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Projected phenological shifts in stratification and overturning of ice-covered Northern Hemisphere lakes

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Lei Huang [1,2] ✉, R. Iestyn Woolway [3], Axel Timmermann [2,4] & Keith B. Rodgers [5]

The seasonal cycle of vertical mixing is crucial for lake ecosystems, yet its future under climate change remains uncertain. While lake stratification shifts have been widely studied, the annual overturning duration changes are less clear. Using sub-daily simulations from a fully coupled numerical Earth system model, we assess phenological changes in stratification and overturning in Northern Hemisphere ice-covered lakes. We find the total stratification duration (comprising both summer and winter phases) is projected to decrease by 0.7, 4.6, and 6.9 days in 2029, 2067, and 2096, respectively, under global temperature increases of 1.5 °C, 3 °C, and 4.5 °C. Conversely, the duration of overturning is expected to increase by 0.7, 4.2, and 8 days annually. Notably, these changes are asymmetrical, with most of the overturning extension occurring in the fall, following the peak growing season. This extended overturning could affect lake ecosystems, particularly through enhanced ventilation of bottom layers and altered nutrient cycling.

Profound thermodynamic alterations of lakes under global warming have already been identified in observations[1–6], with consistent behavior having been identified in models[7,8]. These rapid changes encompass several facets of lake thermodynamics, including changes in ice cover phenology[9], shifts in open water thermal habitat[10,11] and alterations in the seasonal cycle of vertical mixing[12–16]. Rising lake temperatures are expected to drive more frequent and intense algal blooms[17] and perturb CO_2 flux exchanges between lakes and the atmosphere[18]. Lakes can also experience deoxygenation of hypolimnetic waters due to the combined effects of reduced ventilation and active respiration[19]. Notably, the phenology of lake thermodynamics, encompassing the duration of ice cover[7,20–22] and vertical stratification[6], proves to be highly sensitive to the effects of climate change.

The timing of ice cover onset and breakup, and the duration of thermal stratification, play pivotal roles in shaping the life cycles of organisms within lakes. For example, phytoplankton blooms are often tied to the early spring ice breakup[23]. Rapid changes in the phenology of thermal stratification and mixing can lead to mismatches in crucial phenological events for aquatic species[24]. Studies have demonstrated a strengthening of summer stratification with an increasing temperature difference between surface and subsurface layers[25,26]. In tandem with changes in the strength of stratification, the phenology of lake mixing is also changing. High-resolution observations from Lake Michigan, for instance, indicate an extended duration of summer stratification and a delayed timing of fall overturning[1]. Numerical models predict that the mixing regimes of lakes will change by the end of the 21st century, with some lakes transitioning from experiencing seasonal stratification to becoming permanently stratified[8]. In contrast to the alterations anticipated during the warmer seasons, the strength and duration of inverse stratification during the colder seasons, which impacts nutrient cycling under ice and cascades into subsequent seasons[12,14], is diminishing[27]. While prior studies have separately documented changes in the duration and strength of stratification in warm and cold seasons, the shifts in the phenology of stratification, encompassing both summer and winter stratification, have remained underexplored. The effect on the total number of overturning days, which influences the ventilation of the hypolimnion and nutrient supply efficiency to the epilimnion, remains uncertain.

Results

Spatial patterns of Northern Hemispheric stratification and overturning in ice-covered lakes

Our analyses of the LISSS simulations in the CESM2 Large Ensemble indicate notable variability in the climatological mean duration of stratification and overturning along latitudinal gradients during the period from 1850 to 1860 (Figs. 1 and 2). The total duration of stratification increases from the equator towards the poles, with zonal mean stratification duration reaching approximately 240 days annually at 30°N. Northward of 30°N, the rate of increase lessens, and the zonal mean duration is more than 250 days

[1]College of Resource Environment and Tourism, Capital Normal University, Beijing, China. [2]Center for Climate Physics, Institute for Basic Science, Busan, South Korea. [3]School of Ocean Sciences, Bangor University, Menai Bridge, UK. [4]Pusan National University, Busan, South Korea. [5]WPI-Advanced Institute for Marine Ecosystem Change, Tohoku University, Sendai, Japan. ✉e-mail: huanglei@cnu.edu.cn

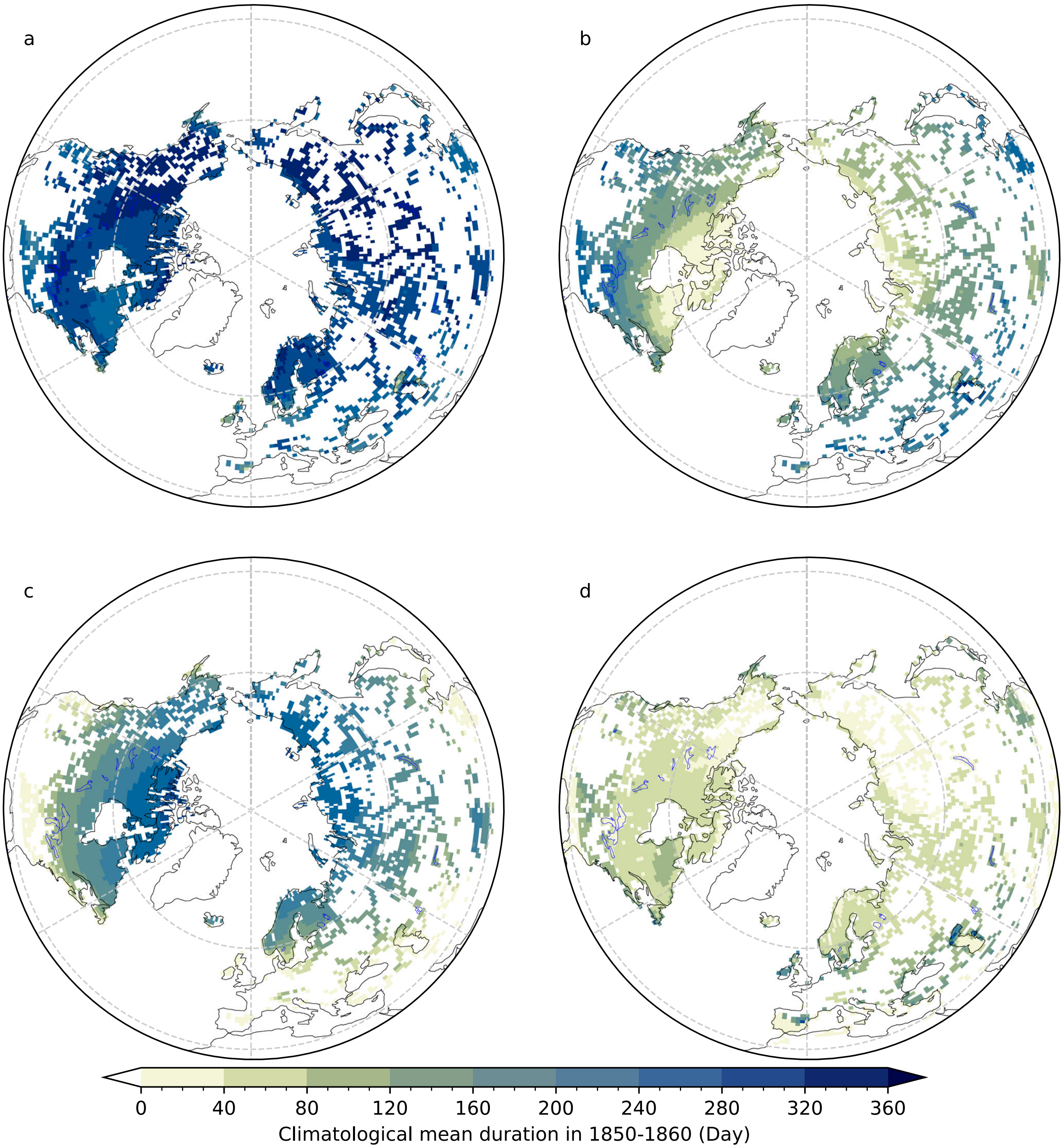

Fig. 1 | Ensemble mean of climatological mean stratification phenology of Northern Hemisphere lakes over 1850–1860. Panel **a** shows the total number of stratification days annually, which is the additive duration of summer stratification (**b**) and inverse stratification (**c**) for individual grid points. Annual duration of overturning is shown in **d**. All results are based on a 90-member ensemble mean from the CESM2 large ensemble.

in Arctic regions. However, in regions north of 30°N, the duration of summer stratification and inverse stratification shows rapid latitudinal changes. The zonal mean duration of summer stratification decreases to near 0 days from 30°N to the pole. Conversely, inverse stratification becomes more pronounced north of 30°N, where lake ice cover persists during winter. Latitudinal variations in the duration of summer stratification and inverse stratification are clearly shown in Fig. 1b, c. In the Arctic, the annual duration of inverse stratification exceeds 250 days. Figure 2 suggests that the zonal mean duration of summer stratification and inverse stratification exhibits a linear correlation with the annual mean surface air temperature, and they all vary almost linearly along latitudes. In contrast to the latitudinal variation in total stratification, the duration of overturning decreases from the equator to the poles, with the longest duration occurring in tropical regions (Fig. 2). Lakes in Alaska and eastern Siberia exhibit the shortest duration of overturning events, with less than 40 days of overturning each year (Fig. 1d). Our simulations illustrate that overturning primarily occurs during the Fall season, spanning from September to November (Supplementary Fig. S4).

Surface air temperature plays a pivotal role in influencing the duration of stratification and overturning. The spatial pattern and seasonal variation

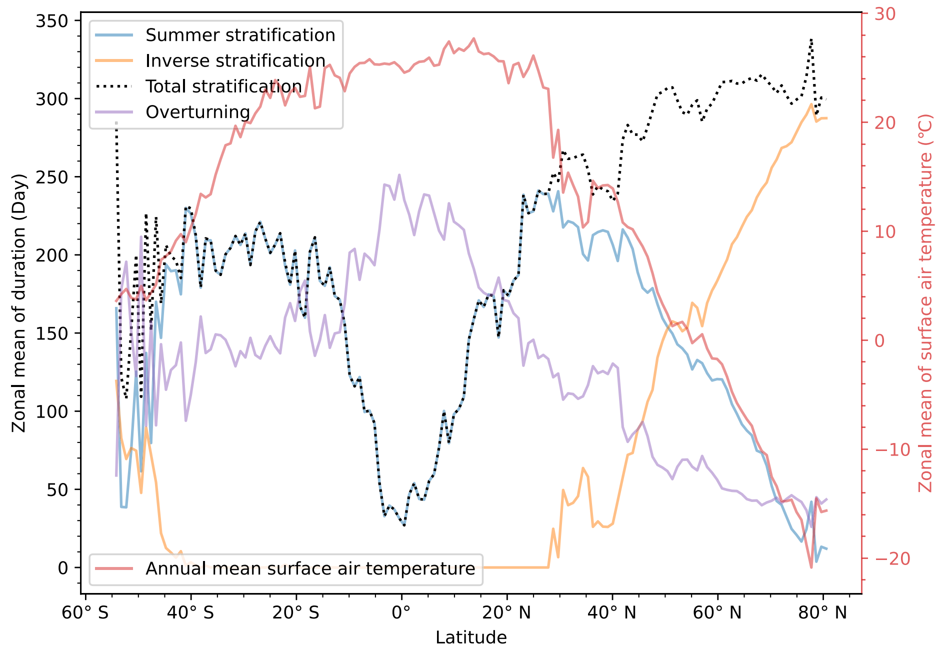

Fig. 2 | Latitudinal variation of the ensemble mean of total stratification days (i.e., the additive duration of summer stratification and inverse stratification), summer stratification days, inverse stratification days, overturning days, and annual mean surface air temperature. The y-axis label to the left represents the zonal mean of duration (in days), and the y-axis label to the right represents the zonal mean of annual mean surface air temperature. The zonal mean values are averaged over all 90 ensemble members and all grid points with lakes present in 1° latitude intervals.

of inverse stratification (Supplementary Fig. S5) are determined by ice cover duration (Supplementary Fig. S6), which is in turn shaped by surface air temperature. Additionally, wind speed, depth, and surface area are other important contributors. For example, large and deep lakes such as Lake Superior and Great Slave Lake have shorter durations of overturning but longer durations of total stratification than adjacent lakes (Fig. 1a, d) due to their higher thermal inertia.

Projected future changes in the duration of stratification and overturning

Our simulations suggest that future projected changes in the duration of total stratification vary considerably across lakes (Fig. 3). In the region surrounding Hudson Bay, particularly the Quebec-Labrador Peninsula, and the coastal area of the Barents Sea and the Kara Sea, the ensemble mean annual duration of total stratification is expected to increase by 4.5, 8.4, and 10 days in 2029, 2067, and 2096, respectively. Conversely, other Northern Hemisphere ice-covered lakes, mainly categorized as Northern Temperate[28], will experience a remarkable reduction in the annual duration of total stratification, decreasing by 5.8, 14.9, and 24.1 days, respectively. On average, Northern Hemisphere ice-covered lakes (categorized as lakes experiencing ice cover in 1850–1860) will experience a decrease in total stratification duration of 0.7, 3.6, and 6.9 days, respectively. It's important to note that the changes in the duration of summer stratification and winter inverse stratification are asymmetrical, and it is this asymmetry that determines whether the total stratification in a lake will increase or decrease.

In our simulations, the duration of summer stratification is anticipated to increase in ice-covered lakes across the Northern Hemisphere (Fig. 3). This extension of summer stratification is attributed to the increased stability of the water column, a consequence of rising surface water temperatures under future global warming. Additionally, a reduction in surface wind speed (referred to as "stilling" of the planetary boundary layer, see Fig. 4) during the Northern Hemisphere's warming seasons serves as another significant factor in the extension of summer stratification[6]. Despite the moderate changes in simulated near-surface wind speed during summer, its contribution to stratification dynamics is disproportionately important since momentum flux scales with the square of surface wind speed. Conversely, the duration of inverse stratification decreases in ice-covered lakes (Fig. 3). This shortened inverse stratification is primarily driven by changes in momentum flux input due to ice loss in the future. In winter, when ice cover is present, ice prevents the transmission of momentum flux from the air to the water, rendering momentum flux input equal to 0. Figure 4 illustrates a substantial increase in momentum input due to the loss of lake ice during the cold seasons. Our projections indicate that the spatial pattern of monthly changes in lake ice cover (Supplementary Fig. S7) duration determines the pattern of monthly changes in inverse stratification (Supplementary Fig. S8). Consequently, increased momentum flux input leads to a reduction in the duration of inverse stratification.

Our simulations indicate an increase in the annual duration of overturning (see Fig. 3) in Northern Temperate lakes. On average, this increase amounts to 4.3, 11.5, and 18.2 days in 2029, 2067, and 2096, respectively. In Northern Hemisphere ice-covered lakes, the duration of overturning is projected to increase by 0.7, 4.2, and 8 days, respectively. Our simulations further suggest that the duration of overturning will decrease in summer (Supplementary Fig. S9). This decrease is attributed to increased water column stability due to rising surface water temperatures and the global stilling effect (Fig. 4). However, the duration of overturning is expected to increase significantly during the cold season (Supplementary Fig. S9) induced by increased momentum flux input due to ice loss. The prolongation of cold season overturning duration outweighs the decrease in summer overturning duration, resulting in a net increase in the number of overturning days.

It is noteworthy that in the vicinity of Hudson Bay and the coastal regions of the Barents Sea and the Kara Sea (as indicated by pink dots in Supplementary Fig. S10's inset), lake water columns will transition from mixed to stratified systems throughout the summer. This transition is likely a consequence of the anomalous summer warming projected in these regions (Fig. 3 in ref. 21). The extension of summer stratification (Supplementary Fig. S11) surpasses the contraction of inverse stratification in cold seasons (Supplementary Fig. S8), culminating in a net increase in total stratification duration for these regions. Conversely, in Northern Temperate lakes, the drastic reduction in inverse stratification due to the loss of lake ice prevails over the lengthening of summer stratification, resulting in a decrease in total stratification but an increase in overturning duration. The extension of overturning is particularly pronounced in lakes at the southern periphery of the ice-covered lake distribution area (marked by green dots in Supplementary Fig. S10's inset), where the enhancement of overturning is projected to persist throughout the winter.

Asymmetrical shifts in the phenology of summer stratification and overturning

Our analysis has quantified shifts in the phenology of summer stratification, indicating a prolongation of summer stratification at both its onset and termination (Supplementary Fig. S12). This implies that stratification will commence earlier in spring and continue for a longer duration into fall. Nevertheless, the shifts in the onset and termination dates are asymmetrical. The negative values in the first row of plots in Fig. 5 suggest that, for most ice-covered lakes in the Northern Hemisphere, the spring advancement of stratification exceeds the fall prolongation. This pattern is reversed for lakes

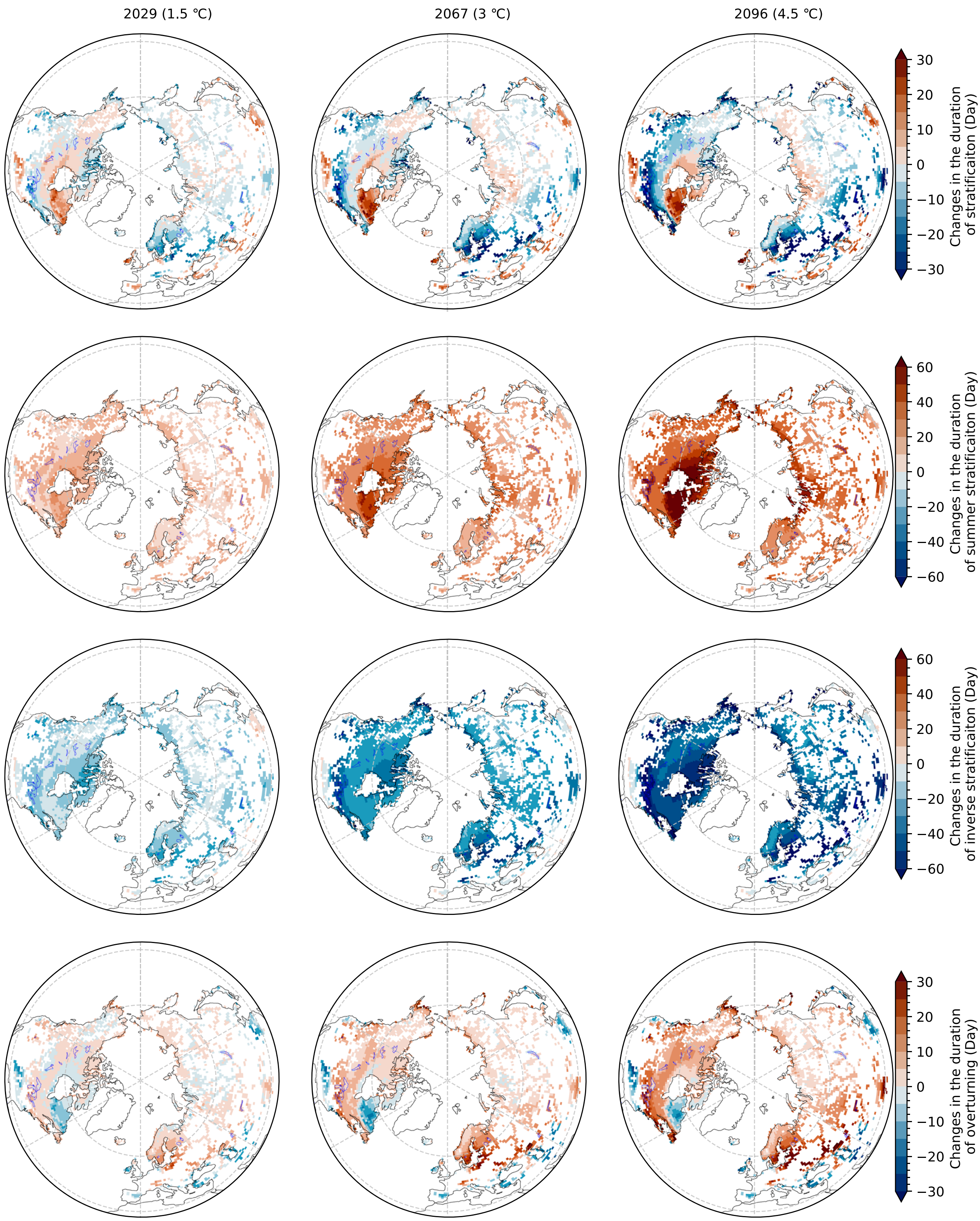

Fig. 3 | Changes in the ensemble mean duration of stratification and overturning in 2029, 2067, and 2096, corresponding to global warming levels of 1.5 °C, 3 °C, and 4.5 °C, respectively. Shown are changes in additive duration of summer stratification and inverse stratification in the first row, duration of summer stratification in the second row, duration of inverse stratification in the third row, and duration of overturning in the fourth row. The global warming levels are quoted relative to the climatological mean of the pre-industrial era, which is calculated from the mean over 1850–1860 in the CESM2-LE.

in the Scadinavian Peninsula, Baffin Island, and Northeastern Siberia, where the fall delay of stratification is more pronounced than the spring advancement. Noticeably, this asymmetry intensifies in tandem with the increasing levels of global warming. At a global warming level of 1.5 °C, this asymmetry is considered negligible. It becomes prominent when global warming reaches 4.5 °C. For instance, this asymmetry could reach up to 20 days for lakes in the Tibetan Plateau and southern East European Plain.

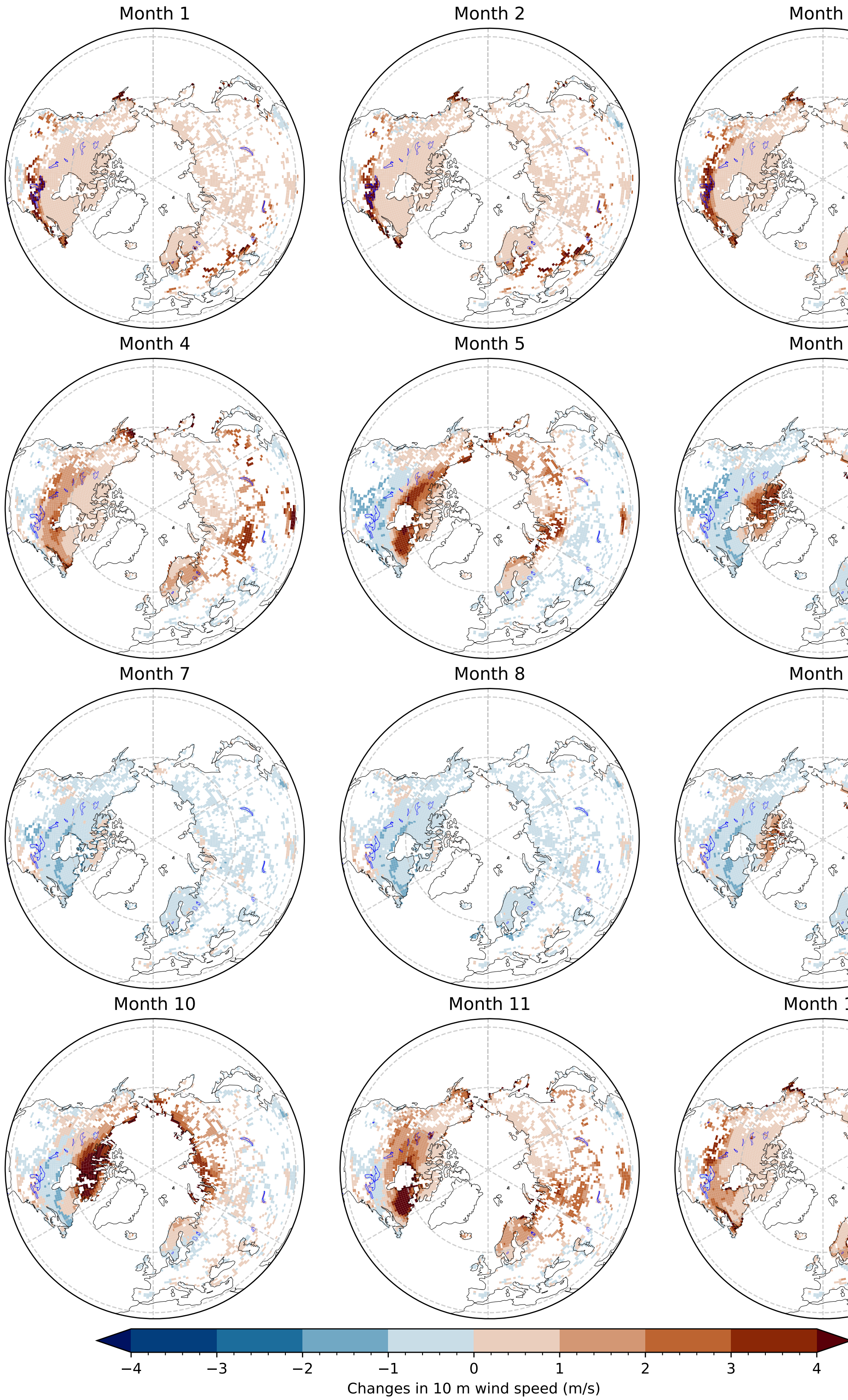

Fig. 4 | Changes in ensemble mean monthly mean of surface wind speed in 2096 which corresponds to the global warming level of 4.5 °C relative to pre-industrial conditions. As lake ice cover impedes momentum transfer into the water column, wind speed driving water mixing is set to zero when there is ice cover present.

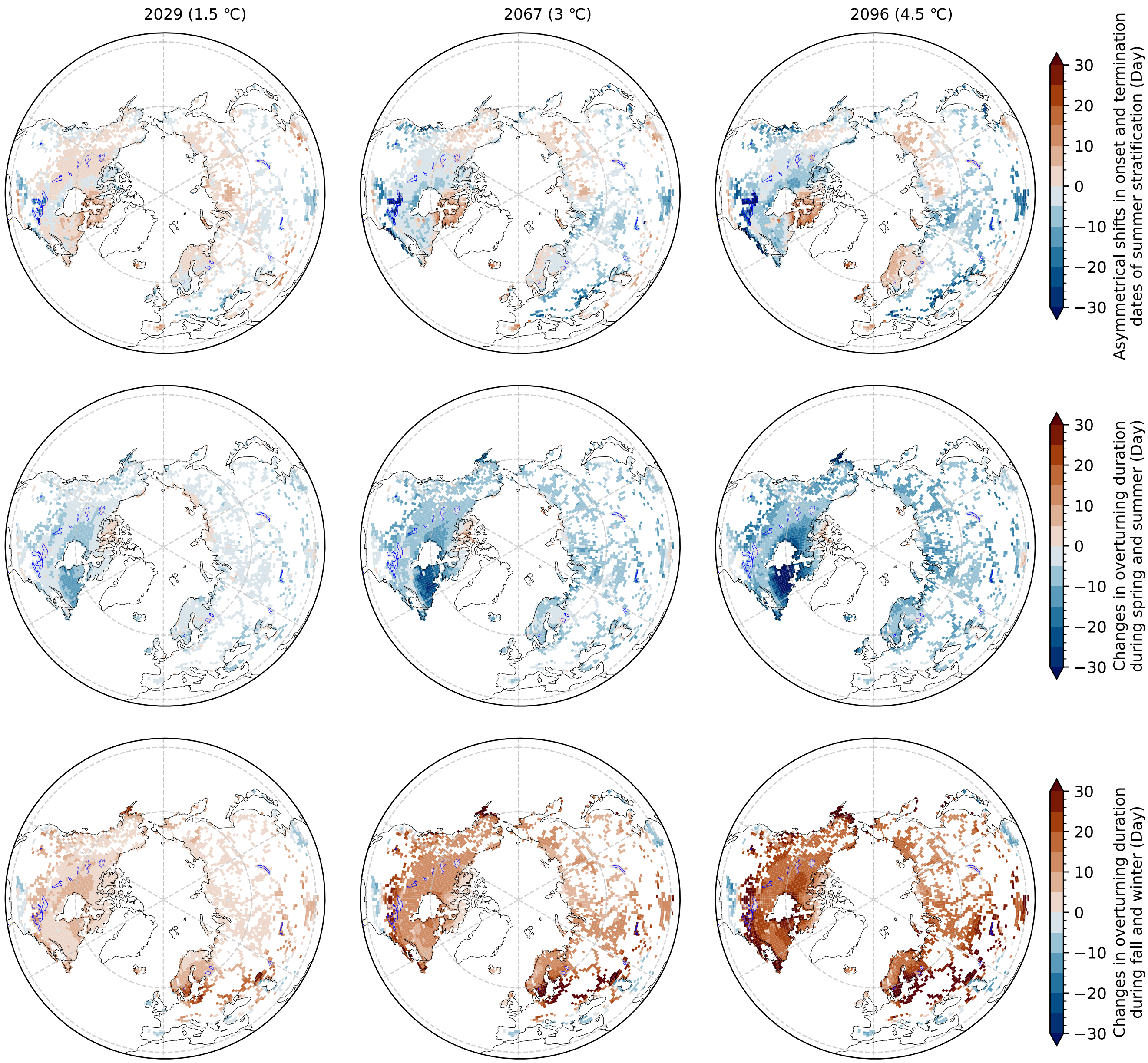

Fig. 5 | Projected asymmetrical changes in the phenology of summer stratification and overturning. Panels in the first row depict the projected asymmetrical shifts in onset and termination dates of summer stratification, so as to highlight the earlier onset in spring versus the delayed termination in fall. Here, negative values indicate that the spring advancement of stratification exceeds the fall prolongation, with positive values indicating the opposite. The panels in the second row show projected changes in overturning duration during spring and summer, spanning from April to September. Likewise, the third row presents overturning duration changes in fall and winter, spanning from October to March of the following year.

The asymmetry in overturning phenology changes is also evident. Supplementary Fig. S10a illustrates that the alterations in overturning events are considerably more pronounced in fall and winter compared to spring. The pattern of asymmetry is further emphasized in the second and third rows of Fig. 5. The projected trend indicates a decrease in overturning duration during spring and summer, in contrast with an increase during fall and winter. In spring, the loss of ice does not significantly amplify overturning events (Supplementary Fig. S9) but rather leads to an advanced onset of summer stratification (Supplementary Fig. S12). This advancement is attributed to the ice albedo feedback mechanism, which is triggered by earlier ice loss[29], resulting in additional spring warming and, consequently, enhanced stratification. Conversely, in fall and winter, while global warming extends summer stratification into fall, the delayed initiation of ice formation extends the open water period, thereby increasing the overturning duration. Consequently, the overturning duration is anticipated to shorten in the warm seasons, namely spring and summer, but to lengthen in the cold seasons, namely fall and winter.

The ice albedo feedback plays a crucial role in driving the asymmetry of projected phenological shifts in summer stratification. The spatial distribution of ice loss (Fig. 1c in ref. 21) closely aligns with the pattern of this asymmetry (the first row's plots in Fig. 5). While the onset and termination of lake ice cover appear symmetric (Fig. 1a, b in ref. 21), the feedback's influence on lake water warming is not. The absorption of shortwave radiation due to ice albedo feedback is substantial in the spring but minimal in late summer and fall (refer to the fourth column of plots in Fig. 3 in ref. 21). Consequently, lakes experiencing rapid ice loss, such as those around Hudson Bay, show a marked advancement in spring stratification driven by the strong ice albedo feedback, resulting in a greater shift in spring compared to fall. In contrast, for regions such as the Scadinavian Peninsula, Baffin Island, and Northeastern Siberia, where lake ice loss is less pronounced, the spring advancement of stratification is weaker. For these lakes, the prolongation of stratification in fall outweighs the earlier onset in spring.

Discussion

Global warming exerts opposing effects on lake mixing across warm and cold seasons, complicating the evaluation of its impact on the vertical cycling of nutrients, water, and energy in lake ecosystems. In this study, using lake model output from the CESM2-LE, we investigated projected changes in the duration of stratification and overturning in Northern Hemisphere ice-covered lakes in 2029, 2067, and 2096, respectively. Our results indicate that summer stratification in 2096 (corresponding to a global warming level of 4.5 °C) will increase by 38.2 ± 4.9 days (quoted uncertainties represent the standard deviation of the large ensemble members, Supplementary Note 1) relative to the preindustrial era. We also project that inverse stratification will decrease by 45.1 ± 5.4 days by 2096. These quantities are in the range of estimations (i.e., 33.3 ± 11.7 days and 53.9 ± 19.9 days, respectively) under an RCP8.5 concentration pathway in refs. 6, 27 which uses the lake-climate model ensemble mean in the Inter-Sectoral Impact Model Intercomparison Project phase 2b (ISIMIP2b).

Of particular interest here is the similarity in the uncertainties identified for our study and those of refs. 6, 27, as the sources of uncertainty are very different. The uncertainties derived from refs. 6, 27 represent model uncertainty stemming from a difference in parameterizations and model design. Such uncertainty can be reducible in that future model developments with improved process representation may be expected to lead to convergence of simulated model states. The uncertainty emphasized in our study, on the other hand, derives from natural variability in the climate system, and is thereby intrinsically irreducible. Viewed more broadly, our results indicate that within the context of shared community goals of improving projection skill with lakes embedded in ESMs, modeling community projections in the future can be expected to benefit substantially from future model development, but nevertheless that natural variability in the system means that uncertainty will always be an important part of projections in lake conditions.

Our findings reveal that the total stratification duration in the majority of ice-covered lakes in the Northern Hemisphere is projected to decrease. In tandem with this, the annual overturning duration is expected to increase by an average of 8 days by 2096. However, a distinct pattern emerges for lakes in the vicinity of Hudson Bay and the coastal regions of the Barents Sea and the Kara Sea, where the annual overturning duration is anticipated to decrease, yet the stratification duration will increase. Unlike other ice-covered lakes where stratification intensifies in spring and late summer, these lakes will experience heightened stratification throughout the summer, attributed to the significantly increased buoyancy flux input due to anomalous warming in these areas (refer to the second column of plots in Fig. 3 in ref. 21). It is important to note that the changes in overturning and stratification exhibit asymmetry within the annual cycle. The increase in overturning events predominantly occurs in fall, post the peak growing season for most species. Moreover, stratification extends during the growing season, yet its expansion is asymmetric at both the onset and termination. In regions experiencing rapid lake ice loss, such as around Hudson Bay, the spring advancement of stratification is projected to surpass its prolongation in fall, owing to the robust ice albedo feedback. The implications of these changes in overturning and stratification on nutrient supply and ventilation within aquatic ecosystems remain a topic for future research, particularly through the integration of biogeochemical models with physical models[30,31].

As a consequence of a lack of a universal definition of lake stratification[8,32–35], we have categorized stratification based on temperature differences between the bottom and surface layers. Using an empirical method with a single metric introduces a potential element of uncertainty to the calculation of lake stratification. Nevertheless, consistency in the change patterns of total stratification and overturning, which is defined in an objective way (full water column mixing) consolidates the robustness of our results. As a 1-dimensional thermal dynamic model, the wind-driven eddy diffusion scheme may result in an overestimation of stratification when simulating deep lakes, as discussed in our evaluation of simulated Lake Michigan water temperatures. It is important to bear these uncertainties in mind when interpreting the simulation results. While this study evaluated stratification changes driven by atmospheric factors, it is essential to acknowledge that other factors, such as water depth and transparency, can also contribute to stratification changes[36–40]. In our simulation, we employed a model by area-weighting lake properties (e.g., depth, transparency) within individual grid cells. Although this method cannot capture the within-grid variability due to variations in lake properties, it is advantageous in robustly identifying large-scale patterns of climate-induced changes. In this context, our work plays a crucial role in a "hierarchy of models" approach to evaluate and comprehend how lakes respond to climate change. To address biases stemming from the lack of resolution at critical scales, future simulations conducted with three-dimensional models[41–43] and high-resolution configuration data (e.g., transparency and bathymetry) are needed. Such endeavors fall beyond the scope of this study and will require collaborative efforts within the research community in the future[44,45]. Despite the inherent uncertainties and biases, this study provides invaluable insights into the potential future changes in Northern Hemisphere lake ecosystems, with significant implications for the ecological services provided by these lakes.

Methods

Lake model simulation

To elucidate forced changes in the phenology of lake stratification, we employed the results of the Lake, Ice, Snow, and Sediment Simulator[46] (LISSS), which is a 1-dimensional thermodynamic lake model embedded in the CESM2 earth system model[47]. This lake model is fully coupled to the atmospheric module with a 30-min integration time step and a horizontal resolution of 0.9° × 1.25°. LISSS's heat balance involves solar radiation absorption, longwave radiation exchange, and sensible/latent heat flux between the lake and atmosphere, with conduction transferring heat within layers. The model uses non-vegetated surface formulations with aerodynamic resistances for the heat fluxes calculations. It is capable of simulating vertical heat diffusion in the water column, the growth and decay of lake ice cover, and represents snow superposed on ice cover. The water mixing scheme includes wind-driven eddy diffusion, convective mixing, molecular diffusivity, and enhanced eddy diffusivity in deep lakes. The model takes the area-averaged depth of all known lakes[48] as the modeled water depth in individual grid cells and applies 10 vertical layers to represent the water column in conjunction with representing 0-5 snow layers. When ice cover is present, the wind stress driving water mixing is set to zero to eliminate wind-driven mixing beneath the ice. This adjustment does not affect the snow sublimation processes. Our simulation was conducted as part of the CESM2 large ensemble project[49], which represents the Earth system evolution over 1850–2100 CE for 100 realizations (i.e., 100 members) and is forced with an SSP370 emission scenario during the period of 2015–2100 CE (Supplementary Note 1). The range of variability of the individual members is taken to represent the range of possible outcomes of the Earth system, and the ensemble mean calculated for each timestep is taken to represent the trajectory of the forced changes in the Earth system. Thus, our simulations are particularly valuable in clarifying the role of anthropogenic-induced climate change in the seasonality changes of lake thermodynamics by deconvolving natural variability from anthropogenic signal from local to global scale.

Categorization of stratification and overturning

In this study, a water column is classified as experiencing overturning if at least one instance of full-column convection is detected within any of the 48 half-hour time steps throughout the day. This categorization is based on a diagnostic variable that tallies the number of layers affected by convection. Complementing this process-based approach, we also utilized an empirical method, as outlined by ref. 8, to assess lake water column stratification. This method relies on daily mean lake water temperatures, which are accessible within a 90-member subset of the CESM2 large ensemble project dataset.

The water column is categorized as having summer stratification when the surface is 1 °C warmer than the bottom and as having inverse stratification when the bottom is 1 °C warmer than the surface of unfrozen layers. Employing a 1 °C threshold for classifying lake stratification ensures that all days not characterized by overturning are designated as stratified, leaving no days uncategorized. We calculated the climatological mean of the annual duration of stratification (i.e., the additive duration of summer stratification and inverse winter stratification, hereafter referred to as total stratification) and overturning in 1850–1860 when anthropogenic forcing impacts on the Earth's climate are minimal and we treated this as representing the pre-industrial state. Subsequently we considered perturbations relative to the pre-industrial state for the cases where global mean surface temperature reached 1.5 °C, 3 °C, and 4.5 °C, with these warming levels being reached for the ensemble mean in 2029, 2067, and 2096, respectively.

Validation of lake simulation results

We evaluated the simulated ice phenology and lake surface temperature in the CESM2 large ensemble (2001–2020) against satellite-based observations (Supplementary Fig. S1). Since our model is embedded in a fully coupled earth climate system, that means our model does not necessarily follow the actual climate change trajectory due to natural variability of the climate system. Therefore, we evaluated our results based on the climatological mean of both simulation results and observations. We identify model skill in simulating the duration of ice cover (Supplementary Fig. S1a), the date of ice on (Supplementary Fig. S1b), and the date of ice off (Supplementary Fig. S1c) for a collection of 3102 ice-covered lakes in the Northern Hemisphere covering the period from 2001-2020 (ref. 50). The three ice phenology metrics have correlation coefficients larger than 0.9 between simulations and observations. The validation based on observed lake surface temperature in summer (i.e., July, August, and September) from 1267 ice-covered lakes in the Northern Hemisphere[51] (Supplementary Fig. S1d) also demonstrates the model's simulation skill for lake temperature during the ice-free season, with a correlation coefficient equal to 0.93 and a root mean square error of 2.2 °C for the period of 1995–2012. The LISSS model's performance is on par with the most proficient lake models featured in the ISIMIP 2b dataset (Supplementary Fig. 7 in ref. 52; ref. 53). The LISSS model demonstrates a similar level of accuracy in predicting surface and subsurface lake water temperatures (Supplementary Fig. 5 in ref. 52) when compared to, for example, the Simstrat-UoG model. The Simstrat-UoG model, which incorporates a turbulence closure scheme for lake mixing, has been validated against in-situ summer temperature observations (Supplementary Fig. 6 in ref. 52).

The LISSS model's accuracy in simulating lake temperatures throughout the year and at various depths in Lake Michigan (Supplementary Fig. S2) and Sparkling Lake (Supplementary Fig. S3) was assessed. Despite their size and depth differences, both lakes showed simulated mixing layer depths close to observations during summer. In autumn, Lake Michigan's simulated mixing layer was slightly shallower than observed, but the stratification and mixing states were accurately captured. This discrepancy might be due to the model's simplified wind-driven mixing and lack of three-dimensional processes in large lakes. Sparkling Lake's observed fall overturning was accurately simulated, as was Michigan's winter overturning from January to April. Sparkling's winter inverse stratification was also well simulated. In spring, LISSS effectively simulated Sparkling's temperature profile, while Michigan showed an earlier surface warming, leading to slightly stronger stratification in May. This could affect projections of stratification duration. Overall, LISSS accurately simulated the annual cycle of stratification and overturning in both lakes, suggesting its appropriateness for global lake stratification projections.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The dataset supporting the figures in this study is publicly accessible and can be retrieved from Zenodo at the following link: https://zenodo.org/records/14209772 (ref. 54). The outputs of CESM2-LE are available at: https://www.cesm.ucar.edu/projects/community-projects/LENS2/data-sets.html. The satellite-derived lake surface temperature (ARC-Lake v3; Merchant and MacCallum, 2018) used for the validation are accessed from https://researchdata.reading.ac.uk/186/. The satellite-derived lake ice phenology data[50] used for the validation are accessed from https://figshare.com/articles/dataset/Global_annual_lake_ice_phenological_dataset_1861-2099/19424801. The in-situ lake temperature data for Lake Michigan were obtained from the NOAA National Centers for Environmental Information Archives, with the accession ID 0190726. The in-situ lake temperature data for Sparkling Lake were obtained from the Environmental Data Initiative data portal[55].

Code availability

The analysis and visualization codes are available from https://github.com/geohuanglei/Lake_stratification_phenology and https://zenodo.org/records/14209772 (ref. 54).

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Author contributions
L.H., R.I.W., A.T. initiated the project. L.H. provided the model projections. K.R., and A.T. were instrumental in producing the large-scale simulations. L.H. led the data analysis, the design of visualizations, and the writing of the manuscript. All authors participated in discussions, revisions, and the final production of this manuscript.

Competing interests
The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Lei Huang.

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