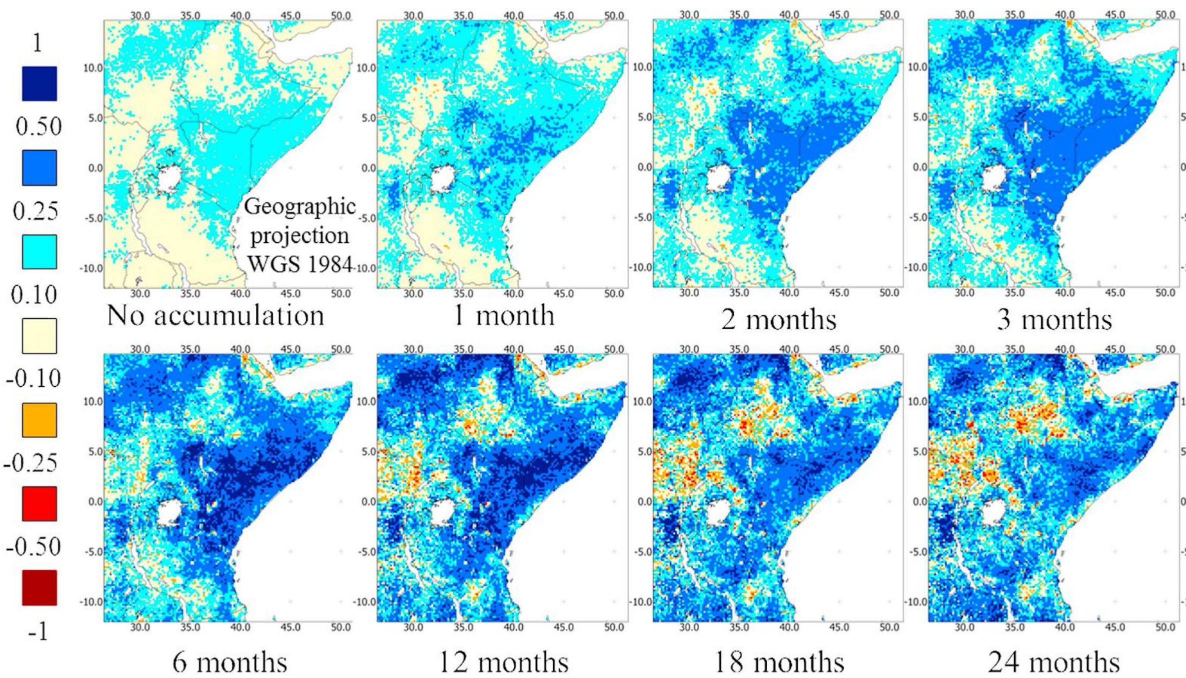

Illustration 2: Positive correlation between precipitation (here taken from PERSIANN) and vegetation activity (NDVI, here taken from AVHRR + VGT). The different panels represent different windows of precipitation accumulation. From these results it can be inferred that drier conditions will lead to lower vegetation activity. Illustration from Hawinkel et al. (2016).

To avoid possible confusion regarding terminology, we rephrased this paragraph in the revised manuscript:

> The warm ENSO events are usually linked to a higher amount of precipitation **in East Africa**, where**as** the colder ENSO events tend to result in ~~a below average~~ **below-average** rainfall (Mutai & Ward, 2000**; Hawinkel et al., 2016**). However, ~~studies have shown that~~ the ENSO impact **substantially varies across** ~~depends on~~ the region**, and notably West of Lake Tanganyika, the ENSO index and precipitation amounts are anticorrelated (Hawinkel et al., 2016)**. ~~For a warm ENSO, t~~**T**he area west of Lake Tanganyika therefore shows **reduced vegetation activity during warm ENSO events** ~~poor vegetation conditions~~ (Plisnier et al., 2000; **Hawinkel et al., 2016**).

L169-174. This whole passage is unclear.

Thank you for this comment, we propose the following modification to increase the clarity of the passage:

> The final process that should be considered is the surface energy balance, as this is the driving force of the lake-atmosphere interactions. ~~This balance contains parameters that can be compared with the COSMO-CLM² data and will determine the stability of the atmospheric boundary layer above the lake surface and the resulting lake-atmosphere interactions.~~ **This balance determines** the stability of the atmospheric boundary layer above the lake surface and the resulting lake-atmosphere interactions (Verburg and Antenucci 2010; Verburg et al. 2011). It also ~~determines (to a large extend) the lake's heat budget by setting the upper boundary conditions, which affects the metabolism, physiology, and behaviour of aquatic organisms, since it defines the thermal structure of the lake (Saur & Anderson, 1954; Wetzel & Likens, 2000).~~ **influences the lake's heat budget and thereby defines the thermal structure of the lake. The latter affects the metabolism, physiology, and behaviour of aquatic organisms (Saur & Anderson, 1954; Wetzel & Likens, 2000). The parameters presented in the surface energy balance can all be compared to data from COSMO-CLM².**

L193-195. This passage is unclear. Which part of the heat budget at the surface simulated by the model? Which part is neglected? What is the relaxation term? What is the "certain period" for which heat is retained into the lake and then released?

Thank you for raising this point. In SLIM 3D, the heat budget is controlled by the temperature equation. Inside the lake, heat is advected by the currents and mixed by the turbulent diffusion. A key element of the heat budget is the surface boundary condition necessary for the temperature equation. In this study, we implemented this condition as a relaxation source term towards the 2-meter air temperature provided by COSMO-CLM². This relaxation is added as a source term to the temperature equation and reads

$$relax = f(z)\,(Tref - T)\,/\,\tau$$

where f(z) is a linear function varying from 1 at the surface and to 0 at the relaxation depth z_r and beyond; Tref is the near-surface air temperature from COSMO-CLM² and tau is the relaxation time. In the revised manuscript, the part of the model description about the heat budget reads:

In this study, SLIM 3D is applied to Lake Tanganyika in the same setup as that of Delandmeter et al. (2018). The model configuration is described in detail in the latter study and summarised hereafter. The only external forcings to the model are the surface wind stress and surface heat flux. The first one is prescribed using simulated data from COSMO-CLM². The second one is parameterized using a relaxation term towards the 2-meter air temperature, which is also available from COSMO-CLM². The use of the relaxation term requires only the near-surface air temperature as input and has the advantage of simplicity and stability. Other parameterizations require more input data and, more complex, they can potentially lead to lake model instabilities, especially when spatial or temporal scales differ between the lake and surface model. The relaxation is controlled by two parameters: z_r, the distance to the surface until which it is applied and τ, the relaxation time. z_r is set to 12 m, corresponding to the photic depth (Descy et al., 2016) which is used as a proxy to the water column affected by solar radiation and other fluxes. After calibration, τ is set to 10 days (Delandmeter et al., 2017).

L232-240. Given what is stated in the paper, SLIM 3D and FLake are not proper models to hold a comparison between 1D and 3D lake models, as they neglect different relevant phenomena: SLIM 3D does not consider the full heat budget at the water surface interface, while FLake does not consider temperature variations within the epilimnion.

We agree with the reviewer that these are two key limitations of the models we apply. However, despite these limitations we do feel that such a comparison is warranted and yields interesting results, as detailed hereafter. To start, both models have been applied to Lake Tanganyika in previous studies with results published in the peer-reviewed literature (Thiery et al., 2014a; 2014b; 2015; 2016; Docquier et al., 2016; Delandmeter et al., 2018; Woolway and Merchant, 2019). While 3D-modelling of the African Great Lakes is the current research frontier (e.g. Delandmeter et al., 2018; Kranenbrug et al., 2020), 1D models, and FLake in particular, are still widely used research tools. For example, FLake is one of the models participating in the Lake Model intercomparison Project (LakeMIP; Stepanenko et al., 2010; 2013; 2014; Thiery et al., 2014; Guseva et al., 2020) and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; Frieler et al., 2017), the model represents lakes in ERA5 (Woolway and Maberly, 2020; Herschbach et al., 2020) and it is the most widely used model for representing lakes in numerical weather prediction systems and climate models (e.g. Mironov et al., 2010; Martynov et al., 2012; Balsamo et al., 2012). More recently, FLake became the reference for large-scale climate change impact assessments on lake temperatures and mixing regimes (Woolway and Merchant, 2019; Maberly et al., 2020; Woolway and Maberly, 2020). Given the widespread use of this model, we believe that its evaluation is highly relevant, especially in data scarce regions such as tropical east Africa.

The SLIM 3D evaluation shows that the current representation of the surface heat flux is able to capture the observed lake surface temperature patterns (Fig. 3 in the initial manuscript). In fact, SLIM 3D outperforms FLake in terms of the lake surface temperature representation, even though FLake arguably has one of the most advanced representations of the surface heat budget among existing lake models (Mironov et al., 2010). However, the application of SLIM 3D also highlighted that the absence of a full heat budget in this model impedes a detailed assessment of the drivers of heat budget changes and the inclusion of secondary effects such as atmospheric humidity and radiation changes. Implementing a full heat budget in the model is therefore a priority for future model development for the SLIM 3D team at UCLouvain, even though it comes with great challenges.

L241-245. **I do not understand this whole section. ARC Lake is never mentioned before in the paper and its use is not clearly explained here.**

Thank you for this comment. We modified the paragraph as follows:

> ~~ARC stands for Along track scanning radiometers Reprocessing for Climate (Thiery et al., 2015). The radiometers are sensors which are part of the European Space Agency's Earth Observing missions. The aim of the ARC Lake is to derive observations of lake surface water temperatures and lake ice covers of major lakes for 1991 until 2010 (http://www.laketemp.net/home_ARCLake/).~~
>
> **The Along-Track Scanning Radiometers Reprocessing for Climate applied to Lakes (ARC Lake; MacCallum and Merchant 2012) provides satellite-based observations of lake surface water temperatures and lake ice covers of major lakes for 1991 until 2010 (http://www.laketemp.net/home_ARCLake/). All radiometers considered by ARC Lake are part of the European Space Agency's Earth Observing missions. A previous analysis of ARC Lake data over Lake Tanganyika highlighted the very close agreement between the ARC Lake satellite product and multi-year in situ lake surface temperature observations at two locations in the lake (Thiery et al., 2014a), demonstrating that the ARC Lake product represents a reliable observational reference product for this lake. The lake surface water temperatures given by ARC Lake are therefore used to assess the skill of both the SLIM 3D (EVAL simulation, see below) and the FLake model.**

L246-254. **Given that climate change is an ongoing process and that the thermal structure of deep meromictic lakes presents a thermal inertia in the scale of years up to centuries, why didn't you perform a single simulation of the 1980-2099 time span? That way, you would have been able to properly simulate the response of Lake Tanganyika to climate evolution, including temperature dynamics within the hypolimnion. Simulating separate time spans may be acceptable for lakes which display annual mixing, but it is strongly elusive for a meromictic basin.**

Thank you for this comment. We fully agree that one transient simulation would provide more information, in particular regarding changes in the deep layers characterised by strong inertia. However, high-resolution meteorological information, both in space and time, is a very important driver of the model, so we can only work with high-resolution regional climate data for forcing SLIM. Given this constraint, there are no transient climate projections available (the transient simulations with the highest spatial resolution are ~50km (0.44°) from CORDEX-Africa, with forcing fields available only at daily or monthly resolution). Climate simulations with sufficient spatial and temporal resolution are only available for time slices (Thiery et al., 2016).

We now clarified this in the method section of the revised manuscript:

> The latter was also run of a 30-year period, but with a simulation start date, which is 90 years after that of HIS. **While a single transient simulation covering the entire 21th century would enable the study of changes in deep layers characterized by strong inertia, meteorological forcing with sufficient spatial and temporal resolution is unfortunately not available for this region, hence the choice for two time slice simulations using available high-resolution meteorological forcing.**

L260-261. A 1D model is supposed to give a horizontally averaged estimation of water temperature. How does the FLake simulation compare against the horizontally averaged observed surface water temperature from ARC Lake?

As we note in our response to the next comment by reviewer 1, our 1D simulations are column-wise representations of the water temperature profile on a 0.0625° x 0.0625° grid, that is, they represent the three-dimensional water temperature structure of Lake Tanganyika but thereby ignore horizontal heat transport occurring within the lake (which is why we call it a 1D model). As such, the FLake simulations at one particular location in the lake can be compared against both in-situ and remote-sensing based lake surface temperature estimates. This comparison has already been conducted for two locations in Lake Tanganyika: Kigoma (northern basin; 4.858S, 29.598E) and Mpulungu (southern tip; 8.738S, 31.048E; Thiery et al., 2014a). The results of this evaluation shows that FLake captures the annual mean lake surface temperature as well as the phase of the seasonal cycle, but overestimates the amplitude of the seasonal temperature cycle (Illustration 3). More details of this evaluation procedure are provided in Thiery et al., 2014a and Thiery et al., 2015. Interestingly, the in-situ and satellite-based temperature observations show a marked correspondence, confirming that the ARC Lake product can be used as a reference product in the comparative evaluation of FLake and SLIM 3D across all lake pixels (Illustration 3). Finally, given the explicit spatial representation of lake temperatures and the substantial spatial temperature variability occurring in Lake Tanganyika (as also noted by reviewer 2), we see little added value of horizontal averaging of the FLake and SLIM 3D simulations.

We now added an explicit reference to prior evaluation efforts in the revised manuscript:

> **A previous analysis of ARC Lake data over Lake Tanganyika highlighted the very close agreement between the ARC Lake satellite product and multi-year in situ lake surface temperature observations at two locations in the lake (Thiery et al., 2015), demonstrating that the ARC Lake product represents a reliable observational reference product for this lake. The lake surface water temperatures given by ARC Lake are therefore used to assess the skill of both the SLIM 3D (EVAL simulation, see below) and the FLake model.**

We also updated the method section to better explain the characteristics of the Flake simulations and to motivate why we use this data (see next comment).

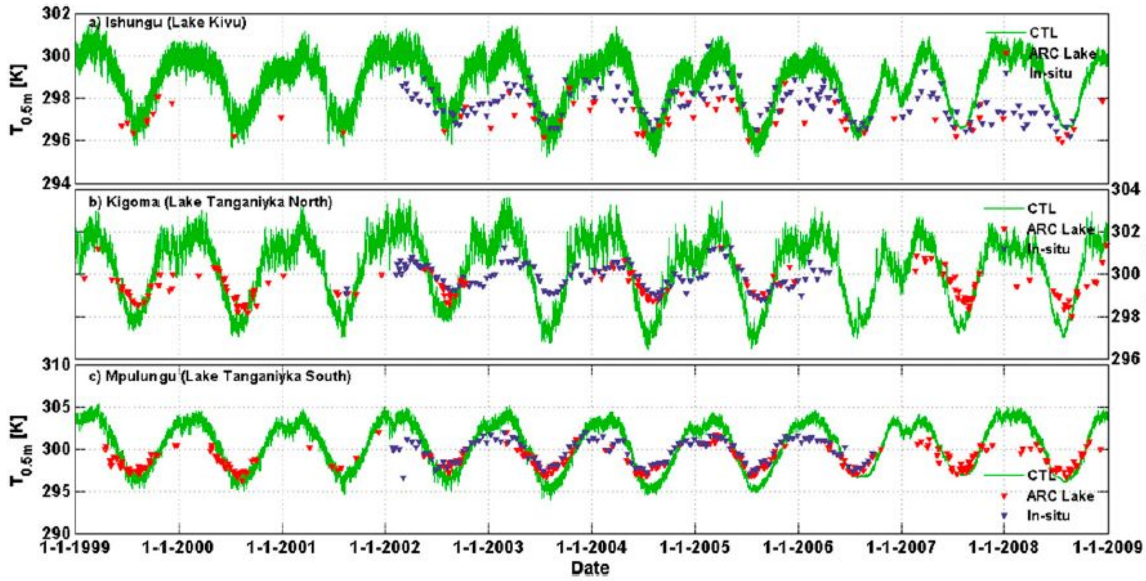

Illustration 3: Modeled (green lines), remotely sensed (ARC-Lake; red triangles) and bimonthly, in situ observed (blue triangles) lake temperatures (K) at (a) Ishungu (Lake Kivu; 2.348S, 28.988E), (b) Kigoma (Lake Tanganyika's northern basin; 4.858S, 29.598E), and (c) Mpulungu (Lake Tanganyika's southern basin; 8.738S, 31.048E) at a depth of 0.5m (lake surface water temperatures in case of ARC-Lake) (from Thiery et al., 2015).

L268-271. This comparison does not make sense, as the two models produce different outputs and the 1D one cannot reproduce horizontal surface temperature variations by definition. The two models should be compared over a common basis, i.e. over horizontally averaged temperature.

We agree with the reviewer that a single 1D model simulation cannot represent horizontal surface temperature variations. However, in this study we perform an array of 1D simulations that cover the entire lake and which allow for the study of horizontal temperature patterns over the lake. In particular, the 1D model FLake, or in other words the single-column model, was run once for every grid cell in a ~7 x ~7km grid (0.0625° x 0.0625°) covering the entire Lake Tanganyika. The model thus represents the lake through a set of independent vertical columns, that is, there is no horizontal heat exchange below the surface. But each column is subject to its own, local meteorological forcing, leading to different hydrothermal conditions at different locations in the lake. In particular, this approach captures the effect of the more pronounced seasonal cycles of temperature and atmospheric humidity (i.e. increasing dry season - wet season contrast) towards the southern end of Lake Tanganyika, leading to spatially and temporally varying surface heat fluxes, water temperature and mixing dynamics.

We also would like to note that the comparison to the 1D model simulations does not represent the core of the paper; they merely represent an existing data set (from Thiery et al., 2015) which is used as a benchmark when evaluating SLIM 3D. In particular, the comparison of FLake and SLIM 3D in the evaluation against ARC Lake serves to confirm our initial hypothesis that a sophisticated 3D model outperforms a simplified (but widely-used) 1D model, suggesting that the added value of including horizontal hydrodynamics and heat exchange in SLIM 3D outweighs the drawback of a simplified surface energy budget representation in SLIM 3D compared to FLake.

In the revised manuscript, we now provide a clear description of FLake model setup and clarified the motivation for this comparison between SLIM 3D and FLake:

The 1D model that will be used to evaluate the benefits of a 3D model over a 1D model is FLake. FLake is a one-dimensional model, which is interactively coupled **at the subgrid-scale level** to COSMO-CLM². **As such, FLake simulates a single-column water temperature profile in every COSMO-CLM² grid cell with non-zero lake area fraction. This approach enables the study of horizontal water temperature variations caused by spatially-varying meteorological conditions, but ignores horizontal water and heat transfers below the surface. [...] As a widely-used parameterization scheme in numerical weather prediction systems *(e.g. Mironov et al., 2010; Balsamo et al., 2012)*, climate models *(e.g. Mironov et al., 2010; Martynov et al., 2012)* and climate reanalyses *(Woolway and Maberly, 2020; Herschbach et al., 2020)*, FLake encompasses a relatively detailed representation of the surface energy budget. This enabled the model to become a reference tool for large-scale climate change impact assessments on lake temperatures and mixing regimes (Woolway and Merchant, 2019; Maberly et al., 2020; Woolway and Maberly, 2020).**

L272-276. This whole passage is unclear.

We now reworked the paragraph:

At the centre of the lake, a cold bias for the 1D model occurs. ~~For the specific case of the centre of the lake, the 3D model considers the water velocities, and since this is a very windy area, this might explain the cold bias of the 1D model. After the validation of the 1D model, done by Thiery et al. (2015),~~ **Based on this evaluation,** we hypothesize~~d~~ that the system reacts too fast on seasonal meteorological changes, which means that it overshoots at every seasonal transition. **This overshooting happens twice per year, leading to a stronger heating or cooling effect than expected.** Their explanation for this was the lack of heat storage, since the 1D model underestimated the thermocline depth. **A second explanation might be the increased wind velocities in the centre of the lake, leading to higher water velocities, which are accounted for in the 3D model.**

L279-281. This does not make sense. See the comments above.

Here we kindly refer to our response to comment L268 of Reviewer 2.

L281-282. I would say that for a lake of the size of Lake Tanganyika, the possibility of introducing spatially heterogeneous boundary conditions in the 3D model plays a larger part than 3D circulations on reproducing spatial heterogeneity, especially if only surface temperature is accounted. Moreover, which boundary conditions were used to drive the 1D model? Were atmospheric boundary conditions averaged over the lake surface or were data at the lake deepest point considered?

Thank you for this comment. Firstly, we refer to the answer to comment L268 of Reviewer 2. A key point to realise here is that the 1D simulations also receive spatially heterogeneous meteorological forcings from the COSMO-CLM² regional climate model (in fact, FLake was run interactively within that climate model). As such, the relevant differences between the '1D' and 3D runs are the inclusion *of 3D circulation in SLIM 3D and a different representation of the surface energy fluxes. We hope that the modified method section now clarifies this point.*

L288-290. What kind of instabilities are the authors referring to? It is not clear in the sentence.

These instabilities have been investigated and appeared to have come from post-processing. We have re-run most of the figures and removed some (see more details in the following comments).

Figs. 4 and 5. Such large numerical instabilities (as in Fig. 4a) cannot be presented in a journal paper. The Authors should identify the causes and address them. I see that the bathymetrical profile of the shores is roughly sketched through large steps. Does this affect calculations? By the way, what is the resolution of the numerical mesh of the SLIM 3D model? It is not specified in the paper. Wasn't a better bathymetry available? Most importantly, where are the cross sections placed?

These instabilities are indeed too large. As, due to a computer crash, we could not retrieve the data to re-plot these specific figures, they have been removed from the manuscript and the analysis can be done based on Fig. 14 and Fig. 15. The mesh resolution used in this study is 10 km, which cannot be highly improved due to the large computational cost for such a long period of simulation, but the mesh resolution does not affect the model stability at this level. The bathymetry data used in this study are the same as for modelling studies as Naithani et al. (2003, 2007), Gourgue et al. (2011). The cross section is defined on Fig. 2. The steep bathymetry on a 10-km grid could lead to inaccuracies close to the bottom boundary, but SLIM handles discontinuities in the bathymetry such that gravity waves are not affected by the steep bathymetry.

The reference to Fig. 2 (now Fig. 1b) has been added to the captions of all cross-sections (which are all shown further in this answer letter), such that the reader does not need to search for this information.

L301-302. Why should the centre of the lake be the location of maximum turbulence? It is not clear.

The model also accounts for surface water velocities, where the centre of the lake shows the highest speeds in both directions (north to south and vice versa, depending on the season). Illustration 4 shows the average monthly surface water velocities (as obtained from the EVAL simulation) with positive values for northbound displacements and negative for southbound displacements.

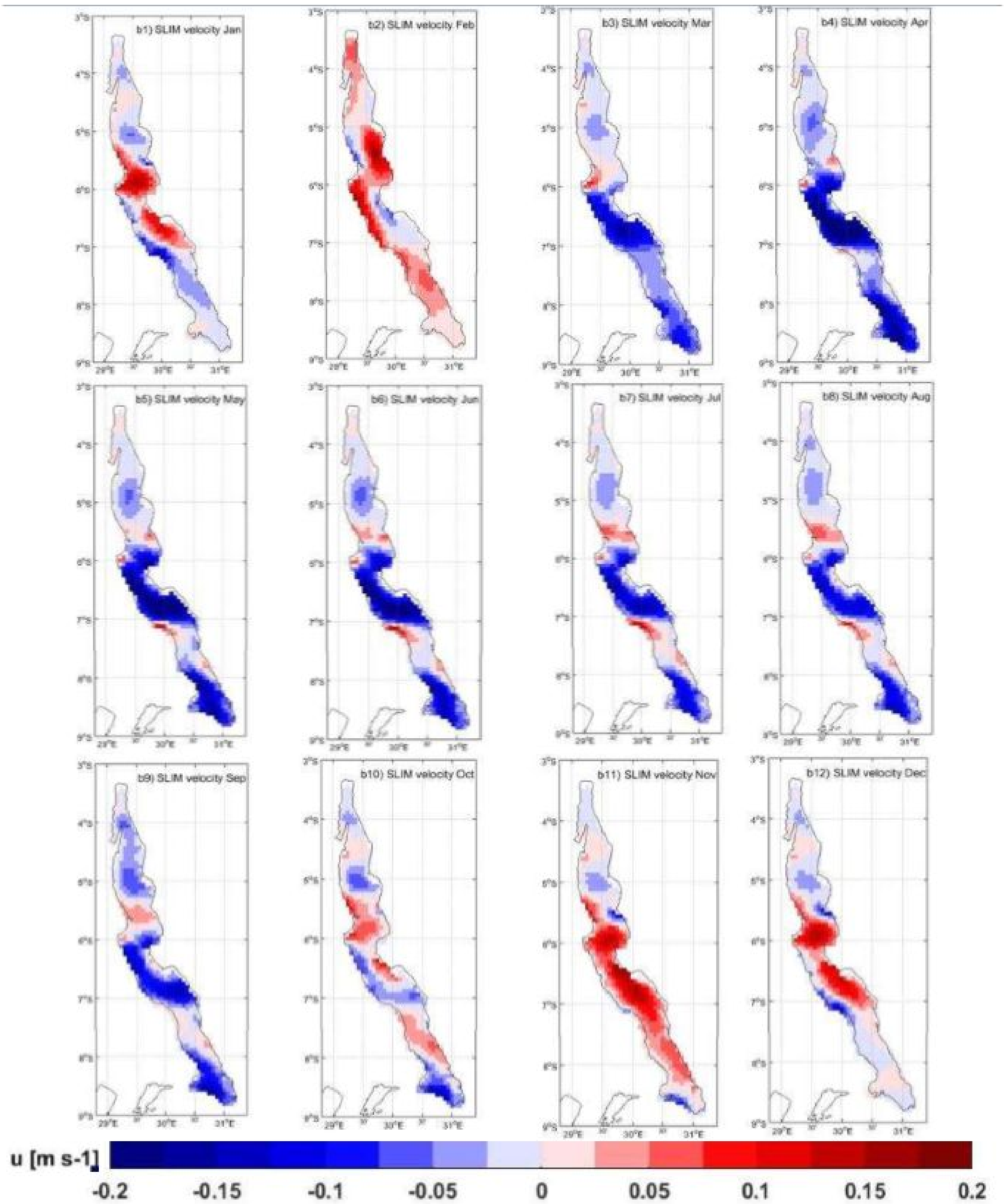

Illustration 4: Monthly average surface water velocity obtained from the EVAL simulation with positive (red) values showing northbound displacement and negative (blue) values showing southbound displacement.

<u>L310-313.</u> Such information should be conveyed within the Methods, not in the Results.

Thank you for this comment, we have moved this to the Methods paragraph.

<u>L313-314.</u> A basic investigation should be performed to understand such issue.

Thank you for this remark. To avoid any spin-up issues, the HIS and FUT simulations have been done with a 12 years spin-up period. For this, we know it is sufficient, as the model has been validated for a 5-year period (with 16 months spin-up included) by Delandmeter et al., 2018.

L314-316. This sentence is puzzling. Do the Authors imply that climate change has negligible effect on lake surface temperatures?

No, this sentence is not yet a climate change comparison. We mean that the evaluation simulation and the historical simulation, which both represent the present-day climate but were forced by different meteorology (a reanalysis and GCM downscaling, respectively), maintain the same average surface water temperature. This implies that replacing the meteorological forcing of the highest quality (i.e. reanalysis downscaling) with a lower-quality forcing (GCM downscaling) has only limited (negative) effect on the SLIM 3D simulation quality. As a consequence, we can use GCM downscaling as meteorological forcing for the present-day and future climate.

We now reworded this to:

> Fig. ~~6~~**4** shows **that the** ~~the difference in~~ average surface water temperature **closely agree** between the EVAL and HIS simulations **under present-day conditions** ~~(for their entire periods), where almost no difference can be observed~~. **This implies that replacing the meteorological forcing of the highest quality (i.e. a reanalysis downscaling) with a lower-quality forcing (i.e. a GCM downscaling) has only limited effect on the SLIM 3D simulation quality. As a consequence, the GCM downscaling can be used as meteorological input to drive SLIM 3D under present-day and future climate conditions.**

Fig. 6. What is the reason behind the sparse blue points? I suspect there is an error of some sort in data processing or in model results.

We now discovered that these pixels are an artefact of the postprocessing. Unfortunately, due to a computer crash, this figure could not be updated. As the message of this figure is still of high importance, we have decided to keep it in.

L320-321. How is the spatial IQR calculated? Which data are used to determine the distribution of results? At which time?

For the spatial IQR, the monthly mean temperature at each point has been calculated. Thereafter, each month has been averaged out over the full duration of the simulation. Per month, the IQR over the entire set of data points has been calculated. As per request of referee 2, the added value of Fig. 8, Fig. 9 and Fig. 10 is too small to remain in the manuscript, therefore, these have been removed. We have updated the text as follows:

> In Fig. ~~7~~**5**~~, Fig. 8, Fig. 9 and Fig. 10~~, the interquartile range (IQR) of both the HIS and FUT simulations are shown, based on **the** ~~both temporal and~~ spatial variations. Fig. ~~7~~**5** shows the monthly mean temperatures for both simulations, where the IQR on the spatial variation ~~in~~ **is**

indicated.**This has been done by calculating the monthly mean surface water temperature value over the full area, for each month, averaged over the 30 years of simulation period. Then, the same calculation was done for each point on the surface, and the IQR was calculated based on the variation between these results, and their spacial average.** This **result** tells us that at any point in time, the coldest zones of the FUT simulation are still warmer than the hottest ones of the HIS simulation. ~~Not only the spatial variation can be represented, Fig. 8, Fig. 9 and Fig. 10 show the temporal IQR at different locations, based on the variation of the monthly mean temperatures over the 30 years.Only in Mpulungu, which is located at the southern tip of the lake, the IQR is +/- 1 K, which is double the value of Bujumbara and Kigoma. However, in this area, the interseasonal temperature variation is also twice as much as in the rest of the lake, as this is the area where the thermocline climbs up first.~~

Fig. 11. What is the reason behind the sparse green points? See the comment above.

Thank you for this comment. These sparse points are a consequence of a postprocessing artefact and are no longer present in the revised manuscript. Please find below the new figure (in the revised manuscript Fig. 6).

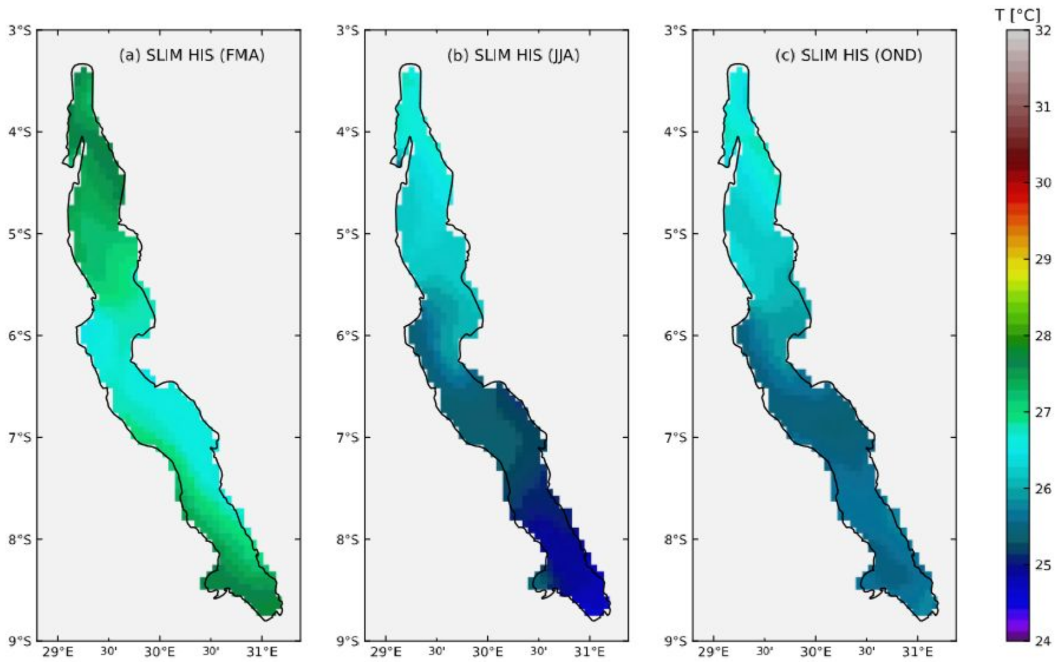

Fig. 6: Mean seasonal surface water temperature from the HIS simulation

<u>L352-353.</u> This sentence is not clear.

Thank you for this comment, we changed the sentence as follows:

> In addition, the ~~external~~ **atmospheric** heating **during the** ~~in~~ FUT **simulation** influences the water temperature ~~approximately~~ 75 m ~~during the dry season and~~ to 100 m **deeper than the heating in the HIS run. The 75 m extra occurs during the dry season, the 100 m occurs** during the wet season**.** ~~deeper than it was the case for HIS.~~

<u>Figs. 14 and 16</u> Why do numerical instabilities always arise in January? See the comment above.

See the comment above, please find below the new figures. Fig. 14 and Fig. 15 are merged to Fig. 9; Fig. 16 and Fig. 17 are merged to Fig. 10.

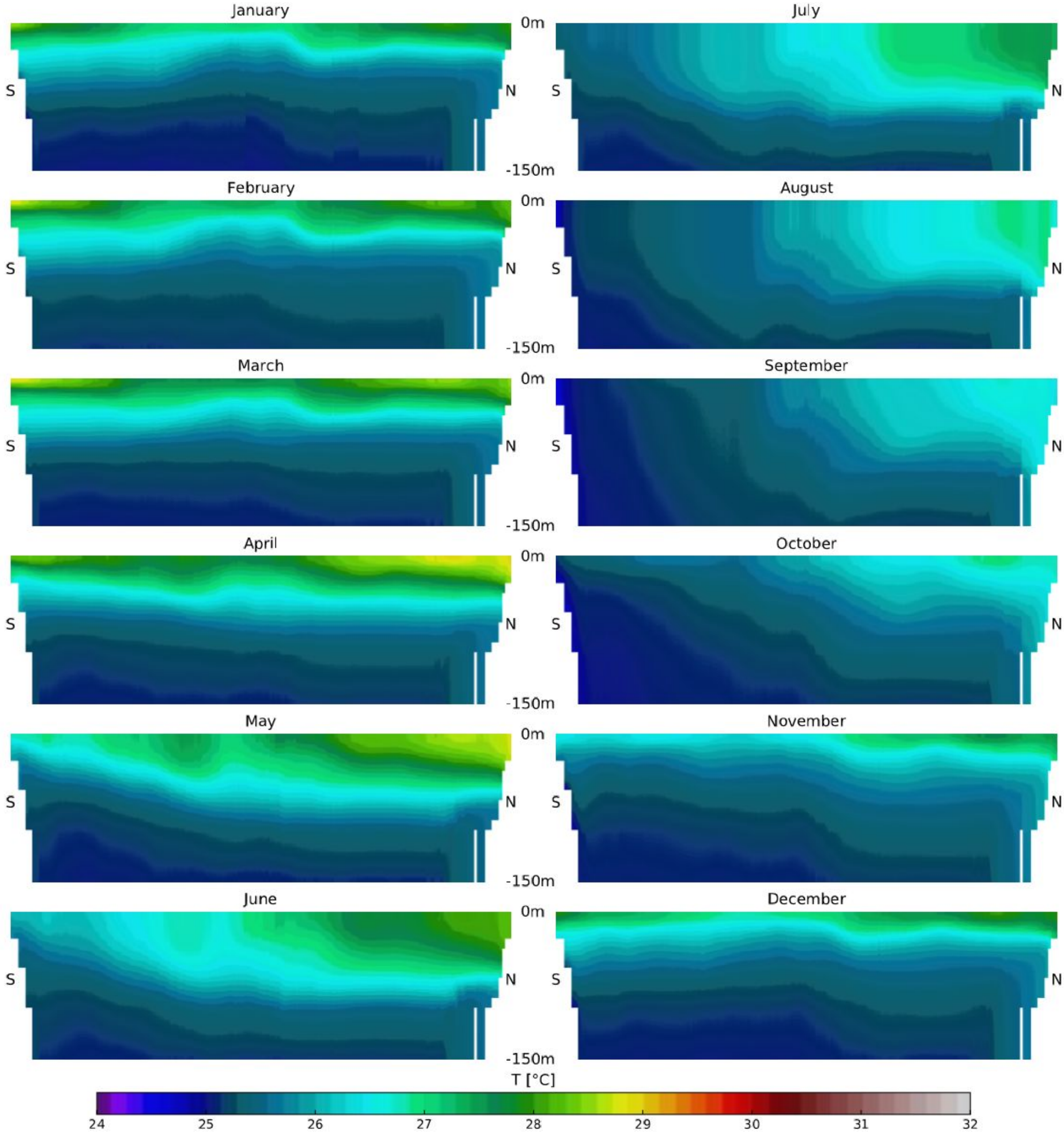

Fig. 9: Monthly water temperature cross-sections (as defined in Fig. 1b) obtained by the HIS-simulation.

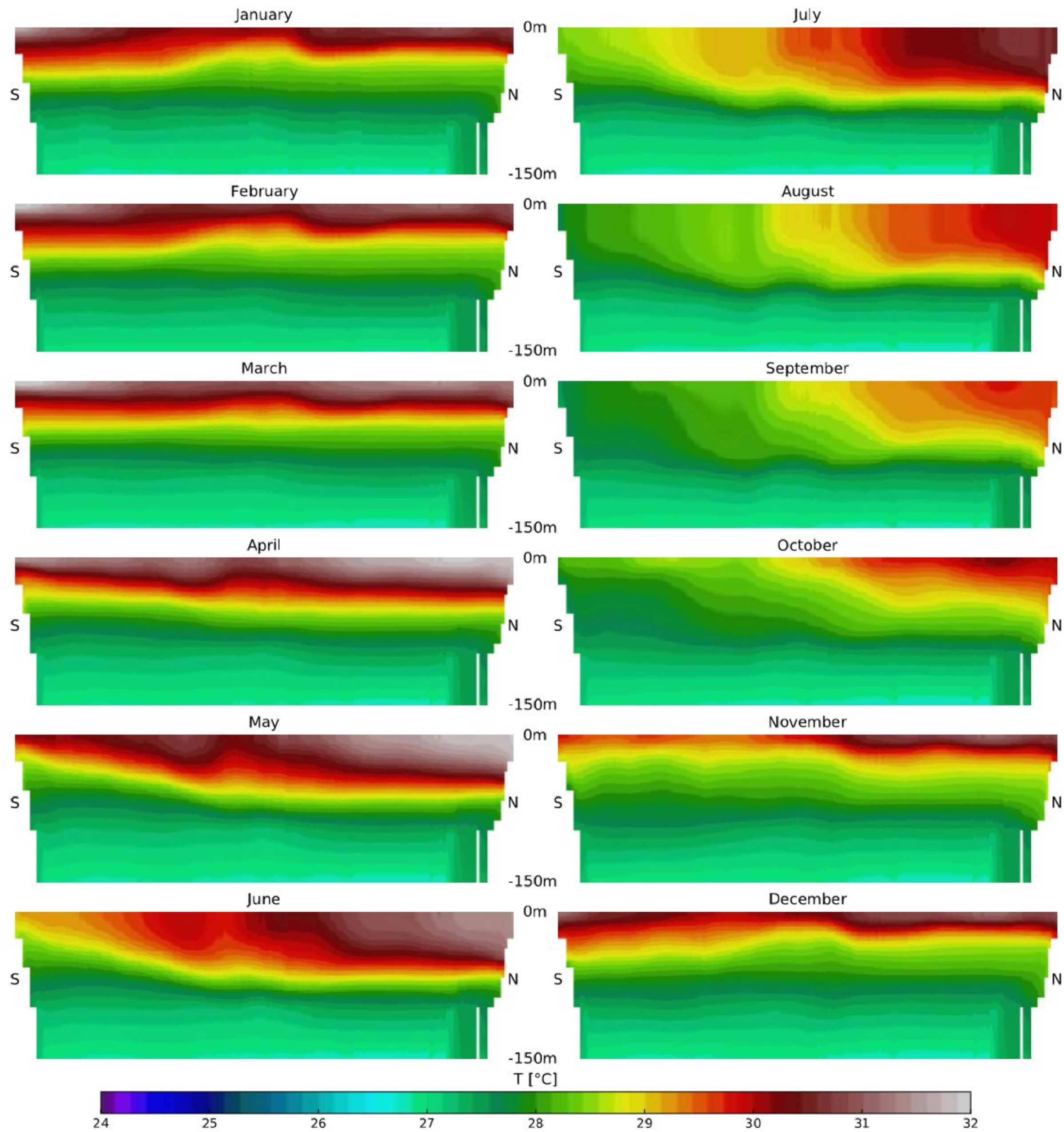

Fig. 10: Monthly water temperature cross-sections (as defined in Fig. 1b) obtained by the FUT-simulation.

L382. Which kind of additional validation was performed in this work which confirms that the model can be used for climate change projections?

Thank you for this comment. As the model is still quite new, so far no additional validations have been done.

L399-400. How is this possible? ARC Lake provided observations of surface temperature only.

Thank you for this comment. Because the upwelling of the thermocline is visible at the surface as a colder water mass moves from south towards the centre, and back to the south. The part where the colder water moves back to the south goes faster in ARC Lake than in the simulation, meaning that the thermocline reinstates faster in reality than what we simulate. We have added this as follows:

> The comparison **of the surface water temperatures** with ARC Lake confirms this statement. **However, when observing the surfacing and submerging of the cold water mass in ARC Lake, and comparing it with the simulated SLIM 3D thermocline movement, it** ~~but~~ indicates that the reconstruction of the thermocline can still be improved.

L402-404. This sentence misses a verb.

Thank you for pointing this out, we have modified the sentence as follows:

> However, studies have shown that the heat flux will only be properly represented, when local values of air density, kinematic air viscosity and latent heat of vaporization **are included in the model** (Verburg & Antenucci, 2010).

Anonymous Referee #2

General comments: The authors have investigated how the temperatures in Lake Tanganyika will evolve in response to climate change. The evolution of lakes thermal structure under climate change has been largely investigated over the last decades with countless number of publications. Yet, African lakes remain poorly investigated. Lake Tanganyika is especially interesting given his very specific features. However, I do not think this paper reaches the scientific standard to be published at this stage. There is no presentation of the model, no calibration and validation of the model (this is an issue regarding reproducibility). Figures are barely discussed. I counted for instance 3 lines of text for 4 figures. I encourage the authors to rework the manuscript in order to strengthen the message. Specific comments are provided in the annotated manuscript.

Thank you for this feedback. We agree on the importance of this work and thus implement the suggested improvements to the manuscript. Delandmeter et al. (2017) comprehensively presented the model. Since this study uses SLIM in the exact same setup, there is no need to repeat all the details of the model here, but you are right that a better overview of the model, including details over the external forcings, numerical parameters (mesh size, time step) should be provided. A description of the model has now been added (see below for the mesh and answer to Referee #1 ***L193-195.*** *for forcings) to provide more insight to the reader. To expand the discussion and interpretation of the results, Piet Verburg, an expert on Lake Tanganyika, joined the author team.*

L14-17. Rephrasing of the sentence

Thank you for this comment, we rephrased the sentence as follows:

> Despite the vital importance of Lake Tanganyika ~~and other African inland waters~~ for local communities **and the reported effects of climate and weather on its ecosystem functioning, fish availability and water quality**, very little is known about the **potential**

> impacts of future climate change on the functioning of ~~these~~ **this** lacustrine system~~s~~. ~~This is remarkable, as projected future changes in climate and associated weather conditions are likely to influence the hydrodynamics of African water bodies, with impacts cascading into ecosystem functioning, fish availability and water quality.~~

L20-21. Instead say what can be reproduced with 3D and how the current mixing system works.

We have modified the text as follows:

> The ~~simulated inter~~seasonal variability of the lake with this 3D model ~~explains how the current mixing system works~~ **allows us to reproduce the temperature variations and indicate that the mixing is driven by an upwelling of the thermocline, moving from the south to the center of Lake Tanganyika**.

L26. Use °C instead in the manuscript.

Thank you for this suggestion, we now consistently use °C throughout the revised manuscript.

L27. Unclear. Which mixing mechanism?

We have changed this sentence as follows:

> ~~This temperature-induced stratification fully shuts down the earlier explained mixing mechanism.~~
>
> **This temperature-induced stratification prevents the surfacing of the thermocline, eventually shutting down upwelling.**

L30. I would use present tense here.

Thank you for this comment, we have rephrased the sentence as follows:

> ~~Besides large-scale consequences~~ **Climate change** ~~will also impact~~ **also affects the functioning of inland water bodies.**

L38-39. Reference needed.

This sentence has been removed as the quality of the source was not clear.

Fig. 1. Please add more information.

Thank you for this suggestion. We now merged figure 1 and 2 of the original manuscript. The caption of the new figure 1 reads:

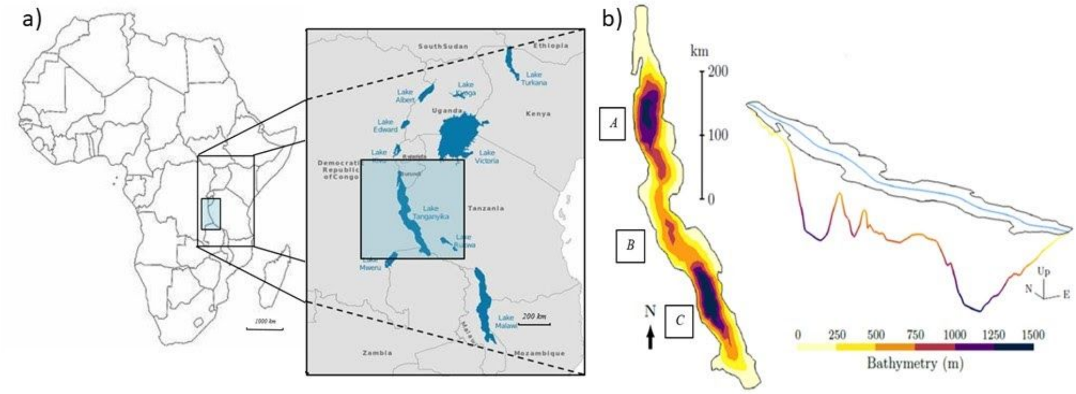

Fig. 1: **(a)** Location of Lake Tanganyika **(3°20'S - 8°48'S; 29°12'E - 31°12'E), surrounded by Burundi, Tanzania, Zambia and DR Congo; (b) Cross section Lake Tanganyika with basins A: Kigoma, B: Kungwe, C: Kipili (Delandmeter et al., 2018)**

L59. Maybe define convection here.

We have modified added convection as follows:

> A dryer atmospheric boundary layer ~~favours~~ **enhances** evaporation from the surface water, and since this is an endothermic reaction, the water surface temperature decreases, which ~~allows warmer water from below to rotate upwards, increasing the mixing.~~ **drives the natural convection. This means that the different temperatures in the water cause density variations, leading to buoyancy forces. In this case, it will lead to upwelling of the underlying warmer water, driving the mixing mechanism.**

L63-65. This should be moved to the conclusion.

Thank you for this suggestion. In the revised manuscript we moved this text to the conclusion section.

Table 1. Alphabetical order would be more useful.

Thank you for this suggestion. We agree and changed the table to alphabetical order.

Acronym	**Description**
ARC	Along track scanning radiometers Reprocessing for Climate
CLM	Community Land Model
CMIP5	Coupled Model Intercomparison Project

CORDEX	Coordinated Regional Climate Downscaling Experiment
ENSO	El Niño-Southern Oscillation
EVAL	Evaluation simulation
FUT	Future simulation
GCM	General circulation model
HIS	Historical simulation
IQR	Interquartile range
ITCZ	Intertropical Convergence Zone
MPI-ESM-LR	Max-Planck-Institut für Meteorologie Earth System Model running on low resolution grid
NCAR LSM	National Center for Atmospheric Research Land Surface Model
PFT	Plant Functional Type
RCP	Representative Concentration Pathway
SLIM	Second-generation Louvain-la-Neuve Ice-ocean Model

Table 1: List of acronyms (in **alphabetical** order ~~of appearance~~)

L92. Approximate length of 1800 km or 1828 km.

Thank you for this comment. As the shoreline length is not always well defined, we changed the phrase as follows:

> [...] an approximate length of ~~1828~~ **1800** km.

Fig. 2. I would merge with Figure 1

*Thank you for this suggestion, in the revised manuscript we merged both figures and display them as Fig 1a,b (see your comment **Fig. 1**).*

L106. Not needed reference.

Thank you for this comment. The reference has been removed.

L115. Add also the formal name.

Thank you for this comment. We would like to point out that the full name is given on L111.

L131-135. Can be simplified. You don't need to introduce Fr as you do not use it after.

Thank you for this suggestion, as referee #1 also had comments on this, the section has been removed in the revised manuscript:

> ~~The Froude number represents the ratio of inertia forces to gravity forces, which leads to , where and In the south and north of the lake, the Froude number is mainly < 1, which implies orographic blocking, while the central parts of the lake allow overflow of the near-surface (south)easterlies (Docquier et al., 2016).~~

L147. Do you actually use rain as input data in SLIM?

Good point, and thank you for pointing it out. We don't, so technically this section is not explicitly used in the rest of the work. However, we would suggest keeping it, as it provides a broader understanding of the lake's meteorological situation. For more information regarding the input parameters, we kindly refer to our answer on comment ***L193-195.*** *of reviewer 1.*

L157. This sentence is unclear and should be rephrased to gain in clarity.

We have rephrased the sentence as follows:

> ~~Due to the high heat capacity of water, lake rich regions experience – like coastal regions – a more moderate climate since the lakes will act as a buffer in transitioning between warmer and colder periods.~~ **As water has a high heat capacity, lakes can act as a buffer towards the atmosphere, while transitioning between warmer and colder periods. This is most known as the explanation for coastal areas' milder winters, but is also present in lake-rich regions.**

L177. No, the thermocline can't behave as an internal wave.

We have changed this sentence to:

> The thermocline ~~dynamics mainly behave as an internal wave~~ **is subject to a seiche**, governed by the topography and the atmospheric pressure and wind stress (Docquier et al., 2016; Verburg et al., 2011).

L183. The strong differential cooling in Lake Tanganyika is a key feature (Verburg et al., 2010) that is barely discussed here.

We thank the reviewer for pointing this out. We have brought our text in line with the findings of Verburg et al (2011), probably the paper that the reviewer meant. The findings regarding the *differential cooling and circulation pattern of Verburg et al (2011) were confirmed by modelling by Delandmeter et al 2018, now also referenced.*

L185. Grid size, number of cells, time stepping, input parameters, I do not see any of the minimum information needed for a publication. As it is, there is no way to reproduce any of the results.

You are right that the model setup is not sufficiently documented in the paper, although it is the same as in Delandmeter et al. (2018). A comprehensive model description is not repeated in the revised manuscript, but key elements are now provided to help the reader to have a good understanding of the model without need to read Delandmeter et al. (2017):

> The 3D component of the Second-generation Louvain-la-Neuve Ice-Ocean Model (SLIM 3D, www.slim-ocean.be) is a baroclinic model that solves the hydrostatic flow equations under the Boussinesq approximation by means of a discontinuous Galerkin finite element method on an unstructured grid (Blaise et al., 2010; Kärnä et al., 2013; White et al., 2008). It has been applied to coastal waters such as the Burdekin plume in the Great Barrier Reef (Delandmeter et al., 2015), the Columbia River region of freshwater influence (Vallaeys et al., 2018), the Congo estuary (Vallaeys et al., 2020 (submitted)) and Lake Tanganyika (Delandmeter et al., 2017).
>
> ~~The most recent version of SLIM 3D runs with an estimated surface heat flux for which a relaxation term in the upper layer of the lake is use as defined in Delandmeter et al. (2017). With this relaxation term, the simulated heat will be held in the lake for a certain period, after which it is released back into the air.~~
> ~~Input data for this model comes from COSMO-CLM² (see 3.2 COSMO-CLM²) and will provide the required temperature and wind speed forcing.~~
>
> **In this study, SLIM 3D is applied to Lake Tanganyika in the exactly same setup as that of Delandmeter et al. (2017), in which the model is comprehensively described. The only external forcings to the model are the surface wind stress and surface heat flux. The first one is prescribed using data from COSMO-CLM². The second one is parameterized using a relaxation term towards the surface temperature, which is also available in COSMO-CLM². The choice of the relaxation term, requiring the surface temperature only, has the advantage of simplicity and stability. Other parameterizations require more input data and, more complex, they can lead to spurious results, especially when spacial or temporal scales differ between the lake and surface model. The relaxation is controlled by two parameters: z_r, the distance to the surface until which it is applied and tau_r, the relaxation time. z_r is set to 12 m, corresponding to the photic depth (Descy et al., 2016) which is used as a proxy to the water column affected by solar radiation and other fluxed. After calibration, tau_r is set to 10 days (Delandmeter et al., 2017).**

To already answer your questions about the numerics, the domain is discretized into a mesh of about 13 000 triangular prisms, with a horizontal resolution of 10 km. The vertical resolution is varying, with horizontal levels located at 0, 2 and 5 m, then every 10 m down to 100 m, and deeper at 150, 200, 300, 500, 700, 950, 1200, 1400 and 1500 m. The time step is set at 10 minutes.

L188. One reference for this sentence is enough.

We adopted this suggestion. While SLIM 3D was built in various steps corresponding to those different papers, we only keep the last one (Kärnä et al., 2013). The reader can find references to the other papers through that last one.

L193. Maybe you can develop a bit why this relaxation term is needed.

In the revised manuscript we now provide a more detailed description of the SLIM model including the relaxation term. We refer to our response to a previous comment for the revised text.

L219-220. What is MPI-ESM-LR GCM?

MPI-ESM-LR GCM stands for Max-Planck-Institut für Meteorologie Earth System Model running on low resolution grid global climate model. It is given in the acronym table, but it should indeed be included in the text on first appearance. We have added it as follows:

> The second COSMO-CLM² simulation represents a 33-year integration (1981-2010) using information from the **Max-Planck-Institut für Meteorologie Earth System Model running on low resolution grid global climate model (**MPI-ESM-LR GCM**)** as global boundary conditions.

L222. HIS simulation is not defined.

Thank you for this comment, it should indeed be clarified on first use of the abbreviation. The same goes for FUT and has been included in the manuscript as follows:

> Comparison of the **historical (HIS) and future (FUT)** simulations enables assessment of the projected future changes in climate under a high emission scenario without mitigation **(see Table 2 for details on these simulations).**

L231. Lake Tanganyika is a canonical example of lakes with strong variability. I do not see the point of evaluating the benefit of 3D model vs 1D model for this lake.

We agree with the reviewer that a single 1D model simulation cannot represent horizontal surface temperature variations. However, in this study we perform an array of 1D simulations that cover the entire lake and which allow for the study of horizontal temperature patterns over the lake. In particular, the 1D model FLake, or in other words the single-column model, was run once for every grid cell in a ~7 x ~7km grid (0.0625° x 0.0625°) covering the entire Lake Tanganyika. The model thus represents the lake through a set of independent vertical columns, that is, there is no horizontal heat exchange below the surface. But each column is subject to its own, local meteorological forcing, leading to different hydrothermal conditions at different locations in the lake. In particular, this approach captures the effect of the more pronounced seasonal cycles of temperature and atmospheric humidity (i.e.

increasing dry season - wet season contrast) towards the southern end of Lake Tanganyika, leading to spatially and temporally varying surface heat fluxes, water temperature and mixing dynamics.

In the revised manuscript, we now provide a clear description of FLake model setup and clarified the motivation for this comparison between SLIM 3D and FLake:

> The 1D model that will be used to evaluate the benefits of a 3D model over a 1D model is FLake. FLake is a one-dimensional model, which is interactively coupled **at the subgrid-scale level** to COSMO-CLM². **As such, FLake simulates a single-column water temperature profile in every COSMO-CLM² grid cell with non-zero lake area fraction. This approach enables the study of horizontal water temperature variations caused by spatially-varying meteorological conditions, but ignores horizontal water and heat transfers below the surface. [...] As a widely-used parameterization scheme in numerical weather prediction systems *(e.g. Mironov et al., 2010; Balsamo et al., 2012)*, climate models *(e.g. Mironov et al., 2010; Martynov et al., 2012)* and climate reanalyses *(Woolway and Maberly, 2020; Herschbach et al., 2020)*, FLake encompasses a relatively detailed representation of the surface energy budget. This enabled the model to become a reference tool for large-scale climate change impact assessments on lake temperatures and mixing regimes (Woolway and Merchant, 2019; Maberly et al., 2020; Woolway and Maberly, 2020).**

L241. Please be specific and indicate what you do regarding ARC Lake for Lake Tanganyika.

Thank you for this comment. We modified the paragraph as follows:

> ~~ARC stands for Along track scanning radiometers Reprocessing for Climate (Thiery et al., 2015). The radiometers are sensors which are part of the European Space Agency's Earth Observing missions. The aim of the ARC Lake is to derive observations of lake surface water temperatures and lake ice covers of major lakes for 1991 until 2010 (http://www.laketemp.net/home_ARCLake/).~~
>
> **The Along-Track Scanning Radiometers Reprocessing for Climate applied to Lakes (ARC Lake; MacCallum and Merchant 2012) provides satellite-based observations of lake surface water temperatures and lake ice covers of major lakes for 1991 until 2010 (http://www.laketemp.net/home_ARCLake/). All radiometers considered by ARC Lake are part of the European Space Agency's Earth Observing missions. A previous analysis of ARC Lake data over Lake Tanganyika highlighted the very close agreement between the ARC Lake satellite product and multi-year in situ lake surface temperature observations at two locations in the lake (Thiery et al., 2014a), demonstrating that the ARC Lake product represents a reliable observational reference product for this lake. The lake surface water temperatures given by ARC Lake are therefore used to assess the skill of both the SLIM 3D (EVAL simulation, see below) and the FLake model.**

L256. I do not see a model validation here.

Apologies for the confusion; we in fact performed a model evaluation, whereby we compare two model simulations (one with Flake and one with SLIM) to an independent observational reference *product (ARC Lake). We now reworded ‘model validation’ to ‘model evaluation’ throughout the revised manuscript.*

Concerning the model validation, this was performed in Delandmeter et al., (2017), where the model reproduced the vertical profile of the temperature evolution at two different locations for a period of two years. This comparison highlighted the ability of the model to reproduce the expected stratification, which is crucial in the dynamics of Lake Tanganyika, as well as modelling events when the thermocline outcrops at the surface. Since the model is used here in the same configuration using the same external forcing, the validation still holds for the present study.

L260. I do not see the point of comparing a 3D model with a 1D model in a system with permanent lateral inhomogeneities.

*We kindly refer to our response to comment **L231** of reviewer 2.*

L261. This is not a model validation.

*Thank you for pointing this out. As mentioned in our response to comment **L256**., we have renamed this to model evaluation.*

L269. If the point is to show cold and warm bias, then, you can show surface water temperature anomalies.

In figure 3a-f we plot the difference between the absolute temperature in the reference product (ARC Lake) and the model simulation (FLake and SLIM), which represents the model bias during each of the three considered seasons. Plotting the bias of the seasonal anomalies in both products would mask a potential existing systematic bias in one of the model simulations (e.g. the weak warm bias in SLIM). For this reason we decided to show the bias in the absolute values per season.

L286. I do not see any validation of the model with in-situ observations. It is a strong deviation from best practice that should be at the minimum carefully motivated.

While we do not compare our model simulations with in-situ observations, we evaluate our model output against satellite-based lake surface temperature data (ARC Lake), which was found to be of high quality in an earlier assessment for Lake Tanganyika.

*As we note in our response to comment **L231** by reviewer 2, our 1D simulations are column-wise representations of the water temperature profile on a 0.0625° x 0.0625° grid, that is, they represent the three-dimensional water temperature structure of Lake Tanganyika but thereby ignore horizontal heat transport occurring within the lake (which is why we call it a 1D model). As such, the FLake simulations at one particular location in the lake can be compared against both in-situ and remote-sensing based lake surface temperature estimates. This comparison has already been conducted for two locations in Lake Tanganyika: Kigoma (northern basin; 4.858S, 29.598E) and Mpulungu (southern tip; 8.738S, 31.048E; Thiery et al., 2014a). The results of this evaluation shows that FLake captures the annual mean lake surface temperature as well as the phase of the seasonal cycle, but overestimates the amplitude of the seasonal temperature cycle (Illustration 3). More details* *of this evaluation procedure are provided in Thiery et al., 2014a. Interestingly, the in-situ and satellite-based temperature observations show a marked correspondence, showing that the ARC Lake product can be used as a reference product in the comparative evaluation of FLake and SLIM 3D across all lake pixels (Figure 3 in the original manuscript). GIven the limited availability of in-situ water temperature data and the apparent high quality of the ARC Lake satellite product, we decided to perform the model evaluation using ARC Lake as a reference product.*

We now added an explicit reference to prior evaluation efforts and a motivation for the use of ARC Lake as an observational reference in the revised manuscript:

> **A previous analysis of ARC Lake data over Lake Tanganyika highlighted the very close agreement between the ARC Lake satellite product and multi-year in situ lake surface temperature observations at two locations in the lake (Thiery et al., 2014a), demonstrating that the ARC Lake product represents a reliable observational reference product for this lake. The lake surface water temperatures given by ARC Lake are therefore used to assess the skill of both the SLIM 3D (EVAL simulation, see below) and the FLake model.**

L289-290. I do not understand. What are those numerical instabilities? Why aren't they affecting the mixing? Are they long lasting?

Thank you for pointing this out. We discovered that the instabilities are an artefact of the post-processing procedure and are no longer present in the updated figures. Unfortunately, due to a computer crash, we could not redo the EVAL figures. Therefore, we have decided to remove Fig. 4 and Fig. 5 from the manuscript.

L291. Please rephrase.

Thank you for this comment, we have rephrased the sentence as follows:

> The ~~variations~~ **magnitude of the seasonal temperature fluctuations** are expected to be ~~varying with~~ latitude-**dependant**, which can also be seen in our results (Kraemer et al., 2015).

L292. I can't understand this paragraph. What do you want to highlight? There are no references to figures.

*The main goal of this paragraph is to describe the current situation of Lake Tanganyika based on the model results shown in Fig. 4 and Fig. 5. As mentioned in your comment **L 289-290**, we have removed these figures from the manuscript. The same analysis can be done based on Fig. 14 and Fig. 15, which have been merged (Fig. 9 in the revised manuscript) and the reference has been added as follows:*

> When combining this with the high average atmospheric temperature, induced by its equatorial location, it explains why the highest surface water temperatures along the lake can be found here **(see Fig. 9)**.

Fig. 4-5. Figures 4 and 5 should be merged. You can also reduce the size to make it fit over one page.

As mentioned above, Figures 4 and 5 have been removed. However, in line with this suggestion, we have merged Fig. 14 with Fig. 15 and Fig. 16 with Fig. 17. Please refer to comment ***Figs.14 and 16*** *of referee 1 for the revised figures.*

Fig. 5. Kelvin degrees are not practical units for environmental studies. I would follow with a thick black line the thermocline to clearly highlight the evolution of the thermal structure and the lateral variability.

Thank you for this comment. As mentioned above, we now express all temperatures consistently in °C. Indicating the thermocline with a thick black line, however, will be difficult as there is no exact definition of the exact depth of the thermocline and the temperature gradient is very weak in Lake Tanganyika (in contrast to e.g. midlatitude lakes), making it difficult to automatically compute thermocline depth based on a vertical temperature gradient.

L302. Do you actually show the wind field?

We have added the figure below from Docquier et al., 2016 to the manuscript in section 2.2 as shown below:

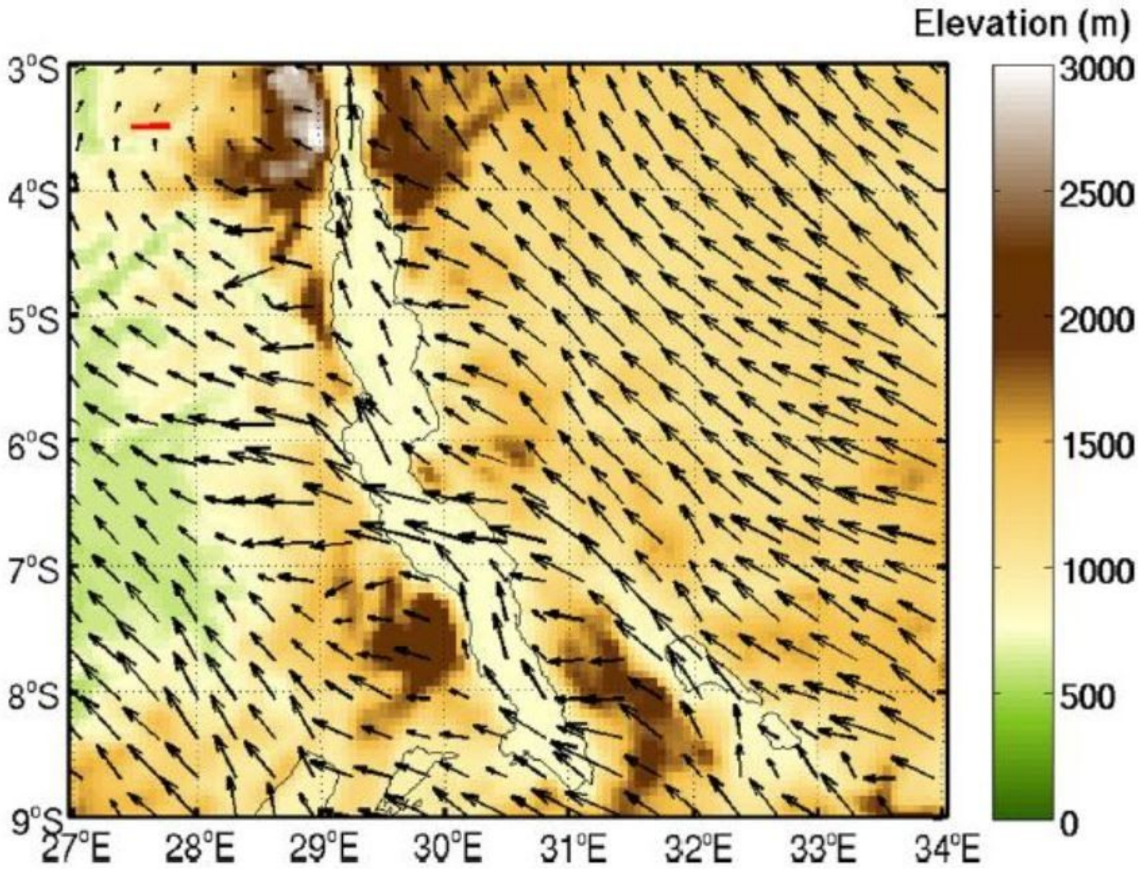

Fig. 2: Wind path and surface elevation map. The red line (upper left corner) shows the scale of the wind speed equal to 3 m s-1 (Docquier et al., 2016 - Fig. 9).

<u>L304.</u> Due to what? As it is written, it is only speculative.

This whole paragraph has been removed and text brought in line with the findings of Verburg et al. 2011.

~~The southern part of the lake has deeper mixing due to the bigger contrast between the dry and wet seasons. This means that although the total average temperature of the water column is not that different, the surface water temperature will be lower. The same reasoning goes for the centre of the lake, which is the most turbulent part due to the internal water transport, combined with the presence of strong winds due to the flat landscape. The combination of the latter will also result in deeper mixing, reducing the average surface water temperature. In Fig. 4 and Fig. 5, it is also shown that the middle of the lake has weaker stratification due to this.~~

The southern part of the lake has deeper mixing due to the effect of the strong southerly winds during the cool season. As a result, the minimum surface water temperature is lower at the south end of the lake.

L315. **Seasonal?**

Indeed, the plots shown are seasonal averages. We have updated the text as follows:

> Fig. ~~6~~**3** shows the difference in average **seasonal** surface water temperature between the EVAL and HIS simulations (for their entire periods**, averaged for FMA, JJA and OND**), where almost no difference can be observed.

L315-316. **What is the quantitative assessment to say this?**

We have settled on the margin of +/- 0.5 °C to make this statement.

> Fig. 3 shows the difference in average seasonal surface water temperature between the EVAL and HIS simulations (for their entire periods, averaged for FMA, JJA and OND), where almost no difference **(variations smaller than +/- 0.5 °C)** can be observed.

Fig. 6. **What are the cold pixels that we see?**

We now discovered that these pixels are an artefact of the postprocessing. Unfortunately, due to a computer crash, this figure could not be updated. As the message of this figure is still of high importance, we have decided to keep it in.

Fig. 6. **We cannot understand the figure based on the caption. Please provide the necessary details regarding what is plotted.**

We have updated the manuscript as follows:

> Fig. ~~6~~**4**: Seasonal relative surface water temperature plots**, comparing the HIS and EVAL surface water temperatures for the three selected seasonal periods (FMA, JJA and OND).**

Fig. 7-9. **Combine Figs 7-9 in one smaller figure with subpannels. There are 4 lines to discuss 3 figures. Either develop on why this figure is important, what do you see, what do you conclude, or remove the figures. This is a general comment. In my view, the little discussion based on Figs 7-9 can be done based on Figs 11-13. I suggest to remove Figs 7-9 and provide more in-depth analysis of the remaining figures.**

Thank you for this suggestion. There were actually four figures, namely Figs 7-10. Indeed, there is little discussion, especially on the temporal IQR figures. Therefore, we removed Figs 8-10 to reduce the amount of figures in this paragraph. The discussion will be expanded in the revised manuscript, including a comparison with similar findings from Verburg and Hecky, 2003 (see Illustration 5).

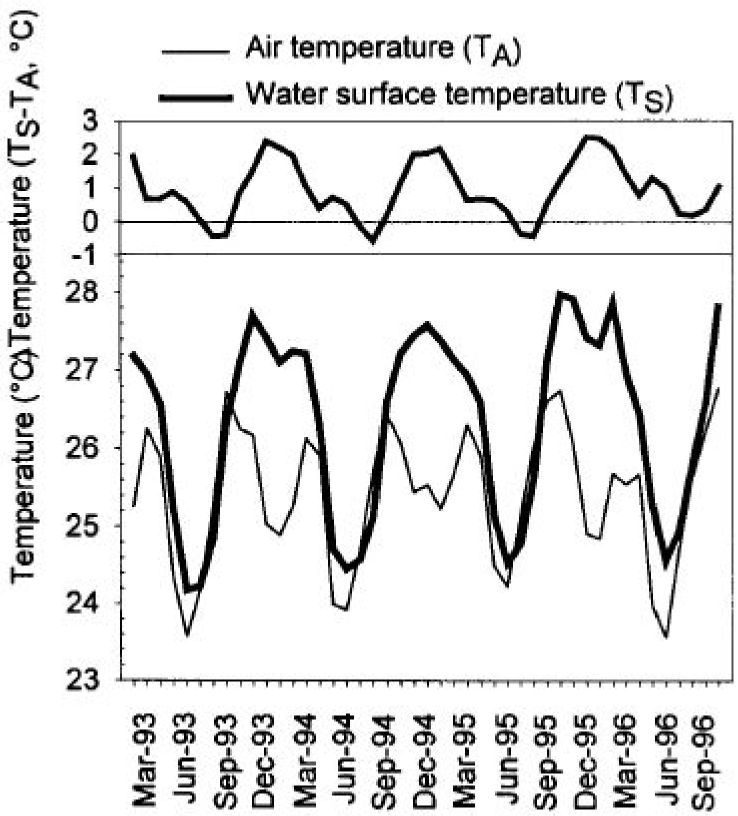

FIG. 9. Monthly mean temperature at 1 m depth (T_S) and of the air 2.6 m above the lake surface (T_A) off Mpulungu. In the upper panel the difference between water and air temperature (T_S - T_A) is plotted.

Illustration 5: Fig. 9 from Verburg and Hecky, 2003

<u>L338.</u> What do you mean by "wave"? This is a physical dynamical process traveling up North?

If indeed the effect is there (as discussed, it is within the margin of error),, this is the remainder of the initial thermocline upwelling. We have updated the text as follows:

> A small wave of increased heat can be observed, travelling from south to north before the dry season, but since the average temperature difference is at the minimal scale, this might be within the margin of error as well. **If this phenomena is actually there, it is the remainder of the initial thermocline upwelling.**

<u>Fig. 13.</u> Why do you use a -5 +5° scale here? A 2°C-5°C scale would provide more details. Also we do not expect any lake cooling over the coming century. Same comment as above, 4 figures discussed in 3 lines.

Thank you for this suggestion, the scale will be 1.5 °C - 3.5 °C in the next version of the manuscript. We have also rescaled Fig. 18 and Fig. 19 according to this suggestion and merged them according to your earlier suggestion. The discussion has been brought in line with the findings of Verburg et al., 2011 and Delandmeter et al., 2018. As the new color scale shows non-uniform warming, the discussion will be expanded significantly, for instance to reflect the suggested faster warming in the northern half of the lake in October-December. These model observations may tie in with changes in the horizontal circulation pattern described by Verburg et al., 2011 caused by climate warming.

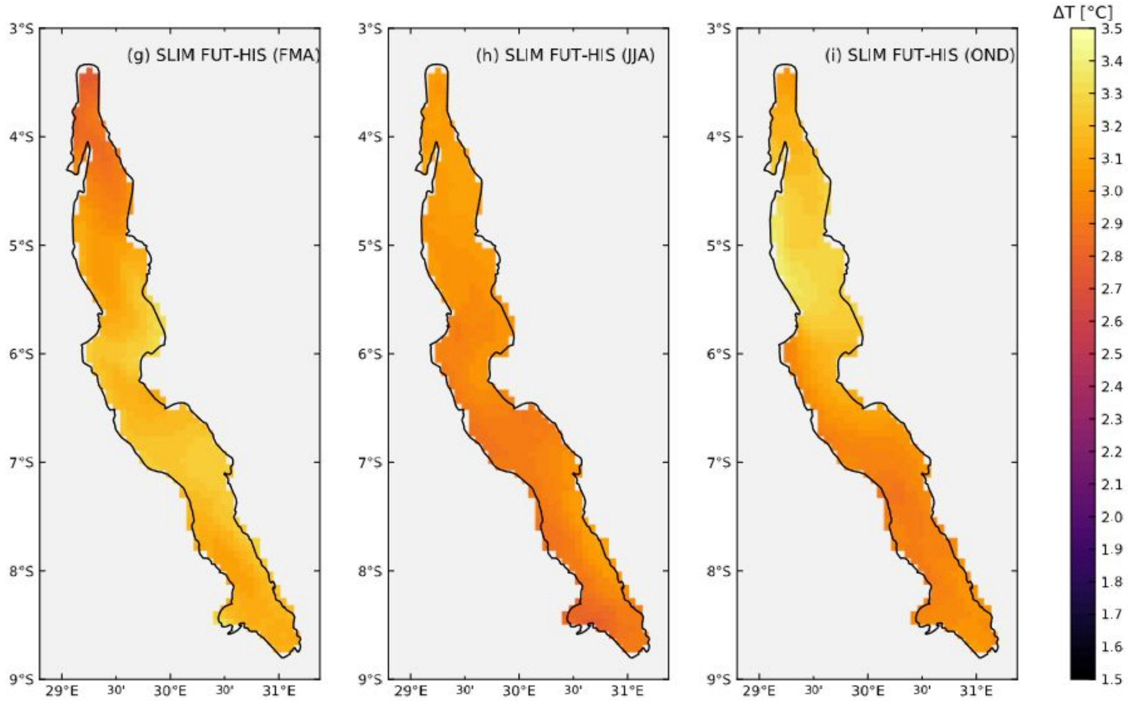

Fig. ~~13~~ **8**: Relative increase in seasonal surface water temperature (FUT - HIS)

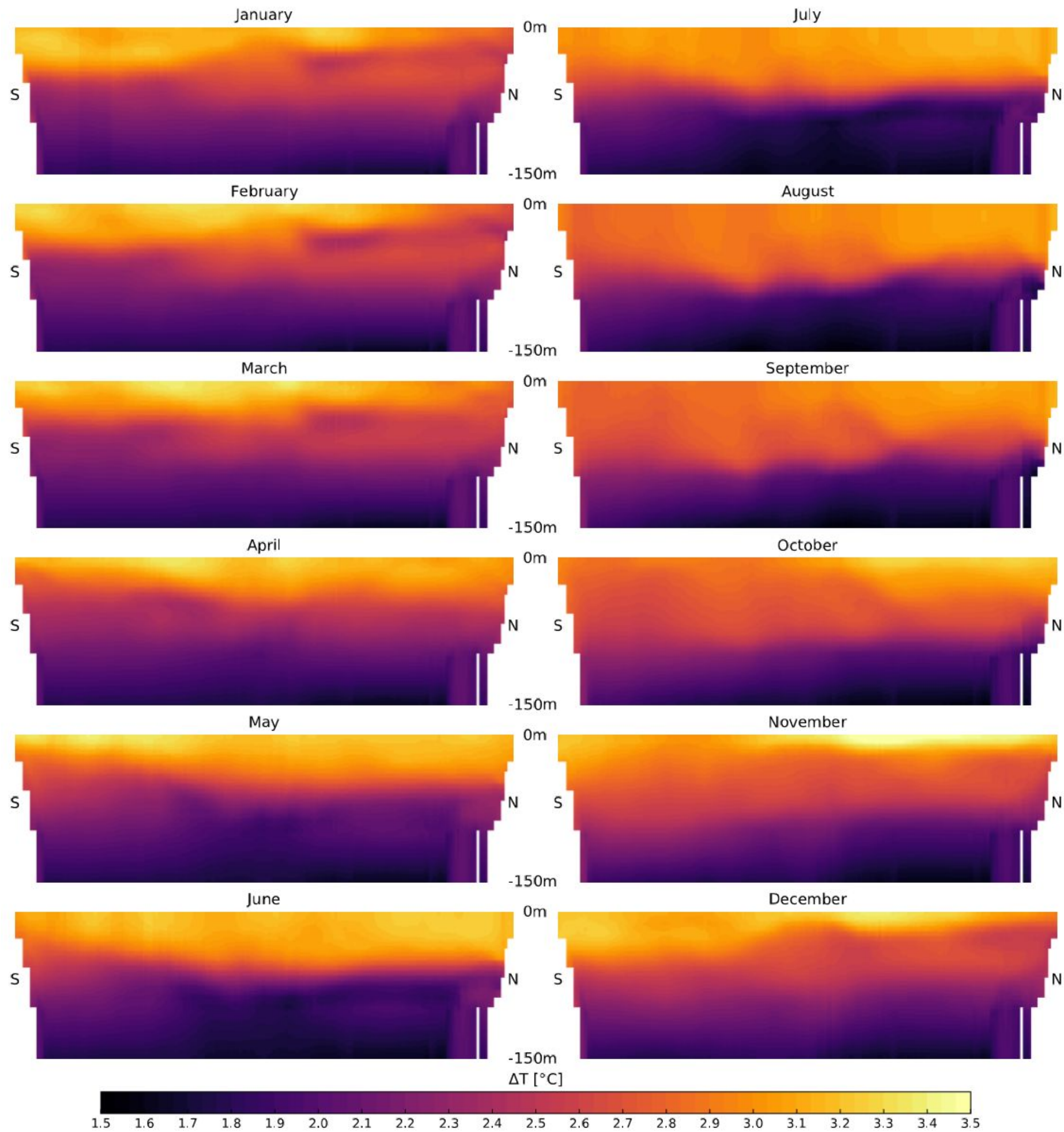

Fig. 11: Monthly relative increase in water temperature cross-sections (as defined in Fig. 1b) obtained by the difference between the FUT- and HIS-simulation.

References

Balsamo, G., Salgado, R., Dutra, E., Boussetta, S., Stockdale, T., & Potes, M., 2012, On the contribution of lakes in predicting near-surface temperature in a global weather forecasting model. Tellus A: Dynamic Meteorology and Oceanography, 64(1), 15829.

Coulter, G, W., (2003), Hydrological changes in relation to biological production in Southern Lake Tanganyika. Limnology and Oceanography 8: 463-477. doi: 10.4319/lo.1963.8.4.0463.

Docquier, D., Thiery, W., Lhermitte, S., van Lipzig, N.P.M., 2016, Multi-year wind dynamics around Lake Tanganyika, Climate Dynamics, 47(9), 3191-3202.

Frieler, K., Lange, S., Piontek, F., Reyer, C. P., Schewe, J., Warszawski, L., ... & Geiger, T., 2017, Assessing the impacts of 1.5 C global warming–simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). Geoscientific Model Development.

Guseva, S., Bleninger, T., Jöhnk, K., Polli, B.A., Tan, Z., Thiery, W., Zhuang, Q., Rusak, J., Yao, H., Lorke, A., Stepanenko, V., 2020, Multimodel simulation of vertical gas transfer in a temperate lake, Hydrology and Earth System Sciences, 24, 697-715.

Hawinkel, P., Thiery, W., Lhermitte, S., Swinnen, E., Verbist, B., Van Orshoven, J., Muys, B., 2016, Vegetation response to precipitation variability in East Africa controlled by biogeographical factors, Journal of Geophysical research - Biogeosciences, 121, 2422-2444.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz‐Sabater, J., ... & Simmons, A., 2020, The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999-2049.

Kranenburg, W., Tiessen, M., Veenstra, J., De Graaff, R., Uittenbogaard, R., Bouffard, D., Sakindi, G., Umutoni, A., Van de Walle, J., Thiery, W., van Lipzig, N.P.M., 2020, 3D-modelling of Lake Kivu: horizontal and vertical flow and temperature structure under spatially variable atmospheric forcing, Journal of Great Lakes Research, 46, 947-960.

Lau, M.P., G. Valerio, M. Pilotti, and M Hupfer. 2020. Intermittent meromixis controls the trophic state of warming deep lakes. Sci Rep 10, 12928. https://doi.org/10.1038/s41598-020-69721-5

Maberly, S. C., O'Donnell, R. A., Woolway, R. I., Cutler, M. E., Gong, M., Jones, I. D., ... & Thackeray, S. J., 2020, Global lake thermal regions shift under climate change. Nature Communications, 11(1), 1-9.

Martynov, A., Sushama, L., Laprise, R., Winger, K., & Dugas, B., 2012, Interactive lakes in the Canadian Regional Climate Model, version 5: the role of lakes in the regional climate of North America. Tellus A: Dynamic Meteorology and Oceanography, 64(1), 16226.

Mironov, D., Heise, E., Kourzeneva, E., Ritter, B., Schneider, N., & Terzhevik, A., 2010, Implementation of the lake parameterisation scheme FLake into the numerical weather prediction model COSMO, Boreal Environmental Research.

Stepanenko, V. M., Goyette, S., Martynov, A., Perroud, M., Fang, X., & Mironov, D., 2010, First steps of a Lake Model intercomparison project: LakeMIP, Boreal Environmental Research.

Stepanenko, V. M., Martynov, A., Jöhnk, K. D., Subin, Z. M., Perroud, M., Fang, X., ... & Goyette, S., 2013, A one-dimensional model intercomparison study of thermal regime of a shallow, turbid midlatitude lake. Geoscientific Model Development, 6(4).

Stepanenko, V., Jöhnk, K. D., Machulskaya, E., Perroud, M., Subin, Z., Nordbo, A., ... & Mironov, D., 2014, Simulation of surface energy fluxes and stratification of a small boreal lake by a set of one-dimensional models. Tellus A: Dynamic Meteorology and Oceanography, 66(1), 21389.

Thiery, W., Martynov, A., Darchambeau, F., Descy, J.-P., Plisnier, P.-D., Sushama, L., van Lipzig, N.P.M., 2014a, Understanding the performance of the FLake model over two African Great Lakes, Geosci. Model Dev. 7, 317-337.

Thiery, W., Stepanenko, V.M., Darchambeau, F., Fang, X., Jöhnk, K.D., Li, Z., Martynov, A., Mironov, D., Perroud, M., Subin, Z.M., van Lipzig, N.P.M., 2014b, LakeMIP Kivu: evaluating the representation of a large, deep tropical lake by a set of one-dimensional lake models, Tellus A 66, 21390.

Thiery, W., Davin, E.L., Panitz, H.-J., Demuzere, M., Lhermitte, S., van Lipzig, N.P.M., 2015, The impact of the African Great Lakes on the regional climate, J. Climate, 28(10), 4061-4085.

Thiery, W., Davin, E.L., Seneviratne, S.I., Bedka, K., Lhermitte, S., van Lipzig, N.P.M., 2016, Hazardous thunderstorm intensification over Lake Victoria, Nature Communications, 7, 12786.

Verburg, P., & Antenucci, J. P. (2010). Persistent unstable atmospheric boundary layer enhances sensible and latent heat loss in a tropical great lake: Lake Tanganyika. Journal of Geophysical Research Atmospheres, 115(11), 1–13. https://doi.org/10.1029/2009JD012839

Verburg, P., Antenucci, J. P., & Hecky, R. E. (2011). Differential cooling drives large-scale convective circulation in Lake Tanganyika. Limnology and Oceanography, 56(3), 910–926. https://doi.org/10.4319/lo.2011.56.3.0910

Woolway, R. I., & Merchant, C. J., 2019, Worldwide alteration of lake mixing regimes in response to climate change. Nature Geoscience, 12(4), 271-276.

Woolway, R. I., & Maberly, S. C., 2020, Climate velocity in inland standing waters. Nature Climate Change, 1-6.