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Key Points:

- Regional Ocean Modeling System modeling reveals climate effects on Lake Tanganyika's thermal patterns and circulation, influencing ecosystems and fisheries
- Modeling shows upwelling aligns with past observations, revealing unrecognized September–November downwelling on the lake's west side
- Modeling reveals Lake Tanganyika's circulation patterns, vital for understanding biodiversity dynamics and guiding fisheries management

Supporting Information:

Supporting Information may be found in the online version of this article.

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Understanding the 3D Hydrodynamics of Lake Tanganyika: Insights From Modeling Circulation Patterns Using a 3D ROMS Model

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Abstract This study simulates circulation patterns in Lake Tanganyika, an economically vital lake in East and Central Africa that has experienced significant warming, and reduced fishery yields in recent decades. We use Regional Ocean Modeling System to analyze thermal stratification, wind-driven processes, and circulation dynamics within the lake. Our findings show surface temperatures ranging from ~25.8°C to ~27.8°C seasonally, with a notable increase of up to 0.4°C below 150 m depth between 2001 and 2020. Primary upwelling occurs in the southern region from May to August, while secondary upwelling is observed in the north from November to February. Bathymetric variations influence upwelling and downwelling processes. Our results emphasize that the interaction between atmospheric and hydrodynamic factors regulates the nutrient distribution, which is crucial for fisheries and biodiversity. We also highlight the importance of modeling in understanding the warming trends and ecological responses of Lake Tanganyika to climate change.

Plain Language Summary Our study investigated the complex interactions shaping the ecosystem dynamics of Lake Tanganyika, a vital freshwater fishery and biodiversity hotspot in East and Central Africa. The lake is undergoing significant changes likely linked to regional climate change. Using a numerical model called ROMS (the Regional Ocean Modeling System), we examined how air temperature, wind, and bathymetry influence circulation patterns, which in turn influence nutrient distribution and overall ecosystem health. We found notable seasonal variations in water temperature: the southern regions are cooler during the dry season, while the surface remains uniformly warm in the wet season. Our research also revealed a concerning increase of up to 0.4°C at depths greater than 150 m between 2001 and 2020. We identified key factors over the annual cycle including thermal stratification, upwelling, and seasonal mixing that influence nutrient and heat distribution. These findings highlight critical areas of upwelling and downwelling which are essential for nutrient circulation and fisheries health. Understanding these processes is vital for maintaining Lake Tanganyika's ecosystem, and our research underscores the importance of conserving and sustainably managing the lake for the well-being of current and future communities.

1. Introduction

The inland fishery sector in tropical Africa, particularly in East and Central regions, is vital to local economies and nutritional security (Funge-Smith & Bennett, 2019; Kolding et al., 2015; Temesgen et al., 2019; Youn et al., 2014). With high population densities and limited economic development, lakes in these areas are essential for the livelihoods of local communities (Béné & Heck, 2005; Kafumbata et al., 2014). However, rapid population growth and climate change have increased the need for sustainable management of these resources (Allison, 2004; Cowx & Ogutu-Owaho, 2019; Njock & Westlund, 2010; Sarch & Allison, 2001).

Lake Tanganyika, located in East and Central Africa, is shared by Tanzania, the Democratic Republic of Congo (DRC), Burundi, and Zambia (Figure 1). It is the second oldest lake in the world (Cohen et al., 1993; Salzburger et al., 2014) and was formed within the East African Rift Valley through extensional tectonic activity (Tiercelin & Lezzar, 2002). The lake extends ~673 km in length and has an average width of ~50 km, making it the longest freshwater lake in the world and the second largest by volume. Lake Tanganyika is meromictic, with surface nutrient loading primarily dependent on internal circulation, which supports a fishery based on seasonal upwelling and mixing across the mixolimnion (Coulter & Spigel, 1991). This rich fishery is crucial for local livelihoods (Allison et al., 1996; Ronco et al., 2020).

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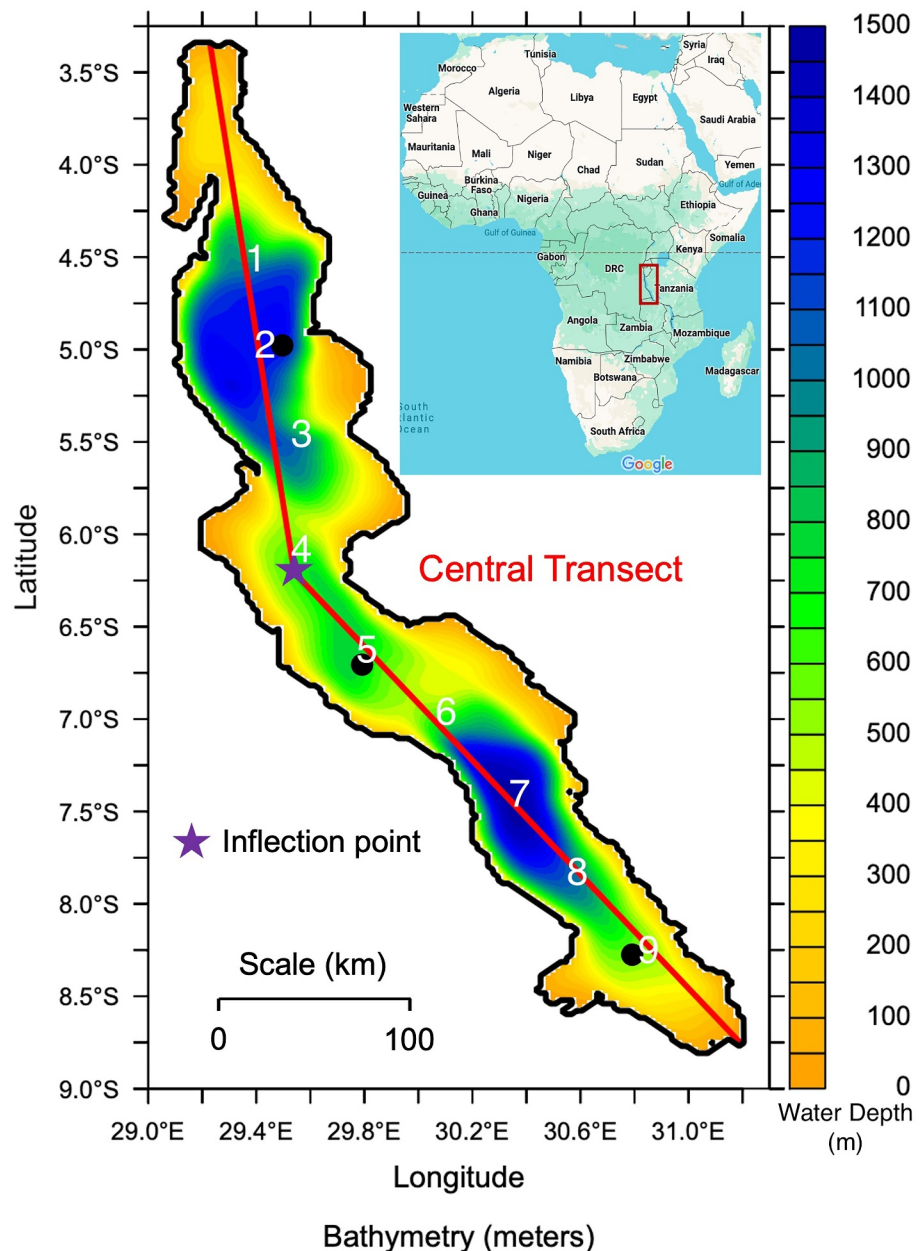


Figure 1. Bathymetry map of Lake Tanganyika. The inset shows the lake's location in the East African Rift Valley (red rectangle). The red line depicts a central transect used for presenting depth profiles in subsequent figures, with a purple star marking the transect's inflection point. Black dots mark model evaluation sites which are compared against instrumental measurements reported in Ehrenfels et al. (2023). White numbers indicate approximate locations of instrumental data collection.

Due to its tropical location near the equator, Lake Tanganyika experiences a relatively stable climate characterized by two distinct seasons. The dry season, from May to September, features cool air temperatures, strong southeasterly winds associated with the latitudinal shift of the African equatorial rain belt (Nicholson, 2018), and limited rainfall. Significant heat loss occurs during this period through evaporation driven by these winds (Verburg & Hecky, 2003), resulting in prominent wave activity and mixing between the warm upper layer and cooler lower layers, which lowers the thermocline. Conversely, the wet season (October to April) is marked by substantial rainfall, increased cloud cover, weak northeasterly winds, and elevated temperatures (Savijärvi, 1997; Savijärvi & Järvenoja, 2000; Verburg & Hecky, 2003). Rainfall replenishes the lake and contributes to stable

water levels. During this season, the lake surface is calm, the thermocline shoals, and stratification occurs. Surface temperatures fluctuate from $\sim 25^{\circ}\text{C}$ in the dry season to $\sim 28^{\circ}\text{C}$ in the wet season (Verburg & Hecky, 2003).

The fishery of Lake Tanganyika is a crucial economic and social resource for neighboring countries. Its productivity is tied to nutrient dynamics and lake circulation, driven by seasonal variations in upwelling and mixing (Coulter & Spigel, 1991). Local communities rely on the lake's fish as a primary protein source for food security and as an export commodity (Mölsä et al., 1999; Van der Knaap et al., 2014), with approximately 40% of their animal protein intake derived from this fishery (O'Reilly et al., 2003). Sustainable management is essential due to threats from overfishing and illegal fishing, which could disrupt the lake's ecosystem (Lowe et al., 2019; Plisnier et al., 2018). Collaborative efforts involving governments, fishing communities, and conservation organizations are underway to ensure the sustainability of this resource (Lowe et al., 2019).

However, climate change poses significant risks to the Lake Tanganyika fishery (Cohen et al., 2016; Kamulali et al., 2022; Kraemer et al., 2015; Naithani et al., 2011; O'Reilly et al., 2003; Plisnier et al., 2018; Tierney et al., 2010; Verburg & Hecky, 2009). Increasing air temperatures over the past century have intensified stratification and reduced upwelling of nutrients into surface waters, potentially decreasing primary productivity and fishery yields (O'Reilly et al., 2003; Plisnier, 1998, 2004; Tierney et al., 2010; Verburg & Hecky, 2003; Figure S1a in Supporting Information S1).

Given the potential impacts of projected future climate change, our study presents a novel analysis of climate-driven circulation patterns in Lake Tanganyika using the Regional Ocean Modeling System (ROMS). ROMS has also been employed to model other large African lakes, such as Lake Victoria (Nyamweya et al., 2016). This study focuses on Lake Tanganyika's seasonal circulation and critical zones of upwelling and downwelling, marking the first comprehensive attempt to integrate data-driven modeling with climate impact assessments specifically for this lake. Understanding the modeled circulation patterns provides essential insights for monitoring the spatial distribution of nutrients and primary production zones within Lake Tanganyika, thereby offering tools for more effective fishery management and future sustainability strategies (Coulter & Spigel, 1991; Plisnier et al., 1999, 2023; Verburg et al., 2011).

2. Data and Methods

2.1. The Regional Ocean Modeling System (ROMS)

ROMS is a widely used computational tool for simulating and understanding the behavior of oceanic and large lake systems (Haidvogel et al., 2008). ROMS is a 3D primitive-equation layered ocean model that describes fluid motions resulting from wind, heat, and freshwater forcing, and employs computationally efficient algorithms to parameterize subgrid-scale processes (Warner et al., 2005). In this study, we use ROMS version 4.0. A full description of ROMS can be found in Shchepetkin and McWilliams (2005), McWilliams (2009), and on the ROMS website (<https://www.myroms.org>, last accessed: 21 May 2024).

ROMS has been extensively utilized for research across various domains of oceanography and limnology, including studies on coastal circulation patterns (Chen & He, 2015), Lake Victoria circulation (Nyamweya et al., 2016), marine upwelling events (Bao et al., 2016; Lanerolle et al., 2006), pollutant and nutrient transport (Fayman et al., 2023), coastal erosion (Blaas et al., 2007), and climate change impacts on marine environments (Alexander et al., 2020; Costa et al., 2012; Nagy et al., 2019; Torresan et al., 2019; Wang et al., 2008). It has been particularly valuable for studying lake dynamics, thermal stratification, nutrient cycling, circulation patterns affecting water quality, harmful algal blooms, and climate variability impacts on lakes (McKinney et al., 2018; Nyamweya et al., 2016).

ROMS simulations have proven valuable for environmental management and decision-making. Policymakers use ROMS results to assess the potential impacts of human activities and climate change on specific regions or water bodies (Hollowed et al., 2020), informing resource management strategies such as fisheries management and pollution control. The versatility of ROMS makes it essential for studying fluid dynamics in oceans and large lakes, providing insights into both scientific and practical applications.

In this study, we use ROMS to analyze circulation patterns in Lake Tanganyika, focusing on thermal stratification, current dynamics, and wind-driven upwelling and downwelling. Our aim is to enhance our understanding of these processes and their effects on heat distribution within the lake's ecosystem. We seek valuable insights into

how future climate change could impact circulation, nutrient regeneration, productivity, and the health of Lake Tanganyika's fishery.

Our Lake Tanganyika grid has a nominal horizontal resolution of ~ 2.1 km, covering approximately 610 km from south to north (286 grid points) and 235 km from west to east (110 grid points). The model uses a terrain-following vertical coordinate system with 16 levels, varying in thickness according to bathymetry, designed to effectively capture stratification, particularly in the upper layers where significant thermal gradients occur. The uppermost 20% of the lake's depth is represented by nine layers with thicknesses of 1 m (surface), 4 m, 10 m, and progressively larger increments at greater depths. The depth distribution for a model grid point in the middle of the lake, with a bottom depth of 1,245 m, is as follows (depths in meters): 1, 5, 15, 31, 52, 80, 115, 160, 215, 282, 364, 464, 585, 731, 908, 1,122. This configuration provides finer resolution in the mixed layer and thermocline, with the bottom layer representing the last 19% of the total depth. The model's bathymetry and topography are based on a map prepared by Tiercelin and Mondegue (1991) and digitized by TCarta (<https://tcarta.com>). Additional model parameters can be found in Table S1 in Supporting Information S1.

Model simulations were conducted on the University of Arizona's high-performance computing system (<https://hpc.arizona.edu>). The model was initialized with no motion at a uniform temperature of 23.5°C and a uniform salinity of 1 practical salinity unit (psu), consistent with Lake Tanganyika's freshwater characteristics. We then simulated four complete annual cycles under conditions representative of the year 2000, after which the circulation and thermal structure reached a quasi-steady state. This state became the initial condition for our simulations, and the simulation clock was reset to 1 January 2000. Although the lake's salinity is generally reported around 0.4‰ (Vezzulli et al., 2021) and 0.58 psu (Branchu & Bergonzini, 2004), we adopted a uniform salinity of 1 psu for simplicity, as variations are expected to have a negligible effect on density and mixing processes.

We acknowledge the existence of major river connections in the region but believe their impacts on the lake's hydrodynamics are minimal. Due to a lack of quantifiable data on riverine inputs and outputs, we have not incorporated these contributions into our model. Although riverine inputs could influence hydrodynamics, the absence of reliable data limits our ability to accurately represent these effects. Therefore, our model assumes minimal riverine impacts, which warrants further investigation in future studies.

The ROMS Tanganyika model is forced over a 21-year period using observed monthly meteorological data from the ECMWF ERA5 reanalysis data set (Hersbach et al., 2020). Monthly averages of surface air temperature, net longwave radiation fluxes, solar radiation, air pressure, humidity, rainfall, and wind components were extracted for Lake Tanganyika from 2000 to 2020, focusing on the central transect region to minimize land influence. The grid values were averaged to provide a consolidated representation of each variable across the lake.

Model performance was evaluated by comparing simulated temperature trends with lake-wide hydro-acoustic survey data from Ehrenfels, (2020) [Data set]. This involved comparing temperature profiles at nine monitoring stations around the lake in 2018 with simulated profiles from the lake's three basins for the same year, as shown in Figure S2 in Supporting Information S1.

In addition to our primary modeling approach, we conducted several sensitivity tests to assess the robustness of our results. These included applying MERRA-2 forcing data to evaluate performance relative to ERA5, testing a 30-layer configuration to determine if this would improve the accuracy of temperature profile simulations, and increasing the ERA5 temperature by 1.5°C while keeping other parameters constant to assess the model's sensitivity to temperature changes.

3. Results

3.1. Model Performance and Evaluation of Temperature Simulations

Our simulation of Lake Tanganyika satisfactorily approximates observed temperature patterns, effectively capturing surface temperatures and a well-mixed thermocline down to approximately 80 m (Figure S2a in Supporting Information S1). The model aligns closely with prior instrumental measurements (Verburg & Hecky, 2003) for lake surface temperature. However, we identified two key discrepancies: a lack of uniformity in temperature between depths of 20 and 60 m and a consistent overestimation of about 0.5°C at 300 m (Figure S2a–S2d in Supporting Information S1). We attribute these discrepancies to the model's vertical resolution of only 16 layers. While the model captures general temperature trends well, it smooths out finer fluctuations throughout the

extensive water column. These performance disparities underscore the need for increased vertical resolution to better capture temperature dynamics in Lake Tanganyika. However, such improvements would require significant additional computational resources and time, which are beyond the current scope of model development. The model accurately reproduces enhanced stratification during the warm season compared to the cool season (Figure 3).

Using MERRA-2 forcing data resulted in an annual average overestimation of lake surface temperature by 0.3378°C compared to ERA5 data, due to higher average air temperatures and lower wind speeds in the MERRA-2 data set.

To further assess model performance, we compared simulations with different layer configurations. The 30-layer setup yielded a root mean square error (RMSE) of 0.537, while the 16-layer configuration had a higher RMSE of 0.583 for the upper 300 m (Figure S2c in Supporting Information S1). The RMSE for depths of 800 m was 0.800 (Figure S2b in Supporting Information S1), indicating better performance in the upper water column than in deeper layers (Figure 1).

The model's sensitivity to forcing fields is noteworthy. Applying a 1.5°C increase to the ERA5 data to test model sensitivity resulted in an average surface temperature rise of 1.4°C from the surface down to a depth of 30 m in the north, 1°C from north to south at a depth of 70 m, and 0.4°C at a depth of 300 m in the north and 220 m in the south in December (Figure S2e in Supporting Information S1). In July, this increase led to a rise of 1.4°C in the extreme north to a depth of 100 m, 1°C to a depth of 150 m in the north, and a 0.8°C increase in the southern basin. Additionally, there was a 0.4°C increase to a depth of 170 m in the north and to 300 m in the south (Figure S2f in Supporting Information S1).

3.2. Spatial and Temporal Temperature Variability

The simulations demonstrate significant month-to-month spatial and temporal variability in upper water column temperatures throughout the annual cycle (Figures 2 and 3). The surface water temperature exhibits seasonal fluctuations, with noticeable variations between the northern and southern, as well as the eastern and western regions of Lake Tanganyika. From December to March, surface temperatures become nearly uniform during the warmest months. The lowest simulated surface temperatures occur in July and August ($\sim 25.8^{\circ}\text{C}$ in the south and $\sim 26.4^{\circ}\text{C}$ in the north), coinciding with the strongest winds. As air temperatures rise and northwest winds decrease in October and November, warm water accumulates along the west coast, creating an east-west temperature gradient ($\sim 26.6^{\circ}\text{C}$ in the east and $\sim 27.4^{\circ}\text{C}$ in the west—Figure 2). A key limitation of our study is the lack of observational validation in the western (DRC) portion of the lake, where the absence of instrumental data prevents verification of the inferred temperature gradient. This limitation raises concerns about the reliability of the modeled east-west gradient, and we acknowledge that confidence in these results is limited without ground-truthing. In December, a shift in wind direction to the south mixes the surface water, leading to a gradual warming to peak values ($\sim 27.8^{\circ}\text{C}$) before declining in February and March (Figure 2).

3.3. Influence of Atmospheric Conditions on Circulation Patterns

Circulation patterns in Lake Tanganyika are significantly influenced by air temperature and wind conditions. During the warmer months (November–April), higher air temperatures and lower wind speeds contribute to increased lake surface temperatures. Conversely, during the cooler months (May–October), lower air temperatures and higher wind speeds lead to lower lake surface temperatures.

3.4. Stratified and Mixed Thermocline Conditions

Figure 3 illustrates the simulated temperature profile along our North-South transect for December (stratified conditions) and July (mixed conditions). In December, the thermocline is located at ~ 80 m in the north and ~ 20 m in the south. In July, the thermocline rises closer to the surface in the south while dropping to ~ 150 m in the north, becoming less distinct due to mixing with cooler water from deeper layers.

3.5. Horizontal Circulation and Upwelling Patterns

Figure S3 depicts the horizontal water circulation patterns for July and December. The modeled surface currents closely follow the observed wind curl for Lake Tanganyika (Verburg & Hecky, 2003). Primary upwelling occurs

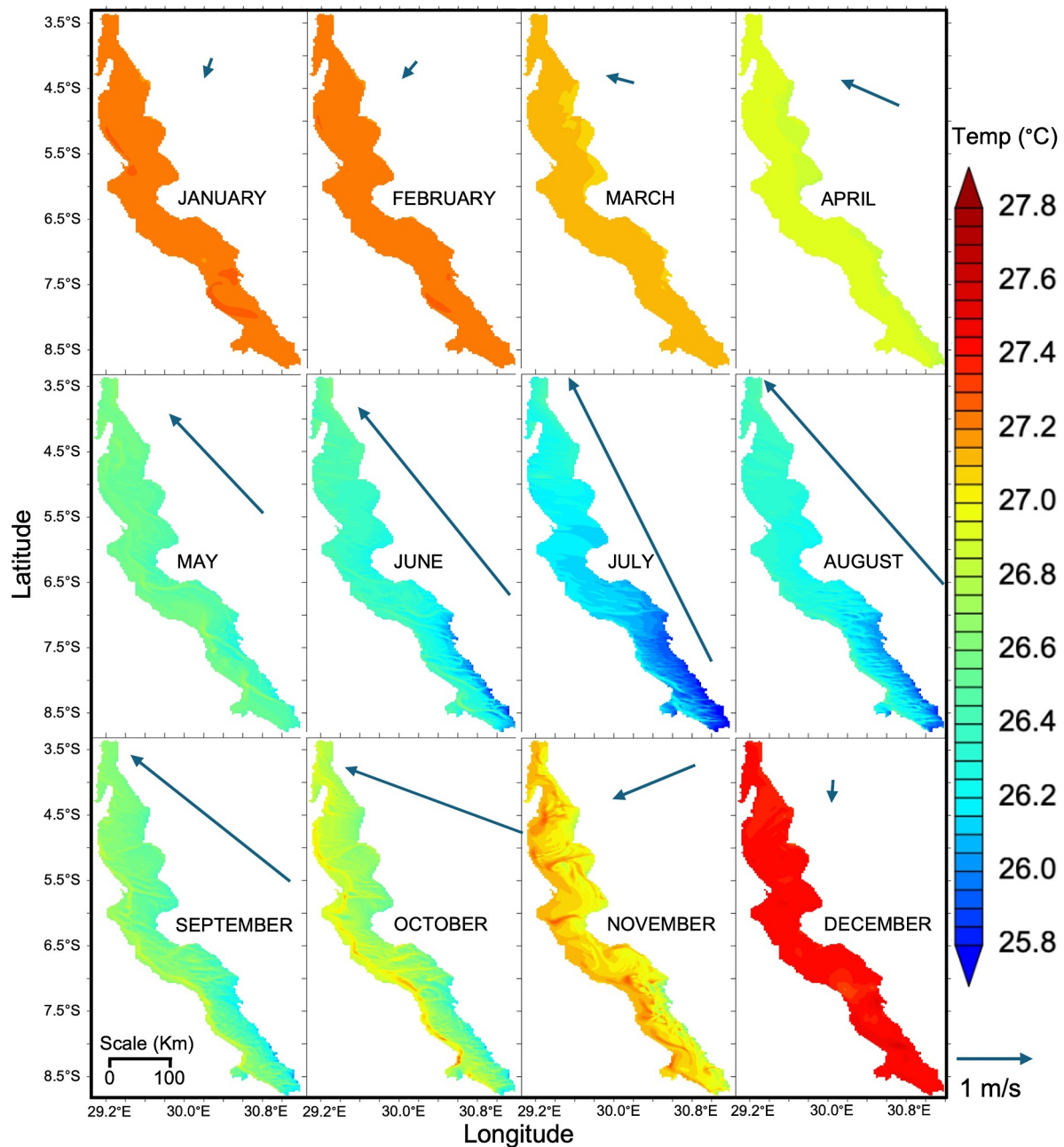


Figure 2. Simulated monthly surface temperatures for Lake Tanganyika in 2020, illustrating seasonal variations. Higher temperatures occur from November to April, and lower temperatures from May to October. The inter-monsoon seasons are represented by the periods of March–April and September–October. During these times, the winds transition from northeast trade winds to southeast trade winds, and vice versa, which impacts the lake's thermal regime. Blue arrows denote wind vectors representing wind forcing over the lake, with a scale (at bottom right) indicating the length of a 1 m/s wind vector.

in the southern and southeastern regions during the southeast trade winds and the relaxation of the northeast trade winds (March and April), while secondary upwelling occurs in the northern regions during the northeast trade winds and the relaxation of the southeast trade winds (September and October). In July (Figures S3a and S3c in Supporting Information S1), surface currents along the central transect show a northwestward component within the top 50 m, with sinking at the northern end of the lake. Return currents flow southeastward at depths between 100 and 200 m before resurfacing in the south. By December (Figures S3b and S3d in Supporting Information S1), surface currents exhibit a southward component at around 50 m in the northern basin, deepening to 100 m in the southern basin.

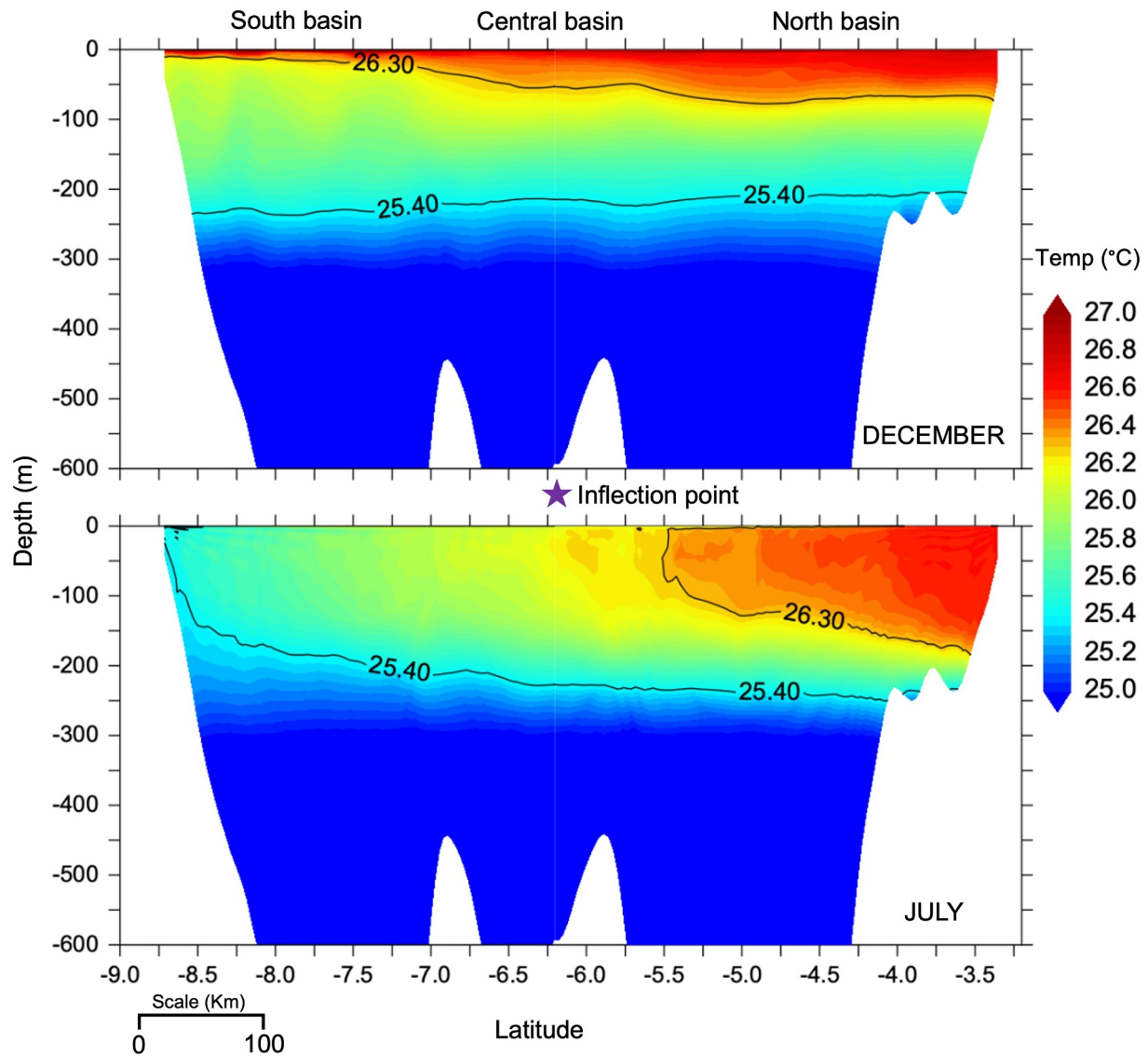


Figure 3. Simulated temperature-depth profiles for the central transect of Lake Tanganyika in July and December 2020, representing the peaks of the southeast and northeast trade winds, respectively. In July, the thermocline tilts northwards; in December, it is predominantly horizontal with a notable deviation in the southern basin, where it approaches the surface. The inflection point from Figure 1 is marked with a purple star. The 26.3°C isotherm shows the positions of the thermocline during the warmest and coolest months of the year. The 25.4°C isotherm, which rises to the surface in the southern basin, is associated with upwelling, while it is found at greater depths in the northern basin, indicating downwelling during the coolest and windiest months of the year.

3.6. Long-Term Temperature Trends

Figure S1 indicates significant warming trends in Lake Tanganyika, particularly at depths exceeding 150 m, with temperatures rising by up to 1.2°C over the past century (panel a). Model data covering two decades, from 2001 to 2020, show a 0.4°C increase at this depth (panel b).

4. Summary and Discussion

Understanding circulation patterns in Lake Tanganyika is crucial for insights into fisheries and ecosystem services vital to local communities. Upwelling processes introduce cooler, nutrient-rich waters to the surface, stimulating phytoplankton growth that forms the base of the aquatic food web and sustains fish species essential for local food security and economic viability.

Upwelling in Lake Tanganyika is driven by wind-induced mixing and thermal stratification. From May to September, southeasterly trade winds prevail, pushing warm surface waters northward and tilting the thermocline. This rising thermocline in the southern basin facilitates the upward movement of nutrient-rich waters, leading to primary upwelling, particularly pronounced during the austral winter when lower temperatures and higher wind speeds disrupt stratification and promote the mixing of and upwelling of cooler waters (Coulter & Spiegel, 1991).

The simulated seasonal oscillations and spatial variations in surface water temperature highlight the lake's dynamic thermal regime. The interplay between air temperature and wind conditions creates varying temperature profiles. High temperatures and low wind speeds cause surface warming and stratification, while low temperatures and high winds mix water layers and facilitate upwelling.

In July, our model shows stratified conditions extend halfway along the lake's length from the north, with cooler temperatures in the southern half due to upwelling. In December, stronger stratification is observed, with a deeper thermocline in the northern region, as documented by Plisnier et al. (2023). This seasonal cycle illustrates the lake's dynamic thermal regime influenced by air temperature and wind.

From March to November, the predominant surface currents flow northwestward, driven by southeasterly winds, which is consistent with prior observations (Coulter & Spiegel, 1991; Savijärvi & Järvenoja, 2000). As upwelling begins in May/June, cooler waters from below cause surface cooling that progresses northward (Figure S4 in Supporting Information S1), leading to downwelling in the northern basin. By November, the Intertropical Rain Belt shifts southward, changing wind direction to northeasterly (Savijärvi & Järvenoja, 2000), causing surface currents to follow this new direction. During this period, rising air temperatures and reduced wind speeds cause the upwelling of previously submerged warm waters in the north, resulting in secondary upwelling (Coulter & Spiegel, 1991; Plisnier et al., 2023) and a uniform warming of the lake. Precipitation levels are also elevated.

Localized upwelling has been observed along the lake's eastern and western shores during inter-monsoon seasons (March/April and September/October), likely due to the formation of Kelvin waves, which facilitate nutrient exchange (Plisnier et al., 2023).

Bathymetry plays a critical role in shaping surface and subsurface currents. Variations in current behavior across different depths and distances from the central transect to the shoreline (Figure S3 in Supporting Information S1) indicate that interactions with the lakebed influence current patterns, particularly near shallower areas along the indented coastline. This interaction may create multiple localized upwelling and downwelling zones along the shoreline.

Enhancing the temporal resolution of our model to include local wind patterns could reveal finer-scale patterns of shoreline upwelling and downwelling documented over shorter timescales (Plisnier et al., 2023).

Prior studies have shown that phosphate levels correlate with mixed layer depth, increasing during the dry season and decreasing during the wet season. Changes in physical forcing can alter the timing and intensity of biogeochemical blooms, with phytoplankton growth influenced by temperature and thermocline depth (Naithani et al., 2012). However, Lake Tanganyika has significantly warmed in recent decades, resulting in a shallower thermocline and decreased productivity, as corroborated by several studies (Cohen et al., 2016; Tierney et al., 2010). While we find that increased wind stress may promote phytoplankton production, these conclusions are inferred rather than modeled. Previous research indicates that rising temperatures decrease phytoplankton and zooplankton biomass due to shallower thermoclines (Verburg and Hecky, 2003, 2009). Conversely, Naithani et al. (2012) propose that higher temperatures coupled with stronger winds could increase nutrient availability, potentially boosting primary production. Given the absence of integrated ecological or biogeochemical modules in our model, further exploration of these interactions in future modeling scenarios is necessary to understand the implications for fisheries productivity and ecosystem health.

Understanding climate change's impact on fishery productivity is crucial for adapting management strategies. Central to this is understanding the influence of circulation dynamics on ecological balance. Directly modeling fishery productivity in Lake Tanganyika is challenging due to insufficient data for model evaluation, especially on the western DRC portion. Therefore, hydrodynamic modeling, potentially enhanced by simple ecological models, emerges as the best approach to assess fluctuations in productivity. Utilizing ROMS with high-resolution forcing and existing measurements can provide insights into future circulation patterns, particularly in light of ongoing lake warming.

Planning for climate variability and formulating policies that integrate both physical and ecological dynamics are critical for maintaining the lake's role in providing livelihood resources. The observed warming trends highlight the urgent need to understand the ecological and biogeochemical consequences, as warming may disrupt species composition and biodiversity, affecting thermal stratification and oxygen levels vital for aquatic life. These shifts pose socio-economic risks for communities reliant on fishing, underscoring the importance of integrating these insights into effective management strategies to address climate change impacts.

5. Conclusion

Lake Tanganyika, with its ecological and socioeconomic significance, has been the focus of our study on circulation patterns using ROMS. Our findings provide insights into thermal stratification, circulation patterns, and wind-driven upwelling and downwelling processes. While we did not model nutrient concentrations and flux rates, prior studies indicate a strong positive correlation between upwelling and nutrient delivery to surface waters, enhancing productivity (O'Reilly et al., 2003; Plisnier et al., 1999; Sarvala et al., 1999). The nutrient module in ROMS (Fennel et al., 2006) enables future applications to explore the implications of circulation changes for nutrient delivery.

Our analysis reveals significant seasonal variations in surface water temperature, highlighting the dynamic thermal regime of Lake Tanganyika. The interplay of air temperature, wind conditions, and water movement drives the lake's circulation patterns. These findings emphasize the complex relationship between atmospheric dynamics and circulation, affecting nutrient and heat distribution in the water column. Model simulations provide insights into the spatial distribution of upwelling and downwelling regions, demonstrating the crucial role of bathymetry in modulating surface and subsurface currents. Observed primary and secondary upwelling events during different wind patterns illustrate localized changes in nutrient circulation, impacting the ecosystem's health and productivity.

The implications of our study extend to guiding future management and conservation efforts. By utilizing ROMS with finer temporal and vertical resolution, we can enhance predictive capabilities for climate change impacts on fisheries and ecological balance. The significant warming trends observed, particularly at depths exceeding 150 m, underscore the urgency of understanding ecological and biogeochemical consequences of these changes, which may disrupt species composition and affect local fisheries.

Our findings emphasize the importance of continued monitoring and research to ensure the sustainability of Lake Tanganyika's fishery and ecosystem. The strong east-west temperature gradients observed during part of the year cannot currently be validated due to a lack of physical observations along the DRC west side of the lake. Addressing this gap should be a priority for future data collection to enhance the validation of our model predictions. Collaborative initiatives involving stakeholders and local communities are crucial for implementing effective management strategies to safeguard the long-term health and productivity of this vital freshwater resource. ROMS modeling can help forecast future circulation in Lake Tanganyika, an important objective for subsequent research.

By bridging the gap between scientific research and practical applications, our study contributes to the broader conservation and management objectives necessary for preserving the ecological integrity and socioeconomic value of Lake Tanganyika for current and future generations.

Inclusion in Global Research

For years, the University of Arizona has partnered with the Tanzania Fisheries Research Institute (TAFIRI) on research focused on the East African Rift Valley lakes. The lead author, a TAFIRI researcher, is pursuing a PhD in Geosciences at the University of Arizona with university support.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The ROMS source code is available at <https://www.myroms.org> (login required). ERA5 data used as model forcing, data for model evaluation, model output files, and animations showing annual lake circulation are available in Kamulali et al. (2025). Additionally, data for model evaluation is accessible from Ehrenfels (2020). PyFerret v7.63 (<https://ferret.pmel.noaa.gov/Ferret/>) was used for data visualization.

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