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Modelling impact climate-related change on the thermal responses of lakes

ANA I. AYALA



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Abstract

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In response to climate-related changes, lakes worldwide have experienced warmer surface water temperatures, shorter ice cover periods and changes in lake stratification. As these aspects of lake dynamics exert substantial control over nutrient availability, oxygenation and biogeochemical cycling, predicting changes in lake water temperature and stratification dynamics can improve our understanding of the consequences of warming on lake ecosystems. This thesis investigates the long-term and short-term (extreme event) effects of climate change on lake thermal dynamics using 1D hydrodynamic lake models.

Long-term lake water temperature simulations showed that water temperatures and thermal stratification metrics were projected to clearly shift toward lake thermal conditions that are consistent with a warmer climate at the end of the 21st century, i.e. warmer surface and bottom temperatures and a stronger and longer duration of summer thermal stratification as a result of an earlier onset of stratification and later fall overturn. The simulated lake thermal structure was controlled by energy exchange between the lake surface and the atmosphere (surface heat fluxes) and wind stress. The individual surface heat flux components were projected to change substantially under future climate scenarios. However, the combined changes showed compensating effects, leading to a small overall change in total surface heat flux, that was still sufficient to lead to important changes in whole-lake temperature. On a seasonal scale, spring heating and autumnal cooling were projected to decrease, while only small changes were projected in winter and summer. An extended analysis during summer using 47 lakes showed that while all lakes gained heat during summer under all scenarios, differences in the amount of heat gained during historical and future conditions were small. Additionally, hydrodynamic lake models performed well in reproducing the magnitude and direction of changes in lake temperature and stratification metrics during storms and heatwaves. However, the lake model performance decreased in accuracy compared to non-extreme condition, which should be taken into account.

1D hydrodynamic lake models have been shown to be powerful tools to predict long-term and short-term climate-related changes in lake thermal dynamics, making an in-depth analysis of the surface heat fluxes possible.

Keywords: Modelling, climate change, lakes, thermal structure, surface heat fluxes, extreme events

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To the memory of my father

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

- I. Ayala, A. I., Moras, S., and Pierson, D. C. (2020). Simulations of future changes in thermal structure of Lake Erken: proof of concept for ISIMIP2b lake sector local simulation strategy. *Hydrology and Earth System Sciences*, 24(6), 3311–3330.
- II. Ayala, A. I., Mesman, J. P., Jones, I. D., de Eyto, E., Jennings, E., Goyette, S., and Pierson, D. C. (2022). Climate change impacts on surface heat fluxes in a deep monomitic lake. *Under review in Journal of Geophysical Research: Atmospheres*
- III. Ayala, A. I., Mesman, J. P., Jones, I. D., Schmid, M., Råman Vinnå, L., Woolway, R. I., Goyette, S., and Pierson, D. C. (2023). Analysis of summer heat budget of lakes under a changing climate across a geographic gradient. *Manuscript*
- IV. Mesman, J. P., Ayala, A. I., Adrian, R., de Eyto, E., Frassl, M. A., Goyette, S., Kasparian, J., Perroud, M., Stelzer, J. A. A., Pierson, D. C., and Ibelings, B. W. (2020). Performance of one-dimensional hydrodynamic lake models during short-term extreme weather events. *Environmental Modelling and Software*, 133, 104852.

Additional Papers

In addition to the papers included in this thesis, the author contributed to the following papers:

- I. Moras, S., Ayala, A. I., and Pierson, D. C. (2019). Historical modelling of changes in Lake Erken thermal conditions. *Hydrology and Earth System Sciences*, 23, 5001-5016.
- II. Engel, F., Attermeyer, K., Ayala, A. I., Fischer, H., Kirchesch, V., Pierson, D. C., and Weyhenmeyer, G. A. (2019). Phytoplankton gross primary production increases along cascading impoundments in a temperature, low-discharge river: Insights from high frequency water quality monitoring. *Scientific Reports*, 9(1), 1-13.
- III. Wilson, H. L., Ayala, A. I., Jones, I. D., Rolston, A., Pierson, D. C., de Eyto, E., Grossart, H.-P., Perga, M.-E., Woolway, R. I., and Jennings, E. (2020). Variability in epilimnion depth estimation in lakes. *Hydrology and Earth System Sciences*, 24(6), 5559-5577.
- IV. Mesman, J. P., Ayala, A. I., Goyette, S., Kasparian, J., Marcé, R., Markensten, H., Stelzer, J. A. A., Thayne, M. W., Thomas, M. K., Pierson, D. C., and Ibelings, B. W. (2022). Drivers of phytoplankton responses to summer wind events in a stratified lake: A modeling study. *Limnology and Oceanography*, 67(4), 856-873.

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Abbreviations

α	Water albedo
e_a	Atmospheric water vapor pressure
e_s	Saturated water vapor pressure at the lake surface temperature
P_{10}	Turbulent wind energy flux
Q_e	Latent heat flux
Q_h	Sensible heat flux
Q_{lin}	Incoming long-wave radiation
Q_{lnet}	Net long-wave radiation
Q_{lout}	Outgoing long-wave radiation
Q_{rad}	Radiative flux
Q_{sin}	Incoming short-wave radiation
Q_{snet}	Net short-wave radiation
Q_{total}	Total or net surface heat flux
Q_{tur}	Turbulent heat flux
T_a	Air temperature
T_{avg}	Whole-lake temperature
T_w	Lake surface temperature
w_{10}	Wind speed

Introduction

There are over 100 million lakes covering approximately 4% of the Earth's surface (Verpoorter et al., 2014) and holding 87% of the liquid surface freshwater (Gleick, 1993). Lakes are biodiversity hotspots (Reid et al., 2019) and provide a wide range of ecosystem services such as water supply, food, flood control, hydropower, transportation, recreation and tourism (Schallenberg et al., 2013; Deines et al., 2017; Rinke et al., 2019). Lakes are also sentinels of climate change, where any changes in the surrounding catchment or overlying atmosphere due to climatic variations will affect the lake ecosystem (Adrian et al., 2009).

A changing climate

Earth's global average temperature has been rising since the preindustrial period largely driven by human activities, particularly the emission of heat-trapping greenhouse gases. The decadal global surface (land and ocean) temperature anomaly for 2011-2020 was the warmest decade measured, with a surface global temperature anomaly of 1.09 °C (0.95-1.20 °C) relative to 1850-1900 (IPCC, 2021). Global average temperature is expected to continue to rise and is likely to exceed 1.5-2°C during the 21st century unless sharp reductions in greenhouse gas emissions occur in the coming decades (IPCC, 2021).

Climate change is also affecting other climate variables, including solar radiation, wind speed and specific humidity. Solar radiation has been shown to have undergone decadal variations since the mid-20th century, with decreases occurring from the 1950s to the 1980s ("dimming") followed by a recovery and increases ("brightening") during the late 1980s and 1990s, which were associated with changes in atmospheric transparency (clouds, aerosols and radiatively active gases) (Wild, 2009; Wild, 2012; Wild, 2016). The specific humidity, the amount of water vapor held in the atmosphere, is increasing rapidly in response to rising air temperature according to the Clausius–Clapeyron relationship. Observed global mean specific humidity has increased by 0.07 g kg⁻¹ decade⁻¹ for the period 1973-2002 (Willett et al., 2007). Wind speed experienced a decrease ("stilling") in the northern hemisphere (Vautard et al., 2010) and an increase in the southern hemisphere (Deng et al., 2021) during 1980-2010. The decrease in wind speed in the northern hemisphere may be

associated with changes in surface roughness (forest growth, land use changes and urbanization) and accelerating Arctic warming, meanwhile the increase in wind speed in the southern hemisphere is caused by the enhanced Hadley cell (Deng et al., 2021). The stilling reversed around 2010 and wind speed over land has recovered, being presumably determined by decadal ocean-atmosphere oscillations (Zeng et al., 2019). All these changes in climate variables have a direct impact on the lake thermal dynamics.

Warming lake surface waters

In response to climate change, lakes worldwide have experienced warmer summer surface water temperature, and have increased at an average rate of $0.34^{\circ}\text{C decade}^{-1}$ from 1985 to 2009 (O'Reilly et al., 2015), with greater warming in mid- and high-latitude lakes in the northern hemisphere than in low-latitude lakes in the northern hemisphere and the southern hemisphere (Schneider & Hook, 2010). This lake warming is driven primarily by rising air temperature (Schmid et al., 2014; Butcher et al., 2015). However, in some lakes surface water temperatures are rising faster than local air temperature during summer (O'Reilly et al., 2015), often due to earlier onset of thermal stratification (Austin & Colman, 2007), increasing incoming solar radiation (Schmid & Köster, 2016), a decrease in wind speed (Woolway et al., 2019) and/or changes in water clarity (Jones et al., 2005; Rose et al., 2016). An earlier onset of thermal stratification as a result of milder winter condition, together with increased solar radiation and air temperature during spring (Zhong et al., 2016; Schmid & Köster, 2016), leads to a shallower mixed layer and consequent reduction in the volume of water directly affected by the exchange of energy at the water-air interface during the summer (smaller thermal inertia). This in turn, results in a more rapid increase in lake surface water temperature than expected from the increase air temperature alone (Piccolroaz et al., 2015). Wind speed stilling reduces the magnitude of the mechanical vertical water mixing, leading to lower vertical transfer of heat gain with depth, and leads to an increase in surface water temperature, a decrease in bottom temperature and a strengthening of thermal stratification (Woolway et al., 2017). Water clarity determines how much solar radiation is absorbed and the resulting heat is distributed in the water column (Persson & Jones, 2008; Read & Rose, 2013). A decline in clarity enhances surface water warming and thermal stratification (Rose et al., 2016; Pilla et al., 2018), while increasing clarity has the opposite effect, amplifying whole-lake and bottom warming, while reducing surface warming (Rose et al., 2016).

Warming rates are modulated by lake morphology (Kraemer et al., 2015; Winslow et al., 2015). Shallow lakes have lower heat storage capacity, responding most directly to short-term variations in atmospheric conditions compared to deep lakes, where heat can be readily transferred through the

water column by wind mixing. While deep lakes require stronger wind speed to completely mix (Magee et al., 2016), their large surface area or fetch increase the effect of mixing and vertical transfer of heat to the lake bottom (Rueda & Schladow, 2009). Winslow et al. (2015) analysed warming rates from 142 lakes exposed to similar regional climate conditions across Wisconsin (US) from 1990 to 2012 and found that larger lakes ($>0.5 \text{ km}^2$) showed faster warming than smaller lakes ($<0.5 \text{ km}^2$), with warming rates for large lakes consistent across all depths, while in small lakes warming trends were found to be strongest in shallow waters.

The majority of studies evaluating the response of lake temperature to climate change have mainly focused on the surface water temperature during the summer period as well as the strength of thermal stratification. However, the effects of climate change are not uniform across seasons and lake depths (Winslow et al., 2017; Toffolon et al., 2020; Pilla et al., 2020), so a full understanding of climate change impacts requires a knowledge of the effects throughout the year and throughout the water column. For example, in Lough Feeagh (Ireland) the rate of change in annual minimum surface temperature between 1976 and 2014 was considerably higher ($0.34 \text{ }^\circ\text{C decade}^{-1}$), and four times faster than the rate of change in summer surface water temperature ($0.08 \text{ }^\circ\text{C decade}^{-1}$; July-September) (Woolway, Weyhenmeyer, et al., 2019). In Lake Erken (Sweden) rates of change in epilimnion temperature between 1989 and 2017 were faster in autumn than spring, while changes were non-significant in summer (Moras et al., 2019). In the northern hemisphere, lakes are experiencing shorter winters, with an accelerated loss of ice cover. Ice phenology records for 60 lakes showed that, on average, ice-on was 11 days later, ice-off was 6.8 days earlier and ice duration 17 days shorter per century, with the rate of ice-on and ice duration six times faster in the past 25 years (1992-2016) than previous quarter centuries (Sharma et al., 2021). The response of bottom water temperature to warming is less clear and has been observed to show inconsistent trends in the direction and magnitude of temperature change, in contrast with the largely consistent and rapid warming reported for surface water temperatures. In a study of 102 well monitored lakes by Pilla et al. (2020), bottom temperature trends, on average, showed little change ($+0.06 \text{ }^\circ\text{C decade}^{-1}$) ranging from $-0.68 \text{ }^\circ\text{C decade}^{-1}$ to $+0.65 \text{ }^\circ\text{C decade}^{-1}$. Overall lake bottom temperature responded to complex interactions between surface energy exchange and lake thermal stratification (mixing and stability), with bottom water temperatures declining with increasing lake depth, increasing with increasing water clarity and decreasing with fetch (Butcher et al., 2015).

Lake ecosystems effects of climate change

Effects of climate change on lake ecosystems have been observed globally. Warming water temperature leads to shifts in the timing and magnitude of phytoplankton blooms, as well as shifts in phytoplankton species composition (Winder & Sommer, 2012). Spring phytoplankton blooms occur earlier in the year as a result of an excess lake warming and an earlier ice break-up and/or earlier onset of thermal stratification (Peeters et al., 2007). Cyanobacteria are strong competitors at high temperatures, since they tend to grow at higher optimal temperatures compared to diatoms (above 25 °C) (Huisman et al., 2018), although, the mean optimal growth temperature for cyanobacteria and green algae can be similar (Lürling et al., 2013). Also the temperature dependence of growth rate as function of temperature is steeper for cyanobacteria (Visser et al., 2016). Warming of the water surface also leads to a more stable stratification, so the response of cyanobacterial growth with warmer temperatures can be suppressed by nutrient limitation. However, many cyanobacteria species have the ability to regulate their buoyancy to exploit habitats under intensified stratification (Paerl & Huisman, 2008) and acquire nutrients by nitrogen fixation (Huisman et al., 2018) or from sediment sources as resting akinetes (Hense & Beckmann, 2006). Cyanobacteria can produce toxins and harmful algal blooms (high toxic bloom intensity) and can impair the safety of drinking, irrigation, fishing and recreational waters. Climate warming will likely generate changes in lake fish community size-structure (Lindmark et al., 2019), life history traits (smaller body size, earlier reproduction and shorter life span) (Ohlberger, 2013; Wootton et al., 2022), feeding modes (shift towards broader diet, with greater importance of omnivory and herbivory), habitat use (stronger association with littoral areas and a greater proportion of benthivores) and winter survival (minimizing winter mortality) (Jeppesen et al., 2010). Stronger lake stability and a longer duration of thermal stratification can reduce water circulation and facilitate hypolimnetic oxygen depletion, by preventing deep-water oxygen replenishment (Foley et al., 2012; North et al., 2014; Jane et al., 2021), contributing to a “temperature–oxygen squeeze” where the suitable cold-water habitat for fish is eroded due to low oxygen concentrations (Magee et al., 2019) which can also lead to increased fish mortality (Till et al., 2019). Anoxic conditions at the sediment-water boundary enhances sediment phosphorus release (Hupfer & Lewandowski, 2008) and dissolved iron and manganese release (Schultze et al., 2017), organic carbon mineralization (Gudasz et al., 2010) and methane production (Bastviken et al., 2011; Marotta et al., 2014; Vachon et al., 2019).

Extreme events and effects on lake physics

Along with a changing climate, weather and climate extremes such as heatwaves, storms, rainfall and droughts, are modifying, including their frequency, intensity, spatial extent, duration and timing (Seneviratne et al., 2012; Pradhan et al., 2022). Simultaneously, some locations face an increase in droughts (Dai, 2013), while others experience more intense precipitation (Myhre et al., 2019). Warm temperature extremes (heatwaves) are increasing (Russo et al., 2015; Sánchez-Benítez et al., 2018), while cold extremes are declining (Lorenz et al., 2019).

Extreme weather events have a direct effect on lake physics. Wind events (storms) promote turbulent and convective mixing, weakening thermal stratification and deepening the mixed layer, cooling the surface water temperature (Stockwell et al., 2020). Heatwaves or windless periods have the opposite effect as compared to storms. The primary response of lakes is an increase in surface water temperature, which in turn results in enhanced lake stability (larger bottom-surface density gradients), a shallower mixed layer and colder hypolimnetic temperature (Jankowski et al., 2006). Extreme rainfall can cause increase in river flows, and in summertime river flows are often colder than lake surface waters, so in lakes with short-residence time can lead to a reduction in surface water temperature and even the loss of stratification (Klug et al., 2012). Rainfall can also increase the dissolved organic matter concentration in rivers resulting in greater light attenuation and warmer lake surface temperature (Strasskraba & Hocking, 2002). The impacts of extreme events on the physical parameters in a lake are often short-lived (Jennings et al., 2012; Stockwell et al., 2020), however, they can also have a longer effect (Andersen et al., 2020), depending on the time of year when they occur (Mi et al., 2018).

Lake models driven by climate model outputs

Lake water temperature and thermal dynamics result mainly from the exchange of energy between the lake surface and the atmosphere, including surface heat fluxes (i.e. surface heating or cooling ; Fink et al., 2014; Schmid & Read, 2022) and wind stress (vertical turbulent mixing; Imboden & Wüest, 1995; Wüest & Lorke, 2003). Throughflows (advective heat flux; de la Fuente, 2014) and sediment exchanges (geothermal heat flux; Fenocchi et al., 2017) also contribute to the lake thermal structure but to a lesser extent, and are modulated by lake morphometry (Butcher et al., 2015; Kraemer et al., 2015). Predicting how climate change will alter lake thermal dynamics requires an understanding of the interactions between the atmosphere and lakes.

Numerical modelling plays a key role in estimating the sensitivity of the lakes to changes in the weather and climate. One-dimensional (1D) hydrodynamic lake models are frequently used to characterize hydrodynamics in lakes

due to their computational efficiency, lower data needs, minimal calibration requirements and skill in simulating vertical thermal stratification dynamics (at seasonal and decadal time scales). Lake models driven by climate model outputs allow us to understand how lake water environments have responded to historical changes (Moras et al., 2019), how they could behave under future climate change, and how mitigation or management strategies can be developed to ensure water security for future generations (Ladwig et al., 2018; Mi et al., 2020; Feldbauer et al., 2020). When undertaking climate change impact studies, hydrodynamic lake models are usually driven by daily resolution climate model outputs. However, the agreement between observations and simulations of full-profile temperatures are more accurate when the lake models are forced by hourly meteorological input (Bruce et al., 2018; Moore et al., 2021). In recent years, there has been an increasing number of studies about the impact of climate change on lakes, which focus on changes in water temperature (Shatwell et al., 2019), stratification phenology (Woolway et al., 2021), loss of ice cover (Grant et al., 2021; Sharma, Blagrave, et al., 2021; Woolway, Denfeld, et al., 2021), alterations in mixing regimes (Woolway & Merchant, 2019), evaporation (Wang et al., 2018; Zhou et al., 2021; La Fuente et al., 2022), lake heat content (Vanderkelen et al., 2020) and methane production (Jansen et al., 2022). However, the total surface heat flux and the individual heat flux components that will change under future climate also deserve attention, since it is their seasonal dynamics that strongly affects all of the above-mentioned projected changes.

Finally, several recent studies have also applied lake models to study the effects of extreme weather events on lake thermal structure or lake ecology. For example: Mi et al. (2018) applied a lake model to investigate the impact of wind events (storm) of different intensities and timings on lake thermal structure; Chen et al. (2019) assessed the ecological response of a summer-stratified lake to heatwaves; Woolway et al. (2020) used a lake model to look at changes in thermal structure during heatwaves; Gal et al. (2020) assessed the impact of climate warming and increased frequency of heatwaves on lake thermal regimes, and Woolway, Jennings, et al. (2021) investigated how lake heatwave intensity and duration will respond to climate change. However, we do not know how accurately lake models simulate observed lake thermal structure during short-term events (e.g. at an hourly scale), since 1D hydrodynamic lake models are often calibrated and verified using measured data collected at a longer than hourly interval.

Aims of the Thesis

Previous research has shown the historical response of lakes to climate-related changes based on both direct observations and model simulations using long-term records of meteorology and lake water temperature. To evaluate future changes, driving lake model with climate model outputs allows one to better understand the process-based mechanisms by which climate change will influence lake thermal dynamics. The overall aim of this thesis was to examine the long-term and short-term (extreme events) effects of climate change on lake thermal dynamics using 1D hydrodynamic lake models. The main focus for each paper includes the following:

- Prior to performing future simulations of lake water temperature, the ability of lake models to reproduce water temperature is evaluated to improve confidence in model predictions. The temporal resolution of the meteorological data used for driving lake models usually range from daily to hourly or even shorter, and the accuracy of the lake model simulations is often improved by increasing the time resolution of the meteorological forcing. **Paper I** aims to evaluate the importance of input data frequency (time step) on the accuracy of surface water temperature simulations and to assess the impact of climate change on lake thermal structure at different levels of global warming when a lake model is driven by climate model projections at different frequency.
- Lake water temperature and thermal dynamics respond mainly to the exchange of energy between the lake surface and the atmosphere, including surface heat fluxes and wind stress. **Paper II** aims to investigate changes in total surface heat flux and individual heat flux components during the historical period and during three future emission scenarios compared with a control climate scenario in a monomictic ice free lake using simulation data over the entire year. **Paper III** also aims to investigate changes in total surface heat flux and individual heat flux components, but between the historical period and future climate scenarios at late century using 47 lakes during a more restricted time period when all would experience summer conditions.
- Lakes models are known to be skilful reproducing water temperature at seasonal time scale, but it is less well known how well lake

models perform at shorter time scales, particularly during extreme events. **Paper IV** aims to test the ability of lake hydrodynamic models to reproduce the impacts of extreme weather events on lakes.

Materials and Methods

Study sites

A total of forty-seven lakes are evaluated in this thesis (Figure 1), varying in geographical location, morphometry and mixing regime. **Papers I and II** are case-lake studies while **Papers III and IV** are multi-lake studies.

Paper I focuses on Lake Erken in Sweden, which has a relatively shallow depth and large surface area that leads to large interannual variability in the timing and patterns of thermal stratification.

Paper II, concerns Lough Feeagh, which is located on the west coast of Ireland and is influenced by the Gulf Stream, experiencing mild winters and summers meaning that this lake remains ice-free year-round.

Paper III, includes forty-seven lakes. Their geographical locations cover three of the main climatic groups in the Köppen-Geiger climate classification (Peel et al., 2007) arid (one lake), temperate (twenty lakes) and boreal (twenty-six lakes). The lakes represent a wide range of surface area (0.07 to 980 km²), maximum depth (6 to 309.7 m) and elevation (-210 to 2843.8 masl). Four lakes are polymictic and the other have a consistent summer stratified period, including twenty-eight dimictic lakes and fifteen monomictic lakes. The reported light extinction coefficient ranges from 0.1 to 3.7 m⁻¹, indicating a wide range of trophic status.

Paper IV, is a three-lake study which includes, one dimictic, relatively shallow depth, large surface area and mesotrophic lake (Erken, Sweden), one monomictic, deep, medium-size and dystrophic lake (Feeagh, Ireland) and one polymictic, shallow and eutrophic lake (Müggelsee, Germany).

Lake models

Numerical lake models are powerful tools for testing hypothesis or scenarios that would be impossible to test using observational studies (for example: long-term climate change scenarios), and to gain further understanding of how lakes behave, complementing lake monitoring programs. Lake models have often been developed for a specific application, so different formulations, parameterisations and numerical schemes have been developed and applied in 1D lake models. Three open-source 1D hydrodynamic lake models, namely GOTM (General Ocean Turbulent Model; Burchard et al., 1999; **Papers I and**

IV), Simstrat (Goudsmit et al., 2002; **Papers II, III and IV**) and GLM (General Lake Model; Hipsey et al., 2019; **Paper IV**), have been used in this thesis. These models have been extensively used to simulate thermal stratification with applications covering different lake morphometries and climate forcing, and they have demonstrated a remarkable ability to simulate water temperature profiles (GOTM: Moras et al., 2019; Moore, 2020; Simstrat: Perroud et al., 2009; Stepanenko et al., 2013; Thiery et al., 2014; Schwefel et al., 2016; Råman Vinnå et al., 2021; Bärenbold et al., 2022; GLM: Bueche et al., 2017; Bruce et al., 2018; Fenocchi et al., 2018; Ladwig et al., 2018; Feldbauer et al., 2020). The main differences between the models are indicated below.

GLM applies a flexible layer structure (Lagrangian grid), which allows the layers to contract or expand in response to inflow, outflow, surface mass fluxes (evaporation, rainfall and snowfall) or vertical mixing. GOTM and Simstrat have instead a fixed layer structure (Eulerian grid). All three models are turbulence models. In GOTM and Simstrat turbulence mixing is solved by two dependent equations of production and dissipation of turbulence kinetic energy (TKE), where the source of TKE is generated by wind stress from the wind and buoyancy production ($k-\epsilon$ turbulence model). GOTM provides different turbulence closure parameterisations and Simstrat also allows for a transfer of wind energy to the deep water via internal seiche motions (Gaudard et al., 2017). However, GLM applies an energy balance approach, where layer mixing occurs when the TKE provided to the surface mixed layer by wind stirring, convective overturn, shear production between layers and Kelvin-Helmholtz (K-H) billowing, exceeds a potential energy threshold. Moreover, mixing below the mixed layer depth is represented through a parameterisation of the eddy diffusivity coefficient to local gradients of buoyancy and shear. The parameterisation of the turbulent fluxes at the water-air interface differs from model to model, based on Fairall et al. (1996) in GOTM, Livingstone & Imboden (1989) in Simstrat and Imberger & Patterson (1981) in GLM. Simstrat and GLM also include parameterisations for snow and ice dynamics (Simstrat: Gaudard et al., 2019; GLM: Hipsey et al., 2019). In addition, GOTM, Simstrat and GLM can simulate water quality dynamics and ecosystem interactions either by coupling biogeochemical models using the Framework for Aquatic Biogeochemical Models (FABM; Bruggeman & Bolding, 2014) for GOTM or coupling to the Aquatic Ecodynamics Modelling Library (AED; Hipsey, Boon, et al., 2019) for Simstrat and GLM.

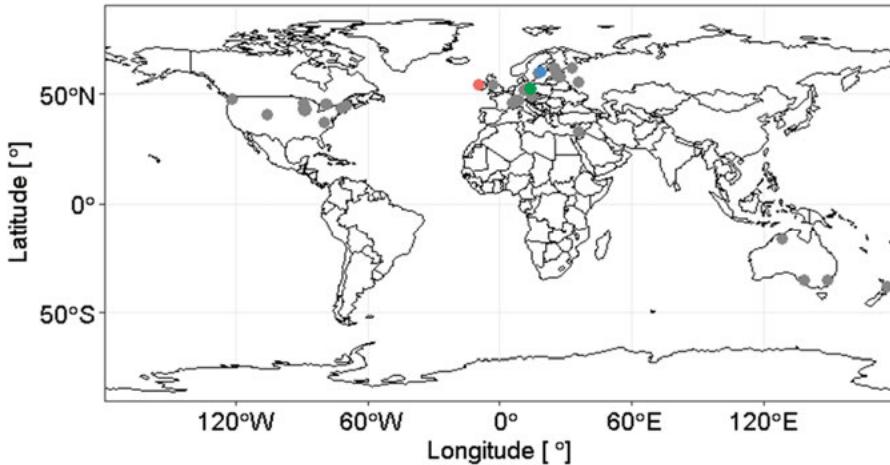


Figure 1. Location of all study lakes (n=47). **Paper I** (n=1; Erken – blue), **Paper II** (n=1; Feeagh – red), **Paper III** (n=47) and **Paper IV** (n=3; Erken – blue, Feeagh – red and Müggelsee – green).

Model set-up

The general data requirements to run the lake models, GOTM, Simstrat and GLM, are: lake location (latitude and longitude), lake bathymetry (surface area per depth of the lake), time series of meteorological forcing and hydrological flows, observed water temperature profiles (for initialising temperature profiles and calibration) and light extinction coefficient (or similar, as e.g. e-folding depth in GOTM; usually obtained from Secchi depth measurements).

Meteorological forcing includes air temperature ($^{\circ}\text{C}$), wind speed (m s^{-1}), incoming solar radiation (W m^{-2}), relative humidity (%), incoming long-wave radiation (W m^{-2}) and precipitation or snow rates. Incoming long-wave radiation was either directly provided to the model (**Paper II and III**) or parameterised by the model from cloud cover (0-1; calculated according to Martin & McCutcheon, 1999) and other prescribed meteorological variables (**Papers I and IV**). Simstrat requires vapor pressure (mbar) rather than relative humidity. This was derived from air pressure (mbar) and specific humidity (kg kg^{-1}) according to Leppäranta (2015) (**Papers II and III**) or derived from relative humidity and air temperature according to Woolway et al. (2015) (**Paper IV**).

The meteorological time series requires a constant time step and cannot contain missing values. Complete observed data sets (**Papers I and IV**) may not always be available, either due to missing or non-gap-free variables; the latter usually requiring gap filling by linear interpolation (small data gaps) or based on machine learning algorithms (longer data gaps) (Moras et al., 2019). However, there are a wide range of reanalysis products available covering a

variety of timescales and temporal and spatial resolutions (Lindsay et al., 2014). These reanalysis data (**Papers II and III**; EWEMBI; Lange, 2019) combine both observations and model-based forecasts to estimate a consistent gridded time series of multiple climate variables (Parker, 2016).

The temporal resolution of the meteorological data used for driving the lake models can usually range from daily (**Papers I, II and III**) to hourly (**Papers I and IV**) or even shorter (10-minute resolution; **Paper IV**). Increasing the time resolution of the meteorological forcing can improve the accuracy of the lake model simulations as shown by Bruce et al. (2018) and Moore et al. (2021). There are various downscaling techniques available that convert daily meteorological variables into sub-daily or even hourly time step (Waichler & Wigmosta, 2003; Guo et al., 2016). Nowadays, Artificial Neural Networks are increasingly being used because of their ability to learn and model non-linear and complex relationships (Khatib & Elmenreich, 2015). In **Paper I** daily average meteorological data (derived from averaging observed hourly data) were disaggregated to form a synthetic hourly data set, in order to assess the importance of the time resolution of the forcing data (hourly vs daily) for predictions of daily water temperature and consequently in the lake model performance.

Hydrological variables (inflow and outflow discharges, inflow temperatures) are optional. Model settings related to the water balance allow for varying or fixed water levels depending on the hydrological data availability, which may be particularly relevant for water bodies with strong water level fluctuations, such as reservoirs. Water level fluctuations were not accounted for in **Papers I, II and III** due to the unavailability of future climate scenarios for inflow water temperature (following ISIMIP protocol; Golub et al., 2022), and in **Paper IV** because hydrological data were not available at a much lower frequency than the meteorological forcing data.

Calibration and validation

Model calibration and validation are crucial procedures used to assess the robustness of thermodynamic lake models. Calibration procedures are conducted in order to adjust the model parameters within their feasible range in order to minimise the error between the observed and simulated water temperatures (Huang & Liu, 2010). The calibration parameters usually are selected according to their importance for the model or because of their site-specific characteristics. Scaling factors for meteorological forcing are parameter values that are often calibrated to compensate for systematic biases between the meteorological conditions over the lake and at the closest meteorological station. Unknown or uncertain model-specific parameters (e.g. minimum turbulent kinetic energy, k_{min} , in GOTM or fraction of wind energy that is transferred to internal seiches, a_{seiche} , in Simstrat) are approximated through

manual or automated calibration when no direct measures are available or cannot be assumed based on previous studies. The calibration period is usually determined by the availability of water temperature observations, however the longer the period used for calibration, the greater the robustness in the estimation of the calibrated parameters (Larsen et al., 2007).

Automatic calibration algorithms can often identify multiple parameters sets that provide equally good model performance, i.e. a diverse set of model configurations on the basis of available observations (commonly referred to as equifinality; Beven, 2006). Thus, this is a challenge to choose a single set of parameters among others. Equifinality is inevitable unless we have a model that describes in detail all the hydrodynamic processes and observations minimising errors. Reducing the number of calibrated parameters, increasing the number of observations used for calibration or demonstrating a suitable model performance in another simulation period such as validation period may be a way to overcome this issue.

Different automatic calibration techniques were used to calibrate each model, but in all cases model performance was optimized by minimizing the difference between simulated and observed water temperature. GOTM applied the program Auto-Calibration Python (ACPy), developed by Bolding and Bruggeman (<https://bolding-bruggeman.com/portfolio/acpy/>) (**Paper I**) or the updated version Parallel Sensitivity Analysis and Calibration (ParSAC; Bruggeman & Bolding, 2020) (**Paper IV**). It uses a differential evolution algorithm to optimize the maximum likelihood objective function of the root mean square error (RMSE) between observations and simulations. Simstrat used PEST (Model-Independent Parameter Estimation and Uncertainty Analysis) software package (Doherty, 2010) to minimise the sum of squares of the error between observations and simulations (**Papers II, III and IV**). GLM was calibrated using the function *neldermead()* of the R package *nloptr* (Ypma et al., 2022), that applied the Nelder-Mead simplex algorithm (Nelder & Mead, 1965) to minimise the RMSE (**Paper IV**).

Typically, calibrated model performance is also evaluated against observations that are not used in the model calibration period. Evaluation of model fit is also used to test whether models are acceptable for a given purpose when operating outside of the period used for calibration in a process known as validation (Ladwig et al., 2018; Feldbauer et al., 2020).

In calibration and validation, model performance is usually measured by quantitative metrics (in combination with visual inspection). We often calculate goodness-of-fit metrics, such as the Mean Bias Error (MBE), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE; Nash & Sutcliffe, 1970) or the correlation coefficient (R) to describe the model fit to the data. However, to-date there are no well-defined and common rules or standard measures (e.g. cut-off value to approve or reject a model) to decide when models are fit for a given purpose (Hipsey et al., 2020).

There are many impactful subjective modelling decisions, such as the ones affecting the use of any one of different available input data sets (data quality and frequency), model structure (model selection), parameter calibration (parameter selection and their feasible range, and calibration method) and model performance metrics, that are sources of uncertainty and will impact the accuracy of the simulations for a given application.

Climate scenarios

The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; <https://www.isimip.org/>) is a community-driven modelling effort with the goal of providing a quantitative assessment of global climate change impacts at different levels of global warming in a consistent setting across multiple sectors. To address this challenge ISIMIP develops and provides a set of climate and socioeconomics forcing data for consistent cross-sectoral climate impact modelling.

ISIMIP2b climate change bias-corrected climate model projections (Frieler et al., 2017) at daily temporal and 0.5° horizontal resolutions for the variables listed in Table 1 were available for each grid box overlying each study lake in **Papers I, II and III**. Specifically, projections from the Global Climate Models (GCMs): GFDL-ESM2M (Dunne et al., 2012; Dunne et al., 2013), HadGEM2-ES (Collins et al., 2011; Jones et al., 2011), IPSL-CM5A-LR (Dufresne et al., 2013; Hourdin et al., 2013) and MIROC5 (Watanabe et al., 2010) were used. Scenarios were available covering the periods of pre-industrial control (PiControl) from 1661 to 2099, representing a climate with natural variability under a stable CO₂ concentration of 286 ppm (scenario without anthropogenic climate warming); historical warming from 1861 to 2005 based on historical changes in atmospheric CO₂ concentration; and three future scenarios referred to as Representative Concentration Pathways (RCPs): RCP 2.6, 6.0 and 8.5 from 2006 to 2099. The RCP-label indicate the increase in the radiative forcing in W m⁻² in the year 2100 relative to pre-industrial values (van Vuuren et al., 2011), i.e. the additional energy taken up by the Earth system due to the enhanced greenhouse effect. Each RCP is estimated based on plausible combination of projected economic activity, energy intensity, population growth and socio-economic development. RCP 2.6 (low-emission scenario) is so-called “peak-and-decline” scenario, which means radiative forcing peaks at 3.1 W m⁻² by mid-century and then declines to 2.6 Wm⁻² by 2100. RCP 6.0 (medium-high-emission scenario) emissions peaks in 2080, then declines to 6.0 W m⁻² by 2100 and remains stable after that. RCP 8.5 (high-emission scenario), referred to as “business as usual”, it is the worst-case scenario in which emission rise continuously during the 21st century reaching a level of 8.5 W m⁻² in 2100.

The hydrodynamic lakes models (GOTM – **Paper I**, Simstrat – **Papers II and III**) were forced by the ISIMP2b products to evaluate the impact of climate change on lake thermal stratification (**Paper I**) and lake surface heat fluxes (**Papers II and III**), after model calibration using historical observed meteorological data (**Paper I**), and global gridded data set of historical climatic input (EWEMBI; Lange, 2019), which is the same dataset used to bias correct the ISIMIP GCM-derived scenarios (**Papers II and III**).

Table 1. Bias-corrected variables in the ISMIP2b climate dataset.

Variable name	Abbreviation	Units
Near-surface relative humidity	hurs	%
Near-surface specific humidity	huss	kg kg ⁻¹
Precipitation	pr	kg m ⁻² s ⁻¹
Snowfall flux	prsn	kg m ⁻² s ⁻¹
Surface pressure	ps	Pa
Surface downwelling long-wave radiation	rlds	W m ⁻²
Surface downwelling short-wave radiation	rsds	W m ⁻²
Near-surface wind speed at 10 m	sfcWind	m s ⁻¹
Eastward near-surface wind speed at 10 m	uas	m s ⁻¹
Northward near-surface wind speed at 10 m	vas	m s ⁻¹
Near-surface air temperature	tas	K
Daily maximum near-surface air temperature	tasmax	K
Daily minimum near-surface air temperature	tasmin	K

Extreme weather event identification

There is no universal definition of extreme events, which are often considered easy to recognise but difficult to define. A widely accepted definition is the one from the Intergovernmental Panel on Climate Change (IPCC; Seneviratne et al., 2012) which defined an extreme (weather or climate) event as “the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends (‘tails’) of the range of observed values of the variable”. There is a little consensus about the threshold value, but usually 5th or 10th percentiles are used.

In **Paper IV** ten wind events (storms) and ten temperature events (heatwaves) were identified at the study lake locations (Erken, Feeagh and Müggelsee; Figure 1) in order to assess the performance of the lake models (GOTM, Simstrat and GLM) during the extreme weather events. The wind events were defined from the wind energy flux from the atmosphere (P_{10} ; Wüest et al., 2000) as the top 5% of daily sums of P_{10} for the April–October period. The heatwaves were defined using air temperature data, picking the two highest three-day summed temperature periods for each month from April to August (see **Paper IV** for more details). These extreme (wind and temperature) events were compared with ‘reference’ wind and temperature events, selecting these

as periods with values closest to the median daily sums of P_{10} and highest three-day summed temperature, respectively.

Lake thermal metrics

A range of thermal metrics derived from lake temperature profiles were calculated in **Papers I and IV** for the purpose of assessing the lake models' performance (at different temporal resolution of meteorological forcing in **Paper I** and during extreme weather events in **Paper IV**) and the impact of climate change (**Paper I**). Surface and bottom temperatures were the shallowest and deepest observation in the water column, respectively. The thermocline depth was defined as the lake depth of maximum density gradient. The whole-lake temperature and lake stability (Schmid Stability, Idso, 1973; Brunt-Väisälä buoyancy frequency) were calculated using the functions *whole.lake.temperature()*, *schmidt.stability()*, *buoyancy.freq()* of the R package *rLakeAnalyzer* (Read et al., 2011; Winslow et al., 2022). The mixed layer depth was defined using the absolute difference density from the surface method following Wilson et al. (2020), for a threshold of 0.15 kg m^{-3} . The duration of the direct thermal stratification was the longest continuous period in which the bottom-surface density difference of the lake water was greater than 0.1 kg m^{-3} . The date of the onset and break-up of the direct thermal stratification were defined as the first time that this density difference persisted for more than 5 days and was absent for at least 5 days respectively (Kraemer et al., 2015).

Heat budget of lakes

The heat budget of a lake, is defined by the exchange of heat with the surrounding environment. It includes the imbalance in heat inputs and outputs at the lake surface (net surface heat flux), advective heat transport (the entry or release of heat by inflows and outflows respectively) and geothermal heat flux (sediment heat exchange). In **Papers II and III**, the advective and geothermal heat fluxes were set to zero, so the heat budget is computed by considering only the net surface heat flux.

The net or total surface heat flux (Q_{total} , W m^{-2}) is the sum of radiative fluxes and turbulent heat fluxes:

$$Q_{total} = Q_{snet} + Q_{lin} + Q_{lout} + Q_e + Q_h$$

The heat fluxes are positive when the lake gains heat from incoming long-wave radiation, Q_{lin} , net short-wave radiation, Q_{snet} , and to a lesser extent from sensible heat flux, Q_h , or latent heat flux, Q_e , and negative when the lake loses heat largely from outgoing long-wave radiation, Q_{lout} , but also from Q_h or Q_e .

The direct and diffusive solar radiation (near-ultraviolet, visible light and near-infrared radiation) that reaches the lake surface, Q_{sin} , varies according to geographic location, time of day, season, local landscape and weather conditions (e.g. cloud cover). A fraction of Q_{sin} is reflected by the lake surface and it is controlled by the albedo, α , so that $Q_{snet} = Q_{sin} \cdot (1-\alpha)$. Of the remaining solar radiation, a portion is strongly absorbed by the water surface. What remains is approximately 65% of Q_{snet} and is in the visible and ultra violet wavelengths (Thiery et al., 2014) and this penetrates through the lake water column and is absorbed according to the Beer-Lambert law.

The incoming long-wave radiation, Q_{lin} , is the thermal infrared flux from the atmosphere and is influenced by water vapor, cloud cover and trace greenhouse gases. Long-wave radiation is also emitted from the lake, Q_{lout} , as a function of the fourth power of the absolute lake surface temperature (Imboden & Wüest, 1995), being the largest heat loss term in the heat budget.

The vertical turbulent latent and sensible heat fluxes are bidirectional (adding or removing heat to or from the lake). The latent heat flux, Q_e , is the heat gained or lost via change of state from water to vapor (evaporation) or from vapor to water (condensation), respectively. It depends on the vapor pressure vertical gradient across the air-water interface and most of Q_e occurs as evaporation, which causes a heat loss. The sensible heat flux, Q_h , is the heat transferred across the lake surface and the atmosphere via convection, depending on the water-air temperature difference and most of Q_h are losses from the lake. Both turbulent heat fluxes are also modulated by winds and the atmospheric conditions above the lake.

A summary of the total heat flux components parameterisations at the air-water interface for the ice-free period in Simstrat are provided in **Papers II and III**.

Results and Discussion

Testing ISIMIP2b lake sector strategy (I): Performance of daily average temperature simulations in Lake Erken driven by daily and hourly meteorological forcing **(Paper I)**

Three different meteorological data sets, (1) hourly observed data, (2) daily average observed data derived from the first data set and (3) synthetic hourly data created from the daily data set using Generalised Regression Artificial Neural Networks (GRNN), were used to force GOTM and evaluate the effects of these data sets on simulations of Lake Erken water temperature. Full-profile temperatures were simulated accurately by GOTM for all three datasets, with an average RMSE of 0.95 and 0.66 °C for the calibration and validation periods, respectively. The model fits were similar to other studies in Lake Erken (Moras et al., 2019; Mesman et al., 2022). When comparing goodness-of-fit metrics for water temperature simulations (and derived thermal metrics) forced with the three different input data sets, the simulations forced by daily input were slightly less accurate than those forced with either observed or synthetic hourly data (Table 2). For example, RMSEs for full-profile temperatures for the calibration period were 1.04, 0.94 and 0.88 °C for the three input datasets, with lower errors associated with simulations driven by hourly meteorological data sets, whereas for the validation periods the RMSEs were comparable for all data sets. Changes in the model parameters adjusted during the calibration process, showed that the calibration procedure could compensate for some limitations related to the temporal resolution of the model forcing data.

Table 2. GOTM Lake model performance evaluation of RMSE for all defined thermal metrics using water temperature simulations results from running lake model driven by daily (24 h met), hourly (1h met) and synthetic hourly (Synthetic 1h met) meteorological data sets for the calibration (2006-2014) and validation (2015-2016) periods in Lake Erken.

	Calibration		
	24h met	1h met	Synthetic 1h met
Full-profile temperature [°C]	1.04	0.94	0.88
Surface temperature [°C]	0.69	0.72	0.61
Bottom temperature [°C]	1.33	1.24	1.16
Whole lake temperature [°C]	0.57	0.52	0.49
Schmidt stability [J m ⁻²]	22.09	21.69	19.64
Thermocline depth [m]	2.77	3.07	2.84
Duration of stratification[day]	9.25	14.25	14.94
Onset of stratification [day]	1.54	1.12	1.17
Loss of stratification [day]	1.54	5.87	9.13
	Validation		
	24h met	1h met	Synthetic 1h met
Full-profile temperature [°C]	0.63	0.69	0.68
Surface temperature [°C]	0.54	0.64	0.54
Bottom temperature [°C]	0.68	0.59	0.74
Whole lake temperature [°C]	0.48	0.59	0.51
Schmidt stability [J m ⁻²]	13.27	13.5	13.26
Thermocline depth [m]	2.86	3.27	3.18
Duration of stratification [day]	8.75	8.28	7.11
Onset of stratification [day]	0.71	10.61	0.71
Loss of stratification [day]	8.94	15.26	7.21

Testing ISIMIP2b lake sector strategy (II): Long-term modelled changes in thermal stratification in Lake Erken (**Paper I**)

Here, we assessed how projected climate trends are likely to change lake water temperature and thermal stratification in Lake Erken. Lake model simulations were made using both original daily resolution of ISIMIP2b products and the hourly disaggregated data using GRNN from four climate models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC5) under RCP 2.6 and RCP 6.0.

Water temperature simulations showed that for all thermal metrics there will be a clear shift in the lake thermal conditions that are consistent with a warmer climate. Surface and bottom water temperatures were projected to increase with stronger and shallower stratification, an earlier stratification onset, a later fall overturn and consequently, a longer stratification period (Figure 2; Tables 3-4). Projected changes under RCP 2.6 showed most of the changes occurred in the first half of the century as a result of the projected mitigation

measures being adopted. In contrast, under RCP 6.0 the greater changes were projected at the end of the 21st century as a result of increased greenhouse gas (GHG) emissions. In general, there were significant changes in all the metrics describing thermal stratification. The exception to this is the GFDL-ESM2M climate model which showed lower or non-significant changes. The other three models (HadGEM2-ES, IPSL-CM5A-LR and MIROC5) showed more consistent and larger future anomalies compared to GFDL-ESM2M. This illustrates the complexity of climate model-lake model interactions and clearly shows the importance of ensemble model simulations, as adopted by ISIMIP, for evaluation the effect of climate change on lakes. Similar trends in the anomaly distributions were seen when the GOTM model was forced with either mean daily or synthetic hourly data. Detailed comparison of the results derived using the two different forcings suggested that the simulated changes were slightly greater when simulations were forced with the mean daily data. However, in both cases the same direction in the trends and the same overall descriptions of change were found. This comparison helped justify the use of a daily time step for ISIMIP lake sector simulations, which greatly reduce their computational cost.

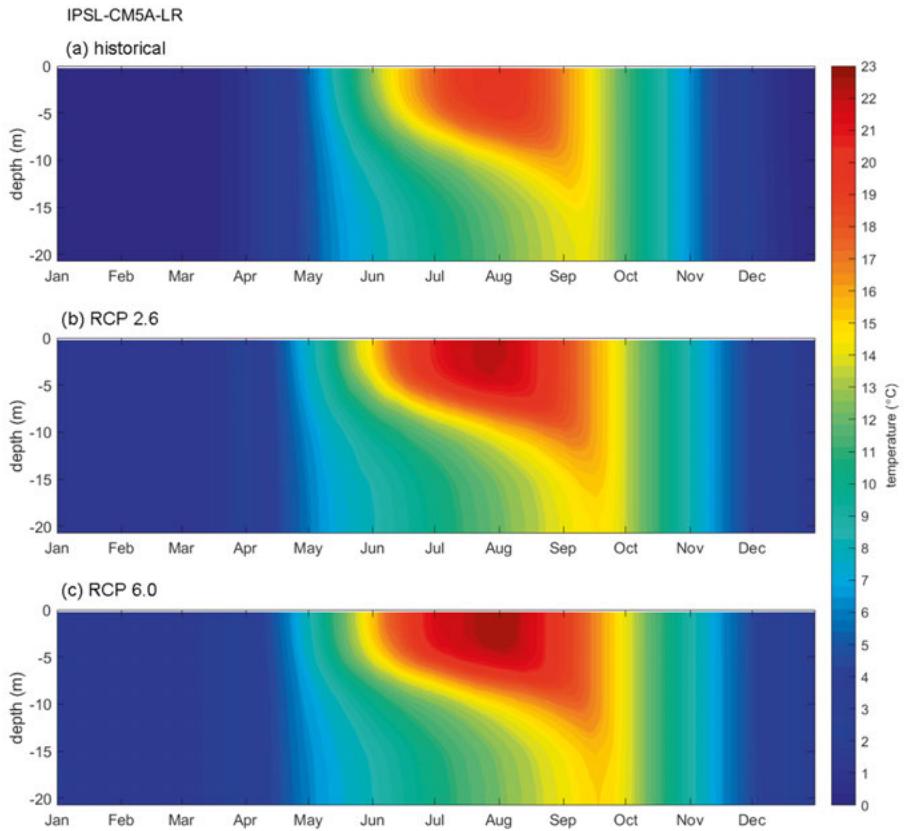


Figure 2. Lake Erken isotherms for the (a) historical, (b) RCP 2.6 and (c) RCP 6.0 scenarios derived from daily IPSL-CM5A-LR projections. The temperature matrix used to make these plots was created by averaging the simulated daily temperature profiles for all years associated with each scenario.

Table 3. Average thermal metrics for the reference period (1981-2010) and average projected changes in thermal metrics for the mid-century (2041-2070) and the late century (2071-2100) under RCP 2.6 in Lake Erken.

		RCP 2.6					
		24h met			Synthetic 1h met		
		Reference period	Mid-century	Late century	Reference period	Mid-century	Late century
Surface temperature [°C]	GFDL-ESM2M	13.73	0.87	0.97	13.89	0.64	0.72
	HadGEM2-ES	13.67	2.16	2.43	13.92	1.61	1.84
	IPSL-CM5A-LR	13.71	2.31	1.97	13.91	1.75	1.47
	MIROC5	13.42	2.10	1.80	13.70	1.65	1.40
	Ensemble	13.63	1.86	1.79	13.86	1.41	1.36
Bottom temperature [°C]	GFDL-ESM2M	9.27	0.37	0.21	9.68	0.29	0.20
	HadGEM2-ES	9.40	0.41	0.43	9.84	0.21	0.23
	IPSL-CM5A-LR	9.30	1.02	0.63	9.61	0.69	0.40
	MIROC5	8.87	0.72	0.96	9.29	0.43	0.72
	Ensemble	9.21	0.63	0.56	9.60	0.41	0.39
Whole-lake temperature [°C]	GFDL-ESM2M	12.46	0.61	0.67	12.84	0.44	0.51
	HadGEM2-ES	12.55	1.48	1.65	12.97	1.08	1.25
	IPSL-CM5A-LR	12.41	1.87	1.49	12.75	1.37	1.10
	MIROC5	12.09	1.57	1.53	12.56	1.17	1.15
	Ensemble	12.38	1.38	1.34	12.78	1.01	1.00
Schmidt stability [J m ⁻²]	GFDL-ESM2M	69.42	13.71	16.85	65.06	10.90	12.22
	HadGEM2-ES	67.39	40.16	45.49	63.48	32.14	36.59
	IPSL-CM5A-LR	69.13	34.25	32.82	67.11	27.32	25.17
	MIROC5	70.45	32.90	21.15	68.08	28.91	16.99
	Ensemble	69.10	30.26	29.08	65.93	24.82	22.74
Thermocline depth [m]	GFDL-ESM2M	-7.82	0.21	0.27	-8.51	0.32	0.30
	HadGEM2-ES	-8.22	0.64	0.79	-8.76	0.60	0.71
	IPSL-CM5A-LR	-7.77	0.17	0.23	-8.21	0.25	0.31
	MIROC5	-7.78	0.53	0.20	-8.44	0.73	0.31

	Ensemble	-7.90	0.39	0.38	-8.48	0.47	0.41
Duration of stratification [day]	GFDL-ESM2M	127	4	9	130	3	7
	HadGEM2-ES	125	20	20	127	16	16
	IPSL-CM5A-LR	124	13	14	127	11	10
	MIROC5	125	15	11	128	12	10
Onset of stratification [day]	Ensemble	125	13	13	128	10	11
	GFDL-ESM2M	131	-3	-5	131	-3	-4
	HadGEM2-ES	132	-10	-13	133	-8	-10
	IPSL-CM5A-LR	133	-8	-7	133	-7	-6
Loss of stratification [day]	MIROC5	134	-10	-10	133	-7	-9
	Ensemble	132	-8	-9	132	-6	-7
	GFDL-ESM2M	258	2	2	260	2	2
	HadGEM2-ES	256	9	8	259	8	7
	IPSL-CM5A-LR	260	3	3	263	2	1
	MIROC5	257	5	2	260	5	2
	Ensemble	258	5	4	261	4	3

Table 4. Average thermal metrics for the reference period (1981-2010) and average projected changes in thermal metrics for the mid-century (2041-2070) and the late century (2071-2100) under RCP 6.0 in Lake Erken

		RCP 6.0					
		24h met			1h met		
		Reference period	Mid-century	Late century	Reference period	Mid-century	Late century
Surface temperature [°C]	GFDL-ESM2M	13.71	1.03	1.67	13.89	0.81	1.28
	HadGEM2-ES	13.56	3.04	4.04	13.84	2.29	2.98
	IPSL-CM5A-LR	13.64	2.60	3.62	13.86	1.92	2.69
	MIROC5	13.41	1.98	2.97	13.69	1.52	2.28
	Ensemble	13.58	2.16	3.08	13.82	1.64	2.31
	GFDL-ESM2M	9.23	0.94	1.24	9.66	0.68	0.9
Bottom temperature [°C]	HadGEM2-ES	9.32	0.42	0.91	9.75	0.15	0.42
	IPSL-CM5A-LR	9.29	1.18	1.19	9.61	0.88	0.79
	MIROC5	8.94	0.98	1.18	9.34	0.77	0.9
	Ensemble	9.19	0.88	1.13	9.59	0.62	0.75
	GFDL-ESM2M	12.44	1.06	1.61	12.83	0.79	1.20
	HadGEM2-ES	12.44	1.96	2.81	12.89	1.45	1.98
Whole-lake temperature [°C]	IPSL-CM5A-LR	12.36	2.12	2.75	12.72	1.57	1.99
	MIROC5	12.11	1.69	2.41	12.59	1.27	1.84
	Ensemble	12.34	1.71	2.39	12.76	1.27	1.75
	GFDL-ESM2M	69.90	4.94	12.26	65.42	4.50	9.79
	HadGEM2-ES	66.43	59.78	77.57	63.18	48.50	61.43
	IPSL-CM5A-LR	67.52	38.67	64.62	65.73	28.06	49.23
Schmidt stability [J m^{-2}]	MIROC5	68.96	23.08	42.42	66.39	17.49	31.83
	Ensemble	68.20	31.62	49.22	65.18	24.64	38.07
	GFDL-ESM2M	-7.82	-0.39	-0.22	-8.50	-0.17	-0.08
	HadGEM2-ES	-8.23	1.02	1.26	-8.77	0.98	1.23
	IPSL-CM5A-LR	-7.83	0.28	0.59	-8.26	0.24	0.64
	MIROC5	-7.83	0.09	0.34	-8.51	0.28	0.49
Thermocline depth [m]							

	Ensemble	-7.93	0.25	0.49	-8.51	0.33	0.57
Duration of stratification [day]	GFDL-ESM2M	126	2	6	129	2	7
	HadGEM2-ES	123	26	34	126	22	27
	IPSL-CM5A-LR	123	16	27	126	13	21
	MIROC5	124	16	22	128	12	17
	Ensemble	124	15	22	127	12	18
Onset of stratification [day]	GFDL-ESM2M	131	-4	-5	131	-3	-6
	HadGEM2-ES	133	-15	-19	133	-12	-15
	IPSL-CM5A-LR	133	-10	-16	133	-8	-12
	MIROC5	134	-14	16	133	-11	-14
	Ensemble	133	-11	-14	133	-9	-11
Loss of stratification [day]	GFDL-ESM2M	257	-1	0	263	-4	-2
	HadGEM2-ES	255	11	16	258	10	13
	IPSL-CM5A-LR	260	3	8	263	2	5
	MIROC5	257	3	7	260	2	5
	Ensemble	257	4	8	261	3	5

Surface heat fluxes under a changing climate in Lough Feeagh (**Paper II**)

The heat gain by Lough Feeagh from 1976 to 2099 for the GCMs ensemble was, on average, 0.0066, 0.0150 and 0.0429 W m⁻² respectively for RCP 2.6, 6.0 and 8.5 (Figure 3). These small positive imbalances in the total surface heat flux, Q_{total} , lead to an increase in whole-lake temperature, T_{avg} , of 0.64, 1.16 and 2.75 °C over this 124-year period. In contrast, under PiControl heat output exceed heat inputs resulting in an average rate of heat loss of -0.0061 W m⁻² (Figure 3), that is, a decrease in T_{avg} of 0.12 °C.

The turbulent heat and radiative surface fluxes (individual components of Q_{total}) showed non-significant changes under PiControl over time (Figure 4). However, under future GHG emission scenarios significant changes were projected for the individual heat flux components, primarily for Q_e , Q_{lin} and Q_{lout} (Figure 4). The increase in net radiative flux was compensated by the decrease in turbulent heat flux (i.e. increase in turbulent heat losses), resulting in the small increase in Q_{total} described above.

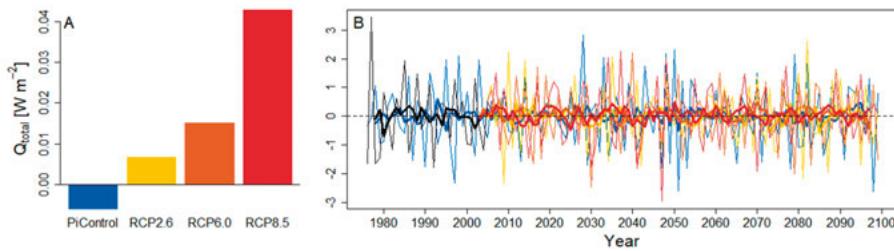


Figure 3. Total surface heat flux, Q_{total} , from 1976 to 2099 under PiControl (blue), historical (black) and future climate forcing: RCP 2.6 (yellow), RCP 6.0 (orange) and RCP 8.5 (red) in Lough Feeagh. A Average over the period 1976 to 2099. B Annual average from 1976 to 2099. The thin coloured lines show the yearly averages across all GCMs and the thick lines show the 5-year centred moving average of the ensemble.

Seasonal surface heat fluxes under a changing climate in Lough Feeagh (**Paper II**)

On a seasonal scale in Lough Feeagh, the largest projected changes in Q_{total} were in spring and autumn. Both, spring heating and autumnal cooling significantly decreased under all future GHG emission scenarios while much smaller changes (an order of magnitude lower) were projected in summer and winter (Figure 5).

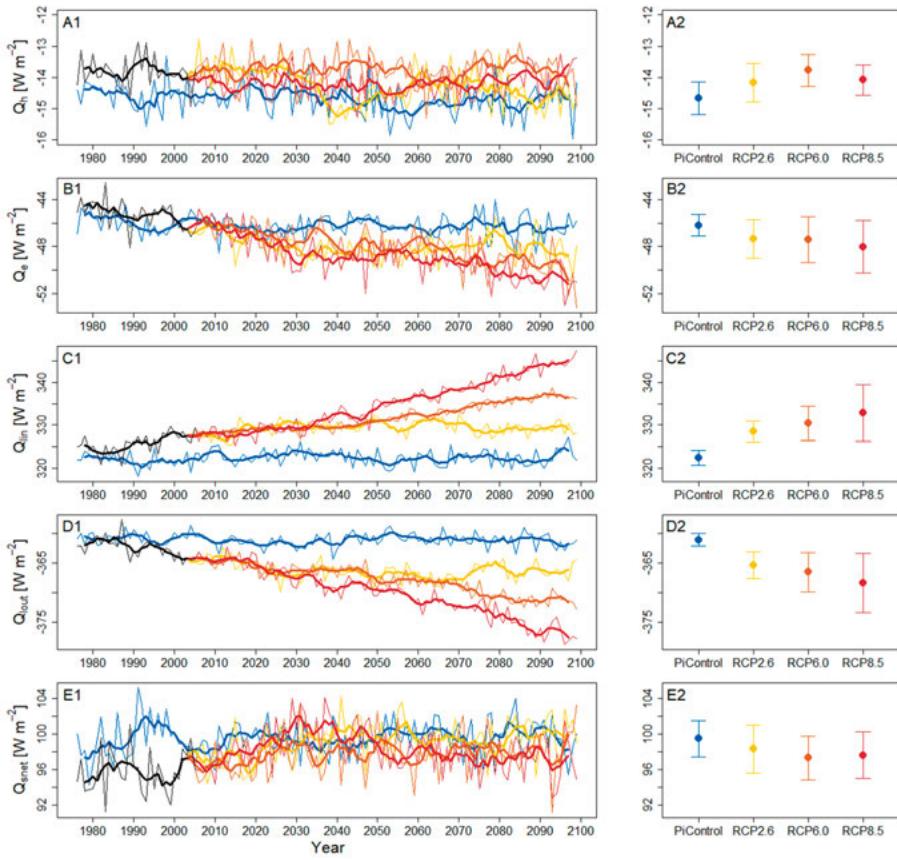


Figure 4. A Sensible heat flux, Q_h , B latent heat flux, Q_e , C incoming long-wave radiation, Q_{lin} , D outgoing long-wave radiation, Q_{lout} , E net short-wave radiation, Q_{snet} , from 1976 to 2099 under PiControl (blue), historic (black) and future climate forcing: RCP 2.6 (yellow), RCP 6.0 (orange) and RCP 8.5 (red) in Lough Feeagh. 1 Annual average from 1976 to 2099, the thin line shows the yearly average across all GCMs and the thick line show the 5-year centred moving average of the ensemble. 2 Average and standard deviation over the period 1976 to 2099.

In spring for future GHG emission scenarios, an earlier onset of thermal stratification as a result of a milder winter and warmer spring (higher air temperature, T_a , and increased Q_{lin}) together with a decrease in wind speed, w_{10} , led to a shallower mixed layer and, in turn, warmer surface water temperatures, T_w , that promoted larger heat loss by Q_h , Q_e and Q_{lout} compared to the PiControl scenario. The significantly increased Q_h heat loss responded to a larger water-air temperature difference, T_w-T_a , (i.e. faster increase of lake surface water temperature than the overlying air). The significant increase in Q_e heat loss was largely explained by the increased water-air vapor pressure gradient, e_s-e_a . Surprisingly, solar radiation in Lough Feeagh was projected to be lower under future GHG emission scenarios than under PiControl, with the largest

reduction in spring. These combined effects led to an overall reduction in spring lake heating during the future GHG emission scenarios compared to PiControl.

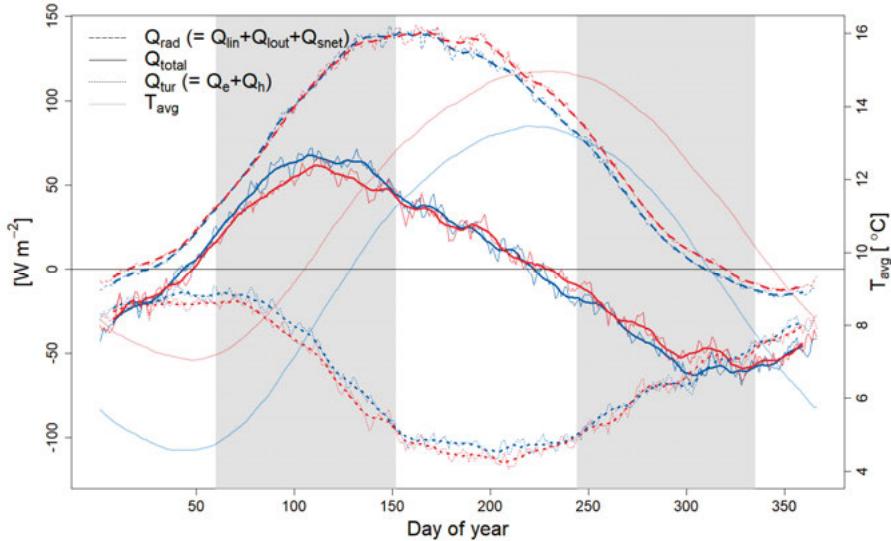


Figure 5. Seasonal total surface heat flux, Q_{total} , turbulent surface heat flux, Q_{tur} , radiative surface heat flux, Q_{rad} , and whole-lake temperature, T_{avg} , from 2070 to 2099 under PiControl (blue) and RCP 8.5 (red) in Lough Feeagh. The thin line shows the daily average across all GCMs and the thick line show the 14-day centred moving average of the ensemble. The shaded areas in the background denote the different seasons (spring: days of the year 60-151, summer: 152-243, autumn: 244-334 and winter: 1-59 and 335-365). The surface heat fluxes are positive when the lake gains heat and negative when the lake loses heat.

During autumn, the summer lake thermal conditions were extended (delay in the break-up of thermal stratification) under future GHG emission scenarios, driven by a warmer atmosphere (greater T_a and Q_{lin}) and lower w_{10} , resulting in an increase in Q_e and a decrease in Q_h of similar magnitude, so that no changes were projected for the turbulent heat flux. In contrast, the net radiative heat flux was projected to increase, as a result of a reduction in net long-wave radiation, Q_{net} , while Q_{snet} was similar in magnitude to PiControl. Therefore, a reduction in lake cooling was projected in autumn.

Summer surface heat fluxes under a changing climate across 47 lakes (**Paper III**)

The average heat gain, Q_{total} , over the summer period during the historical period (from 1976 to 2005) across all lakes was 24.17 ± 15.71 W m⁻² (quoted

uncertainties represent the standard deviation across the lakes) and ranged from 1.05 to 64.58 W m⁻² (Figure 6), with larger Q_{total} in deeper lakes. Q_{total} was the result of the opposite effect of the heat absorbed by the lake surface due to Q_{snet} (207.08±25.44 W m⁻²) and Q_{lin} (342.73±30.89 W m⁻²) and the heat emitted from the lake surface due to the Q_h (-19.25±6.35 W m⁻²), Q_e (-86.26±26.20 W m⁻²) and Q_{lout} (-420.13±16.04 W m⁻²) (Figure 7), leading to a summer surface water temperature, T_w , of 22.42±2.76 °C. The magnitude and timing of maximum summertime heat content increased and was later for deeper lakes (Oswald & Rouse, 2004; Rouse et al., 2005). Larger Q_{total} in deeper lakes could be explained by the relation between lake depth and heat storage.

Climate model projections suggested that the individual components of the summer surface heat flux will change substantially by 2070-2099 (relative to 1976-2005) (Figure 7). The radiative flux absorbed by the lake surface was projected to increase, with ΔQ_{snet} of 11.93±4.91, 12.55±5.45 and 17.40±8.81 W m⁻² between RCP 2.6, 6.0 and 8.5 and ΔQ_{lin} of 9.28±1.98, 19.11±3.29 and 33.01±5.44 W m⁻² between RCP 2.6, 6.0 and 8.5, being responsible for the lake surface warming of 1.77±0.38, 2.96±0.47 and 4.72±0.70 °C between RCP 2.6, 6.0 and 8.5. As a result of the higher T_w , the lake surface emitted additional heat to the atmosphere by Q_{lout} , Q_e and Q_h . The projected ΔQ_{lout} (-10.13±2.11, -17.09±2.71 and -27.54±4.07 W m⁻² between RCP 2.6, 6.0 and 8.5) and ΔQ_e (-11.33±3.50, -16.48±5.07 and -25.10±7.37 W m⁻² between RCP 2.6, 6.0 and 8.5) contributed equally, on average, to the increased emitted heat flux from the lake surface. In contrast, a decrease in Q_h was projected (0±0.85, 1.46±1.07 and 3.20±1.94 W m⁻² between RCP 2.6, 6.0 and 8.5) because summer T_w was projected to increase less than T_a . The ratio of Q_h to Q_e , referred to as the Bowen ratio, and the ratio of Q_e to Q_{lout} were projected to decrease and increase respectively, indicating that Q_e was projected to gain relative importance over Q_{lout} and Q_h at the end of the 21st century.

The strength of the changes in the individual surface heat flux components between historical and future conditions was explained primarily by the magnitude and direction of the changes in the climate drivers. Lakes which were projected to experience higher T_a , e_a or Q_{sin} were also expected to experience higher T_w , and consequently higher Q_{lout} . Regarding turbulent heat fluxes, lakes which were projected to experience higher T_a should expect a decrease in Q_h as a result of a reduction in T_w-T_a , and furthermore lakes experiencing higher e_a should expect a decrease in Q_e as a result of a reduction in e_s-e_a . However, an increase in Q_{sin} was likely to increase the lake heat loss by Q_h and Q_e . Lakes which were projected to experience slower w_{10} , were also expected to experience higher T_w , and consequently greater Q_{lout} , and were likely experience higher Q_h and Q_e heat loss as a result of an increase in T_w-T_a and e_s-e_a respectively.

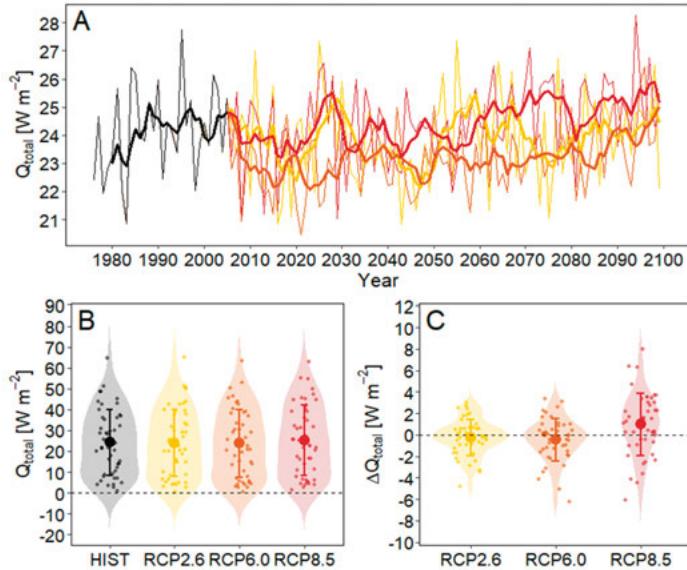


Figure 6. Summer average of total surface heat flux, Q_{total} , from 1976 to 2099 under historical (black) and future climate forcing RCP 2.6 (yellow), RCP 6.0 (orange) and RCP 8.5 (red). A Annual summer average, the thin line shows the yearly average and the thick line show the 5-year centred moving average (average across lakes and GCMs). B Summer average over the historic period (1976-2005) and under RCP 2.6, 6.0 and 8.5 (2070-2099) for each lake (average across GCMs). C Summer average difference between RCPs (2070-2099) and historic period (1976-2005) for each lake (average across GCMs).

The changes in the projected individual surface heat flux component described above occurred in opposite directions, and they tended to cancel each other out. This led to the net change in the total heat budget and thus the accumulation of heat in the lake over the summer being nearly the same in both historical and future conditions (ΔQ_{total} : -0.25 ± 1.67 , -0.45 ± 1.98 and 0.96 ± 2.8737 W m⁻² for RCP 2.6, 6.0 and 8.5; Figure 6), similar to the results reported in Lough Feeagh during summer (**Paper II**).

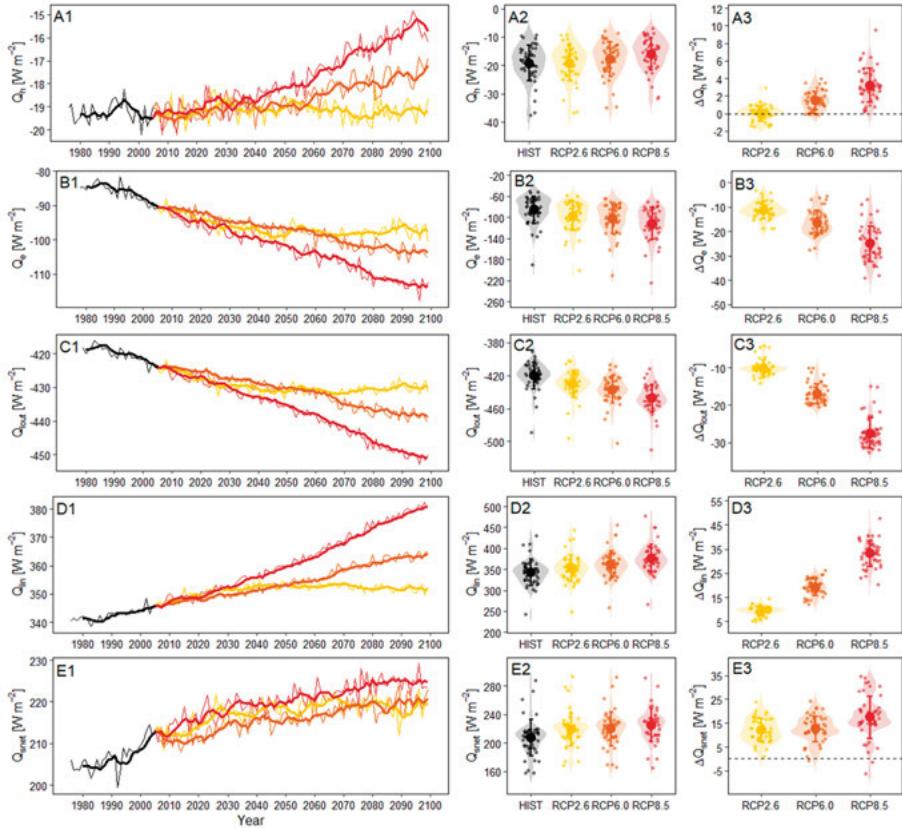


Figure 7. A sensible heat flux, Q_h , B latent heat flux, Q_e , C outgoing long-wave radiation, Q_{lout} , D incoming long-wave radiation, Q_{lin} , E net short-wave radiation, Q_{snet} , from 1976 to 2099 under historic (black) and future climate forcing: RCP 2.6 (yellow), RCP 6.0 (orange) and RCP 8.5 (red). 1 Annual summer average, the thin line shows the yearly average and the thick line show the 5-year centred moving average (average across lakes and GCMs). 2 Summer average over the historic period (1976-2005) and under RCP 2.6, 6.0 and 8.5 (2070-2099) for each lake (average across GCMs). 3 Summer average difference between RCPs (2070-2099) and historic period (1976-2005) for each lake (average across GCMs).

The time period analysed was focused on a fixed period representing summer, being June-August in the northern hemisphere and December-February in the southern hemisphere. We focused on this period largely because, the surface heat fluxes are not fully parameterised under lake ice conditions in Simstrat, making annual comparisons impossible between lakes with different periods of ice cover. The projected changes in summer Q_{total} by the end of the 21st century remained, in general, unchanged. However, when examining each lake, Q_{total} could experience either a future decrease or an increase relative to historical conditions. This can be explained by a number of possible processes linked to the timing of thermal stratification. During summer, lakes are usually thermally stratified, isolating the lake surface from the subsurface layers.

Under climate change summer thermal stratification is strengthened and extended due to an earlier onset and a latter break-up, as shown by both observations (Moras et al., 2019) and future climate projections (**Paper I**; Woolway et al., 2021). This consequently, will have an effect on Q_{total} . During the summer Q_{total} shifts from positive to negative (from net heating to net cooling; e.g. Figure 5), when lake surface water temperature peaks, close to the end of summer or even at the beginning of autumn for deep lakes. Latter break-up of thermal stratification could modify the timing of the shift in Q_{total} to a later date in the fixed summer period, promoting a decreased net cooling after the shift point (as shown in Lough Feeagh during autumn, **Paper II**) and thus in an increase in summer Q_{total} . An earlier onset of thermal stratification and consequently warmer surface water temperatures could promote an increase in the heat emitted from the lake surface and thus a decrease in Q_{total} during spring (as shown in Lough Feeagh during spring, **Paper II**). Therefore, for those lakes where the onset of thermal stratification occurs later in spring, Q_{total} could decrease during the first part of the summer, promoting an overall decrease in summer Q_{total} .

Performance of modelling the effect of extreme weather events within lakes (**Paper IV**)

Here we assessed the performance of the lake models (1) for 1-year calibrated and 11-year validation period and (2) during extreme and reference events within the validation period. Model fits for the validation period showed a good agreement between observed and simulated water temperatures, RMSE values ranged from 0.68 to 1.84 °C, in line with other studies (Perroud et al., 2009; Stepanenko et al., 2013; Bruce et al., 2018; Moras et al., 2019; Moore et al., 2021). Simstrat and GOTM performed better than GLM. GLM produced satisfactory results of simulated temperature in the calibration and validation periods with RMSEs of 0.77 and 1.18 °C respectively in Lough Feeagh. Similar results were reported by Bruce et al. (2018) with a RMSE 0.72 °C during the calibration period and by Moore et al. (2021) with RMSEs of 0.82 and 1.17 °C respectively during calibration and validation periods. In addition, Moore et al. (2021) also reported lower RMSEs for Simstrat and GOTM. In general, all models performed better during the reference events compared to extreme events (Figure 8). Lough Feeagh had the lowest MAEs during storms and heatwaves compared to other lakes and MAEs were slightly higher during heatwaves compared to storm. During extreme events Simstrat and GOTM had similar MAEs, while MAEs for GLM were higher.

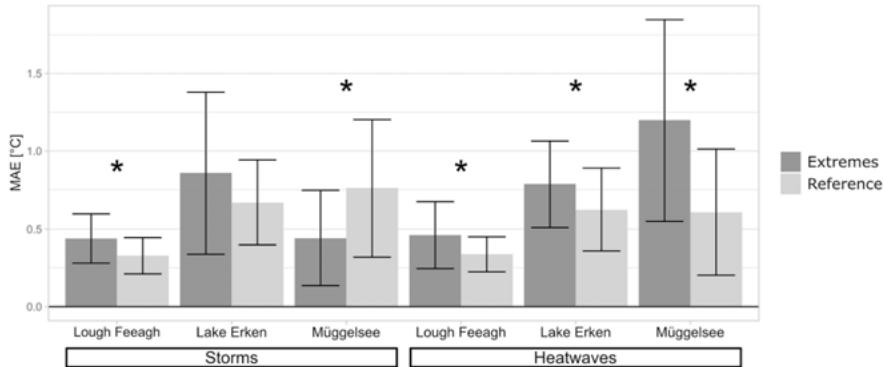


Figure 8. Mean Absolute Error (MAE, °C) for full-profile temperatures, comparison between extreme and reference (wind and temperature) events. The bars and error bars indicate the average (over all models) and standard deviation, respectively, and the asterisk represents the statically significant difference in MAEs.

The behaviour of Simstrat and GOTM for either calibration and validation periods or extreme weather events was more similar to each other than GLM, which is likely the result of a similar process description and parametrization. For example, Simstrat and GOTM apply a $k-\epsilon$ turbulence model (Burchard et al., 1999; Goudsmit et al., 2002) and a fixed layer structure, while GLM adopts an energy balance approach and a flexible layer structure (Hipsey et al., 2019). Therefore, the use of a model ensemble can be seen as a way of translating differences in model formulation and limitations into a credible confidence band around the mean prediction.

The observed data showed that during storms (Figure 9) for the two deeper lakes of this study (Lough Feeagh and Lake Erken), surface temperature decreased and the bottom layers warmed as a result of a deepening of the surface mixed layer and a decrease in Schmid stability, in agreement with previous studies (Jennings et al., 2012; Andersen et al., 2020). However, whole-lake temperature was only slightly affected. Lake Müggelsee was completely mixed during the ten studied events, cooling down at all depths. In four out of ten events, lake stratification was re-formed within a few days after the storm as a result of a direct respond to post-event weather conditions. When stratification was re-established the lower heat storage capacity of this shallow lake, resulted in very small changes in Schmid stability and mixed depth compare to pre-event lake conditions. During storms all models accurately simulated changes in surface and whole-lake temperature, while bottom lake temperature was also reproduced but with less accuracy. Simstrat and GOTM reproduce lake stability (shown as Schmid stability and buoyancy frequency) more accurate than GLM. And the changes in mixed layer depth was the least accurate for all models.

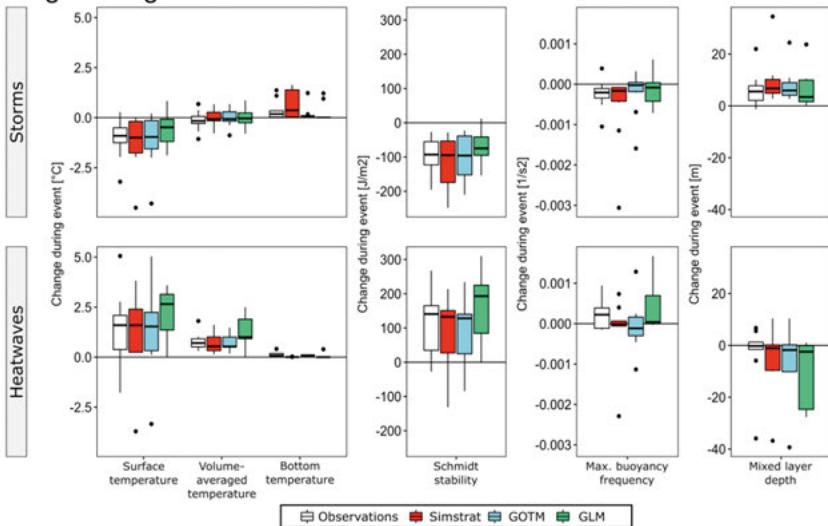
The effects of heatwaves on the lake (Figure 9), were opposite to the effects of storms. Heatwaves enhanced lake stability in Lough Feeagh and Lake

Erken, with warmer waters at all depths, but with the greatest increases in temperature at the surface than at the bottom. This also led to an increased whole-lake temperature. In Müggelsee water temperature increased at all depths to a similar extents and stratification was found to occur during most of the heatwaves, in line with Wilhelm & Adrian (2008). However, two days after the heatwaves, lake thermal conditions returned to pre-event levels, as a result of a relatively uniform increase in the temperature at all depths in the water column, so that any changes in lake stability and mixed layer depth did not remain. During heatwaves simulated changes had slightly lower performance for surface and whole-lake temperature and Schmid stability than during storms. Simstrat and GOTM performed better than GLM for all metrics, except for bottom temperature. The mixed layer depth performed better during heatwaves compared to storms for Simstrat and GOTM.

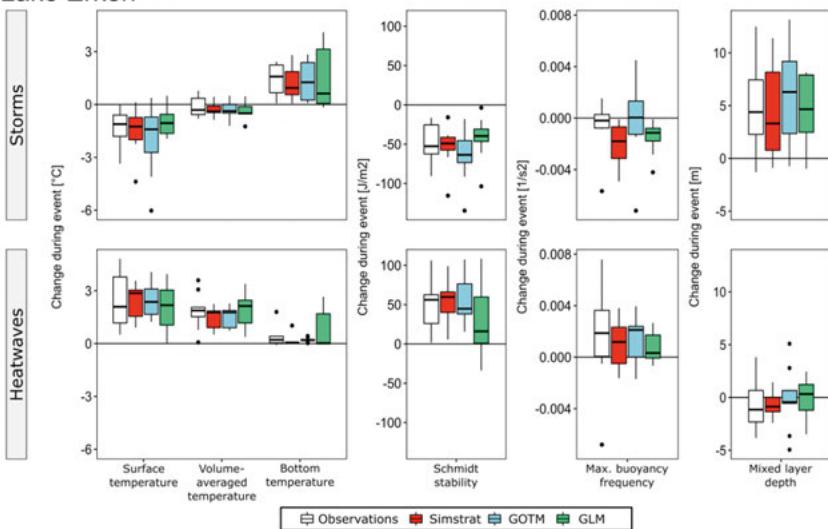
We found that simulations during extreme weather events generally were temporarily less accurate in predicting lake conditions. However, during these events larger model uncertainty is expected due to larger energy fluxes and more rapid changes in thermal gradients in the water column occurring over a shorter temporal scale. Furthermore, model coefficients assigned during long-term calibration are likely to be poorly matched for extreme conditions and can promote errors. The 1D assumptions omitting horizontal processes which may lead to an incomplete description of lake thermal dynamics, especially during extreme weather events. For example, the generation of internal waves by wind events, causing mixing for an extended period of time after an event (Imboden & Wüest, 1995). Spatial heterogeneity, can also come into play as shallow areas respond more rapidly to fluctuations in weather conditions than deep areas. Storms are often also associated with increased inflow and changes in turbidity (Klug et al., 2012) and these processes were not addressed by the model set-up.

Despite these increases in model errors during events, all models were able to reproduce the overall direction and magnitude of changes in thermal metrics in response to extreme wind and temperature events. On average, changes in surface and whole-lake temperature and Schmid stability were simulated more accurately than bottom temperature and mixed layer depth during wind and temperature events.

a) Lough Feeagh



b) Lake Erken



c) Müggelsee

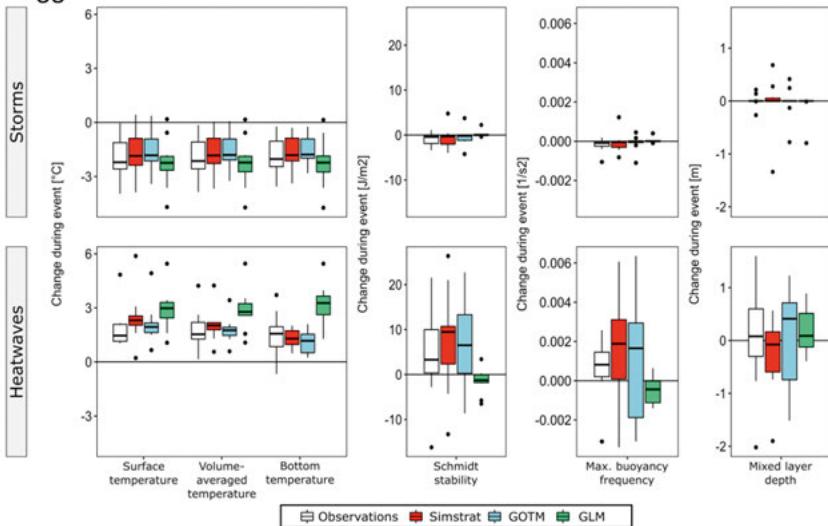


Figure 9. Changes in surface, bottom and whole-lake temperatures, Schmidt stability, buoyancy frequency and mixed layer depth during storms and heatwaves for a) Lough Fecagh, b) Lake Erken and c) Lake Müggelsee. The change during the event was calculated as the difference between the average over the two days after the event and the average over the two days before the event.

Conclusions and Future Perspectives

Testing ISIMIP2b lake sector strategy

In **Paper I** we performed the first test simulating lake thermal structure following the ISIMIP2b lake sector protocol applied to Lake Erken. The lake model simulated accurately daily water temperature when the model was forced with either daily or (observed and synthetic) hourly inputs. Future climate simulations showed that lake thermal metrics were projected to change consistently with a warmer climate. These projected changes in lake thermal metrics were similar when the model was forced by either daily or synthetic hourly ISIMIP2b products. Therefore, the original climate model projections at a daily resolution can be sufficient as the input to lake models simulating water temperature and lake thermal structure.

The warmer the lake, the greater the net lake heat gain?

Papers II and III showed that individual surface heat flux components are projected to change substantially under future GHG emission scenarios.

In **Paper II** the combined changes in the individual surface heat flux components showed compensating effects, leading to a small change in total surface heat flux sufficient to lead important changes in whole-lake temperature over the time scale of climate change. On a seasonal scale, the largest projected changes in total surface heat flux were in spring and autumn. Both spring heating and autumnal cooling decreased under future GHG emission scenarios, while only small differences in the total surface heat flux were projected in winter and summer between PiControl and future GHG emission scenarios. All this leads to counter-intuitive results suggesting that in a warming world there will be less heat, not more, entering Lough Feeagh during the spring, and little change in net heating over the summer or net cooling over the winter compared to PiControl. The significant simulated increases in whole-lake temperature are therefore, largely due to reduced heat loss during autumn.

In **Paper III** 47 lakes were analysed during the summer period. The results showed that surface water temperature was projected to increase at the end of the 21st century due to an increase in incoming short- and long-wave radiation. The warmer lake surface also led to higher lake heat losses by outgoing long-wave radiation, and latent and sensible heat fluxes. Altogether, the net heat budget and thus the accumulation of heat in the lakes over summer remains

almost unchanged between the historical and future conditions. However, a shift in the contributions of the individual heat fluxes was projected, with the latent heat flux increasing in relative importance.

Is lake modelling a viable approach to assess the effect of extreme weather events on lakes?

Paper IV showed that all lake models were able to reproduce the overall direction and magnitude of change in lake thermal structure during either extreme wind or temperature events, but the precision of the water temperature simulations was lower compared to non-extreme conditions.

What's next?

In **Paper III** we followed the same modelling strategy for both large and small lakes, using a 1D lake model which has a demonstrated skill in simulating thermal stratification dynamic at a reasonable computational cost. However, the response of lake warming is heterogeneous over the horizontal dimension (Woolway & Merchant, 2018; Toffolon et al., 2020; Calamita et al., 2021), primarily promoted by lake morphometry, influencing the seasonality in the surface heat fluxes (Rouse et al., 2005). Using a different modelling approach, such as that proposed by Gaillard et al. (2022), a multi-column lake model could be used to reasonably reproduce the horizontal variability of the seasonal surface heat exchanges between the lake surface and the atmosphere while avoiding the high computational cost of a 3D lake model.

Long-term lake ice phenological records have shown a global decline of lake ice cover (Sharma et al., 2021) and by the end of this century up to 5679 lakes of 1.35 million may permanently lose ice cover if greenhouse gas emissions continue to be emitted at current levels (Sharma, Blagrave, et al., 2021). Warmer climate conditions that are projected during winter under future climate scenarios and the shortening or losing of ice cover period promote warmer surface water temperature and potentially modified lake heat loss. Therefore, a full parametrizations of surface heat fluxes in the presence of ice conditions can improve our understanding of whole year changes in the lake surface heat fluxes that ultimately control changes in lake thermal structure. Therefore, development of lake models that include realistic representations of the winter heat flux should be a priority for future work.

In ISIMIP2b lake sector we worked on the premise that lake water temperature variation results solely from the exchange of energy between the lake surface and the atmosphere (Golub et al., 2022). The omission of the advective heat flux (inflow) is relevant for water bodies with strong water level fluctuations and a rapid water exchange, such as reservoirs or lakes with short residence time. The impact of the advective heat flux on the total surface heat flux depends on the difference in temperature between the inflow and the lake surface. While a warmer inflow will flow into the surface layer and therefore directly modify the lake surface water temperature and in turn the total surface

heat flux, a colder inflow may not directly affect either lake surface water temperate or total surface heat flux. Changes are also projected in the magnitude and timing of the inflow and may directly or indirectly affect the projected surface heat fluxes. Implementations of the advective heat flux in model simulations will lead a better understanding of surface heat fluxes in reservoirs.

The studied lakes in **Paper III** comprise temperate and boreal lakes located mostly in the northern hemisphere. This may lead to bias in the analysis as the model results may not capture processes in lakes close to the equator. Tropical lakes experience smaller seasonal variations in air and surface water temperature leading to different thermal dynamics and in turn a different configuration in the individual surface heat flux components. Future works should include more lake water temperature observations close to the equator in order to provide a more complete overview of the projected global changes.

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Summaries

Summary

The Earth is being subject to unequalled warming, the average global temperature has increased by a little more than 1°C since 1880, with the last decade being the warmest on record resulting in more frequent and extreme storms and unprecedented heatwaves. Human activities including the burning of fossil fuels, deforestation, agriculture and land-use changes are responsible for rising levels of greenhouse gases that trap more of the sun's energy, increasing the global temperature. Climate change is having significant and far-reaching impacts on lake ecosystems. Lakes are experiencing shorter periods of ice cover, as well as warmer summer surface water temperatures, resulting in earlier and longer summer stratified periods, alterations in lake mixing regimen and changing water storage. All this leads to a cascade of ecological consequences, such as a reduction in dissolved oxygen, enhanced cyanobacteria blooms and loss of habitat for native cold-water fish. These lake responses to climate change also have implications for ecosystem services, such as water supply, hydropower, food provisioning, transportation and recreation.

Process-based lake models are essentially a set of mathematical equations based on physical laws that simulate dynamic in-lake processes, and have been extensively employed as tools to advance the understanding of lake behaviour. Advances in computing power and data collections have accelerated the use of lake models. One-dimensional (1D) hydrodynamic lake models are frequently used to characterize hydrodynamics in lakes due to their computational efficiency, minimal calibration requirements and skill in simulating thermal stratification dynamics (at seasonal and decadal time scales). Lake models driven by climate model outputs allow us to understand how lake water environments could behave under future climate change (climate change assessment) and to develop mitigation or management strategies to ensure water security for future generations. In this thesis, I investigate both long-term and short-term (extreme events) effects of climate change on lake thermal dynamics using 1D hydrodynamic lake models.

The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; <https://www.isimip.org/>) is a community-driven modelling effort with the goal of providing a quantitative assessment of global climate change impacts at different levels of global warming in a consistent setting across multiple sectors. To address this challenge ISIMIP develops and provides a set of

climate and socioeconomic forcing data for consistent cross-sectoral climate impact modelling. In the first chapter of this thesis, we performed the first test of simulating lake thermal structure using daily ISIMIP2b bias-corrected climate model projections as input data to force the GOTM lake model applied to Lake Erken (Sweden). The temporal resolution of the meteorological data used for driving lake models usually ranges from daily to hourly or even shorter, and the accuracy of the lake model simulations is often improved by increasing the time resolution of the meteorological forcing. To assess the importance of the temporal resolution of the forcing data (daily vs hourly) for predictions of daily water temperature, daily average meteorological data (derived from averaging observed hourly data) were disaggregated (using Generalised Regression Artificial Neural Networks) to form a synthetic hourly data set. GOTM simulations were made using both original daily resolution, as available from ISIMIP2b products, and using the hourly disaggregated data. Simulations were made using four climate models under different future climate scenarios. GOTM accurately simulated daily water temperature when the model was forced with either daily or (observed and synthetic) hourly inputs. Future climate simulations showed that water temperatures and thermal stratification metrics are projected to clearly shift toward the lake thermal conditions that are consistent with a warmer climate at the end of the 21st century, i.e. warmer surface and bottom temperatures and a stronger and longer duration of summer thermal stratification as a result of an earlier stratification and later fall overturn. Those projected changes in lake thermal metrics were similar when the model was forced by either daily and synthetic hourly ISIMIP2b products. Therefore, we could recommend to the ISIMIP lake sector community that the original climate model projections at a daily resolution can be sufficient for the purpose of simulating water temperature.

The simulated lake water temperature and thermal dynamics resulted from exchange of energy between the lake surface and the atmosphere, including surface heat fluxes (i.e. surface heating or cooling) and wind stress (vertical turbulent mixing). We assumed that the projected increase in lake water temperatures are due to a reconfiguration of the individual surface heat flux components. In chapter two, we investigate the changes in the total surface heat flux and the individual flux components in a monomictic lake (Lough Feeagh, Ireland) when a 1D hydrodynamic model (Simstrat) was forced by ISIMIP2b products. In order to quantify the effect of climate change, the projected surface heat fluxes for the historical and three future scenarios with different levels of warming were compared with a control climate scenario based on pre-industrial greenhouse gas levels (picontrol). We found that individual surface heat flux components were projected to change substantially under future climate scenarios driven by changes in atmospheric forcing. The increased lake heating by net radiative flux was counteracted by increased lake heat loss by turbulent heat flux, leading to a small positive change in total surface heat flux, but sufficient to lead to an important change in whole-lake temperature.

At the seasonal scale, the largest change in total surface heat flux was projected in spring and autumn. Both spring heating and autumnal cooling were projected to decrease under future climate scenarios compared to the picontrol climate scenario, while projected changes in total surface heat flux during winter and summer were much smaller. All of this leads to the counter-intuitive results that in a warming world there will be less heat, not more, entering Lough Feeagh during the spring, and little change in net heating over the summer or net cooling over the winter compared to pre-industrial climate, so that increases in whole-lake temperature are large due to reduced heat loss during autumn.

In chapter three we expanded the surface heat fluxes analysis over 47 lakes but during the summer period when the lake is strongly thermal stratified and the surface layer is almost thermally isolated from the subsurface waters. We took a different approach in this study, to quantify the effect of climate change, we compared the projected surface heat fluxes for the historical period with those associated with late century climate change. We assume that the projected changes in summer surface water temperature will be controlled mainly by changes in the individual surface heat flux components. The results showed that summer lake surface temperatures were projected to increase due to increased incoming long-wave and short-wave radiation. The increased lake surface temperatures also led to greater heat losses by outgoing longwave radiation, and latent and sensible heat fluxes. Altogether, the net heat balance and thus the accumulation of heat in the lakes over summer remained almost unchanged. However, shifts in the contribution of the individual heat flux components were projected, with the latent heat flux gaining relative importance.

The last chapter of this thesis was focused on the evaluation of lake model performance, but this time under extreme conditions. Recently, several studies have applied 1D hydrodynamic lake models to study the effect of extreme weather events on lake thermal structure. However, we do not know how accurately lake models simulate observed lake thermal structure during short-term events (e.g. on an hourly scale), since it is a common practice to assess the accuracy of the lake model over longer timescales (e.g. at the interannual scale). Here, we assess the performance of three 1D hydrodynamic lake models (Simstrat, GOTM and GLM) in reproducing observed changes in water temperature and thermal stratification during storms and heatwaves in three different lakes (Lough Feeagh – Ireland, Lake Erken – Sweden and Lake Müggelsee – Germany) using high-frequency data. For each lake, ten storms and ten heatwaves were identified and used to assess how well the model reproduced the hydrothermal changes associated with the events and also how these compared with ten reference (non-extreme) time periods. The models reproduced the overall direction and magnitude of changes in water temperature and thermal stratification metrics during both storms and heatwaves with accurate timing and little bias (significant over or underestimation were found in a few cases). However, the lake model performance decreased in accuracy

compared to non-extreme conditions. We concluded that 1D lake models can be an adequate tool to study changes in thermal structure during extreme events, but that increased uncertainty should be taken into account.

In conclusion, 1D hydrodynamic lake models have been shown to be a powerful tool to predict long-term and short-term climate-related changes in lake thermal dynamics, while also making possible in-depth analysis of the surface heat fluxes. This thesis furthered our understanding of process-based mechanisms by which climate change will influence lake thermal dynamics and heat exchange between the lake surface and the atmosphere. A better understanding of the effects of climate change on lakes can help society better anticipate future lake conditions and develop optimal mitigation and management strategies.

Sammanfattning

Jordens klimat blir allt varmare. Sedan 1880 har den globala medeltemperaturen stigit med drygt 1 °C, och de senaste 10 åren är de varmaste någonsin uppmätta. Det har bland annat lett till en högre frekvens av extremväder såsom stormar och extremhetta. Ansvarig för denna förändring är människans utsläpp av växthusgaser genom förbränning av fossila bränslen, avskogning, jordbruk och annan förändring i markanvändning. De höjda halterna av växthusgaser håller kvar mer värme i jordens atmosfär, och därfor stiger temperaturen.

Denna klimatförändring har en långtgående påverkan på ekosystem i sjöar. Perioden där sjöar är istäckta blir allt kortare, och ytvattnet blir allt varmare på somrarna, vilket leder till lägre perioder av skiktade vattenmassor på somrarna, förändringar i hur vattenmassor blandas, och mängden vatten i sjön. Dessa fysikaliska förändringar har massiv påverkan på ekologin, eftersom de påverkar vattnets halt av syrgas, stimulerar algbloomingar, och hotar att slå ut fiskar som är anpassade till ett liv i svalare vatten. Detta påverkar också hur vi människor kan använda sjöarnas ekosystemtjänster, såsom dricksvatten, vattenkraft, fiske, transport och rekreation.

För att förstå sjöarnas beteende när de utsätts för störningar används ofta processbaserade modeller, som består av sammanlänkade matematiska ekvationer som utifrån fysikens lagar simulerar processerna i sjön. Sådana modeller utnyttjas i allt större utsträckning i takt med att beräkningskraften och data-mängden ökar. Endimensionella (1D) hydrodynamiska modeller kan beräkna vattnets rörelser i sjöar och används ofta eftersom de är effektiva beräkningsmässigt, inte behöver mycket kalibrering, och kan simulera dynamiken i vattentemperatur över djupet på tidsskalor från månader till dekader. Dessa sjömodeller kan köras med ingångsdata från klimatmodeller, och på sätt kan vi få en inblick i hur framtida klimatförändringar kan komma att påverka sjöekosystem. Därmed kan dessa modeller hjälpa oss att utveckla strategier som säkrar tillgången till sjöarnas ekosystemtjänster för framtida generationer.

I den här avhandlingen har jag med hjälp av endimensionella hydrodynamiska modeller undersökt effekterna av klimatförändring på dynamiken i sjövattnets temperatur, på lång sikt men även för kortvariga extrema händelser. Ingångsdata för mina modeller har kommit från ISIMIP (Inter-Sectoral Impact Model Intercomparison Project; <https://www.isimip.org/>), ett stort internationellt samarbete av forskare inom klimatmodellering som söker att kvantifiera klimatförändringens påverkan på jordens ekosystem och mänskliga samhällen på ett harmoniserat sätt. ISIMIP utvecklar och tillhandahåller simuleraade data av framtida klimat och socioekonomiska förhållanden, som sedan kan användas för att modellera effekterna av dessa framtida förändringar.

I första kapitlet av den här avhandlingen testade vi för första gången att simulera dynamiken i en sjös vattentemperatur utifrån dagliga väderdata från klimatsimuleringarna i ISIMIP2b, genom att tillämpa sjömodellen GOTM på

sjön Erken, utanför Norrtälje. Tidsupplösningen i de meteorologiska data som driver sjömodeller sträcker sig vanligtvis från timmar (eller kortare) till dagar, och modellernas förutsägelser blir ofta mer precisa när ingångsdata är på en längre tidsskala. För att undersöka huruvida tidsskalan i ingångsdata (per dag eller per timme) påverkar prognoser av daglig vattentemperatur, använde vi en algoritm kallad Generalised Regression Artificial Neural Networks för att generera syntetiska timvisa data utifrån dagliga data. Simulationer inom GOTM använde dels ingångsdata på daglig tidsskala (från ISIMIP2b) och dels de syntetiska timvisa data. Ingångsdata från fyra olika klimatmodeller och olika scenarier av mänskliga åtgärder mot klimatförändring användes för simuleringarna. Det visade sig att GOTM simulerade vattentemperatur i Erken på en daglig tidsskala stämde väl överens med uppmätt vattentemperatur, både när dagliga eller timvisa ingångsdata användes. I ett framtid klimat, dvs mot slutet av detta århundrade, visar modellen att både yt- och bottenvattnet blir varmare, att sommarens period av skiktade vattenmassor blir längre, och att ombländningsperioden på hösten kommer senare. Dessa slutsatser påverkades inte av tidsupplösningen i ingångsdata (daglig eller timvisa). För kommande studier är därmed daglig upplösning i meteorologiska ingångsdata från klimatmodellerna tillräckligt för att kunna simulera klimatförändringens effekter på vattentemperaturen i sjöar.

Dynamiken i den simulerade sjövattentemperaturen resulterade från utbytet av energi mellan sjön och atmosfären, bland annat värmearbete vid sjöytan (sjöytan blir varmare eller kallare) och vindens tillförsel av energi för vertikal turbulent ombländning. Vi antog att den simulerade ökningen i sjöns vattentemperatur berodde på en förändring i olika delprocesser som formar det totala värmearbrytet vid sjöytan. I kapitel 2 undersökte vi förändringarna i det totala värmeflödet vid ytan och dess olika delprocesser i sjön Lough Feeagh på Irland, genom att driva den endimensionella hydrodynamiska modellen Simstrat med klimatdata från ISIMIP2b. För att kunna utröna klimatförändringens påverkan jämförde vi simuleringar av värmeflöden vid sjöytan under olika scenarier av klimatförändring med ett kontrollscenario där växthusgashalten hålls konstant på förindustriella nivåer. Vi fann att de olika delprocesserna som formar värmearbrytet vid sjöytan kraftigt kommer att förändras i ett framtid klimat på grund av ändrade atmosfärsförhållanden. Den ökade uppvärmningen av sjövattnet på grund av högre värmestrålning motverkades av en ökad värmeförlust genom turbulent värmeflöde, vilket resulterade i en ökning av det totala värmeflödet som var liten, men tillräckligt stor för att leda till en tydlig höjning av sjöns vattentemperatur. Den största ökningen i värmeflödet prognosticeras på våren och hösten, och en minskning i både uppvärmning under våren och avkyllning under hösten. Förändringarna var mycket mindre under sommar och vinter. Oväntat nog förutsäger modellen alltså att det i en varmare värld kommer att vara ett mindre, inte större, flöde av energi från atmosfären till Lough Feeagh under våren, inga större förändringar under

sommar och vinter, och att den totala ökningen av sjövattentemperaturen beror på en minskad värmeförlust under hösten.

I kapitel 3 utökades analysen av värmearitytet till 47 sjöar under sommarperioden, när temperaturskiktningen är tydlig och det varma ytvattnet är termiskt isolerat från det kalla bottenvattnet. För att kvantifiera effekten av klimatförändring jämfördes sjöarnas modellerade värmearitytet vid seklets slut med det modellerade historiska värmearitytet. Modellberäkningarna visade att vattentemperaturen vid sjöytan under sommaren kommer att öka på grund av högre instrålning av både långa och korta våglängder. Den ökade vattentemperaturer ledde också till en högre värmeförlust genom ökningar i utstrålning av långa våglängder, latent samt sensibelt värmeflöde. Sammanlagt resulterade detta i mycket ringa förändringar i sjöarnas nettovärmebalans och accumulation av värme under sommaren. Betydelsen av latent värmeflöde prognosticerades öka i jämförelse med andra processer som bidrar till sjöarnas värmearitytet.

Sista kapitlet utvärderar sjömodellernas tillförlitlighet när det gäller simulerings av extrema händelser. Endimensionella hydrodynamiska modeller har tidigare använts för att studera effekten av extremväder på sjöars temperaturförhållanden, men det är osäkert hur ackurata dessa simuleringarna är eftersom noggrannheten i modellernas prediktioner i vanliga fall utvärderas på längre tidsskalor, t ex över flera år. Vi utvärderade noggrannheten i simuleringen av vattnets temperatur och termisk skiktning under stormar och värmeböljor av tre endimensionella hydrodynamiska modeller (Simstrat, GOTM och GLM) och i tre olika sjöar (Erken, Lough Feeagh och Müggelsee i Tyskland), med hjälp av högfrekventa mätdata från dessa sjöar. För varje sjö identifierades 10 stormar och 10 värmeböljor, och vi undersökte hur bra modellerna reproducerade dynamiken i vattentemperatur som orsakades av dessa extrema händelser, i jämförelse med 10 tidsperioder med icke-extremt väder. Modellerna lyckades reproducerera riktningen och storleken av förändringar i vattentemperatur och skiktning som orsakas av både stormar och värmeböljor, med korrekt tidsförlopp och utan systematisk vinkling mot över- eller underskattning (även om sådan förkom i enstaka fall). Modellernas simuleringar var dock mindre ackurata vid extremväder än vid normala väderförhållanden. Endimensionella hydrodynamiska modeller kan därför anses vara ett lämpligt verktyg för att undersöka hur extremväder påverkar sjöars termiska struktur, men resultaten bör tolkas med viss försiktighet.

Sammanfattningsvis visar den här avhandlingen att endimensionella hydrodynamiska modeller är kraftfulla verktyg för prognosar av klimatrelaterade förändringar i dynamiken i sjöars vattentemperatur, både på långa och på korta tidsskalor. Avhandlingen visar även att dessa modeller även möjliggör en djupare analys av värmearitytet mellan sjöar och atmosfären. Därmed lämnar den här avhandlingen ett bidrag mot bättre förståelse av mekanismerna bakom klimatförändringens effekter på sjöar, och hjälper samhällets förvaltning av vattenresurser genom att förutse förväntade framtida förändringar, vilket

möjliggör utvecklingen av förvaltningsstrategier som lindrar effekterna av klimatförändring.

Résumé

La Terre est soumise à un réchauffement sans précédent. La température moyenne planétaire a augmenté d'un peu plus de 1°C depuis 1880, la dernière décennie étant la plus chaude jamais enregistrée, ce qui a entraîné des tempêtes plus fréquentes et violentes et des vagues de chaleur inégalées. Les activités humaines liées à la combustion de combustibles fossiles, à la déforestation, à l'agriculture et aux changements d'affectation des terres sont responsables de l'augmentation des concentrations de gaz à effet de serre qui piègent une plus grande partie de l'énergie fournie par le soleil faisant par conséquent augmenter la température mondiale. Le changement climatique a des répercussions importantes et néfastes sur les écosystèmes lacustres. Les lacs connaissent des périodes d'englacement plus courtes, ainsi que des températures des eaux de surface plus élevées en étés, ce qui entraîne des périodes de stratification estivale plus précoces et plus longues, des modifications du régime de brassage des lacs et un changement du niveau et donc du stockage de l'eau. Tout cela entraîne une cascade de conséquences écologiques, telles qu'une réduction de l'oxygène dissous, une prolifération des cyanobactéries et une perte d'habitat pour les poissons indigènes. La réponse des lacs au changement climatique a également des impacts sur les services écosystémiques, tels que l'approvisionnement en eau douce, l'hydroélectricité, l'approvisionnement en nourriture, sur les transports et les loisirs.

Les modèles numériques de lacs, qui sont basés sur un ensemble d'équations mathématiques reposant sur les principes de la physique simulant les processus dynamiques des lacs, ont été largement utilisés comme outils pour faire progresser la compréhension du comportement des lacs. Les progrès en matière de puissance de calcul et de collecte de données ont accéléré l'utilisation de ces derniers. Les modèles de lac hydrodynamiques unidimensionnels (1D) sont fréquemment utilisés pour caractériser l'hydrodynamique des lacs en raison de leur efficacité, d'exigences minimales en matière d'étalonnage et de la capacité à simuler la dynamique de la stratification thermique (à des échelles de temps saisonnières et décennales). Piloter des modèles numériques de lacs avec des sorties de modèles climatiques nous permet de comprendre comment les milieux aquatiques des lacs pourraient se comporter en réponse à un changement climatique futur (évaluation du changement climatique) et de développer des stratégies d'atténuation ou de gestion pour assurer la sécurité de l'eau pour les générations futures. Dans cette thèse, j'étudie les effets à long terme et à court terme (événements extrêmes) du changement climatique sur la dynamique thermique des lacs en utilisant des modèles de lacs hydrodynamiques 1D.

Le projet de comparaison intersectorielle des modèles d'impact (ISIMIP ; <https://www.isimip.org/>) est un effort de modélisation mené par la communauté dont l'objectif est de fournir une évaluation quantitative des impacts du changement planétaire à différents niveaux de réchauffement

mondial dans un cadre cohérent à travers plusieurs secteurs. Pour relever ce défi, ISIMIP développe et fournit un ensemble de données de forçage climatiques et socio-économiques pour une modélisation intersectorielle cohérente des impacts climatiques. Dans le premier chapitre de cette thèse, nous avons effectué le premier test de simulation de la structure thermique des lacs en utilisant les projections quotidiennes du modèle ISIMIP2b, corrigées de leurs biais, comme données d'entrée pour forcer le modèle de lac GOTM appliqué au lac Erken (Suède). La résolution temporelle des données météorologiques utilisées pour forcer les modèles de lac va généralement de la journée à l'heure ou même plus courte, ce qui permet d'améliorer la précision des simulations du modèle de lac en augmentant la résolution temporelle du forçage météorologique. Afin d'évaluer l'importance de la résolution temporelle des données de forçage (quotidienne vs horaire vs journalière) pour les prévisions de la température quotidienne de l'eau, les données météorologiques moyennes quotidiennes (dérivées de la moyenne des données horaires observées) ont été désagrégées (à l'aide de réseaux neuronaux artificiels à régression généralisée, GRNN) pour former un ensemble de données horaires synthétiques. Les simulations avec GOTM ont été effectuées en utilisant à la fois la résolution journalière originale, telle que disponible dans les produits ISIMIP2b, et en utilisant les données désagrégées toutes les heures. Les simulations ont été réalisées sur la base de quatre modèles climatiques dans le cadre de différents scénarios climatiques futurs.

GOTM a simulé avec précision la température quotidienne de l'eau lorsque le modèle a été forcé avec des données quotidiennes ou horaires (observées et synthétiques). Les simulations du climat futur ont montré que les températures de l'eau et les paramètres de stratification thermique devraient clairement évoluer vers des conditions thermiques lacustres compatibles avec un climat plus chaud à la fin du 21st siècle, c'est-à-dire des températures de surface et de fond plus élevées et une stratification thermique estivale plus intense et plus longue en raison d'une stratification plus précoce et d'un renversement automnal plus tardif. Ces changements projetés au sein des paramètres thermiques des lacs étaient similaires lorsque le modèle est forcé par les produits ISIMIP2b quotidiens et synthétiques horaires. Par conséquent, nous pouvons recommander à la communauté du secteur lacustre d'ISIMIP que les projections originales du modèle climatique à une résolution quotidienne peuvent être adéquates pour simuler la température de l'eau.

La température de l'eau du lac et la dynamique thermique simulées résultent de l'échange d'énergie entre la surface du lac et l'atmosphère, y compris les flux thermiques de surface (c'est-à-dire le chauffage ou le refroidissement de la surface) et la contrainte du vent (mélange turbulent vertical). Nous avons supposé que l'augmentation prévue de la température de l'eau du lac est due à une reconfiguration des composantes individuelles du flux thermique de surface. Dans le chapitre deux, nous étudions les changements du flux thermique de surface total ainsi que de ses composantes individuelles dans un lac

monomictique (Lough Feeagh, Irlande) lorsqu'un modèle hydrodynamique 1D (Simstrat) a été forcé par des produits ISIMIP2b. Afin de quantifier l'effet du changement climatique, les flux thermiques de surface projetés pour le scénario historique et trois scénarios futurs avec différents niveaux de réchauffement ont été comparés au scénario climatique de contrôle, ce dernier considérant des concentrations de gaz à effet de serre préindustrielles (pi-control). Nous avons constaté que les composantes individuelles du flux thermique de surface devraient changer de manière substantielle dans les scénarios climatiques futurs, donc sous l'effet des changements du forçage atmosphérique. L'augmentation du réchauffement du lac par le flux radiatif net a été contrebalancée par une augmentation de la perte de chaleur du lac par le flux de chaleur turbulent, ce qui a conduit à un petit changement positif dans le flux de chaleur de surface total, mais suffisant pour entraîner un changement important dans la température du lac entier. À l'échelle saisonnière, le changement le plus important dans le flux thermique de surface total a été projeté au printemps et en automne, le réchauffement printanier et le refroidissement automnal devant diminuer dans le cadre du scénario climatique futur par rapport au scénario climatique pi-control. En revanche, les changements prévus dans le flux thermique total de surface en hiver et en été étaient beaucoup plus faibles. Tout cela conduit à des résultats contre-intuitifs : dans un monde qui se réchauffe, il y aura moins de chaleur, pas plus, qui entrera dans le Lough Feeagh au printemps, et peu de changement dans le chauffage net pendant l'été ou un refroidissement net pendant l'hiver par rapport au climat préindustriel, de sorte que les augmentations de la température du lac entier est importante en raison de la réduction des pertes de chaleur pendant l'automne.

Dans le chapitre 3, nous avons étendu l'analyse des flux thermiques de surface à 47 lacs, mais que pendant la période estivale, lorsque les lacs sont fortement stratifiés thermiquement et que leur couche de surface est presque isolée thermiquement des eaux de subsurface. Mais dans ce cas, pour quantifier l'effet du changement climatique, nous avons comparé les flux de chaleur de surface de la période historique avec celles projetées à la fin du siècle. Nous supposons que les changements projetés de la température estivale de l'eau de surface seront contrôlés principalement par les changements des composantes individuelles du flux thermique de surface. Les résultats montrent que les températures de surface des lacs en été devraient augmenter en raison de l'augmentation du rayonnement entrant à ondes longues et à ondes courtes. L'augmentation des températures de surface des lacs entraîne également des pertes de chaleur plus importantes par le biais du rayonnement sortant à ondes longues et des flux de chaleur latente et sensible. Dans l'ensemble, le bilan thermique net et donc l'accumulation de chaleur dans les lacs pendant l'été demeure pratiquement inchangé. Cependant, on prévoit un changement dans les contributions des composantes individuelles du flux de chaleur, le flux de chaleur latente gagnant en importance relative.

Le dernier chapitre de cette thèse s'est concentré sur l'évaluation des performances du modèle de lac mais cette fois-ci dans des conditions atmosphérique extrêmes. Récemment, plusieurs études ont appliqué des modèles de lacs hydrodynamiques 1D pour étudier l'effet d'événements climatiques extrêmes sur la structure thermique des lacs. Cependant, nous ne savons pas avec quelle précision les modèles de lac simulent la structure thermique des lacs observés pendant les événements à court terme (par exemple à l'échelle horaire), car il est courant d'évaluer la précision du modèle de lac sur des échelles de temps plus longues (par exemple à l'échelle interannuelle). Ici, nous évaluons la performance de trois modèles de lac hydrodynamiques 1D (Simstrat, GOTM et GLM) dans la reproduction des changements observés de la température de l'eau et de la stratification thermique pendant les tempêtes et les vagues de chaleur dans trois lacs différents (Lough Feeagh - Irlande, Lac Erken - Suède et Lac Müggelsee - Allemagne) en utilisant des données à haute fréquence. Pour chaque lac, dix tempêtes et dix vagues de chaleur ont été identifiées et utilisées pour évaluer dans quelle mesure les modèles reproduisent les changements hydrothermaux associés aux événements et comment ceux-ci se comparent à dix périodes de référence (non extrêmes). Les modèles ont reproduit la direction générale et l'ampleur des changements de la température de l'eau et des paramètres de stratification thermique pendant les tempêtes et les vagues de chaleur avec un synchronisme précis et peu de biais (une surestimation ou une sous-estimation significative n'a été constatée que dans quelques cas). Cependant, les performances du modèle de lac ont diminué en termes de précision par rapport aux conditions non extrêmes. Nous concluons alors que les modèles de lac 1D peuvent être un outil adéquat pour étudier les changements de la structure thermique des lacs pendant les événements extrêmes, mais que cette incertitude doit être prise en compte.

En conclusion, les modèles de lacs hydrodynamiques 1D se sont avérés être un outil puissant pour prédire les changements à long et court terme liés au climat dans la dynamique thermique des lacs et permettant également une analyse approfondie des flux de chaleur de surface. Cette thèse a contribué à une meilleure compréhension, basée sur les processus physiques, de la manière dont le changement climatique influencera la dynamique thermique des lacs et l'échange de chaleur entre la surface des lacs et l'atmosphère. Une meilleure compréhension des effets du changement climatique sur les lacs peut aider à anticiper dans le développement de stratégies d'atténuation et de gestion.

Resumen

La Tierra está experimentando un calentamiento sin precedentes. La temperatura media anual ha aumentado algo más de 1 °C desde 1880, y la última década ha sido las más cálida, lo que ha provocado tormentas más frecuentes y graves y olas de calor sin precedentes. Las actividades humanas vinculadas a la quema de combustibles fósiles, la deforestación, la agricultura y el cambio en el uso del suelo son responsables del aumento de las concentraciones de gases de efecto invernadero que atrapan más energía solar y, por tanto, aumentan la temperatura global. El cambio climático está teniendo un impacto importante y negativo en los ecosistemas lacustres. Los lagos experimentan períodos de congelación más cortos y temperaturas superficiales del agua más altas durante el verano, dando lugar a períodos de estratificación más tempranos y prolongados, modificando el régimen de mezcla de los lagos y cambiando el nivel y, por tanto, el almacenamiento de agua. Esto provoca una cascada de consecuencias ecológicas, como la reducción de oxígeno disuelto, la proliferación de cianobacterias y la pérdida de hábitat para los peces autóctonos. La respuesta de los lagos al cambio climático también tiene consecuencias en los servicios del ecosistema, como el suministro de agua dulce, la energía hidroeléctrica, el abastecimiento de alimentos, el transporte y las actividades recreativas.

Los modelos numéricos lacustres, que se basan en un conjunto de ecuaciones matemáticas basadas en principios físicos que simulan los procesos dinámicos en los lagos, se han utilizado de forma generalizada como herramienta para avanzar en la comprensión del comportamiento de los lagos. Los avances en capacidad de cálculo y recopilación de datos han acelerado su uso. Los modelos lacustres hidrodinámicos unidimensionales (1D) se utilizan con frecuencia para caracterizar la hidrodinámica de los lagos debido a su eficacia, sus requisitos mínimos de calibración y su capacidad para simular la dinámica de la estratificación térmica (en escalas de tiempo estacionales y decenales). Modelos numéricos lacustres impulsados con salidas de modelos climáticos nos permite comprender mejor cómo podrían comportarse los medios acuáticos lacustres como consecuencia del futuro cambio climático (evaluación del cambio climático) y desarrollar estrategias de mitigación o gestión para garantizar la seguridad hídrica para las generaciones futuras. En esta tesis, estudio los efectos a largo plazo y corto plazo (eventos extremos) del cambio climático en la dinámica térmica de los lagos utilizando modelos lacustres hidrodinámicos 1D.

El Proyecto de Intercomparación de Modelos de Impacto Intersectorial (ISIMIP; <https://www.isimip.org/>) es una iniciativa comunitaria de modelización cuyo objetivo es proporcionar una evaluación cuantitativa de los impactos del cambio climático mundial a diferentes niveles de calentamiento global en un marco coherente a través de varios sectores. Para hacer frente a este desafío, ISIMIP desarrolla y proporciona un conjunto de datos de forzamiento

climático y socioeconómico para la modelización intersectorial coherente de los impactos climáticos. En el primer capítulo de esta tesis, realizamos la primera prueba de simulación de la estructura térmica lacustre utilizando proyecciones diarias corregidas por sesgo de los modelos climáticos ISIMIP2b como datos de entrada para forzar el modelo lacustre GOTM aplicado al Lago Erken (Suecia). La resolución temporal de los datos meteorológicos utilizados por los modelos lacustres suele variar entre diaria y horaria, o incluso menos, mejorando la precisión de las simulaciones de los modelos lacustres al aumentar la resolución temporal del forzamiento meteorológico. Para evaluar la importancia de la resolución temporal de los datos de forzamiento (diaria frente a horaria) en la predicción de temperatura del agua diaria, se desagregaron datos meteorológicos medios diarios (derivados de promediar datos horarios observados) para formar un conjunto de datos horarios sintéticos (utilizando redes neuronales de regresión generalizada). Las simulaciones con GOTM se realizaron utilizando tanto la resolución diaria original, productos de ISIMIP2b, como con los datos desagregados por horas. Las simulaciones se realizaron utilizando cuatro modelos climáticos para diferentes escenarios climáticos futuros. GOTM simuló con precisión la temperatura del agua diaria cuando el modelo se forzó tanto con datos diarios como horarios (observados o sintéticos). Las simulaciones climáticas futuras han mostrado que se espera que las temperaturas del agua y los parámetros de estratificación térmica evolucionen hacia unas condiciones térmicas lacustres acordes con un clima más cálido a finales del siglo XXI, es decir, temperaturas superficiales y del fondo del lago más elevadas y una estratificación térmica estival más fuerte y prolongada debido a un inicio de la estratificación más temprano y una inversión otoñal más tardía. Estos cambios proyectados en los parámetros térmicos lacustres fueron similares cuando el modelo se forzó con los productos de ISIMIP2b diarios y horarios sintéticos. Por lo tanto, podemos recomendar a la comunidad del sector lacustre de ISIMIP que las proyecciones originales de los modelos climáticos con resolución diaria pueden ser suficientes para simular la temperatura del agua.

Tanto la temperatura del agua como la dinámica térmica del lago simulada son el resultado del intercambio de energético entre la superficie del lago y la atmósfera, incluyendo los flujos de calor superficial (es decir, el calentamiento o enfriamiento de la superficie) y los esfuerzos del viento (mezcla vertical turbulenta). Suponemos que el aumento previsto para la temperatura del agua del lago se debe a una reconfiguración del flujo de calor superficial. En el capítulo dos, nosotros investigamos los cambios en el flujo de calor superficial y en los componentes individuales de dicho flujo en un lago monomictico (Lough Feeagh, Irlanda) cuando el modelo lacustre hidrodinámico 1D (Simstrat) se forzó con productos de ISIMIP2b. Para cuantificar el efecto del cambio climático, se compararon los flujos de calor superficial para el escenario histórico y tres escenarios futuros con diferentes niveles de calentamiento global con un escenario climático de control basado en los niveles de

gases de efecto invernadero preindustriales (picontrol). Hemos constatado que los componentes individuales del flujo térmico cambiarán sustancialmente en los escenarios climáticos futuros, como resultado de los cambios en el forzamiento atmosférico. El aumento del calentamiento del lago a través del flujo radiactivo neto se vio compensado por un aumento de la pérdida de calor del lago a través del flujo de calor turbulento, lo que dio lugar a un pequeño cambio positivo en el flujo de calor superficial total, pero suficiente para provocar un cambio significativo en la temperatura de todo el lago. A escala estacional, el mayor cambio en el flujo de calor superficial total se proyectó en primavera y otoño, tanto el calentamiento primaveral como el enfriamiento otoñal están previstos que disminuyan para los escenarios climáticos futuros en comparación con el escenario climático picontrol. Mientras que los cambios previstos en el flujo de calor superficial total durante el invierno y el verano fueron muchos menores. Todo ello conduce a resultados contraintuitivos: donde en un mundo que se calienta, entrará menos calor, no más, en Lough Feeagh durante la primavera, y habrá pocos cambios en el calentamiento neto durante el verano o en el enfriamiento neto durante el invierno en comparación con el clima preindustrial, de modo que los aumentos significativos de la temperatura total del lago se deben a la menor perdida de calor durante el otoño.

En el capítulo tres ampliamos el análisis de los flujos de calor superficial a 47 lagos, pero durante el periodo estival, cuando el lago está fuertemente estratificado térmicamente y la capa superficial está casi aislada térmicamente de las aguas subsuperficiales. Pero en este caso, para cuantificar el efecto del cambio climático, comparamos los flujos de calor superficial proyectados para el periodo histórico con los asociados al cambio climático de finales de siglo. Suponemos que los cambios previstos en la temperatura superficial estival del agua estarán controlados principalmente por los cambios en los componentes individuales del flujo de calor superficial. Los resultados mostraron que se prevé un aumento en la temperatura superficial de los lagos en verano debido al incremento de la radiación entrante de onda larga y onda corta. El aumento de la temperatura superficial de los lagos también provocará mayores pérdidas de calor por radiación de onda larga saliente y flujos de calor latente y sensible. En conjunto, el balance térmico neto y, por tanto, la acumulación de calor en los lagos durante el verano permanecerá prácticamente inalterada. Sin embargo, se proyectó un cambio en las contribuciones de los componentes individuales del flujo de calor, con el flujo de calor latente ganando importancia relativa.

El último capítulo de esta tesis se centró en evaluar el rendimiento de los modelos lacustres, pero esta vez bajo condiciones extremas. Recientemente, varios estudios han aplicado modelos lacustres hidrodinámicos 1D para estudiar el efecto de fenómenos climáticos extremos en la estructura térmica de los lagos. Sin embargo, desconocemos la precisión con la que los modelos lacustres simulan la estructura térmica de los lagos observada durante eventos de corta duración (por ejemplo, a escala horaria), ya que es una práctica

habitual evaluar la precisión de los modelos lacustres a escalas temporales más largas (por ejemplo, a escala interanual). Aquí, evaluamos el rendimiento de tres modelos lacustres hidrodinámicos 1D (Simstrat, GOTM y GLM) en la reproducción de los cambios observados en la temperatura del agua y la estratificación térmica durante tormentas y olas de calor en tres lagos diferentes (Lough Feeagh – Irlanda, Lago Erken – Suecia y Lago Müggelsee - Alemania). Para cada lago, se identificaron diez tormentas y diez olas de calor para evaluar en qué medida los modelos reproducen los cambios hidrotermales derivados de dichos eventos y se compararon también con diez períodos de referencia (no extremos). Los modelos reprodujeron la dirección general y la magnitud de los cambios en la temperatura del agua y los parámetros de estratificación térmica durante las tormentas y las olas de calor con una sincronización precisa y poco sesgo (en unos pocos casos se detectaron sobreestimaciones o subestimaciones significativas). Sin embargo, el rendimiento de los modelos lacustres disminuyó en términos de precisión en comparación con condiciones no extremas. Concluimos que los modelos lacustres 1D pueden ser una herramienta adecuada para estudiar los cambios en la estructura térmica durante fenómenos extremos, pero debe tenerse en cuenta el aumento de la incertidumbre.

En conclusión, los modelos lacustres hidrodinámicos 1D han demostrado ser una potente herramienta para predecir a largo y corto plazo los cambios relacionados con el clima en la dinámica térmica de los lagos y también permiten un análisis en profundidad de los flujos de calor superficial. Esta tesis ha contribuido a una mejor comprensión, basada en procesos, de cómo influirá el cambio climático en la dinámica térmica de los lagos y en el intercambio de calor entre la superficie del lago y la atmósfera. Una mejor compresión de los efectos del cambio climático en los lagos puede ayudar a anticipar el desarrollo de estrategias de mitigación y gestión.

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