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LETTER

Snow removal cools a small dystrophic lake

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Scientific Significance Statement

Rapidly warming winters with uncertain snow conditions will change lake ecosystems. No studies have been conducted which examine how snow-free conditions will change lake temperatures in dark-water (dystrophic) lakes. This study shows that throughout a snow-free winter, a dystrophic lake in northern Wisconsin responded differently than would be expected in a clear-water lake, by losing heat much more rapidly in early and mid-winter than when snow covered.

Abstract

Limnological understanding of the role snow plays in under-ice thermal dynamics is mainly based on studies of clear-water lakes. Very little is known about the role snow plays in the thermal dynamics of dystrophic lakes. We conducted a whole lake experiment on a small, 8 m deep dystrophic bog lake in northern Wisconsin, where we removed all snowfall over two consecutive winters. Due to weather variability, only 1 year had predominantly black ice. Under these conditions, the lake rapidly cooled in early and mid-winter, compared to snow covered conditions that insulated the lake from heat loss. The lake also rapidly gained heat in late winter resulting in isothermal conditions well in advance of ice-off. These results show how water clarity modulates the influence of snow on under-ice thermal dynamics, which is relevant to futures with snow droughts.

Winter climate drives the formation and persistence of lake ice, which fundamentally alters lake hydrodynamics through a reduction in wind stress and a decrease in heat exchange across the air–water interface (Kirillin et al. 2012). The presence of snow on top of lake ice is an important, and often overlooked, driver of under-ice lake physics and ecology (Cavaliere et al. 2021). Snow is much more effective than ice in reflecting and scattering incoming solar radiation and light, and has a low thermal conductivity. In lakes covered with more than 10 cm of snow, most surface irradiance is prevented from reaching the water column (Bolsenga and Vanderploeg 1992; Bramburger et al. 2022; Zhao et al. 2023). Under-ice productivity is then limited by light availability (Bramburger et al. 2022; Socha et al. 2023), which limits trophic transfer of energy (Hrycik and Stockwell 2021).

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Author Contribution Statement: HAD and RL led data analysis and manuscript development. HAD and NRL designed the experiment and secured funding. PS and NRL led field and buoy operations.

Data Availability Statement: South Sparkling Bog temperature, snow, and ice data and available at: https://doi.org/10.6073/pasta/4d3823341c961c05ba231ce92e4c12ca, and https://doi.org/10.6073/pasta/962fa57959ff9828eb6f1cbda79b82c0. All data and code are available at https://doi.org/10.5281/zenodo.13882474.

Additional Supporting Information may be found in the online version of this article.

Lake snow and ice physics, including ice mechanics, ice structure, optics, and heat transfer are all critical to lake ecosystem dynamics. Following the thermal winter regimes recognized by Kirillin et al. (2012), lakes undergo three phases during winter: (1) *Pre-Winter*, during which a lake releases heat to the atmosphere. Pre-winter begins once the surface temperature reaches maximum density and further cooling helps to stabilize the water column; (2) *Winter 1*, where a snow-covered ice layer insulates the lake from solar radiation, and circulation and mixing are driven by heat release from the sediment; and (3) *Winter 2*, in which the snow layer has disappeared and solar radiation can penetrate through the ice cover. Solar radiation heats the surface water layer below the ice causing the water column to become less stable, which results in a negative buoyancy flux and penetrative convective mixing (Bouffard and Wüest 2019). Radiatively driven convection through solar radiation is quite effective in mixing the water column (Ulloa et al. 2019). Although the intention of this nomenclature was not to decree a strict phenology to ice-covered lakes, *Winter 1* and *Winter 2* are often seen as early/midwinter and late winter phases, respectively, with the timing of these phases dependent on lake morphology and snow cover.

The presence of snow on a lake delays the onset of *Winter 2* and is a function of both climate and wind (Sturm and Liston 2003). On large lakes, extensive fetch allows strong winds to blow snow off the lake ice and/or redistribute it unevenly. Observations from the Laurentian Great Lakes and Lake Baikal have shown that snow-free conditions commonly spur under-ice phytoplankton growth (Katz et al. 2015; Ozersky et al. 2021; Zepernick et al. 2024). Even on moderate-sized lakes, like 39.6 km^2 Lake Mendota, in southern Wisconsin, snow-free conditions are not uncommon and can have cascading effects on lake physics and biology (*see* box 2 in Cavaliere et al. 2021). In contrast, small lakes surrounded by tree canopy or topography are wind-sheltered and are unlikely to experience wind-redistribution of snow. As a result, snow-free conditions are rare, and few empirical observations exist from small, sheltered, snow-free lakes during early and midwinter; even though these types of lakes are common in alpine, north-temperate, and boreal zones.

While snow-free conditions are atypical for small, sheltered lakes, these conditions may increase with winter climate change and snow droughts (Huning and AghaKouchak 2020; Siirila-Woodburn et al. 2021). In the northern United States, winter is warming faster than summer (Marvel et al. 2023), which, for lakes, means a future with less lake ice (Grant et al. 2021; Huang et al. 2022). On top of warming, winter precipitation has increased over the last half-century and is predicted to continue to increase. However, it is highly variable due to weather phenomena like polar vortex events that decrease snowfall (WICCI 2021) or global climate patterns like El Niño-Southern Oscillation, that can result in snow droughts (Fang and Leung 2023). Most recently, the El Niño winter of 2023–2024 resulted in a snow drought in northern Wisconsin, with the region receiving 90 cm less snow than 1991–2020 climate normal.

Here, we were interested in investigating the role of snow cover in driving under-ice thermal dynamics throughout an entire winter season on a small, sheltered dystrophic lake. The high light attenuation of our study lake is distinct from previous studies of snow-free, clear-water lakes (Kirillin et al. 2021). As discussed, snow is an extremely effective insulator, with a thermal conductivity 10–20X less than ice (Adams 1976). The presence of snow reduces ice thermal gradients, which limits the conductive heat transfer through ice (Rafat et al. 2023). We hypothesized that snow-free ice-covered conditions throughout an entire winter, would increase black-ice thickness as well as the penetration of solar radiation through the ice into the water column, effectively inducing radiatively driven convective mixing similar to *Winter 2* dynamics, which would result in a warmer water column, and deeper convective mixing throughout the water column.

Methods

From 2019 to 2021 we carried out a snow manipulation experiment on a small dystrophic lake in northern Wisconsin. South Sparkling Bog (SSB, 46.003°N, 89.705°W) is a 0.44 ha dystrophic, bog lake with maximum depth of 8 m, located in Vilas County in northern Wisconsin (Fig. 1). SSB has high concentrations of dissolved organic carbon (DOC; 16–27 mg L^{-1}), and high light attenuation (Socha et al. 2023). Additional, nonmanipulated reference lakes include Trout Bog (1 ha, 8 m deep, 46.041°N, −89.686°W) and Crystal Bog (0.6 ha, 2.5 m deep, 46.007°N, −89.606°W), both dystrophic bog lakes, and mesotrophic Allequash Lake (164 ha, 8 m deep 46.0383°N, −89.620°W). Trout Bog is the most similar to SSB in terms of hydrology, maximum depth, and water clarity. All lakes have no shoreline development. Climate data were obtained from the US National Oceanic and Atmospheric Administration's integrated database of daily climate summaries for Minocqua, Wisconsin, station USC00475516. Mean daily air temp was calculated as the average of the daily maximum and minimum.

Snow was removed from the surface of SSB over the winters of 2019–2020 and 2020–2021 via a snowblower and a snowplow attached to the front of an ARGO all-terrain vehicle. Snow was removed immediately following every snow event. In 2019–2020, a large snowfall concurrent with lake freeze-up in November resulted in primarily white ice on SSB. In 2020–2021, the lake froze during cold, calm conditions, resulting in entirely black ice formation.

An under-ice buoy was deployed in SSB to collect temperature measurements every 10 min (Onset HOBO Pendant, accuracy ± 0.53°C, resolution 0.14°C at 25°C), at seven depths of 0.75, 1.25, 1.50, 2.00, 3.00, 4.50, and 7.50 m in 2018–2019, depths of 0.70, 1.20, 1.45, 1.95, 2.95, 4.45, and 7.45 m in 2019–2020, and 0.73, 1.23, 1.48, 1.98, 2.98, 4.48, and 7.48 m in 2020–2021 (Dugan 2023). For simplicity, we

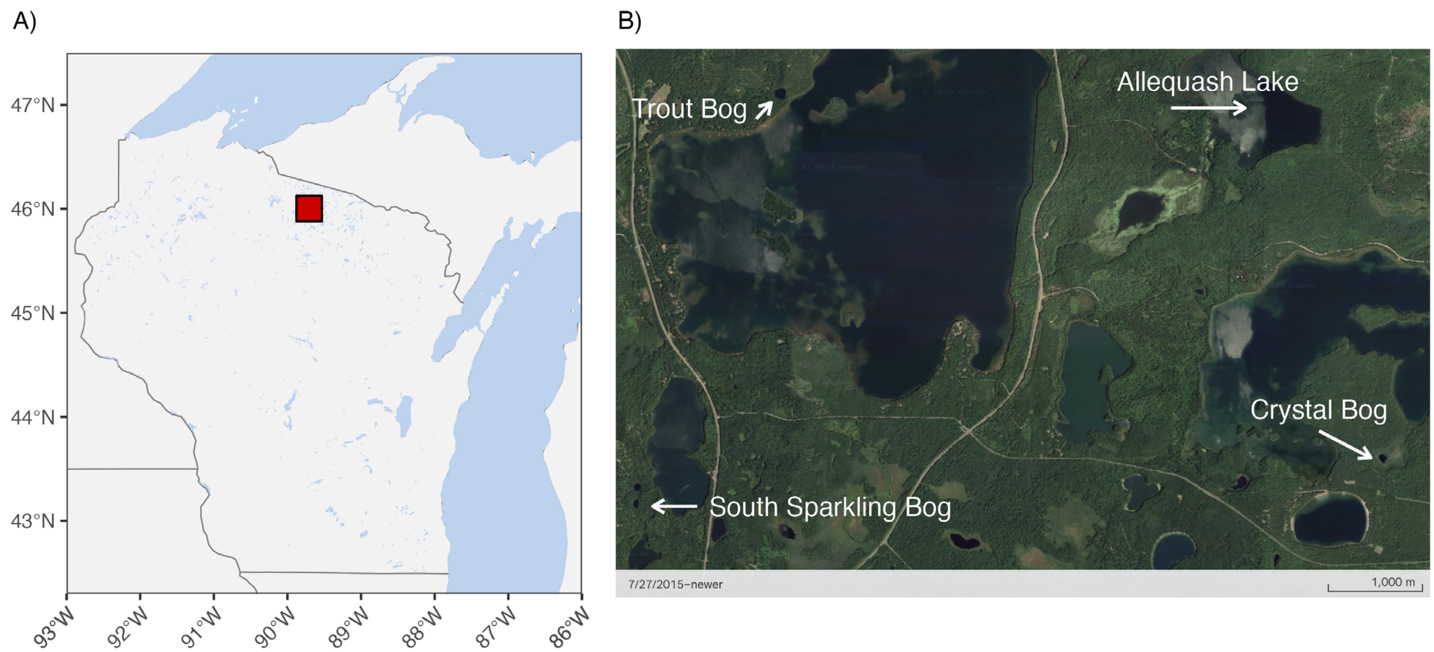

Fig. 1. (**A**) The location of South Sparkling Bog (manipulation lake), Trout Bog, Allequash Lake, and Crystal Bog in northern Wisconsin, USA, and (**B**) a satellite image showing the forested watershed surrounding the lakes. Source: Google Earth imagery.

will refer to the depths by their initial deployment depths in 2018–2019. A similar under-ice buoy was deployed in Trout Bog to collect temperature measurements every minute (Analog Devices temperature sensors) at 14 depths (1.2, 1.45, 1.7, 1.95, 2.2, 2.7, 3.2, 3.7, 4.2, 4.7, 5.2, 5.7, 6.2, and 7.2 m). Both buoys were anchored near the middle of the lake at least 20 m from any sampling holes and not maintained during the winter. Manual temperature profiles were conducted approximately biweekly to monthly during the winter with a handheld YSI Pro-ODO meter through an 8-inch auger hole at both SSB and Trout Bog. Water quality sampling is described in Socha et al. (2023). The North Temperate Lakes Long-term Ecological Research (NTL-LTER) site provided additional temperature profile data for Trout Bog, Crystal Bog, and Allequash Lake (NTL-LTER 2023). On both SSB and Trout Bog, snow depths were determined by averaging 10 random samples across the surface of the lake. Total ice, black ice, and white ice thicknesses were measured in the auger hole (Socha 2022).

Data processing

Water temperature data were averaged to hourly data. Each profile was interpolated on a vertical grid from 0.15 m to SSB's maximum depth of 7.5 m with a spatial discretization of 0.1 m. Water temperature profiles were converted into density profiles using Millero and Poisson (1981) and assuming no salinity effects as specific conductance was < 20 μS cm^{-1}.

SSB bathymetry was mapped in spring 2020 using a depth finder mounted to a small boat. Thin plate regression splines were used to interpolate 6000 individual depth soundings to 1 m depth contours. Using the bathymetry, we calculated hourly values of internal energy E normalized on lake surface area (J m^{-2}):

$$E = \frac{1}{A_s}\int_0^{z_m} T(z)c_w\rho(z)A(z)dz \tag{1}$$

where A_s is the surface area (m^2), z_m is the maximum lake depth (m), T is water temperature (°C), c_w is specific heat of water (J kg^{-1} K^{-1}), and ρ is density of water (kg m^{-3}). For the internal energy calculations, we assume that horizontal temperature gradients are negligible and that significant temperature gradients occur mainly over the vertical axis.

Results

In the three study years, the duration of ice on SSB and Trout Bog varied between 155 d (frozen 09 November 2018–13 April 2019), 169 d (frozen 06 November 2019–24 April 2020), and 140 d (frozen 16 November 2020–05 April 2021). Degree days below freezing from 1 November to 30 April were 1373, 1065, and 1031 in the three winters, respectively (Fig. 2A). In February and March 2019 and 2020, total ice thickness on Trout Bog and SSB was similar (< 4 cm difference). In 2021, total ice thickness on Trout Bog reached 42 cm, whereas SSB reached 59 cm, with 86% black ice (Fig. 2B). As discussed in Socha et al. (2023), even though SSB was plowed free of snow in 2019–2020, the magnitude of white ice prevented light penetration into the water column.

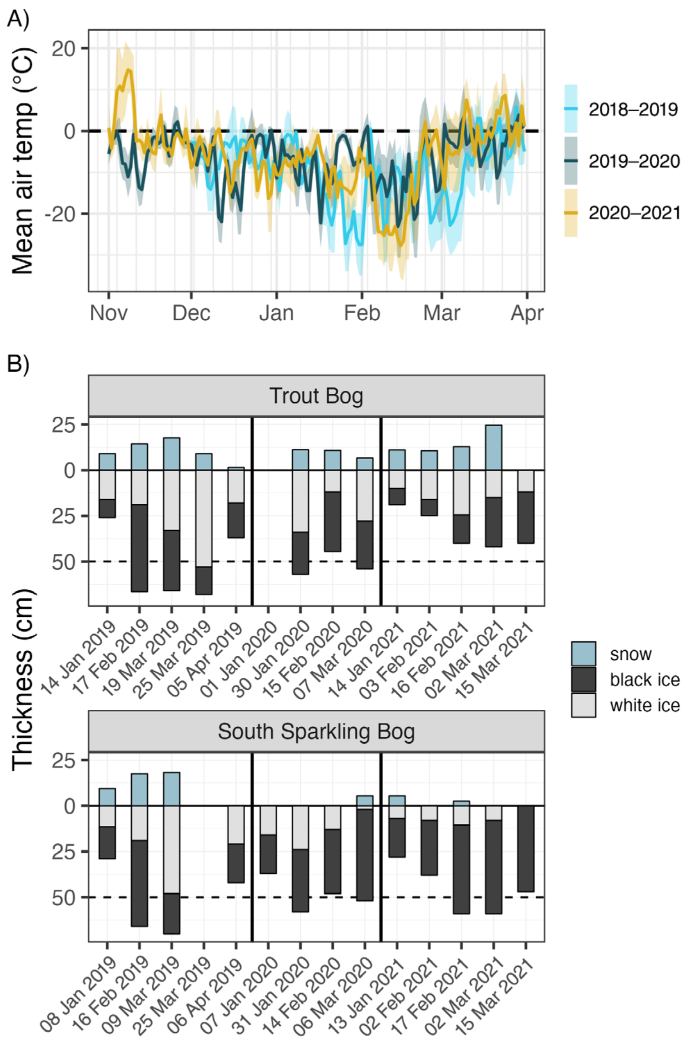

Fig. 2. (**A**) Mean daily air temperatures in Minocqua WI across the 3 yr of study. (**B**) Snow (light blue), white ice (white), and black ice (black) thickness on Trout Bog and South Sparkling Bog from three consecutive winters. The *x*-axis denotes date of sampling. Horizontal dashed line highlights 50 cm of total ice thickness.

Mean maximum daily photosynthetically active radiation (PAR) at 0.7 m depth was 0.11 and 0.24 μmol m^{-2} s^{-1} in January to February 2019 and 2020, respectively, and remained low at 0.06 and 1.08 μmol m^{-2} s^{-1} in March. In 2021 under snow-free conditions, PAR was 5.17 μmol m^{-2} s^{-1} in January to February and 47.30 μmol m^{-2} s^{-1} in March.

In the winter of 2018–2019 when no snow was removed from SSB, overall lake water temperatures were the warmest with gradually increasing deepening of the surface layers over the course of winter until ice breakup and mixing happened in late April/early May (Supporting Information Fig. S1; Fig. 3A–F). In the snow-removal years, the water column at 0.75–2 m depth was colder than in the reference year (Fig. 3A–C). The 4°C isotherm was deepest in 2020–2021. However, in 2020–2021, the lake fully mixed prior to ice-on, which cooled the water at 7.5 m depth to 4°C (Supporting Information Fig. S1C; Fig. 3F). The bottom water remained cooler (difference of < 0.5°C) than previous years for the duration of winter. In comparison to nearby lakes, the winter of 2020–2021 had the warmest under-ice temperatures in Allequash, Crystal, and Trout Bog, but the coldest temperatures in SSB relative to the two previous winters (Supporting Information Fig. S2).

In 2018–2019 and 2019–2020, the 7.5-m thermistor was consistently above 4.2°C throughout most of the winter, which is above the maximum density of freshwater (Supporting Information Figs. S2 and S3). The persistence of bottom water above 4°C is likely due to increased dissolved solids at depth which stabilize the temperature profiles (Cortés and MacIntyre 2020). Manual sampling of SSB revealed small gradients in water-column–specific conductance (<10 μS cm^{-1}) in 2018–2019. DOC was 0.60–2.2 mg L^{-1} higher at 7 m than 0–3 m in 2018–2019, and 1.2–8.6 mg L^{-1} higher in 2019–2020. In 2020–2021, the DOC gradient was <1 mg L^{-1} (unpublished data).

The storage of internal energy in SSB differed between the years. From November to March, energy storage was highest in 2018–2019 when the lake was snow covered. Although depth-specific water temperature dynamics differed between the two snow removal seasons, their overall internal energy was similar (Fig. 3G) due to similar surface water temperatures which made up the majority of lake volume. Over the course of all three winters, internal energy was decreasing over the winter period highlighting the cooling of the water column. Minimum internal energy was about 8.0×10^7, 7.7×10^7, and 7.5×10^7 J m^{-2} for 2018–2019, 2019–2020, and 2020–2021, respectively. In 2020–2021, SSB started gaining energy in early March, almost a month earlier than in 2018–2019 and 2019–2020. Diurnal fluctuations of water temperature at 0.75 depth began in early March in 2020–2021, indicative of penetrating solar radiation. In 2020–2021, the lake reached a water temperature closest to 4°C at ice-off, rather than in the weeks following ice-off (Fig. 3G).

Overall, the thermal dynamics in SSB were influenced by snow cover. The presence of snow of appreciable thickness on top of lake ice did slow the transfer of heat from lake ice to the atmosphere due to the low thermal conductivity of snow (Leppäranta 2023). When snow covered, SSB cooled slowly in early and mid-winter due to the low thermal conductivity of snow (Fig. 4A). Snow cover also caused SSB to gain heat very slowly preceding ice breakup in the spring. Similar dynamics were captured in Trout Bog in 2020–2021 (Fig. 4D). Snow removal caused rapid heat loss due to the high thermal conductivity of ice in early winter, and also rapid heat gain from radiation in late winter (Fig. 4C).

Discussion

Snow removal caused SSB to have distinct differences in thermal dynamics between years, which were accentuated

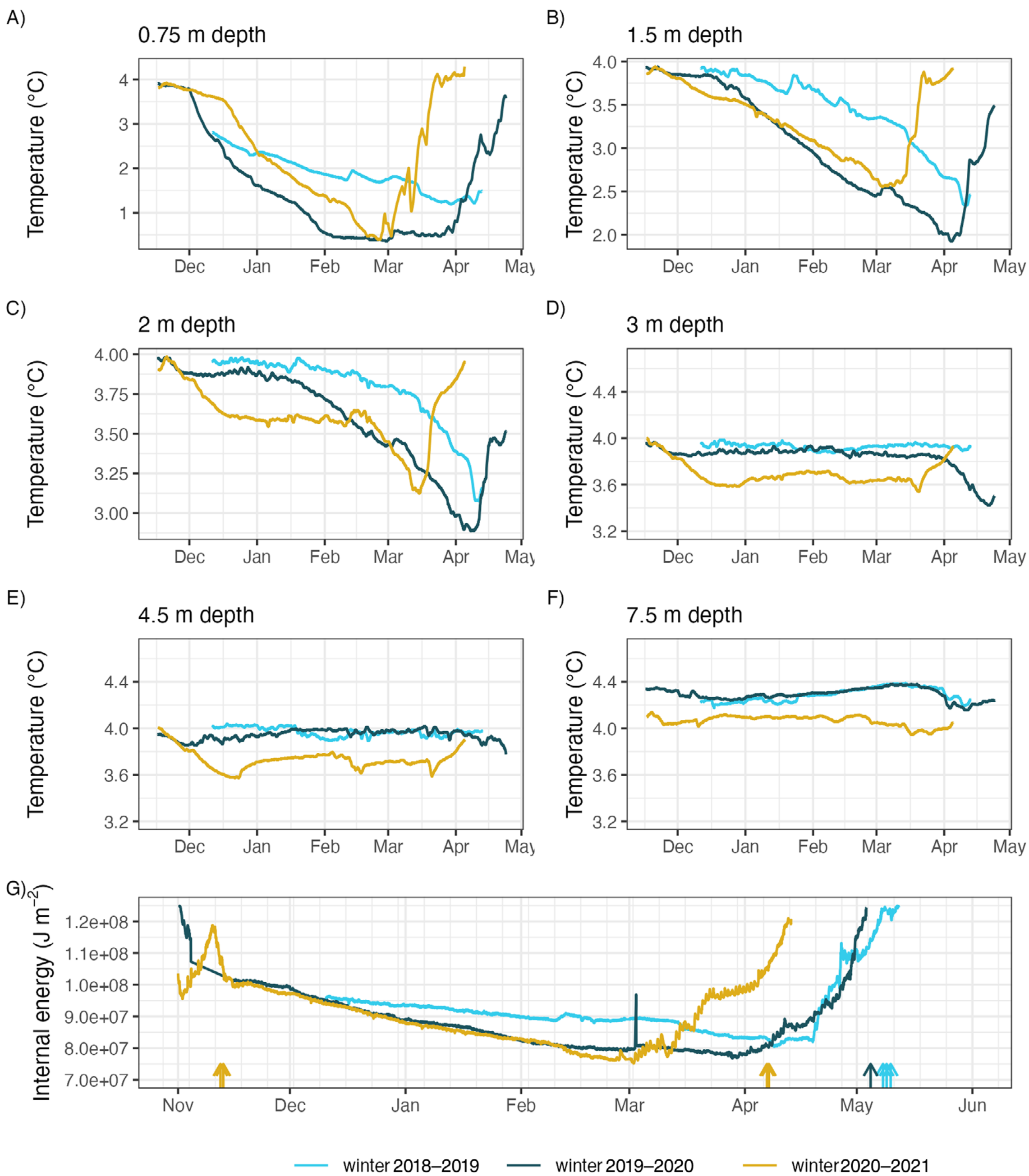

Fig. 3. (**A–F**) Water temperature time series at different depths. Temperatures plotted are a 24-h rolling average of 10-min thermistor data. The 1.25 m thermistor is not shown. (**G**) Energy times series of SSB over three winters. Arrows along the *x*-axis denote days when minimum water temperature was closest to 4°C.

in 2020–2021 when SSB had primarily black ice (Fig. 4B,C). We hypothesized that a snow-free SSB would be warmer as atmospheric radiation would be able to penetrate into the lake and radiatively driven convection would transport the heat downward. Our experiment revealed that our hypothesis was incorrect, as both seasons of snow removal resulted in overall lower water temperatures and less internal energy stored in the water column in early and mid-winter.

Lake cooling under snow-free conditions contrasts with the finding of lakes warming under similar surface conditions. On the Tibetan Plateau, Ngoring Lake was described as a "solar heat collector" (Kirillin et al. 2021). Over many months of ice cover, Ngoring Lake warmed, almost isothermally, from < 1°C to the temperature of maximum density, driven by thermal convection by solar radiation. Furthermore, the latter half of winter was characterized by strong heating and stratification under ice.

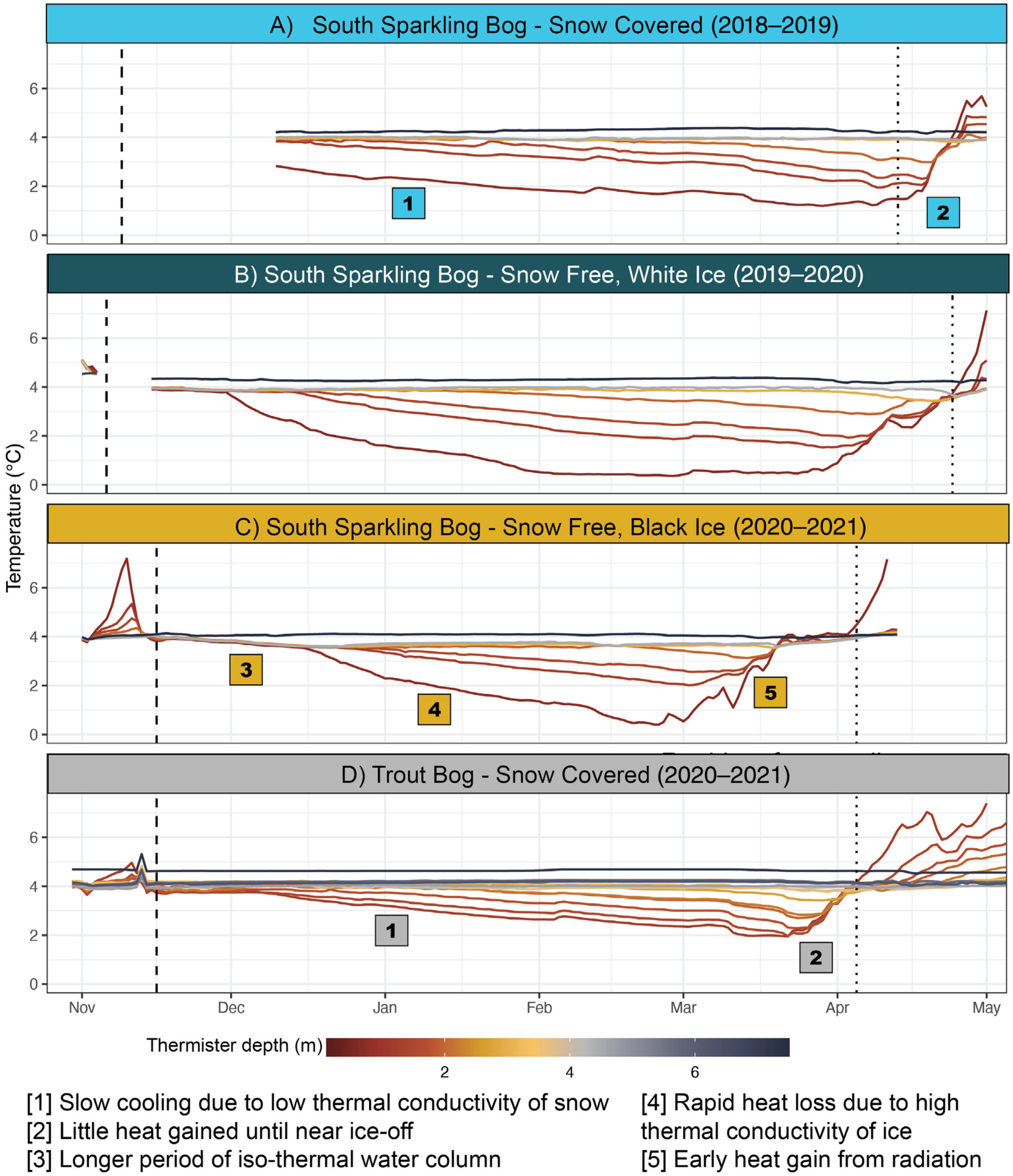

Fig. 4. Water temperature thermistor time series across the 3 yr of study at South Sparkling Bog (**A–C**) and from 2020 to 2021 in Trout Bog (**D**). Description of observed processes are noted in [1]–[5]. Dashed vertical lines represent ice-on and ice-off.

These divergent outcomes, cooling vs. warming, are likely driven by water clarity. Ngoring Lake has a light extinction coefficient of 0.25 m $^{-1}$, while SSB's is 1.6–4.2 m^{-1} (Socha et al. 2023). That equates to a euphotic zone of $\sim$ 20 m in Ngoring Lake vs. $\sim$ 1–2 m in SSB.

Due to SSB's low water clarity, much of the heat gain during the winter would be directly at the surface, rather than deeper into the water column as would be found in a clear lake. Temperature profiles from SSB show a large temperature gradient (1.4–2°C m^{-1}) with depth in the upper two meters, below which temperatures are near-constant (Supporting Information Fig. S2). SSB's temperature profile is in contrast to nearby Allequash Lake (winter light attenuation = 0.8 m^{-1}), where there is a $\sim$ 0.5°C m^{-1} temperature gradient to the bottom of the 7 m deep lake (Supporting Information Fig. S2). Lacking a full heat flux analysis, our data imply that any surface water heat gain through solar radiation was less than the surface layer heat loss in early to mid-winter.

There are two other important characteristics of SSB to note. The first is that sediment heat flux is likely low, which is consistent with high-light attenuation. The bottom of SSB remains near 4°C year-round, and therefore the sediments are rarely gaining heat. SSB also likely receives little heat from groundwater inflow, similar to other bogs in the nearby area (Watras and Hanson 2023). The second is that the surface water did not stratify immediately following ice-on, which is contrary to what might be expected of cooling surface waters that should stabilize and inversely stratify the water column rapidly. One hypothesis is rapid ice growth in SSB caused the rejection of dissolved organic matter from the ice layer into the water column (Belzile et al. 2002). Since SSB is a dystrophic lake, the quantity of rejected solutes could be quite high, leading to density driven convection that mixed cool surface water downward. In all years, early-winter convection ceased by January and the water column stratified (Fig. 4).

Our experiment created the scenario of a lake remaining frozen, yet snow-free for 5 months. With climate change, and uncertainty around precipitation projections and snow droughts, years with little to no snow in north-temperate regions may transpire. In fact, a snow drought was experienced during the El Niño winter of 2023–2024, with many lakes in our study region remaining snow free for months. Our experiment revealed that the thermal influence that no-snow has on lakes depends on the time of year and the water clarity of the lake. In our dystrophic study lake, in early winter, when solar radiation and air temperatures are low, removing snow as an insulator leads to lake cooling. Similar to clear-water lakes, in late spring, as solar radiation increases and air temperatures rise, no snow leads to rapid heat gain and radiatively driven convection. Across all lake types, snow-free conditions in the spring are important in setting up spring conditions. If a lake is isothermal prior to ice-off, it is more likely to fully mix prior to spring stratification, which is important for reoxygenation of the water column (Dugan 2021; Hazuková et al. 2024).

The influence that ice and snow conditions and water clarity have on lake circulation under ice has important implications for under-ice ecology. Circulation is important for keeping planktonic species like diatoms, which are known to proliferate in cold and low-light conditions, in suspension (Jones 1998; Ferris and Lehman 2007; Kong et al. 2021), and for the redistribution of oxygen (Yang et al. 2017, 2020). While replicating this study is difficult given the logistical investment in clearing snow from the surface of a lake, similar conditions may be experienced naturally and monitored via under-ice sensor deployments. While our experiment provides empirical evidence of lake cooling from snow removal, further study should be given to how light attenuation across a gradient of lakes modulates winter heat fluxes and circulation.

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