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3D-modelling of Lake Kivu: Horizontal and vertical flow and temperature structure under spatially variable atmospheric forcing

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Abstract
With the increasing extraction of methane from Lake Kivu, there is a growing need to evaluate the effect of such operations on the lake’s permanent density stratification. This requires understanding of the spatial structure and variability of flow velocities and constituents in Lake Kivu. In this study, we develop a 3D hydrodynamic model of Lake Kivu, set-up within DELFT3D at a 750 m grid spacing and forced by COSMO-CLM atmosphere model results at a 2.8 km grid spacing. Validation shows that the model correctly reproduces the generation and breakdown of the temperature stratification in the upper mixed layer and predicts flow velocity magnitudes and directions similar to measurements both at the surface and at greater depth. Analysis of currents reveals a surface current pattern with two clockwise circulations, one around the whole lake and a smaller one in the northern part, with velocities around 0.1 m/s. This pattern is consistently present over an (ensemble-)averaged day, both in the wet and in the dry season, while day-by-day variations are large. Time-averaged deep currents are found to be a few mm/s at maximum. However, the variations can be substantial, with standard deviations up to 2 cm/s for the currents at 220 m depth, attributed to internal seiches. The temperature stratification, present during the entire wet season, is found to first break down in the dry season in the southern part of the lake. This is explained by the spatial differences in the wind stress and the evaporation heat fluxes during the dry season.

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Introduction
Lake Kivu, on the border between the Democratic Republic of the Congo and Rwanda, is one of the African Great Lakes and part of the East African Rift. Its depth is 240 m on average but reaches up to 485 m (Fig. 1). The water balance of the lake, which has a surface area of 2400 km² and a catchment area of only about three times the surface area (Muvundja et al., 2009), is determined by significant precipitation and evaporation, by inflow from subaquatic groundwater discharges and over 100 tributaries and rivers, and outflow through the Ruzizi River, which subsequently flows into Lake Tanganyika. A special characteristic of the meromictic Lake Kivu is a strong and persistent density stratification with the major pycnocline at approximately 260 m depth (Ross et al., 2015) which is primarily maintained by salinity and causes entrainment of heat, dissolved carbon dioxide and methane in the deeper parts of the lake (see Fig. 2). The latter has motivated scientific research on this lake particularly in the last decennia, as plans have been developed and are being implemented to extract the methane for electrical power production and safety reasons. The salinity and CO₂ result from several subaquatic geothermal groundwater discharges. In the deeper layer, these discharges are generally characterized by relatively high temperatures, salinity and CO₂ concentrations (Degens et al., 1973; Ross et al., 2015). The high methane concentrations are a result of microbial activity
in the deeper anoxic layers and subsequent accumulation beneath the salinity-stratification (Pasche et al., 2011; Wüest et al., 2012), and the latest studies estimate the total methane content below the major pycnocline at about 40 km$^3$ STP (Schmid et al., 2019).

Fig. 1. Lake Kivu, with bathymetry, model grid and locations of measurements used for model validation (Gisenyi, Kibuye and Ishungu indicating the position of temperature measurements and ADCP 1–3 those of velocity measurements). The red line indicates the vertical cross section for temperature structure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Typical vertical profiles of (a) temperature, (b) salinity, (c) carbon dioxide and (d) methane in Lake Kivu, horizontally-uniformly applied as initial conditions for the model simulations (profiles from Schmid et al., 2004. Panel (e) shows the cumulative effects of temperature $T$, salinity $S$, and the concentrations of CO$_2$ and CH$_4$ on the vertical profile of the water density.
The gas accumulation rate is a topic of discussion, with recent measurements suggesting Lake Kivu is presently close to a dynamic equilibrium where methane from decomposing organic material and reduced carbon dioxide is recharged at a rate similar to the loss to shallower layers (Boehrer et al., 2019). On a more detailed level, a spectacular staircase of more than 300 steps appears in the density, temperature and salinity distribution of Lake Kivu caused by double diffusion due to the different molecular diffusivities of heat and dissolved substances (Sommer et al., 2013a,b; Sommer et al., 2014). The staircase is a strong indicator for the absence of significant external, shear-produced turbulence, which would otherwise destroy these regular and pronounced small-scale structures. Therefore, it is generally assumed in numerical studies that vertical turbulence can be neglected for the depths where double-diffusive staircases have been observed (Schmid et al., 2005).

In the deep water (>200 m depth), the temperature and salinity are horizontally nearly homogeneous throughout the main basin and typically vary by less than 0.02°C and 0.01 PSU from the basin-average (Schmid et al., 2005). Larger variations are only observed at the northwestern locations as a result of the overflow of water from the Gulf of Kabuno (Tietze, 1978) and near the inflow of subaquatic springs (Ross et al., 2015). The horizontal homogeneity of salinity and temperature implies that horizontal mixing occurs over a much shorter time scale than vertical transport processes (Schmid and Wüest, 2012). Vertical currents are very limited and occur primarily as a result of the subaquatic groundwater discharges (SCDs) and are therefore likely to be localized around these discharges. To-date there are only circumstance indicators regarding horizontal (deep) currents. Water density measurements by Tietze (1978) indicated that the pycnocline can vary over a limited depth over time, potentially explained by internal waves or seiches (Tietze, 1978, p. 104 and 108), which can occur in a strongly stratified lake especially in case of uniform near-resonant forcing by daily wind events or periodic influxes of characteristic water-masses. However, so far, no data on current velocities are available to corroborate this hypothesis.

The top layer of the lake, or mixolimnion, presents seasonal variation in the thickness of its mixed layer. This top layer, also called “biozone”, is an ecosystem that hosts all aerobic life-forms in Lake Kivu (Wüest et al., 2009), and the oxygenation pattern of this layer varies with the mixing. From September till May (the wet season), a temperature stratification is present within the biozone. Deep mixing (until about 50–70 m depth) occurs during the dry season, when the temperature stratification of the upper layer is broken up each year around August. Meteorological information is the key to understand this stratification behaviour, as heat exchange with the atmosphere causes surface heating and cooling while wind drives upper layer mixing, can cause surface upwelling and plays a role in the heat exchange with the atmosphere as well. Over Lake Kivu, air temperatures were found to be relatively constant over time on a seasonal scale (Bruggen, 2015; Rooney et al., 2018). Most of the variation occurs in a daily pattern, with an average around 25°C and variation up to 3°C within a day. Precipitation in and around Lake Kivu exhibits a bimodal pattern, with an annually repeating cycle of dry (June-August) and wet (September-May) months, and a daily peak around late afternoon – early evening (Bruggen, 2015). Lake evaporation, on the other hand, shows only limited seasonal variability due to the relatively constant air temperature (Muvundja et al., 2014; Bruggen, 2015; Vanderkelen et al., 2018), and has a maximum during the dry season when dry atmospheric conditions increase evaporative demand (Thiery et al., 2014a). Wind data from an automated offshore weather station (AWS Kivu, located on the Rwanda Energy Company platform, 1° 43’ 30” S, 29° 14’ 15” E, off the coast of Gisenyi at roughly 3 km from the northern shore of Lake Kivu; Thiery et al., 2014a) showed a seasonal cycle, with stronger winds occurring during the onset of the dry season (around May), and a daily cycle with a drop at around mid-morning, and relatively constant speed during the rest of the day (Bruggen, 2015). At the measurement location, a land breeze prevailingly originating from the northeast was observed at night, while the direction switched during mid-morning – coinciding with the drop in the wind speed – and was coming from the center of the Lake, directed towards the north (Bruggen, 2015) till around 16:30 (local time). These observations are slightly different from the general daily pattern over the larger African Great Lakes which experience peak precipitation and thunderstorm activity during the night and early morning (Thiery et al., 2015, 2016, 2017; Van de Walle et al., 2020). This difference is possibly explained by the measurement location which might be too close to the shore to experience the characteristic African Great Lake conditions (Camberlin et al., 2018).

So far, the hydrodynamic behavior of Lake Kivu and the economical, ecological and safety aspects of potential methane extraction strategies have been investigated using, for example, 1D vertical numerical models (e.g. Wüest et al., 2009; Wüest et al., 2012; Thiery et al., 2014b). The strength of these models is that they are fast and can be applied to investigate many gas extraction and reinjection scenarios, long time-scales (up to decades), and detailed investigation into vertical fluxes. In the 1D vertical models, horizontal homogeneity of salinity and temperature is assumed. However, the spatially varying wind, potential presence of internal waves, and especially the local disturbances by extractions and reinjections related to the methane extraction plants (and their potential interaction) make it relevant to investigate also the horizontal structure of flow, temperature, salinity and concentration of dissolved gases at various depths within the lake. For that, a 3D modelling is needed.

This paper results from a project to develop, test and validate a 3D hydrodynamic model to study the potential impact of large-scale methane extraction on Lake Kivu. In this study we develop a 3D hydrodynamic model of Lake Kivu, validate this for temperature stratification behavior and for currents using newly measured flow velocities, and explore the spatial patterns and variations in flow and temperature. The set-up of this paper begins with the representation of the governing processes in the Delft3D hydrodynamic modelling software, the model schematization, the simulation set-up, the information used to force the model, and the data used for model validation, including the unique flow velocity measurements obtained as part of this study. Thereafter, we discuss the data-model comparison for vertical temperature profiles and flow velocity information at three locations in the lake. Based on the model results, we then analyze the patterns and variability in the horizontal currents at the surface and at greater depths, as well as the temperature structure. Finally discussion and conclusions about the success and applicability of the modelling efforts are presented.

Methods

Governing processes and their representation in Delft3D-Flow

The 3D model of Lake Kivu has been developed in Delft3D-FLOW, the hydrodynamic module of the Delft3D modelling suite (Deltares, 2014). Delft3D-FLOW is a hydrostatic Reynolds-Averaged Navier-Stokes modelling framework solving the equations for horizontal momentum transport, continuity and transport of constituents, in this case heat content, salinity, and in the future carbon dioxide and methane, with their respective conductivity or molecular diffusivity. A k-ε turbulence model, including buoyancy effects on turbulence, is applied as the turbulence closure model.
The equations are solved using an implicit finite difference method (Alternating Direction Implicit) on a staggered curvilinear grid. For the present application, the equation of state in the modeling system has been adapted to include the effect of carbon dioxide and methane on the water density as well as the haline contraction for the salt composition of Lake Kivu following Schmid et al. (2002). The hydrodynamic module Delft3D-FLOW applied in the present study can be two-way coupled to a wave module to include surface wave induced stresses and mass fluxes and to a near-field module (e.g. the CORMIX near-field expert system) using the coupling system COSUMO (Morelissen et al., 2013) to introduce the entrainment and initial spreading of local discharges (e.g. from methane extraction plants) in a future study. Also coupling to a water-quality module (biochemical processes) is an option of the Delft3D suite.

Considering forcing, the effect of wind on the lake is accounted for by forcing the momentum equations at the free surface with wind stress, which can vary in space and time. Wind effects on mixing are automatically included through the increase of turbulence production with the increase of vertical shear in the horizontal velocity. Other included meteorological drivers are space and time varying atmospheric pressure on the water surface, evaporation and precipitation, and heat exchange through the surface. Heat fluxes accounted for are (net) influxes from shortwave solar and longwave atmospheric radiation, and heat losses due to emitted longwave radiation (back radiation), evaporation (free and forced convection of latent heat) and convection (free and forced convection of sensible heat). The forced convection of latent and sensible heat depends on the air temperature, the water temperature near the free surface, relative humidity and wind speed. Discharge and withdrawal of water at the model boundaries, e.g. by rivers and sub-aquatic sources, are included in the equations through source and sink terms.

Thus, Delft3D-FLOW simulates three-dimensional unsteady flow and transport phenomena resulting from meteorological forcing, including the effects of density differences due to a non-uniform distribution of temperature, salinity, methane and carbon dioxide like buoyancy related turbulence damping, density-driven flow, long (hydrostatic) surface and internal waves and seiching motions. Shorter-scale (breaking) internal waves are not solved, and relative humidity, originating from COSMO-CLM atmosphere model simulations (Van de Walle et al., 2020) and spatially uniform estimates of cloudiness. The COSMO-CLM model and the atmospheric forcing are further discussed in the next section. In addition to the atmospheric forcing, the 3D model of Lake Kivu was forced by sub-aquatic groundwater discharges based on Ross et al. (2015) and Schmid et al. (2005) to account for sub-aquatic inflow of fresher water (mostly between 180 and 250 m depth) and deep (warm) geothermal inflows with high carbon-dioxide and salinity levels (down to 485 m). An overview of the characteristics of these sub-aquatic discharges is given in Table 1. Inflow at the water surface via rivers was included based on measurements of flow rates in 21 rivers around the lake by Muvundja et al. (2009). An additional 20 rivers were included at arbitrary locations to account for uncharted rivers and flows, which were given a fixed flow rate based on the water balance presented by Muvundja et al. (2009, 2014). Finally, the lake has one outflow (Ruzizi river), with a discharge in the model based on Muvundja et al. (2009). An overview of the modelled rivers flowing in and out of the lake is given in Table 2.

Simulations were carried out for the time span 1/1/2012–31/12/2013, with COSMO-CLM results for this period as atmospheric input, and the typical discharges from rivers and sub-aquatic sources as discharge-input. The first half year is considered spin-up time. Noteworthy choices for physical parameters in these simulations are the following. The wind drag coefficient $c_d$ is wind speed dependent following the formulation of Wüest and Lorke (2003), with a minimum drag coefficient for a wind speed $U_{10}$ of 5 m/s and increasing drag for both larger and smaller wind speed explained from wave-induced surface roughness $d$ is wind speed dependent following the formulation of Stanton number and convection (Dalton number) are assumed constant, namely $1.1 \times 10^{-4}$, which is in the range found from measurements (e.g. Bourras et al., 2019) and has been applied in other modelling studies. Both from theoretical and observational perspective, indications exist that, also for these parameters, the use of wind speed dependent coefficients would be a better way to model the physical processes, especially in case of an unstable atmospheric boundary layer above the water surface (Verburg and Antenucci, 2010). After a brief sensitivity study, that advanced formulation has not (yet) been applied here. Relevant numerical choices are: the time step is 1 min in these simulations, which run at a speed of about 180 simulated days in 1 day runtime on 12 3.6 GHz cores. Time series output put with 1-hour intervals is generated for all relevant parameters at multiple locations in the domain for the full length of the simulation. For two periods of one month, namely January 25 till February 24, 2013, in the wet season and July 24 till August 23, 2013, full 3D results are stored at 3-hour intervals.

Atmospheric forcing from COSMO-CLM

The regional climate model COSMO-CLM that provides the atmospheric forcing to the hydrodynamic model is a non-hydrostatic limited-area atmospheric prediction model describing compressible flow in a moist atmosphere based on the primitive thermo-hydrodynamic equations (see e.g., Doms, 2011; Doms et al., 2011; http://www.cosmo-model.org) applied in climate mode (http://www.clm-community.eu/; Rockel et al., 2008). The used simulation runs provided 1-hourly output at a spatial resolution of 0.025° (about 2.8 km). Output is available for the years 2011–2016. The 1-hourly output of 1/1/2012–31/12/2013 has been used to force the hydrodynamic model.

To illustrate the spatial and diurnal variation of the wind forcing, Fig. 3 shows wind patterns at various moments during the
day, ensemble-averaged over 2012 and 2013. During the night, the wind is blowing from the land to the lake, and along both sides of the island, towards a convergence zone above the north part of the lake. Though weakening in time, this pattern is consistently present till around 8:00 in the morning (Central African Time). Between 8:00 and 9:00 winds are very weak, and the pattern starts to change, with winds primarily directed from the lake to the land between 09:00 and 16:00. After 17:00, the land breeze picks up to change, with winds primarily directed from the lake to the land again, with especially during the first part of the night (relatively) strong southwesterly winds over the passages on both sides of the island, the strongest on the west side. This diurnal wind pattern is consistent with a stronger day-night air temperature variation over land compared to water, and the orography around Lake Kivu. Besides this diurnal variation, there is a seasonal variation, with the spatial wind patterns varying slightly over the year, and the strongest wind breeze occurring during the dry season. This is illustrated in Fig. 3 by the magnitude of the wind stress $|\tau_w| = c_d \rho_a |U_{10}|^2$ averaged over a month in both the wet season (panel g) and the dry season (panel h) (with $\rho_a$ the density of the air). The pressure, temperature and relative humidity also show this seasonal variation, while the interannual variation is small (Fig. 4). Note that the 21-day averaged wind speed and pressure do differ for the two locations shown, while temperature and relative humidity are nearly identical. Considering the large role of the COSMO-CLM output in this study, a brief verification of the spatial and temporal variability in the wind using data from two measurement stations is included in Electronic Supplementary Material Appendix S1.

Data used for model validation

The 3D hydrodynamic model has been validated for temperature stratification behavior in the upper 80 m and flow velocities both near the surface and at larger depth, over time periods up to multiple months to just over a year. As no time period exists for which temperature data, velocity data and meteorological forcing are all three available at the same time, we follow the strategy of a non-synchronous validation: Simulations have been carried out for 2012–2013 covering the time span of the temperature data, with COSMO-CLM results for that period as meteorological input, allowing for a direct data-model comparison on temperature. The velocity validation compares model results for velocity for shorter periods within the time span of the validation simulation with newly obtained velocity measurements for a similar period but in another year, zooming in on characteristic features of the measured and modelled velocities such as typical magnitude, direction and possibly oscillatory behaviour.

The temperature validation data consist of time series measurements from CT-sensors at various depths below fixed moorings near Gisenyi in the north and near Kibuye, about 40 km to the south, and high resolution vertical CTD-profile measurements at various moments in time at about those same locations near Gisenyi and Kibuye and also a third location near Ishungu, near the south side of the lake, about 35 km away from the location near Kibuye (see Fig. 1) (Descy and Guillard, 2014). The temperature time series for location Gisenyi were measured from 9/10/2012 to 3/12/2013 and those for Kibuye from 11/10/2012 to 3/7/2013, in both cases just below the surface and about every 10 m up to 70 m depth with an interval of 5 min. To compare the development of the vertical temperature structure over time according to model and measurements, these time series have been interpolated vertically (linear interpolation).

The velocity data have been obtained as part of this study through three deployments of an upward and downward looking ADCP (Nortek Signature 500 and Signature 55 respectively) mounted on a subsurface buoy. The three deployment locations are indicated in Fig. 1, the buoyy depth, cell height, time span of the data and range in depth where the current velocity data is considered valid are indicated in Table 3. The latter is based on the criteria of (i) a signal to noise ratio larger than 3 dB and (ii) a correlation threshold of at least 60%. The configuration was set up to measure both surface currents and deep currents in each deployment. However, during deployment 1 the subsurface buoy ended up much lower in the water column than intended due to entanglement with an auxiliary rope; and, as a result, no surface currents were measured. For deployment 3, even though an alternating pulse mode was applied, the results of the downward looking ADCP are considered not valid based on the mentioned criteria, which is attributed to insufficient seeding at this location and

Table 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Depth/range [m]</th>
<th>Flow [m³/s]</th>
<th>Temperature [°C]</th>
<th>Salinity [g/l]</th>
<th>CO₂ [mmol/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGD_A1</td>
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<td>200</td>
<td>14.3</td>
<td>22.7</td>
<td>2.1</td>
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<tr>
<td>SGD_A2</td>
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<td>193</td>
<td>7.7</td>
<td>22.7</td>
<td>2.1</td>
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<td>23.3</td>
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</tr>
<tr>
<td>SGD_H</td>
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<td>25.3</td>
<td>6</td>
<td>107.9</td>
</tr>
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<td>SGD_I</td>
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<td>26</td>
<td>6</td>
<td>107.9</td>
</tr>
<tr>
<td>SGD_J</td>
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<td>1.35</td>
<td></td>
<td></td>
<td>107.9</td>
</tr>
</tbody>
</table>

Table 2
Characteristics of modelled river inflows and outflow (based on Muvundja et al., 2009, 2014).

<table>
<thead>
<tr>
<th>Name</th>
<th>Flow [m³/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Koko_N4</td>
<td>2.07</td>
</tr>
<tr>
<td>Muregeya_N3</td>
<td>1.79</td>
</tr>
<tr>
<td>Musogora_N2</td>
<td>0.83</td>
</tr>
<tr>
<td>Nyabahanga_N1</td>
<td>0.6</td>
</tr>
<tr>
<td>Gisayo_S1</td>
<td>0.03</td>
</tr>
<tr>
<td>Buhari_S2</td>
<td>0.13</td>
</tr>
<tr>
<td>Kirano_S3</td>
<td>0.54</td>
</tr>
<tr>
<td>Magarame_S4</td>
<td>0.43</td>
</tr>
<tr>
<td>Kawa_B1</td>
<td>0.27</td>
</tr>
<tr>
<td>Mugaba_B2</td>
<td>0.26</td>
</tr>
<tr>
<td>Murhandu_B3</td>
<td>1.29</td>
</tr>
<tr>
<td>Kakumbu_B4</td>
<td>0.69</td>
</tr>
<tr>
<td>Mpungwe_B5</td>
<td>1.87</td>
</tr>
<tr>
<td>Mushuva_B6</td>
<td>1.04</td>
</tr>
<tr>
<td>Lwire_K1</td>
<td>7.3</td>
</tr>
<tr>
<td>Cirhanyobwa_K2</td>
<td>1.6</td>
</tr>
<tr>
<td>Nyabarongo_K3</td>
<td>0.5</td>
</tr>
<tr>
<td>Luziza_K4</td>
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</tr>
<tr>
<td>Binyabihira_G2</td>
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</tr>
<tr>
<td>Kihira_G3</td>
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</tr>
<tr>
<td>Mubambiro_G1</td>
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</tr>
<tr>
<td>riv_23 – riv_42</td>
<td>2.38</td>
</tr>
<tr>
<td>Ruzizi_Outflow</td>
<td>-114.16</td>
</tr>
</tbody>
</table>
depth to get valid results from the 55 kHz instrument. Therefore, the results of deployments 1 and 2 down looking will be used to validate for ‘deep’ currents, and the results of deployments 2 and 3 upward looking for surface currents.

**Results (1): Validation**

**Data-model comparison for temperature profiles**

To verify the model’s ability to reproduce the stratification and its development over time in the upper part of the lake, model results for temperature near Gisenyi, Kibuye and Ishungu are compared with measurements in Figs. 5–7, respectively. The upper panel compares modeled and measured time series at about 10, 30 and 70 m depth, the central panel shows the development in time of the vertical structure according to the data based on vertical interpolation of the time series measured at fixed depths. The lower panel shows this same development according to the model results, together with the incidental high-resolution measurements with the CTD profilers.

Firstly, the model reproduces the observed stratification behavior over the year as a temperature stratification with a gradually downward moving interface between October and end of June (all three locations), followed by destratification, deep mixing and a period without strong temperature stratification from July to September (fixed level CT time series data only for Gisenyi and Ishungu). Also, the slight reduction of the temperature in the upper part of the water column around December solstice is present in the model results. The direct comparison of the time series (panel a) shows that also quantitatively the reproduction is good, though for Gisenyi and Kibuye the water below the interface is 0.1–0.2°C colder in the model results compared to the measurements. Considering differences between the locations, the measurements show a temperature stratification extending less far downward near Ishungu compared to Gisenyi and Kibuye, while also the temperature in the upper water column in August is lower. This difference is also present in the model results.
Data-model comparison for flow velocity

As flow velocity data and model results cover different years, we cannot directly compare measured and computed velocity time series, but rather compare seasonal behavior, considering typical magnitude, direction, variation and internal wave dynamics. This approach assumes that although the exact time development of the wind and therefore the flow in the lake differs between the years of the measurements and the years of the simulation, the wind patterns, statistics and seasonal variations are comparable from one year to another. This assumption of limited interannual variability is supported by Fig. 4, discussed before. The data-model comparison is shown in Figs. 8 and 9 with Fig. 9 showing current roses of magnitudes and directions for both surface currents and currents at larger depth at the three locations of ADCP deployment while Fig. 8 shows the underlying measured and modelled velocity time series for the currents at intermediate depth at one of these locations, namely ADCP2 at 75.5 m depth. It can be seen in Fig. 8 that for this location both modelled and measured velocities are greater in north–south direction compared to east–west direction. For both measured and modelled velocities, the time series averaged velocities are very small, while the standard deviations of especially the northward velocities are significantly larger, respectively 1.8 and 1.9 cm/s for measurements and model results. Note that both signals contain small daily oscillations and more significant oscillations with a period of 7–10 days. This signal is understood as internal waves in response to wind forcing (more on this below). The more extended comparison in Fig. 9 shows that for location ADCP1, depth 162 m, velocities are very small (<0.02 m/s) and no clear directional preference is found in either measurements nor model results. The velocities for ADCP2, depth 75.5 m, are more than twice as large both in measurements and

Table 3

Information on the ADCP deployments, providing data used to validate the model for flow velocities.

<table>
<thead>
<tr>
<th>Deploy nr.</th>
<th>Buoy depth [m]</th>
<th>Total depth [m]</th>
<th>Signature type [kHz]</th>
<th>Cell height [m]</th>
<th>Time span data</th>
<th>Nr. Days of data</th>
<th>Range of valid data [m depth]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130</td>
<td>465</td>
<td>Up) 500</td>
<td>2</td>
<td>27/11/'17 – 19/06/'18</td>
<td>204</td>
<td>115–127</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Down) 55</td>
<td>5</td>
<td>27/11/'17 – 20/04/'18</td>
<td>150–190</td>
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<td>2</td>
<td>10</td>
<td>418</td>
<td>Up) 500</td>
<td>2</td>
<td>24/06/'18 – 24/10/'18</td>
<td>122</td>
<td>2–9</td>
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<td></td>
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<td>Down) 55</td>
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<td>24/06/'18 – 07/10/'18</td>
<td>105</td>
<td>30–90</td>
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<td>3</td>
<td>24</td>
<td>360</td>
<td>Up) 500</td>
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<td>14/11/'18 – 13/01/'19</td>
<td>60</td>
<td>5–19</td>
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<td></td>
<td></td>
<td></td>
<td>Down) 55</td>
<td>5/10</td>
<td>14/11/'18 – 13/01/'19</td>
<td>60</td>
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Fig. 5. Data-model comparison for water temperature at location Gisenyi. (a) model results (lighter lines) and measurements (darker lines) for temperature time series at about 10 m (blue), 30 m (red) and 70 m depth (green); (b) development in time of the vertical temperature structure, based on vertical interpolation of the fixed depth CT-time series measurements (with the gray arrows indicating the vertical position of the instruments, interval about 10 m); (c) model results (background shading) together with vertical temperature profiles from the incidental high-resolution CTD-profile measurements (colored circles, with the gray arrows indicating the point in time of the profile measurements, and the temperature shown by the color of the circle using the same color bar as for the model results). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
model results and show the clear south-north directional preference but absence of a net current discussed with Fig. 8. Also, for the near surface currents at location ADCP2, depth 8.5 m, the modeled and measured velocity magnitudes agree well, and though currents to the south-west are weaker and occurring less in the model compared to the measurements, for both data and model almost all records are found in either the northwesterly or southwesterly quadrant. Only for ADCP3, 13 m deep, the model results are distinctly different from the measurements, as the latter show strong northward currents for the major part of the record which are not present in the model results. As the COSMO-CLM wind data often show strongly sheared winds near ADCP3, we hypothesize the model-data differences are mainly related to slight shifts in the wind pattern between the COSMO-CLM output for 2013 and the real wind forcing in 2018. Based on the results for velocity magnitudes and directions and those for temperature and stratification behavior, it is concluded that the model quality is sufficient to use the model for further analysis.

Results (2): Exploration

Horizontal structure of surface currents

With the validated 3D numerical model, we can now study the horizontal structure and variability of temperature and flow velocities. The ensemble-averaged surface current patterns in Fig. 10 (a-c) show that, although some variability is present in the strength of the flow over the (ensemble-averaged) day, the pattern is rather consistent, with northward flow on the west side of...
the lake and southward directed currents especially in the northeastern corner. The northward flow is the strongest during the night, in line with the wind forcing. Overall, two clockwise circulations are present, one around the whole lake and a smaller one limited to the northern part. The averaged pattern is very similar for the wet season (Fig. 10 d) and dry season month (Fig. 10 h), though weaker in the (more windy) dry season. This might be explained by a stronger daytime lake breeze and more variable position of the local air pressure maximum/minimum over the lake in the dry season, resulting in less favorable winds for the development of the circulation currents. Effects of this seem visible at 14:00 (Fig. 10 f). Not only the variation over the (ensemble-averaged) day (Fig. 10 e-g), but also the variation between the days is larger in the dry season, with standard deviations about 1.5 times greater (lake averaged value around 0.10 m/s versus 0.06 m/s for the wet season) and surface currents incidentally exceeding 0.5 m/s.

Behavior of horizontal currents at larger depth

At greater depths, the horizontal currents are significantly smaller. At 220 m depth, which is about 40 m above the lake's main density gradient, the model predicts averaged velocities of, at maximum, only a few mm/s (Fig. 11), and no significant differences between the seasons. If a structure can be detected for these very small velocities, it is a counter-clockwise circulation in the northern part of the lake and northward velocities on the eastern side of the lake near Kibuye. Note that at this depth (220 m), the lake is horseshoe shaped, hence horizontal circulation cannot extend southward of this island. The variations in the flow velocities, illustrated in Fig. 11 b) by the standard deviation, are much larger than the mean flow, as in Fig. 8 for 75.5 m depth. These variations are the greatest on the eastern side of the lake, with a focus at the ‘constriction’ at a latitude of 1.9° South, about the location of the second ADCP deployment.

The variations are further explored in Fig. 12, using model results for the location ADCP2 (Fig. 1). The wind spectra show that the wind energy is predominantly present at diurnal and semi-diurnal frequency, the first matching the land breeze - lake breeze alternation, the latter as second harmonic covering differences in strength and duration of land breeze and lake breeze. The profiles show that, except in the mixolimnion, the mean currents are extremely small, while the standard deviations, reflecting the energy in eastward and northward oscillatory motions, are of order 1 cm/s also at larger depth. The most energy is present in the northward velocity component, with a peak around the lake's main density gradient at 250 m. Spectra for the northward velocity at various depths show that, similar to the wind forcing, near the surface most energy is present on the diurnal and semi-diurnal frequencies. However, at greater depth, a substantial part of the energy is found at approximately 0.03 h^{-1}, 0.016 h^{-1} and between 0.005 and 0.008 h^{-1} (periods of 33 h, 62 h and 125–200 h, i.e. 5–8 days),

Fig. 8. Data-model comparison for horizontal flow velocities. (a) Measured eastward (orange) and northward (blue) velocities at location ADCP2 for 75.5 m depth during deployment from June till October 2018; (b) Modelled eastward (orange) and northward (blue) velocities at the same location and depth, but for time period June till October 2013. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
which is understood as internal seiches in the multi-layer system in response to the wind forcing. At 220 m depth, particularly the latter oscillation is strong and completely dominates the time series. Adopting a basin length along the axis of approximately 100 km for the horseshoe shaped basin at 220 m depth, such an internal seiche would require a wave propagation velocity $c$ of approximately 0.35 m/s, which seems feasible considering the density difference and the thickness of the layer above the main density gradient.

We conclude that Lake Kivu’s response to wind forcing exhibits a direct response near the surface and internal waves oscillations in the deep interior. Yet, the presence of diffusive-type staircases structure at depth indicates that the shearing associated with internal wave activities remain weak. Further fundamental study could investigate the interaction between double diffusive staircases and internal wave processes.

**Horizontal variation in the temperature structure**

Fig. 10. Horizontal flow velocities at the water surface. Upper row: ensemble-averaged velocities at (a) 2:00, (b) 14:00 and (c) 20:00 Central African Time, resulting from ensemble-averaging of model output for the wet season month (January 25 till February 24, 2013); (d) average over the full month; Bottom row: the same for the dry season month (July 24 till August 23, 2013).

Fig. 11. Horizontal flow velocities at 220 m depth. (a) Averaged velocity; (b) standard deviation; both for the month in the dry season (July 24 till August 23, 2013).

Horizontal flow velocities at 220 m depth. (a) Averaged velocity; (b) standard deviation; both for the month in the dry season (July 24 till August 23, 2013).

Fig. 13 shows the upper 140 m of a north–south cross section of simulated temperature over the lake averaged over two weeks in the wet season – when the stratification is strong – and two weeks in the dry season – when the stratification is in the process of breaking up. The cross section is taken just east of Idjwi Island (Fig. 1). It is observed that the horizontal temperature structure is much more homogeneous during the wet season compared to the dry season. In the first case, the thermocline is present over the entire cross section, though positioned slightly higher in the water column in the northern part of the cross section. In the second case, the structure is much less horizontally uniform, and stratification is almost absent at the southern side of the lake, while there is still stratification present on the northern side. Apparently, the stratification breaks up first on the south side of the cross section, which we explain from spatial variability of the wind stress and the heat flux related to wind-driven evaporation. For the two weeks in the wet season, the wind stress is very low and, except for a local reduction to almost zero at 40 km from the north side, around $5 \times 10^{-3}$ N/m$^2$ along the whole cross section.
Also, the evaporation heat flux is quite uniform and, except for an increase at the very north end, around 135 W/m² from the lake upward. For the dry season, it was found earlier that the overall evaporation heat loss is greater, attributed to the lower relative humidity (Thiery et al., 2014a). The greater evaporation heat loss is found here as well for the two weeks in the dry season. However, compared to the two weeks in the wet season, the evaporation heat loss is much more spatially varying, increasing from 150 W/m² to 200 W/m² from north to south. We explain this from the larger spatial variability of the wind stress, increasing from $5 \times 10^{-3}$ N/m² to $15 \times 10^{-3}$ N/m² from north to south (compare Fig. 3 g), which not only provides greater mixing energy on the south side, but also enhances the evaporation heat loss. This causes a faster cooling and breakdown of stratification in the southern lake. Note that all other heat fluxes were found to be much more spatially uniform. There totals add up to a heat influx of about 130 W/m² for the two weeks in the wet season and 140 W/m² for the two weeks in the dry season. This means that there is a net heat loss over the whole cross section during the two weeks in the dry season, but more importantly that this loss is increasing from about 10 W/m² north to 60 W/m² in the south. Note that the resulting temperature differences may affect the surface currents, compare (Verburg et al., 2011).

**Discussion**

Within this study, the first 3D hydrodynamic modeling of Lake Kivu was developed. The main advantage of such a model over existing 1D modeling tools is the inclusion of the horizontal dimensions. This provides many opportunities for future applications. Most importantly, it allows for investigation of horizontal effects of extractions and reinjections related to the methane extraction present and future plants. This includes research into potential mutual interference among multiple extraction plants, which is an important question when considering the feasibility to split up the lake and its methane sources in various concession areas. For this, the model could be coupled to near-field discharge models through the coupling system COSUMO (Morelissen et al., 2013) to introduce the entrainment and initial spreading of local discharges. The standard coupling to the Delft3D water quality (biochemical processes) module provides the opportunity to add to the model methane and carbon dioxide generation and reduction processes in Lake Kivu following the analysis of Pasche et al. (2011), which would allow studying of the fate of reinjections and their dissolved gas contents as the result of flow velocities, mixing, and biochemical production and destruction combined. Another application toward improved water quality could be...
tracing of plastics and pollutants to identify sources. The model also opens new avenues for the study of effects of climate change on the lake. With all these applications, we consider the present study as the start of a more extensive approach. For now, mainly due to computational limitations, the present hydrodynamic model can best be applied to investigate a limited number of scenarios for up to about 1–3 years (compared to decades and large numbers of scenarios with very high vertical resolution for the various existing 1D models).

Conclusions

In relation to increasing methane extraction for energy production, there is a growing need to understand the spatial structure and variability of flow velocities and constituents in Lake Kivu, as well as interest in tools to predict them. In this study we developed the first 3D hydrodynamic model of Lake Kivu, validated the model for temperature stratification behavior and flow velocities, and explored the spatial structure and variations in flow velocities and temperature. The model is set-up within DELFT3D at a 750 m grid spacing and forced using results from a COSMO-CLM atmosphere model simulation at a 2.8 km grid spacing, which yields winds with significant spatial, diurnal and seasonal variations. Based on the validation, it is concluded that the 3D hydrodynamic model correctly reproduces the generation and breakup of the temperature stratification in the upper layer and predicts flow speed and directions similar to flow measurements both at the surface and at greater depth. Further exploration of the model results revealed a surface current pattern on the lake with two clockwise circulations, one around the whole lake and a smaller one limited to the northern part, with velocities around 0.1 m/s. On an (ensemble-) averaged day, this pattern is present over the whole day, both in the wet and in the dry season, though day-by-day variations can be large. Time-averaged deep currents were found to be a few mm/s at maximum, without clear difference between the seasons. However, on shorter time scales the variations in the deep currents can be substantial, particularly on the east side of the lake, with standard deviations up to 2 cm/s nearshore of Idjwi island for the currents at 220 m depth. Exploration of the horizontal variation in the temperature structure in the upper biozone for a north–south cross section over the lake east of Idjwi island revealed that the temperature stratification, which is consistently present during the wet season, first breaks up in the dry season in the southern portion of the lake. This is explained by the spatial differences in wind stress and evaporation heat fluxes during the dry season. The 3D hydrodynamic model provides a foundation for further extension to include schematized methane extraction plants to investigate extraction/reinjection scenarios on time-scales up to 1–3 years.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix S1. Verification COSMO-CLM wind forcing

As described in section 2, results from the regional climate model COSMO-CLM simulations are used to force the hydrodynamic model. This is done to account for the strong spatial variability in the wind. Although extended validation of the COSMO-CLM results is beyond the scope of this study, a brief verification of the spatial and temporal variability in the wind using available data is considered relevant to support this approach. Fig. S1 shows wind roses for COSMO-CLM output and measurements at two location on/near the lake, namely the Automated Weather Station AWS Kivu off the coast of Gisenyi and the land-based wind station near Kibuye at the east side of the lake. Their locations are indicated in Fig. 3. For both locations, COSMO-CLM model and observations show similar wind speeds and preferential directions: wind from the northeast occurs most often at the AWS Kivu platform near Gisenyi while southeasterly winds prevail near Kibuye. These wind directions are in line with the lake breeze effects discussed in section 2.3 and the comparison confirms the large spatial variability found in the COSMO-CLM results. For Gisenyi, this directional preference is stronger in the measurements, and the wind speed is slightly higher (compare share of wind speed exceeding 3 m/s in COSMO-CLM results and measurements). Fig. S2 compares the diurnal, seasonal and interannual variation in COSMO-CLM results and measurement for the location of the AWS Kivu platform. Both show the diurnal pattern, with a drop in the wind speed around 9:00 and especially in August also around 18:00. Both show a similar seasonal variation, with the stronger winds and larger variations in the wind speed in August. For both model and measurements, the interannual variation is relatively small, with similar variation patterns for the two years shown. Note that the COSMO-CLM results tend to underestimate the wind speed during the second half of the night / early morning, 3:00-9:00, especially in August (which matches with the larger share of low velocities discussed for Fig. S1). This might also explain why sensitivity tests with wind dependent Stanton and Dalton numbers in the description of the heat flux processes of evaporation and convection resulted in general in an underestimation of the temperature in the upper layer of the lake: with wind dependent coefficients, wind velocities of approximately 2.0 m/s instead of 3.5 m/s during the night result in increased nightly heat fluxes from lake to atmosphere and subsequently increased nighttime cooling.
Fig. S1. Comparison of wind statistics from COSMO-CLM model and measurements. Left column: for the location of the offshore AWS Kivu (location 1° 43′ 30″ S, 29° 14′ 15″ E) near Gisenyi in the northeast of the lake, using model results and data for the period 2013-2016; Right column: for the location of the land-based wind station near Kibuye (2014-2015) at the eastern side of the lake, with information from the period 2014-2015. Upper row: COSMO-CLM results; Bottom row: wind station measurements. For location of the wind stations, see Figure 3. The length of the bars denotes the percentage of the record within the wind direction and speed range belonging to the bar. The color of the bars denotes the wind speed range, see colorbar, so dark blue means wind speeds between 1 and 2 m/s.

Fig. S2. Comparison of COSMO-CLM output and measurements for wind speed at the location of the AWS Kivu using a simplified boxplot showing daily, seasonal and interannual variability. Left column: COSMO-CLM model results; Right column: measurements. Upper row: for a month in the wet season; Bottom row: for a month in the dry season. Dots: median of all values in the considered month for the hour indicated on the x-axis. Lines: range between the 1st and 3rd quartile of the same set of values. Time is Central African Time. (The exact periods considered are January 25 till February 24, and July 24 till August 23, to match the hydrodynamic output).