A framework for ensemble modelling of climate change impacts on lakes worldwide: the ISIMIP Lake Sector

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Abstract

Empirical evidence demonstrates that lakes and reservoirs are warming across the globe. Consequently, there is an increased need to project future changes in lake thermal structure and resulting changes in lake biogeochemistry in order to plan for the likely impacts. Previous studies of the impacts of climate change on lakes have often relied on a single model forced with limited scenario-driven projections of future climate for a relatively small number of lakes. As a result, our understanding of the effects of climate change on lakes is fragmentary, based on scattered studies using different data sources and modelling protocols, and mainly focused on individual lakes or lake regions. This has precluded identification of the main impacts of climate change on lakes at global and regional scales and has likely contributed to the lack of lake water quality considerations in policy-relevant documents, such as the Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). Here, we describe a simulation protocol developed by the Lake Sector of

the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) for simulating climate change impacts on lakes using an ensemble of lake models and climate change scenarios. The protocol prescribes lake simulations driven by climate forcing from gridded observations and different Earth system models under various Representative Greenhouse Gas Concentration Pathways, all

5 consistently bias-corrected on a 0.5° x 0.5° global grid. In ISIMIP phase 2, 11 lake models were forced with these data to project the thermal structure of 62 well-studied lakes where data were available for calibration under historical conditions, and for nearly 17,500 lakes using uncalibrated models and forcing data from the global grid where lakes are present. In ISIMIP phase 3, this approach was expanded to consider more lakes, more models, and more processes. The ISIMIP

10 Lake Sector is the largest international effort to project future water temperature, thermal structure, and ice phenology of lakes at local and global scales and paves the way for future simulations of the impacts of climate change on water quality and biogeochemistry in lakes.

1. Introduction

15 Even though there are over 117 million lakes on Earth, and they cover only tiny fraction (~3%) of the Earth's continental surface (Verpoorter et al., 2014), lakes are among the most anthropogenically altered ecosystems on Earth (Carpenter et al., 2011, Jenny et al. 2020), and while many impacts on lakes are local, climate change is a global driver interacting with all other pressures influencing lakes, regardless of their scale. It is necessary to disentangle the global impacts of

20 climate change from other anthropogenic pressures to strengthen mitigation and adaptation measures. However, global estimates of historical and future lake responses to climate change have largely been carried out as site-specific studies with different goals, data and modelling protocols, which complicates the generalization of simulated impacts at regional and global scales (Settele et al., 2014; Masson-Delmotte et al., 2018).

Historical records show that lakes are already responding to climatic change by warming (O'Reilly et al. 2015, Pilla et al., 2020, Jane et al., 2021, Gal et al., 2020), experiencing declining ice cover (Sharma et al. 2019; Weyhenmeyer et al. 2011), shifting thermal habitats (Kraemer et al., 2021), changing mixing regimes (Woolway and Merchant, 2019 ; Kraemer et al. 2015), and decreasing oxygen levels (Jane et al., 2021). However, long-term monitoring data remain limited to a relatively small number of well-studied lakes, while time series from automated high sampling frequency monitoring buoys are still generally short (Marcé et al. 2016). The existing empirical evidence needs to be combined with lake models to understand how lakes have responded to historical changes (Moras et al., 2019) and how they could behave under future climatic change. Numerous numerical models have been used to assess climate change impacts on lake ecosystems (Ayala et al. 2020 2019; Piccolroaz, Woolway, and Merchant 2020; Hansen et al. 2017; Schwefel et al. 2016); however, the climate change impacts synthesized in the recent IPCC reports remain limited to a small number of lakes, regions or specific impact models or climate change scenarios (Kramer et al. 2015, Masson-Delmotte et al., 2018). Multi-model ensemble simulations are increasingly used to obtain more robust assessments of freshwater ecosystem responses to climate change, but so far, only a few lakes have been assessed following a multi-model approach (Perroud et al. 2009; Trolle et al. 2014; Stepanenko et al. 2010; 2013; 2014; Thiery et al. 2014; Gal et al. 2020; Guseva et al., 2020). To date, no multi-model ensembles have been used over a broad range of lakes to make either hindcast or future climate simulations, which would allow evaluating the variability in model output related to different model formulations or parametrizations.

The ISIMIP framework (www.isimip.org) provides a set of climate and socioeconomic forcing data to make consistent historical hindcast and future climate impact projections and evaluate impacts in response to policy-relevant climate change scenarios. ISIMIP is organized in different sectors ranging from hydrology to human health, all of which make use of common and openly provided input data. As part of ISIMIP, we initiated the Lake Sector and developed a lake model simulation protocol to assess climate change impacts on lakes and to provide robust scientific evidence of historical and potential future lake ecosystem changes. To this end, we used two complementary

strategies: (i) a local strategy to simulate 62 well-studied lakes where sufficient data were available for lake specific model parameterization and calibration; and (ii) a global strategy that applied lake models to a generic lake for each land grid cell of the 17,500 ISIMIP global grid with information on lake surface area and depth. The simulation setup described by the protocol enables projecting

5   and attributing impacts of climate change on lake water temperature. The protocol allows incorporating uncertainties derived from the differences in global climate models (GCMs), the differences in lake impact model structure, and lake geographical and ecosystem characteristics. The standardized output produced by the hydrodynamic lake models included vertical profiles of water temperature and metrics describing thermal and ice conditions at daily to annual time scales.

10 The multi-model ensemble provided a systematic overview of plausible future responses of lake ecosystems to a warming climate at an unprecedented geographical coverage. The forcing data from the GCM ensemble further enabled us to quantify lake responses to changes in meteorological variables other than air temperature, e.g., from wind velocity or cloud cover (Woolway et al., 2019, Mi et al., 2018), including their potential interactions with increases in air temperature. Completed

15 and ongoing thermal regime simulations will provide the foundation for the modelling of water quality, greenhouse gas emissions, algal blooms (Janssen et al., 2019), and water level fluctuations to be addressed in future ISIMIP rounds.

Here, we describe the protocol for the global- and local-scale intercomparison of lake models in phase 2 (ISIMIP2) as well as the extensions implemented for the ongoing phase 3 round (ISIMIP3).

20 First, we provide an overview of the climate data and climate change scenarios available through ISIMIP that were used as forcing data for lake impact models. Next, we explain the rationale behind the ISIMIP Lake Sector, give an overview of the impact simulations, and briefly describe the lake models used at local and global spatial domains. Finally, we highlight some examples of the first lake impact model simulations from the ISIMIP2 simulation phase and illustrate how the

25 simulations allowed us to quantify sources of uncertainty in future projections.

The Lake Sector simulations are the first consistent ensemble projections of climate change impact on lakes, which will provide guidance to researchers, policymakers, and water managers as well as

enable comparison of impacts with other sectors participating in ISIMIP. Given the importance of lake thermal structure in regulating lake processes, ISIMIP2 simulation results from the Lake Sector provide a fundamental contribution to lake specific policy recommendations in reports from organizations like the IPCC, the Intergovernmental Science-Policy Platform on Biodiversity and

5 Ecosystem Services (IPBES), and the UN Environment Programme World Water Quality Alliance (UNEP-WWQA). Furthermore, the work described here paves the way for lake water quality simulations playing a fundamental role in international policy.

2. The Lake Sector in the ISIMIP framework

The ISIMIP2 simulation framework was divided into two simulations rounds: ISIMIP2a and

10 ISIMIP2b. ISIMIP2a focused on historical simulations, which were forced with gridded climate reanalysis products based on observed meteorological data. The ISIMIP2b simulation round focussed on quantifying the impacts of GCM-derived historical and CMIP5 (Coupled Model Intercomparison Project Phase 5) projected climate change relative to a pre-industrial control (Frieler et al., 2017). For the Lake Sector, ISIMIP2a simulations centred around the calibration of

15 lake models at the local scale that were used for the future climate ensemble simulations in ISIMIP2b. These simulations also evaluated the lake models' ability to simulate observed climate variability and extremes at both local and global scales. The subsequent simulation phase, ISIMIP3a-b, will build on the latest gridded observations and CMIP6 global climate model simulations to provide meteorological forcing and improve the representation of non-climatic input

20 data, such as land use and a dynamic global lake mask, which will be used to produce a new generation of lake model simulations.

The inception of the Lake Sector and the gathering of the first collection of models, modelling teams, and lake data providers greatly benefited from contributions from two global collaborative projects.   First,   the   Lake   Model   Intercomparison   Project   (LakeMIP,

25 https://www.unige.ch/climate/lakemip) started in 2008 (Stepanenko et al., 2010) with the objective

of comparing the thermodynamic regime of lakes (including lake-atmosphere interactions) in a wide range of climatic conditions and mixing regimes as simulated by several one-dimensional lake models (Perroud et al. 2009, Stepanenko et al., 2013, 2014; Thiery et al., 2014; Guseva et al., 2020). Second, the Global Lake Ecological Observatory Network (GLEON, https://gleon.org, Weathers et

5 al., 2013) started in 2005, with the aim of conducting innovative science by sharing and interpreting lake data to understand, predict, and communicate the role and responses of lakes in a changing global environment.

3. Experimental setup

10 The simulations followed the network-wide simulation protocols for ISIMIP 2a-b (Frieler et al., 2017; Schewe et al., 2019) and ISIMIP3a-b (see https://www.isimip.org/protocol/ for an overview). Here, we describe the rationale and specifics of simulations in the Lake Sector. Lake model simulations were conducted in two spatial domains: local and global (Fig. 1). Climate change impacts were simulated for existing lakes in the local domain and "representative" lakes in the

15 global domain. These two complementary spatial domains balanced the need for site-specific information and the need for a global assessment of climate change impacts on lakes. All temperature simulations were conducted under the assumption that the water level of the lakes remained constant and, therefore, the lakes were decoupled from their watersheds. This assumption allowed us to make evaluations of lake dynamics based on meteorological forcing data only and

20 was judged acceptable for this first phase of lake sector simulations. It is planned that subsequent simulations, especially those that will evaluate changes in lake biogeochemistry, will abandon this simplification and contribute to cross-sectorial collaborations.

3.1 Case-study lakes in the local domain

Lakes in the local domain had sufficient information to allow the lake models to be parameterized using individual lake bathymetry and to be calibrated against measured water temperature profiles. Consequently, the local lake data set was a unique resource for testing and evaluating lake model performance.

For ISIMIP2, bathymetric data and historical data on water temperature from 52 lakes and 10 reservoirs (Fig. 1a, Table S1) were shared among participating modelling teams. Since reservoirs were treated like regular lakes in the simulations, all waterbodies are hereafter called "lakes" (see section 4.3). The geographical distribution of the lakes encompassed a gradient of five major climatic groups in the Köppen-Geiger climate classification, including tropical, arid, temperate, boreal, and polar. Temperate and boreal lakes located in the Northern Hemisphere comprised 87% of all case-study lakes. The surface area of lakes ranged from 0.011 to 2,700 km², with an average and median area of 121.1 and 8.9 km^2, respectively. Two-thirds of lakes covered surface areas between 1 and 100 km^2. The average and median mean depth of lakes were 26.3 and 10.8 m (range: 1.7-304.8 m), where 90% of the lakes were deeper than 3 m. The Secchi depths reported for 49 of the lakes were 4.9 m (average) and 3.5 m (median) and ranged from 0.5 m to 32 m, which indicated a wide range of lake trophic status.

In ISIMIP3, the same approach is followed, but the number of lakes is expanded. This is achieved through a data call to the research community, and by capitalizing on existing data harmonization efforts (e.g., Pilla et al., 2021).

3.2 Representative lakes in the global domain

Lakes in the global domain considered a generic lake in each of the 17,500 grid cells that contain lakes within the ISIMIP2 0.5° by 0.5° global grid. Uncalibrated lake model simulations were performed on each of these generic lakes.

To assign the bathymetry to these generic lakes in the global domain of ISIMIP2, the average lake depth and lake surface area were calculated based on a rasterized version of the Global Lake and Wetland Database (Lehner and Doll, 2004). Specifically, for each grid cell, average lake depth and lake surface area values were calculated from all lake data contained within that cell. Lake

5 bathymetry for each cell was assumed to be cylindrical. The 17,500 generic lakes are assumed to be representative of all lakes within each 0.5° grid cell (Subin et al., 2012). This approach based on mean lake characteristics in the grid cell could not account for the spatial distribution, variability, and non-uniform distribution in the depth and area of lakes in a grid cell. However, similar representations of lakes were used in Earth System and Numerical Weather Prediction Models

10 (Subin et al., 2012, Balsamo et al., 2012, Thiery et al., 2015, 2016, Vanderkelen et al., 2021). The grid cell lake representation was a necessary trade-off between computational feasibility and global representativeness. In the case of the global simulation model CLM4.5 (see section 3.3.2 below), all representative lakes had a constant 50 m depth. The global-scale lake coverage made it possible to represent lakes in all major climatic classes and their subclasses, which was not possible in the

15 local lake domain. The global average, median and maximum surface area were 146 km^2, 67 km^2, and 3091 km^2, respectively, while lakes with an area between 10 and 100 km^2 comprised 60% of all lakes. The mean depth of the representative lakes ranged from 1.9 to 1000 m, with average and median values of 12.9 m and 10 m, respectively (see Fig 3a).

In the ISIMIP3 simulation round, an updated lake mask including reservoirs was used (Fig. 3b and

20 c). This new lake mask was based on the HydroLAKES (Messager et al., 2016) and Global Reservoir and Dam databases v1.3 (GRanD; Lehner et al., 2011), containing 1.42 million individual lake polygons and 7320 reservoir polygons. These polygons were converted to the 0.5° by 0.5° ISIMIP grid, giving lake area fraction per grid cell (Vanderkelen et al., 2020). In addition, the new datasets accounted for the increase in lake area due to reservoir construction, based on GRanD. The

25 lake depth dataset providing average lake depth per grid cell, was updated to the Global Lake Database v3 (Choulga et al., 2019), for which the original data was remapped from 30'' to match

the ISIMIP grid. Lake depth was, however, static and hence did not account for reservoir operations. The lake input was published with the following DOIs: https://doi.org/10.48364/isimip.263794 (for ISIMIP3a) and https://doi.org/10.48364/isimip.383948 (for ISIMIP3b).

3.3 Lake models participating in ISIMIP

5   Currently, 10 different lake impact models participate in the ISIMIP Lake Sector, where for some models two different versions were applied (Table 1). There are 8 lake models providing calibrated simulations in the local domain: air2water4par, air2water6par, ALBM, FLake-IGB, GLM, GOTM5.1, MyLake, and Simstrat. The global ensemble consists of 6 lake impact models: ALBM, CLM, GOTM5.3, LAKE, Simstrat-UoG and VIC-LAKE. In the sections below, these models are

10   briefly described. For the models that contribute to both the local and global spatial domains, the global impact model section (3.3.2) only describes the differences compared to the local version of the model used.

3.3.1. Lake models for local simulations

15   **air2water** is a hybrid of a physically based and statistical model which simulates lake surface water temperature and epilimnion thickness solely based on air temperature as external forcing (Piccolroaz et al., 2013). The model estimates lake temperature in a single layer characterized by a time-varying thickness according to an empirical relationship accounting for the effect of thermal stratification. Within ISIMIP, two different versions of this model provided simulations for local

20   lakes: air2water4par and air2water6par; these two setups of the model differ in the number of parameters affecting the lake thermal dynamics (Piccolroaz et al., 2016). The air2water model has been applied in lakes of varying climatic and morphometric conditions worldwide (Toffolon et al., 2014; Prats and Danis, 2019; Piccolroaz et al., 2020).

The Arctic Lake Biogeochemistry Model (ALBM) is a one-dimensional process-based coupled

25   lake hydrodynamic and biogeochemistry model (Tan et al., 2015). The model simulates water

temperature dynamics, ice phenology, phytoplankton and dissolved nitrogen, oxygen, carbon dioxide and methane. ALBM was originally developed for Arctic lakes (Tan et al., 2015, 2017) but has been used for other lakes across the globe (Guo et al., 2020, 2021; Tan et al., 2018). The thermal regimes of lakes is simulated in ALBM using 1D thermal diffusion equations in both water and

5   sediment columns with atmospheric boundary conditions driven by sensible heat, latent heat, thermal radiation, and solar radiation. ALBM simulates 51 irregular lake layers. Snow and ice dynamics are solved using one snow layer, one white/gray ice layer that is formed when too much snow is accumulated, and multiple black ice layers (Tan et al., 2018).

FLake-IGB (v2.0) is a one-dimensional model specifically designed to represent the effects of

10 inland waters in climate models and numerical weather prediction systems (Mironov et al., 2008). FLake uses a two-layer parametric representation of the lake water column. The upper layer is vertically homogeneous, representing the surface layer produced by wind and convective mixing at the lake surface. The lower layer represents the thermally stratified part of the water column. Two additional layers simulate the ice cover and the lake sediment. The vertical temperature distribution

15 in each layer is modelled by a parameterized function of vertical coordinate, derived from a self-similar representation of the temperature profile. For calculation of surface heat fluxes, the model input includes standard meteorological variables describing the air-lake interaction: air temperature and humidity, wind force, and long-wave atmospheric radiation (or cloud amount for its calculation). The short-wave solar radiation enters the model equations as the volumetric source

20 term distributed across the water column. The FLake-IGB version used here uses longwave radiation as a direct input, instead of calculating it from cloud cover.

The General Lake Model (GLM, v3.0) is a one-dimensional hydrodynamic lake model, which simulates temperature stratification in lakes (Hipsey et al., 2019). It uses a flexible Lagrangian grid, and an energy budget approach to simulate mixing. The vertical layer structure can change in

25 number and thickness throughout a simulation, following changes in stratification and lake volume. In this study, we based the initial number of layers on the initial water depth. In addition, GLM includes modules for surface heat exchange and ice/snow dynamics, vertical mixing, and water

balance dynamics. GLM can be coupled to the Aquatic Ecodynamics Modelling Library (AED) to simulate water quality dynamics and ecosystem interactions.

The General Ocean Turbulence Model (GOTM v5.3) is a one-dimensional model that simulates the most important hydrodynamic and thermodynamic processes related to vertical mixing (Umlauf

5 et al. 2005). GOTM was developed by Burchard et al. (1999) for modelling turbulence in the oceans, but it has been recently adapted for use in lakes (Sachse et al., 2014). Typically, GOTM is used as a stand-alone model for investigating the dynamics of boundary layers in natural waters, but it can also be coupled to a biogeochemical model using the Framework for Aquatic Biogeochemical Models (FABM; Bruggeman and Bolding, 2014)

10 **MyLake (v1.12)** is a one-dimensional process-based model used to simulate physical, chemical and biological dynamics in lakes (Saloranta & Andersen 2007). The model simulates thermal stratification, lake ice and snow cover and phosphorus-phytoplankton dynamics. It also contains a simple sediment box-model. Optionally, the lake layers can be defined according to water volume.

Simstrat (v2.1.2) is a one-dimensional hydrodynamic model, which specifically includes vertical

15 mixing induced by internal seiches that is not included in most other models (Goudsmit et al., 2002). The model uses layers of fixed depth and supports multiple options for external forcing, comprising several meteorological variables or surface energy fluxes. The model simulates thermal stratification, ice and snow formation (Gaudard et al., 2019). Simstrat has been applied in lakes of varying climatic and morphometric conditions (e.g., Thiery et al., 2014; Kobler and Schmid, 2019;

20 Mesman et al., 2020) and is operationally applied to a suite of Swiss lakes (Gaudard et al., 2019).

3.3.2. Lake models for global simulations

The Community Land Model (CLM). Version 4.5 of CLM (Lawrence et al., 2011, Oleson et al., 2013) is a land surface model that includes simulations with the Lake, Ice, Snow and Sediment

25 Simulator (LISSS; Subin et al., 2012). The CLM4.5 model has been used by multiple ISIMIP sectors with one consistent setup. CLM4.5 simulations and their outputs have been analysed to

assess climate change impacts across a range of indicators within ISIMIP (e.g., Schleussner et al., 2018, Lange et al., 2020, Ito et al., 2020, Gudmundsson et al., 2021, Pokhrel et al., 2021, Gaedeke et al., 2021, Reinecke et al., 2021; Thiery et al., 2021).

LAKE is an extended one-dimensional model, that simulates thermodynamic, hydrodynamic and
5 biogeochemical processes in the water column and the bottom sediments of the lakes (Stepanenko et al., 2016). The model simulates vertical heat transfer considering the penetration of short-wave radiation (Heiskanen et al., 2015), ice, snow and bottom sediments. The model explicitly accounts for the exchange of momentum, heat, and dissolved gases between water and the inclined bottom.

VIC-LAKE is a 1D lake model derived from the Variable Infiltration Capacity (VIC) Macroscale
10 Hydrologic Model (Bowling et al., 2010) and optimized for simulations at a sub-daily timescale. The model is based on a lake energy balance by Hostetler and Bartlein (1990), Hostetler et al (1991) and Patterson and Hamblin (1988). Turbulent mixing is solved with Henderson-Sellers thermal diffusion models using parametrized eddy diffusivity (Henderson-Sellers, 1985). The model also contains an ice module, which dynamically simulates lake ice and ice snow cover.

15 **Simstrat-UoG v1** is based on Simstrat v1.4, which is described above, but additionally includes an ice routine and varying albedo.

3.4. Input data

3.4.1 ISIMIP2a

20 The Lake Sector simulation protocol for ISIMIP2a in its current form was completed in early 2020 and focused on the calibration of models in the local lake domain using the gridded ISIMIP2a data set. Eight lake models participated in this local lake simulation round. The calibration of the global lake models was unfeasible because of lack of a global-scale data set of measured lake water temperatures.

Meteorological data from 1979 to 2016 at 0.5° global grid (EWEMBI, "EartH2Observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP", Lange, 2019a) were used to calibrate the local lake models. Meteorological data from the grid cell from each lake's geographical location (Fig. 1 and Table S1) were used for the model calibration. Since the majority of lakes
5 lacked nearby weather stations, the uniform EWEMBI data allowed us to include a broader diversity of lakes and avoid cumbersome data harmonization. Since the EWEMBI data set was also used to help bias-correct the future climate scenarios used in the ISIMIP2b simulation round (Frieler et al., 2017, Lange, 2019b), the performance of calibrated lake models can be indicative of their ability to simulate past and future climate change when forced by the ISIMIP bias-corrected data. In addition
10 to the calibration runs that were limited to periods when observed water temperature data were available, the local sector modellers were encouraged to drive their lake models with the complete EWEMBI data record between 1979-2016. This was aimed at evaluating the lake models' abilities to reproduce effects of observed meteorologic variability and extreme events on thermal simulations. These simulations could also be used for benchmarking simulations forced with
15 modelled future climate conditions from GCMs. In addition to the EWEMBI data set, five other reanalysis data sets were provided in ISIMIP2a for modelers to use as inputs according to their capacities, with the goal of exploring the effect of input data choice on simulation outcomes. All datasets are described and referenced in the simulation protocol document (https://www.isimip.org/protocol/2a/).

20 Data providers supplied historical measured water temperature profiles for 62 lakes (Fig. 1a, Table S1). Lake data had to meet two criteria to be included in the local lake data set: (1) data needed to overlap with the EWEMBI time span and temperature profiles needed to encompass at least two consecutive years in the case of (sub)-daily sampling frequency, or at least five consecutive years in the case of (sub)-monthly sampling frequency. These criteria enabled intra- and inter-annual
25 variability to be captured in water and meteorologic conditions in the model calibration procedure. A few lakes from under-represented geographical locations (e.g., tropics) were included despite shorter water temperature records.

Water temperature data were harmonized to a uniform data format and visually quality-controlled to remove outliers. In addition to water temperature, the data providers supplied detailed information of the lake depth and hypsometric data to characterize the morphometry of lake basins, which are required as input to most of the lake models.

3.4.2 ISIMIP2b

ISIMIP2b was designed to compare lake responses to simulated historical and projected future climates relative to pre-industrial climates with a focus on improving the understanding of the effects of global warming in the range of 1.5°C to 2°C (Frieler et al. 2017). The lake ensemble

10 included simulations forced by bias-adjusted data from four GCMs, covering historical and up to three Representative Greenhouse Gas Concentration Pathways (RCPs): a low (RCP2.6), medium-high (RCP6.0), and high emission scenario (RCP8.5). The past and future responses of lakes from these simulations were compared to simulations forced by bias-adjusted pre-industrial control (picontrol) climate data from the same four GCMs to quantify differences from pre-industrial

15 conditions. These differences can be thought to represent the "pure" effect of ongoing changes in climate on simulated lake water temperatures, with minimal confounding effects from changes in further human influences that were identical between the two sets of simulations.

Climate input data for ISIMIP2b were derived from four GCMs, namely GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC5 (Taylor et al., 2012; Frieler et al., 2017) that were

20 available from CMIP5. These GCM results had a wide range of projected warming rates, with GFDL-ESM2M and HadGEM2-ES representing the lower and higher ends of the warming spectrum, respectively. The data management team at the Potsdam Institute for Climate Impact Research (PIK) bias-adjusted the GCM data with a reference dataset of atmospherics observations (EWEMBI, Lange, 2019a) using the statistical transfer functions by Hempel et al. (2013) modified

25 to correct known biases in modelled variables (Frieler et al., 2017). The bias correction was aimed at preserving trends and distributions of modelled variables relative to observed atmospheric

observations. All meteorologic data, except horizontal wind components were bias corrected. The list of output meteorological variables from GCMs that were used to drive the lake models can be found in Table 2.

Lake Sector simulations followed the ISIMIP2b protocol (Fig. 1, Frieler et al., 2017,
5   https://www.isimip.org/protocol/#isimip2b). To estimate the effects of historical climate warming, lake model simulations forced with data from historical based emission scenarios were compared with simulations forced with the picontrol scenario. Likewise, to evaluate future climate impacts, lake model simulations were forced with data from the RCP trajectories (RCP2.6, RCP6.0, and RCP8.5) and compared to results from simulations forced with picontrol. The timespans of different
10   climate change scenarios were 1661-1860 (picontrol), 1861-2005 (picontrol and historical), 2006-2099 (picontrol, RCP2.6, RCP6.0, and RCP8.5). An extended period between 2100 and 2299 was also used for simulations based on available results for specific emission scenarios (picontrol emissions, RCP2.6) to evaluate longer-term changes in global temperature that meet the Paris Agreement objectives (Frieler et al., 2017).

15   Since the lake modelling strategy was specifically designed to evaluate only thermal changes resulting from changing atmospheric conditions under the assumption of no watershed inputs (constant lake level), the simulations are not influenced by any changes in land use or socio-economic conditions that would affect watershed inputs to the lakes or changes driven by changes in lake trophic status. The pre-industrial reference simulations (picontrol emissions) assumed fixed
20   socio-economic conditions and land use (1660-1860). CLM4.5 provides additional sets of simulations according to protocols for other ISIMIP sectors (i.e., biomes, agriculture, water (global), permafrost) with a combination of socio-economic (1860-soc and 2005-soc) and CO_2 fertilization (2005-co2) scenarios. Lake temperature simulations that were a component of CLM4.5 did not account for these additional scenarios.

3.4.3 ISIMIP 3a and b

The protocol for the third simulation round of ISIMIP3, which is currently ongoing, is largely similar to the ISIMIP2 protocol, but includes counterfactual climate forcing in ISIMIP3a, and the next generation (CMIP6) of climate model forcing and various emission scenarios in ISIMIP3b.

5   Below, we highlight the main differences between both simulation rounds.

In ISIMIP3a, the observational climate forcing covers the period 1901-2016 and consists of the Global Soil and Wetness Project version 3 (GSWP3; Dirmeyer et al., 2006), homogenized to W5E5 for the period 1901-1978 (Lange, 2019a) and a combination of the W5E5 dataset (Lange, 2019b, Cucchi et al., 2020) for the period 1979-2016 and GSWP3 before that. This observational dataset

10 was bias-corrected using observations from Global Precipitation Climatology Centre (GPCC) (more details at https://climatedataguide.ucar.edu/climate-data/gpcc-global-precipitation-climatology-centre) and Climatic Research Unit (CRU) (more details at https://crudata.uea.ac.uk/cru/data/hrg/) using the method outlined in Lange (2019b). In addition to providing data for the evaluation and calibration for local lake models, ISIMIP3a provides

15 counterfactual climate forcing, which is a detrended version of the historical climate forcing (Mengel et al., 2021). Models driven by the counterfactual climate and other historical human pressures provide a baseline to compare with to determine climate change impacts. In ISIMIP3b, the climate forcing is updated to include the next generation of CMIP6 simulations, which were bias-corrected with a new adjustment routine correcting the simulations towards the W5E5

20 observational data (https://www.isimip.org/gettingstarted/isimip3b-bias-correction/). Climate simulations from five GCMs were provided, namely GDFL-ESM4, UKESM1-0-LL, MIP-ESM1-2-HR, IPSL-CM6A-LR and MRI-ESM2-0. In addition to the picontrol and historical emission simulations, the future simulations include the SSP1-RCP2.6, SSP3-RCP7 and SSP5-RCP8.5 emission pathway scenarios. Following the CMIP6 protocol, the simulation periods were updated

25 to 1601-1849 for pre-industrial, 1850-2014 for historical and 2015-2100 for future simulations.

3.4.4 Climate data availability

All bias-adjusted meteorologic forcing data provided by ISIMIP sectors have a daily temporal resolution and a 0.5°×0.5° spatial (i.e., ~50 km at the equator) resolution. Data are publicly accessible at the DKRZ server at PIK for registered ISIMIP users, and at the ISIMIP data repository

5 (https://data.isimip.org/) for all others. While most models in the Lake Sector performed simulations at daily time steps, some models required temporally disaggregated forcing data at sub-daily time steps. The modelling teams performed temporal disaggregation using their customary approaches (see more details in Section 4). For simulations in the local domain, data were extracted for grid cells corresponding with the lakes' geographic locations. No further downscaling or local

10 corrections were applied to ensure consistency in the forcing data applied to all local lakes.

3.5 Lake parameterization

To account for variations in individual lake responses to meteorological drivers (Kraemer et al., 2015, Shatwell et al., 2019, Heiskanen et al., 2015), there were only two types of data needed by

15 the lake models: a description of the lake bathymetry and information on the lake water transparency, necessary for estimating the diffuse attenuation coefficient of incoming shortwave radiation.

3.5.1 Bathymetry

20 Most lake hydrodynamic models require the hypsographic relationship between depth and surface area, which is critical for determining layer volumes and storage and the vertical transfer of heat. Data providers supplied these bathymetric data for each lake in the local domain. The two versions of air2water versions did not require information on lake bathymetry.

In the global domain, the bathymetry of the representative lakes in each 0.5°×0.5° grid cell was

25 derived from a rasterized version of the Global Lake and Wetland Database (Lehner and Doll, 2004;

Toptunova, 2019) for ISIMIP2 and derived from the HydroLAKES database (Messager et al., 2016) for ISIMIP3. For each grid cell, the average lake depth and lake surface area values for all the lakes in the grid cell were computed. In the case of the LAKE model, both surface area and mean depth of global lakes were obtained from GLDBv2 (Choulga, 2014). For all of the lake models, a

5 cylindrical shape was assumed to represent lake bathymetry. The gridded lake masks for the surface area and mean depths can be accessed online (https://data.isimip.org/).

3.5.2 Water transparency

Water transparency may mediate a lakes' response to climate change (Butcher et al., 2015, Magee

10 et al., 2016, Shatwell et al., 2019). The attenuation coefficient (K_d, m^{-1}) of shortwave radiation is a key parameter to describe water transparency in the lake models (Potes et al., 2012). In all simulations, single non-varying values of K_d were used.

For simulations in the local domain, multi-season and multi-year water transparency data were available from 49 lakes that were used to calculate a diffuse attenuation coefficient (K_d) value or a

15 mean Secchi depth (Z_{SD}, m) (Table S1). When only Z_{SD} measurements were available, K_d was estimated at $1.7/Z_{SD}$. If both mean Z_{SD} and K_d were provided, the directly measured K_d was used. When both K_d and Z_{SD} were lacking, we approximated Kd as a function of mean lake depth following the equation derived for 88 Swedish lakes (Hakanson et al., 1995)

$$K_d = 1.1925*\max(mean\_depth,1)^{-0.424}$$

Or from maximum depth following the expression derived for 1,258 global lakes (Woolway et al. 2021):

$$K_d = 5.681*\max(max\_depth,1)^{-0.795}$$

For ISIMIP2a, the different modelling teams defined the best method to parameterize transparency based on the specific lake model requirements and previous protocols developed for calibration and simulation with any given model. Consequently, transparency parameterizations varied both with lake models and the spatial domain of simulations. In the local domain, measured K_d values derived

5 from Z_{SD} or Hakanson's expression were used in ALBM, Simstrat, and GLM, whereas FLake runs adopted the approach outlined in Woolway et al (2021). In GOTM and MyLake, the mean K_d was determined in the calibration process. The two air2water models did not require water transparency. In the global scale simulations, the grid-varying mean depths of the lakes were used to estimate K_d values from Hakanson's expression in all lake models except for VIC-LAKE. This estimation

10 process is also in the CLM4.5 (Oleson et al., 2013). In the VIC-LAKE model, two-band (visible and near-infrared) Beer's law radiation constants were used to parameterize transparency (Bowling and Lettenmaier, 2010).

3.5.3 Water balance

15 The water balance and/or water inputs and withdrawals were not considered in the ISIMIP2a-b simulation rounds to simplify the setup and execution of the temperature simulation for lakes that were not expected to undergo large seasonal fluctuations in water level. The formulations of some lake models (e.g., air2water or FLake) do not explicitly include hydrological balances. Additionally, the precipitation and evaporation component of water mass exchange was switched off (i.e., only

20 heat exchange occurred) or compensated with a closure term (e.g., CLM4.5) in all models. We acknowledge that omission of water balance (water inputs and outputs) may have a significant impact on the simulated climate change impacts in the seven lakes or reservoirs with large water level fluctuations (Table 1), thus caution should be used when evaluating the results for these lakes.

3.6 Calibration of local lake models in ISIMIP2a

Eight lake models had specific parameters and coefficients calibrated based on what each modelling group felt was appropriate for use with their specific lake model (Table 3). Each modelling group defined reasonable coefficient ranges based on past experience and the physical constraints that

5 would set limits on the parameter and coefficient values. For each model, the same calibration routine and objective function was applied to all lakes in the local domain. Different objective functions (e.g., RMSE, NSE, Pearson r; see Table S2) were adopted by the different models. In all cases the model performance was optimized by minimization of the difference between simulated and measured water temperature.

10 The number of calibrated parameters and coefficients in a specific model ranged from one (FLake) to nine (ALBM, Table 3). The calibrated coefficients were mostly related to processes controlling surface heat and energy fluxes, turbulent kinetic energy and wind stress, and light attenuation. Other calibrated coefficients for specific processes were model-specific, including sediment structure and heat fluxes (ALBM), seiches (Simstrat), and ice/snow energy fluxes (MyLake, Simstrat). To allow

15 for comparing the lake models' performance in predicting measured water temperature, for all lake models two common metrics of model fit were calculated in post-processing (not necessarily coincident with the calibration metrics): the root-mean-square error (RMSE) and coefficient of determination (R2, Table 3).

20 ### 3.7 Long-term simulations in ISIMIP2b

The ensemble of lake models in both the local and global domains was forced with the bias-corrected GCM outputs for the no-climate-change, historical, and future climate change scenarios (picontrol, historical, RCP2.6, RCP6.0, RCP8.5). When running the long-term simulations, the calibrated models for each lake were used, so that each model was optimized for that lake based on

25 the historical calibration described in section 3.6 above. Spin-up periods used with the local lake models varied and were dependent on the protocols and experience of each modelling group (Table

S2). When a spin-up period was used, the spin-up data were created either by repeating the initial year(s) of the scenario input data, and then adding these duplicate data to the beginning of the forcing data, or by using a portion of the historical scenario to spin-up future scenario simulations. Initial conditions used for water temperature profiles in the local lake simulations also varied with

5 model and geographical location and were based on either observed temperature profiles, an assumed isothermal 4°C profile, or related to the mean annual air temperature at the local lake location. A more detailed description of the modelling workflows that were used to spin-up and initialize each model in the local domain is given in Table S2.

For simulations in the global domain, most lake models used parameter and coefficient values that

10 were set according to previous experience with each model: For GOTM, the average values of calibrated coefficients from the GOTM local lakes (Table 3) and default values for the coefficients that were not calibrated (Umlauf 2005 manual, Sachse et al., 2014) were used. Similarly, the methods for spinning up the models in the Global Domain also varied depending on the practices applied by each modelling group. Groups working in the global domain tended to use longer spin

15 up periods and to use data from either the picontrol or historical scenarios to create the spin up data that were added to the scenario forcing data. The initial water temperature profiles used in the global lake simulations also varied. In some cases, the models were initialized as homogenous profiles often based on the mean annual air temperature or linear profiles based on the mean annual air temperature and an assumed 4°C bottom temperature, or linear profiles using a fixed surface and

20 bottom temperature. A description of the modelling workflows that were used to spin-up and initialize each model in the global domain is given in Table S3. More detailed model-specific simulation set-ups can also be found at https://www.isimip.org/impactmodels/.

3.8. Output data format

25 All outputs from the models were aggregated to daily averages (Table 4, Table S4). The vertical resolution of the simulated water temperature profiles in the local domain was reported at 0.5 m

intervals for lakes with <50 m maximum depth and at 1 m intervals for lakes > 50 m. However, the vertical resolution of simulated temperatures in the global domain was limited by file storage capacity. The number of reported layers depended on the depth of the representative lake and ranged from 1 to 13 (GOTM, LAKE, Simstrat-UoG), from 1 to 50 (ALBM) and from 1 to 1000 (VIC-

5   LAKE). Output from CLM4.5 was grid-invariable, representing water temperature in 10 layers. The remainder of reported variables (thermodepth, surftemp, bottemp represented a single value, which was either calculated using the approach presented in the simulation protocol; see https://www.isimip.org/protocol/2b/) or was directly outputted by the lake model (Table 4, Table S4). The Lake Sector simulation protocol provides the model performance metrics used during

10   calibration of lakes in the local spatial domain (Table 3). A full list of variables simulated within ISIMIP2b is summarized in Table S4.

4. Results and discussion

4.1. Results from ISIMIP2a

15   **4.1.1. Calibration and performance of local lake models**

The simulated water temperatures from the calibrated lake models compared well to the measured water temperature data. Based on the simulation data from 62 lakes, a robust fit for all eight local lake models was found, with a multi-model mean RMSE of 1.50°C that ranged from 0.98°C (air2water6par) to 2.41°C (FLake, Table 3). The coefficients of determination ($r2$) ranged from 0.59

20   (MyLake) to 0.96 (air2water6par), with the multi-model average value of 0.84. The lake models predicting surface water temperature, air2water4par and air2water6par, as would be expected, showed lower prediction errors compared to the lake models predicting full water temperature profiles. While the multi-model mean goodness of fit was reasonable for most lakes, 16% of lakes showed RMSE larger than 2°C, indicating less certain predictions (Table 3, Table S1). For

individual models, the number of lakes with RMSE exceeding 2°C varied from 3 lakes (5%, air2water4par) to 40 lakes (65%, FLake).

Although the ISIMIP2a forcing data used a daily time step and a 0.5° spatial resolution, the prediction errors in water temperature were relatively small (Table 3) even though these input data

5 are, in general, less than optimal for the simulations of individual lakes (Bruce et al., 2018). An exception is the air2water model that, owing to its statistical data-driven calibration of model's parameters has been shown to be able to provide the same projections irrespective of the nature of the air temperature dataset used to drive the model (Piccolroaz et al., 2018). The average errors in the prediction of water temperature observations were comparable with previous multi-model

10 and/or multi-site modelling studies, where the mean RSME in water temperature predictions ranged from 1.10°C to 2.79°C (Stepanenko et al., 2013, Winslow et al., 2017, Bruce et al., 2018, Piccolroaz et al., 2020). Similarly, the prediction of epilimnetic temperature showed lower errors compared to predictions of hypolimnetic temperature (Winslow et al., 2017, Bruce et al., 2018).

The calibration of the local lake models also has implications for simulations of lakes in the global

15 domain. Three local lake models (ALBM, GOTM, Simstrat) were also used as global models, therefore the ranges of the calibrated parameters c be used to constrain the parameterization of global simulations in future ISIMIP simulation rounds (Gao et al., in review). This is particularly important in view of the greater uncertainty in the global domain results (Vanderkelen et al., 2020; Woolway et al., 2021; Grant et al., 2021) and the lack of global data products to calibrate global

20 lake models.

4.1.2 Model response to observational vs simulated forcing data

In addition to simulations using ISIMIP2a forcing, the ALBM and FLake models were also used for simulations forced by EWEMBI observational data (1979-2016). This will allow for assessment

25 of the difference in model output when used with observational forcing data compared to simulations with GCM forcings during the historical time period. Given that impacts under past and future climates are modelled with bias-adjusted GCMs, a comparison with simulations using the

observed data used for bias correction will allow an assessment of how simulations forced with the GCM historical inputs compare with those forced using observed (historical) climate (see also Piccolroaz et al., 2018 for a similar analysis). This can give an estimate of the uncertainty in the ISIMIP GCM scenarios and the bias correction method. There are so far no studies for this

5 application of the ISIMIP2a simulations, but the existing simulation outputs archive are publicly accessible and hold potential for further study.

4.2. Results from ISIMIP2b

4.2.1. Impacts of past and future climate change on lakes

10 Time-series of ensemble simulations of lake surface temperature for local lakes over the historical (1851-2005) and future (2006-2100) periods are shown in Figure 2a. Each ensemble combines the results from 62 well-studied lakes and three separate calibrated lake models. Mean annual surface water temperatures increased by 0.15°C at the end of the historical period (present-day, 1976-2005) relative to the pre-industrial control. These simulations support *in situ* observations that lakes across

15 the globe are already warming (Woolway et al., 2020; O'Reilly et al., 2015). Future projections (2006-2099) accounting for low (RCP2.6) to high (RCP8.5) greenhouse gas emissions under present-day socio-economic conditions, provide ensemble estimates of warming of 1.38°C, 2.46°C and 3.85°C by the end of the century (2070-2099) relative to pre-industrial control, respectively (Fig. 2a). For example, the strong mitigation measures associated with RCP2.6 resulted in lake

20 surface temperature remaining below the 2°C anomaly. The ensemble predictions provide a consistent projection of a slower surface water warming under RCP2.6, starting at mid-century (Fig. 2a) than for other greenhouse gas emission scenarios.

Based on the anomalies between the pre-industrial control and future scenarios, all lake models showed similar warming rates and trajectories of change. However, the GOTM local simulations

25 were on average 1.75°C warmer than simulations from ALBM and Simstrat, probably because the version of GOTM used for the local lake simulations had only a very rudimentary description of

the effects of lake ice on surface heat exchange. These results show the importance of using an ensemble of models to increase the robustness of simulated past and future changes and making interpretations less dependent on a single or small suite of the lake models used (Trolle et al., 2014). The common fundamental output from all lake models was water temperature, and for most models,

5 this output is in the form of a full vertical profile at a daily time step. These data and other related model output were also aggregated to different metrics describing lake hydrodynamics, e.g., thermocline depth, the onset of stratification, energy and heat fluxes at the air-water interface, and lake ice characteristics and dynamics (Table 4). The methods to calculate these metrics are defined in the Lake Sector protocol (https://www.isimip.org/protocol/), and for additional metrics, the full

10 lake water temperature profiles can be further processed by users.

The average changes in surface and bottom water temperature for the 62 lakes for the RCP8.5 greenhouse gas emission scenario, using the GOTM model forced by the four GCM outputs are shown in Figure 2b. Results from the ensemble simulations of the local lakes' future responses show faster warming of surface waters (local-lake mean 4.08°C) than bottom waters (1.49°C) by

15 2070-2099. On average, the difference between surface and bottom water temperature anomaly was 2.6°C. There was a wide range of lake responses in the local domain (Figure 2b), with an average range in the change in surface temperatures anomalies derived from the ensemble of 2.28°C and bottom temperature of 3.22°C. These results are consistent with previous findings of the diverse responses in lake surface temperature across the globe (O'Reilly et al., 2015; Pilla et al., 2020)

20 depending on a complex interaction of climate regions (Piccolroaz et al., 2020), lake morphology (Toffolon et al., 2014), and atmospheric conditions (Spence, 2013), and changes in the responses in bottom temperatures being influenced by the lake's morphometric characteristics (Kraemer et al., 2015). The Lake Sector local domain provides information on the lake-specific characteristics related to morphometry and water transparency (Table S1) to enable investigation of how the

25 observed differences in responses to climate warming is influenced by lake characteristics.

The variability in Figure 2b is a result of both variable lake responses and the differences in the forcing associated with the four GCMs. The mean change in surface water temperatures under

RCP8.5 until the end of the 21st century ranged from 2.39°C (when forced by GFDL-ESM2M) to 5.34°C (when forced by IPSL-CM5A-LR). A similar pattern was observed for bottom temperature, although the differences were less pronounced (1.19-1.78°C). The changes in the mean surface temperature followed the differences in the air temperature projected by the four GCMs. Sorted

5   from colder to warmer based on simulated impacts on air and water temperature on the local lakes, the GCMs are ranked in the order of GFDL-ESM2M, MIROC5, HADGEM2-ES, and IPSL-CM5A-LR. Similar differences were observed in water temperature and ice changes by Woolway et al. (2019). These results indicate that the choice of the GCM has a large effect on the changes predicted by the lake models. Using outputs from several GCMs, following the ISIMIP protocols, therefore,

10   provides the advantage of including ensemble forcing data in simulations of climate change impacts on lakes, increasing the robustness of predictions.

The results of global domain simulations made with the GOTM model are shown in Figure S1 for three greenhouse gas emission scenarios and as an ensemble of four GCMs. Under RCP2.6, the emission scenario with the strongest mitigation measures, the global mean annual lake surface

15   temperature was projected to be 12.7°C (range: 3.8–29.4°C) by the end of the 21st century (Figure 2C, Fig. S1a). However, global mean lake surface temperatures of 13.4°C (4.2–30.4°C) and 14.3°C (4.8–31.6°C) were projected for the medium-high emission (RCP6.0) or high-end emission scenario (RCP8.5), respectively (Figure S1c, e). Mean annual lake temperature were projected to increase by 0.9°C (0.53-1.32°C), 1.7°C (1.0 – 2.3°C), and 2.6°C (1.6-3.6°C) under these three greenhouse

20   gas emission scenarios relative to the pre-industrial control (Fig. S1b, d, f). Simulations in the global domain allowed the documentation and visualization of spatial variations in lake thermal structure that are simply not possible using geographically constrained data in the local domain. The most pronounced spatial pattern was a latitudinal gradient of warming of global lakes (Fig. 2C, Fig. S1). These results corroborate previous global-scale modelling studies, although here the results are

25   based on ensemble simulations compared to single model simulations.

5. Conclusions

Modelling the impact of climate change at a global scale using an ensemble of lake models requires data, vision, ambition, and a strong collaborative network of researchers from a range of disciplines. The first ensemble model simulations in the Lake Sector of the Inter-Sectoral Impact Model
5 Intercomparison Project (ISIMIP), has leveraged such a network to design and execute a protocol that has now provided state-of-the-art scientific evidence of climate change impacts on lakes under low to high greenhouse gas emission scenarios. The Lake Sector protocol in the local domain allows for the calibration of lake models forced with historical ISIMIP2a inputs and parametrized using site-specific data of bathymetry. Comparison of simulated and measured water temperature from
10 62 well-studied lakes facilitated detailed calibration and evaluation of the models in the local domain and suggested reasonable parameter and coefficient values for the uncalibrated models that were used in the global domain. Simulations in the global domain provided daily outputs of lake thermal conditions at a consistent 0.5°×0.5° global grid resolution.

Our simulations at both the local and global resolution quantify past and future changes in water
15 temperature, energy and heat fluxes, and ice in unprecedented geographical coverage. Simulations by the ISIMIP Lake Sector also provide previously unattainable opportunities to evaluate the levels of uncertainty in simulations related to the differences in forcing data between reanalyses, GCMs, emission scenarios, and in model structure and parameterization among lake models.

Simulations by the ISIMIP Lake Sector have and will continue to estimate the range and robustness
20 of plausible lake responses to global warming either at 1.5°C above pre-industrial levels as defined by the ISIMIP2b protocol or for any other future greenhouse gas emission scenarios. This work furthers the state-of-the-art in freshwater science (Vanderkelen et al., 2020; Grant et al., 2021; Woolway et al., 2021).

Here, we have described the first stage of simulations undertaken by the ISIMIP Lake Sector, which
25 were performed under the simplifying assumption that hydrologic inputs from the lake watershed had minimal effects on the simulated thermal structure. While this is a reasonable assumption for lake hydrodynamic simulations, it will clearly not be the case for simulations of lake

biogeochemistry and ecology that will strongly depend on the nutrient inputs from the lake watershed. Within the ISIMIP framework, the simulated climate change impacts are (inter-) comparable with results from 13 other sectors, supporting cross-sectoral aggregation of impacts (Vanderkelen et al., 2020). Ultimately, we expect that the improved simulations of lake

5 hydrodynamics presented here will form a robust basis for more complex simulations of water quality, lake level fluctuations, and other greenhouse gas emissions scenarios in upcoming simulation rounds, where lake water quality models can be coupled to the hydrologic and biogeochemical outputs from other sectors of the ISIMIP.

Code and data availability

10 The simulation protocol used in the Lake Sector of the ISIMIP2a-b and ISIMIP3a-b simulation rounds has no common code associated with it. The source codes for specific models are either publicly available or can be requested from the model leaders. A full list of models is available at https://www.isimip.org/impactmodels. Input to the models for ISIMIP2b can be found here: https://data.isimip.org/, for ISIMIP3a here: https://doi.org/10.48364/isimip.263794 and for

15 ISIMIP3b here: https://doi.org/10.48364/isimip.383948. All publicly available primary and secondary input and models' output data are publicly available at https://data.isimip.org/ and data availability status is continuously updated.

Author contributions

M.G., W.T., R.M., D.P. coordinate the lake sector, with key contributions over the past years of

20 I.V., D.M., R.I.W., L.G. and E.J.. J.S., F.Z., K.F., and M.Me. are part of the ISIMIP core team, provided the meteorological input data, and liaise the lake sector with the whole project. M.G., W.T., D.M., R.I.W., V.Y.B., D.B., R.-M.C., A.V.B., B.D., G.G., M.G., A.B.G.J., G.K., R.L., M.Ma., T.M., M.P., S.P., L.R.V., M.S., T.S., V.M.S., Z.T., and H.Y. conducted the lake model simulations. W.T., D.B., R.-M.C., G.G., G.K., M.Ma., T.M., M.S., H.Y., R.A., M.A., O.A., L.A.,

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Competing interests

5 The authors declare that they have no conflict of interest.

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Tables

Table 1. Overview on lake impact models participating in the Lake Sector of ISIMIP2a/b.

Lake model and version	Brief model description Defining features and key processes	Spatial domain[(1)]	Timestep Simulated / Reported [Hours]	Vertical structure / layers reported	Parameterization of turbulent fluxes at air-water interface	Turbulent mixing parameterisation	Water-sediment interface parameterisation	Ice module	Key references
air2water4par (ver. 2.0.0)	A hybrid physically-based/statistical model to predict Lake Surface Water Temperature (LSWT) and epilimnion thickness relying solely on air temperature as external forcing.	L	24/24	Single layer / 1	From simplified version of the net heat flux	Bulk semi-empirical relations that can be derived from turbulence theory of Henderson-Sellers	N	N	Piccolraz et al. (2013) Piccolroaz (2016)
air2water6par (ver. 2.0.0)	As above but with six parameters	L	24/24	Single layer / 1	Same as above	Same as above	N	N	Piccolroaz et al. (2013) Piccolroaz (2016)
ALBM (ver. 2.0)	One-dimensional process-based lake biogeochemistry model that can simulate the dynamics of water temperature, ice phenology, dissolved oxygen, phytoplankton and carbon	L/G	24/24	Multilayer / 51	Calculated following the method of Koehler et al. (2014)	Henderson-Sellers thermal diffusion model with wind-driven eddy diffusivity	Y	Y	Tan et al. (2015)
CLM (ver. 4.5)	3D	G	6/24	Multilayer / 10	Calculated as the harmonic mean of the conductivities of the neighboring layers	Hendenson-Sellers thermal diffusion model with wind driven diffusivity	Y	Y	Subin et al., (2012) Oleson et al., (2013)
Flake-IGB (ver. 1.0)	One-dimensional bulk model of the lake thermal regime specifically designed to parameterize inland waters in climate models and numerical weather prediction systems.	L	3/24	Two-layer self-similar structure / 4	The Monin-Obukhov similarity relations	The water surface temperature is equal to the mixed-layer temperature, this is computed from calculation and constant update of heat fluxes	N	Y	Mironov et al. 2008
GLM (ver. 3.0.0)	A one-dimensional open source hydrodynamic model. It simulates temperature	L	24/24	Multilayer/ 0.5m - max.depth	Algorithm used in Imberger and Patterson (1981)	Energy balance approach for surface layer mixing, eddy diffusivity	N	N	Hipsey et al. (2019)

Model	Description	Scale[1]		Layers		Turbulence			Reference
	stratification in lakes. It uses a flexible Lagrangian grid and an energy budget approach for mixing.						approach for deep mixing		
GOTM (ver. 5.1)	A one-dimensional water column model for the most important hydrodynamic and thermodynamic processes related to vertical mixing in natural waters.	L	24/24	Multiple/ 0.5m - max.depth	Based on Fairall et. al. (1996)	k-ε model	N	N	Umlauf et al., (2005); Burhard et al., (2006);
GOTM (ver. 5.3)	As above	G	24/24	Multilayer / 10	Based on Fairall et. al. (1996)	k-ε model	N	Y	Umlauf et al., (2005); Burhard et al., (2006);
LAKE (ver. 2.0)	1D model for lake thermohydrodynamics and biogeochemistry	G	24/24	Multilayer/ 20	Based on Monin–Obukhov similarity theory	k-ε model / Henderson-Sellers thermal diffusion model	Y	Y	Stepanenko et al., (2016)
MyLake (ver. 1.12)	One-dimensional lake model w ice module.	L	24/24	Multilayer/0.5 m - max.depth	Difussion coefficient in heat balance	Hondzo and Stefan thermal diffusion model	Y	Y	Saloranta & Andersen (2007)
Simstrat (ver. 2.1.2)	One dimensional lake model with deep seiche mixing, ice- and river intrusion module	L	24/24	Multilayer/ 0.5m - max depth	Dirichlet condition	k-ε turbulence model with buoyancy and internal seiche parameterization	N	Y	Goudsmit et al., (2002)
Simstrat-UoG (ver. 1.0.0)	As above	G	3/24	Multilayer/ 1-13	Dirichlet condition	k-ε turbulence model with buoyancy and internal seiche parameterization	N	Y	Goudsmit et al., (2002)
VIC-Lake (ver. 1.0)	One dimensional lake lake model derived from the Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model.	G	6/24	Multilayer / 1000	Based on Hostetler and Bartlein (1990)	Henderson-Sellers thermal diffusion model with parameterized eddy diffusivity	N	Y	Bowling & Lettenmaier (2010)

[1] Spatial scale of simulated impacts: L – Local (site-specific); G-Global

Table 2. Standard climate forcing variables used to govern lake models to simulate past, present, future changes in local and global lakes

Variable	Abbrevation	air2water4par	air2water6par	ALBM (local/global)	CLM45	Flake-IGB (local)	GLM3.0	GOTM 5.1 (local)	GOTM 5.3 (global)	LAKE2.0	MyLake1.12	Simstrat 2.1 (local)	Simstrat UoG (global)	VIC-LAKE
Near-surface relative humidity [%]	hurs			●			●				●			●
Near-surface specific humidity [kg kg^{-1}]	huss				●	●		●	●	●		●	●	
Precipitation [kg m^{-2} s^{-1}]	pr			●	●		●	●	●	●	●	●	●	●
Snowfall flux [kg m^{-2} s^{-1}]	prsn			●										
Surface pressure [Pa]	ps			●				●	●	●	●	●	●	●
Surface downwelling longwave radiation [W m^{-2}]	rlds			●	●	●	●			●		●	●	●
Surface downwelling shortwave radiation [W m^{-2}]	rsds			●	●	●	●	●	●	●	●	●	●	●
Near-surface wind speed at 10m [m s^{-1}]	sfcWind			●	●	●	●	●	●	●	●	●	●	●
Near-surface air temperature [K]	tas	●	●	●	●	●	●			●	●	●	●	●
Daily maximum near-surface air temperature [K]	tasmax			●		(●)								
Daily minimum near-surface air temperature [K]	tasmin			●		(●)								
Eastward near-surface wind [m s^{-1}] [1]	uas							●				●	●	
Northward near-surface wind [m s^{-1}] [1]	vas							●				●	●	

[1] uncorrected

Table 3. Summary of local domain calibration of lake models participating in the ISIMIP2a/b simulation rounds. Summary statistics for calibrated parameters and models' performance represent the cross-site mean, median [minimum – maximum].

Lake model and version	Calibrated parameter name	Parameter abbreviation [units]	Cross-site calibrated parameters summary statistics	Model fit	
				RMSE	r2
air2water4 par (ver. 2.0.0)	1 Fit parameter (residual effect) 2 Fit parameter (processes depending on air temp) 3 Fit parameter (processes depending on surface lake temp) 4 Scale of lake surface temperature that determines the strength of the thermal stratification	a1 [°C d^{-1}] a2 [d^{-1}] a3 [d^{-1}] a4 [°C]	0.21, 0.12 [-0.04 – 2.00] 0.06, 0.04 [0.009 - 0.36] 0.06, 0.05 [0.009 - 0.40] 18.07, 12.88 [1.64 - 77.25]	1.17, 1.10 [0.64 - 2.41]	0.94, 0.97 [0.13 - 0.99]
air2water6 par (ver. 2.0.0)	1 Fit parameter (residual effect) 2 Fit parameter (processes depending on air temp) 3 Fit parameter (processes depending on surface lake temp) 4 Scale of lake surface temperature that determines the strength of the thermal stratification 5 Amplitudeof annual met forcing 6 Phase of annual met forcing	a1 [°C d^{-1}] a2 [d^{-1}] a3 [d^{-1}] a4 [°C] a5 [°C d^{-1}] a6 [-]	0.42, 0.24 [-0.72 - 1.99] 0.047, 0.03 [0.005 - 0.18] 0.06, 0.04 [0.01 - 0.25] 15.71, 11.63 [2.73 - 77.25] 0.29, 0.16 [0.02 - 1.81] 0.48, 0.53 [0.01 - 0.98]	0.98, 0.94 [0.51 - 1.96]	0.96, 0.98 [0.39-0.99]
FLake (ver. 1.0)	1 Parameter for profile relaxation time	c_relax_C [-]	0.357, 0.234 [0.001 - 0.9]	2.41, 2.34 [1.01 - 4.40]	NA
ALBM (ver. 2.0)	1 Heat capacity of sediment 2 Diffuse attenuation correction factor 3 Heat transfer coefficient scaling factor 4 Sediment heat capacity 5 Turbulent diffusivity scaling factor 6 Sediment porosity 7 Snow density 8 Sediment density 9 Wind shielding factor	cps [J kg^{-1} K^{-1}] feta [-] hwt [-] ks [W m^{-1} K^{-1}] ktscale [-] por [-] roun [kg m^{-3}] rous [kg m^{-3}] wstr [-]	1397, 1472 [770 – 1923] 1.04, 0.57 [0.10 - 6.26] 1.52, 1.09 [0.57 - 4.57] 1.25, 1.04 [0.26 - 2.82] 1.26, 1.19 [0.54 - 2.57] 0.43, 0.43 [0.30 - 0.59] 233, 175 [100 – 725] 2089, 2013 [1549 - 2662] 1.39, 0.51 [0 - 8.85]	1.44, 1.27 [1.27 - 3.07]	0.89, 0.93 [0.10 - 0.99]
GLM (ver. 3.0.0)	1 Diffuse attenuation coefficient 2 Longwave (or cloud) scaling factor 3 Wind speed scaling factor	Kw [m^{-1}] lw_factor [-] wind_factor [-]	0.75, 0.46 [0.05 - 4.21] 1.01, 1.02 [0.77 - 1.33] 1.30, 1.24 [0.5 – 2.0]	1.55, 1.34 [0.35 - 4.81]	0.84, 0.94 [0.00-0.98]
GOTM (ver. 5.1,	1 e-folding depth for non-visible fraction of light 2 e-folding depth for visible fraction of light 3 Minimum turbulent kinetic energy 4 Surface heat-flux factor 5 Shortwave radiation factor 6 Wind factor The automated calibration program PARSAC (https://bolding-bruggeman.com/portfolio/parsac/) was used)	g1 [m] g2 [m] k_min [m^2 s^{-2}] x10^6 shf_factor [-] swr_factor [-] wind_factor [-]	1.07, 1.12 [0.0006 - 3.52] 2.58, 1.98 [0 - 19.82] 1.95, 0.98 [0.14 – 10] 0.70, 0.66 [0.5 - 1.30] 1.11, 1.17 [0.52 - 1.57] 1.32, 1.38 [0.5 – 2.0]	1.31,1.24 [0.26 - 5.17]	0.92, 0.95 [0.09-0.99]
MyLake (ver. 1.12)	1 Melting ice albedo 2 Melting snow albedo 3 Wind shelter parameter 4 Minimum stability frequency 5 Non-PAR diffuse attenuation coefficient 6 PAR diffuse attenuation coefficient	alb_melt_ice [-] alb_melt_snow [-] C_shelter [-] Kz_N0 [s^{-2}] x10^3	0.53, 0.45 [0.40 - 0.99] 0.55, 0.48 [0.40 - 0.98] 0.44, 0.39 [0.001 - 0.98] 0.41, 0.43 [0.014 - 0.99] 2.07, 1.88 [0.46 - 3.90] 0.95, 0.85 [0.40 - 1.96]	1.82, 1.83 [0.40 - 3.02]	0.59, 0.72 [-3.78 - 0.95]

		swa_b0 $[m^{-1}]$ swa_b1 $[m^{-1}]$			
Simstrat (ver. 2.1.2)	1 Fraction of wind energy transferred to seiche energy 2 As above, during summer in lakes >100 km^2 3 As above, during winter in lakes >100 km^2 4 Fraction of forcing wind to wind at 10m 5 Fit parameter scaling the shortwave radiation entering the snow/ice 6 Fit parameter scaling absorption of IR radiation from sky	a_seiche[1] [-]x10³ a_seiche_s [2] [-]x10³ a_seiche_w[2] [-]x10³ f_wind [-] p_albedo [-] p_radin [-]	8.94, 0.75 [0.00001 - 185.8] 2.12, 1.008 [0.099- 8.01] 2.93, 1.17 [0.32 - 12.49] 1.05, 1.03 [0.1 - 1.97] 1.20, 1.0 [0.49 – 2.0] 0.97, 0.97 [0.8 - 1.2]	1.35, 1.11 [2.6e-4 - 8.03]	0.95, 0.97 [0.76 - 0.99]

[1] a_seiche parameter was calibrated for lakes < 100 km^{-2} (n=51)

[2] a_seiche_s and a_seiche_w parameters were calibrated separately for summer and winter months in lakes > 100 km^{-2} (n=8)

Table 4. Common output variables reported by local (L) and global (G) models participating in the Lake Sector of ISIMIP2a/b. Highlighted are variables outputted by at least 50% of lake impact models. Watertemp variable is a full water temperature profile. Naming of lake models and variables are ordered in an alphabetical order (see Table S4 for a list of full variable names).

Impact model	albedo	bottemp	extcoeff	ice	icetemp	Icethick	lakeheatf	lakeicefrac	latentheatf	Lup	momf	sedheatf	sensheatf	snowtemp	snowthick	strat	surftemp	swup	thermodepth	turbdiffheat	watertemp
Air2water 4par (L)																	●		● (1)		
Air2water 6par (L)																	●		● (1)		
ALBM (G)						●	●		●	●	●	●	●		●			●			●
ALBM (L)						●	●		●	●	●	●	●		●			●			●
CLM4.5 (G)								●													●
FLake (L)		●		●	●	●	●		●	●	●	●	●			●	●		●		●
GLM (L)	●	●		●		●										●	●		●		●
GOTM (G)																					●
GOTM (L)	●	●														●	●		●		●
LAKE (G)	●	●	●			●	●	●	●	●	●		●		●		●	●	●		●
MyLake (L)	●		●			●	●		●			●	●		●	●			●		●
Simstrat (G)	●	●			●	●	●	●	●	●			●		●		●	●	●		●
Simstrat (L)		●		●		●	●		●	●			●		●	●			●		●
VIC-Lake (G)	●			●	●	●			●	●			●	●	●	●	●	●	●		●

5 (1) the model provides a time-varying estimate of the well-mixed surface layer participating to the heat exchanges with the atmosphere

Figures

Figure 1: Map of lakes at local (A) and global (B) scales participating in the ISIMIP2a/b Lake Sector.
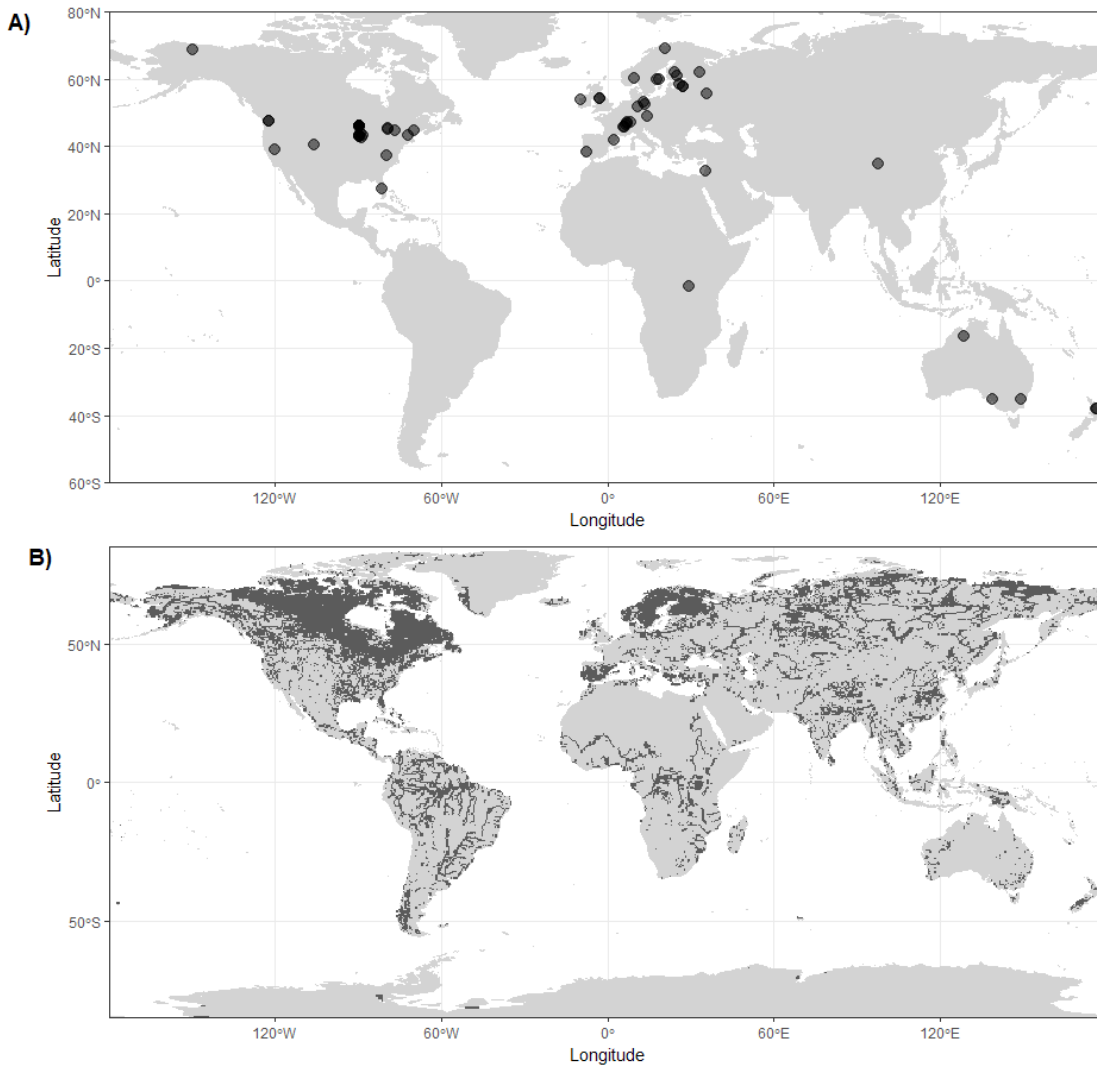
Figure 2: Example output data in the ISIMIP2b Lake Sector. **(A)** Local model time series of mean annual surface temperature derived from ensemble simulations for a period 1861-2100 (historical and future) averaged across lakes and climate models. Color-coding indicates greenhouse gases scenarios; line types differentiate lake models. **(B)** Temperature changes by 2070-2099 compared to pre-industrial levels in summer mean temperature at two lake depths simulated with GOTM (local) model evaluated with data from four climate models under RCP8.5. **(C)** Global outlook for the mean annual surface temperature of lakes by the end of the XXI century (2070-2099) under RCP2.6 simulated with GOTM global.
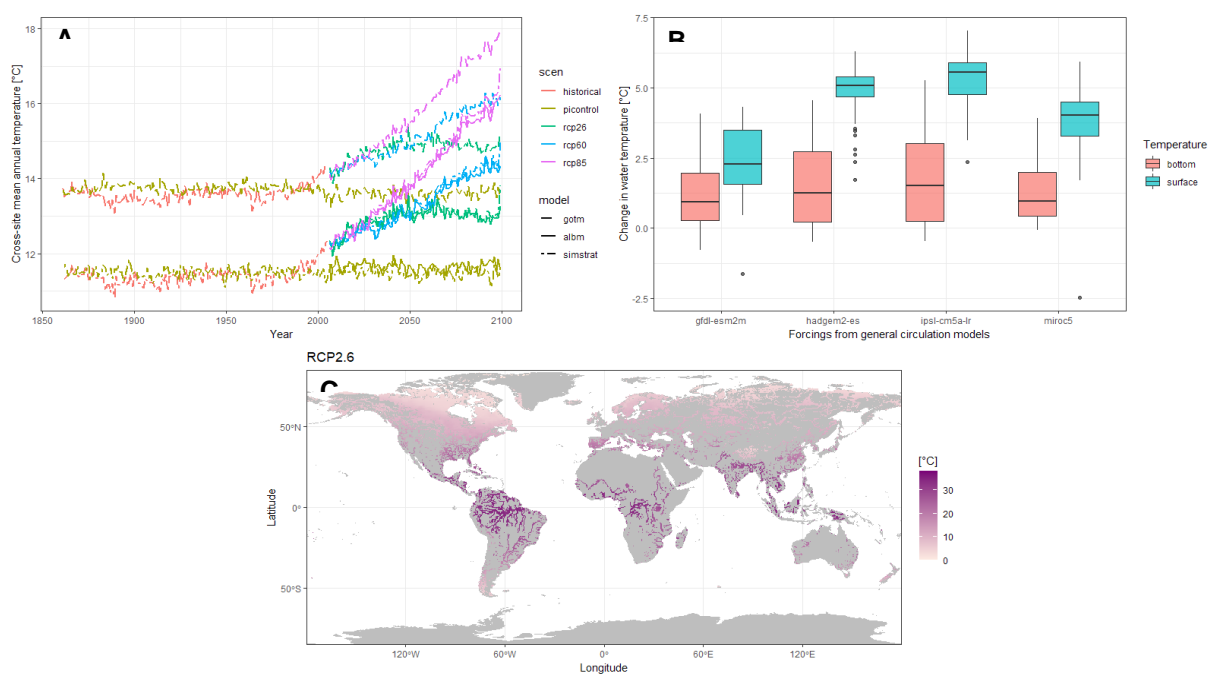
Figure 3. Maps of lake depth, natural lake and reservoir area fractions used in the ISIMIP3 simulation round. Lake depths are derived from GLDB v3 (Choulga et al., 2019), natural lake area fraction from HydroLAKES (Messager et al., 2016) and reservoirs from GRanD (Lehner et al., 2011). Figure adapted from Vanderkelen et al. (2020)