Title: Impacts of Changing Winters on Lake Ecosystems will Increase with Latitude

Running head: Larger Climate Impacts on High Latitude Lakes

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Abstract:

Climate warming is especially pronounced in winter and at high latitudes. Warming winters are leading to loss of lake ice and changing snow cover on seasonally freezing lakes. Past neglect of the ice cover period by lake scientists has resulted in critical data and theory gaps about the role of winter conditions in lake ecosystem function and the effects of changing winters on aquatic systems. Here we use simple models to show that the latitudinal interaction between ice cover duration and light flux seasonality has profound and underappreciated implications for lake ecosystems. Our models focus on light and temperature, two paramount drivers of ecosystem processes. We show that the amount of light arriving in lakes while they are ice covered increases non-linearly with latitude and that light climate of high latitude lakes is much more sensitive to changing winter conditions than that of lower latitude lakes. We also demonstrate that the synchronicity between light flux (a key controller of primary production) and temperature (which controls invertebrate production) decreases with latitude. Our results indicate that ice loss will lead to greater change to the productivity and nature of biotic interactions in higher latitude aquatic ecosystems and make several testable predictions for understanding the consequences of climate-induced changes across latitudinal gradients.

Keywords: Limnology, Climate Change, Winter Ecology, Ice, Arctic, Boreal

Introduction

Climate warming in the northern hemisphere is especially pronounced and rapid during winter and at high latitudes (Overland et al. 2020; IPCC 2021). Warmer winters decrease lake ice cover duration and thickness, impact ice transparency, and modify winter precipitation patterns and the accumulation of snow on lake ice (Mudryk et al. 2020; Sharma et al. 2022; Weyhenmeyer et al. 2022). Determining how these changing winter conditions affect the ecology of seasonally frozen lakes —and how lakes will respond to future winter warming — is challenging due to historic neglect of the ice cover period by most aquatic scientists.

Growing recognition of this winter knowledge gap is motivating limnologists and other environmental researchers to pay closer attention to winter and how winter conditions shape terrestrial and aquatic ecosystems and set the stage for the following seasons (Hampton et al. 2016; Berge et al. 2020; Hébert et al. 2021; Studd et al. 2021). Much of this new research is necessarily ecosystem- and site-specific and is only starting to produce synthetic frameworks for integrating winter into the full annual ecological cycle (e.g., Cavaliere et al. 2021; Jansen et al. 2021; Yang et al. 2021). The relative scarcity of winter data, regional focus of many winter studies, and gaps in theory make it difficult to detect patterns and test general hypotheses about winter ecology across broad spatial scales and to make predictions about the future of lake ecosystems.

Here we build on recent work in winter limnology to propose an explanatory framework for how winter conditions and processes integrate into the annual ecology of lakes across large latitudinal and climatic gradients. Our framework is focused on the interaction between latitudinal gradients in solar irradiance and latitudinal and regional patterns in ice and snow cover. We show that the interaction between these factors has important and not widely-recognized consequences for the light and temperature regimes of seasonally ice-covered lake. Light and temperature are paramount physical drivers of lake ecosystem function, directly affecting primary and secondary production and the fate of organic carbon. We demonstrate that the amount of light reaching the water column of lakes during the ice cover period increases non-linearly with latitude. We also show that high latitude lakes are more sensitive to climate-driven changes in their light climate than lower latitude lakes. Finally, we show that the synchronicity between light (a key controller of primary production) and temperature (which controls respiration and secondary production) decreases with latitude but becomes increasingly coupled with loss of ice.

Together, these results indicate that the ecological consequences of ice cover loss and other changes in winter conditions (e.g., changing ice clarity and snow conditions) will be greatest at high latitudes, with the impacts of climate change increasing from temperate, to boreal, to arctic lakes. Many of the elements of our proposed framework are also highly relevant for high elevation lakes, which – even at lower latitudes– typically experience long periods of ice cover.

Insolation and ice cover across latitudes

From the equator to the poles, there is a 2.4-fold decrease in total, top-of-atmosphere, annual solar energy flux, from 1.53×10^5 W/m^2 at 0° to 6.32×10^4 W/m^2 at 90°N/S. The seasonality of solar flux also changes with latitude, becoming increasingly variable at higher latitudes. This culminates in periods of complete darkness in winter ('polar night') and continuous light in summer ('midnight sun') beyond the Arctic and Antarctic Circles (66.3°N/S). This global-scale variation in solar energy flux drives latitudinal temperature gradients, with generally longer and colder winters at higher latitudes. More severe winters lead to earlier ice-on, later ice-off, thicker ice, and longer ice cover duration on high latitude lakes (Fig. 1A, B).

Lakes are unevenly distributed across the Earth's surface (Downing et al. 2006). They peak in abundance between 50 and 70°N, regions with large seasonal variation in insolation and generally cold winters (Fig. 1B). It is well-known that most of the world's lakes freeze for at least part of the year (e.g., Denfeld et al. 2018). What has not been as well-appreciated is that, on an annual basis, most lakes that freeze are frozen for longer than they are ice free. The median ice cover duration across the world's seasonally frozen lakes is estimated to be 218 days (Wang et al. 2022) and, on average, lakes above ~55°N are frozen for more than half of the year (Fig. 1B). At these high latitudes, lake ice persists late into the year and, moving poleward, increasingly overlaps with the summer period of peak light. High latitude lakes may therefore still be covered by ice during the 'midnight sun' period (Fig. 1C). At lower latitudes, many high elevation lakes also remain frozen for large parts of calendar spring and summer.

Crucially, the latitudinal interaction between lake ice cover duration and solar flux seasonality means that, at higher latitudes, a larger fraction of annual light reaches the Earth's surface when lakes are covered by ice (Fig. 1C, D). For example, at 45°N, approximately 28% of total annual solar radiation reaches the Earth' surface while lakes are ice covered. In contrast, at 75°N, approximately 56% of total annual solar radiation arrives while lakes are covered by ice (assuming median ice cover periods for both latitudes and discounting cloud cover; Fig. 1C, E). This variation in the timing of incoming solar energy in relation to ice cover phenology has important consequences for lake ecology and how lake ecosystems across latitudes respond to climate change.

Ice, snow, light, and temperature

Ice and snow attenuate light, restricting the amount of solar energy that reaches the water column of ice-covered lakes and is subsequently available for photosynthesis and heating and mixing the water. Light attenuation by ice depends on ice clarity. Clear ('black') lake ice is much more transparent than cloudy ('white') lake ice. A 1-m layer of very clear black ice (with a light attenuation coefficient K_d≈0.32 m^{-1}, Belzile et al., 2001) transmits >70% of photosynthetically available radiation (PAR) reaching its surface, compared to less than 1% for the same thickness of white ice (K_d≈5 m^{-1} or more). Snow attenuates light more efficiently than ice, and just 20 cm of snow can block 99% of PAR (Prowse & Stephenson 1986), with higher attenuation for new snow with low moisture content than for wet and/or metamorphosed snow (Perovich 2007). Thus the thickness and characteristics of ice, and even more so, snow, exert strong control on a lake's underwater light environment during winter (Cavaliere et al. 2021). In regions where black ice predominates and there is little snowfall (or limited snow retention on the ice), under-ice light levels can be high (Prowse & Stephanson 1986; Welch et al. 1987; Imbeau et al. 2021; Bramburger et al. 2023). This is also the case both during the late ice cover season when the snow has melted as well as in response to increasingly common mid- and late-winter rain-on-snow events (Hansen et al. 2014). On the other hand, in regions and periods characterized by thick snow and predominance of white ice, the under-ice environment can be very dark.

The large seasonality of solar flux at higher latitudes and overlap between the ice cover period and peak solar irradiance mean that ice and snow have increasingly important consequences for lake light regimes and total annual light budgets at higher latitudes. We illustrate these consequences using simple models where we use a combination of realistic ice and snow cover phenologies, light attenuation coefficients, and solar flux patterns to examine how the light environment of lakes changes across latitude and gradients in winter climate conditions (Fig. 2A, B). Briefly, we modeled the year-round light environment (i.e., the light flux reaching the top of the water column) of seasonally-frozen lakes at 45, 55, 65, and 75°N, using daily cloud-free irradiance data to determine the potential light flux to the lake. For ice cover periods, we included median, short (median minus 1 month), and long (median plus 1 month) ice cover durations, with median values based on the global lake ice phenology data from Wang et al. (2022). Short and long ice cover periods were included to explore how variation in ice cover duration, whether driven by anthropogenic factors (climate change-driven ice loss) or regional climate (altitude, continentality) interacts with light flux and impacts ecosystem processes. Seasonal ice and snow thickness and phenology were simulated based on literature data, published model results, and personal observations by the authors (e.g., Greenbank 1945; Schindler et al. 1974; Welch et al. 1987;

Dibike et al. 2012; Leppäranta 2015; Grosbois et al. 2017; Yang et al. 2020; Xie et al. 2023; Ghane and Boegman 2023). We used a range of realistic light attenuation coefficients for ice (K_d = 2-5) and an intermediate attenuation coefficient for snow (K_d =15; Leppäranta et al. 2012) to estimate the potential amount of light reaching the water under the ice and snow. See supplementary information section for additional detail. This approach enabled us to evaluate total lake light budgets as well as the amount of light reaching the top of the water column during the open water and ice cover periods across the modeled scenarios.

Our models reveal several important and robust patterns. First, the total annual light flux reaching the water column of lakes across the full year decreases with increasing latitude and ice cover duration (Fig. 2A). Second, the total light flux reaching the water column during the ice cover period also tends to decrease with latitude, but has the potential to increase with ice cover duration in each latitude band, and is also very strongly influenced by ice transparency and snow cover conditions (Fig. 2B). In our simulations, ice thickness and clarity generally had less effect on the under-ice light environment than snow cover, and modeled under-ice levels were in good agreement with diverse empirical observations (e.g., Schindler et al., 1974; Welch et al. 1987; Belzile et al., 2001; Lei et al., 2011; Bramburger et al., 2023; Shchapov and Ozersky 2023). For example, 0.5 m of snow-free ice in our models transmitted between ~8 and 37% of the light reaching its surface, depending on the ice K_d. Just 5 cm of snow over white ice (K_d=5), reduced under-ice light levels to <4% of surface light. Forty cm of snow over 0.5 m of ice, permitted less than 0.1% of incident light to reach the unfrozen water. Because of their large effect on light transmission, the degree to which snow and ice thickness and clarity influence total winter light flux also increases with increased duration of the ice cover period (Fig. 2B).

Third, the proportion of total annual light reaching the water column during the ice cover season increases with latitude and ice cover duration (Fig. 2C). In other words, lakes at high latitudes and with longer ice cover duration for a particular latitude band receive more of their total annual light budget when they are covered by ice. In our models, lakes at 75°N, received up to 40% of their total annual light budget during ice cover (median = 10.5 % across all simulation scenarios). In contrast, lakes at 45°N received no more than 17% of their total annual light budget during ice cover, with a median of 5.5% across all scenarios. Given the strong seasonality of cloud cover in the Arctic (high cloud cover in summer and early autumn and low cloud cover in late spring; Liu & Schweiger 2017), our approach may actually underestimate the amount of light reaching high latitude lakes during their ice-cover period.

Finally, the effects of natural and climate change-induced variation in ice cover duration are also magnified with latitude (Fig. 2D). Because a larger fraction of the annual light budget arrives during the ice cover period at high latitudes, a one-month difference in ice cover duration has a larger effect on a lake's under-ice (and total annual) light environment at higher latitudes. This means that an equal duration of ice cover loss will have different impact on lakes across latitudes or lakes that experience different winter severity. In particular, high latitude lakes and lakes that have especially long ice cover periods (e.g., because of a strongly continental climate or high altitude), will experience much larger increases in their annual light budgets than lakes with shorter ice cover duration. For example, a loss of 1 month of ice cover (15-day earlier ice-off in spring and 15-day later ice-on in fall) for a lake with median ice cover duration at 45°N (142 days) will lead to a 9 – 38% (median = 13%) increase in total annual light flux; an equivalent loss of ice cover for a lake that has an extra month of ice cover duration at 45°N will lead to an 17 – 80% (median = 20%) increase in total annual light. In contrast, similar losses of ice for a lake at 75°N, would result in an increase of 13 – 42% (median = 37 %) in annual light flux for a lake with a median (270 days) ice cover duration and of 20 –104% (median = 74%) for one that has an extra month of ice cover. The degree of increase in total light will be strongly related to snow depth and ice clarity, with the greatest increases for lakes that experience deep snow cover and thick white ice.

Latitudinal patterns of solar flux and ice cover seasonality also have important consequences for lake temperatures and their response to future climate warming. At lower latitudes, ice-off generally occurs earlier in spring, when light levels are still increasing toward their annual maximum. At these latitudes, water temperature in most lakes increases rapidly after ice-off, stratification often sets in quickly, and the epilimnion continues to gain heat through the summer, reaching high temperatures by July (Fig. 3A). For example, in central Minnesota (USA, 45°N), ice-off typically occurs in late March, stratification sets in within 2 – 3 weeks, and peak summer temperatures reach 25°C or more (e.g., Tansim et al. 2021). At high latitudes, ice cover persists longer (e.g., until mid-July on Victoria Island, Canada, 70°N; Imbeau et al. 2021), and overlaps more closely with the annual peak of solar flux than at lower latitudes (Fig. 3A). While radiative heating of the under-ice water does contribute to the heat budget of high latitude lakes and cause under-ice convective mixing, it rarely increases water temperatures above 4°C, and most of the heating does not occur until ice is off the lake. High latitude lakes that do stratify may do so sometime in June – July, reach peak temperatures of 12 – 15°C in August, then cool rapidly and freeze by September or October. In many parts of the Arctic, lakes above 60°N never stratify, with peak summer temperatures of no more than 5 – 10°C (Schindler et al. 1974; Welch et al., 1987; Sorvari et al. 2000; MacIntyre et al. 2009; Saros et al. 2016).

These differences in the timing of water heating and solar flux lead to latitudinal variation in the synchronicity between the timing of peak light and peak temperatures. At lower latitudes, peak light and peak temperatures are closely coupled. In central Minnesota, the period of peak irradiance occurs when lakes are stratified and the surface temperature is >20°C (Fig. 3A). At high latitudes, the timing of peak light and temperature are decoupled. Irradiance peaks during late ice cover and shortly after ice-off when the lake is mixed and the water column is still cold. By the time lakes at 70°N reach maximum surface temperatures in August, light levels are already decreasing from their June peak. Thus, the portion of the annual light budget that arrives when water temperatures are low is greater at high latitudes. Light and temperature are the main physical controllers of many biological and biogeochemical processes, and the latitudinal variation in their synchronicity will have important consequences for lake ecosystems. This latitudinal pattern also once again highlights that high latitude lakes with long ice cover periods are more susceptible to ecological change due to ice loss than lower latitude lakes.

Consequences for biology

Light is the main physical driver of primary production in aquatic systems, with temperature becoming increasingly important under light-saturated conditions (Tilzer et al. 1986; Fahnenstiel & Scavia 1987; Sterner 2010, Edwards et al. 2016; Sherman et al. 2016). In contrast, invertebrate metabolism, activity, and production are strongly temperature-dependent, from the individual to the community level (Patalas 1975; Herzig et al. 1980; Plante and Downing 1987; Huntely and Lopez 1992; Hansen et al., 1997; Shuter and Ing 1997; Kelley and Jones 2023). Thus, seasonal variation in irradiance and temperature across latitudes should result in predictable latitudinal patterns in the timing and magnitude of primary and secondary production and the interaction between these processes. We explore how these processes play out across latitudes and snow and ice cover regimes with a simple conceptual model (see supplementary information section) of primary and secondary production and biomass dynamics for lakes at 45°N and 75°N, varying ice cover duration and snow conditions and using published and unpublished data to simulate annual temperature dynamics. In our models, primary production is driven primarily by light, with a secondary role for temperature (Q_{10} = 1.5; Sherman et al. 2016). Secondary production is primarily driven by temperature (Q_{10}=2.7; Huntely and Lopez, 1992; Hansen et al., 1997). Primary producer biomass changes in response to production and due to grazing by invertebrates, with consumption proportional to consumer biomass. While this model relies on numerous simplifying assumptions, we believe it serves as a useful idealized representation of phytoplankton, periphyton, zooplankton, and littoral zoobenthos dynamics and highlights the main consequences of the latitudinal variation in the seasonality of light and temperature, including due to variation in ice and snow regimes.

Latitudinal variation in total annual solar flux, solar flux seasonality, and ice cover duration –with lower and more seasonally variable solar flux and longer ice cover duration at high latitudes– suggest that total annual primary production of lakes should decrease with increasing latitude (as has been shown by, for example, Brylinsky and Mann 1973) and display greater seasonal variability. Longer ice cover and its greater overlap with the period of peak solar irradiance at high latitudes also means that a higher proportion of the total annual pelagic and benthic littoral primary production will occur under the ice and shortly after ice-off, when the water is still cold (Fig. 3). The greater overlap between peak irradiance and ice cover at higher latitudes also means that climate change-driven loss of late season ice cover will result in greater relative increases in total annual primary production in higher latitude lakes (Fig. 3). The degree to which snow cover conditions and ice clarity affect the timing and magnitude of under-ice primary production will also be generally greater at higher latitudes, meaning that changes in snowfall, its accumulation and retention, as well as ice transparency will have larger consequences for primary production at high latitudes (Fig. S3).

Integrated annual zooplankton and littoral zoobenthos production and biomass can also be expected to decrease with increasing latitude because of lower average annual temperatures and primary productivity (Fig. 3). The invertebrates of high latitude lakes experience long periods of low temperatures, darkness, and low plant food availability during late fall and most of winter. At 75°N, the open water period of most lakes is brief and peak temperatures rarely exceed 10°C. Thus, high latitude lakes will produce less invertebrate biomass across the year with lower peak summer production rates and biomasses compared to lower latitude lakes. The long period of unfavorable winter conditions in high latitude lakes should also result in lower invertebrate biomasses through the winter and less survival until spring (Kunkel, et al. 2016; Hébert et al. 2021).

The partly independent effects of light and temperature on primary and secondary production should result in an increasing mismatch between the timing of peak plant and invertebrate consumer growth with latitude. At lower latitudes, temperature and light increase approximately in tandem, peaking concurrently in mid-summer (Fig. 3A). At higher latitudes, there is a considerable lag between increasing light and maximum water temperatures, resulting in a peak solar flux when water temperatures are still around 4°C or lower (e.g., if lakes are still ice-covered). This increasing mismatch should have implications for plant-grazer interactions, the relative importance of top-down vs. bottom-up controls on primary producers, and the fate of primary production across latitudes.

Planktonic and benthic littoral grazers should exert weaker top-down pressure on spring and summer phytoplankton and periphyton in high latitude lakes, where under-ice and early spring plant growth occur at low temperatures that are less favorable to grazer activity. Weaker top-down effects on spring primary producers at high latitudes could also be exacerbated by less overwinter survival of zooplankton (Hébert et al. 2021) and littoral zoobenthos. This should result in higher annual primary producer to grazer biomass and production ratios at high latitudes as well as reduced utilization of primary production by consumers. High latitude lakes may therefore have more efficient export of ungrazed phytoplankton to the sediments for either burial or consumption by profundal benthic organisms, and higher relative standing stocks of littoral periphyton. Loss of ice will increase the synchronicity of light and temperatures at high latitudes, resulting in a possible reduction in primary producer to grazer production and biomass ratios and higher potential for top-down control of primary production (Fig. 3). In regions where climate change is leading to increased snow cover, deep snow (or opaque ice) can delay substantial primary production until later in spring, also increasing the synchronicity between primary and secondary production relative to lakes with little snow and clear ice (Fig. S3).

Caveats and conclusions

Lakes vary widely in depth, elevation, concentrations of nutrients, optical properties regulated by dissolved and particulate matter, and species composition. To focus on the role of ice and snow cover in shaping lake ecosystems across latitudes, we chose to focus on how idealized phytoplankton-zooplankton and periphyton-littoral zoobenthos food chains may respond to expected changes in light and temperature, which are paramount drivers of lower food web processes in lakes. Our estimates of underwater light availability carry uncertainties related to seasonal and regional differences in cloud cover, snow phenology and characteristics, water clarity, and mixing regimes. Many factors and food web components (e.g., the microbial loop, fish) that were omitted here have important impacts on lake ecosystems, interact with ice and snow conditions and, like climate, vary across large geographical scales. As such, any small set of individual lakes from different latitudes may not conform to the patterns we discuss here. Nonetheless, our three key claims of: 1) an increased relative role of under-ice and cold water period primary production in high latitude lake ecosystems; 2) greater sensitivity of high latitude lakes to ongoing and predicted future changes in snow and ice conditions; and 3) the greater relative change in productivity and biotic interactions that high latitude lakes will experience with climate change driven reductions in lake ice cover, are based on first principles and suggest many testable predictions about the full year seasonality of lakes across broad latitude gradients, including the role of winter and ice cover in shaping lake ecosystems.

Figures:

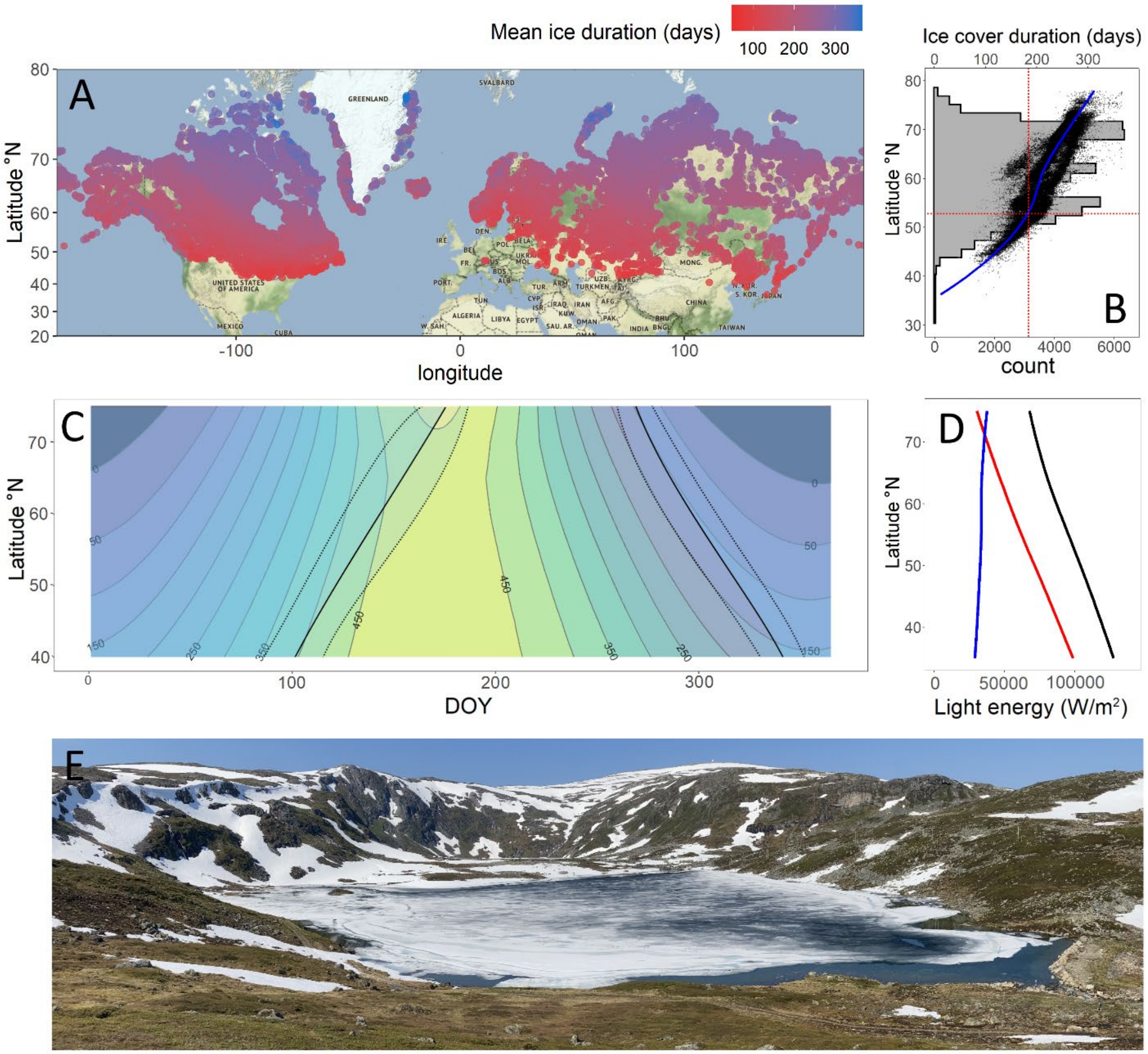

Fig 1: A) ice cover duration across 67,291 lakes from Wang et al. (2022); B) frequency distribution of seasonally-freezing lakes (gray histogram), with median ice cover duration across latitudes (blue line) in the northern hemisphere; and red dashed lines showing approximate latitude where median ice cover duration = 183 days (based on results from Wang et al. 2022); C) contour plot showing annual pattern of solar flux (W/m^2/day) between 30°N and 80°N with average (solid black line) and ±1SD (dotted black line) timing of ice-on and ice-off across the 67,291 lakes shown in panel A; D) change in total potential (not accounting for clouds) solar irradiance arriving at the Earth's surface (black line) across latitudes in relation to amount of light arriving during the typical ice cover

period (blue line) and open water periods (red line) for lakes with median ice cover duration across latitudes; E) Lake Mellomvatnet, (69.71°N, 18.82°E; 396 m A.S.L) on June 27, 2022, one week after the summer solstice.

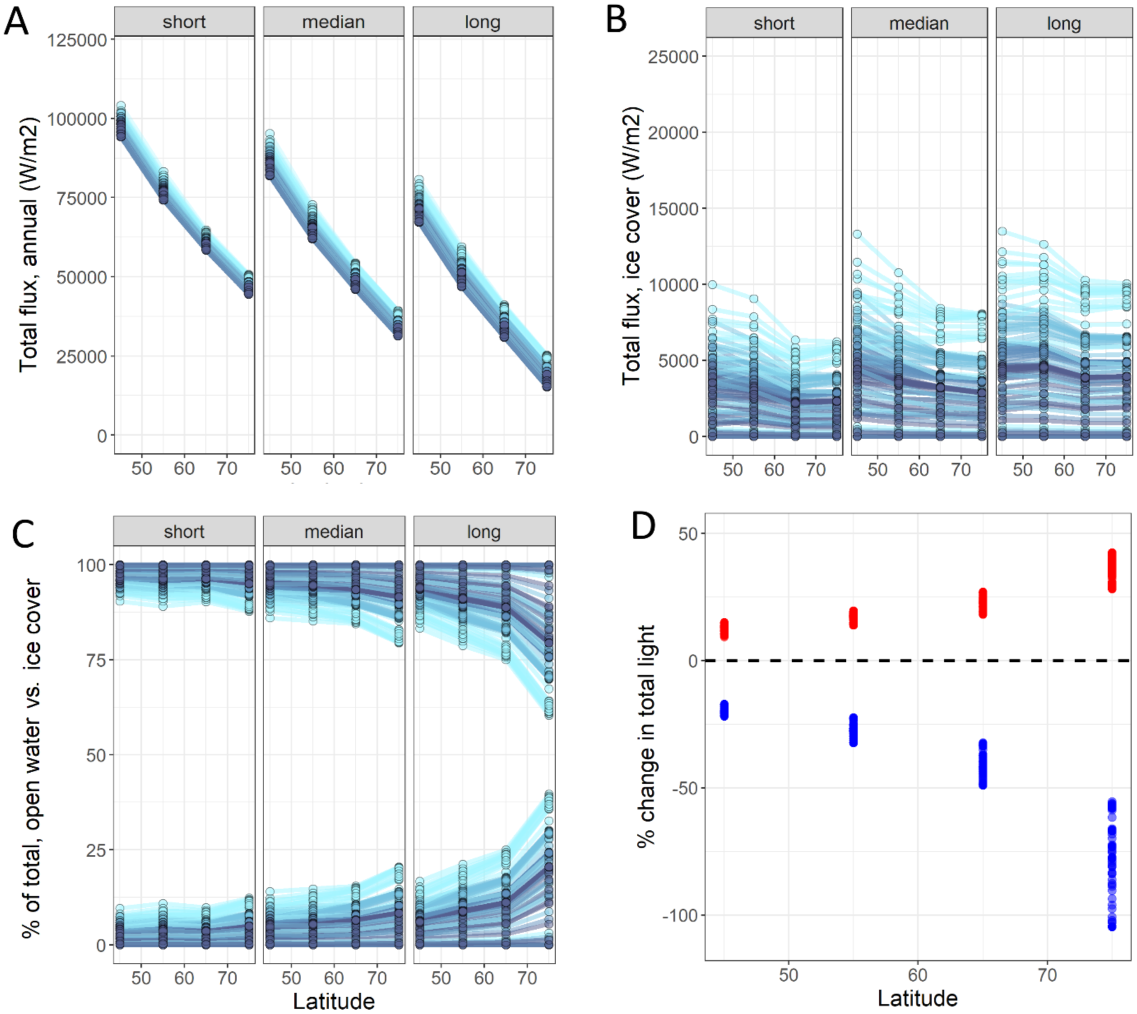

Fig 2: Light environment in lakes as a function of latitude and ice and snow conditions. A) total light flux reaching the water column of lakes across latitudes (45°N to 75°N) under short, median, and long ice cover duration scenarios for each latitude band. Points and lines represent variation due to snow cover conditions (duration & thickness) and variation in light attenuation by ice (K_d ranging from 1 to 5, represented by light to dark blue color). B) same as in A, but showing total flux reaching the water column during the ice cover period. C) the relative portion of total annual light flux reaching the water column during the open water period (lines and points along top portion of panel) vs. during the ice cover period (bottom portion of panel); interpretation of points and lines as in panels A and B. D) percent change in the total annual light level arriving into a lake among median (black dashed line), short (red points), and long (blue points) ice cover duration scenarios across latitudes.

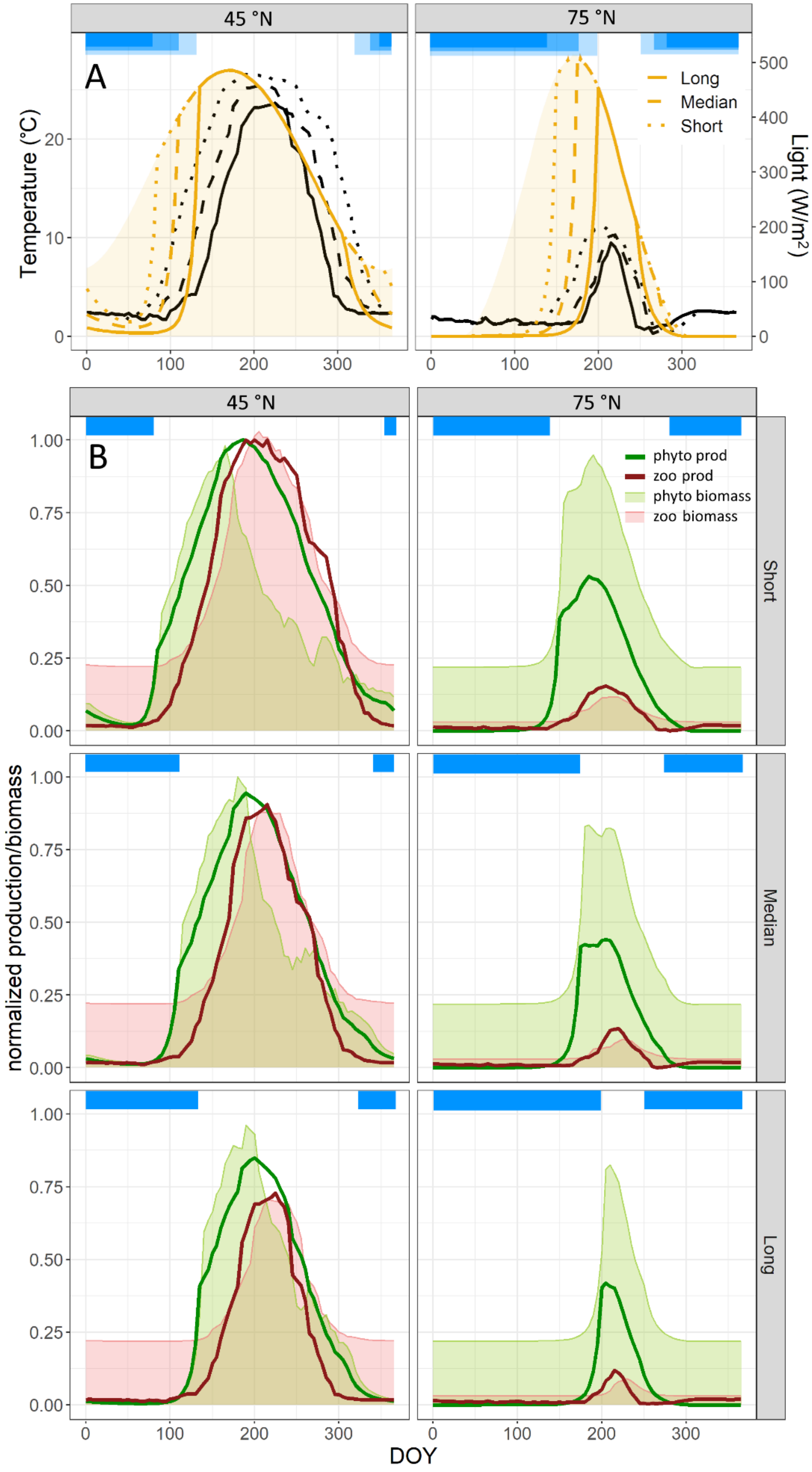
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Fig 3: Seasonality and predicted effects of variation in ice cover duration on physical conditions (light, temperature) and plankton and littoral benthic productivity/biomass at 45°N and 75°N. A) Seasonality of solar flux (light yellow background) and effect of attenuation by ice and snow (ice K_d=3, snow duration at 80% of ice cover duration, 5 cm max thickness) on the under-ice light environment (yellow lines), along with surface water temperature (black lines), with line type (solid, dashed, dotted) corresponding to different ice cover duration scenarios (short, medium, long). B) Normalized modelled primary (phytoplankton and phytobenthos) and secondary (zooplankton and littoral zoobenthos) production and biomass across ice cover duration scenarios. Light blue blocks show ice cover duration for the three ice cover duration scenarios.

Data availability

No original data were used in this manuscript. All sources of published data are referenced.

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Author contributions:

TO and AP conceived the manuscript and TO, AP, MR, and EL developed the ideas. TO led writing of the text, with input from AP, MR, and EL. TO performed all modelling and data visualization with input from AP, MR, and EL.

Competing interest declaration:

The authors declare no competing interests.

Supplementary information:

This file contains additional information on modelling ice and snow cover conditions, light penetrations through snow and ice, and primary and secondary production, as well as figures S1-3. Fig. S1 illustrates the ice and snow cover duration and thickness scenarios used to model the underice light flux. Fig. S2 shows the effect of different snow and ice cover duration and thickness scenarios, along with effects of varying the ice light attenuation coefficient on the underice light environment across modelled scenarios in relation to potential available solar flux. Fig. S3 illustrates the effect of extreme snow conditions on light, temperature and biotic processes.

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Supplementary information section

Model details:

<u>Ice and snow cover scenarios</u>: to assess the effect of snow and ice cover on the light climate of lakes across latitudes, we constructed ice and snow cover scenarios for lakes in 10° latitude intervals (45, 55, 65, 75 °N). Ice cover duration, ice-on, and ice-off dates were determined based on values in the Global Annual Lake Ice Phenological Dataset 1861-2099 (Wang et al. 2022). The dataset contains satellite-derived ice phenology data for the years 2001-2020 for 74,245 global lakes. We trimmed the dataset by excluding lakes that did not freeze every year during the 20 years of the observation period, lakes that were < 30 °N, and lakes at elevation >1,000 m above sea level (ASL), leaving us with a set of 67,291 observations. We averaged ice-on, ice-off and ice-cover duration data for the available 20 years for each of the lakes. Few low-elevation lakes below ~40 °N regularly froze, so further analyses were restricted to the 45-75 °N latitude interval.

Ice thickness evolution for each latitude (e.g., 45 °N) was modelled based on the median ice-on and ice-off dates for lakes in the corresponding 10 ° latitude band (e.g., 40-50 °N), a wide range of literature data on empirical and modelled ice evolution in diverse lakes (Greenbank 1945; Schindler et al. 1974; Welch et al. 1987; Dibike et al. 2012; Leppäranta 2015; Grosbois et al. 2017; Yang et al. 2020; Clark et al. 2022; Xie et al. 2023; Ghane and Boegman 2023; Shchapov and Ozersky 2023), and the author's personal observations. Ice growth in fall/winter and its destruction in the spring were modelled as a 4th-order polynomials (Fig. S1), with maximum thickness increasing from 0.7 to 1.5 m from 45 to 75 °N. In addition to these 'median' scenarios, we created ice cover models for a hypothetical 'long' ice cover season for each latitude (e.g., for a high elevation location or a location with a cold continental climate), and 'short' ice cover season scenarios, as might be expected under continuing climate change or a relatively warm maritime climate. The 'long' and 'short' scenarios have 1-month longer and 1-month shorted ice cover scenarios compared to the median scenarios, with lakes in the 'long' scenarios having a 15-day earlier ice-on and 15-day later ice-of then the 'median' lakes. Similarly, the 'short' scenario lakes have 15-day later ice-on and 15-day earlier ice-off than 'median' lakes. These 'long' and 'short' ice cover scenarios allowed us to assess how lakes with different ice cover duration and at different latitudes compare and respond to climate-driven ice loss. The maximum ice thickness for each latitude bands was increased or decreased by 20 cm for the 'long' and 'short' scenarios, respectively to represent the decreased ice thickness that typically corresponds to shorter ice cover duration.

Snowfall amounts and the accumulation of snow on lakes are highly variable on global and regional scales (Kunkel et al. 2016; Pulliainen et al. 2020; Dou et al. 2021). We modelled several snow cover scenarios for all of the above-described ice cover scenarios. Three basic scenarios were examined: 60%, 80%, and 100% scenarios corresponded to snow cover over the ice for 60%, 80%, and 100% of the ice cover season, centered on the middle of the ice cover period. Thus, for 60% scenarios, the first and last 20% of the ice cover period were snow free, and so on. The near absence of snow over the ice at the start and end of the ice cover season is typical of many locations. For each snow-cover duration scenario we also varied maximum snow thickness in 5 cm increments, from 0 cm to 80 cm. Snow accumulation and melting was modelled 3rd order polynomial equations (Fig. S1). Thus, our snow cover scenarios capture diverse conditions between the two extremes of completely snow-free ice (e.g., lakes in cold desert regions) and ice that is covered by a thick blanket of snow for the entire period of ice cover (e.g., high elevation lakes).

<u>Underice light climate:</u> We used our snow and ice cover scenarios to model the potential light climate under ice and snow cover for lakes across latitudes and with varying ice cover and snow cover regimes. We obtained daily cloud-free solar flux data (as W/m2) for 45, 55, 65, and 75 °N from NASA's ModelE AR5 Insolation at Specified Location website (NASA 2023). Daily solar flux data were combined with daily modelled ice and snow thickness and with realistic ice and snow light attenuation coefficients (kd) to determine the amount of solar energy potentially penetrating the snow and ice cover and entering the unfrozen water (Fig. S2). We varied ice kd values from 2 to 5 in increments of 1 to include the natural variation in ice clarity on our estimates of light climate; snow kd was set at 15 (Prowse & Stephenson 1986; Belzile et al., 2001; Leppäranta et al. 2012; Bramburger et al. 2023; Shchapov and Ozersky 2023). The combination of solar flux data with modelled ice and snow phenology allowed us to determine how much solar radiation arrived into lakes during the open-water and the ice-cover period across diverse ice and snow cover scenarios and to assess how variation in snow cover and ice duration affects the light budget of lakes across latitudes.

<u>Primary and secondary production and biomass:</u> to illustrate the ecological consequences of latitudinal variation in light and thermal regimes we used simple models to approximate how primary producer (phytoplankton and periphyton) and consumer (zooplankton and littoral zoobenthos) production and biomass responds to seasonal variation in light and temperature conditions for a lakes at 45 °N and at 75 °N, experiencing 'median', 'short', and 'long' ice cover. Our models are not meant to be fully realistic, but rather to capture how the relatively independent effects of light and temperature affect primary and secondary production and their synchronicity. Primary production was estimated mainly as a linear function of light with a secondary effect of temperature, using a Q10 value 1.5 (Sherman et al. 2016). Secondary production was modelled solely as a function of temperature, using a Q10 value 2.7 (Huntley

and Lopez 1992). Consumer biomass is simply a function of production and mortality, the latter parametrized to ensure that values return to baseline at the end of the year. Primary producer biomass is a function of production and loss, which is proportional to consumer biomass and also parametrized so it returns to baseline values at the end of the year. We emphasize that we do not claim that our very simple model is a realistic and complete representation of producer-consumer interactions and dynamics. Rather, it serves as an idealized heuristic representation of plant and animal dynamics (e.g., Sommer at al. 2012), which are differentially affected by light and temperature.

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Supplementary figures:

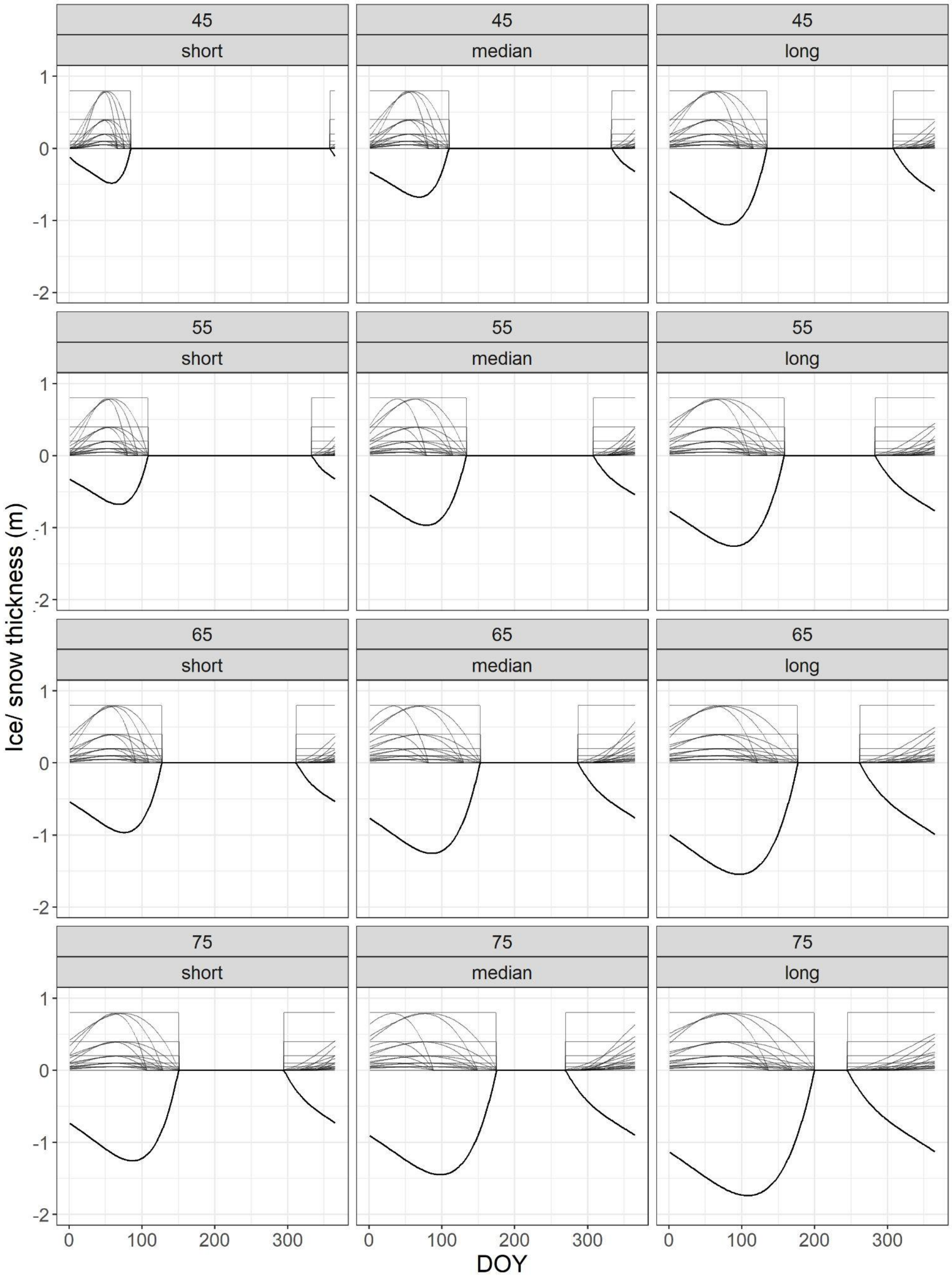


Fig S1: Modelled ice (negative values) and snow (positive values) thickness scenarios across latitudes and ice cover duration ranges. These ice and snow scenarios, along with realistic snow and ice light attenuation values, were used to model under-ice light regimes (Fig. S2).

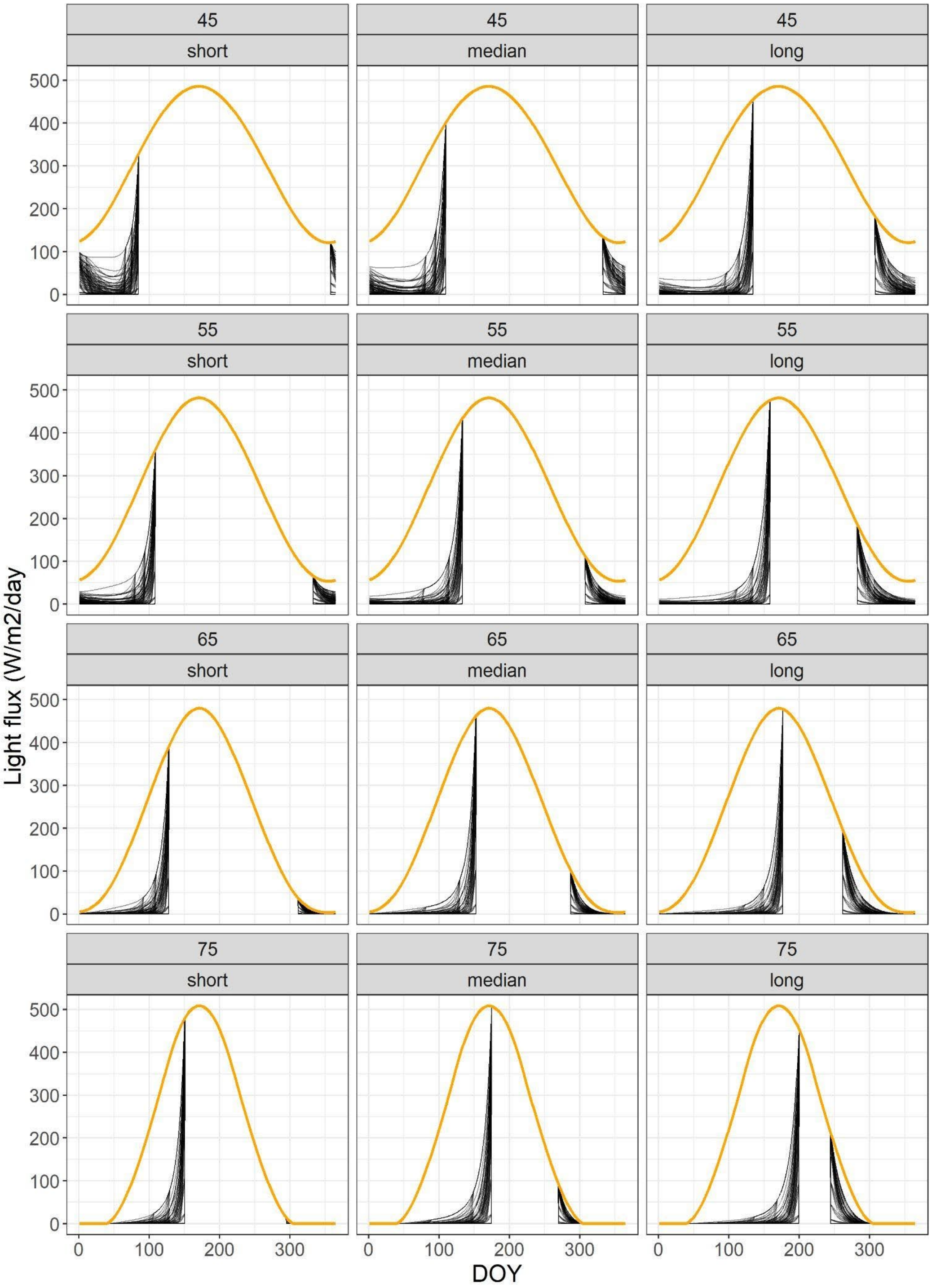
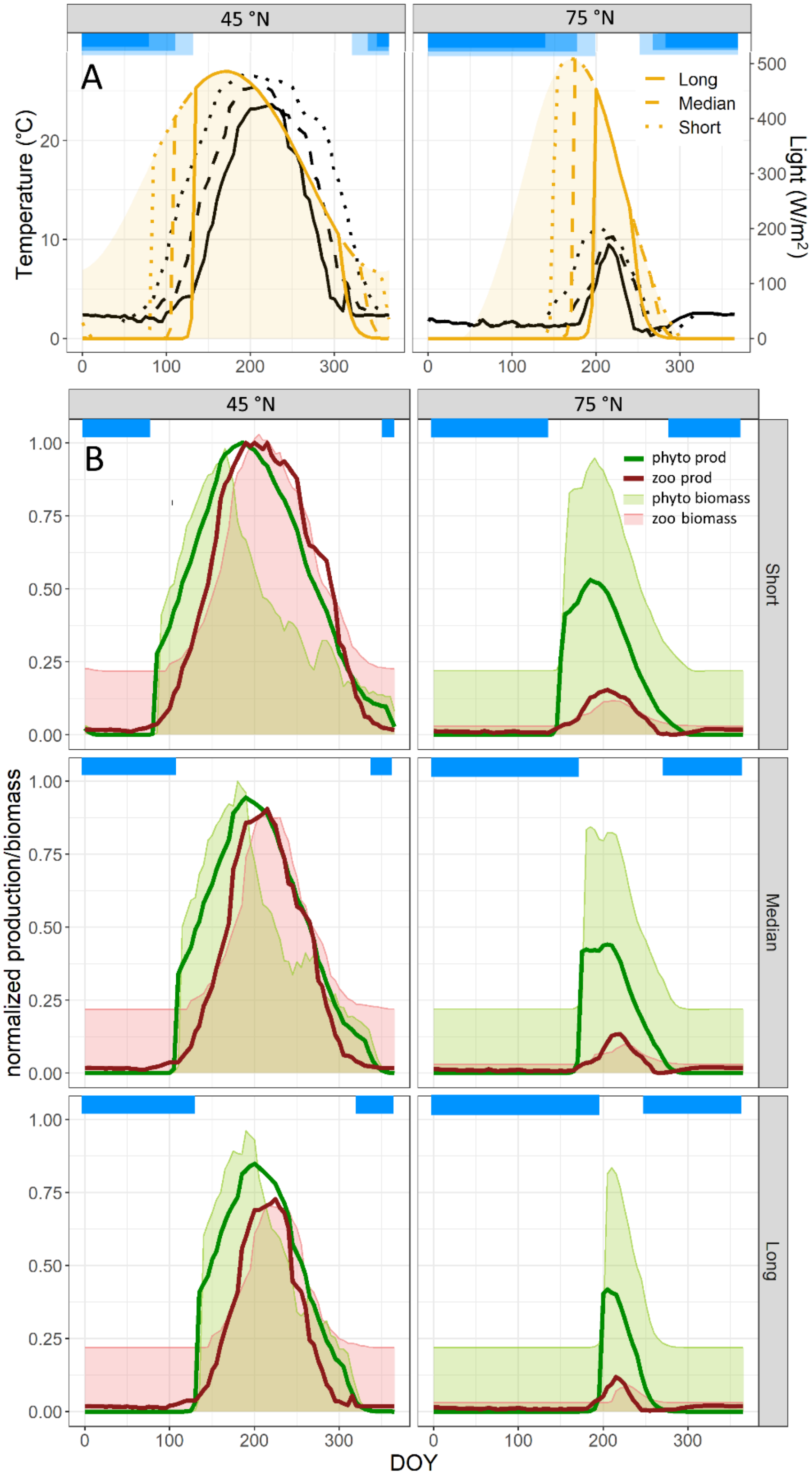


Fig S2: Modelled light flux scenarios. Yellow lines represent maximum (cloud-free) potential daily light flux, not accounting for attenuation by snow and ice. Thin black lines represent underice light, after accounting for attenuation by light and snow under different ice and snow duration and thickness scenarios and attenuation coefficients.



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698 **Fig S3**: same as main text Figure 3, but for long (snow cover duration= 100% of ice cover duration) and

699 thick (80 cm) snow cover.