



The impact of seasonal variability and climate change on lake Tanganyika's hydrodynamics

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Abstract

In this paper, we project future changes in the hydrodynamics of Lake Tanganyika under a high emission scenario using the three-dimensional (3D) version of the Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM 3D) forced by a high-resolution regional climate model. We demonstrate the advantages of 3D simulation compared to 1D vertical models. The model captures the seasonal variability in the lake, with seasonal deep mixing and surfacing of the thermocline. In a simulation of current conditions, the thermocline in the south of the lake moves upward from a depth of 75 m until it reaches the lake surface during August and September. We compare the current conditions with an end-of-the-century simulation under a pessimistic emission scenario (RCP 8.5) showing that surface water temperature increases on average by 3 ± 0.5 °C. Because deeper water warms less, the stratification increases in the upper 150 m of the water column. This temperature-induced stratification reduces mixing and prevents the outcropping of the thermocline, eventually shutting down the ventilation of deep water in the south basin. Our results highlight the extreme changes likely faced by Lake Tanganyika if global greenhouse gas emissions are not curbed.

Keywords Climate change · SLIM · Numerical model · Lake Tanganyika

1 Introduction

In recent decades, climate change has impacted ecosystems and societies on all continents as well as the global ocean, highlighting their sensitivity to a changing climate. Climate change has also affected 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 (see Sect. 2.4) located between Burundi, DR Congo, Tanzania and Zambia (Fig. 1a). Lake Tanganyika is the second oldest, second deepest lake in the world. Despite the vital importance of Lake Tanganyika as a food source for local communities and the reported effects of climate change on its ecosystem functioning, water quality and fish availability,

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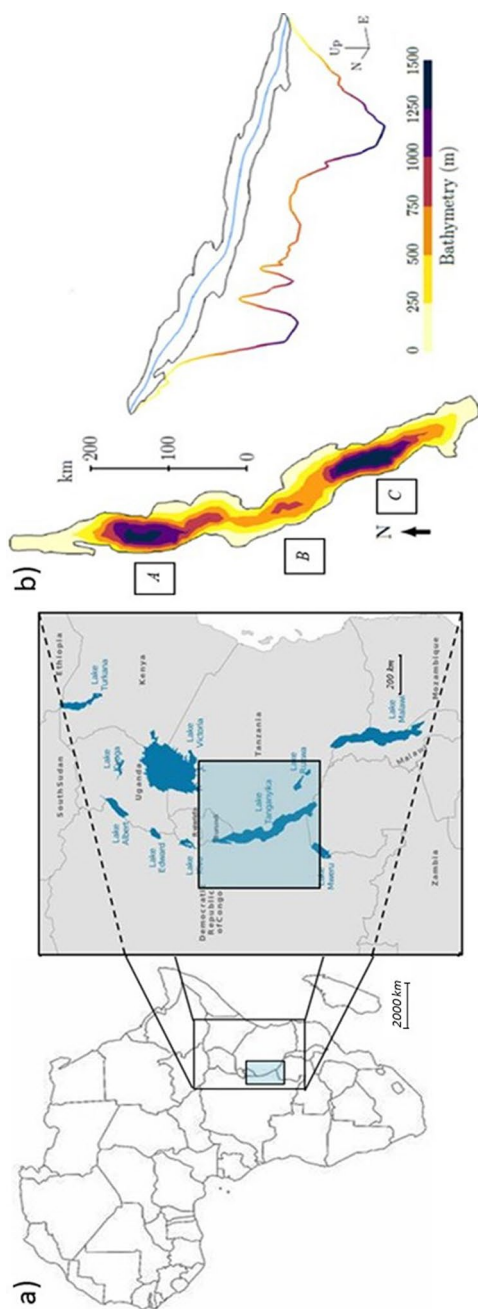


Fig. 1 **a** Location of Lake Tanganyika ($3^{\circ}20'S-8^{\circ}48'S$; $29^{\circ}12'E-31^{\circ}12'E$), surrounded by Burundi, Tanzania, Zambia and DR Congo; **b** Bathymetric map with basins A: Kigoma, B: Kungwe, C: Kipili (adapted from [7])

the potential impacts of future climate change on the functioning of this lacustrine system have not been addressed. The countries surrounding Lake Tanganyika being relatively poor, their inhabitants strongly depend on local resources for their basic needs. The lake fulfils an essential role in this supply, mainly because of the intensive fishery [40]. Roughly 25–40% of the protein diet of approximately 1,000,000 people living around the lake comes from these fisheries [30]. The main fishery is on pelagic clupeids (sardines) which for their diet strongly depend on plankton productivity. In turn plankton depends on nutrient supply by vertical mixing between deeper and shallower water layers and an efficient carbon transfer from plankton to fish [50, 62]. However, stratification of the water column reduces exchanges between the nutrient-poor epilimnion and the nutrient-enriched hypolimnion [6, 32], limiting primary productivity [57].

Past climate change has already influenced stratification and the functioning of Lake Tanganyika. Long-term changes reported include a rise in surface water temperature and increased stability of the water column [21]. The enhancement of stratification by atmospheric warming, resulting in reduced vertical mixing, has led to significant changes in the nutrient supply to the epilimnion [20, 57, 23, 59, 61]. Primary productivity has decreased as indicated by increased water transparency, reduced uptake of dissolved silica by diatoms and decreased phytoplankton biomass [57]. Historical records suggest a 30% decrease in fish production due to climate change [30]. 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 [3] by nearshore upwelling of anoxic hypolimnetic water. Deep vertical mixing may occur less frequently in the future, but may have greater impact when it does happen [22].

However, there is no study of how Lake Tanganyika will respond to projected future climate change. In this study, we compare the present-day variability with projected future conditions in the hydrodynamics of Lake Tanganyika. We (i) assess the advantage of a 3D hydrodynamic lake model [7] compared to a set of 1D (vertical) lake models [37] which ignore horizontal transport, (ii) examine the effect of present-day seasonal atmospheric variability on lake hydrodynamics by a short-term simulation, and (iii) examine future climate change effects on the lake hydrodynamics. To this end, we use high-resolution dynamical downscaling of reanalysis products and a global climate model (GCM) as input for the 3D version of our hydrodynamic model, i.e., the Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM 3D, <https://www.slim-ocean.be/>, the acronyms are listed in Table 1 along with their meaning).

2 Background

2.1 Lake Tanganyika

Lake Tanganyika has a surface area of 32,900 km², a maximum length of 673 km, an average width of 50 km, an average depth of 570 m and a maximum depth of 1470 m. The catchment covers an area of 231,000 km², which means it drains an area equivalent to almost the entire United Kingdom. It is the second oldest lake in the world (after Lake Baikal, Russia). Its three basins were formed during different time periods. The oldest (central) basin, began to form 9–12 million years ago, shortly followed by the northern basin (7–8 million years ago), and the southern basin more recently (2–4 million years ago). It is the second deepest lake in the world and holds the second largest anoxic

Table 1 List of acronyms and their meaning (in alphabetical order)

Acronym	Description
ARC	Along track scanning radiometers reprocessing for climate
CLM	Community land model
CMIP5	Coupled model intercomparison project
COSMO	Consortium for small-scale modelling
CORDEX	Coordinated regional climate downscaling experiment
ECMWF	European centre for medium-range weather forecasts
ENSO	El Niño-southern oscillation
ERA	ECMWF re-analysis
EVAL	Evaluation simulation
FUT	Future simulation
GCM	Global climate 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
RCM	Regional climate model
SLIM	Second-generation Louvain-la-Neuve Ice-ocean Model

volume of water (total volume of 18,900 km³ or 16% of the world's surface freshwater, 60–70% of this volume is anoxic) in the world, after the Black Sea. The lake is located in a deep narrow trough of the western branch of the Rift Valley of East Africa, and it stretches from 3°20' to 8°48' S and 29°5' to 31°15' E (Fig. 1a). The three basins are Kigoma (1310 m deep), Kungwe (885 m deep) and Kipili (1470 m deep) (Fig. 1b). The shoreline has an approximate length of 1800 km at an altitude of 773 m and is mainly surrounded by steep mountains.

The location of the lake ensures—thanks to the low latitude, high temperatures and abundant light availability year-round—favourable conditions for fish productivity. The planning, management and development of the local fisheries is challenged by the fluctuations in fish catches and differences in species composition between each catch [35].

Lake Tanganyika has been classified as pseudo-eutrophic (i.e. holding both eutrophic and oligotrophic characteristics) due to the relatively high productivity of the lake, combined with high water transparency, low nutrient concentrations in the epilimnion and low phytoplankton densities.

Air temperature at Lake Tanganyika followed the global trend according to O'Reilly et al. [30]. However, air temperature over the lakes may have increased faster than the global mean [30, 57]. After relatively little change from 1945 to the 1970s, lake warming accelerated from the late 1970s onward, coinciding with the timing of regional precipitation and air temperature changes [30].

The Coordinated Regional Climate Downscaling Experiment (CORDEX; [11]) provides regional climate projections for Africa under various future Representative

Concentration Pathways (RCPs). The results are obtained by downscaling information from Global Climate Models participating in phase 5 of the Coupled Model Inter-comparison Project (CMIP5, [46]). Under RCP8.5 (the “business as usual” scenario, where 8.5 stands for a radiative forcing of 8.5 W/m^2 at the end of the twenty-first century), the CORDEX ensemble projects an increase in precipitation towards the coast, whereas more inland, the climate evolves to drier conditions. Over Lake Tanganyika, which is approximately 1000 km inland, the ensemble projects a decrease in precipitation [43]. Finally, due to climate change, a southward shift in the Intertropical Convergence Zone (ITCZ) is observed. If this shift were to continue, the effect of the southern wind is expected to decrease in the area of the lake, leading to further reduced mixing [51]. Apart from long-term climate change, the effects of climate variability on the lake should also be considered, as annual to multi-decadal climate variability in the region contains strong cyclic patterns.

2.2 Orography and climate

As most of the lake is surrounded by mountainous areas, orography exerts a strong effect on the local climate conditions [41, 42]. Wind speed and direction over Lake Tanganyika are strongly affected by the surrounding orography. Orographic effects include both dynamic effects, in which mountains affect the large-scale wind field, and thermodynamic effects, in which heating or cooling of mountain-slope surfaces generates flow.

In the centre of the lake, greater wind speeds occur, explained by a channelling effect along the mountain valleys and the lower drag coefficient over water compared to land.

While the seasonal migration of the intertropical convergence zone determines seasonality, regional factors like lakes, vegetation and topography modulate the large-scale pattern [9, 15, 47].

Most of the area surrounding Lake Tanganyika experiences a single rainfall season, with slight variation in the amount and timing of the precipitation. In the northern part of the lake, rain occurs (120–170 mm per month) mainly from December to May. Around Tabora (central area), rain intensity varies the most (60–220 mm per month). In the southern part of Lake Tanganyika, the wet season runs from December to April with an average precipitation of 100–150 mm per month, whereas from June to October, it hardly ever rains [13, 43].

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. At the north end of the lake this period is characterized by ‘short’ rains, whereas, after a brief period of decreased rainfall (January–February), longer rains occur around the boreal spring (March–May), driven by the northward migration of the ITCZ. The interannual variability of these events are linked to atmospheric processes, which determine surface temperature, monsoons, trade winds, and (anti)cyclones. The short rains are especially subject to variability associated with the El Niño-Southern Oscillation (ENSO) [38]. The Southern Oscillation is the driving force behind fluctuations in the atmospheric pressure and monsoon rainfall. The warm ENSO events are usually linked to a higher amount of precipitation in East Africa, whereas the colder ENSO events tend to result in below-average rainfall [15, 27]. However, the impact of ENSO varies substantially across the region, and notably west of Lake Tanganyika, the ENSO index and precipitation are anticorrelated [15]. Vegetation growth in the area west of Lake Tanganyika is therefore reduced during warm ENSO events [15, 36].

2.3 Lake-atmosphere interactions

While meteorological conditions drive lake hydrodynamics, the presence of lakes in turn influences the local climate in several ways. Because water has a high heat capacity, lakes can act as a buffer while the atmosphere transitions between warmer and colder periods. This effect explains coastal areas' milder winters, but is also present in regions with a relative high proportion of lake surface. The minimum winter temperatures will be higher, and maximum summer temperatures lower than they would be without the presence of a large lake surface. The magnitude of this effect depends on the size of the lake [17, 18]. When the lake is in a mountainous area, like Lake Tanganyika, it will also significantly enhance precipitation in its vicinity [10, 17]. Wind speed is also affected by the presence of the lake, and the presence of the ITCZ [41]. Simulations have shown that the lake's influence on the wind speed is stronger early in the morning, and that the (daytime) lake and (night-time) land breezes, induced by the presence of the lake, are enhanced by south-easterly trade winds [47, 56]. However, Docquier et al. [9] also shows that the influence of orography on wind speed's spatial variability has a bigger impact than the lake-land breeze system.

Lastly, the surface energy balance, the balance of exchanges of heat by sensible and latent heat flux and radiation, interacts with the stability of the atmospheric boundary layer above the lake surface and the lake-atmosphere interactions [54, 55]. The surface energy balance determines the seasonal changes in heat content in the lake and affects its thermal structure. The components of the surface energy balance can be compared to results from regional climate modelling.

2.4 Hydrodynamics

Lake Tanganyika is a meromictic lake with an anoxic monimolimnion (lower, dense layer of the lake). It is meromictic, meaning it never completely mixes vertically, in part because of the continuous presence of a thermocline. The thermocline is subject to an internal seiche, governed by topography, atmospheric pressure and wind stress [9, 55]. During the dry season, southerly winds cool the surface water in the south of the lake by driving high heat loss through evaporation. As a result, isotherms come to the surface at the south end and reduced stratification allows deep seasonal convective mixing [55]. Advection moves cool water from the south end to the north at the depth of the metalimnion, and a return current in the upper water layer carries relative warm water from north to south [7, 55]. The wind events follow a cyclic pattern, with a period of 3–4 weeks, which is close to the first free mode of oscillation of the lake, resulting in a quasi-resonance of the internal wave [12, 28, 29].

3 Methods

3.1 SLIM

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 [19]. It has been applied to coastal waters, such as the

Burdekin plume in the Great Barrier Reef [8], the Columbia River region of freshwater influence [52], the Congo estuary [53] and Lake Tanganyika [7].

In this study, SLIM 3D is applied to Lake Tanganyika in exactly the same setup as that of Delandmeter et al. [7], 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 is prescribed using simulated data from the regional climate model COSMO-CLM² (see below). The second is parameterized using a relaxation term towards the 2-m 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 numerical stability. Other parameterizations require more input data and, being more complex, can potentially lead to lake model instabilities, especially when spatial or temporal scales differ between the lake model and surface model. The relaxation is controlled by two parameters: z_r , the depth below the surface above which it is applied and τ , the relaxation time. z_r is set to 12 m, 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 [7].

3.2 COSMO-CLM²

COSMO-CLM² is a comprehensive and frequently updated regional climate model. The first building blocks of the model were a joint effort of the Consortium for Small-scale Modelling (COSMO) and the Climate Limited-area Modelling Community (CLM-community), resulting in a 3D, non-hydrostatic regional climate model COSMO-CLM [39]. In COSMO-CLM², [5] the default land surface parameterisation module in COSMO-CLM, TERRA-ML, has been replaced by the Community Land Model v. 3.5 (CLM3.5, [31]).

The community land model CLM is a merging between a community-developed land model focused on biogeophysics and an expansion of the NCAR Land Surface Model (NCAR LSM) to include the carbon cycle, vegetation dynamics, and river routing. To represent land heterogeneity in CLM, a subgrid hierarchy has been established, where each cell gets a certain land unit assigned, which can be glacier, wetland, vegetated, lake or urban. In the land unit sublevel, the soil properties are defined, including colour, texture, depth and thermal conductivity. To every land unit, a second sub-grid level is assigned, called the column, which captures the variability of the soil and snow state variables. The third sub-grid level is called the plant functional type (PFT) and can assign up to 4 out of the 15 possible types to a certain column. The added value of COSMO-CLM² compared to the default COSMO-CLM configuration regarding the representation of the near-surface climate has been established for several domains including Europe [4, 5] and Sub-Saharan Africa [1, 47].

In this work, we use three high-resolution simulations with COSMO-CLM², conducted by Thiery et al. [47, 48] over the African Great Lakes region to force SLIM 3D. The first regional climate simulation, termed EVAL, consists of a reanalysis downscaling for a 10-year period (1999–2008). Results from the EVAL simulation represent the ‘best guess’ of the recent regional climate and may be employed for model evaluation purposes and analysis of present-day spatio-temporal patterns.

The second COSMO-CLM² simulation represents a 30-year historical (HIS) integration (1980–2009) 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. The third COSMO-CLM² simulation was obtained by downscaling MPI-ESM-LR for a future (FUT) 30-year period 2070–2099 under Representative

Concentration Pathway (RCP) 8.5. Comparison of the HIS and 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).

Each COSMO-CLM² simulation was conducted at a horizontal resolution of ~ 7 km (0.0625°) and is nested within a COSMO-CLM simulations run at ~ 50 km (0.44°) resolution in the framework of the Coordinated Regional Climate Downscaling Experiment (CORDEX; [33]). As such, COSMO-CLM² is used to downscale global-scale information from a reanalysis or GCM to the African Great lakes region via a continental-scale intermediate nesting step. The final nesting step has been tailored to the region by (i) applying COSMO-CLM in its tropical configuration [33], (ii) implementing a high horizontal resolution providing pioneering representation of the local topography and (iii) using a 1D lake model aimed at representing tropical lake surface water temperatures [47].

After pre-processing, the COSMO-CLM² output was arranged in a well-defined order, such that it could be used as input for SLIM 3D. Three runs were performed (Table 2), EVAL, HIS and FUT. The evaluation simulation (EVAL) was run over a 10-year period to validate the model and investigate the effects of interseasonal meteorological variations on the lake's hydrodynamics. The historical simulation (HIS) was run over a 30-year period, where the results were used both to evaluate the difference between the ERA-interim and GCM downscaling, and as a reference for the future simulation (FUT). The latter was also run for a 30-year period, but with a simulation start date 90 years after that of HIS. While a single transient simulation covering the entire 21st 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.

3.3 FLake

To evaluate the benefits of a 3D model we compare results with the 1D model FLake. This model was interactively coupled at the subgrid-scale level to COSMO-CLM². 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. The meteorological input fields of the FLake model are similar to that of SLIM; however, in contrast to SLIM, the integral energy budget is computed by the model. The model considers two layers, i.e., a surface mixed

Table 2 Technical specifications for the three simulations performed in SLIM 3D

SLIM simulation name	EVAL	HIS	FUT
Global-scale forcing for COSMO-CLM ²	ERA-interim	GCM downscaling	GCM downscaling
Simulation period start	01/01/1999	01/01/1980	01/01/2070
Simulation period end	31/12/2008	31/12/2009	31/12/2099
Time step	10 min	10 min	10 min
Model spin-up (before the start of the simulation period)	2 years	12 years	12 years
Meteorological spin-up (before the model spin-up)	1 year	1 year	1 year

layer, and a thermocline just below. The mixed layer is assumed to be thermally homogeneous, whereas temperature decreases with depth in the thermocline [47].

As a widely-used parameterization scheme in numerical weather prediction systems (*e.g.* [2, 26]), climate models (*e.g.* [25, 26]) and climate reanalyses [16, 60], 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 [23, 60, 61]. FLake has been proven to be comparable to other 1D lake models for different lake types and climatic conditions [1, 14, 34, 44, 45]. Besides this, there have been offline tests for several African Great Lakes, concluding that FLake performs well in the estimation of lake surface temperatures [49].

3.4 ARC lake

The Along-Track Scanning Radiometers Reprocessing for Climate applied to Lakes (ARC Lake; [24]) provides satellite-based observations of lake surface water temperatures 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 [49], 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.

4 Results

4.1 Model evaluation

For both the 3D model SLIM 3D (EVAL) and 1D model Flake, the difference in surface water temperature compared with data from ARC Lake was calculated. In Fig. 2a1–a3), the average difference of the 1D model is shown per season. The most marked deviations occurred during the dry season (June to August), when there was a strong underestimation of the temperature in the central and southern part of the lake. During the later part of the wet season (February to April), temperatures were overestimated, especially at the northern and southern ends, while during October–December a warm difference occurred mainly in the northern region.

The difference between the SLIM 3D EVAL results and the ARC Lake data were consistently smaller (see Fig. 2b1–b3) than the difference between Flake's result and the ARC Lake data. The cool temperature difference seen in the Flake simulation in the south and centre during the dry season was absent from the SLIM 3D simulation. The small warm temperature difference in the southern tip during the wet season was smaller and the year-long warm temperature difference in the north was reduced (although still present).

Based on these results, we hypothesize that the lake reacts faster than expected to seasonal meteorological changes. This leads to a stronger heating or cooling effect. The difference in the 1D-model results may be explained by insufficient heat storage in the model, since this model underestimated the thermocline depth. A second explanation might be the higher wind velocities in the centre of the lake, leading to higher water velocities, which

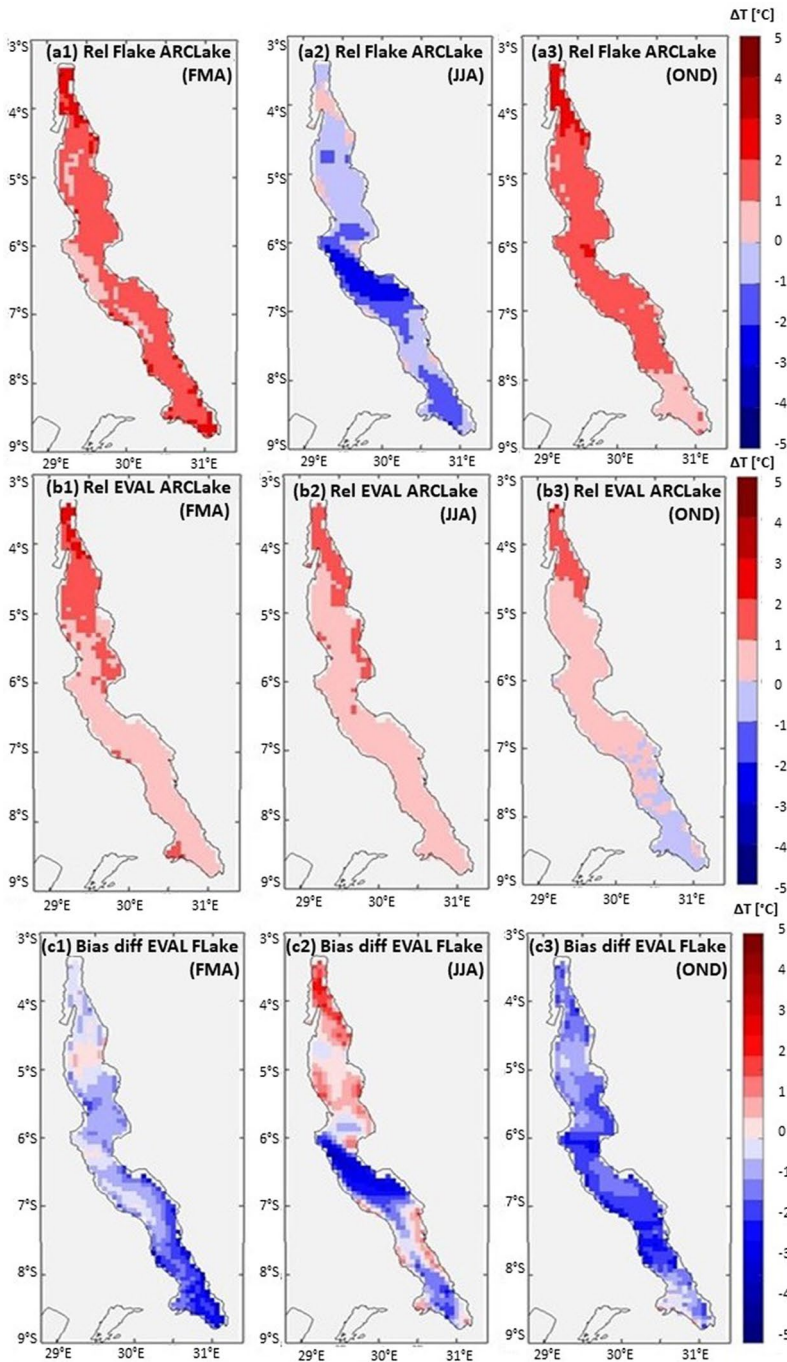


Fig. 2 Seasonal surface water temperature difference between the Flake (**a1–a3**) and EVAL (**b1–b3**) against the ARC Lake reference product (simulation—reference) for the months February–April (FMA), June–August (JJA) and October–December (OND) and the relative differences between the EVAL and the Flake simulation analysis (**c1–c3**)

are accounted for in the 3D model. In the 3D model, a certain buffer is apparent, resulting in a slight delay in heating effects, but cooling effects are still strongly represented. It may therefore be that the breakdown of the stratification is better simulated than re-stratification by SLIM. The relaxation function to represent the surface heat flux [7], which includes a delay compared to changes in meteorological variables, may also contribute to the cold temperature difference at the centre of the lake compared to the 1D model. However, in general, SLIM 3D improves the simulation of the lake surface water temperature compared to FLake (1D), underlining the importance of accounting for 3D hydrodynamics (Fig. 2c1–c3)). The effect of a better 3D circulation in SLIM is clearly of greater importance than the better simulated surface heat flux in FLake. Further development is needed to improve the heat flux representation in SLIM, since this could enhance the quality of the model results.

4.2 Interseasonal variation

The annual variation of water temperatures in the top 150 m of the water column, resulting from the HIS simulation, is displayed in Fig. 3 (panels a1 and a2). The top 150 m was selected because below this depth there are no seasonal effects on the temperature [58]. Figure 3 shows the extremes of the dry and wet season, and monthly plots are in Fig. S1.

The magnitude of the seasonal temperature fluctuations is expected to differ from north to south [20], as also seen in our results. The northern part of Lake Tanganyika is surrounded by mountains, resulting in lower wind speeds, which explains why the highest surface water temperatures along the lake can be found here (Fig. 4).

The southern part of the lake has greater surface cooling and 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 southern end of the lake.

In general, according to Naithani et al. [28, 29], wind and air temperature have little to no influence below 100 m depth. This corresponds to the thermocline never being below 75 m (Fig. 3). Lake evaporation is on average stronger in the dry season because of higher wind speeds from the southeast (trade winds), resulting in cooling of the surface water and a position of the thermocline closer to the surface, although the latter is not replicated by SLIM. The dry season period is also colder, contributing to lower surface water temperature.

4.3 Model evaluation—30-year simulation

This section concerns the longer simulations (HIS and FUT), forced with meteorological data from the GCM downscaling without reanalysis. A major difference is that for EVAL the data originated from a downscaling of the reanalysis ERA interim. In the longer simulations, the quality has been improved by corrections in the output every six hours, based on all available measurements. Another difference is in the runtime of the simulation, as it has never been tested whether one or two years of spin-up are enough to obtain equilibrium in the model. Fig. S2 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. 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. Therefore, the GCM downscaling is appropriate

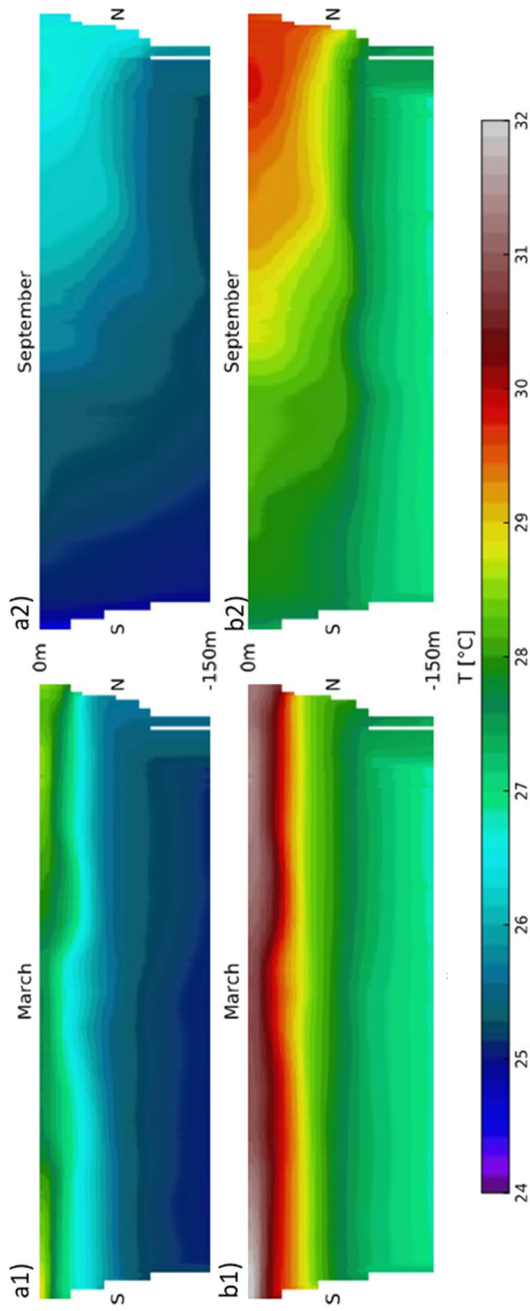


Fig. 3 Monthly water temperature cross-sections (as defined in Fig. 1b) obtained by the HIS-simulation (a1, a2) and FUT-simulation (b1, b2)

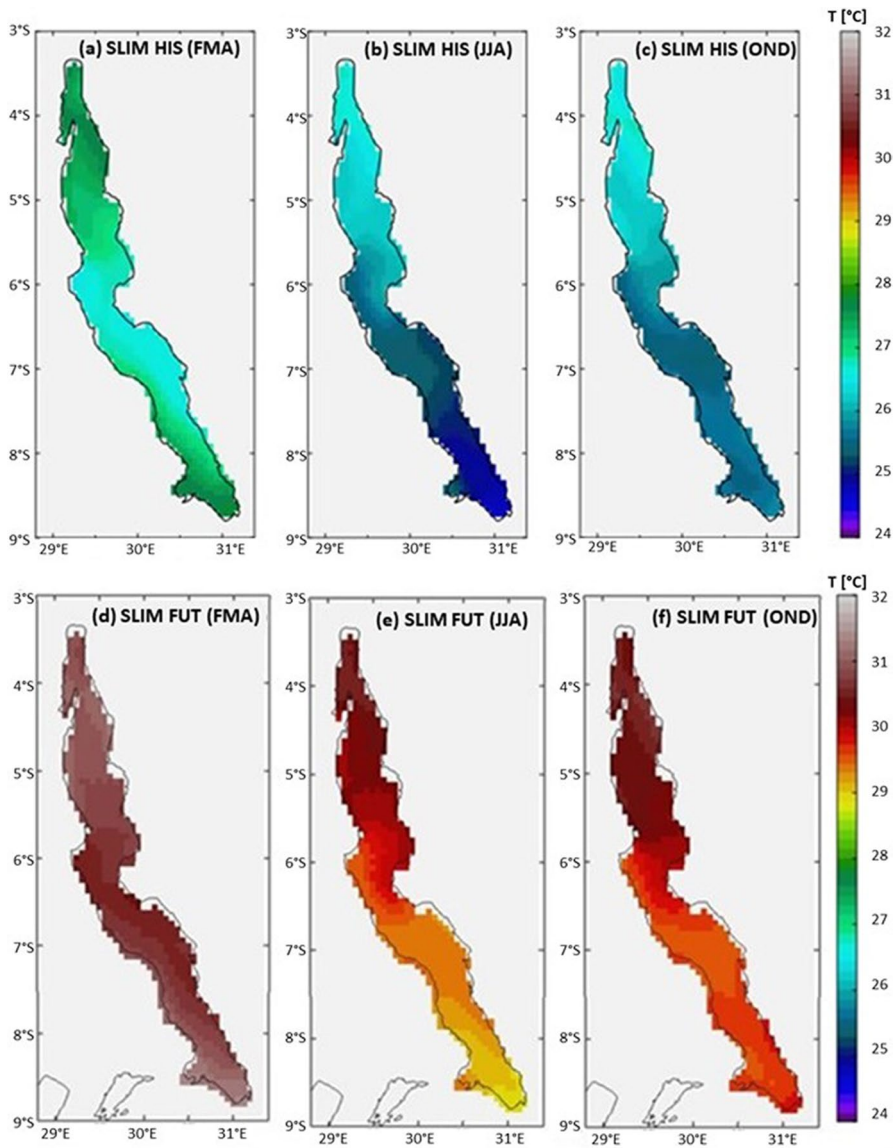


Fig. 4 Mean seasonal surface water temperature from the HIS (a–c) and FUT (d–f) simulations

as meteorological input to drive SLIM 3D under present-day and, hopefully, future climate conditions.

Figure 5 shows the monthly lake-wide mean temperatures for the HIS and FUT simulations, with the interquartile range (IQR) of the spatial variation calculated from the monthly surface water temperature averaged over the full lake 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

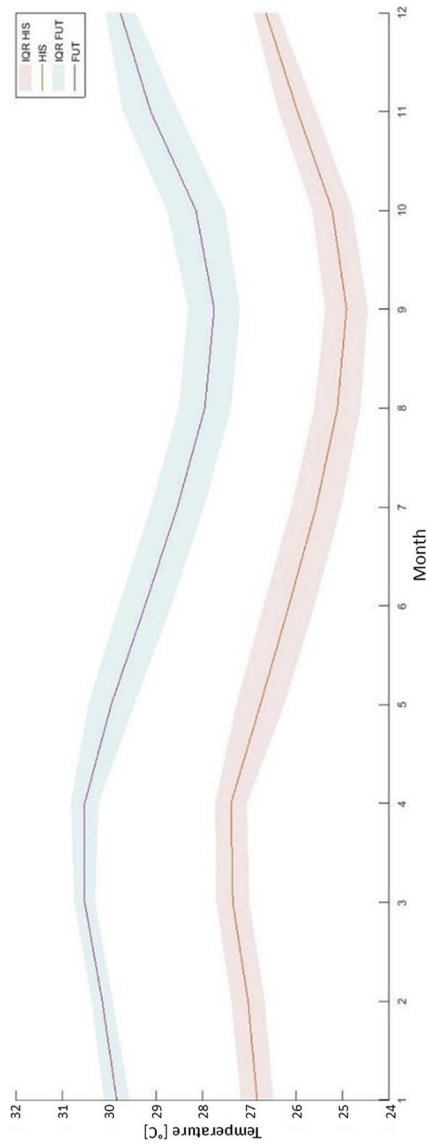


Fig. 5 Spatial IQR on surface water temperature for HIS (red) and FUT (blue)

results, and their spatial average. At any point in time, the coldest locations were warmer in the FUT simulation than the warmest locations in the HIS simulation.

4.4 Climate change simulation—30-year simulation

The comparison between the FUT (Fig. 3b1, b2 and 4d–f) and HIS (Fig. 3a1, a2 and 4a–c) simulations shows uniform warming. The surface water temperature increases over the entire lake, over the entire year by 3 ± 0.5 °C. In the FUT simulation the location of the maximum surface temperature moved more distinctly from south to north between the warm (January to April) and the dry cool to early warm season. This suggests relative more warming in the north in the dry and early warm season and may reflect changes in the horizontal circulation, which has been described to occur in the lake [7, 55]. However, since the average temperature difference is small, it might be an artefact.

A second important observation is the strengthening of the stratification during the dry season, as shown by comparing Fig. 3 panels b1 and b2 with panels a1 and a2. Whereas in the current situation, during June to November, the thermocline surfaced from the south end to the centre of the lake, this occurred only in July to October in the FUT scenario, resulting in longer duration of stratification (Figs. S1 and S3).

The difference in average temperature between the HIS and FUT simulations (Fig. S4 in the supplement), plotted over the depth, shows that the gradient overall increases, with a maximum at the surface level, resulting in a much stronger stratification of the lake. Water quality and the renewal of nutrients from deep water are linked to the strength of the stratification. Increased stratification results in a severe reduction of the mixing, and thus potentially in a strong decrease in nutrient supply to the ecosystem and eventually to the fish population.

The fact that relative humidity is not accounted for in the model might affect modelled water temperatures, perhaps depending on the season. If the seasonal cycle becomes more pronounced, the dry season becomes drier, resulting in more evaporation and lower surface water temperatures, and if the warm wet season becomes more humid, the surface water temperature may increase even more. SLIM may benefit from a better representation of the surface heat flux.

5 Discussion

Our results suggest that unabated climate change will induce important changes in the lake's mixing regime, with potentially severe implications for its ecosystem. This is because the input of nutrients in the upper layer is likely to be drastically reduced, thereby impacting phytoplankton growth and, hence, the whole food web.

The conclusions of this paper are based on numerical simulations, for which input data and calibration are provided by other models or remote sensing. A comprehensive evaluation of the model system with in-situ measurements has been performed by Delandmeter et al. [7], and our additional validation confirms that the model can be used for climate change projections.

FLake is a numerical model designed specifically to have a very low computational cost, and a key strength of the model is the balance between physical realism and very low computational resource demand. For a single lake, it can simulate hundreds of years in a matter of seconds on a personal computer. SLIM 3D, on the other hand, displays

high numerical accuracy and has the ability to capture complex hydrodynamic processes, including for example Kelvin waves. This accuracy however comes at a higher computational cost, which requires the model to be run a high-performance computing (HPC) system. However, SLIM 3D offers opportunities for improvement, such as implementation of an improved surface heat flux representation and accounting for the effect of relative humidity. The input data were also obtained from only one regional climate simulation, linked to SLIM 3D. Other climate simulations may generate somewhat different outcomes. Moreover, this study considered only one climate change scenario (the high-emission scenario RCP 8.5), not accounting for lower greenhouse gas concentration scenarios. With lower emission scenarios, the simulated effects are expected to be less strong.

Together with suggested improvements in future simulation work, a major effort should be put towards testing the sensitivity of results for a range of representative concentration pathways and GCM/RCM combinations.

6 Conclusions

The hydrodynamics of Lake Tanganyika are driven by the interaction between the lake and climate. External forcing by wind, temperature and relative humidity induce variations in the water temperature and circulation patterns. While modelling studies of Lake Tanganyika exist, this is the first analysis of the effects and consequences of future climate change on the lake hydrodynamics.

One goal of this work has been to compare SLIM 3D to a 1D model, as used previously in modelling Lake Tanganyika's hydrodynamics, interactively coupled to COSMO-CLM² (FLake), and to assess the accuracy of the output by comparing it to satellite surface water temperature data (ARC Lake). To this end, SLIM was forced by a reanalysis downscaling with the regional climate model COSMO-CLM² for the period 1980–1999. The overall performance of SLIM 3D was better than that of Flake (up to 2 °C difference in relative surface water temperature, see Fig. 2). However, comparison of the surface water cooling and warming shown in the ARC Lake data with the changes in thermocline depth simulated by SLIM 3D, suggests that the simulation of the thermocline can be improved. Nevertheless, as expected a 3D circulation model is a major improvement compared to a 1D water column model. Suggested future work includes the implementation of more realistic surface heat flux simulation in SLIM 3D, as this might improve the simulation of the thermocline. However, studies have shown that the surface heat fluxes will only be properly represented, when local values of air density, kinematic air viscosity and latent heat of vaporization are included in the model [54].

The second goal of the study was the analysis of the results of a simulation using SLIM 3D. A 10-year simulation showed a strong response to climate seasonality, especially in the southern part of the lake. As the centre of the lake is surrounded by mountains, winds speeds are highest there, leading to enhanced mixing. The north of the lake remained warmest, mainly as a result of lower wind speeds.

A third goal of this paper was to use a new atmospheric dataset to force SLIM 3D, obtained by downscaling a global climate model (GCM) with COSMO-CLM². The consistency of the SLIM simulation output forced by the reanalysis and by GCM downscaling was tested first. This comparison showed almost no difference.

The final projection was 30 years under a high-emission scenario (RCP 8.5), starting in 2070, which was compared to a historical reference simulation starting in 1980.

Our main conclusion is that the surface water warmed by 3 °C, averaged across seasons and the entire lake. The period in which the thermocline surfaces during the dry season was reduced in the future simulation, and stratification in Lake Tanganyika will be stronger. The longer persistence of the thermocline through the year has two causes. First, the depth of the thermocline overall increases. Second, the temperature gradient in the top layer and thermocline increases, which results in a more stable thermocline. Both effects make the thermocline more resistant to mixing, given similar wind speeds. Increased stability of the thermocline is the main finding of our study, suggesting that reduced mixing may decrease the productivity of the lake ecosystem further than it has already done during the past century [30, 57].

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Declarations

Competing interests The authors declare no competing interests.

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