nature portfolio

Peer Review File

Major changes in fish thermal habitat diversity in Canada’s Arctic lakes due to climate change

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

27th Sep 23

Dear Mr Gillis,

Your manuscript titled "Projected impacts of climate change on fish thermal habitat diversity in Canada’s Arctic lakes" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. In particular, we ask that you demonstrate that your results are robust when considering the landscape based on freshwater ecoregions (rather than terrestrial ecozones). Please also conduct additional model groundtruthing. Please highlight all changes in the manuscript text file.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees’ comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren’t able to submit it within this time so that we can discuss how best to proceed. If we don’t hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Michael Stukel, PhD
Editorial Board Member
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Clare Davis, PhD
Senior Editor

Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors present interesting analyses and models to estimate climate-induced changes the thermal structure of lakes in Canada's Arctic. They have maximized the use of the limited observed data for the region to validate the modelling approaches applied for different thermal metrics. This work will be of broad interest to readers because the relative pace of climate change is fastest in Arctic compared to other regions of the globe yet, the ecological implications of these changes are understudied. The content of the Gillis et al. paper is consistent with the scope of recent papers published in Communications Earth & Environment. I recommend that the manuscript is suitable for publication after major revisions.

Major suggestions:
Why terrestrial ecozones and not freshwater ecoregions? Although there is overlap between the two, the freshwater ecoregions were delineated with knowledge of freshwater fish species turnover/nestedness (and other factors) and may better ground the thermal habitat results into more meaningful biogeographic compartments. Suggest authors either: 1) summarize by fw ecoregions; 2) compare differences between t and fw in the supplemental; and/or 3) mention in methods that fw ecoregions are another landscape-level spatial boundary but was not assessed for 'X' reasons. One could argue that the terrestrial boundaries are closely tied to temperature because they reflect some of the factors that influence temperature e.g., climatic variables, landforms etc. but again, summaries of habitat change are more meaningful when they are linked to fw ecoregions that a reader can then follow-up to understand the types of fw habitats, fish communities etc.

Supplemental has 20 tables and ~31 figures. While informative and transparent, some of the tables and figures are redundant with results presented in the main body/other parts of the supplemental and may not be necessary given publication of the data to Dryad. See suggestions in document to streamline supplemental.

Discussion needs revision to focus on the results and limitations of this study and less on 'known' summaries e.g., the entire last paragraph is well-established/known. It would be stronger to end on the preceding paragraph that discusses next steps. See suggestions in document to streamline Discussion.

Minor suggestions: annotated throughout the manuscript and supplemental word documents attached to review.

Reviewer #2 (Remarks to the Author):

The authors present a thorough and highly interesting prediction of future Arctic and subarctic lake habitats under multiple climate scenarios. Arctic environments are changing rapidly but details on how these changes will affect biotic communities at a regional scale is difficult to determine due to a discrepancy between how data are collected. Biological data, species occurrence and interactions etc, are often gathered at a local level (i.e. lake or catchment specific) which makes extrapolations across sparsely populated Arctic regions highly challenging. In contrast, climate models work well at these broad regional scales but are often difficult to apply at a lake specific level due to hydro-morphological variations. Gilis and colleagues appear to have squared this circle by combining detailed climate models, with lake hydro-morphological data and fish species distribution models to develop a through prediction of future habitat suitability for fishes under different climate scenarios. This is a very exciting development which will be of interest to a wide variety of scientists.

I will admit that the analytical methods are somewhat beyond me so my will defer to a reviewer with greater experience in climate model and instead will focus on the ecologically relevant data which is included in the models. Overall, the authors are to be commended on an incredibly thorough analysis. I was initially skeptical of their ability to accurately model such a complex scenario but was reassured by a thorough description of their methods. For example, the inclusion of predicted windspeed, fetch area and storm prevalence in addition to temperature and ice cover when estimating lake stratification is encouraging and supports their findings. Further, their inclusion of fish distribution data seems appropriate. As such, my concerns are largely assuaged and I have remarkably few comments for so detailed an analysis.

My principal concern relates to ground truthing of the model predictions. The authors present a solid ground truthing of their estimated relationship between lake size and maximum depth (Fig S3), and showed reasonable accuracy when ground truthing estimates of surface water temperature at two Artic lakes. However, further ground truthing is not conducted, given the complexity of the subsequent models estimating lake stratification and thermocline depth this seems to be a weakness in the paper and should be addressed by the authors. For example, could they include a ‘leave one out’ type analysis of known lake stratification data to see how well their models reflect these known data?

This is an important paper, which will be of great interest to a wide variety of researchers. Provided the authors can verify their models as outlined above I suggest it is highly suitable for publication in this journal.

Projected impacts of climate change on fish thermal habitat diversity in Canada's Arctic lakes

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Abstract

Climate warming is a major disruptor of fish community structure globally. We use large-scale geospatial analyses of 447,079 Canadian Arctic lakes to provide ecozone-specific predictions of climate impacts on lake thermal habitat diversity. Increases in maximum surface temperature (+2.4-6.7 °C), ice-free period (+14-38 days), and thermal stratification presence (+4.2-18.9%) occur under all climate scenarios. Lakes, currently fishless due to deep winter ice, open up; many thermally uniform lakes become stratified and thermally diverse. ~~In the far north, native cold-water fish production increases, free from the threat of invasives; in the south, competition from invasive species with higher thermal preferences limit such increases.~~ Across ecozones, most lakes exhibit significant shifts in thermal habitat. The prevalence of thermally diverse lakes more than doubles, providing refuge for coldwater taxa. Ecozone-specific differences in the distribution of thermally diverse and thermally uniform lakes determine optimal strategies for adapting fish resource use to climate change.

Commented [A1]: Although this is a fair statement, these effects weren't explicitly studied in the manuscript. Suggest using limited space in abstract to add another line about thermal habitat results that reflects novelty of this work.

Main Text

Introduction

Ongoing global climate change is drastically altering ecosystems[1] – particularly those in the Arctic[2] – due to the amplification of polar warming through positive cryospheric feedback mechanisms[3]. Lakes integrate atmospheric and catchment-level inputs providing a robust indicator of the impacts of climate change[4], and the remoteness of Arctic lakes ensures that they exhibit the effects of anthropogenic climate change, relatively free from the effects of other anthropogenic stressors[5,6]. Furthermore, lake warming patterns are size-dependent: larger, shallower lakes warm throughout the water column, forming thermally uniform systems; smaller, deeper lakes stratify thermally, with the lower part of the water column remaining cold and isolated from the warmer surface waters, forming thermally diverse systems. Stratification strength is expected to increase with climate warming, particularly for deeper lakes[7]. Lake ice break-up and freeze-up are also sensitive to climate conditions with break-up generally occurring earlier and freeze-up later[8,9]. Increases in ice-free season of two to five weeks are projected by 2050, with deeper lakes experiencing the greatest delays in freeze-up date and northern lakes experiencing the greatest overall impact[9–11]. Increased lake surface water temperatures, extended ice-free seasons, and enhanced thermal stratification with climatic warming will have major impacts on lake water quality, habitat for aquatic biota, and overall ecosystem productivity[12–16].

Arctic freshwater fish communities are dominated by species belonging to the coldwater thermal guild[17]. They are an important ecological and economic resource[18], and the effects of climate warming on them will be complex[19]. Climate warming may render some waterbodies less suitable for coldwater fish production[20], while expanding or establishing new thermal resources for coldwater species in lakes which were previously unsuitable[21]. Climate change will

Commented [A2]: Mention importance for subsistence – e.g., https://www.sciencedirect.com/science/article/pii/S0301479719312526 also promote the expansion of habitat suitable for coolwater and warmwater fish species with potentially negative effects on coldwater fish production[22]. In thermally diverse communities, coldwater species will face enhanced competition from resident coolwater species, especially in small lakes where spatial resource overlap is high[23]. Expansion of cool and warmwater fish habitat will allow existing coldwater communities to be invaded by species from these guilds, again with likely negative effects on coldwater fish production. Understanding the potential effects of climate change on Arctic freshwater fisheries resources requires a comprehensive assessment of how atmospheric and catchment-level processes affect the thermal dynamics of Arctic lakes and how those changes, in turn, affect the diversity of habitats suitable for different fish thermal guilds. We provide such an assessment in this paper, focusing on (i) predicting the impacts of climate change on the seasonal progression of thermal structure in Canadian Arctic Lakes, and (ii) assessing how those impacts would change the character and diversity of the fish communities present in those lakes. To meet these objectives, we estimated the thermal structure of all Canadian Arctic lakes with surface areas > 10 ha (N = 447,079). Lake morphometry (maximum and mean depth) was estimated using GIS-based landscape methods and these estimates were ground-truthed using empirical morphometric data from 167 Arctic lakes[13]. We obtained historical (1986-2005) and potential future (Representative Concentration Pathways; RCP4.5 and RCP8.5; 2050 and 2100) climate data to predict seasonal changes in lake thermal structure resulting from projected alterations in local air temperature and wind strength using validated lake temperature and ice phenology models[10,24–28] (Figure 1, see Methods). Our projections focus particularly on how lake morphometry shapes the impacts of climate change on the diversity of thermal habitats available to support fish from different thermal guilds.

Results

Lake Temperature and Ice Projections

We show historical conditions and projected future conditions (2100, see supplementary material for 2050) under two future climate scenarios, ~~or Representative Concentration Pathways,~~ representing moderate and high greenhouse gas emissions, respectively (RCP4.5 and RCP8.5).

Significant lake warming is projected (Figure 2, Table S1). Mean maximum surface water temperatures were 14.3 °C (±3.33 SD) for the historical period, with increases of 2.6 °C under RCP4.5 and 6.6~~7~~ °C under RCP8.5 by 2100. The mean ice break-up day of year ~~to~~(183.8) during the historical period shifted 6.2 days earlier under RCP4.5 and 12.4 days earlier under RCP8.5. The mean ice freeze-up date (288.6 during the historical period) shifted 11.2 days later under RCP4.5 and 25.1 days later under RCP8.5. Accordingly, the mean ice-free season increased (from a mean of 104.6 days) by 17.6 days under RCP4.5 and 37.7 days under RCP8.5. Projected patterns of change are similar across lake size class (Table S2). The greatest changes are seen in northern ecozones, with ice-free season under RCP8.5 for the Arctic Cordillera and Northern Arctic (50 and 46 days, respectively) being approximately double that of southwesterly Taiga Cordillera and Boreal Cordillera (22 and 25 days, respectively) (Figure 3, Table S3).

Commented [A3]: Suggest removing Table S1, including some of the values in the text below. Also see other comments in Supplemental.

Commented [A4]: See note in Methods section re: ecozones

Lake Thermal Habitat Projections

We classified lakes as barren, thermally diverse, or thermally uniform for every climate change scenario: (i) barren – winter ice thickness > mean lake depth, fish cannot survive over winter; (ii) thermally diverse – thermally stratified in summer, so that deepwater refuges are provided for coldwater fish; (iii) thermally uniform – thermally mixed in summer, so that warming leads to increased vulnerability to invasion from coolwater and warmwater species. We show how climate change affects: (i) the percentage of barren lakes present in each ecozone (Figure 4), (ii) shifts in the percentage of thermally diverse vs thermally uniform lakes (Figure 5), and (iii) the relative amount of thermal habitat available for each thermal guild in those lakes deemed capable of supporting fish (Figure 6). We measure thermal habitat in volume-days[17] – this includes both the total number of days with suitable thermal habitat, and the total volume of suitable thermal habitat. See figure headings and supplementary material for methodological details.

Prevalence of thermal stratification increases under climate change. Thermally stratified lakes increase from 15.8% in the historical period, to 23.8% under RCP4.5 and more than double (+ 34.7%) under RCP8.5 (Table S4). These trends vary by ecozone, with the far north Arctic Cordillera shifting from 100% mixed lakes under all climate scenarios to the majority being stratified under RCP8.5, while the Boreal Cordillera undergoes a much less drastic shift (Table S5).

Barren and thermally uniform lakes decrease, and thermally diverse lakes increase in total number and total volume under climate change (Figures 2, 4 and 5, Tables S8 and S9). This is driven by thermally uniform lakes becoming thermally diverse (Table S10). Barren lakes predominate numerically across climate scenarios, mostly in the Northern Arctic and Southern Arctic, comprising roughly half of all lakes (45.9-52.0%). However, they make up little of the total lake volume due to their shallowness (3.9-5.2%) (Figure 4). Thermally diverse lakes account for the most volume (53-64.3%) but are scarcest numerically (14.3-21.6%) except under RCP8.5 (32.5%). This is driven by thermally diverse lakes being deeper than other lakes, hence compensating in volume for what they lack in numbers. Thermally uniform lakes are numerically

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(29.3-33.7%, aside from RCP8.5: 21.6%) and volumetrically (31.7-41.7%) in the middle. Barren lakes that shift status are typically reclassified as thermally uniform (1.8-4.9%), with some becoming thermally diverse (0.2-1.2%). More often, however, thermally uniform lakes switch to thermally diverse as they begin to stratify under climate change (4.8%-17.1%) (Table S10).

Ice-free coldwater thermal habitat in thermally diverse and thermally uniform lakes decreases across climate scenarios, whereas coolwater and warmwater habitat increases. However, trends vary across ecozones (Figure 6). Ice-free volume-days increase under climate change across ecozones, with the greatest increases being in the far north (e.g., Arctic Cordillera, Northern Arctic, 24.6-76.5% increase in ice-free volume-days). The Boreal Shield sees a marked increase in total ice-free volume-days (+28.5% RCP8.5), exhibiting one of the greatest increases in relative coolwater and warmwater thermal habitat. Ice-free volume-days for coldwater fishes decreased from 96.2% of the total ice-free thermal habitat to 84.1% (RCP4.5) and 61.1% (RCP8.5). Coolwater volume-days increased from 3.8% to 15.3% (RCP4.5) and 29.5% (RCP8.5). Warmwater habitat increased from 0% historically to 0.6% (RCP4.5) and 9.4% (RCP8.5) (Table S6). The greatest relative decrease in coldwater habitat is projected for the Taiga Shield, which shifted from 90.9% coldwater historically to 35.5% (RCP8.5) (Figure 6, Table S7). For coolwater habitat, the greatest relative increase is projected for the Southern Arctic, which shifted from 100% coldwater historically to 51.7% coolwater (RCP8.5). Lastly, warmwater habitat saw the greatest relative increase in the Boreal Plains, where it was historically absent and rose to 54.2% (RCP8.5).

Projected longer ice-free seasons under climate change increase the total amount of open-water thermal habitat in Canadian Arctic Lakes, with the supply for each lake type and thermal guild varying greatly across ecozones (Figures 6 and S1, Table S11). Overall, open-water volume-days increases (+14.4% RCP4.5, +30.3% RCP8.5), with coldwater habitat remaining almost at historical levels for RCP4.5 and dropping by 19.1% for RCP8.5. As coldwater habitat drops, we see increases in coolwater and warmwater habitat. Across scenarios, coldwater habitat remains at similar levels for thermally diverse lakes, with reductions in the south roughly balanced by gains in the north; however, there are marked increases overall in coolwater and warmwater habitat – mainly in the Taiga Plains, Taiga Shield, and Boreal Plains – where they were nearly absent historically (Figure S1C). The coldwater habitat decrease is due to thermally uniform lakes, which transition from coldwater dominant to coolwater dominant in all but the far north (Figure S1D). Coldwater habitat supply predominates and warmwater habitat is low to absent across all lake classifications under all but RCP8.5. Coldwater habitat continues to dominate for thermally diverse lakes, but thermally uniform lakes are comprised of only 45.4% coldwater under RCP8.5, with coolwater nearly taking over. Furthermore, under RCP8.5, warmwater habitat rises from ~ 0% to 9.4% of the total.

Discussion

We assessed the effects of potential future climate change on Arctic lakes and foreseeable effects on fish species of different thermal guilds under two future scenarios. We showed that the proportion of thermally diverse lakes increases under climate change, and coldwater habitat supply is projected to be resilient. Under all climate scenarios, however, thermally diverse lakes shift from providing almost exclusively coldwater habitat to additional coolwater habitat and previously absent warmwater habitat. These changes may make these lakes habitable to larger populations of coolwater ~~species~~ and ~~invasive~~ warmwater species[29]; should they be introduced or naturally expand to these systems through connected waterways. ~~This could increase indirect~~

Commented [A6]: Remove, not needed and known, competition, predation etc.

competition and overall resource use to the detriment of local coldwater species[30]. Furthermore, although thermally uniform lakes decrease in prevalence under climate change, they too will become more favourable to coolwater and warmwater species, becoming habitable corridors for southerly species to access warming northern lakes[31]. Overall, barren lakes decrease in prevalence under climate change as ice thickness lessens, tending to become thermally uniform more often than thermally diverse, which may create opportunities for fish species to colonize and establish in these lakes. These previously absent limnetic resources may become breeding grounds for coolwater and warmwater invaders[13].

Commented [A7]: They most likely will become habitat for nearby coldwater species first. Consider removing.

Our projections of Arctic lakes' thermal structure generally align with global lake projections over the 21st century. We projected Arctic lakes to gain 37.7 ice-free days by 2100 under RCP8.5 (Table S1), which is close to the projected average of 40 days for lakes in the Northern Hemisphere by Grant et al. (2021)[32]. Our projection of maximum surface water temperature under RCP8.5 was higher (an increase of 6.7 °C, Table S1) compared to the global average of 4 °C projected by Grant et al. (2021)[32], which is consistent with the global trend that ice-covered lakes are warming more rapidly than lakes without seasonal ice-cover[33].

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The projected effects of climate change on inland fishes are well-documented and show an unfavourable trend for coldwater species, but most of this work focuses on intensively studied regions south of the Arctic[34,35]. Subsistence fisheries for anadromous Arctic charr (*Salvelinus alpinus*) in Nunavut are important to local communities and their sustainability may hinge on the severity of climate change and changes in community composition through invasive species from the south[36,37]. We show here a much-needed estimate of the historical state of thermal habitat supply in Arctic lakes, providing a reference point for future studies of this much-imperilled region. Range shifts of Arctic fish species are already well-documented in the marine

~~environment[38], and it follows that freshwater species are shifting their ranges[13].~~ The limited connectivity of the Arctic hydrological network, however, promotes the diversity of Arctic fishes[31], and thus it is important to consider whether suitable thermal habitat supply is present even in small lakes, as we have shown here. ~~The presence of open-water suitable thermal habitat is important for the ongoing productivity of fish species[17].~~ Fish community productivity in Canada's Arctic lakes is greater than predicted by species-energy theory, highlighting the notion that these habitats may serve as important refugia for coldwater fishes under climate change as their southern range limits become more stressed[39,40].

Commented [A9]: Not sure "promotes" is the correct word perhaps "maintains"

Commented [A10]: Obvious, does not need to be stated.

Policy development and decision-making regarding the protection and restoration of Arctic lakes can be informed by conceptual models weighing the projected effects of climate change – as estimated in our study – and potential future watershed disturbance[41]. With a focus on native coldwater species, true "refuge" lakes would include lakes projected to be thermally diverse, or those that under climate change, will retain suitable thermal habitat[41]. ~~Different management strategies are more applicable for thermally uniform lakes, depending on their coldwater habitat availability under climate change.~~ Thermally uniform lakes that retain ample coldwater habitat ~~under climate change~~ may be suitable candidates for protection that limits ~~, as increased~~ watershed development, which may render them no longer suitable for these species[41]. ~~Thermally uniform lakes that become marginally suitable for coldwater taxa under climate change, however, could be candidates for restoration, as reduced watershed disturbance could make them suitable[41].~~ In cases where thermally uniform lakes become unsuitable for coldwater fish under climate change even with reduced watershed development, these will likely develop into new fish communities of coolwater and possibly warmwater species in the most southern lakes[41]. Informing management decisions based on lake ecosystem resilience and how lakes

Commented [A11]: Policy, decision-making and management paragraphs can be more concisely written to allow room to discuss limitations/considerations of this approach paragraph.

Commented [A12]: Don't think this sentence is necessary given relative level of watershed disturbance in Arctic regions vs southern Canada could respond to multiple stressors allows for the prioritization of conservation actions to maintain critical habitat for coldwater fish species. This framework must consider the context of the Arctic environment in terms of restoration being targeted to limit direct anthropogenic effects and recognizing the shifting permafrost environment's role in the development of effective habitat enhancements. Access, cost, and logistical challenges will dictate the feasibility of these efforts.

Management implications vary because of the differential regional responses to climate change shown here. The projected increase in thermal diversity is greatest in the far north, specifically the Arctic Cordillera and Northern Arctic yet, the persistence of coldwater habitats (Figure 5); however, coldwater thermal habitat continues to dominate these regions (Figure 6). This offers the possibility suggests that productivity may increase among existing – or newly established – coldwater fish communities[13] via . These systems would provide warmer but accessible surface waters with longer growing seasons for coldwater taxa and littleno chance of invasion from far away coolwater and warmwater fish species from the south, as it is still too cold for them and far away from source invasive populations[42]. Management implications in the far north therefore would be to explore potential increases in sustainable harvests as conditions change. This possibility becomes muted further south: the Southern Arctic ecozone provides roughly half coolwater and half coldwater habitat under RCP8.5 (Figure 6) and hence is vulnerable to coolwater taxa invasions with possibly negative consequences for coldwater fish production[27]. Thermal diversity remains at similar levels under RCP8.5 in the central south ecozones of the Taiga Plains, Taiga Shield, and Boreal Plains (Figure 5); however, the loss of coldwater habitat and increase in coolwater and warmwater is the greatest here (Figure 6). Therefore, the threat to coldwater fish production in these regions is greatest because the opportunities for coldwater fish production offered by higher productivity in warming surface waters is countered by the prospect of those waters becoming too warm for efficient access by coldwater fish[43]. Waters that become essentially too warm for use by coldwater fish may permit successful invasion by species belonging to coolwater and warmwater guilds. This possibility is accentuated by the geographical proximity of source populations in the south, and the hydrological invasion route offered by the Mackenzie River Basin through the Taiga Plains ecozone[44]. Management implications in these regions should focus on vigilant monitoring and regulation of introductions of coolwater and warmwater fish species. If invasions do occur, there may be little chance of coldwater communities persisting in warming thermally uniform lakes, whereas thermally diverse lakes are likelier to sustain these species and therefore should be considered for protection. The southwesterly Taiga Cordillera and Boreal Cordillera maintain a high degree of thermal diversity (Figure 5) and small – though present – increases in coolwater and warmwater habitat (Figure 6). In these regions, careful attention and monitoring efforts should be put towards identifying potential establishment points for invaders from the south.

Important issues to consider in future assessments of Arctic freshwater fish diversity include: (i) the role of under-ice winter conditions in shaping oxygen deficits and other factors that could limit population establishment and persistence; (ii) changes in the distribution of freshwater across the Arctic landscape due to permafrost melt and subsequent slumping and drainage; (iii) assessing impacts on thermal diversity within the coldwater guild, paying particular attention to species with thermal preferences below 10 °C (the “Arctic guild”)[45]; (iv) assessing the role of new technologies (e.g., environmental DNA) in designing effective and efficient surveys designed to monitor ongoing impacts. We discuss these issues in the supplementary material.

Winter phenology and taxon-specific winter physiological strategies play a vital role in shaping the zoogeographic boundaries of fish species[46]. The establishment of new fish communities in the Arctic will lead to novel interactions through range expansion, shifts, and contractions for warmwater, coolwater, and coldwater fish species, respectively. This may exacerbate the vulnerability of native coldwater fish species to climate change[35]. Since overall impacts on native coldwater fish taxa will stem from both the direct effects of climate change and the indirect effects of invasives, improved forecasts of future change will hinge on developing a greater understanding of how climate will promote and shape the novel interactions that will arise between native coldwater specie and southerly invaders.

Commented [A13]: Suggest removing this paragraph as is known and adds little to the message of this paper. Instead, it would be good to have a paragraph before the "Important issues" paragraph dedicated to the limitations of this approach e.g., what are the implications of a RMSE 2.4? what are the implications of averaging the TMAX and SWT e.g., temp variability missing https://royalsocietypublishing.org/doi/full/10.1098/rspb.2013.2612, etc.

Methods

Overview of the Methods Used in This Paper

Commented [A14]: Flow and descriptions of methods are good

The following is an overview of the methods that we used in this paper. Each paragraph has an accompanying sub-section within the Methods section that provides more details. To develop the approach used in this paper, we applied both empirical and semi-mechanistic methods to build the set of predictive models needed to fulfill our primary objective: (i) predicting the impacts of climate change on the seasonal progression of thermal structure in Canadian Arctic lakes: and (ii) assessing how those impacts would change the character and diversity of the fish communities resident in those lakes[23,35]. A summary of issues addressed, and methods used follows:

(i) *Ground-Truthing Lake Morphometry*. Lake shape is a primary determinant of lake thermal structure. We used the GIS-based estimates of Canadian Arctic lake morphometry as the basis for our study, hereafter the "Arctic GIS lake database"[13]. Our Arctic GIS lake database provides the basic information (lake area, mean depth, maximum depth) needed to characterize lake shape[13]. We confirmed the accuracy of those estimates by comparing them to an empirical database of 167 Arctic lakes obtained from a variety of sources (see 'Ground-Truthing Lake Morphometry' section below) with morphometrics directly measured from field surveys.

(ii) *Lake-Specific Predictions of Ice Cover Phenology and Maximum Surface Water Temperature*. These are two of the primary elements determining the seasonal pattern of a lake's thermal structure. We mobilized published empirical models to predict the impacts of climate change on these characteristics of Arctic lakes.

(iii) *Lake-Specific Predictions of Thermal Stratification Patterns*. Gorham and Boyce (1989) developed a semi-mechanistic model linking the character of summer thermal stratification in lakes to the following lake-specific characteristics: the density difference between surface and bottom waters in mid-summer, summer wind strength, and lake fetch[24]. Gillis et al. (2021) successfully used this model to predict the presence or absence of seasonal lake thermal stratification[26]. We mobilized various sets of empirical data to ground-truth this model for our set of Arctic lakes. We then used it, along with our other models, to forecast the impacts of climate change on:

- which lakes remain completely frozen through the winter period and hence cannot support a self-sustaining fish community;
- lakes with winter surface ice only and hence having the potential to support self-sustaining fish communities we identify which lakes:
    1. do not stratify during the summer open-water period and hence provide a single, thermally uniform habitat to support their resident fish communities;
    2. stratify into warm surface and cold bottom regions and hence provide a set of thermally diverse habitats to support their resident fish communities.

(iv) *Regional Predictions of the Impact of Climate Change on Stratification Patterns in Canadian Arctic Lakes*. We accessed spatially explicit datasets for historical climate and projected changes in climate for 2050 and 2100 under RCP4.5 and RCP8.5 emission scenarios using historical and future climate data for each lake from the Government of Canada's climate data extraction tool[28] to generate historical and future climate conditions for each lake in our Arctic GIS data base. Using these climate conditions and lake-specific morphometric data as input to the models described above, we estimated historical and future seasonal patterns of thermal structuring for each lake. We then summarized these projected changes across all lakes in each of the 8 terrestrial ecozones comprising the Canadian Arctic region.

Commented [A15]: Why terrestrial ecozones and not freshwater ecoregions? Although there is overlap between the two, the freshwater ecoregions were delineated with knowledge of freshwater fish species turnover/nestedness (and other factors) and may better ground the thermal habitat results into more meaningful biogeographic compartments. Suggest authors either: 1) summarize by fw ecoregions; 2) compare differences between t and fw in the supplemental; and/or 3) mention in methods that fw ecoregions are another landscape-level spatial boundary but was not assessed for 'X' reasons. One could argue that the terrestrial boundaries are closely tied to temperature because they reflect some of the factors that influence temperature e.g., climatic variables, landforms etc. but again, summaries of habitat change are more meaningful when they are linked to fw ecoregions that a reader can then follow to understand the types of fw habitats, fish communities within each etc.

(v) *Regional Predictions of the Impact of Climate Change on Fish Habitat Diversity in Canadian Arctic Lakes*. North American limnetic fish species can be classified into three thermal guilds (cold, cool, warm) based on their thermal preferences. We used the historical and projected future patterns of thermal structuring for each lake in our Arctic data base to generate annual, lake-specific estimates of the supply (the volume-days: m^3 days) of habitat suitable by thermal guild. We then summarized projected changes in suitable thermal habitat supply across all the lakes found in each of the eight Canadian Arctic terrestrial ecozones.

Ground-Truthing Lake Morphometry

We assembled a morphometry database of 167 lakes with measured values for surface area, mean depth, and maximum depth. Sources were the Canadian lake surface water temperature database[27], the Fisheries and Oceans Canada Fishout database[39], Canadian Arctic lake trout (*Salvelinus namaycush*) lakes[13], Cumulative Impact Monitoring Program (CIMP) lakes (pers. comm. Dr. Alyssa Murdoch, York University), and the CLAM database[47] (Figure S2). We used these data to assess the accuracy of the morphometry estimates contained within the Arctic GIS lake database. In the Arctic GIS lake database, GIS landscape layers were used to estimate the mean and maximum depth for each lake identified in the landscape layer[13]. This process was done as follows:

- the local land gradients around the edge of each lake were estimated;
- these gradients were extrapolated from the lake edge inward, generating an estimated shape for the lake basin;
- mean and maximum depth for the lake were calculated from this estimated basin shape.

Commented [A16]: Mention if land gradients were derived from a DEM, and cite DEM source

Given that the relationship between mean and maximum depth reflects the basic geometry of a typical lake then, if the algorithms used in generating mean and maximum depth for the Arctic GIS lake database are reliable, we would expect good correspondence between the mean-maximum depth relationship evident in our 167 directly measured Arctic lakes and the relationship evident in the Arctic GIS lake database. When compared, good correspondence between these two relationships was evident (Figure S3). Since the estimate of basin shape used to estimate mean and maximum depth for the Arctic GIS lake database was derived directly from the local land gradients surrounding the lake, it is reasonable to conclude that validation of the mean-maximum depth relationship is also an indirect validation of the relationships linking lake area to mean depth and maximum depth. Unlike the mean-maximum depth relation, these relationships with lake area are very sensitive to the sampling scheme used to select the lakes for direct measurement. Most lakes in our direct measurement database were chosen because of the known presence of self-sustaining fish populations. ~~Since~~ Because this requires that lakes be deep enough to not freeze to the bottom over winter, we would expect that, at any given lake area, shallow lakes would be under-represented in our directly measured database. This expectation is confirmed by comparing the one data set that was compiled without foreknowledge of fish presence (50 lakes in the CIMP data set, pers. comm. Dr. Alyssa Murdoch, York University) with the data in the remaining 117 lakes in the directly measured database (Figure S4).

Given this result, we would expect that the maximum depth-area relationship in the Arctic GIS lake database would exhibit a similar tendency for shallower lakes to be more common at any given depth than is found in the directly measured database and this expectation was met (Figure S5).

Commented [A17]: 'since' typically associated with time suggest changing to because where appropriate throughout

Lake-Specific Predictions of Ice Cover Phenology

We used empirical lake ice break-up, freeze-up, and thickness models to predict ice cover phenology[10,48] (Table S12). The ice models were derived by relating *in situ* observations of ice phenology and ice thickness for hundreds of Canadian lakes to climate and lake-specific variables through linear regression equations.

The ice break-up model takes the following form:

$$BU = 175.829 + 1.127 \times J_{\mathrm{SPR0}} - 2.945 \times ANG_{\mathrm{SPR0}} + 0.0009 \times SA + 0.491 \times LONG + 0.017 \times EL$$

Where:

BU = ice break-up (day of year)

J_{SPR0} = day of year following the last spring day when the 30-day running mean daily air temperature <0 °C

ANG_{SPR0} = angular elevation of the sun above the horizon at noon on J_{SPR0}

SA = surface area (km^2)

$LONG$ = longitude (decimal degrees)

EL = elevation (m)

The ice freeze-up model takes the following form:

$$FU = 58.092 + 0.830 \times J_{\mathrm{AUT0}} + 7.293 \times Z_{\mathrm{MEAN}}^{0.5} + 0.944 \times T_{\mathrm{AUT0}}$$

Where:

FU = ice break-up (day of year)

J_{AUT0} = day of year following the last fall day when the 30-day running mean daily air temperature >0 °C

Z_{MEAN} = mean depth (m)

T_{AUT0} = mean air temperature for the three-month period where the central month contains J_{AUT0}.

The ice thickness model takes the following form:

$$\ln THK = -3.968 + 0.801 \times \ln IC + 1.103 \times \ln LAT + 0.224/2$$

Where:

$\ln THK$ = the natural logarithm of ice thickness (cm) (reported as m in results to compare with lake depth)

$\ln IC$ = the natural logarithm of ice cover, found by subtracting ice-free days from 365 (ice-free = ice freeze-up – ice break-up) (days)

$\ln LAT$ = the natural logarithm of latitude (decimal degrees)

0.224/2 = root mean square error from the model used for bias corrections in predictions.

Specific ice thickness values are not central to our results compared to other metrics of thermal structure (e.g., ice-free days, lake temperature), but the general trend is important to determine which lakes are considered to have the potential to host fish populations (i.e., is ice thickness > mean depth?). We compared our projections to published projections for the Northern Hemisphere, with the expectation that our projected decreases in ice thickness would be greater ~~since~~ because climate change is expected to particularly impact Arctic ecosystems[2]. We projected lake ice thickness to decrease by 0.21 m (SD = 0.22) on average by 2100 under RCP8.5, which is similar, but slightly higher than the projected average decrease of 0.17 m for the Northern Hemisphere and aligns with our expectation[32].

Lake-Specific Predictions of Maximum Surface Water Temperature

We combined two empirical models in our forecasts of maximum surface water temperature: the T_{MAX} model of Gillis et al. (2021) and the *SWT* model of Sharma et al. (2007)[26,27] (Table S12). The Gillis T_{MAX} model was based on the assumption that the maximum summer water temperature for a lake could be estimated by:

(i) fitting a triangular function to the spring-fall time series of daily surface water temperatures

(ii) estimating the maximum summer temperature (T_{MAX}) as the peak of the fitted function.

The model's training dataset comprised 240 North American lakes, ranging in latitude from 43 – 69° N, each providing a year and lake-specific estimate of T_{MAX}[26].

The T_{MAX} model takes the following form:

$$T_{\mathrm{MAX}} = 9.743 - 0.230 \times \ln SA - 0.0007 \times EL + 0.996 \times T_{\mathrm{JJA}} - 0.003 \times P_{\mathrm{AUG}} + 0.010 \times CR_{\mathrm{JUL}} - 0.362 \times W_{\mathrm{JUL}}$$

Where:

ln *SA* = the natural logarithm of lake surface area (m^2)

EL = elevation (m)

T_{JJA} = mean June, July, and August air temperature (°C)

P_{AUG} = August precipitation (mm)

CR_{JUL} = Cloud-corrected July solar radiation (W m^{-2})

W_{JUL} =July wind mean wind speed (m s^{-1})

The Sharma *SWT* model was based on the assumption that the spring-fall time series of daily surface water temperatures follow a parabolic curve, with the maximum temperature (*SWT*) occurring at the peak of the parabola. The training dataset used to define this model comprised 2381 North American lakes, ranging in latitude from 42 – 82° N[27].

The *SWT* model takes the following form:

$$SWT = -57.88 + 0.79 \times T_{JUL} + 0.26 \times T_{\mathrm{ANN}} - 0.00151 \times (J)^2 + 0.617 \times J - 0.019 \times LONG + \beta$$

Where:

T_{JUL} = mean July air temperature (°C)

T_{ANN} = mean annual air temperature (°C)

J = the day of year when the maximum surface temperature typically occurs, set at 204 for all lakes

LONG = longitude (decimal degrees)

β = a measure of inter-annual variability, set to zero in our study

We compared the projected values for maximum summer surface temperature from these two models across climate scenarios and found that the T_{MAX} estimates were systematically higher than *SWT* (mean ≈ 3.8 °C, SD ≈ 0.43 °C). This was expected given the difference in how the two methods represent the seasonal time series of surface water temperatures – the triangular function would inevitably yield a higher estimate than the parabolic function. We generated

T_{MAX} and *SWT* estimates for each lake and then used the average of these two estimates in all our subsequent projections. This model average technique is sufficient for our study given that relative water temperatures across the landscape is more important than absolutely water temperatures for specific lakes for our analyses to address our objectives.

We did not incorporate in our modelling with the *SWT* equation any of the mean deviations included for each Canadian territory (and province) in Table 4 of Sharma et al. 2007[27]. We used the base model in that study for all estimates. The mean deviations, although they do provide use in some circumstances, are broken down by territory and province and do not reflect physical geographic subdivisions (e.g., ecozones). Given that our study is focused on the regional variation in lake thermal habitat changes and that we used ecozone as our geographic classification system, we decided to refrain from incorporating this into our analyses. Future studies could assess the geographic variation of the results that the *SWT* equation produces on an ecozone level with the goal of producing more accurate predictions of Arctic lake temperatures.

We ground-truthed open-water daily lake surface water temperatures and maximum seasonal surface water temperature with two Arctic Lakes: Alexie Lake (62.68° N, -114.08° W) and Vital Lake (62.61° N, -114.44° W). Data was sourced from Campana et al. 2020 and was collected in 2013 over 135 and 122 days for Alexie and Vital, respectively[13]. See Figure S6 for an illustration of the lake data and our modelling results. T_{MAX} produced a root mean squared error (RMSE) of 2.78 °C (Vital RMSE = 2.86 °C, Alexis RMSE = 2.71 °C), and correlation (r) between predicted and observed was 0.802. *SWT* produced a root mean squared error (RMSE) of 2.52 °C (Vital RMSE = 2.09 °C, Alexis RMSE = 2.86 °C), and correlation (r) between predicted and observed was 0.877. The observed maximum lake surface water temperature for Alexie was

22.0 °C. T_{MAX} predicted a value of 23.1 °C (+1.1 °C observed) and *SWT* predicted 18.1 °C (-3.9 °C observed). The observed maximum lake surface water temperature for Vital was 22.8 °C. T_{MAX} predicted a value of 23.5 °C (+0.7 °C observed) and *SWT* predicted 18.1 °C (-4.7 °C observed). The T_{MAX} model more accurately predicted the peak surface water temperature for these lakes during this year. The *SWT* model more accurately predicted the seasonal range of temperatures as it produced a slightly lower RMSE for the whole year. It is not surprising that the T_{MAX} overestimated the maximum temperature and *SWT* underestimated it as the T_{MAX} model produces a linear seasonal rise and fall, whereas *SWT* produced a parabolic curve. Overall, these results are in line with the results obtained in the studies that developed these models as well as other studies that generated lake temperature predictions across a large landscape[26,27,49,50]. These results suggests that the modelling approach we employed produces reasonable estimates for the purposes of our study. Future research could investigate the potential for additional model testing and refinement with the use of additional high resolution monitoring data.

Lake-Specific Predictions of Stratification and Thermocline Depth

Historical and Future Climate Data

To drive our limnological projections, we obtained historical (1986-2005) and future (2006-2100) climate data for each lake from the Government of Canada's climate data extraction tool[28]. We assessed the future years of 2050 and 2100 for RCP4.5 and RCP8.5. These RCPs represent greenhouse gas concentration trajectories adopted by the Intergovernmental Panel on Climate Change. Depending on the volume of future greenhouse gas emissions, RCP4.5 and RCP8.5 correspond to the radiative forcing values in 2100 (W m^{-2}). Under RCP4.5, emissions peak around 2040 and then decline, whereas, for RCP8.5, emissions continue rising throughout the 21st century[51]. For simplicity, in our figures, we only show the historical scenario along with RCP4.5 and RCP8.5 for 2100 (omitting 2050), given that under 4.5 the results show similar climates for 2050 and 2100, due to 4.5 stabilizing around the mid-21st century[51].

For mean monthly air temperature data and total monthly precipitation, we accessed the tool's statistically downscaled climate scenarios dataset (10 km resolution), based on the Coupled Model Intercomparison Project Phase 5 (CMIP5), which includes 24 climate models with equal model weighting[28]. For mean monthly wind speed, we accessed the tool's Global climate model scenarios dataset (1×1° grid resolution), which is also based on CMIP5, and 29 climate models with equal weighting[28]. The climate data extraction tool's map projection is the World Geodesic System 1984 (EPSG:4326).

We estimated hourly global clear sky ground-level solar radiation (W m^{-2}) for each lake according to published procedures and using their recommended air transmission coefficients for every location, then summarizing the hourly radiation values as monthly means[52]. Next, we used an empirical model to adjust the monthly mean radiation values for location-specific cloud cover[53]. Cloud cover data for the reference period was obtained from the Climatic Research Unit's 0.5×0.5° geographic resolution climate dataset[54].

Coordinates of lakes occurring in coastal areas sometimes fell outside the grid cell data range (~0.2% of lakes). For these lakes, we used the mean climate measure for the respective period and climate scenario based on the finest available mean value for lakes in the same National Topographic System (NTS) grid cell.

The Gorham-Boyce Equation as the Foundation of Our Approach

Gorham and Boyce (1989) present a simple semi-mechanistic model that links climatological variables with the physical theory of mixed layer formation to predict, for a particular lake[24]:

- if the lake stratifies or not
- if the lake does stratify, its thermocline depth (*h*)

Their model is based on the following equations (Table S12):

$$H \cong 3.4\left(\frac{\tau}{\mathrm{g}\Delta\rho}\right)^{0.5} L^{0.5}$$

and

$$h = \frac{CRIT_{\mathrm{MIX}}}{1.7}$$

Where:

h = lake thermocline depth

τ = wind stress associated with summer storms (i.e., stress associated with the maximum sustained wind strength likely to be experienced by the lake during summer)

$\Delta\rho$ = density difference between epilimnion and hypolimnion at the time of maximum heat content

L = maximum lake length

g = gravitational acceleration

H = critical mixing depth

If the lake's maximum depth is ≤ H, then it will not stratify. If the lake's maximum depth > H, then it will stratify with a thermocline depth = h. These equations identify the contending climatic forces that determine the pattern of stratification in a lake of given morphometry (i.e., fixed L): through τ, higher winds drive both the critical mixing depth and consequent thermocline depth deeper; through $\Delta\rho$, higher summer temperatures drive the critical mixing depth, and consequent thermocline depth, shallower. The Gorham-Boyce approach is flexible and has recently been applied to describe a novel thermal categorization of ice-covered lakes[55].

The Gorham-Boyce approach applies to lakes with a cross-basin diameter < 5000 m. The Arctic GIS lake database comprises 98% of lakes with maximum length values < 5000 m. We set the upper limit of thermocline depth at 20 m based on previous studies, which limits the impact of lake length on thermocline depth beyond 5000 m[24,56].

These equations also require that, among lakes that stratify at a given fetch, the maximum depth will be ≥ 1.7 × thermocline depth. We submitted this expectation to an empirical test as described below.

Hanna (1990) provides the most extensive empirical description of the relationship between lake fetch and thermocline depth[57]. The equation produced by Hanna (1990) takes the following form:

$$\ln h = 0.336 \times \ln MEL - 0.245$$

Where:

ln h = the natural logarithm of lake thermocline depth (m) ln *MEL* = the natural logarithm of maximum effective lake length, taken as maximum lake length (*L*) in our study (m)

The green line in Figure S7 is the Hanna relationship multiplied by 1.7 and the blue dots provide the maximum depth-fetch relationship for lakes that consistently stratify (152 lakes in the first figure of Gorham and Boyce 1989)[24]. If the maximum depth is ≥ 1.7 × thermocline depth (as required by the Gorham-Boyce equations) then the green line should define a clean lower bound for the maximum depth data and Figure S7 confirms this expectation. This result provides support for our use of the Gorham-Boyce semi-mechanistic structure as the foundation for our projections. In what follows, we will refer to this 'bounding' relationship (as defined by applying the Gorham-Boyce equations to Hanna's empirical result) as the 'Hanna Line'.

The Gorham-Boyce equations identify the lake-specific elements needed to predict *h* and *H*:

- the water density difference between epilimnetic and hypolimnetic waters at the time of maximum heat content,
- the summer wind regime,
- lake fetch.

The following sections describe how we estimated lake-specific values for the density difference and summer wind regime.

Predicting the Density Difference Between Epilimnion and Hypolimnion

The first table in Gorham and Boyce (1989) (hereafter GBT1) summarizes data on the temperature difference between epilimnion and hypolimnion at the time of maximum heat content for 166 lakes that consistently stratify[24]. These lakes are in North America (n = 109), Europe (n = 23), and Japan (n = 34). Individual values in the table represent values for a single lake, with some lakes identified specifically by name. Where there are many lakes located in a relatively restricted geographic area, values for the smallest and largest (by area) lakes are provided. These lakes are not named specifically. The group in GBT1 labelled mid-NA contains 67 lakes, but some of the lakes in the other groups are included in this group, specifically the Laurentian Great Lakes. However, the smallest lake (surface area = 1.7 ha) is not part of any of the other groups. We used the data in this table to develop a simple regression model for predicting the hypolimnetic and epilimnetic density difference typical of lakes that consistently stratify. There were 22 individual lakes (omitting the Laurentian Great Lakes) identifiable in GBT1, ranging in area from 0.4-64,770 ha (median = 289 ha). We chose these lakes for our analysis of the drivers of the hypolimnetic and epilimnetic density differences. We omitted the Laurentian Great Lakes because of the huge discrepancy in area and volume between these systems and all the other lakes in GBT1. We converted the temperature differences recorded in GBT1 to density differences. We used multiple regression analysis, filtering results using the AIC criterion, to arrive at the following usable (adjusted R^2 = 0.95, n = 22) model for predicting, from known lake variables, the difference in density between hypolimnetic (*HYPO*) and epilimnetic (*EPI*) waters at the time of maximum heat content (Table S12):

$$[HYPO - EPI] = -2.11264 + 0.20607 \times T_{\mathrm{EPI}} - 0.00487 \times [T_{\mathrm{EPI}} \times \log_{10} L]$$

Where:

$[HYPO - EPI]$ = the density difference at the time of maximum lake heat content (g cm^{-3})

T_{EPI} = epilimnetic temperature (°C) at the time of maximum lake heat content

$\log_{10} L$ = $\log_{10}$ lake maximum length, or fetch (m)

In using this model for predicting the density differences for the lakes in the Arctic GIS lake database, we set T_{EPI} = the mean of the T_{MAX} and *SWT* models for maximum surface water temperature. In addition, we used these estimates of maximum surface temperature and density difference to estimate the hypolimnetic temperature.

Predicting Summer Storm Intensity

With both lake fetch and density difference given, the Gorham-Boyce equations predict that H will increase with increases in the wind strength of 'typical' summer storms. An overall increase in H will be accompanied by a drop in the % of lakes in a region that will stratify, and a parallel increase in the thermocline depths (h) of those lakes that still stratify. Our approach to characterizing the strength of summer windstorms proceeded in several steps:

(i) we characterized the historical pattern of summer wind strength variation, typical of our Arctic study area;

(ii) we defined a representative sample of our 447,079 Arctic lakes, containing ~2% (9623 lakes) of the total;

(iii) we used this representative sample of Arctic lakes and the historical pattern of Arctic wind strength variation to determine if there was a typical value for the strength of a summer windstorm that would position the distribution of maximum depth for stratified lakes so that it is was bounded below by the Hanna Line, as illustrated in Figure S7.

Characterizing the Historical Pattern of Summer Wind Strength Variation in the Canadian Arctic

We selected a representative set of Arctic locations as follows:

- for lakes in the Arctic GIS lake database north of 60° N latitude, we calculated the 25^{th}, 50^{th}, and 75^{th} percentiles of latitudes (63.23, 65.82, and 68.38° N) and longitudes (-113.69, -104.25, and -93.01° W);

- we used these points to define a rectangular grid made of nine representative locations that we confirmed were located on land;
- we then identified 12 sites in the neighbourhood of each of these 9 representative locations and used the Government of Canada's Wind Atlas climate tool (www.windatlas.ca) to derive summer wind speed distributions for each of these locations.

The Government of Canada's Wind Atlas climate tool (www.windatlas.ca) gives wind speeds at 10-minute intervals (at 80 m height) throughout June, July, and August; the speeds given are for the years 2008-2010. We adjusted the wind speed at 80 m height to 10 m – the value required for the lake thermal habitat modelling (e.g., Wuest and Lorke 2003) – using the formula provided by Hsu et al. (1994)[58]:

$$U_{10} = U_z \left(\frac{10}{z}\right)^{0.11}$$

where U_z equals the wind measured at height z above the lake's surface.

We analyzed mean wind speeds at three time scales (1, 8, and 24 hours) by fitting a Weibull distribution (see Conradsen et al. (1984) for the relevance of the Weibull distribution as a descriptor of variation in wind strength[59]) to the vector of summer wind speeds (June, July, August) for each site for the 3 summers (2008 to 2010) provided by the Wind Atlas. Summarizing across locations, we found that the value of the Weibull shape parameter (β) increased with time scale (Table S13) but that there was no systematic variation with either latitude or longitude. We assumed that:

- the 1-hour wind speed distribution was the most relevant for estimating H;

- the median value for the 1-hour shape parameter ($\beta = 2.338$) was a reasonable approximation of this parameter for all sites;
- this parameter would be insensitive to changes in climate.

With β fixed, the scale parameter (η) of the Weibull distribution can be easily estimated if the mean wind speed is known. Since mean wind speeds are provided in the projections of historical and future climatic conditions that we use in this study[28], we were able to use these projected mean values and our fixed value for β to estimate future changes in the Weibull distribution for summer wind strength values.

Defining a Representative Sample of the Lakes in Our Arctic GIS Lake Database

We defined a manageable sample of our 447,079 lakes that we could use in a series of simulations designed to determine if there was a single summer windstorm strength measure that would replicate the bounding relationship in Figure S7 for lakes that the Gorham-Boyce model predicts would stratify. We set our sample size at 2% (9623 lakes) of the total number of lakes ($N = 481,784$) in our Arctic GIS lake database. We believe that this sample size is large enough to be representative yet still small enough to allow for logistically feasible simulation times. We used the *slice_sample* function from the R package 'dplyr', parameterized to ensure that the resultant sub-sample of lakes was representative of each ecozone and lake size class in the entire database[60]. We then used this subsample of lakes to simulate how increases in summer wind strength affect the distribution of maximum depth among stratified lakes, given the Gorham-Boyce equations and lake-specific values for:

- fetch,
- epilimnetic and hypolimnetic density difference,

- the location-specific Weibull distribution for summer 1-hour wind strength.

Simulating the Effects of Increasing Summer Storm Strength on the Expected Distribution of Maximum Depth Among Stratified Lakes Under Historical Climatic Conditions

Given the historical value for mean summer wind speed for each lake, we conducted successive simulations at progressively higher levels for storm wind speed until we identified a level that would replicate, in our sample of 9623 lakes, the bounding relationship in Figure S7 for lakes that consistently stratify. We assumed that the local temporal variation in 1-hour summer wind speed was described by a Weibull distribution defined by the local mean wind speed and the shape parameter (β = 2.338) that we determined (see section above) to be typical of sites in our study area. We defined summer storm wind speed as that defined by a fixed percentile value for the cumulative distribution (CD) of this local Weibull function. The same percentile value was applied to all lakes in a particular simulation and each simulation was then characterized by a progressively higher value for this fixed CD percentile. We used this procedure to identify the single percentile value that positioned the simulated maximum depth distribution for stratified lakes so that it was bounded below by the Hanna Line, as illustrated in Figure S7. We used the following formal bounding procedure to do this:

(i) for each simulation, we used quantile regression to estimate the relationship between the first quantile of the maximum depth distribution of stratified lakes and fetch;

(ii) we compare this relationship with the maximum depth/fetch relationship defined by the Hanna Line;

(iii) we declared bounding as successful when the two relationships overlapped.

We found that a match with the Hanna Line was obtained with the CD percentile = 99.9999 (Figure S8). This result is shown in Figure S8. These assumptions have wide implications for the following analyses, and future work could explore other relationships that may further validate the values used in similar analyses.

A detailed description of this fitting procedure for historical climatic conditions follows. For each lake in a simulation:

1. given the fetch and location of the lake, the relevant climate variables were extracted from the historical climate database;
2. the summer maximum temperature and consequent value for the density difference ($\Delta\rho$) was estimated using the empirical models described in previous sections;
3. the local variation in 1-hour mean wind strength (m s^{-1}) was represented as a Weibull function, with the shape parameter set at the value (β = 2.338) we determined to be representative of our study area and scale parameter (η) consistent with the local mean wind speed given in the historical climate database;
4. the 'typical' strength of summer windstorms was set at the value specified by the simulation-specific trial value for the CD percentile for this Weibull function;
5. this value for storm wind strength at 10 m above the lake surface (U_{10}) was included in the following formula for wind stress (τ):

$$\tau \equiv \rho_w u_*^2 = \rho_a C_{D,10} \, (U_{10}^2)$$

where ρ_w is water density (set to 1000 kg m^{-3} here), ρ_a is air density (set to 1 kg m^{-3} here) and $C_{D,10}$ is the drag coefficient for surface winds at 10 m[24];

6. we calculated the drag coefficient using Charnock's Law[61] and an empirical relationship[62]:

$$C_{D,10} = \begin{cases} 0.0044 \times U_{10}^{-1.15},\ U_{10} < 5\ m\ s^{-1} \\ \left[k^{-1} \ln\left(\frac{10g}{C_{D,10}U_{10}^2}\right) + 1.13\right]^{-2},\ U_{10} > 5\ m\ s^{-1} \end{cases}$$

where k is the von Karman constant (0.40), and g is the gravitational acceleration.

7. the resultant values for τ and $\Delta\rho$ were then included in the Gorham-Boyce equation for the critical mixing depth (H);
8. if this estimate for $H \geq$ maximum depth for the lake, the lake was designated as thermally uniform throughout the open-water period;
9. if this estimate for $H <$ maximum depth for the lake, the lake was designated as thermally diverse, with the difference in temperature in mid-summer equal to the epilimnetic-hypolimnetic temperature difference.
10. in the case of some far north lakes, the estimate for maximum surface water temperature was less than the estimated hypolimnetic temperature – in these cases, we designated the lake as thermally uniform.
11. in addition, an upper bound of 20 m for thermocline depth was set based on studies on the Laurentian Great Lakes[24,63].

Once the stratification state for all 9623 lakes was determined using this procedure, we fit a first quartile regression to the distribution of maximum depth values for stratified lakes, with $\log_{10}$ fetch (km) as the independent variable and $\log_{10}$ maximum depth (m) as the dependent variable. We then compared this regression line to the Hanna Line. We carried out a series of these simulations, each one characterized by a progressively higher value for the Weibull CD percentile used to characterize summer storm wind strength. We found the 99.9999 percentile met this fitting criterion (see Figure S8) with 14.6% of the lakes in the sample predicted to stratify under historical climate conditions.

Our use of local wind conditions in the Arctic was predicated on the notion that these would include some degree of the local terrain characteristics, which is mainly a treeless landscape. Southerly lakes would have wind sheltering from trees, and therefore the models that were developed and tested in these locations – though they should be widely applicable in principle – may require special considerations for Arctic systems that we did not fully test. The above tests were grounded in the notion that the Gorham-Boyce model and Hanna Line were based on a wide-ranging array of lakes that were accessible to detailed monitoring programs[24,57]. It is worth noting that although these datasets did not include any lakes north of 60° N, they did contain latitude ranges of 31-54° N (Gorham-Boyce) and 32-55° N (Hanna), along with elevation ranges of 10-3900 m (Gorham-Boyce) and 10-1897 m (Hanna)[24,57], showing that the datasets did reach latitudes close to the Arctic Circle and high elevation lakes. Future research may consider how the environmental context of the Arctic may dictate lake thermal dynamics in ways that differ from temperate regions. Model testing and development would be warranted in this pursuit. Overall, Arctic lakes may be mixed more often than expected due to the lack of buffering from vegetation. We also address this in part by using fetch as our measure of lake size which generates higher prediction rates of mixing than squared surface area.

Sensitivity of Stratification Predictions to Use of Fetch vs Area[2]

We tested the sensitivity of our stratification predictions using the square root of surface area as a measure of lake size, rather than fetch, in the Gorham-Boyce equations. Under the historical conditions used to generate Figure S8, the number of stratified lakes increased from 14% to 21%. This result points to the value of having ‘good’ fetch estimates in the Arctic GIS lake database, rather than just estimates of the lake surface area. This is because we want to prevent an overestimation of stratified lakes with potential thermal refugia for coldwater fish species, as this may exaggerate their thermal resources under future climate scenarios.

Regional Predictions of the Impact of Climate Change on Stratification Patterns in Canadian Arctic Lakes

We compared projections of future (2050 and 2100) stratification patterns under RCP4.5 and RCP8.5 emission scenarios with patterns based on historical (1985-2005) climate conditions[28]. The fitting procedure outlined in the previous sections demonstrated that, under historical climate conditions, a single Weibull CD percentile value could shape the maximum depth distribution of our lake sample to match the expected distribution derived from semi-mechanistic theory founded on the work of Gorham and Boyce (1989) and Hanna (1990)[24,57]. We assumed that this percentile value would be insensitive to the changes associated with future climates and used it to project the impacts of future climate change. The procedure used to project the stratification pattern under each climate change scenario followed that outlined above, except the Weibull CD was fixed at 99.9999 and the climate variables used were extracted from the relevant projected future climate database. Some of the consequences of assuming a fixed CD percentile are outlined below:

(i) an increase in mean summer wind strength will be accompanied by an increase in typical summer storm strength;

(ii) consequently, the percentage of lakes expected to stratify may decline and those lakes that continue to stratify may exhibit deeper thermoclines;

(iii) these directional changes will be opposed if higher wind strengths are accompanied by higher summer surface temperatures, with the overall result determined by the relative strengths of these opposing influences.

Some of these effects are evident in the climate change scenarios that we explored. Specifically, projected storm wind strengths under RCP8.5 are large enough to counter the effects of higher summer water temperatures, leading to deeper projected thermoclines than are evident in both the historical climate simulation and RCP4.5 simulations. These results are shown in (-Tables S14 and S15 and Figure S9).

Regional Predictions of the Impact of Climate Change on Fish Habitat Diversity in Canadian Arctic Lakes

North American limnetic fish species can be classified into three thermal guilds (coldwater, coolwater, and warmwater) based on their thermal preferences[64,65]. This classification forms the basis for the three lake types that are the focus of our thermal habitat projections: thermally diverse, thermally uniform, and barren. Thermally diverse lakes have winter ice thicknesses ≤ their mean depth and are stratified while ice-free. These lakes could support native coldwater fish species and provide refuge during summer from coolwater or warmwater invaders. Thermally uniform lakes also have winter ice thicknesses ≤ their mean depth but are fully mixed while ice-free. These lakes would foster competition among native coldwater and invading coolwater or warmwater species since they have no coldwater thermal refuge. Barren lakes have winter ice thicknesses > their mean depth and can be stratified or mixed when ice-free. These lakes are assumed to be incapable of supporting self-sustaining fish populations because they nearly freeze to the bottom in winter. Barren lakes that no longer freeze beyond their mean depth under future climates represent new potential fish habitat. Our climate change projections focus on: (i) changes in the relative numbers of these three lake types; and (ii) changes in the supply of suitable habitat for each thermal guild.

The models outlined in previous sections (i.e., ice thickness model, stratification occurrence model) were used to classify individual lakes into our three lake types (barren, thermally uniform, and thermally diverse) under historical and future climates. For lakes deemed to stratify by the Gorham-Boyce equations, we applied an additional filter to reduce the chance of overestimating the number of stratified lakes. We required the water density difference between its epilimnion and hypolimnion to be > 0.5 kg m^{-3}. This corresponds to a thermal difference of 2.52 °C given a hypolimnion temperature of 4 °C.

Projections of suitable thermal habitat for each lake type were based on our definition of thermal guilds. Coker et al. (2001) used extant data on the preferred temperature of Canadian freshwater fish to identify three classes or guilds: coldwater - preferred temperature <19 °C; coolwater - preferred temperature [19,25] °C; warmwater - preferred temperature >25 °C[64]. We reviewed the temperature preference data provided in a much more recent compendium for North American freshwater fish[66]. We focused our attention on the 42 species that commonly occur in the Canadian Arctic and concluded that the temperature preference data for these species would be better represented by guild boundaries that were shifted to somewhat lower levels than those presented by Coker et al. (2001)[64]. Therefore, in our projections, we used the following thermal guild definitions: coldwater <16 °C, coolwater [16,22] °C, and warmwater >22 °C.

Our lake-specific projections of annual habitat supply for each thermal guild under each climate scenario were determined as follows. Over the ice-free period, we generated daily temperature vs depth profiles for each lake by assuming:

(i) daily lake surface water temperature $[T(j)]$ varies with day *j* as follows:

$$when\ j \le J_{\mathrm{MAX}}\ \&\ j > BU, T(j) = 4 + \left(\frac{T_{\mathrm{AVG}} - T_{\mathrm{HYP}}}{(J_{\mathrm{MAX}} - BU)^2}\right) \times ((J_{\mathrm{MAX}} - BU)^2 - (j - J_{\mathrm{MAX}})^2)$$

$$when\ j > J_{\mathrm{MAX}}\ \&\ j < FU, T(j) = 4 + \left(\frac{T_{\mathrm{AVG}} - T_{\mathrm{HYP}}}{(FU - J_{\mathrm{MAX}})^2}\right) \times ((FU - J_{\mathrm{MAX}})^2 - (j - J_{\mathrm{MAX}})^2)$$

Where:

T_{AVG} = average maximum surface water temperature (°C), based on the T_{MAX} model[26] and *SWT* model[27]

J_{MAX} = date of T_{MAX} (day of year), or the midpoint between the ice break-up and freeze-up dates

BU = ice break-up date (day of year)

FU = ice break-up date (day of year)

T_{HYP} = starting temperature representative of the lake at ice break-up and the hypolimnion during stratification (°C) (if applicable)

(ii) for thermally uniform lakes, the water temperature from the lake surface to its maximum depth on day *j* is set equal to $T(j)$;

(iii) for thermally diverse lakes, the water temperature from the lake surface to its estimated thermocline depth on day *j* is set equal to $T(j)$; for depths > the estimated thermocline depth, the temperature is set equal to 4 °C.

We calculated the annual habitat supply for each thermal guild as follows. We began by characterizing the shape of the lake basin. We assumed that the basin was cone-shaped and used the known surface area and maximum depth of each lake to generate a value for the dimensionless volume development (V_d) parameter. V_d describes lake basin shape in relation to the volume of a cone with a base area and height equal to the lake's surface area and maximum depth (V_d = mean depth / maximum depth)[67]. We then used this parameter in the R package 'rLakeAnalyzer' and its *approx.bathy* function to divide the total lake volume into successive 0.1 m layers starting at the surface and extending to the bottom of the lake[68]. This permitted us to easily estimate the total lake volume for thermally uniform lakes and the lake volumes above and below the thermocline for thermally diverse lakes (as well as stratified and unstratified barren

Commented [A18]: State if this is the same package used to estimate mean and max depth above in Ground-truthing morphometry lakes). We then calculated the annual habitat supply for fish belonging to each thermal guild as follows:

cold water guild volume-days (CdVD, m^3 days):

$$\sum_{j=BU}^{j=FU} V(j)_{<16}$$

coolwater guild volume-days (ClVD, m^3 days):

$$\sum_{j=BU}^{j=FU} V(j)_{[16,22]}$$

warmwater guild volume-days (WVD, m^3 days):

$$\sum_{j=BU}^{j=FU} V(j)_{[>22]}$$

Where:

$V(j)_{<16}$ = lake volume on day *j* that has a temperature <16 °C

$V(j)_{[16,22]}$ = lake volume on day *j* that has a temperature in the interval [16,22] °C

$V(j)_{>22}$ = lake volume on day *j* that has a temperature >22 °C

We did not attempt to estimate seasonal hypolimnion dynamics in stratified lakes. We assumed that hypolimnetic water would be sufficiently cold to serve as a refuge for coldwater fish species. This assumption is consistent with the range of hypolimnetic temperatures generated using the lake layer density difference model for the historical period (range = 4.00-11.620 °C, mean = 8.451 °C).

Lakes with small, fleeting thermally suitable fish habitat may not have sufficient thermal resources for fish to establish viable populations. For example, if a lake epilimnion reaches 16-17 °C for a few days this could be considered coolwater thermal habitat; however, it is unlikely that this small, transient thermal habitat would be sufficient for a coolwater fish population to establish. We set "establishment thresholds" for coolwater and warmwater fish thermal habitat to prevent including lakes where these temperatures only appear briefly. We based these thresholds on earlier research that linked the northern range limits of typical members of these guilds (yellow perch *Perca flavescens* and smallmouth bass *Micropterus dolomieu*, respectively) to the severity of winter starvation[42], as indexed by mean annual air temperature[27,42,69]. Mean annual air temperatures of -1.8 °C marked the northern distributional limit for yellow perch in North America, and +1.9 °C marked the northern limit for smallmouth bass. In both species, these values for air temperature were associated with annual water temperature regimes that supported low levels of reproductive success due to short growing seasons and consequent long periods of winter starvation[72]. Given this association between the boundary marking population viability (the northern distributional limit) and specific air temperatures, we assumed that the maximum surface water temperature associated with these air temperatures could be used as 'establishment thresholds' for coolwater and warmwater fish populations. Following the approach used in this earlier analysis, we used the empirical model of Shuter et al. (1983) to estimate these maximum surface water temperatures as follows[69]:

$$\ln AP = 3.059 + 0.0422 \times T_{\text{ANN}} - 0.002 \times {T_{\text{ANN}}}^{2} \times \ln TORZ^{3}$$

Where:

ln *AP* = the natural logarithm of maximum surface water temperature (°C)

T_{ANN} = mean annual air temperature (°C)

ln *TORZ* = thermally diverse lakes: the natural logarithm of thermocline depth (m); thermally uniform lakes: the natural logarithm of mean depth (m)

We calculated ln *AP* for all thermally diverse and thermally uniform lakes under the historical climate scenario (barren lakes were excluded because they are assumed to have no fish habitat). We then calculated the mean of the *AP* estimates for all thermal habitat lakes (i.e., thermally diverse, and thermally uniform lakes), resulting in a peak surface water temperature of 19.34 °C at -1.8 °C mean annual air temperature (coolwater establishment threshold), and 22.56 °C at 1.9 °C mean annual air temperature (warmwater establishment threshold). We rounded the coolwater threshold down to 19 °C to be closer to the yellow perch FTP (17.6 °C) and rounded the warmwater fish establishment threshold up to 23 °C to be closer to the smallmouth bass FTP (25 °C).

We also developed a “persistence time threshold” for coldwater fish to be applied to unstratified lakes. This prevented the inclusion of lakes, in our thermal habitat summary, where the entire water column temperature exceeds the upper thermal limit for coldwater fish for extended periods. We based this threshold on the mean upper incipient lethal temperature for coldwater Arctic fish species[66], which is 24.07 °C (n species = 18) rounded down to 24 °C for 14 days or greater. This number of days aligns with field-based estimates of thermal tolerance for coldwater trout species[70].

We only report thermal habitat metrics for lakes that meet the establishment/persistence criteria described above. For example, the warmwater volume-days from a lake that has a peak surface temperature of 22.5 °C would not be included in our cumulative total of warmwater fish habitat because the establishment threshold of 23 °C is not reached in that lake. We calculated indices of the relative amount of thermal habitat available for each thermal guild (see Figure 6, main text) as follows:

- relative amount of coldwater thermal habitat = 100* CdVD/ (CdVd+ClVD+WVD)
- relative amount of coldwater thermal habitat = 100* ClVD/ (CdVd+ClVD+WVD)
- relative amount of coldwater thermal habitat = 100* WVD/ (CdVd+ClVD+WVD)

We conducted all data transformation and analyses in the R statistical environment (R version 4.2.0)[71].

Data Availability Statement

Data for this study will be made available on Dryad once the manuscript is accepted for publication. Access will be provided to editors and reviewers on request.

Code Availability Statement

Code used to conduct the analysis for this study will be made available on Dryad once the manuscript is accepted for publication. Access will be provided to editors and reviewers on request.

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Author Contribution Statement

DPG and BJS conceived, designed, and refined the project. DPG performed most of the analysis and modelling. BJS provided ideas and supporting analyses for the stratification modelling. SEC provided the lake morphometry data base and helped integrate it into the overall analysis. DPG, BJS, CKM and SEC interpreted the results. DPG wrote the manuscript with contributions from BJS, CKM and SEC.

Figures

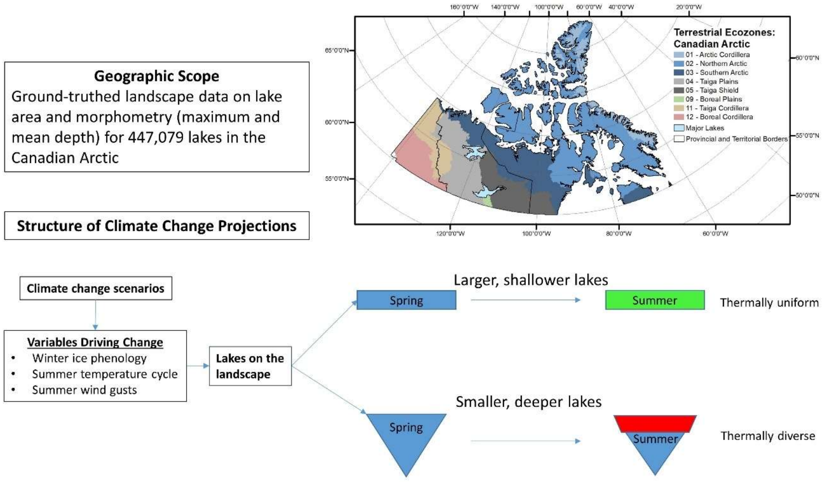

Figure 1. Overview schematic of methods used to generate thermal habitat projections in Canadian Arctic lakes. In this generalization, blue indicates habitat suitable for coldwater fish species, whereas green indicates coolwater habitat and red warmwater habitat.

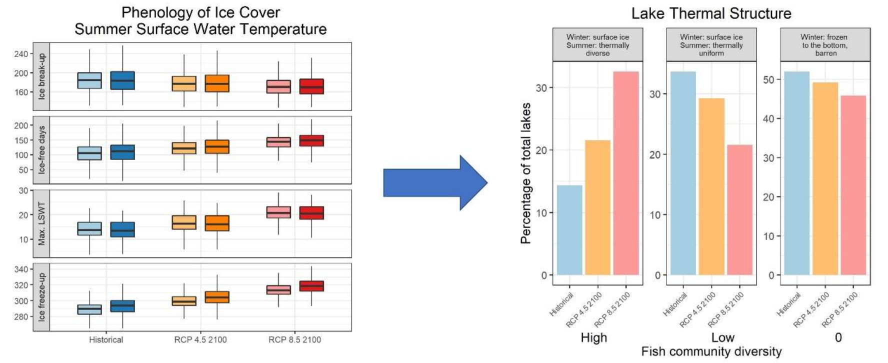

Figure 2. Boxplot showing projected maximum surface water temperature (Max. LSWT, °C), ice break-up, ice freeze-up (day of year), and ice-free days (days). Historical and two future potential climate scenarios (RCP4.5 and RCP8.5 in 2100) are shown. Each scenario shows separate results by lake size class, for "small" lakes on the left (fetch < 5 km, *n* = 438,582 (98.1%)) and "large" lakes on the right (fetch ≥ 5 km, *n* = 8497 (1.9%)). The box height represents the interquartile range (IQR) between the 25th and 75th percentiles. The black line inside the box represents the median. The tails on either side of the box represent either the maximum/minimum value in the data, or the 25th/75th percentile plus 1.5 times the IQR. Outliers beyond the tails are omitted to accentuate the main trends in the data. Including outliers expands the y-axes so that the change in each distribution is visually muted by a few lakes. Furthermore, the modelling system is not designed to simulate extremes (i.e., outliers may be spurious, especially in a large dataset). Across climate scenarios, there is little change in the abundance of barren lakes (decreasing). The greatest shifts occur for thermally diverse lakes (increasing) then thermally uniform lakes (decreasing). Values for each metric with all lakes pooled are summarized in Table S1 for all climate scenarios (including 2050), and summaries by lake size class are in Table S2. The bar plot on the right shows the climate change impacts on the potential

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fish community diversity that can be supported by these lakes. The y-axis shows the percentage of total lakes represented by that lake class under that climate scenario, and the x-axis represents the climate scenario and the fish community diversity that would be supported by thermally diverse (high), thermally uniform (low), or barren lakes (nil).

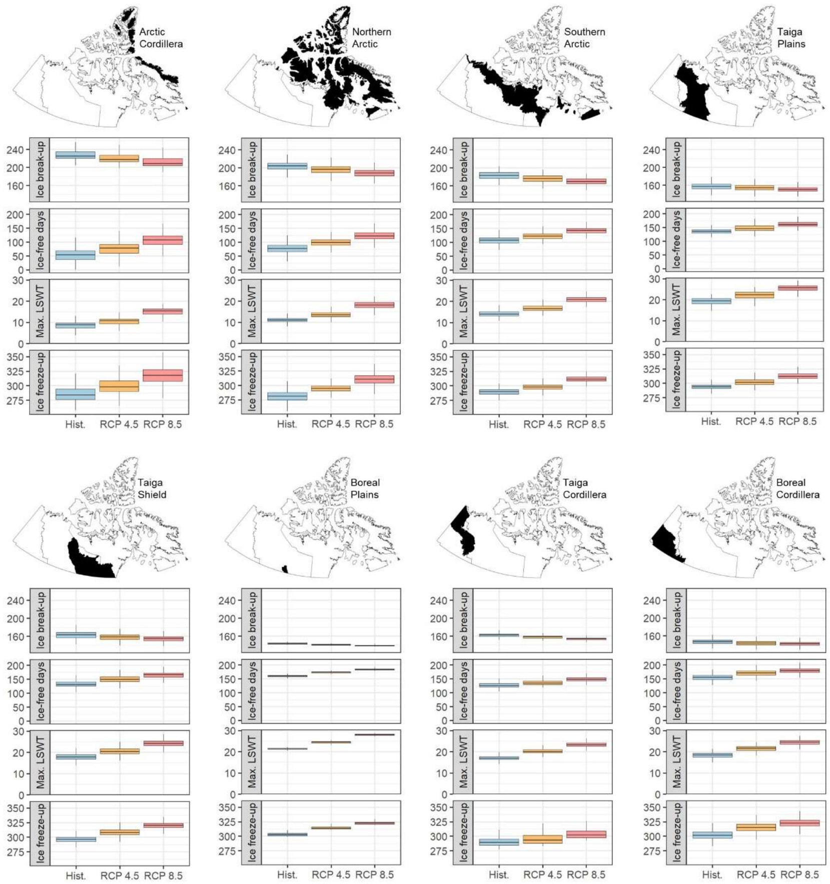

Figure 3. Maximum lake surface water temperature (Max. LSWT, °C), ice break-up, ice freeze-up (day of year), and ice-free days (number of days) projections by ecozone (see Figures 4 and 5 for *n* lakes per ecozone). Historical and two future potential climate scenarios (RCP4.5 and RCP8.5 in 2100) are shown. Y-axes are all set to the global minimum and maximum for each metric across the ecozones. The box height represents the interquartile range (IQR) between the 25th and 75th percentiles. The black line inside the box represents the median. The tails on either

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side of the box represent either the maximum/minimum value in the data, or the 25th/75th percentile plus 1.5 times the IQR. Outliers beyond the tails are omitted to accentuate the main trends in the data. The shifts to earlier ice break-up dates are minor compared to the shifts to later freeze-up dates. The greatest shifts in freeze-up dates occur in the most northerly ecozones, with 20-30 days being typical in the north compared to 5-10 in the south. Aside from the Arctic Cordillera with modest change, the greatest increases in ice-free days occur in the Northern and Southern Arctic, with a decreasing trend moving to more southernly/westerly ecozones. A summary of these metrics by ecozone for all five climate scenarios is in Table S3.

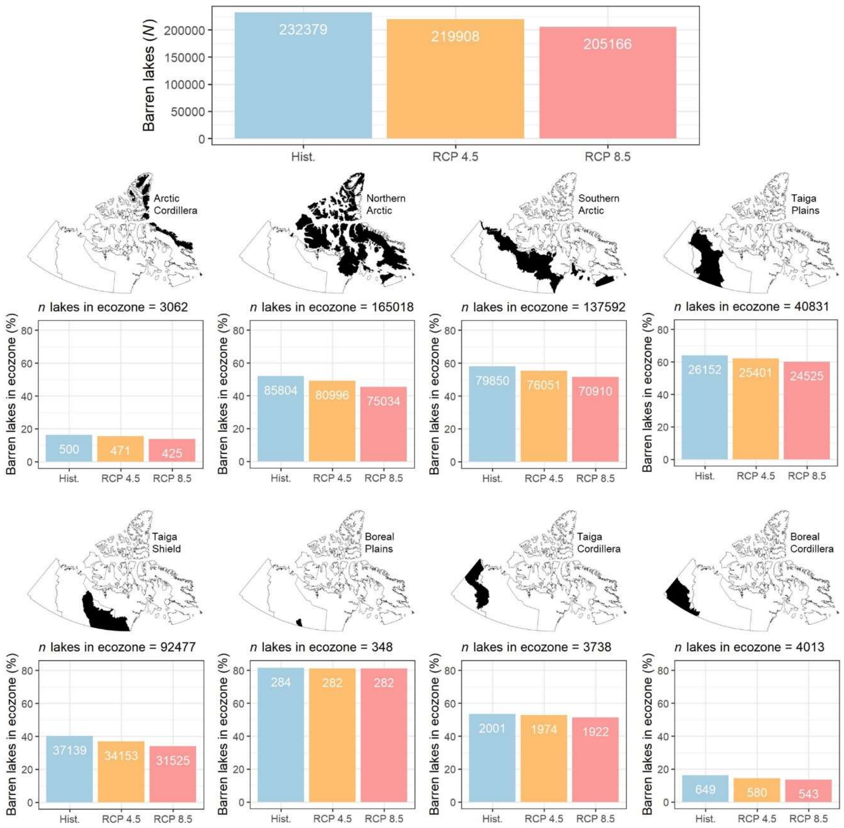

Figure 4. Number and percentage of lakes that are classified as barren under historical and two potential future climate change scenarios (RCP4.5 and RCP8.5 in 2100) overall (top) and by ecozone. Changes in the percentages of barren lakes have similar decreasing trends across ecozones but note that barren lakes are concentrated in the Northern and Southern Arctic ecozones. A tally of barren lakes for all five climate scenarios overall (top) is in Table S8.

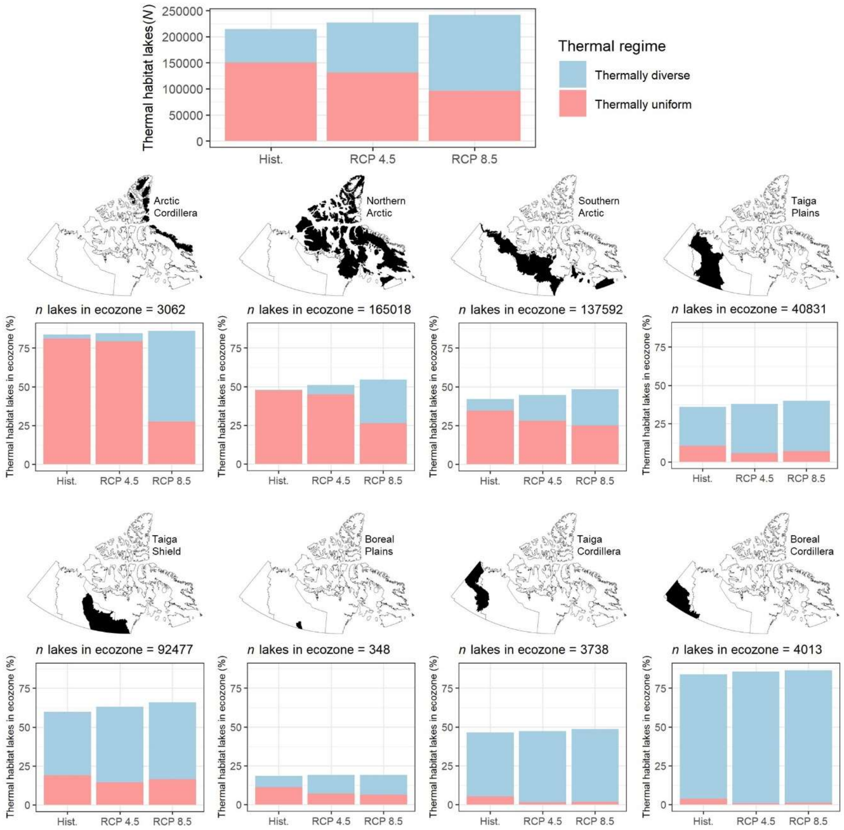

Figure 5. Projected thermal regimes for thermal habitat lakes (i.e., thermally uniform, and thermally diverse lakes, which are included in thermal habitat summaries, with no barren lakes), overall and by ecozone. Barren lakes under each scenario are excluded from these summaries as they are assumed to not support fish. Lakes that transition to thermally uniform or thermally diverse from barren under climate change are included in those scenario's summaries. The y-axis represents the percentage of lakes in that thermal regime and plot titles for each ecozone

represent the number of lakes. Across ecozones, thermally uniform lakes decrease, and thermally diverse lakes increase in abundance. In the Arctic Cordillera and Northern Arctic, thermally uniform lakes continue to dominate under RCP4.5, but are greatly replaced with thermally diverse lakes under RCP8.5. Thermally diverse lakes typically remain so in the Taiga Shield and Taiga Plains. Historical and two future potential climate scenarios (RCP4.5 and RCP8.5 in 2100) are shown. A tally of thermal habitat lakes for all five climate scenarios overall (top) is in Table S8.

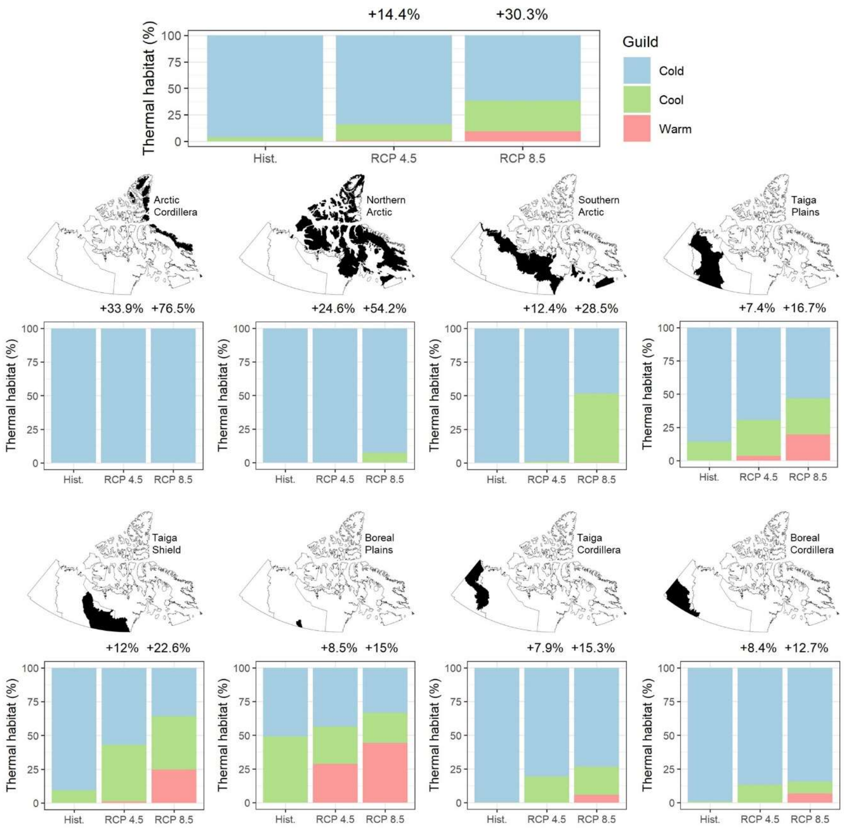

Figure 6. Ice-free volume-days associated with each thermal guild as a percentage of total ice-free thermal habitat under historical and potential future climate change scenarios (RCP4.5 and RCP8.5 in 2100) for thermally diverse and thermally uniform lakes (barren lakes excluded). The total overall change is shown in the top panel, and by ecozone in the remaining panels (see Figures 4 and 5 for *n* by ecozone). Great Bear Lake and Great Slave Lake are excluded from

volume-days calculations, including the supplementary tables. They comprise ~59% of the limnetic volume in the region and as large lakes are subject to complex physical forces, which would skew our results. Barren lakes under each scenario are excluded from these summaries as they are assumed to not support fish. Lakes that transition to thermally uniform or thermally diverse from barren under climate change are included in those scenario's summaries. There are three main groupings of ecozones according to their trends in ice-free volume-days: 1) the Arctic Cordillera, Northern Arctic, and Southern Arctic remain mostly coldwater (except for the Southern Arctic under RCP8.5, which becomes approximately half coolwater), 2) the Taiga Plains, Taiga Shield, and Boreal Plains represent the greatest increases in coolwater and warmwater, and 3) the southwesterly Taiga Cordillera and Boreal Cordillera show small increases coolwater and warmwater. An overall summary (top) of thermal habitat volume-days broken down by lake class and for all five climate scenarios is in Table S11.

Supplementary Material

Supplementary Discussion

The following is a discussion of important issues to consider in future assessments of Arctic freshwater fish diversity.

Under-ice Winter Conditions and Oxygen Deficits

Our analyses focused on the fundamental aspects of lake thermal structure during the open-water season to project shifting Arctic fish community diversity under climate change. Although we did not attempt to explore the under-ice conditions of these lakes, it is important to consider the shortening of the ice-free season. A similar modelling approach has been used to characterize under-ice lake thermal conditions and could be applied to explore this interplay[1]. Other factors will have a role in how these systems change. Under-ice conditions and oxygen dynamics were not a focus in our study, and have implications for sustaining fish life year-round[2]. We defined barren lakes unable to support fish as those which had limited water due to thick lake ice, which supersedes the notion of limited oxygen. Conditions in lakes we did not classify as barren, however, may still be unable to support fish populations because of severe oxygen deficits[3]. Future research could account for these factors and expand the definition of barren lakes.

Freshwater Distribution Changes with Permafrost Melt

Our results project landscape-level changes in the thermal dynamics of Arctic lakes, given the current distribution of freshwater across the Arctic landscape. Warming-induced landscape-level terrestrial and geomorphic changes may affect this distribution and modify our results[4]. Permafrost conditions beneath Arctic lakes are of great importance to these ecosystems through interactions and feedback between lake ice and sediment thermal dynamics and may vary across lake size[5]. Permafrost thaw will alter the number, size, and distribution of lakes across the Arctic[6]. Arctic lakes and ponds are a substantial global source of natural greenhouse gas, and future permafrost thaw may lead to increased annual water body emissions of 20-54% by 2100 if ice-free seasons extend by 20 days[7]. Increasing permafrost melt and its implications for dissolved organic matter in lakes are also worth considering as this can affect the productivity of northern fish communities[8]. The network of Arctic lentic systems is changing with the climate, and trends vary by region, with both increases and decreases in lakes and ponds being documented[4,9,10]. Permafrost melt and subsequent slumping and draining opens up new habitat for fish species to colonize, including southerly invaders[11]. Future work on Arctic lakes and their ability to support different fish species will need to assess these changes in the distribution of freshwater across the northern landscape.

Thermal Diversity Within the Coldwater Guild

The thermal guild boundaries that we applied to our study were based on large assessments of fish species' thermal preferences across North America[12,13]. These studies did not focus on the thermal ecology of the Arctic. There is significant thermal diversity within the coldwater guild, as defined in our analyses. For example, species with thermal preferences below 10 °C having been defined as an "Arctic guild" for freshwater fishes[14]. Further assessments of future Arctic lake thermal conditions should consider breaking the coldwater thermal guild into finer units to gain further insights on how climate change may affect ultra-cold-adapted fishes.

The Role of New Technologies in Future Monitoring

Future work could be bolstered by detailed regional surveys of thermal regimes in lakes of various sizes to further refine future projections. Environmental DNA sampling may also improve our knowledge of species distributions and lay the groundwork for the study of future changes[15].

Lake Morphometry Assessment

Comparison with HydroLAKES

The Arctic GIS lake database was built to develop a lake morphometry dataset focused on the unique geographic qualities of the Canadian Arctic, which represents ~1/3 of global lakes ≥ 0.1 km^2 (~450,000 lakes)[16,17]. The original Arctic GIS lake database includes some lakes in northern Quebec and Ontario, along with some lake trout (*Salvelinus namaycush*) sampling lakes in prairie regions and Labrador. We focused on lakes with central coordinate latitudes ≥ 60° N. Unless otherwise stated, our results are based on this subset of the Arctic GIS lake database.

We compared the Arctic GIS lake database's morphometry values to HydroLAKES, a widely used global lakes dataset[17] (Table S16). The HydroLAKES dataset database was built using regression equations formulated with an extensive global training lakes dataset of training lakes, with the preferred mean depth model using lake area and average slope surrounding the 100 m buffer of the lake as predictors[17]. Both databases have estimates for lake morphometry/bathymetry and are based on the CanVec geospatial dataset (http://maps.canada.ca/czs/index-en.html). Lake counts are similar overall, by lake size, and ecozone (the top, most generalized, and largest level defined by the four-level National Ecological Framework for Canada) are similar for the Arctic dataset and HydroLAKES for both datasets, highlighting the fact that both databases were generated using the same CanVec waterbody area/location data (Table S17). Differences between the Arctic dataset and HydroLAKES likely arise from slight contrasts in data processing procedures and value judgements on what constitutes a lake. For example, within the Canadian Arctic, HydroLAKES contains ~1.3% more lakes than the Arctic dataset.

Lake depth is a key morphometric variable used for estimating potential lake thermal resources. An advantage of the Arctic GIS lake database is that it has estimates for maximum depth, and although this metric has more uncertainty than mean depth, its use permits initial estimates of lake thermal habitat supply in lakes[16]. The training dataset that was used to estimate mean depth for HydroLAKES lacked Canadian Arctic empirical data[17]. The HydroLAKES model coefficients were derived for different lake size classes globally, so any regions that were not used in the HydroLAKES training dataset may be difficult to predict because these regional differences are not captured by the model. The HydroLAKES dataset also contains minimum mean depth boundaries for different lake size classes, and the mean depth model tends to overestimate these values[17]. Furthermore, mean depths < 1 m are never produced by the model despite lakes having these values[17]. This was not a key issue for the HydroLAKES dataset, as the main objective of the original study that presented HydroLAKES was to estimate global lake volume and water residence time, which is dominated by larger, generally more well-studied lakes, whereas the smallest lakes (mean depth < 1 m) were not of primary concern[17]. Producing accurate estimates for lakes of all depths is critical for our study, as shallow lakes that were formerly frozen to the bottom in winter may not be in the future due to climate change. Small lakes comprise a large portion of the Canadian Arctic by sheer numbers. Therefore, although small lakes comprise a small percentage of the total volume and thermal habitat supply, they comprise a large, connected hydrological network for coolwater and warmwater fish species to potentially invade and compete with coldwater residents.

Lake Morphometry Modelling Methods

For the original publication of the Arctic dataset, mean and maximum lake depths were estimated by modelling the surface topography digital elevation model along many transects for each lake across a distance of approximately one lake radius on each side, and splines were fit to the elevation data along transects to estimate lake depth[16]. This value was averaged with a value obtained from the single median slope value in the surrounding topography[16,18]. Analysis of known and estimated lake morphometry revealed no bias among the values[16]. In the original publication of the Arctic GIS lakes database, shallow lakes (maximum depth < 2.5 m, mean depth < 1.75 m) were excluded as they were likely to freeze to the bottom and probably would not support fish populations, a key focus of the initial analysis[16]. Lakes with estimated maximum depths less than 2.5 m or mean depths less than 1.75 m were excluded from the initial study as they were likely to freeze to the bottom and probably would not support fish populations, a key focus of the initial analysis[16]. In the present study, To include these lakes in our study, we used empirical relationships among ground-truthed Arctic lake morphometrics to estimate mean and maximum depths for these originally omitted shallow lakes. we used empirically derived relationships among ground-truthed Arctic lake morphometrics to estimate mean and maximum depths that fell below these minimum thresholds in the initial assembly of the Arctic dataset. We assessed regional trends in estimated lake depth using validated measures of Arctic lake morphometry sourced from previous studies, hereafter the “empirical morphometry database”. We took lake surface area as a reliable measure of lake morphometry that is easy to measure compared to lake depth and should be relatively consistent across datasets regardless of their age. We compared relationships among mean depth, maximum depth, and surface area with the empirical morphometry dataset and subdivided the Arctic GIS lake database by ecozone to determine if regional patterns were apparent. We then overlaid the depth-area relationships of the Arctic GIS lake database and HydroLAKES for which the morphometric variables were available (HydroLAKES lacks a maximum depth estimate) to assess the correspondence of the relationships among ecozones. Although the empirical morphometry database is only a small sample of the total lakes in the Arctic, it provides a reasonable set of boundaries and a baseline with which to contextualize our results. Comparing mean depths from the Arctic and HydroLAKES datasets, we truncated both datasets at 1.5 m because the HydroLAKES model generally did not produce mean depth values in the 1-2 m range[17]. It is worth noting that ~1/3 of the Arctic GIS lake database lakes are omitted based on this filtering step as these lakes are estimated to be very shallow.

Lake Morphometry Modelling Results

Satisfactory models for predicting lake morphometry metrics (mean and maximum depths) were developed using regional inventories of lake resources and empirical datasets gathered across the region. The number of lakes for which empirical estimates were made for morphometry is summarized in Table S18 (< 2% of all lakes). Where one or both depth metrics were missing, alternate estimates were developed using supplementary variables such as lake area and ecozone. Using the empirical morphometry dataset, mean depth was a very good predictor of maximum depth and vice versa ($R^2 = 0.89$, $p < 0.0001$, $N = 167$, Figure S10, Table S19). Lake area was a moderately strong predictor of both depths (mean depth $R^2 = 0.49$, $p <$

0.0001, $N = 167$; maximum depth $R^2 = 0.52$, $p < 0.0001$, $N = 167$, Figure S11, Table S19). Adding ecozone as a predictor improved all models significantly, but only in certain ecozones. Lakes from ecozones #6 (Boreal Shield) and #9 (Boreal Plains) were omitted from the analyses using ecozone as a predictor because they contained two and one lakes, respectively, which was insufficient to conduct the analysis. The above analysis was re-run without those three lakes so that ΔAIC comparison could be completed. ANOVA and ΔAIC results refer to a comparison of linear models without and with ecozone as a predictor. Although the predictions generated from these regression models are reliable, the small number of lakes in the dataset and their heterogeneous geographic distribution limits their applicability. Using ecozone as a predictor in the morphometry equations significantly improved the model fit for predicting maximum depth from mean depth (ΔAIC = 13.21, $R^2 = 0.91$, $p < 0.0001$, $N = 164$), predicting mean depth from maximum depth (ΔAIC = 53.54, $R^2 = 0.93$, $p < 0.0001$, $N = 164$), predicting mean depth from surface area (ΔAIC = 48.05, $R^2 = 0.63$, $p < 0.0001$), and predicting max depth from surface area (ΔAIC = 17.83, $R^2 = 0.56$, $p < 0.0001$); however, only ecozone #3 and #12 for mean depth from maximum depth, #12 for maximum depth from surface area, and #12 for mean depth from surface area was significant within their respective regression equations (Table S20). The relationship between the estimated mean and maximum depths for the Arctic GIS lake database conforms well to the relationship established with the empirical morphometry dataset across ecozones (Figure S10). For example, in the ecozone where the empirical morphometry dataset contains the most lakes (Ecozone #3, $n = 72$) there is good agreement between the distribution of the Arctic GIS lake database's estimated mean depths and that of the empirical morphometry dataset. The empirical morphometry dataset contains many shallow lakes ($n = 46$ lakes ≤ 2 m, ~38% of the dataset), therefore, truncation at shallow depths is missing lots of existing lakes. By continuing to focus on the geographic region contained within the empirical morphometry dataset, the uncertainty is constrained.

Our lake morphometry assessment combined with the regional lakes numbers by size gives us a representation of the morphometry of all lakes across the region. Lakes > 10 ha in Canada north of 60° latitude cover approximately 402,000 km^2, ~10% of the region's total area. The perimeter of these lakes measures approximately 2,271,000 km in length, approximately nine times the entire marine coastline of Canada. The total volume of these lakes equals approximately 6,862 km^3 or approximately 3.7% of global lake volume[17]. The global HydroLAKES dataset[17] overall lake morphometry values for Arctic Canada are close to those presented here. Mean depths in the Arctic GIS lake database are generally lower than those in the global HydroLAKES dataset[17], as the estimated distribution of thermal resources partitioned by ecozone is more right-skewed for the Arctic GIS lake database compared to the Canadian Arctic lakes (Figure S12) and given the differences between the height of the bars in the more positive side of the histogram (Figure S13). Furthermore, our reported surface area is 1.3% higher than HydroLAKES, shoreline length is 12.3% more, and volume is 7.9% less. The top 10 lakes in terms of volume in both datasets have very similar volumes, with the sum of the values presented here being 0.57% greater than that of HydroLAKES. These lakes comprise 65.8% of the total lake volume in our dataset. Therefore, it is likely that the lower overall mean depth corresponding to the many thousands of small lakes in our dataset is driving the lower volume estimate (HydroLAKES mean depth: mean = 3.80 m, median = 3.40 m; Arctic mean depth: mean = 2.51, median = 1.77 m).

Supplementary Tables

Table S1. Estimated increases (mean (standard deviation)) in maximum surface water temperatures (Max. LSWT, °C), ice break-up and freeze-up dates, and the length of the ice-free season across all lakes in the Canadian Arctic GIS lake database.

Period	Historical	RCP4.5 2050	RCP4.5 2100	RCP8.5 2050	RCP8.5 2100
Max. LSWT	14.3 (3.3)	16.7 (3.3)	16.9 (3.5)	16.9 (3.2)	20.9 (3.2)
Ice break-up	183.8 (20.4)	178.9 (18.8)	177.6 (19.3)	177.4 (18.9)	171.4 (17.3)
Ice freeze-up	288.6 (9.4)	297.1 (8.3)	299.8 (8.5)	299.3 (9.2)	313.7 (8.3)
Ice-free days	104.6 (28.3)	118.1 (25.1)	122.2 (25.7)	121.8 (25.9)	142.3 (22.0)

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Table S2. Mean and standard deviation (in brackets) of lake thermal metrics by future climate scenario and lake size class. Small lakes are those with a fetch of less than 5 km, large lakes are those with a fetch of ≥ 5 km. Max. LSWT represents the maximum surface water temperature. Dates are represented by ordinal days.

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Thermal Metric	**Lake Size Class**	**Historical**	**RCP4.5 2050**	**RCP4.5 2100**	**RCP8.5 2050**	**RCP8.5 2100**
Ice Break-up Date	Small	183.8 (20.3)	178.9 (18.7)	177.5 (19.2)	177.4 (18.8)	171.4 (17.2)
	Large	184.7 (24)	180 (22.4)	178.6 (22.8)	178.5 (22.6)	172.5 (20.7)
Ice-free Days	Small	104.5 (28.2)	118.1 (24.9)	122.1 (25.5)	121.7 (25.8)	142.2 (21.9)
	Large	107.9 (34.4)	121.4 (31.6)	125.9 (31.8)	125.3 (32.4)	146.1 (27.4)
Ice Freeze-up Date	Small	288.5 (9.3)	297 (8.2)	299.7 (8.4)	299.2 (9.2)	313.6 (8.3)
	Large	292.9 (12.3)	301.5 (11.6)	304.5 (11.5)	304 (12.3)	318.6 (10.6)
Max. LSWT	Small	14.3 (3.3)	16.7 (3.3)	16.9 (3.5)	16.9 (3.2)	21 (3.1)
	Large	13.9 (3.6)	16.2 (3.7)	16.4 (3.8)	16.4 (3.6)	20.5 (3.5)

Table S3. Mean and standard deviation (in brackets) of lake thermal metrics by future climate scenario and ecozone. Max. LSWT represents the maximum surface water temperature.

Thermal Metric	Ecozone	Historical	RCP4.5 2050	RCP4.5 2100	RCP8.5 2050	RCP8.5 2100
Ice Break-up Date	01 - Arctic Cordillera	225.9 (17.8)	221.6 (18.5)	220 (19.4)	220.3 (18.5)	213.5 (22.4)
	02 - Northern Arctic	203.9 (11)	197.2 (11.2)	196.6 (11.3)	195.9 (11.5)	188.3 (10.8)
	03 - Southern Arctic	182.7 (7.9)	177.3 (7.4)	175.7 (7.5)	175.7 (7.1)	169.4 (6.6)
	04 - Taiga Plains	157.2 (7.5)	154.8 (6.5)	153.8 (7.1)	153.9 (6.8)	150.4 (6)
	05 - Taiga Shield	162.8 (7.6)	160.4 (6.7)	158 (6.4)	158.5 (6.6)	154.5 (5.8)
	09 - Boreal Plains	143.2 (1.7)	142.7 (1.5)	140.7 (1.6)	141 (1.3)	139.1 (1.3)
	11 - Taiga Cordillera	162.5 (5)	159.3 (4.5)	158.5 (4.4)	158.9 (4.6)	154.6 (4.3)
	12 - Boreal Cordillera	146.9 (5.6)	144.7 (5.2)	143.7 (5.1)	144.7 (5.2)	142.4 (4.8)

Ice-free Days	01 - Arctic Cordillera	52.5 (32.5)	69.1 (34.6)	73.8 (35)	73 (35.4)	102.7 (37.4)
	02 - Northern Arctic	77.4 (17.9)	95.1 (16)	98.8 (15.7)	98.4 (16.4)	123.1 (16.1)
	03 - Southern Arctic	106.8 (11.9)	119.2 (9.9)	122.5 (11.7)	121.9 (11.4)	143 (10.7)
	04 - Taiga Plains	136.7 (9.6)	145.2 (10.5)	148.3 (11.6)	147.4 (11.5)	162.1 (9.7)
	05 - Taiga Shield	133.9 (11.7)	144.2 (13.1)	150.7 (11.8)	150.8 (12.7)	165.7 (10.1)
	09 - Boreal Plains	160.1 (3.6)	170 (3.5)	173.9 (3.4)	175 (3.3)	184.2 (3.4)
	11 - Taiga Cordillera	128.3 (9.7)	136.1 (9.1)	137.4 (10)	137.7 (8.7)	149.8 (9.1)
	12 - Boreal Cordillera	155.9 (11.3)	167.4 (11.5)	172 (11.6)	167.3 (11.5)	181.1 (11.1)
Ice Freeze-up Date	01 - Arctic Cordillera	286.2 (13)	296.9 (13.6)	299.5 (13.2)	299.4 (13.9)	317.3 (16.1)
	02 - Northern Arctic	281.5 (9.2)	292.4 (7.6)	295.4 (7.2)	294.4 (8.2)	311.4 (9.4)

	03 - Southern Arctic	289.6 (5.4)	296.5 (5.4)	298.2 (5.9)	297.6 (6.3)	312.4 (6.1)
	04 - Taiga Plains	293.9 (4.9)	300 (5.5)	302.1 (6.1)	301.3 (6.3)	312.5 (5.7)
	05 - Taiga Shield	296.7 (5.8)	304.6 (7)	308.7 (6.3)	309.3 (6.8)	320.2 (5.4)
	09 - Boreal Plains	303.4 (3.2)	312.7 (3.3)	314.6 (3.3)	316 (3.4)	323.3 (3.7)
	11 - Taiga Cordillera	290.8 (8.2)	295.4 (8.8)	295.9 (9.6)	296.5 (8.6)	304.4 (8.7)
	12 - Boreal Cordillera	302.8 (8.8)	312.1 (9)	315.7 (9.3)	312 (9)	323.5 (9)
Max. LSWT	01 - Arctic Cordillera	8.3 (2.2)	9.9 (2.2)	10.2 (2.2)	10.5 (2.3)	14.6 (2.5)
	02 - Northern Arctic	11.1 (1.3)	13.5 (1.5)	13.6 (1.5)	13.9 (1.4)	18.1 (1.7)
	03 - Southern Arctic	14.1 (1.3)	16.6 (1.4)	16.7 (1.4)	16.7 (1.2)	20.8 (1.3)
	04 - Taiga Plains	19.3 (1.5)	21.6 (1.4)	22 (1.7)	21.7 (1.6)	25.5 (1.5)

	05 - Taiga Shield	17.9 (1.5)	20.1 (1.4)	20.6 (1.5)	20.3 (1.5)	24.3 (1.4)
	09 - Boreal Plains	21.4 (0.3)	23.4 (0.3)	24.5 (0.5)	24 (0.3)	28 (0.4)
	11 - Taiga Cordillera	16.9 (1.2)	19.5 (1.2)	20.1 (1.2)	19.6 (1.2)	23.2 (1.2)
	12 - Boreal Cordillera	18.2 (1.4)	20.6 (1.4)	21.4 (1.4)	21 (1.4)	24.3 (1.4)

Table S4. Summary statistics for lakes by mixing class, climate scenario, overall (all lakes included north of 60° N latitude, $N = 447{,}079$).

Mixing class	Historical	RCP4.5 2050	RCP4.5 2100	RCP8.5 2050	RCP8.5 2100
Mixed	376,658 (84.2%)	346,435 (77.5%)	340,679 (76.2%)	357,993 (80.1%)	292,059 (65.3%)
Stratified	70,421 (15.8%)	100,644 (22.5%)	106,400 (23.8%)	89,086 (19.9%)	155,020 (34.7%)

Table S5. Summary statistics for lakes by mixing class, climate scenario, and ecozone (all lakes included north of 60° N latitude, *N* = 447,079). Percentages are shown for each ecozone and scenario.

Ecozone	Total	Mixing Class	Historical	RCP4.5 2050	RCP4.5 2100	RCP8.5 2050	RCP8.5 2100
01 - Arctic Cordillera	3062	Mixed	2,982 (97.4%)	2,961 (96.7%)	2,899 (94.7%)	2,930 (95.7%)	1,227 (40.1%)
		Stratified	80 (2.6%)	101 (3.3%)	163 (5.3%)	132 (4.3%)	1,835 (59.9%)
02 - Northern Arctic	165018	Mixed	164,114 (99.5%)	157,958 (95.7%)	155,057 (94%)	151,480 (91.8%)	116,979 (70.9%)
		Stratified	904 (0.5%)	7,060 (4.3%)	9,961 (6%)	13,538 (8.2%)	48,039 (29.1%)
03 - Southern Arctic	137592	Mixed	126,779 (92.1%)	113,882 (82.8%)	112,927 (82.1%)	119,009 (86.5%)	103,114 (74.9%)
		Stratified	10,813 (7.9%)	23,710 (17.2%)	24,665 (17.9%)	18,583 (13.5%)	34,478 (25.1%)
04 - Taiga Plains	40831	Mixed	28,117 (68.9%)	24,645 (60.4%)	24,239 (59.4%)	28,591 (70%)	24,838 (60.8%)
		Stratified	12,714 (31.1%)	16,186 (39.6%)	16,592 (40.6%)	12,240 (30%)	15,993 (39.2%)
	92477	Mixed	51,759 (56%)	44,489 (48.1%)	43,159 (46.7%)	53,371 (57.7%)	43,524 (47.1%)

05 - Taiga Shield		Stratified	40,718 (44%)	47,988 (51.9%)	49,318 (53.3%)	39,106 (42.3%)	48,953 (52.9%)
09 - Boreal Plains	348	Mixed	322 (92.5%)	304 (87.4%)	295 (84.8%)	317 (91.1%)	295 (84.8%)
		Stratified	26 (7.5%)	44 (12.6%)	53 (15.2%)	31 (8.9%)	53 (15.2%)
11 - Taiga Cordiller a	3738	Mixed	2,017 (54%)	1,797 (48.1%)	1,776 (47.5%)	1,873 (50.1%)	1,766 (47.2%)
		Stratified	1,721 (46%)	1,941 (51.9%)	1,962 (52.5%)	1,865 (49.9%)	1,972 (52.8%)
12 - Boreal Cordiller a	4013	Mixed	568 (14.2%)	399 (9.9%)	327 (8.1%)	422 (10.5%)	316 (7.9%)
		Stratified	3,445 (85.8%)	3,614 (90.1%)	3,686 (91.9%)	3,591 (89.5%)	3,697 (92.1%)

Table S6. Summary of ice-free volume-days corresponding to each thermal guild's temperature range by future climate scenario (all lakes, including barren, included north of 60° N latitude except Great Bear Lake and Great Slave Lake, $N = 447{,}077$).

Guild	**Historical**	**RCP4.5 2050**	**RCP4.5 2100**	**RCP8.5 2050**	**RCP8.5 2100**
Cold	3.09×10^{14} (96.2%)	2.92×10^{14} (84.7%)	3.05×10^{14} (84.1%)	2.98×10^{14} (84.2%)	2.50×10^{14} (61.1%)
Cool	1.21×10^{13} (3.8%)	5.25×10^{13} (15.2%)	5.55×10^{13} (15.3%)	5.46×10^{13} (15.4%)	1.21×10^{14} (29.5%)
Warm	0.00 (0%)	5.01×10^{11} (0.1%)	2.30×10^{12} (0.6%)	1.32×10^{12} (0.4%)	3.84×10^{13} (9.4%)

Table S7. Summary of ice-free volume-days corresponding to each thermal guild's temperature range by future climate scenario and ecozone (all lakes, including barren, included north of 60° N latitude except Great Bear Lake and Great Slave Lake, *N* = 447,077).

Ecozone	**Guild**	**Historical**	**RCP4.5 2050**	**RCP4.5 2100**	**RCP8.5 2050**	**RCP8.5 2100**
01 - Arctic Cordillera	Cold	3.85×10^{12} (100%)	4.88×10^{12} (100%)	5.15×10^{12} (100%)	5.14×10^{12} (100%)	6.60×10^{12} (100%)
	Cool	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)
	Warm	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)
02 - Northern Arctic	Cold	8.35×10^{13} (100%)	9.94×10^{13} (100%)	1.04×10^{14} (100%)	1.03×10^{14} (100%)	8.89×10^{13} (92.1%)
	Cool	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	7.65×10^{12} (7.9%)
	Warm	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)
03 - Southern Arctic	Cold	8.66×10^{13} (100%)	7.37×10^{13} (99%)	7.62×10^{13} (99%)	7.58×10^{13} (99.6%)	5.14×10^{13} (48.1%)
	Cool	0.00 (0%)	7.54×10^{11} (1%)	7.47×10^{11} (1%)	3.24×10^{11} (0.4%)	5.52×10^{13} (51.7%)
	Warm	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	2.68×10^{11} (0.3%)

04 - Taiga Plains	Cold	2.47×10^{13} (82.7%)	2.14×10^{13} (65.1%)	2.24×10^{13} (67.2%)	2.11×10^{13} (65.9%)	1.97×10^{13} (51.5%)
	Cool	5.18×10^{12} (17.3%)	1.12×10^{13} (34.1%)	9.48×10^{12} (28.4%)	1.02×10^{13} (31.8%)	1.05×10^{13} (27.4%)
	Warm	0.00 (0%)	2.67×10^{11} (0.8%)	1.47×10^{12} (4.4%)	7.45×10^{11} (2.3%)	8.08×10^{12} (21.1%)
05 - Taiga Shield	Cold	6.57×10^{13} (90.9%)	4.97×10^{13} (59.6%)	5.15×10^{13} (57%)	4.95×10^{13} (57.2%)	3.80×10^{13} (35.5%)
	Cool	6.61×10^{12} (9.1%)	3.35×10^{13} (40.2%)	3.81×10^{13} (42.1%)	3.65×10^{13} (42.1%)	4.25×10^{13} (39.8%)
	Warm	0.00 (0%)	2.30×10^{11} (0.3%)	7.82×10^{11} (0.9%)	5.61×10^{11} (0.6%)	2.63×10^{13} (24.6%)
09 - Boreal Plains	Cold	7.81×10^{9} (45.5%)	5.37×10^{9} (31.2%)	5.37×10^{9} (31.1%)	4.17×10^{9} (23.4%)	3.90×10^{9} (20.7%)
	Cool	9.37×10^{9} (54.5%)	7.46×10^{9} (43.3%)	5.75×10^{9} (33.3%)	7.06×10^{9} (39.7%)	4.75×10^{9} (25.2%)
	Warm	0.00 (0%)	4.38×10^{9} (25.4%)	6.16×10^{9} (35.7%)	6.57×10^{9} (36.9%)	1.02×10^{9} (54.2%)

11 - Taiga Cordillera	Cold	1.44 × 10^{12} (99.7%)	1.08 × 10^{12} (73.1%)	1.30 × 10^{12} (78%)	1.08 × 10^{12} (72.2%)	1.28 × 10^{12} (70.4%)
	Cool	4.47 × 10^{9} (0.3%)	3.97 × 10^{11} (26.9%)	3.66 × 10^{11} (21.9%)	4.16 × 10^{11} (27.8%)	4.08 × 10^{11} (22.6%)
	Warm	0.00 (0%)	0.00 (0%)	3.25 × 10^{8} (0%)	0.00 (0%)	1.27 × 10^{11} (7%)
12 - Boreal Cordillera	Cold	4.29 × 10^{13} (99.2%)	4.24 × 10^{13} (86.4%)	4.41 × 10^{13} (86.6%)	4.20 × 10^{13} (85.3%)	4.46 × 10^{13} (84.5%)
	Cool	3.30 × 10^{11} (0.8%)	6.65 × 10^{12} (13.6%)	6.76 × 10^{12} (13.3%)	7.24 × 10^{12} (14.7%)	4.58 × 10^{12} (8.7%)
	Warm	0.00 (0%)	1.53 × 10^{8} (0%)	3.50 × 10^{9} (0.1%)	6.08 × 10^{9} (0%)	3.63 × 10^{12} (6.9%)

Table S8. Summary of the number of barren, thermally diverse, and thermally uniform lakes across the Canadian Arctic under different climate periods and scenarios.

Lake Class	**Historical**	**RCP4.5 2050**	**RCP4.5 2100**	**RCP8.5 2050**	**RCP8.5 2100**
Barren	232,379 (52%)	223,016 (49.9%)	219,908 (49.2%)	220,205 (49.3%)	205,166 (45.9%)
Thermally diverse	64,135 (14.3%)	90,590 (20.3%)	96,396 (21.6%)	84,137 (18.8%)	145,493 (32.5%)
Thermally uniform	150,565 (33.7%)	133,473 (29.9%)	130,775 (29.3%)	142,737 (31.9%)	96,420 (21.6%)

Table S9. Summary of the total volume (km^3) of barren, thermally diverse, and thermally uniform lakes across the Canadian Arctic under different climate periods and scenarios (all lakes, including barren, included north of 60° N latitude except Great Bear Lake and Great Slave Lake, *N* = 447,077).

Lake Class	**Historical**	**RCP4.5 2050**	**RCP4.5 2100**	**RCP8.5 2050**	**RCP8.5 2100**
Barren	148.8 (5.2%)	133.7 (4.7%)	129.6 (4.6%)	129.9 (4.6%)	111 (3.9%)
Thermally diverse	1,505.5 (53%)	1,595.7 (56.2%)	1,609.8 (56.7%)	1,570.7 (55.3%)	1,827.1 (64.3%)
Thermally uniform	1,185.1 (41.7%)	1,110 (39.1%)	1,100 (38.7%)	1,138.8 (40.1%)	901.3 (31.7%)

Table S10. Summary of the number and percentage of lakes that stayed in the same lake classification or switched between the historical climate scenario and each of the four future climate scenarios. The first lake classification is the historical one, and the second is the subsequent one under future climate change (e.g., “Barren → Thermally diverse” means that the lake was projected to be a barren lake under historical conditions and is subsequently projected to be a thermally diverse lake under climate change). Percentages express the proportion of lake numbers relative to the total of lakes analyzed (*N* = 447,079).

Lake Classification	RCP4.5 2050	RCP4.5 2100	RCP8.5 2050	RCP8.5 2100
Barren → Barren	223,016 (49.9%)	219,908 (49.2%)	220,205 (49.5%)	205,166 (45.9%)
Barren → Thermally diverse	1,410 (0.3%)	2,086 (0.5%)	1,106 (0.2%)	5,421 (1.2%)
Barren → Thermally uniform	7,953 (1.8%)	10,385 (2.3%)	11,068 (2.5%)	21,792 (4.9%)
Thermally diverse → Thermally diverse	64,135 (14.3%)	64,135 (14.3%)	61,805 (13.9%)	64,123 (14.3%)
Thermally uniform → Thermally uniform	25,045 (5.6%)	30,175 (6.7%)	21,226 (4.8%)	75,949 (17%)
Thermally uniform → Thermally diverse	125,520 (28.1%)	120,390 (26.9%)	129,339 (29.1%)	74,616 (16.7%)

Table S11. Summary of thermal habitat volume-days according to lake classification type and climate scenario (all lakes, including barren, included north of 60° N latitude except Great Bear Lake and Great Slave Lake, $N = 447{,}077$).

Lake class	**Guild**	**Historical**	**RCP4.5 2050**	**RCP4.5 2100**	**RCP8.5 2050**	**RCP8.5 2100**
Barren	Cold	1.28×10^{13} (89.2%)	1.14×10^{13} (83.8%)	1.11×10^{13} (81%)	1.12×10^{13} (83%)	6.25×10^{12} (46.7%)
	Cool	1.55×10^{12} (10.8%)	2.13×10^{12} (15.6%)	2.17×10^{12} (15.9%)	1.98×10^{12} (14.6%)	5.66×10^{12} (42.3%)
	Warm	0.00 (0%)	8.45×10^{10} (0.6%)	4.24×10^{11} (3.1%)	3.28×10^{11} (2.4%)	1.47×10^{12} (11%)
Thermally diverse	Cold	1.81×10^{14} (95.9%)	1.78×10^{14} (83.6%)	1.90×10^{14} (84.8%)	1.80×10^{14} (84.4%)	1.92×10^{14} (68.2%)
	Cool	7.78×10^{12} (4.1%)	3.46×10^{13} (16.2%)	3.26×10^{13} (14.6%)	3.26×10^{13} (15.3%)	6.66×10^{13} (23.6%)
	Warm	0.00 × (0%)	3.48×10^{11} (0.2%)	1.44×10^{12} (0.6%)	6.21×10^{11} (0.3%)	2.30×10^{13} (8.2%)
Thermally uniform	Cold	1.15×10^{14} (97.6%)	1.03×10^{14} (86.6%)	1.03×10^{14} (83%)	1.06×10^{14} (83.9%)	5.19×10^{13} (45.4%)
	Cool	2.80×10^{12} (2.4%)	1.58×10^{13} (13.3%)	2.07×10^{13} (16.6%)	2.01×10^{13} (15.8%)	4.85×10^{13} (42.4%)
	Warm	0.00 × (0%)	6.83×10^{10} (0.1%)	4.33×10^{11} (0.3%)	3.70×10^{11} (0.3%)	1.39×10^{13} (12.2%)

Table S12. Variables needed for each model, their units, and coefficients. Ice phenology models are empirical models derived from Canadian lakes[19]. The T_{MAX} model is an empirical model derived from a dataset of repeated open-water lake temperature profiles[20]. The *SWT* (surface water temperature) model is an empirical model derived from a large database of lake surface water temperature measurements across Canada[21].

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Model element	**Ice freeze-up (day of year)**	**Ice break-up (day of year)**	**ln Ice thickness (cm)**	**T_{MAX} (°C)**	***SWT* (°C)**	**Thermocline depth (m)**	**Hypolimnion-epilimnion density difference (g cm^{-3})**
Intercept/multiplier	58.092	175.829	-3.968	9.742824	-57.88	2.0 ×	-2.11264
Variables and coefficients	0.8303 × J_{AUT0}	1.25676 × J_{SPR0}	0.801 × ln ice cover	-0.2295012 × ln surface area	0.79 × T_{JUL}	τ	0.20607 × T_{EPI}
	7.2925 × $Z_{MEAN}^{0.5}$	-2.9453 × ANG_{SPR0}	1.103 × ln latitude	-0.0006910316 × elevation	0.26 × T_{ANN}	(gravity (9.8 m s^{-2}) ×	-0.004873 × T_{EPI} × $\log_{10}$ fetch

	0.9435 × T_{AUT0}	0.000935 × surface area	0.224/2)	0.9957599 × T_{JJA}	-0.00151 × day of year^2 (204)	Water density difference between epi and hypo at max heat content$^{0.5}$	
		0.4913 × longitude		-0.003398474 × P_{AUG}	0.617 × day of year (204)	× surface area$^{0.5}$	
		0.0169 × elevation		0.01027913 × $CRAD_{JUL}$	-0.019 × longitude		
				-0.3619325 × W_{JUL}			

Table S13. Summary of fitted values for the shape (β) and scale (η) parameters of the Weibull distribution at different time scales (N = 109 sites).

Param	Hours	Min	1st Qu.	Median	Mean	3rd Qu.	Max
β	1	2.046	2.294	2.338	2.321	2.363	2.956
	8	2.172	2.494	2.531	2.564	2.653	3.406
	24	2.407	2.871	2.908	2.994	3.111	4.212
η	1	4.044	5.356	5.616	5.874	6.597	7.151
	8	4.030	5.360	5.612	5.873	6.600	7.153
	24	4.000	5.319	5.575	5.840	6.578	7.120

Table S14. Summary statistics of storm wind strength (m s^{-1}) for historical conditions and our two climate change scenarios, as derived from the output from our sample (*n* = 9623 lakes).

Metric	Historical	RCP4.5 2050	RCP4.5 2100	RCP8.5 2050	RCP8.5 2100
n	9623	9623	9623	9623	9623
Missing	0	0	0	0	0
Mean	10.007	9.9017	9.6734	10.536	10.161
Minimum	5.5647	5.1898	5.0528	5.6805	5.4388
1st Q	8.2849	8.1472	8.1532	9.5323	9.0273
Median	10.487	10.352	10.100	10.833	10.448
3rd Q	11.382	11.513	10.923	11.636	11.108
Maximum	15.897	15.911	16.177	15.377	15.886
Skew	-0.1912	-0.2713	-0.0177	-0.3589	-0.0700
Kurtosis	-0.6662	-0.7890	-0.4833	-0.1633	0.1085

Table S15. Summary statistics of thermocline depth (m) for historical conditions and our two climate change scenarios, as derived from the output from our sample (n = 9623 lakes).

Metric	Historical	RCP4.5 2050	RCP4.5 2100	RCP8.5 2050	RCP8.5 2100
n	1430	2068	2176	1839	3205
Missing	8193	7555	7447	7784	6418
Mean	4.9071	4.7220	4.8415	5.7760	5.1408
Minimum	1.6371	1.4703	1.2727	1.5429	1.2686
1st Q	3.1973	2.8578	2.9271	3.5702	3.3794
Median	3.9988	3.7533	3.8717	4.8670	4.5508
3rd Q	5.5556	5.5617	5.8029	7.0375	6.1941
Maximum	20.000	20.000	20.000	20.000	20.000
Skew	2.8744	2.4335	2.2779	1.8602	2.0010
Kurtosis	10.463	7.9413	7.0219	4.5366	6.5940

Table S16. Basic lake information for different Arctic lake GIS-derived bathymetry estimates.

Dataset	Campana	HydroLAKES
Coordinates	Yes	Yes (Pour point)
Lake area (km^2)	Yes	Yes
Perimeter (km)	Yes	Yes
Fetch (km)	Yes	No (could be estimated from surface area)
Shoreline development	No (could be calculated)	Yes
Volume (million cubic metres)	No (could be calculated)	Yes
Mean depth (m)	Yes	Yes (Volume/area)
Maximum depth (m)	Yes	No (could be estimated empirically)
Discharge ($m^3\ sec^{-1}$)	No	Yes
Residence time (days)	No	Yes
Elevation	Yes	Yes
Slope (degrees)	No	Yes
Watershed area	No	Yes

Table S17. Number of lakes per ecozone in the Arctic GIS lake database[16], HydroLAKES[17], and empirical morphometry datasets.

Ecozone name	**Ecozone ID**	**Arctic**	**Arctic ≥ 60° N**	**HydroLAKES**	**Empirical morphometry**
Arctic Cordillera	1	4,859	3,062	2,942	0
Northern Arctic	2	165,018	165,018	167,722	12
Southern Arctic	3	159,821	137,592	141,245	76
Taiga Plains	4	40,831	40,831	38,211	12
Taiga Shield	5	102,603	92,477	96,005	20
Boreal Shield	6	2	0	0	2
Boreal Plains	9	349	348	95	1
Taiga Cordillera	11	3,738	3,738	2,984	0
Boreal Cordillera	12	4,016	4,013	3,723	44
Hudson Plains	15	547	0	0	0
Total lakes		481,784	447,079	452,927	167

Table S18. Number of lakes in the Arctic GIS lake database[16] that had their morphometry values predicted from empirical equations.

Variable predicted	**Predictor variable**	**Number of lakes**	**Percent of lakes**
Maximum depth	Mean depth	727	0.15%
Mean depth, Maximum depth	Area	5,233	1.09%
Mean depth	Maximum depth	3,113	0.65%
	No prediction required	472,711	98.17%
	Total lakes	481,784	100%

Table S19. Results from the lake morphometry assessment linear regression equations.

Response	**Predictor(s)**	R^2	***F*-statistic**	**Degrees of freedom**	***p*-value**	**Intercept**	**Slope**	***n***
Mean depth	Maximum depth	0.89	1350	$F_{[1, 165]}$	< 0.0001	-0.90	0.93	167
Maximum depth	Mean depth	0.89	1350	$F_{[1, 165]}$	< 0.0001	1.17	0.96	167
Mean depth	Surface area	0.49	161	$F_{[1, 165]}$	< 0.0001	1.31	0.34	167
Maximum depth	Surface area	0.52	178	$F_{[1, 165]}$	< 0.0001	2.38	0.36	167

Table S20. Results from the lake morphometry assessment linear regression comparisons with ecozone as a predictor. ANOVA and ΔAIC results refer to a comparison of linear models without and with ecozone as a predictor.

Response	**Predictor(s)**	R^2	***F*-statistic**	**Degrees of freedom**	***p*-value**	**ΔAIC**	**ANOVA *F*-statistic**	**ANOVA *p*-value**	***n***
Maximum depth	Mean depth, Ecozone	0.91	313.2	$F_{[5, 158]}$	< 0.0001	13.21	5.61	0.0003	164
Mean depth	Maximum depth, Ecozone	0.93	409.3	$F_{[5, 158]}$	< 0.0001	53.54	18.18	< 0.0001	164
Maximum depth	Surface area, Ecozone	0.56	42.47	$F_{[5, 158]}$	< 0.0001	17.83	6.90	< 0.0001	164
Mean depth	Surface area, Ecozone	0.63	56.58	$F_{[5, 158]}$	< 0.0001	48.05	16.29	< 0.0001	164

Supplementary Figures

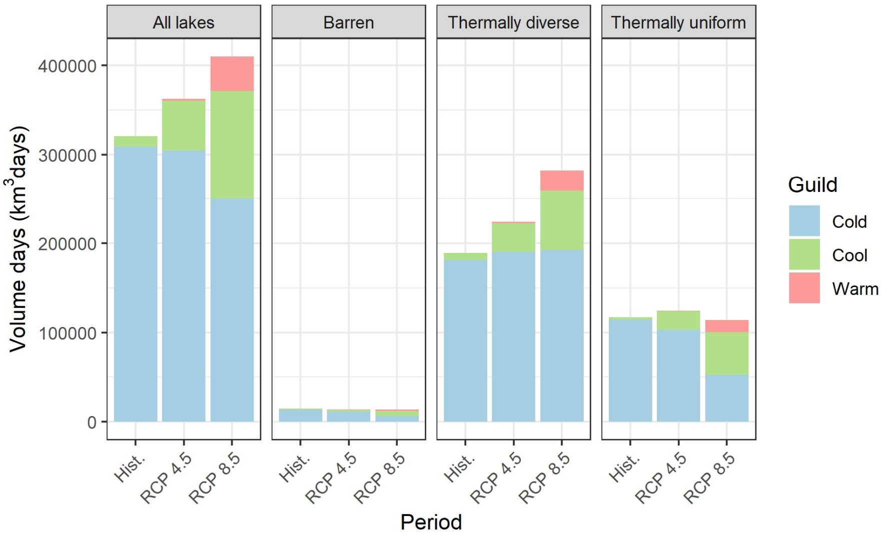


Figure S1A. Ice-free volume-days across different climate scenarios and periods by thermal guild and lake status (all lakes, barren, thermally diverse, or thermally uniform). Great Bear Lake and Great Slave Lake were excluded. Barren lakes – which are excluded from other thermal habitat calculations – are included in the totals here and shown alongside the other two lake classes to illustrate their relatively minor contribution to the regional limnetic volume. A summary of ice-free volume-days for all lakes (left panel) across all five climate scenarios is in Table S6.

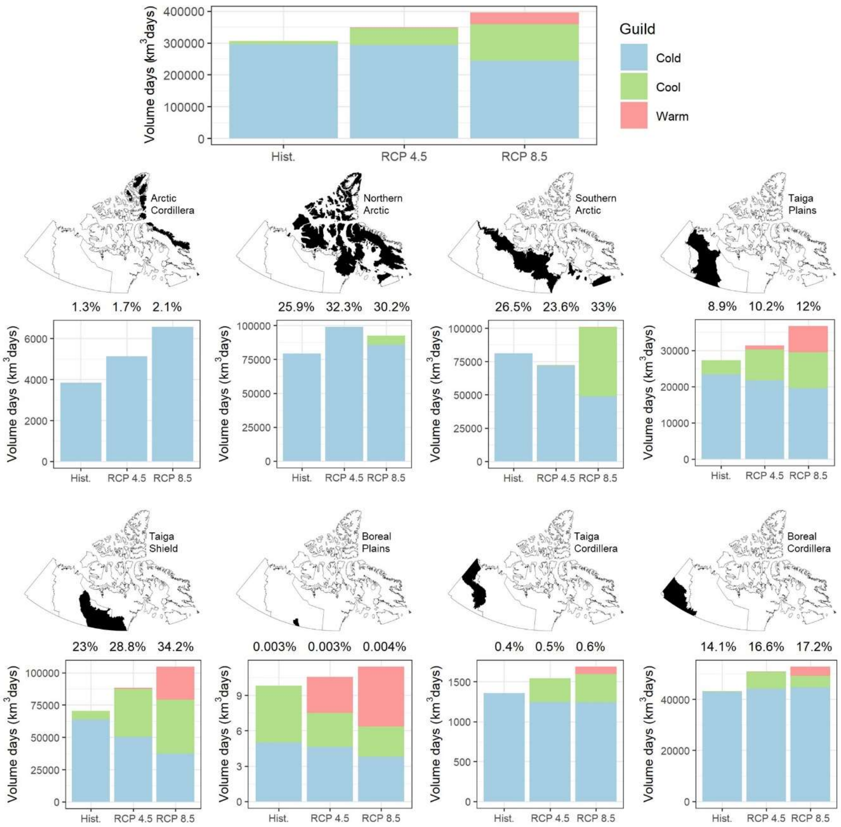


Figure S1B. Ice-free volume-days associated with each thermal guild under historical and potential future climate change scenarios (RCP4.5 and RCP8.5 in 2100) for thermally diverse and thermally uniform lakes pooled (barren lakes excluded). The total is shown in the top panel, and by ecozone in the remaining panels (see Figures 4 and 5 for *n* by ecozone). Great Bear Lake and Great Slave Lake were excluded. The percentages above each bar represent the amount of thermal habitat that each ecozone comprises across the entire study area for that climate scenario.

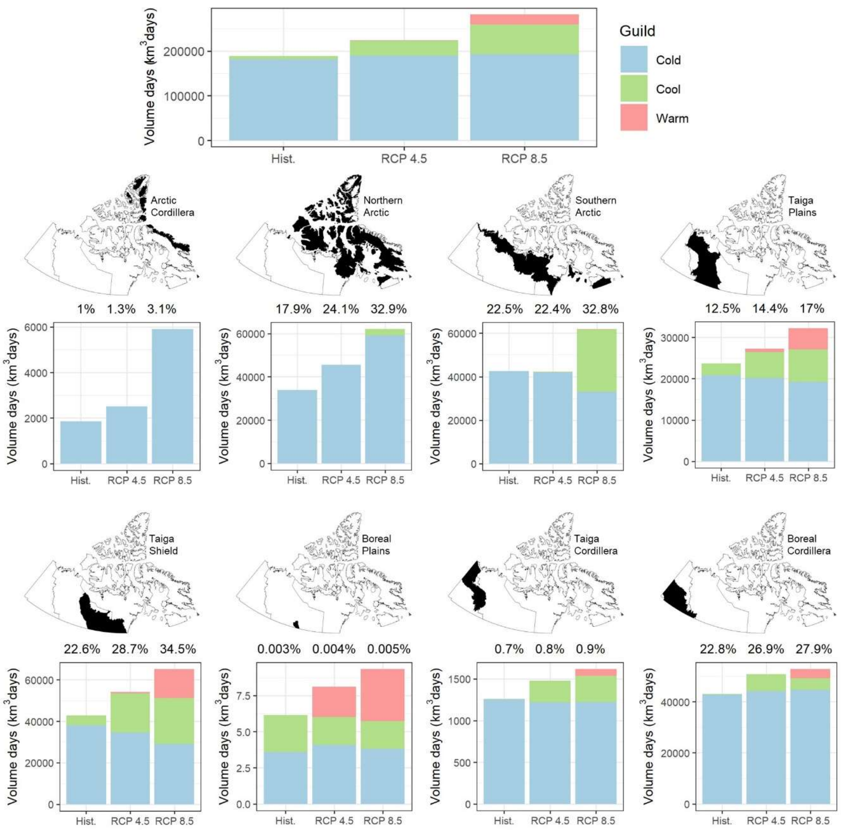


Figure S1C. Ice-free volume-days associated with each thermal guild under historical and potential future climate change scenarios (RCP4.5 and RCP8.5 in 2100) for thermally diverse lakes only. The total is shown in the top panel, and by ecozone in the remaining panels (see Figures 4 and 5 for *n* by ecozone). Great Bear Lake and Great Slave Lake were excluded. The percentages above each bar represent the amount of thermal habitat that each ecozone comprises across the entire study area for that climate scenario. See Table S11 for a summary including all five climate scenarios.

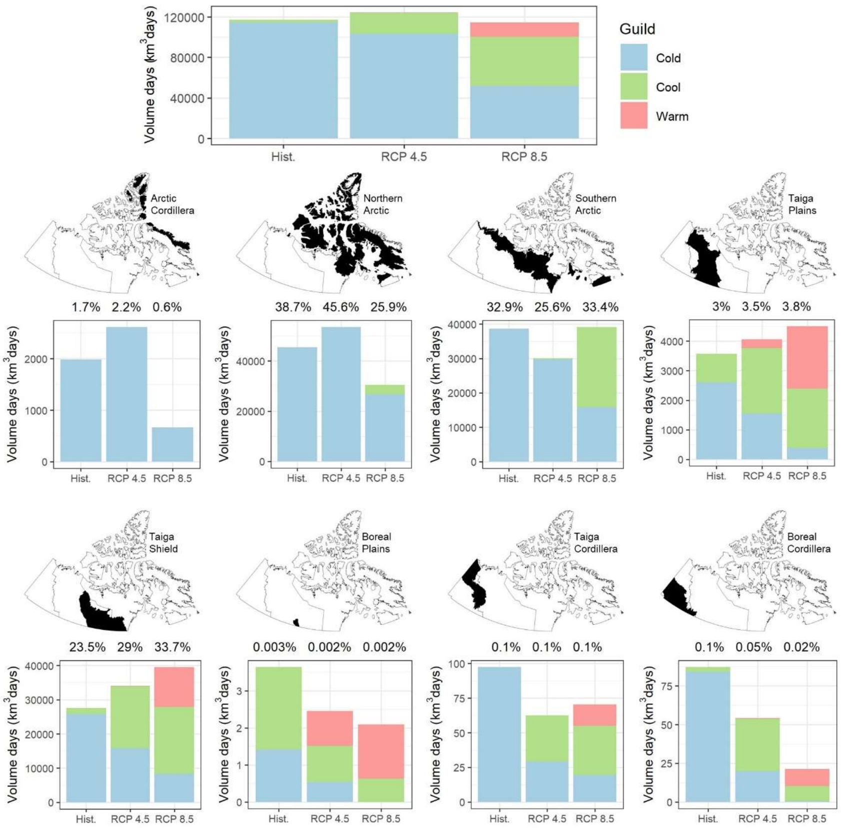


Figure S1D. Ice-free volume-days associated with each thermal guild under historical and potential future climate change scenarios (RCP4.5 and RCP8.5 in 2100) for thermally uniform lakes only. The total is shown in the top panel, and by ecozone in the remaining panels (see Figures 4 and 5 for *n* by ecozone). Great Bear Lake and Great Slave Lake were excluded. The percentages above each bar represent the amount of thermal habitat that each ecozone comprises across the entire study area for that climate scenario. See Table S11 for a summary including all five climate scenarios.

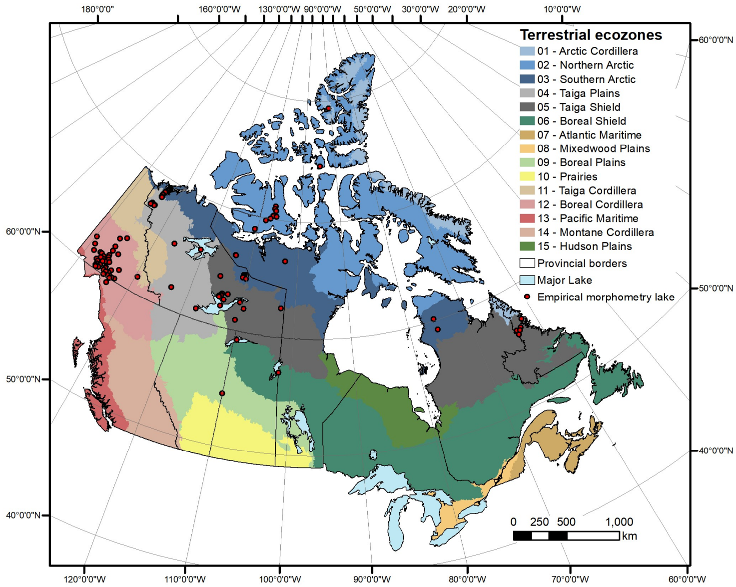


Figure S2. Map showing the ecozones of Canada and the geographic locations of Canadian lakes for which we have ground-truthed morphometry estimates (*N* = 167). These lakes were used to inform the relationships for missing values in the Arctic GIS lake database. Lakes are coloured by Ecozone code.

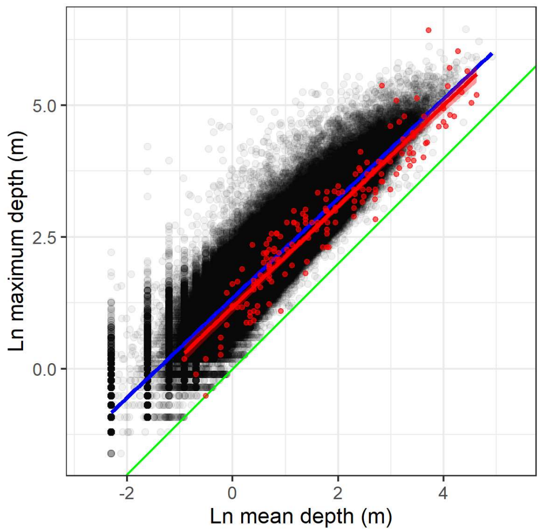


Figure S3. Relationship between final mean and maximum depths in the Arctic GIS lake database[16] (n = 472,711) (black dots, blue regression line) with the empirical morphometry dataset overlaid in red (N = 167). All values have been log-transformed (ln). The green line is the 1:1 line. Lakes from the Arctic GIS lake database with morphometry values predicted by the empirical equations have been left out of this figure (n = 9,073).

Commented [A24]: Inclusion of 1:1 line is a bit odd because one expects that the maxs will be greater than the means in most cases but it is OK to retain 1:1 line, just make axes increments the same.

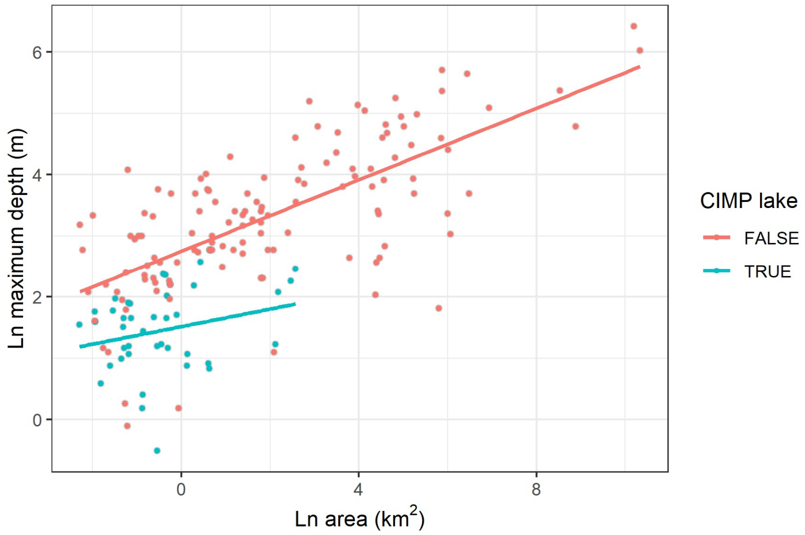


Figure S4. The relationship between lake maximum depth and surface area for our empirically measured lakes database (N = 167). Lakes that are part of the Cumulative Impact Monitoring Program (CIMP) lake dataset are identified (n = 50).

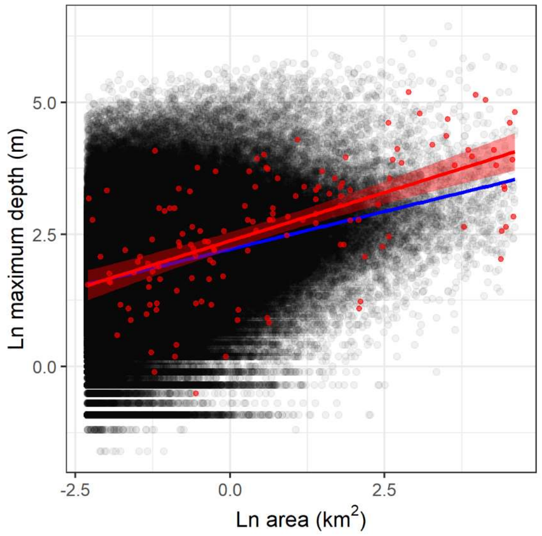


Figure S5. Relationship between area and final maximum depths in the Arctic GIS lake database[16] (*n* = 472,477) (black dots, blue regression line) with the empirical morphometry dataset overlaid in red (*n* = 144). All values have been log-transformed (ln). This plot includes lakes with surface areas between 0.1 and 100 km^2 which is why the full 167 empirical morphometry lakes are not included. Lakes from the Arctic GIS lake database with morphometry values predicted by the empirical equations have been left out of this figure (*n* = 9,073).

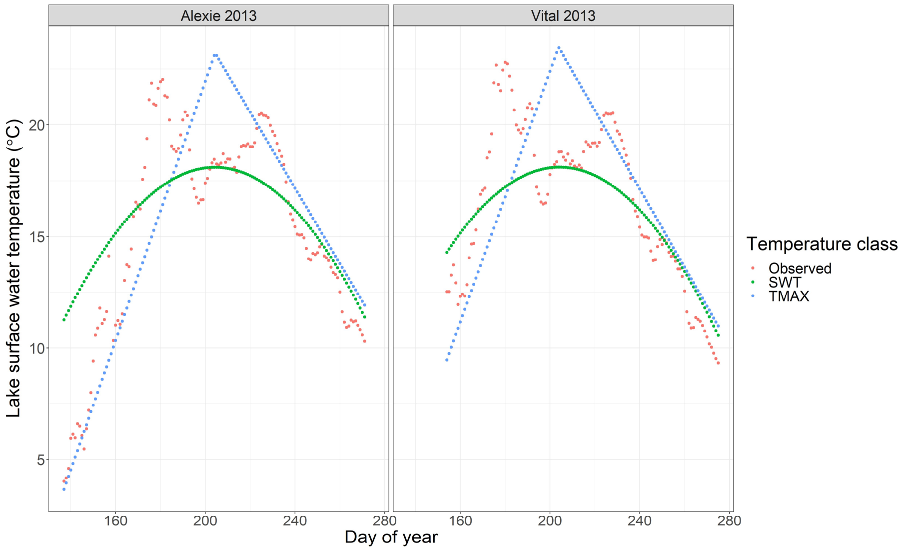


Figure S6. Observed and modelled open-water daily lake surface water temperatures for two Arctic lakes: Alexie Lake (n = 135 days) and Vital Lake (n = 122 days). T_{MAX} predictions were produced using the model from Gillis et al. 2021[20], and the SWT predictions were produced using the model from Sharma et al. 2007[21].

Commented [A25]: Add averaged values from SWT and TMAX to this plot

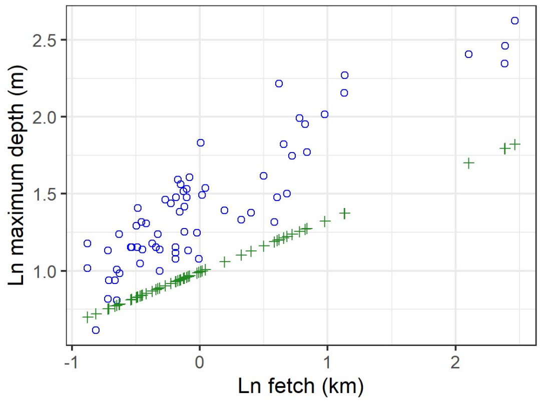


Figure S7. The relationship between log fetch (km) (x-axis) and log maximum depth (y-axis) for stratified lakes featured in Gorham and Boyce 1989[22] (blue circles) (N = 152). The green crosses represent the theoretical minimum value for the lake's maximum depth, based on the estimated thermocline depth derived from lake fetch using. the Hanna (1990)[23] equation, multiplied by 1.7 following Gorham and Boyce (1989)[22]. Most blue circles lie above this theoretical boundary.

Commented [A26]: This figure can be removed or merged with S8 although I realize range of GB lakes would be small collection of points on S8 figure

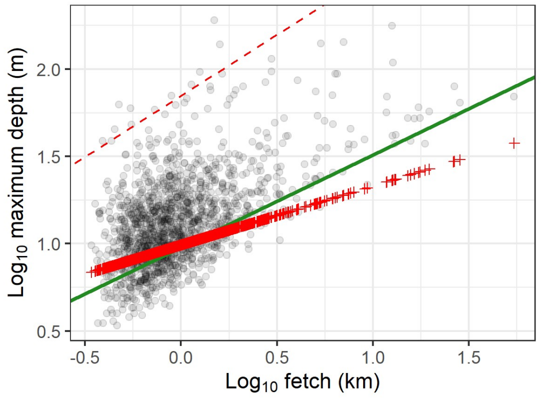


Figure S8. The relationship between $\log_{10}$ fetch (km) and $\log_{10}$ maximum depth (m) for the Arctic lakes predicted to stratify under wind conditions derived from a Weibull distribution with the following parameters: Weibull shape parameter (β) = 2.338, percentile 99.9999. Black circles represent the morphometry values for the 1430 lakes predicted to stratify from the evenly sampled 9623 lakes within the Arctic GIS lake database (~2% of the dataset). The red crosses represent the theoretical boundary estimated using the equation from Hanna (1990)[23], which requires the fetch of each Arctic lake, multiplied by 1.7 following Gorham and Boyce (1989)[22]. The green solid line represents the first quartile regressions of $\log_{10}$ fetch and $\log_{10}$ maximum depth. The red dotted line defines the upper bound for the distribution of maximum depths in the first figure of Gorham and Boyce (1989)[22] ($\log_{10}$ maximum depth (m) = 1.85 + 0.7 × $\log_{10}$ fetch (km)). These Weibull parameters were chosen for subsequent analysis because, out of the other parameter values assessed, the theoretical boundary and the first quartile regression line under these conditions had the greatest overlap.

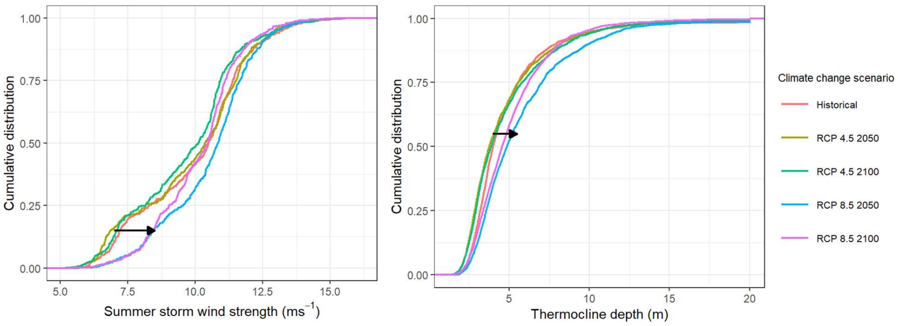


Figure S9. Cumulative distribution for summer storm wind strength and thermocline depth. Parallel projections for increases in both summer storm wind strength and thermocline depth are evident for RCP8.5 – as indicated by the arrows – over and above the projections for both historical climate conditions and RCP4.5.

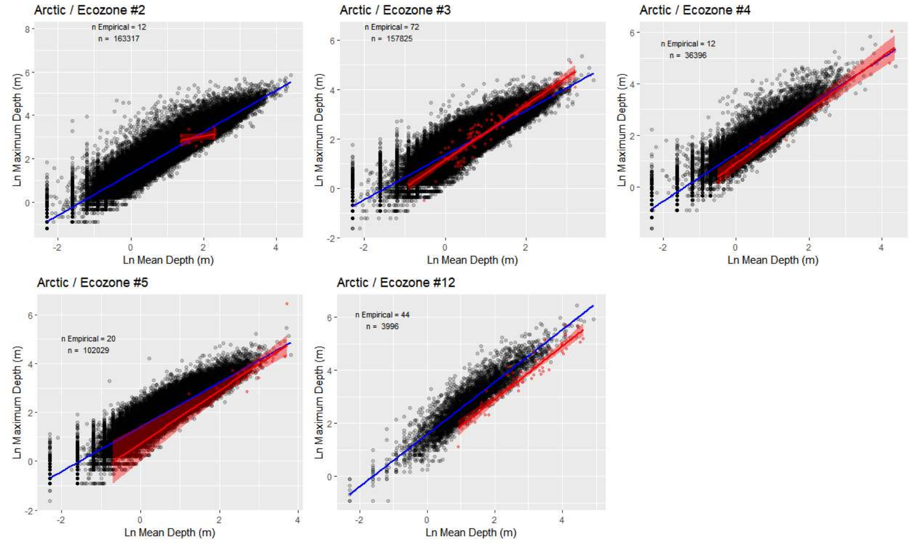


Figure S10. Relationship between final mean and maximum depths in the Arctic GIS lake database[16] (black dots, blue regression line) with the empirical morphometry dataset overlaid in red for the five ecozones with the greatest numbers of empirically validated lakes. The number of lakes for each dataset is indicated on the plots. All values have been log-transformed (ln). Lakes from the Arctic GIS lake database with morphometry values predicted by the empirical equations have been left out of this figure.

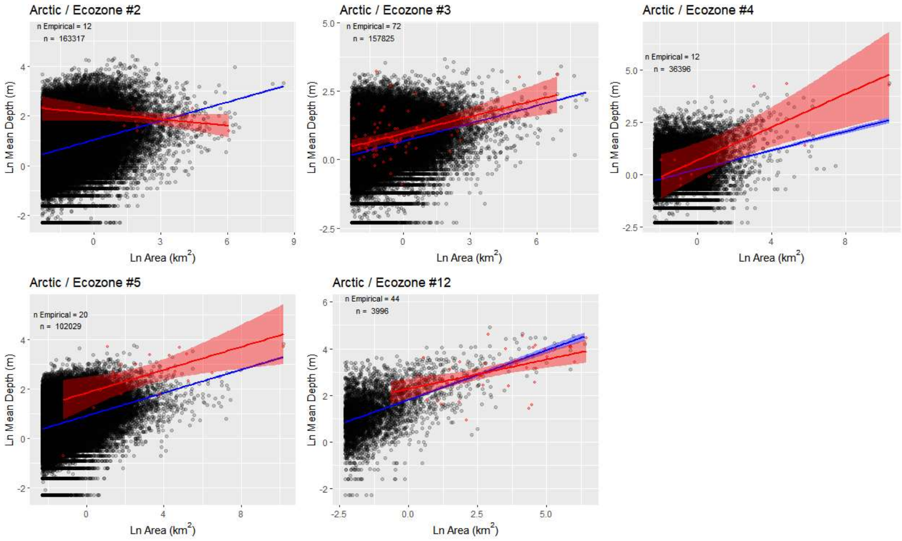


Figure S11. Relationship between area and final mean depths in the Arctic GIS lake database[16] (black dots, blue regression line) with the empirical morphometry dataset overlaid in red for the five ecozones with the greatest numbers of empirically validated lakes. The number of lakes for each dataset is indicated on the plots. All values have been log-transformed (ln). Lakes from the Arctic GIS lake database with morphometry values predicted by the empirical equations have been left out of this figure.

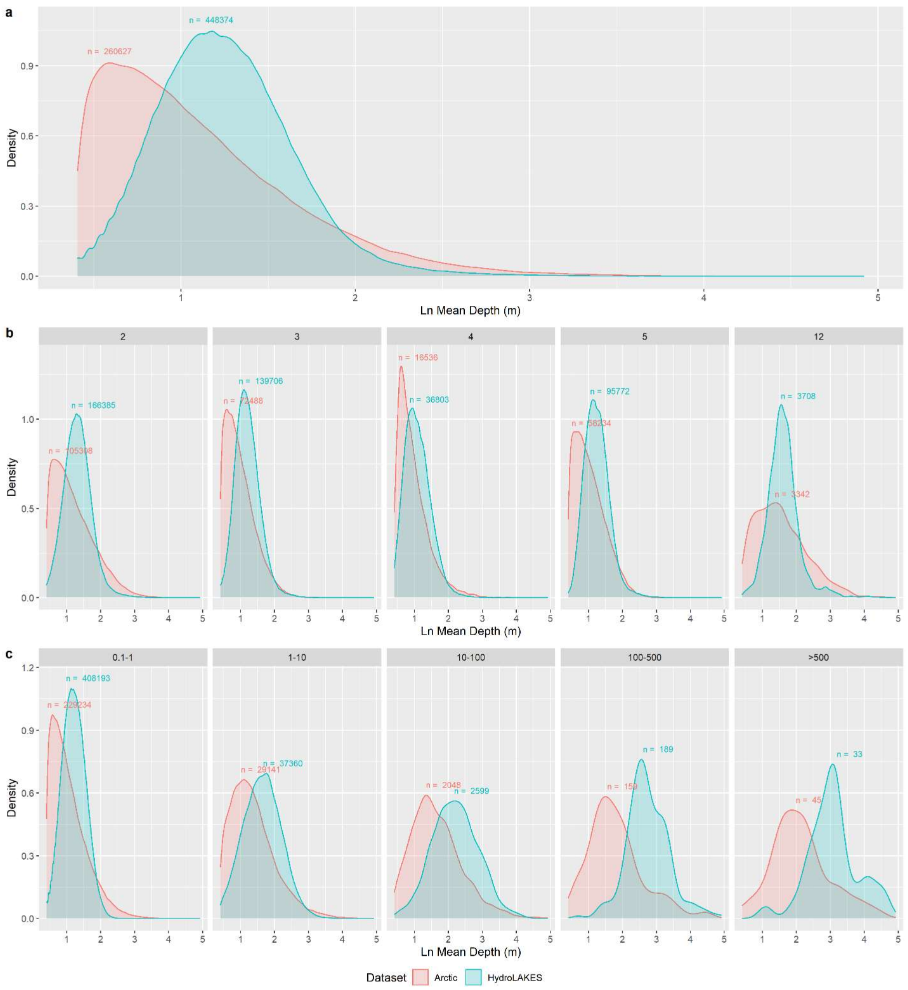


Figure S12. Distribution of mean depth values (log-transformed) among datasets (a), ecozones (b), and lake size classes (c). Sample sizes listed above maximum density plot values. Lakes with mean depths less than 1.5 m have been omitted from this figure.

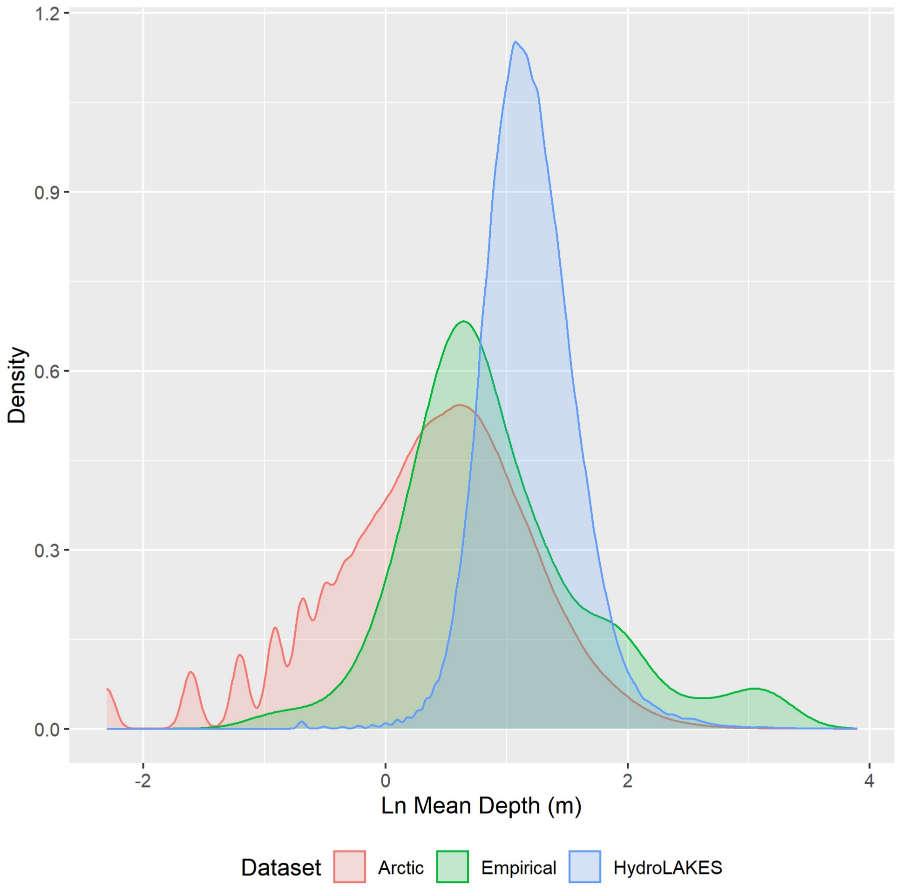


Figure S13. Distribution of mean depth values (log-transformed) for the Arctic (*n* = 135,781), HydroLAKES (*n* = 141,245), and empirical morphometry datasets (*n* = 76). All mean depth values were included in this figure, except for Arctic GIS lake database lakes with morphometry values predicted from equations derived using the empirical morphometry dataset.

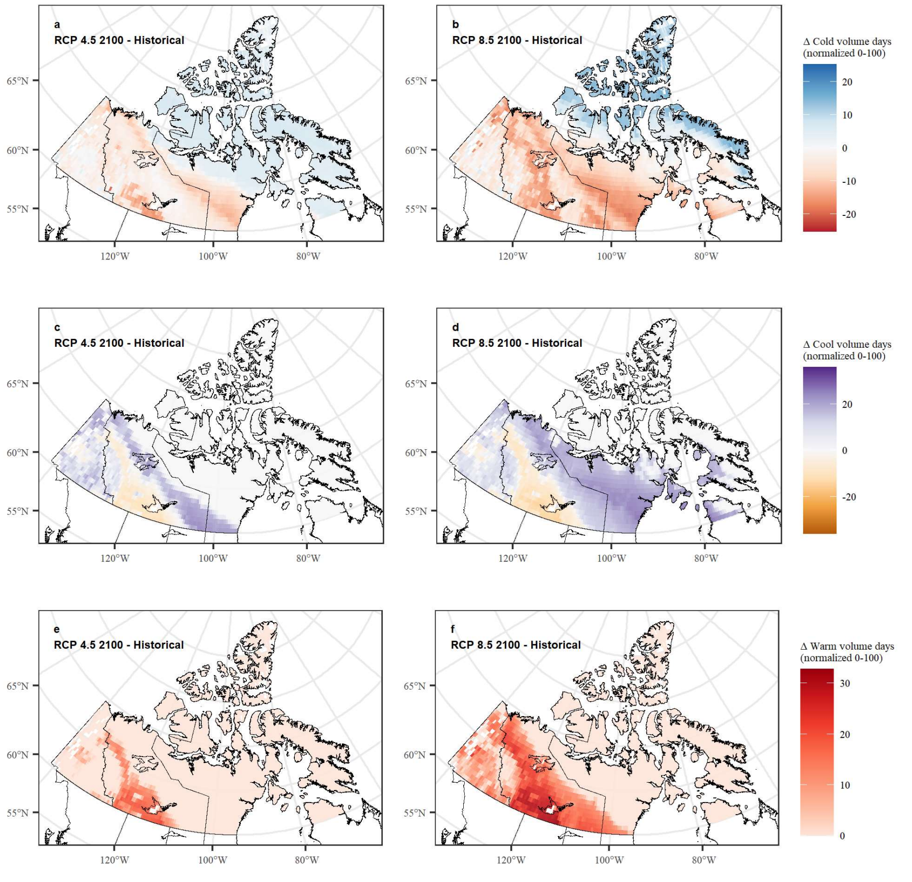


Figure S14. Difference between (Δ) historical and potential future climate scenarios in 2100 for cold-, cool-, and warmwater thermal habitat. Regional averages are represented by 0.5° grid cells. Results are shown for coldwater (a, b), coolwater (c, d), and warmwater (e, f) fishes, and for the RCP4.5 (a, c, e) and RCP8.5 (b, d, f) climate scenarios.

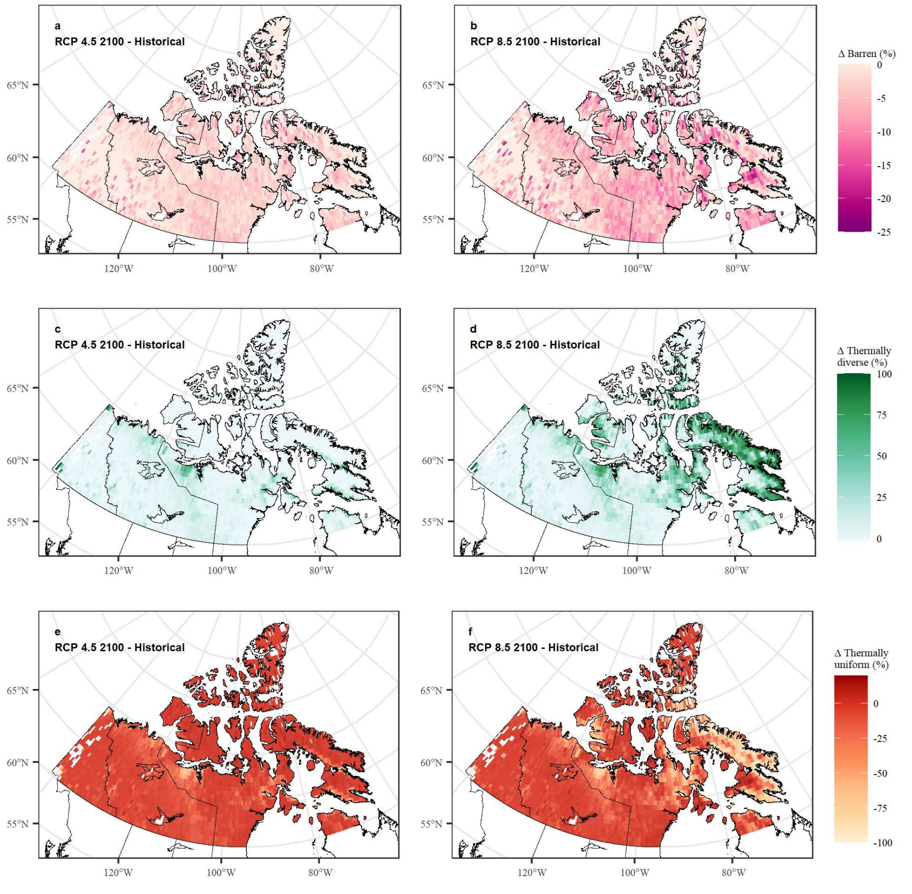
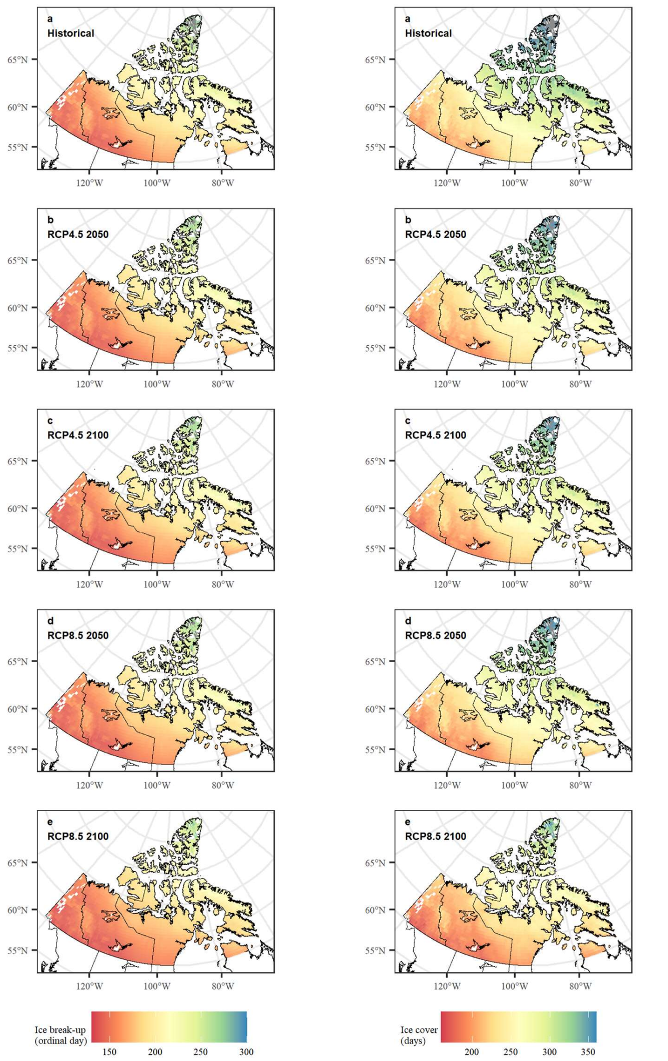
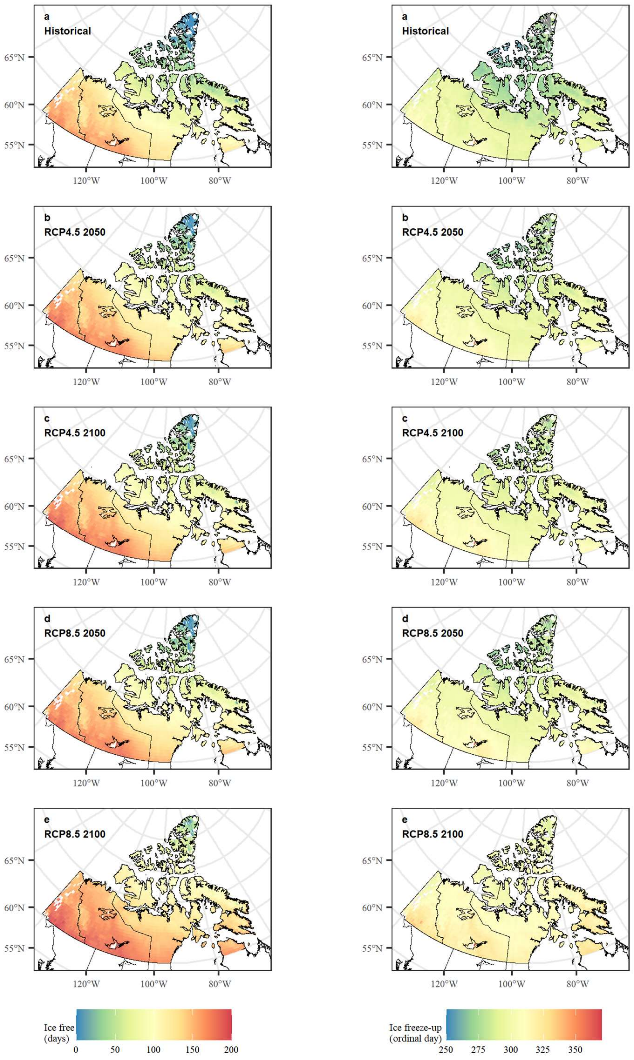


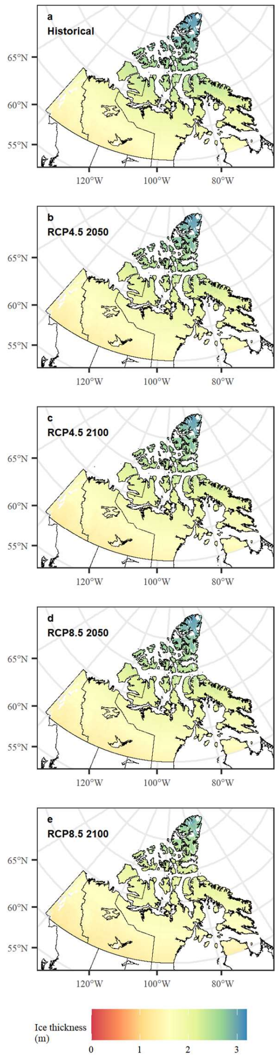
Figure S15. Percent change (Δ) of lakes belonging to different lake classes: barren (a, b), thermally diverse (c, d), and thermally uniform (e, f) represented by 0.5° grid cell averages. Outliers for barren and thermally uniform lakes are shown in dark gray and the colour scales are adjusted such that the extremes are set according to the data without those outliers, affording more emphasis on most of the data. These outliers were defined as below the 1% extreme negative value for barren and above the 1% extreme positive value for thermally uniform.

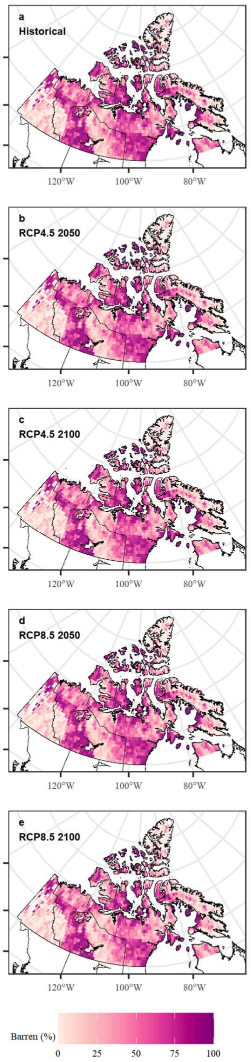


Figures S16 and S17. Ice break-up dates and ice cover days represented by 0.5° grid cell averages for historical (a) and potential future climates under RCP4.5 (b, c) and RCP8.5 (d, e) for 2050 (b, d) and 2100 (c, e).

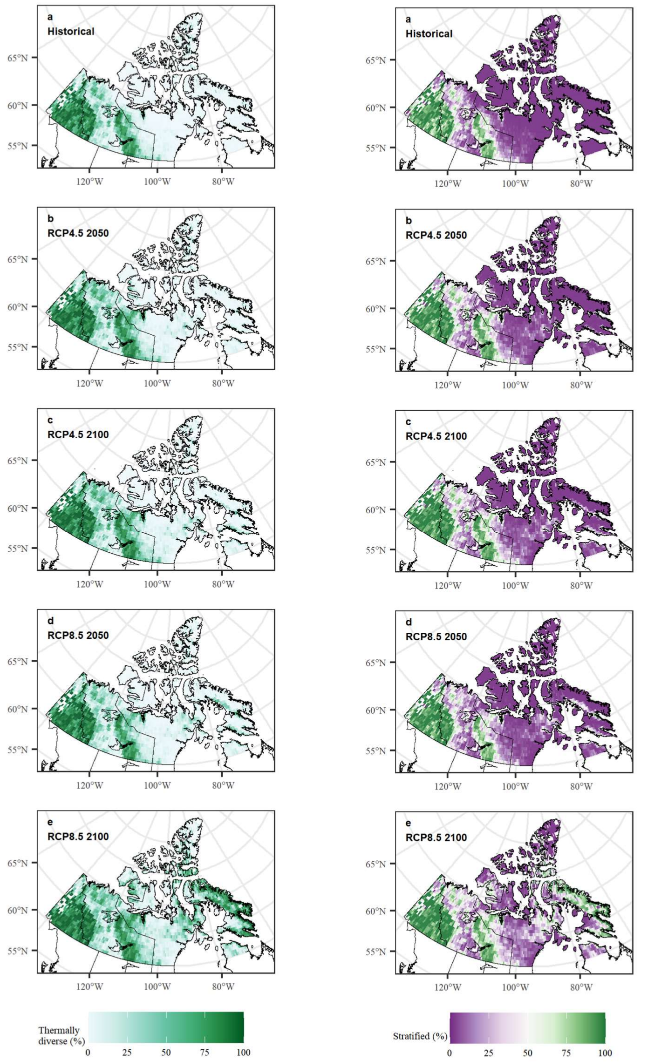


Figures S18 and S19. Ice-free days and ice freeze-up dates represented by 0.5° grid cell averages for historical (a) and potential future climates under RCP4.5 (b, c) and RCP8.5 (d, e) for 2050 (b, d) and 2100 (c, e).

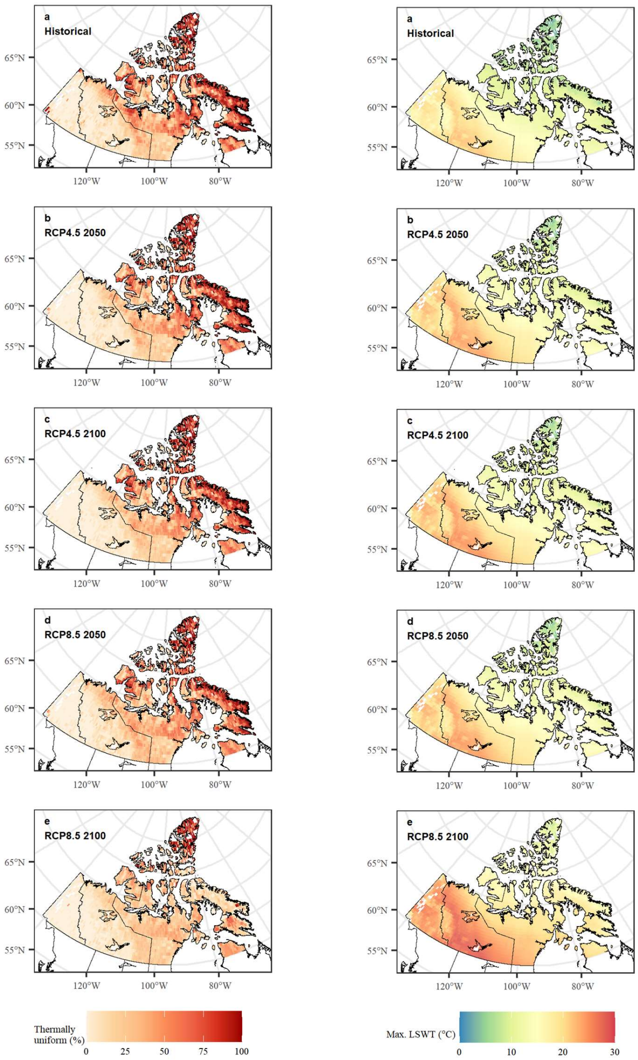




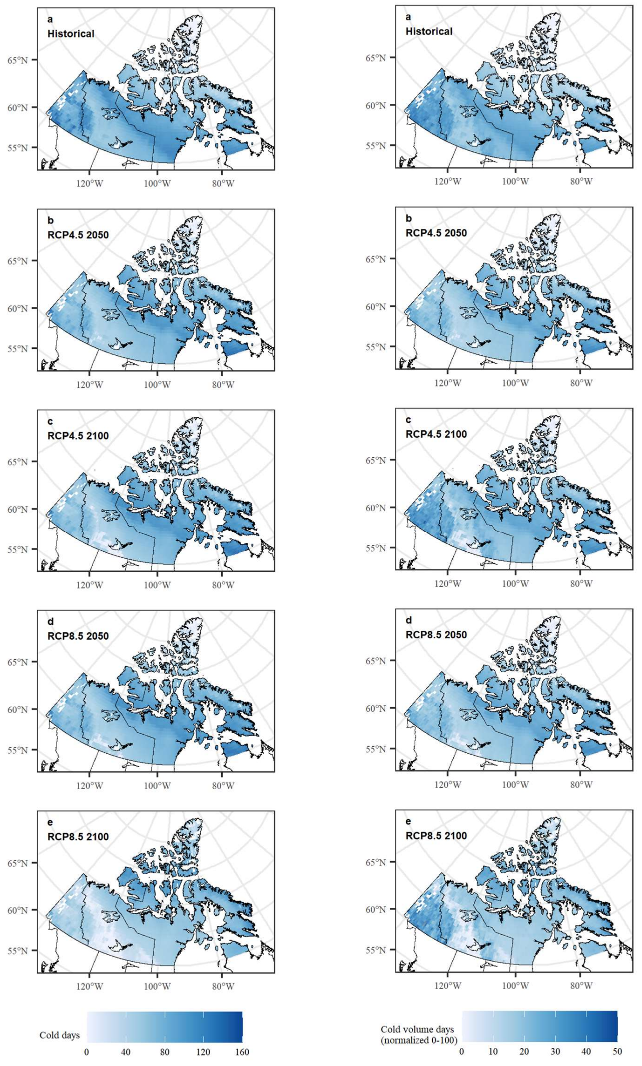
Figures S20 and S21. Ice thickness and percentage of barren lakes represented by 0.5° grid cell averages for historical (a) and potential future climates under RCP4.5 (b, c) and RCP8.5 (d, e) for 2050 (b, d) and 2100 (c, e).



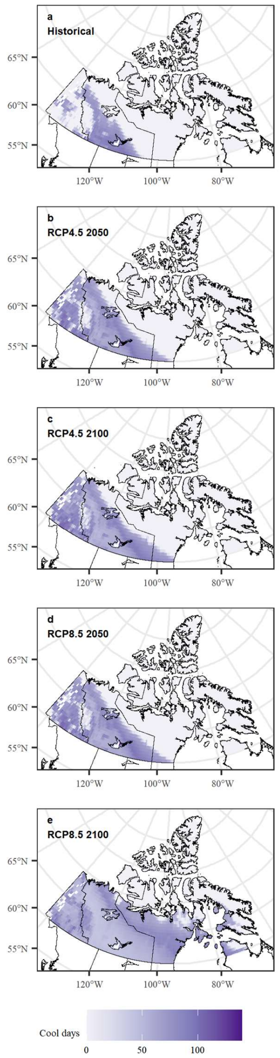
Figures S22 and S23. Percentage of thermally diverse lakes and the proportion of stratified lakes represented by 0.5° grid cell averages for historical (a) and potential future climates under RCP4.5 (b, c) and RCP8.5 (d, e) for 2050 (b, d) and 2100 (c, e).

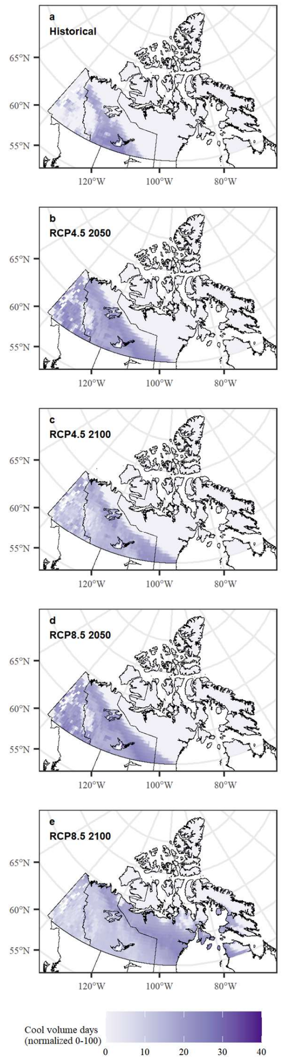


Figures S24 and S25. Percentage of thermally uniform lakes and maximum surface water temperature represented by 0.5° grid cell averages for historical (a) and potential future climates under RCP4.5 (b, c) and RCP8.5 (d, e) for 2050 (b, d) and 2100 (c, e).

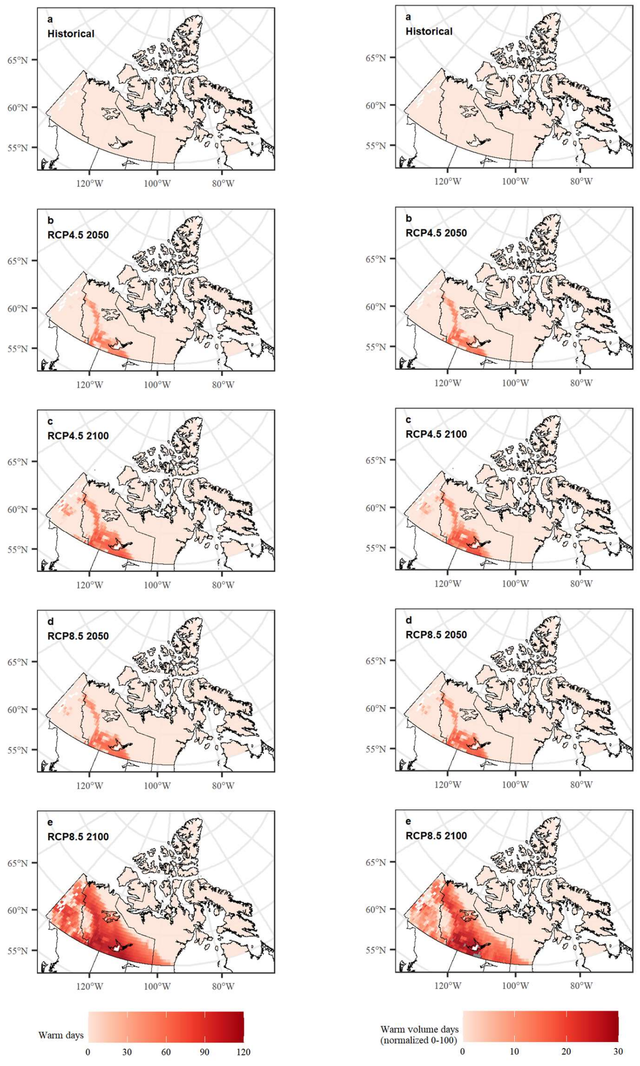


Figures S26 and S27. Cold days and cold volume-days represented by 0.5° grid cell averages for historical (a) and potential future climates under RCP4.5 (b, c) and RCP8.5 (d, e) for 2050 (b, d) and 2100 (c, e).





Figures S28 and S29. Cool days and cool volume-days represented by 0.5° grid cell averages for historical (a) and potential future climates under RCP4.5 (b, c) and RCP8.5 (d, e) for 2050 (b, d) and 2100 (c, e).



Figures S30 and S31. Warm days and warm volume-days represented by 0.5° grid cell averages for historical (a) and potential future climates under RCP4.5 (b, c) and RCP8.5 (d, e) for 2050 (b, d) and 2100 (c, e).

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Reviewer 1 Comments	**Addressed**
Tracked changes throughout.	*Suggested tracked changes incorporated throughout. Caveats are noted with additional comments explaining deviations.*
Abstract Commented [A1]: Although this is a fair statement, these effects weren't explicitly studied in the manuscript. Suggest using limited space in abstract to add another line about thermal habitat results that reflects novelty of this work.	Thank you for the suggestion. We have edited the text to highlight the thermal habitat results. The language was derived from key results stated early on in the Discussion.
Introduction – paragraph 2 Commented [A2]: Mention importance for subsistence – e.g., https://www.sciencedirect.com/science /article/pii/S030147 9719312526	Importance for subsistence has been added along with the suggested reference.
Results – Lake Temperature and Ice Projects – Paragraph 2 Commented [A3]: Suggest removing Table S1, including some of the values in the text below. Also see other comments in Supplemental.	Table S1 removed, values for 2050 included here in text as suggested.
Results – Lake Temperature and Ice Projects – Paragraph 2 Commented [A4]: See note in Methods section re: ecozones	See response in Methods section near the end of "Overview of the Methods Used in This Paper".
Results – Lake Thermal Habitat Projections – Paragraph 3 Commented [A5]: Remove S8	We believe that Table S8 provides a necessary comparison to Table S9 as it shows the contrast between the number of lakes and the volume of lakes. If Table S9 is shown on its own, the reader only gets part of the picture, as illustrated by the results in this paragraph.
Discussion – Paragraph 1 Commented [A6]: Remove, not needed and known, competition, predation etc.	Removed as suggested.
Discussion – Paragraph 1 Commented [A7]: They most likely will become habitat for nearby coldwater species first. Consider removing.	Removed as suggested.
Discussion – Paragraph 2 Commented [A8]: Depends on journal but typically, data citations not included in the Discussion section.	Duly noted. The style and formatting checklist does not refer to this as a requirement, but we will keep it in mind.
Discussion – Paragraph 3 Commented [A9]: Not sure "promotes" is the correct word perhaps "maintains"	Changed from "promotes" to "maintains" as suggested.
Discussion – Paragraph 3	Removed sentence as suggested.

Commented [A10]: Obvious, does not need to be stated.	
Discussion – Paragraph 4 Commented [A11]: Policy, decision-making and management paragraphs can be more concisely written to allow room to discuss limitations/considerations of this approach paragraph.	We appreciate this suggestion and have made some additional edits beyond those already made by the reviewer(s) to make this paragraph more concise.
Discussion – Paragraph 4 Commented [A12]: Don't think this sentence is necessary given relative level of watershed disturbance in Arctic regions vs southern Canada	Removed sentence as suggested and updated the rest of the paragraph to reflect this omission.
Discussion – Final paragraph (removed) Commented [A13]: Suggest removing this paragraph as is known and adds little to the message of this paper. Instead, it would be good to have a paragraph before the "Important issues" paragraph dedicated to the limitations of this approach e.g., what are the implications of a RMSE 2.4? what are the implications of averaging the TMAX and SWT e.g., temp variability missing https://royalsocietypublishing. org/doi/full/10.1098/rspb.2013.2612, etc.	Thank you for the suggestion and recommended reference. We have written a paragraph following your recommendations.
Methods – Overview of the Methods Used in This Paper Commented [A14]: Flow and descriptions of methods are good	Thank you for the feedback.
Methods – Overview of the Methods Used in This Paper – Regional Predictions of the Impact of Climate Change on Stratification Patterns in Canadian Arctic Lakes Commented [A15]: Why terrestrial ecozones and not freshwater ecoregions? Although there is overlap between the two, the freshwater ecoregions were delineated with knowledge of freshwater fish species turnover/nestedness (and other factors) and may better ground the thermal habitat results into more meaningful biogeographic compartments. Suggest authors either: 1) summarize by fw ecoregions; 2) compare differences between t and fw in the supplemental; and/or 3) mention in methods that fw ecoregions are another landscape-level spatial boundary but was not assessed for 'X' reasons. One could argue that the terrestrial boundaries are closely tied to temperature because they reflect some of the factors that influence	Thank you for the important consideration. In response to this, we assigned the dataset's lakes to freshwater ecoregions and conducted some statistical comparisons. This was to determine the degree to which each classification system partitions landscape-level variation in key lake and climate characteristics, specifically, maximum lake depth and maximum lake surface water temperature. Information on these comparisons is in the methods and supplementary material. We have maintained the use of terrestrial ecozones in light of our results and for the reasons outlined in the methods. In the supplement (Figure S10), we show our thermal habitat results in the context of freshwater ecoregions to provide an additional visual comparison and for those who would be interested in seeing this information.

temperature e.g., climatic variables, landforms etc. but again, summaries of habitat change are more meaningful when they are linked to fw ecoregions that a reader can then follow to understand the types of fw habitats, fish communities within each etc.	
Methods – Ground-Truthing Lake Morphometry – Paragraph 1 Commented [A16]: Mention if land gradients were derived from a DEM, and cite DEM source	See source, now included in the sentence, referenced in the same manner as it was in Campana et al. 2020 Nature Climate Change.
Methods – Ground-Truthing Lake Morphometry – Paragraph 2 Commented [A17]: 'since' typically associated with time suggest changing to because where appropriate throughout	Thank you for the suggestion. We have replaced "since" with "because", where appropriate, throughout. In some places, we removed "Since" and inserted "so" in the appropriate spot in the sentence.
Methods - Regional Predictions of the Impact of Climate Change on Fish Habitat Diversity in Canadian Arctic Lakes – Paragraph 5 Commented [A18]: State if this is the same package used to estimate mean and max depth above in Ground-truthing morphometry	We inserted some text specifying that this package was not used in the ground-truthing lake morphometry work.
Figure 2 Commented [A19]: Suggest arranging vertically and increasing size of figures so easier to read labels.	Inserted revised vertical figure.
Figure 3 Commented [A20]: Excellent figures	Thank you for the feedback.
Supplementary Tables – Table S1 Commented [A21]: Remove table because redundant with figure, can add some of the values to text in results (see edits to manuscript file), and data will be available on Dryad should one want to replicate.	Table removed and values added to results.
Supplementary Tables – Table S2 Commented [A22]: See comment for S1 and S3 is more interesting	Removed table as inferred from reference to comment for previous table.
Supplementary Tables – Table S12 Commented [A23]: Remove, already in text	Removed table listing variables for each model as suggested.
Supplementary Figures – Figure S3 Commented [A24]: Inclusion of 1:1 line is a bit odd because one expects that the maxs will be greater than the means in most cases but it is OK to retain 1:1 line, just make axes increments the same	Retained the 1:1 line as recommended and updated figure so that both axes' increments are by 2.
Supplementary Figures – Figure S6A	See updated figure with inclusion of averaged values of SWT and TMAX, shown as TMEAN.

Commented [A25]: Add averaged values from SWT and TMAX to this plot	
Supplementary Figures – Figure S7 Commented [A26]: This figure can be removed or merged with S8 although I realize range of GB lakes would be small collection of points on S8 figure	See updated figure and caption with GB lakes merged.

Reviewer 2 Comments	**Addressed**
The authors present a thorough and highly interesting prediction of future Arctic and subarctic lake habitats under multiple climate scenarios. Arctic environments are changing rapidly but details on how these changes will affect biotic communities at a regional scale is difficult to determine due to a discrepancy between how data are collected. Biological data, species occurrence and interactions etc, are often gathered at a local level (i.e. lake or catchment specific) which makes extrapolations across sparsely populated Arctic regions highly challenging. In contrast, climate models work well at these broad regional scales but are often difficult to apply at a lake specific level due to hydro-morphological variations. Gilis and colleagues appear to have squared this circle by combining detailed climate models, with lake hydro-morphological data and fish species distribution models to develop a through prediction of future habitat suitability for fishes under different climate scenarios. This is a very exciting development which will be of interest to a wide variety of scientists. I will admit that the analytical methods are somewhat beyond me so my will defer to a reviewer with greater experience in climate model and instead will focus on the ecologically relevant data which is included in the models. Overall, the authors are to be commended on an incredibly thorough analysis. I was initially skeptical of their ability to accurately model such a complex scenario but was reassured by a thorough description of their methods. For example, the inclusion of predicted windspeed, fetch area and storm prevalence in addition to temperature and ice cover when estimating lake	Thank you for the feedback on our manuscript.

stratification is encouraging and supports their findings. Further, their inclusion of fish distribution data seems appropriate. As such, my concerns are largely assuaged and I have remarkably few comments for so detailed an analysis.	
My principal concern relates to ground truthing of the model predictions. The authors present a solid ground truthing of their estimated relationship between lake size and maximum depth (Fig S3), and showed reasonable accuracy when ground truthing estimates of surface water temperature at two Artic lakes. However, further ground truthing is not conducted, given the complexity of the subsequent models estimating lake stratification and thermocline depth this seems to be a weakness in the paper and should be addressed by the authors. For example, could they include a 'leave one out' type analysis of known lake stratification data to see how well their models reflect these known data? This is an important paper, which will be of great interest to a wide variety of researchers. Provided the authors can verify their models as outlined above I suggest it is highly suitable for publication in this journal.	Thank you for raising this important point related to ground-truthing the Gorham-Boyce equations we used to estimate lake stratification and thermocline depth. In our revised manuscript (Methods section, subsection "Ground-truthing Goreham-Boyce Predictions of Thermal Structure", Figure S6C), we conducted additional model ground-truthing with Alexie Lake and Vital Lake, as well as a subset of lakes from the Toolik Field Station in Alaska. Our results indicate that the Gorham-Boyce approach produces reasonable estimates of thermocline depth for these lakes. They also indicate that stratification and mixing presence is predicted reasonably well by this approach. We believe that our additional analyses strengthen the foundation of our methods and provide sufficient ground-truthing to this aspect of our work. We hope that our additional analyses sufficiently address your comment.

21st Dec 23

Dear Mr Gillis,

Your manuscript titled "Climate change and fish thermal habitat diversity in Canada's Arctic lakes: A landscape-level assessment" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

Michael Stukel, PhD
Editorial Board Member
Communications Earth & Environment

Clare Davis, PhD
Senior Editor
Communications Earth & Environment

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have done an excellent job addressing the concerns raised for the previous version of the manuscript particularly re: reducing redundancy in the number of figures and tables, inclusion of freshwater ecoregion summaries within the supplemental, and a major re-write of the Discussion.