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Global warming will change the thermal structure of Lough Feeagh, a sentinel lake in the Irish landscape, by the end of the 21st century

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ABSTRACT

Recent developments in impact modelling of global warming on lakes have resulted in a greater understanding of how these vital ecosystems are likely to respond. However, there has been little quantitative analysis of this in an Irish context, despite the importance of lakes in the island's landscape. Here, we explore the impact of global warming on the hydrodynamics and thermal structure of a sentinel Irish lake under future climate scenarios. A 1D lake model, Simstrat, was calibrated and validated using water temperature data collected from Lough Feeagh, a site of long term ecological research in the west of Ireland. Once validated, the model was then driven by daily climate model projections to generate informative thermal metrics for the time period of 2006-2099. Despite the moderating influence of the Atlantic, projections indicate that global warming will have a marked effect on the thermal structure of Feeagh, with surface water temperatures set to warm by 0.75°C under a more stringent mitigation pathway (RCP 2.6) and 2.42°C under a non-mitigation pathway (RCP 8.5). While warming was projected to be greatest in summer in the epilimnion, winter warming was greater than in other seasons in the hypolimnion. Stratification is projected to become more stable and earlier, and the growing season to be longer by 11 to 47 days, depending on mitigation pathways. Future studies could use a similar modelling workflow to investigate the possible

implications of global warming on other Irish lakes, particularly those of specific societal importance or those of conservation interest.

INTRODUCTION

Lakes generally are warming as a result of increasing greenhouse gas emissions (O'Reilly *et al.*, 2015; Grant *et al.*, 2021) with implications for biogeochemistry (Kraemer *et al.*, 2017; Jane *et al.*, 2021), thermal habitat of species (Kelly *et al.*, 2020; Kraemer *et al.*, 2021), ice cover (Sharma *et al.*, 2019; Li *et al.*, 2022) and the phenology of lake processes (Carter & Schindler, 2012; Tao *et al.*, 2018; Woolway *et al.*, 2021b). However, not all lakes are warming to the same extent and there is considerable variability depending on geographic location, altitude and morphometry (Kraemer *et al.*, 2015; O'Reilly *et al.*, 2015; Pilla *et al.*, 2020). Gridded climate data and future climate projections are now relatively easy to access through large data repositories, and understanding the future implications of global warming for the world's lakes has received considerable research interest in the last decade. Some of this effort has come about through the formation of a lake sector within ISIMIP (The Inter-Sectoral Impact Model Intercomparison Project www.isimip.org), which offers a framework for consistently projecting the impacts of climate change across affected sectors and spatial scales (e.g. Frieler *et al.*, 2017). Lake sector outputs have indicated that climate warming will lead to changing mixing regimes in lakes (Woolway & Merchant, 2019), an increased likelihood of heatwaves (Woolway *et al.*, 2021a), shifting seasonality (Woolway, 2023) and increased methane production (Jansen *et al.*, 2022), but anomalous regional differences are apparent (Grant *et al.*, 2021; Golub *et al.*, 2022). Water temperature anomalies in the subpolar North Atlantic, such as the cold blob described by Rahmstorf *et al.* (2015), influence climate on the western fringe of Europe (Josey & Sinha, 2022) and thus the sensitivity of inland lakes to climate warming in this area. Detailed investigation of the projected impacts on lakes situated on the Atlantic fringe of Europe is therefore warranted.

There are approximately 12,208 lakes >0.0001km^2 in the Republic of Ireland, mainly concentrated west of the River Shannon (Dalton, 2018). Ireland's climate is defined as temperate, without a dry season and with warm summers (classification: Cfb) on the Koppen-Geiger classification system (Peel, Finlayson & McMahon, 2007). Lakes on much of the island can be classified as *Northern Warm* or *Northern Temperate* according to the thermal classification system suggested by Maberly *et al*. (2020). Northern Warm lakes have an average annual surface water temperature of 16.3°C and are generally ice-free throughout the year. Towards the north of Ireland, lakes may fall more consistently into the *Northern Temperate* category, with average annual temperatures of 9.8°C. Lakes in the Republic of Ireland have been grouped into 12 typologies for the Water Framework Directive (EC, 2000) based on alkalinity, average depth and area (Free *et al.*, 2006). A provisional type (13) has also been proposed for those high altitude lakes found above 200m (S.I. No. 77/2019). These groups (or types) of lakes are likely to vary in their sensitivity to climate warming, but as yet, very little work has been done on modelling the future impacts of climate change on Irish lakes.

A structured literature search using Web of Science ((ireland* OR irish) AND lake* AND climate AND ("future projection" OR impact*)) identified only 2 papers that quantify the impacts of climate warming on the Irish lakes. Kelly *et al.* (2020) presented future scenarios of winter water temperatures in Lough Bunaveela (Co. Mayo) to determine the likely impacts on spawning of Arctic charr. Golub *et al.* (2022) describe simulations of future lake hydrodynamics and thermal structure for 62 lakes worldwide including Feeagh, as an example of ISIMIP lake sector simulations, but without the detail described in this paper. Although not identified by the search described above, future projections of the surface water temperature of Feeagh were presented in McGinnity *et al.* (2009) as part of an analysis of salmon survival. This work projected water temperature increases of between 0.8°C and 2.3°C in January and 0.8°C and 2.4°C for spring (March, April and May) for the period 2071–2100. In addition, Woolway *et al.* (2020) projected increased maximum surface water temperatures in lakes across Europe (including Ireland) for the period May-October, with lakes being 2.3 to 7.3 °C warmer on average by 2081–2099 depending on location and emission scenario. Finally, a number of papers describe future climate projections for freshwater catchments, including groundwater in a karst catchment (Morrissey *et al.*, 2021) and nutrient and carbon export in Kerry and Mayo (Jennings *et al.*, 2009; Naden *et al.*, 2010). While not directly quantifying lake impacts, these provide useful additional context of the factors affecting Irish lacustrine conditions.

Lough Feeagh (53°56'N, 9°34'W) is a good example of a monomictic, oligotrophic, humic freshwater lake located in the west of Ireland. There is nothing particularly special or anomalous about Feeagh, when compared to other deep humic lakes along the Atlantic coast of Ireland between Donegal in the north to Kerry in the south. What differentiates the lake, however, is the wealth of long term data which have been collected from it, since the formation of the Salmon Research Trust (SRT) on its eastern shore in the mid-1950s (de Eyto *et al.*, 2020a). A multi-decadal *in-situ* lake surface water temperature record has been collected here since 1959 and indicates that average temperatures are warming at a slower rate than many other lakes across the world (O'Reilly *et al.*, 2015). Unlike other lakes across Europe, the maximum surface water temperature of Feeagh did not warm significantly between 1966 and 2015 (Dokulil *et al.*, 2021), although minimum surface water temperatures increased by 0.34°C decade^{-1} between 1973 and 2014 (Woolway *et al.*, 2019). More recent analysis indicates that spring water temperatures are increasing faster than winter and autumn temperatures over the period 1970-2020 (0.25, 0.21 and 0.14°C decade^{-1} respectively), with an annual average rate of 0.18°C decade^{-1} between 1970 and 2020 (de Eyto *et al.*, 2022).

Owing to the shape and situation of the lake (bath-shaped, with one main basin), and the limited number of inflows and outflows, the hydrodynamics of the lake can be simulated by lake models with a high degree of confidence (Bruce *et al.*, 2018; Mesman *et al.*, 2020; Moore *et al.*, 2021). This, coupled with the availability of high resolution observational data, makes Feeagh the ideal site for exploration of global warming in an Irish limnological context. To date, however, there has been no detailed research published on the potential impacts of global warming for lake temperature and physical structure in Feeagh. Both *Ayala et al.* (2023) and Golub *et al.* (2022) quantified the impacts of climate change on Feeagh, using the same or similar workflows as described here. However, the work described in Ayala et al (2023) considered the impacts on climate change on the surface heat flux of Feeagh, rather than the impacts of thermal changes likely to determine biogeochemical and ecological processes within the lake. Golub *et al.* (2022) was primarily focused on describing the development of the lake sector workflows within ISIMIP, and while some examples of variable outputs are described, it does not provide easily accessible detail for a single lake. Rather, overall patterns and trends for lakes across the globe are described. The aim of this work, therefore, was to document lake-specific projected changes in the thermal structure of Feeagh under future climate scenarios, as an index for similar lakes of its type on the west coast of Ireland.

METHODS

SITE DESCRIPTION

Lough Feeagh has a surface area of 3.95km^2, a maximum depth of 46.8m, an average depth of 14.5m, and an average retention time of 172 days (de Eyto *et al.*, 2016) and lies at an altitude of 10 m. It is the largest lake in the Burrishoole catchment, which lies in the Nephin Beg mountains of Co. Mayo and drains into the north east corner of Clew Bay (Fig. 1). Winters and summers in this region are mild (January mean air temperature: 6.3°C, July mean air temperature: 16.1°C, 2012-2021, Met Éireann synoptic station number 1175 www.met.ie/climate/weather-observing-stations) due to the influence of the Atlantic Meridional Overturning Circulation (AMOC) and its constituent Gulf Stream. The mean annual precipitation is 1719mm year^{-1} (2012-2021) with the prevailing wind coming from south-west, straight off the Atlantic Ocean. Average monthly wind speeds are high at 5.0m s^{-1} and the site is subject to multiple storms in any year, including during summer (Andersen *et al.*, 2020). Feeagh is ice-free all year around and, at present, the lake begins to stratify in April, with peaks in the Schmidt stability occurring towards the end of July, and then fully mixing around the end of October each year (de Eyto *et al.*, 2016; Marine Institute, 2020). Its average annual surface water temperature is 11°C (average of daily values between 2012-2021) (Dillane *et al.*, 2018). Similar to many of the lakes along the western seaboard, Feeagh is humic, with a predominate base geology of quartzite and schist, leading to low alkalinity water (-2.7 to 7.5mg l^{-1} $CaCO_3$, MI unpublished data). The overlying soils are mainly poorly-drained gleys and peaty podsols, with blanket peatlands covering the mountain slopes to the north. The land uses in the area are extensive agriculture, mainly hillside grazing by sheep and a small number of cattle, and forestry. Commercial coniferous forest covers a quarter of the freshwater catchment with afforestation starting in the 1950s (Dalton *et al.*, 2014).

LAKE MODEL

Simstrat, the model used in the current study, is a one-dimensional physical model for the simulation of vertical temperature profiles, stratification and mixing, and ice cover in lakes and reservoirs (Goudsmit *et al.*, 2002; Gaudard *et al.*, 2019). The model includes a k-ε closure scheme to model turbulent mixing including the effects of internal seiches on the production of turbulent kinetic energy. River or groundwater inflow can be added at specific depths or as density-dependent intrusions (Gaudard *et al.*, 2017) and allow for water level fluctuations. Simstrat has been applied for modeling lake hydrodynamics covering different morphometries (Perroud *et al.*, 2009; Stepanenko *et al.*, 2013), to provide future predictions under various climate scenarios (Råman Vinnå *et al.*, 2021) and to understand the impact of extreme weather events (Mesman *et al.*, 2020). Most recently, Simstrat has been used to explore the likely impacts of global warming on surface heat budget of Feeagh (Ayala *et al.*, 2023). Simstrat v.2.1.2 has previously been shown to work well in Feeagh, including during short-term extreme events such storms and heatwaves (Mesman *et al.*, 2020). The accuracy of model predictions of water temperature produced by Simstrat is comparable to that of other 1-D lake models (Perroud *et al.*, 2009; Stepanenko *et al.*, 2013; Mesman *et al.*, 2020; Moore *et al.*, 2021). Simstrat has been previously used to model future thermal changes in lakes around the world, including Feeagh (Golub *et al.*, 2022).

MODEL SET-UP AND CALIBRATION

A modified version of the numerical model Simstrat v2.1.2 was used in this study (Ayala *et al.*, 2023). The model was driven by daily meteorological data (air temperature, wind speed and wind direction, atmospheric vapor pressure, incoming short-wave radiation and incoming long-wave radiation) that were retrieved or derived from the global gridded data set of historical climatic input (EWEMBI; Lange, 2019). Inflows and outflows were not included in the model set up for the current simulations, meaning that the water balance was not resolved and surface water level was considered to be constant (Golub *et al.*, 2022). The attenuation coefficient (Kd) of shortwave radiation, a parameter describing the water opacity in the lake model, was calculated from the average of monthly Secchi depth in metres, S_d, measurements from 2005 to 2015 (S_d = 1.74m; de Eyto *et al*.,(2016)) according to the relation $K_d = 1.7 \cdot S_d^{\ -1}$. The initial water temperature profile was derived from a measured temperature profile. The model integration time step was 10 minutes and the simulated water temperature profiles were reported every hour at a vertical resolution of 0.5 m (containing a total of 94 layers). The PEST (model-independent Parameter ESTimation and uncertainty analysis: https://pesthomepage.org/) software was used to calibrate model parameters in order to minimise the error between the observed and simulated water temperatures using a 13 year period (2004-2016) where hourly water temperature observations were available (de Eyto *et al.*, 2020b). The calibrated parameters were scaling factors for meteorological forcing (*p_radin* and *f_wind,* scaling the incoming long-wave radiation and the wind speed respectively) and a model-specific parameter *(a_seiche,* fraction of wind energy that is transferred to internal seiches). The ranges and optimal values of the calibrated parameters are given in Ayala *et al*. (2023). The model performance for the calibration was very good (Ayala *et al.*, 2023), with a high degree of coherence between predicted and observed water temperatures over the full water column (RMSE=0.79°C, NSE=0.95 and BIAS=-

0.0066°C) and was comparable with other model studies in Feeagh (Bruce *et al.*, 2018; Moore *et al.*, 2021).

CLIMATE SCENARIOS

To drive Simstrat and evaluate the hydrodynamic responses to different levels of warming, daily bias-corrected climate model projections of air temperature, wind speed and wind direction, atmospheric vapor pressure, incoming short-wave radiation and incoming long-wave radiation were obtained from the ISIMIP2b climate data set (https://www.isimip.org/) (Fig. 2). Projections of climate variables from four general circulation models (GCMs: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-RL, and MIROC5) were used, covering the historical scenario from 1976 to 2005 and three future scenarios from 2006 to 2099 for the 0.5°grid cell overlying Feeagh (supplemental information). The same EWEMBI dataset used for the model setup and testing described above was used to bias correct these ISIMIP GCM-derived scenarios (Lange, 2019). The historical scenario is based on known changes in atmospheric CO_2 concentration and represents model projections spanning the same time period as observed data. The three future scenarios referred to as Representative Concentration Pathways (RCPs): RCP 2.6, 6.0 and 8.5 encompass a range of potential future global radiative forcing due to increasing anthropogenic greenhouse gases (van Vuuren *et al.*, 2011). RCP 2.6 is the more stringent mitigation pathway where radiative forcing peaks at 3.1W m^{-2} by mid-century and then declines to 2.6W m^{-2} by 2010 and is expected to limit the mean global warming between 0.3 and 1.7°C. RCP 6.0 is an intermediate mitigation pathway in which emissions peak in 2080, then decline to 6.0W m^{-2} by 2010 and remains stable after that and global warming is projected to rise between 1.4 and 3.1°C. Finally, RCP 8.5 is the non-mitigation pathway in which emission rise continuously during the 21st century reaching a level of 8.5W m^{-2} in 2100 and global warming is projected to rise by 2.6 to 4.8°C by the late-21st century (IPCC, 2014).

Once calibrated, Simstrat was driven using the meteorological inputs from the ISIMIP2b climate scenarios. Hourly data were simulated between 1976 and 2005 for the historical scenario, and between 2006 and 2099 for each RCP. A suite of limnologically relevant metrics were derived from daily averages of the simulated hourly temperature profiles. These metrics encompass a range of hydrodynamics that control the thermal structure, biogeochemistry and ecology in lake ecosystems (Table 1). Absolute changes in metrics by the end of the century were calculated for a 30 year window by subtracting the average values simulated for each RCP scenario and GCM combination between 2070-2099 from the average values simulated for the historic scenario (1976-2005) for each GCM, thus ensuring that the historic data used in the comparison were also based on model output. Ensemble values were also calculated by averaging across the four GCMs for each scenario. Where appropriate, seasonal metrics were also calculated (winter - DJF; spring – MAM; summer – JJA; autumn – SON).

RESULTS

In comparison to historical conditions, the annual average surface water temperature of Feeagh was projected to warm by 0.75, 1.64 and 2.42°C by the end of the century, under RCP 2.6, RCP 6.0 and RCP 8.5 respectively (Fig.3). Annual surface water temperatures under all RCPs were quite similar until 2030, after which the time series start to diverge, with projections under RCP 8.5 exceeding 14°C by 2099. The largest absolute changes in surface water temperatures were projected for the summer season under RCP 8.5 (2.6°C), but all seasons across all RCPs were projected to warm to some degree (Table 2). Summer surface water temperatures were projected to exceed 20°C under RCP 6.0 and 8.5 by the end of the century. In terms of annual extremes, minimum annual surface water temperatures were expected to exceed 5°C for all scenarios, in comparison to a historical value of 4.42°C. Under RCP 8.5, minimum annual temperatures were projected to increase to 6.73°C. Maximum annual temperatures, which historically are less than 22°C, were projected to exceed 23°C for both RCP 6.0 and 8.5.

The differences in simulated water temperatures for the surface layer (top 0.5m) and the epilimnion (0-3m) were very similar (Table 2) across seasons (average of 4.059 vs 4.0515 across presented metrics) indicting limited microstratification at the surface layer. Seasonal changes in hypolimnetic temperatures (Fig. 4) differed in timing in comparison to epilimnetic temperatures, as the hypolimnion of Feeagh is warmest in the autumn months, unlike the epilimnion which is warmest in the summer. In the bottom of the lake, temperature changes were projected to be largest during the spring, and smallest in the autumn for all RCPs (Table 2).

Feeagh is currently stratified between April and October (Marine Institute, 2021) and historical simulations project an average stratification length of 198 days for the period 1976-2005. As the water column warms, the length of the stratified period was projected to increase by +10, 19 and 30 days under RCP 2.6, RCP 6.0 and RCP 8.5 respectively (Fig. 5). The most extreme projections, therefore, indicated an increase of one month in the stratification period. The onset of stratification is likely to become earlier in April, with the water column mixing in mid to late November rather than at the start of the month (Table 3). In addition to being of longer duration, the simulations under future climate scenarios indicated that the depth of stratification will get shallower, with the mixed layer (i.e. the depth of water that interacts dynamically contact with the atmosphere) contracting from 6.5m to <5.0m under RCP 8.5 (Fig. 6) during summer. The stratification will also be stronger, with more energy required to fully mix the water column. This is indicated by an increase in Schmidt stability between 6.6 and 32.46J m^{-2} by 2099, from a historical baseline of 58.95J m^{-2} (Table 3).

The growing season, as determined by the number of days in which epilimnetic temperature exceeds 9°C, is currently 217 days, or just over 7 months (Table 3). Under future climate scenarios, this was projected to extend by 11, 30 and 47 days under RCP 2.6, RCP 6.0 and RCP 8.5 respectively (Fig. 7). The results described above are summarized by averaging across GCMs to produce ensemble means.

We note that there is variation in the magnitude of changes projected across the GCMs, but that the patterns are similar across all ensemble members (Supplemental information). The sum total of these projected changes is visible in the water temperature profiles of the lake under historic and future conditions (Fig. 8).

DISCUSSION

Quantifying and understanding how global warming will affect the lake environment will be essential for the future management of these essential resources. Our projections have highlighted key changes in the physical dynamics of Feeagh, particularly in the duration and strength of stratification, which are likely to result in fundamental changes in how this lake ecosystem functions. The warmer water temperatures and longer, more stable, stratifications projected for Feeagh align with global lake projection studies, with some notable differences in magnitude. Simulations of future responses of 62 lakes to climate change indicated average annual warming of surface waters by 1.38, 2.46, and 3.85°C under RCP 2.6, 4.5 and 8.5 respectively by 2070–2099 (Golub *et al.*, 2022). Similarly, Woolway and Maberly (2020) and Grant *et al.* (2021) reported projections of surface water warming by up to 4°C by end-century under RCP 8.5. The comparative values for Feeagh at RCP8.5 is an ensemble mean increase of 2.42°C, indicating that lakes on the western seaboard of Europe may warm less than the global mean, although it is likely that there will be spatial variation within this geographical area resulting from lake characteristics. For example, the surface water of Lough Bunaveela, a smaller, shallower lake at higher elevation in the Burrishoole catchment, was projected to warm by up to 3°C under RCP 8.5 in a previous study (Kelly *et al.*, 2020). Hypolimnetic water temperatures were also projected to increase globally under RCP 8.5 by an average of 1.49°C (Golub *et al.*, 2022), although these bottom water warming projections were more variable than those of surface waters. The hypolimnion of some lakes have also been projected to cool under future climate scenarios (e.g.

Barbosa *et al.*, 2021) while others were likely to warm, but at a slower rate than in surface waters (Shatwell, Thiery & Kirillin, 2019). The degree of hypolimnetic warming reported here for Feeagh is between 0.19 and 1.13°C by 2100, which is certainly at the lower end of the warming trends projected globally, and probably reflects the characteristics and location of the lake, being a relatively large humic lake close to sea level. As the hypolimnion is physically separated from the atmosphere for large parts of the year, warming of hypolimnetic temperatures are driven less by atmospheric changes (e.g. increasing air temperature) and more by specific lake characteristics which determine how heat is transferred through the water column over the annual cycle (Kraemer *et al.*, 2015; Winslow *et al.*, 2015). For example, Pilla *et al*. (2020) show that lake size, elevation, water colour (dissolved organic carbon) and geographic location can explain some of the warming/cooling trends in observed hypolimnetic temperatures. Specifically, small lakes are reported to have less hypolimnetic warming compared to large lakes (Dokulil, *et al.* 2006; Winslow *et al.* 2015), likely a result of transparency and light attenuation becoming less important and wind-driven mixing becoming more important as surface area and fetch increase, leading to decreased sheltering (Pilla *et al.* 2020). This is further complicated in brown lakes such as Feeagh, where humic substances provide a thermal shielding effect, decreasing the light penetration into the hypolimnion and increasing the radiant heating of surface waters and water column stratification (Bartosiewicz *et al.* 2019).

The annual increase in surface water (and epilimnetic) temperatures is perhaps intuitive and expected, given the rate at which global warming is occurring. However, seasonal changes, which combine to produce the annual pattern of warming and cooling, give some surprising indications of how those changes are manifest. The energy budget at the surface interface of a water body and the atmosphere is determined by radiative forcing and turbulent heat flux (Huang, 2015). At our latitude in Ireland, radiative forcing (short and long wave components) increases from the start of the year as the duration of sunlight hours increase, and peaks in summer. Turbulent heat fluxes are the combination of latent heat flux (evapotranspiration and condensation) and sensible heat flux (the heat transfer via turbulent processes between the lake surface and the atmosphere, e.g. wind or convective mixing).

As well as being controlled by vertical gradients in vapour pressure and temperature, turbulent heat flux is strongly influenced by wind speed. The annual heat gain or loss of a lake will therefore be determined by the relative strength of radiative forcing and turbulent heat flux components over the seasons. Projections for Feeagh over the coming century have indicated that radiative forcing will be almost counteracted by significant increases in turbulent heat loss (Ayala *et al.*, 2023). Nevertheless, the combined change in these individual components was net positive, and enough to bring about an overall annual warming of the surface waters. Both spring heating and autumnal cooling significantly decreased under future climate conditions (Ayala *et al.*, 2023), which match with the rates of warming reported here. Although the largest absolute change in temperature, relative to the historic period in the current study, was projected for summer (0.96 - 2.6°C), the largest proportional change was projected for winter (10 – 35 %) followed by spring (8 – 21%), autumn (5 – 19%) and finally summer (5 – 14%). Similarly, the increases that were projected for the minimum and maximum annual temperatures were of a similar magnitude (minimum 0.68 - 2.31°C; maximum 1.17 - 2.99°C depending on RCP). The increase in the minimum temperatures are, however, perhaps more concerning, being proportionally larger (15 - 52%) than those of maximum temperatures (5 - 14%). The combination of these thermal metrics indicates that rates of change in the winter months are likely to cause more stress on the lake's inhabitants than those of summer.

Lakes in the Northern temperate and Northern warm thermal zones (Maberly *et al.*, 2020) are expected to experience an increase in thermal stratification duration of 35.7 ± 11.6 and 31.9 ± 13.9 days respectively under RCP 8.5 (Woolway *et al.*, 2021b). This is similar to that reported here for Feeagh (+30 days) under RCP 8.5 and represents a percentage increase of 15% in the period of time that Feeagh is stratified each year by the end of the century. We note that the stratification in Feeagh is relatively weak when compared to other lakes around the globe (Doubek *et al.*, 2021), owing to the fairly high daily wind speeds and the small difference between air and water temperatures, even in summer. However, our projections indicate that the strength of this stratification is likely to increase (as indicated by the Schmidt stability proportional changes of 11 – 59%), leading to stronger separation between the epi- and hypolimnion. This separation has fundamental effects on lake ecosystems. It restricts dissolved oxygen, nutrients, particles and organisms to specific lake strata with consequent effects on lake ecosystems (Kraemer *et al.*, 2015). For example, stronger lake stratification can lead to increased hypolimnetic anoxia (Jane *et al.*, 2021) with implications for biogeochemical processing in the deep water of lakes (Carey *et al.*, 2022). Thermal habitat availability for a range of organisms (e.g., coldwater fishes) will likely change as a result of stronger, longer stratification (Hansen *et al.*, 2017; Missaghi, Hondzo & Herb, 2017; Kraemer *et al.*, 2021) as hypolimnetic waters become less habitable and epilimnetic temperatures warm. Increasing stability of the mixed layer depth may also promote blooms of cyanobacteria in the phytoplankton community (Wagner & Adrian, 2009), which, as yet, are fairly uncommon in Feeagh.

Across other studies that include projections of lake hydrodynamics, lake specific responses in mixed layer depth are apparent. For example, Ayala *et al.* (2020) reports a shallower mixed layer depth of 0.49 m under RCP 6.0 for Lake Erken, Sweden, while other studies report a slight deepening of the mixed layer in response to multiple RCP scenarios (Missaghi *et al.*, 2017; Barbosa *et al.*, 2021). The mixed layer depth of Feeagh in the summer months was projected to get shallower by 0.65 - 1.51m by the end of century in the current study, from a historical average of 6.47m. As Feeagh has a surface area of 3.95km^2, the current volume of the mixed layer depth is approximately 0.025 km^3, whereas under RCP8.5, it will decrease to 0.019km^3, a volumetric decrease of almost 25%. If we assume that the majority of the mixed layer depth is available for phytoplankton for photosynthesis, this has significant implications for a humic lake like Feeagh where photosynthetic production is already limited as a result of low light availability. The final metric we present in this paper is the growing season, estimated by ascertaining the number of days where epilimnetic temperature exceeds 9°C, a value which has been shown to accurately capture the days when phytoplankton growth is positive at a given latitude (Håkanson & Boulion, 2001). Our projections indicate that the 25% decrease in the volume of the epilimnion available for photosynthetic organisms may be counteracted somewhat by an extended growing season of up to 22% in length under RCP 8.5. However, it is very uncertain what the results of this time for space trade off will mean for annual primary production by the end of the century, as annual succession of phytoplankton species is determined by many variables including the availability of nutrients and light.

Changes in thermal metrics, such as those we describe here for Feeagh, have far reaching implications for the ecology of lakes, which have generally had a fairly predictable annual cycle of plankton succession, driven by nutrient and light availability, top down predation pressure, and inter-specific competition (Sommer *et al.*, 1986; De Senerpont Domis *et al.*, 2013). Earlier onset of stratification has the potential to advance the occurrence of the spring phytoplankton bloom (Anneville *et al.*, 2002; Peeters *et al.*, 2007), with increased abundance of early season taxa and knock on effects over the year. This effect may be compounded by concurrent changes in nutrient loading to a lake driven by changes in the timing of rainfall and inflow (Dalton *et al.*, 2016). In Feeagh, the characteristic annual cycle of phyto- and zooplankton biomass includes a spring bloom of phytoplankton mainly composed of Bacilliarophyta (diatoms), followed by summer peaks in Crytophyta (de Eyto *et al.*, 2016). *Daphnia* dominate the openwater up to July, followed by peaks in *Diaphanosoma* in the late summer. Calanoid copepods are numerous throughout the year. There is some indication that the pelagic community is changing, with the diversity of the size and species of zooplankton decreasing (Calderó-Pascual, 2023), but more work is needed to attribute these changes to climate rather than other variables such as seasonal availability of nutrients, water discharge from the upper catchment, and top-down control by fish. Based on data from other lakes, climate change will make trophic mismatches more likely (Thackeray *et al.*, 2013), as changes in temperature will affect parts of the foodweb differently. In Feeagh, there is a strong likelihood of trophic mismatches as all three of the endemic fish species have migratory components, with a large proportion of the fish biomass leaving the lake in early summer (smolts of Atlantic salmon *Salmo salar* and Sea trout *Salmo trutta*) and autumn/winter (Silver eel *Anguilla anguilla*) (de Eyto *et al.*, 2022). In addition, the resident population of brown trout (*Salmo trutta*) have a strongly seasonal biomass in the lake, moving between spawning streams and the littoral zone in summer (Matthews *et al.*, 1997). All three species therefore are likely to be locally adapted to the seasonal availability of food, and exert a strong top down control on the food web of the lake. For example, we know that salmon smolts travelling through Feeagh have the potential to consume large quantities of *Daphnia* (de Eyto *et al.*, 2020c). As yet, the smolt migration (salmon and trout) from Feeagh has not advanced significantly (de Eyto *et al.*, 2022). In contrast, the start of the silver eel migration has advanced over the last 50 years in Burrishoole by approximately one month (Sandlund *et al.*, 2017), likely a result of warming temperatures in the month leading up the physiologically important “silvering” transformation (Durif, Dufour & Elie, 2005). This highlights the need for continued simultaneous monitoring of trophic levels within the Feeagh foodweb over the coming decades. Scenario-based modelling experiments could provide insights into the occurrence of trophic mismatches and resultant implications for whole lake productivity.

FUTURE MODELLING EXPERIMENTS

The projections for Feeagh described in this paper give a strong indication of changes in lakes in the west of Ireland over the coming century. However, there is scope for developing model scenarios that more specifically address the climate change effects expected in Irish lakes, decreasing the uncertainty in projections, and increasing the usefulness of such exercises for adaptation and mitigation planning. In terms of uncertainty, the projections presented in this paper are based on driving one lake model (Simstrat) with meteorological outputs from four general circulation models, GFDLESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC5, derived during the CMIP5 framework. Sources of modelling uncertainty therefore include both uncertainties within the lake model used and uncertainties from the differing GCMs used to produce meteorological variables. Simstrat has previously been shown to predict water temperatures of Feeagh accurately (Mesman *et al.*, 2020; Golub *et al.*, 2022; Ayala *et al.*, 2023), and objectively better than several other lakes models (Moore *et al.*, 2021), indicating that the choice of this lake model is warranted for this current study. In addition, Grant *et al.* (2021) used multiple lake models to simulate future climate impacts, and concluded that the uncertainty in end-of-century impacts is dominated by the choice of emissions scenario rather than lake model. Nevertheless, the lake modelling community generally recommends the use of several lake models in an ensemble approach as each model has its own strength and weaknesses (Trolle *et al.*, 2014; Frassl *et al.*, 2019; Moore *et al.*, 2021; La Fuente *et al.*, 2022).

There is also inherent variability across GCMs as a result of forcing differences in the assumptions structure and within each GCM. Inclusion of output from additional GCMs in future experiments may give more accurate insight into the range of likely outcomes, notwithstanding the fact that all GCMs in this study projected similar patterns for Feeagh. The GCMs included in this paper resulted from outputs of the CMIP5 framework which has been superseded by CMIP6 in recent years (Eyring *et al.*, 2016). Work by Carvalho *et al.* (2022) has shown that CMIP5 projections of temperature increase across land areas for RCP 4.5 and 8.5 are well in line, although slightly lower, than observed data, indicating that the projections for lake temperatures using a subset of the GCMs used in CMIP5 are relatively certain. However, a specific feature of Ireland's' climate is the buffering provided by the North Atlantic, and its dependence on oceanic conditions (Nolan, Cusack & Fitzhenry, 2023). Of note is the relatively cool spot in the North Atlantic (Rahmstorf *et al.*, 2015; Bryden *et al.*, 2020), which has been related to the slowdown of the AMOC (Atlantic Meridional Overturning Circulation) in recent decades (Caesar *et al.*, 2018, 2021). This has been linked to the relative cooling of Irish marine waters in recent years (McCarthy *et al.*, 2023; Nolan *et al.*, 2023). There is much uncertainty about what any further weakening of the AMOC will mean for the climate of Ireland specifically. Such a weakening in the 21st century is very likely (IPCC 2021), and the degree of weakening will have massive implications for how climate change is felt on the island of Ireland and across the world. The trajectory of the AMOC in the 21st century is one of the largest sources of future uncertainty in climate models (Bellomo *et al.*, 2021). GCMs in both CMIP5 and CMIP 6 all capture this weakening to some extent, but recent work has shown that models used within the CMIP6 framework capture the resultant changes in sea surface temperatures in the North Atlantic better (Borchert *et al.*, 2021). The benefits of moving towards the use of CMIP6 is reflected in the ongoing development of the lake sector within ISIMIP, with the most recent protocols (ISIMIP 3a and 3b) enabling the use of GCM data from CMIP6. This development also offers the possibility of exploring the impact of SSCPs (Shared Socio-economic Pathways) on GHG emissions, and hence on the likely consequences for water quality and quantity in lakes.

In this paper, we have used the protocol of the Lake Sector in ISIMIP2, which includes the simplifying assumption that hydrologic inputs from the lake watershed had minimal effects on the simulated thermal structure (Golub *et al.*, 2022). While this is a reasonable assumption for lake hydrodynamic simulations, it will not be sufficient for simulations of lake biogeochemistry and ecology that strongly depend on the nutrient inputs from the lake watershed (e.g. Dalton *et al.*, 2016). Future work might include inflow and outflow data in any simulations. This is a prerequisite for the use of coupled hydrodynamic-ecological models such as PCLake (Janssen *et al.*, 2019), PROtech (Elliott, 2021) or DYRESM-CAEDYM (Trolle, Skovgaard & Jeppesen, 2008), the use of which will allow a more detailed exploration of the overall effects of climate change on lakes, and the organisms that inhabit them.

Finally, the work described in this paper explores the likely thermal and hydrodynamic impacts of future climate scenarios on one of the 12 types of lakes in Ireland, i.e. deep, low alkalinity lakes larger than 50ha (i.e. type 4 in Free *et al.* (2006)). Future research directions in this area might include a similar exercise for representative lakes in all 12 lake types in Ireland as it is probable that the hydrodynamics of each lake type, and associated ecological characteristics, will respond differently to climate warming. For example, we might expect that the surface water of shallow lakes will warm at a faster rate than for deep lakes (Pilla *et al.*, 2020). Stratification strength and duration also varies with lake size and depth (Butcher *et al.*, 2015), and hence the sensitivity of these variables to global warming is also likely to vary with lake type. Another informative line of investigation would be to quantify climate induced changes to lakes that contain designated species under the habitats directive (EC, 1992), such as Arctic charr (*Salvelinus alpinus*) and Atlantic salmon (*Salmo salar*), or designated lake habitats (e.g. Natural dystrophic lakes and ponds [code 3160] or Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or *Isoeto-Nanojuncetea* [code

3130]). In progressing some of these options, we note that climate projections at a fine spatial resolution are now available through Met Éireann (4km grid squares) (Nolan & Flanagan, 2020; O'Brien & Nolan, 2023), and these may provide a useful resource for impact modelling at a geographic resolution that is higher than climate data currently available through the ISIMIP portal (0.5° grid, equivalent to 55.5 x 32.5km at 54 °N). We conclude with a recommendation that the collection of observational thermal data from a subset of Irish lakes, at appropriate temporal resolution (i.e. daily or sub-daily), is required to validate future modelling experiments. In addition, long term ecological data is required to fully understand the consequent impacts of thermal changes on lake habitats and biota.

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DATA AVAILABILITY

The Simstrat v2.1.2 code is available at https://github.com/Eawag-AppliedSystemAnalysis/Simstrat . Daily bias-corrected climate model projections from ISIMIP2b are available at https://www.isimip.org/gettingstarted/data-access/ . Future climate projection for Lough Feeagh using the modified code in Simstrat v.2.1.2 are available for download here:

https://doi.org/10.5281/zenodo.7413518 . Water temperature profiles for Lough Feeagh are openly accessible here: https://doi.org/10/cvtr . Supplemental information about the meteorological drivers and mode detailed metrics across GCMs used can be found here: https://github.com/IrishMarineInstitute/BurishooleLTER-Public/tree/master/Ayala_et_al_SI_Feeagh_climate_change

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FIGURES

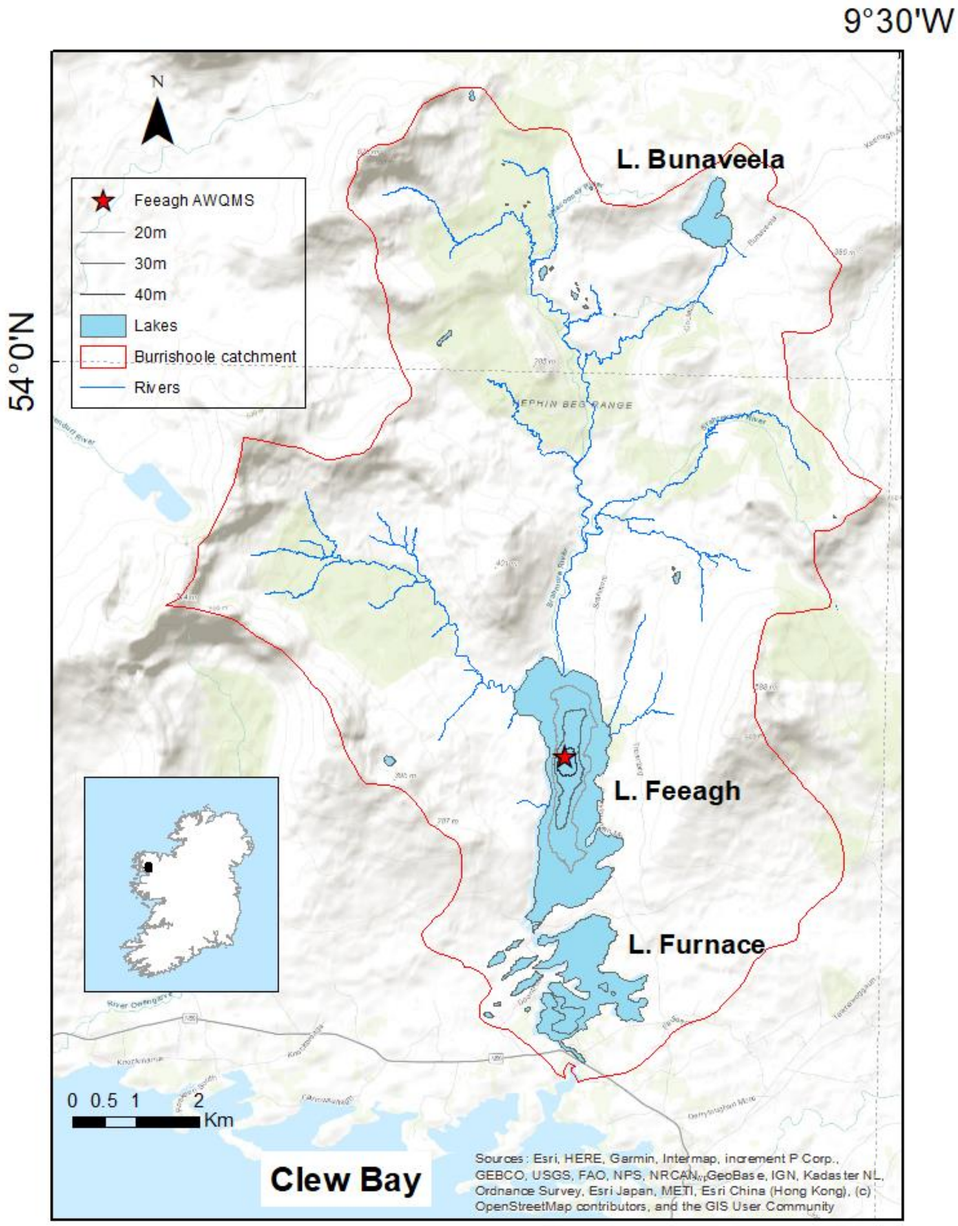

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Fig. 1. Geographic location of Lough Feeagh in the Burrishoole catchment, Co. Mayo, Ireland.

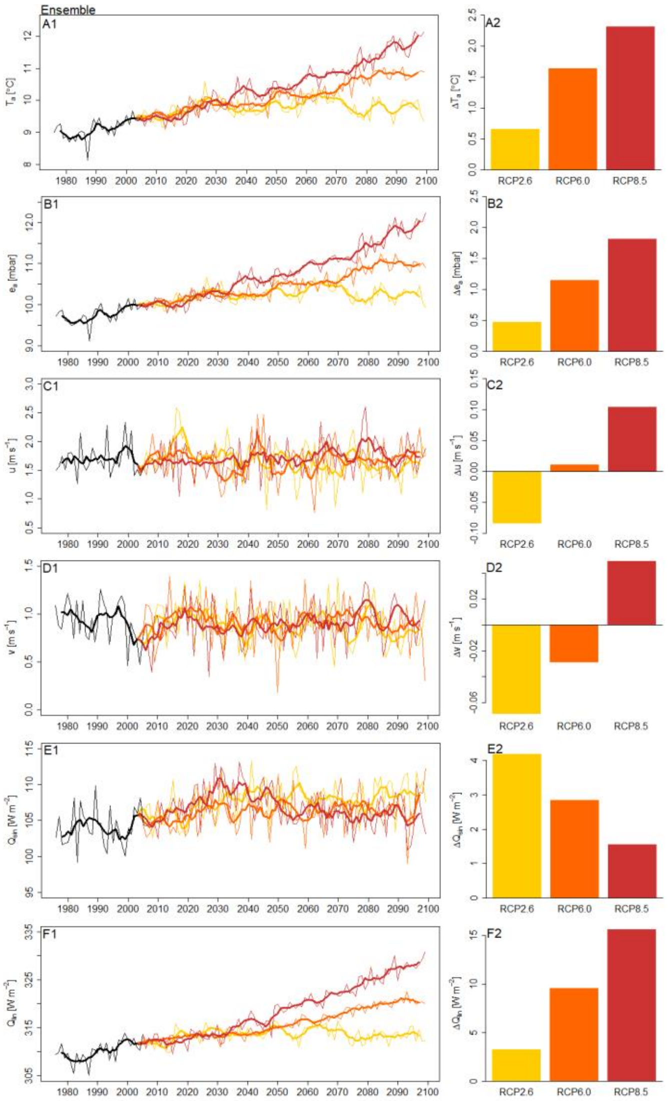

Fig. 2. Climate variables obtained from ISIMIP2b (https://www.isimip.org/), for the 0.5°grid cell overlying Lough Feeagh, and used to drive the lake model applied to Lough Feeagh. Variables are arranged from top to bottom: A: **Air temperature** T_a (°C), B: **Vapor pressure at 2m** e_a (mbar), C: **Wind speed towards the east** u (ms^{-1}), D: **Wind speed towards the north** v (ms^{-1}), E: **Surface incoming short-wave radiation** Q_{sin} (W m^{-2}), F: **Surface incoming long-wave radiation** Q_{lin} (W m^{-2}). Each row displays the projections for 1976 to 2099 under historical (black) and future climate forcing RCP 2.6 (yellow), RCP 6.0 (orange) and RCP 8.5 (red). **1** Annual average of the variable with the thin line showing the yearly average across all GCMs and the thick line show the 5-year centred moving average of the ensemble. **2** Average difference in each variable between RCPs (2070-2099) and historical period (1976-2005) (average across all GCMs).

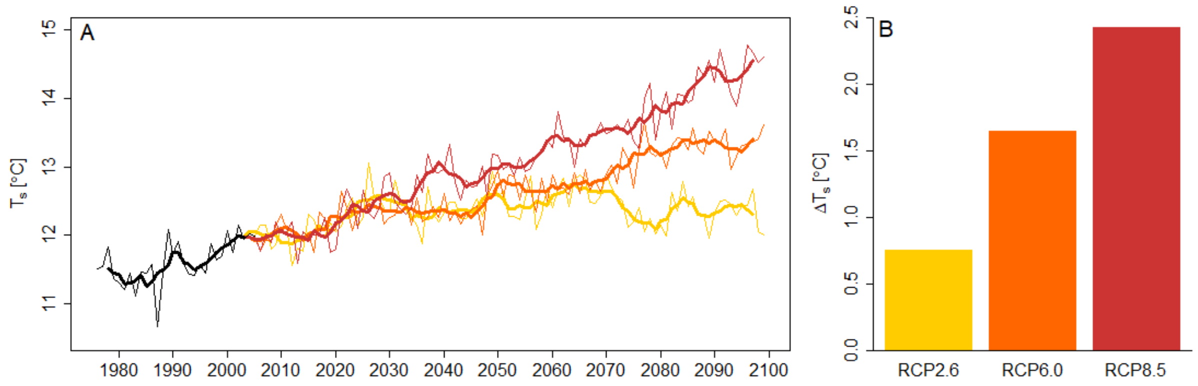

Fig. 3. Surface water temperature °C, T_s, from 1976 to 2099 under historical (black) and future climate forcing RCP 2.6 (yellow), RCP 6.0 (orange) and RCP 8.5 (red). **A** Annual average of T_s, the thin line shows the yearly average across all GCMs and the thick line show the 5-year centered moving average of the ensemble. **B** Average difference in T_s between RCPs (2070-2099) and historical period (1976-2005) (average across all GCMs).

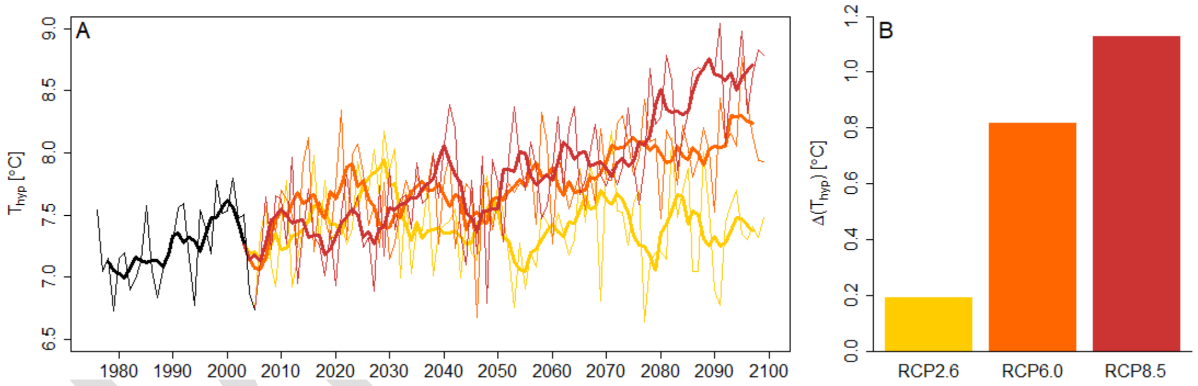

Fig. 4. Hypolimnetic temperature °C, T_{hyp}, from 1976 to 2099 under historical (black) and future climate forcing RCP 2.6 (yellow), RCP 6.0 (orange) and RCP 8.5 (red). **A** Annual average of T_{hyp}, the thin line shows the yearly average across all GCMs and the thick line show the 5-year centered moving average of the ensemble. **B** Average difference in T_{hyp} between RCPs (2070-2099) and historical period (1976-2005) (average across all GCMs).

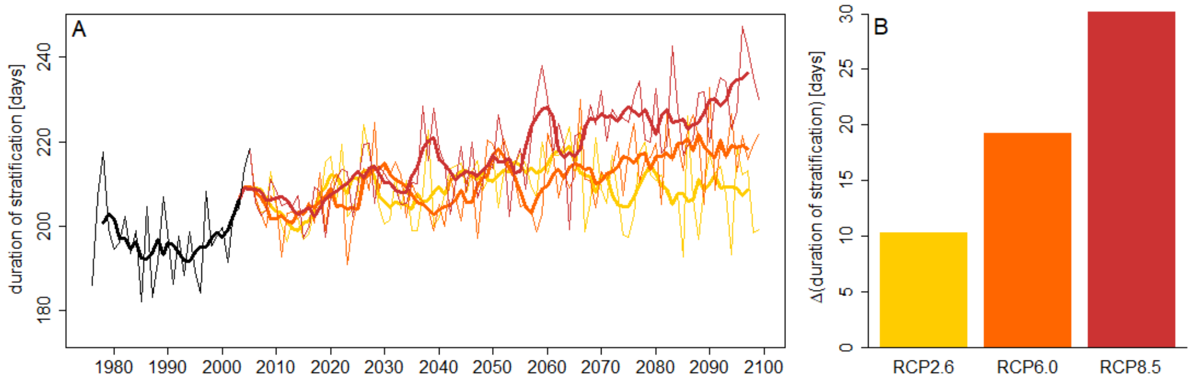

Fig. 5. Duration of direct thermal stratification (number of days) from 1976 to 2099 under historical (black) and future climate forcing RCP 2.6 (yellow), RCP 6.0 (orange) and RCP 8.5 (red). **A** Annual duration of direct thermal stratification, the thin line shows the yearly average across all GCMs and the thick line show the 5-year centered moving average of the ensemble. **B** Average difference in duration of direct thermal stratification between RCPs (2070-2099) and historical period (1976-2005) (average across all GCMs).

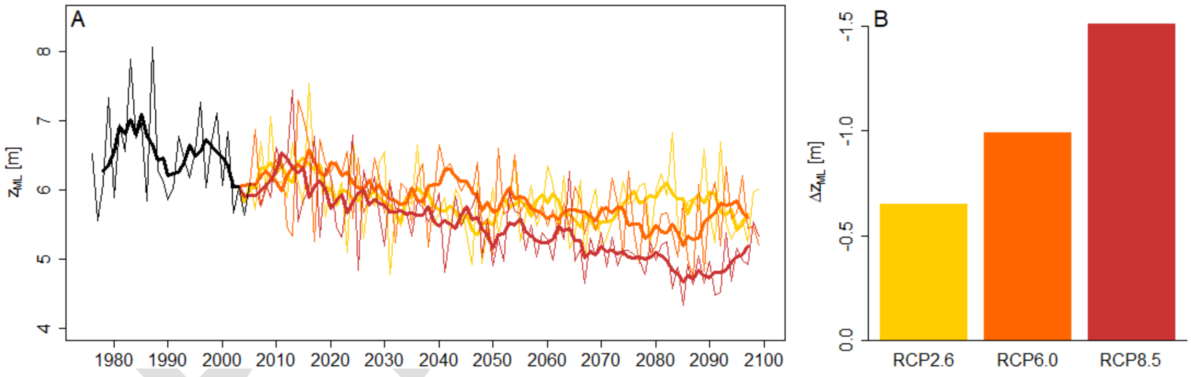

Fig. 6. Mixed layer depth (m), z_{ML}, in the summer (JJA) from 1976 to 2099 under historical (black) and future climate forcing RCP 2.6 (yellow), RCP 6.0 (orange) and RCP 8.5 (red). **A** Annual average of z_{ML}, the thin line shows the yearly average across all GCMs and the thick line show the 5-year centered moving average of the ensemble. **B** Average difference in z_{ML} between RCPs (2070-2099) and historical period (1976-2005) (average across all GCMs).

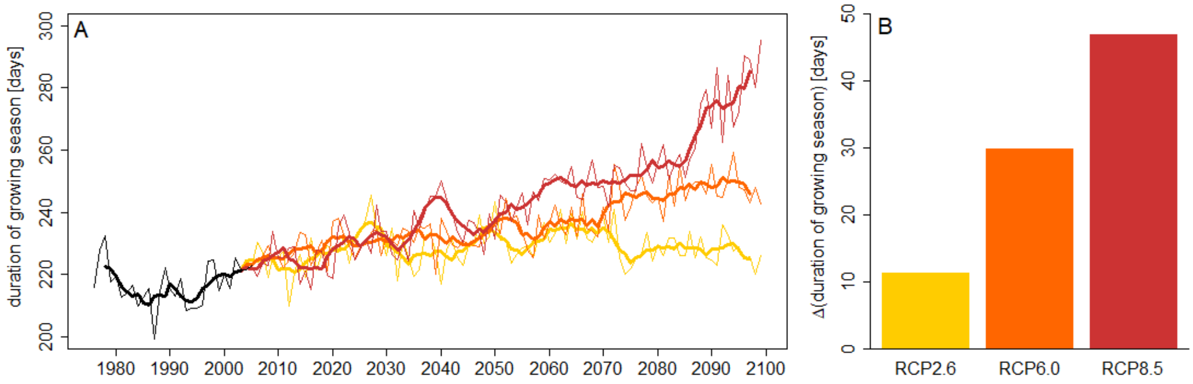

Fig. 7. Duration of growing season (number of days) from 1976 to 2099 under historical (black) and future climate forcing RCP 2.6 (yellow), RCP 6.0 (orange) and RCP 8.5 (red). **A** Annual duration of growing season, the thin line shows the yearly average across all GCMs and the thick line show the 5-year centered moving average of the ensemble. **B** Average difference in duration of growing season between RCPs (2070-2099) and historical period (1976-2005) (average across all GCMs).

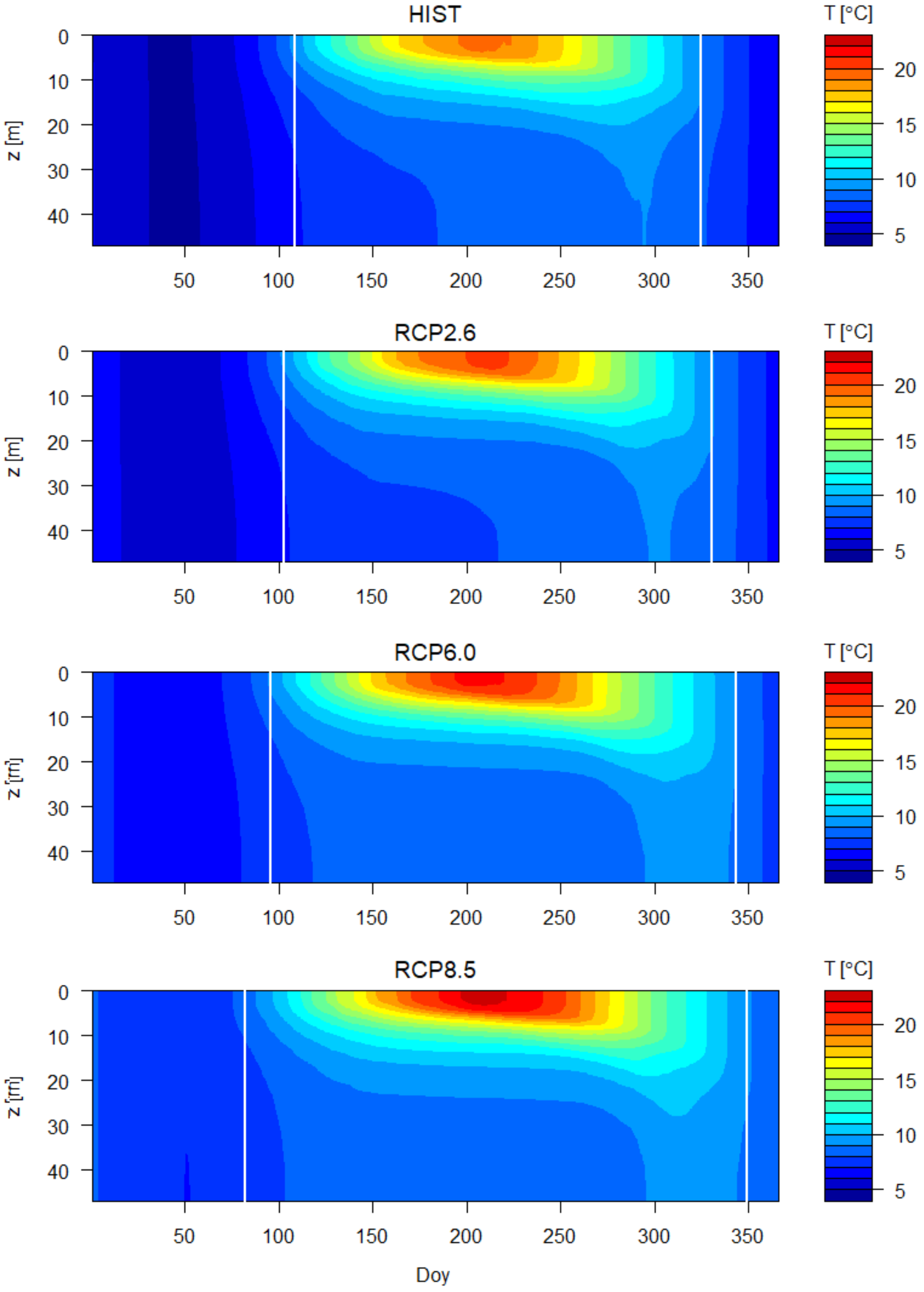

Fig. 8. Water temperature over the depth of Lough Feeagh across the year for under historical (1976-2005) and future (2070-2099) climate forcing scenarios (RCP 2.6, 6.0 and 8.5). White lines indicate the extent of the growing season, defined as the number of days in which epilimnetic temperature exceeds 9 °C.

Table 1. Thermal metrics calculated from water temperature profiles of Lough Feeagh simulated under historical conditions and future climate change scenarios, by the 1-D lake model SIMSTRAT.

Variable	Unit	Description	Reference
Surface water temperature (SWT)	°C	Temperature in the top 0.5 m layer	
Minimum SWT	°C	Minimum annual temperature recorded in the top 0.5 m layer	
Maximum SWT	°C	Maximum annual temperature recorded in the top 0.5 m layer	
Epilimnetic temperature	°C	Volume weighted average temperature in the top 3 meters (0-3 m). Calculated using the function *layer.temperature()* of the R package *rLakeAnalyzer()*	(Winslow *et al.*, 2014)
Hypolimnetic temperature	°C	Volume weighted average temperature over the bottom 3 meters (43.8-46.8 m). Calculated using the function *layer.temperature()* of *rLakeAnalyzer()*	(Winslow *et al.*, 2014)
Thermal stratification onset	Day of year	First day of year where the density gradient between the bottom layer and the top layer is > 0.01kg/m^3, the surface temperature is > 3.98°C for more than 5 consecutive days	
Thermal stratification loss	Day of year	Last day of year where the density gradient between the bottom layer and the top layer is > 0.01 kg/m^3 , the surface temperature is < 3.98°C for more than 5 consecutive days	
Thermal stratification duration	Number of days	Number of days between the onset and loss of thermal stratification	
Mixed layer depth	m	The depth at which the density is > 0.1 kg m^{-3} more than the density of the surface layer (top 0.5 m)	(Wilson *et al.*, 2020)
Stability	J m^{-2}	Calculated using the function *schmidt.stabililty()* of the R package *rLakeAnalyzer()*	(Read *et al.*, 2011; Winslow *et al.*, 2014)
Length of growing season (GS)	Number of days	Number of days in which epilimnetic temperature exceeds 9°C	(Håkanson & Boulion, 2001; Moras, Ayala & Pierson, 2019)

Table 2. Average thermal metrics (water temperature) for the historical period (1976-2005) and average projected change (ensemble mean over 4 GCMs) for the three future climate scenarios (RCP 2.6, 6.0 and 8.5).

Variable	Scenario	Annual	Winter	Spring	Summer	Autumn
Surface water temp (°C)	Historical	11.61	5.83	9.41	18.27	12.83
	RCP 2.6	+ 0.75	+ 0.59	+ 0.75	+ 0.96	+ 0.69
	RCP 6.0	+ 1.64	+ 1.46	+ 1.54	+ 1.86	+ 1.56
	RCP 8.5	+ 2.42	+ 1.99	+ 1.99	+ 2.60	+ 2.43
Minimum SWT (°C)	Historical	4.42				
	RCP 2.6	+ 0.68				
	RCP 6.0	+ 1.63				
	RCP 8.5	+ 2.31				
Maximum SWT (°C)	Historical	21.8				
	RCP 2.6	+ 1.17				
	RCP 6.0	+ 1.84				
	RCP 8.5	+ 2.99				
Epilimnetic water temp (°C)	Historical	11.60	5.84	9.39	18.24	12.84
	RCP 2.6	+ 0.75	+ 0.59	+ 0.74	+ 0.94	+ 0.69
	RCP 6.0	+ 1.64	+ 1.46	+ 1.54	+ 1.85	+ 1.55
	RCP 8.5	+ 2.41	+ 1.98	+ 1.98	+ 2.58	+ 2.42
Hypolimnetic water temp (°C)	Historical	7.24	5.80	6.61	8.04	8.50
	RCP 2.6	+ 0.19	+ 0.61	+ 0.28	- 0.04	+ 0.04
	RCP 6.0	+ 0.82	+ 1.42	+ 0.92	+ 0.33	+ 0.35
	RCP 8.5	+ 1.13	+ 1.87	+ 1.19	+ 0.50	+ 0.49

Table 3. Average thermal metrics (derived from water temperature) for the historical period (1976-2005) and average projected change (ensemble mean over 4 GCMs) for the three future climate scenarios (RCP 2.6, 6.0 and 8.5).

Variable	Scenario	Value
Duration of thermal stratification (days)	Historical	198
	RCP 2.6	+ 10
	RCP 6.0	+ 19
	RCP 8.5	+ 30
Onset of stratification (date)	Historical	18th April
	RCP 2.6	12th April
	RCP 6.0	11th April
	RCP 8.5	6th April
Loss of stratification (date)	Historical	2nd Nov
	RCP 2.6	7th Nov
	RCP 6.0	14th Nov
	RCP 8.5	20th Nov
Mixed layer depth (m) in summer	Historical	6.47
	RCP 2.6	-0.65
	RCP 6.0	-0.99
	RCP 8.5	-1.51
Schmidt stability J m^{-2}	Historical	58.95
	RCP 2.6	+ 6.60
	RCP 6.0	+ 16.25
	RCP 8.5	+ 32.46
Duration of growing season (days)	Historical	217
	RCP 2.6	+ 11
	RCP 6.0	+ 30
	RCP 8.5	+ 47