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Key Points:

- Ward Hunt Lake was capped by thick ice on all sampling dates from 1953 to 2007
- This ice cover then thinned rapidly and was lost completely in August 2011
- Heat advection from water track inflows accelerated this ice loss

Supporting Information:

- Readme
- Figure S1
- Figure S2
- Figure S3

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Rapid disappearance of perennial ice on Canada's most northern lake

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Abstract Field records, aerial photographs, and satellite imagery show that the perennial ice cover on Ward Hunt Lake at Canada's northern coast experienced rapid contraction and thinning after at least 50 years of relative stability. On all dates of sampling from 1953 to 2007, 3.5 to 4.3 m of perennial ice covered 65–85% of the lake surface in summer. The ice cover thinned from 2008 onward, and the lake became ice free in 2011, an event followed by 26 days of open water conditions in 2012. This rapid ice loss corresponded to a significant increase in melting degree days (MDD), from a mean (±SD) of 80.4 (±36.5) MDD (1996–2007) to 136.2 (±16.4) MDD (2008–2012). The shallow bathymetry combined with heat advection by warm inflows caused feedback effects that accelerated the ice decay. These observations show how changes across a critical threshold can result in the rapid disappearance of thick perennial ice.

1. Introduction

The northern cryosphere is experiencing rapid contraction, with pronounced, ongoing losses of ice shelves, sea ice, lake ice, glaciers, ground ice, and summer snow cover [*Derksen et al*., 2012]. In the Arctic and elsewhere, the phenology of lake ice cover has been identified as a sensitive indicator of climate change [*Duguay et al*., 2006; *Magnuson et al*., 2000]. For example, radar satellite imagery of several hundred tundra lakes at Barrow, Alaska, has shown that over a 20 year period (1991–2011) the number of lakes freezing completely to the bottom in winter decreased substantially [*Surdu et al*., 2014]. Polar lakes have long been recognized as sentinels of global climate change [*Adrian et al*., 2009; *Vincent et al*., 1998], and the regime shift from perennial (persistence over decades or longer) to multiyear (persistence for >1 year but rarely >5 years) to seasonal (annual melt out) ice cover has wide-ranging implications for limnological conditions such as lake temperature, light penetration, primary production, oxygen and nutrient availability, water column mixing, and transport pathways [*Veillette et al*., 2010]. Limnological changes can have cascading effects on biological communities, with a gradual or rapid shift from ecosystems dominated by shallow benthic/pelagic communities to the prevalence of deeper water, planktonic communities [*Quayle et al*., 2002; *Smol et al*., 2005].

Several larger lakes in the northern Ellesmere Island region have lost their perennial ice cover in the past decade [*Mueller et al*., 2009; *Veillette et al*., 2010], but Ward Hunt Lake (WHL), located at the northern limit of this region, has been consistently reported as having perennial ice cover about 4 m thick, even in late July, beginning with measurements in the early 1950s [*Hattersley-Smith et al*., 1955]. Our objectives in the present study were to bring together and analyze all available data on ice extent and thickness over WHL during the last half of the twentieth century (since 1953), to include our own observations between 2000 and 2014, and to evaluate the factors contributing to the recent disappearance of this perennial ice cover. We compiled all previous records, undertook temperature measurements in the lake and the inflowing waters, produced a detailed bathymetric map, and obtained new ice thickness measurements and imagery throughout the year, including by automated camera. As the northernmost lake in Canada, WHL is a latitudinal end-member of interest for examining how polar lakes can undergo regime shifts in ice cover.

2. Study Site and Methods

WHL (83°03′07″N, 74°10′30″W; Figure 1) is located 26 m above sea level on Ward Hunt Island (WHI), off the north coast of Ellesmere Island, Nunavut (supporting information Figure S1). This area has a cold, dry climate,

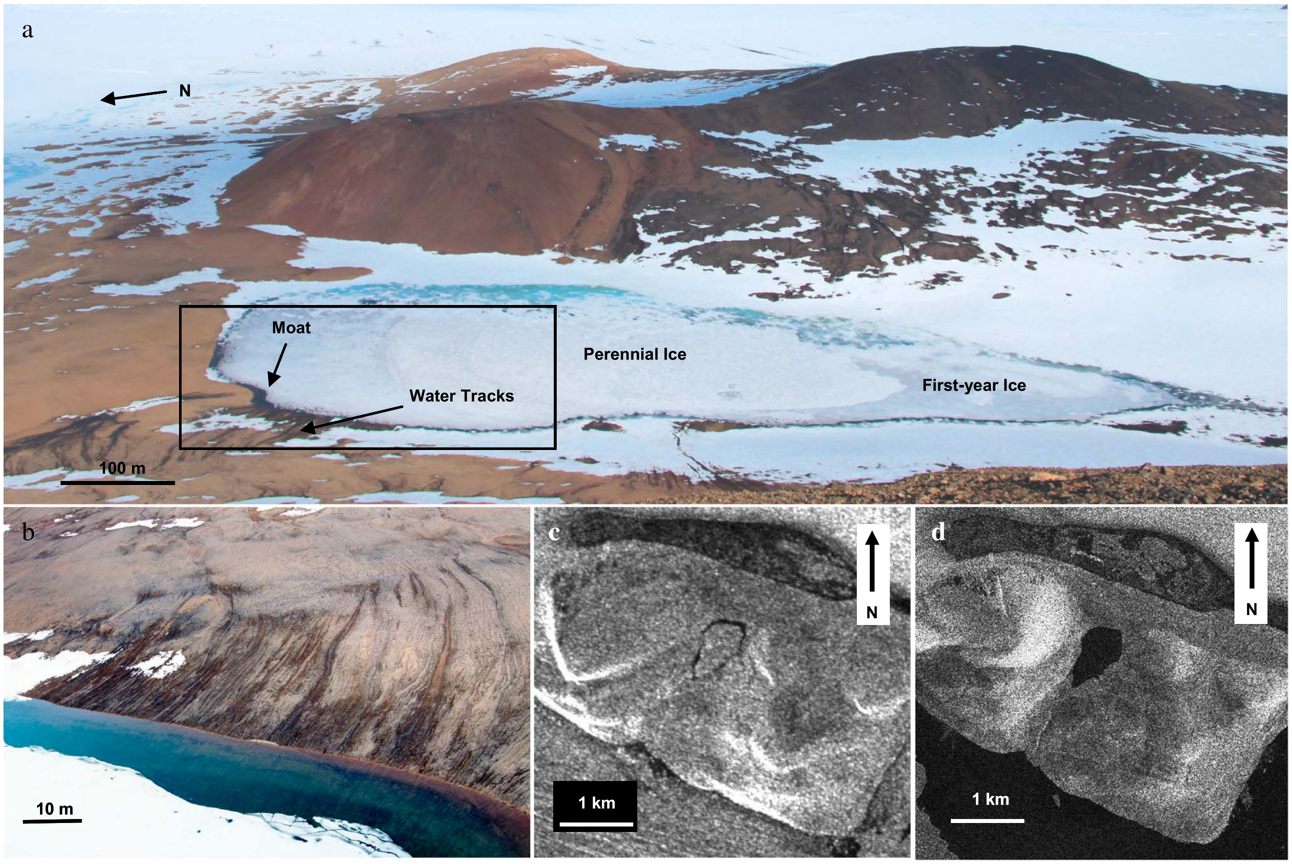

Figure 1. Ward Hunt Lake, Nunavut, Canada. (a) Photograph from Walker Hill, looking eastward, 5 July 2009. The first year ice can be distinguished from the central perennial ice pan that detached from the shore of the lake in summer 2008. Snowmelt had barely begun at the time of the picture, and only a small moat created by water flowing from the water tracks (Figure 1a) had formed. (b) Enlarged view of the water tracks and of the inshore moat. (c) RADARSAT image of WHL on 9 September 2003, showing the extensive coverage by perennial ice, except around the edges of the lake. (d) RADARSAT image on 26 August 2011, showing the complete loss of ice cover over WHL and also the complete loss of the thick ice shelf ice around the southern side of Ward Hunt Island. RADARSAT Data and Products © MacDonald, Dettwiler and Associates Ltd—All Rights Reserved.

with a mean annual air temperature of −18.0°C, an average air temperature of −33.5°C in February and +1.5°C in July (data from 2005–2013) [*Centre d'Études Nordiques (CEN)*, 2014], and precipitation of 154 mm yr^{-1}, as measured at Alert, 170 km to the east (*Environment Canada*, unpublished data available online at http://climate.weather.gc.ca). Until 2008, WHI was entirely surrounded by thick glacial and marine ice, but recent breakup and disintegration of the Ward Hunt Ice Shelf have left WHI partially exposed to the Arctic Ocean and Disraeli Bay [*Vincent et al*., 2011].

WHL is a 0.35 km^2 snow-fed, ultraoligotrophic lake, with a pH between 7.6 and 8.2 [*Villeneuve et al*., 2001]. WHL ice cover extent had not been surveyed prior to this study, but paleolimnological studies of diatom assemblages and pigment concentrations suggested that the lake likely remained permanently frozen over in summer until at least the nineteenth century [*Antoniades et al*., 2007]. Historical variations in ice cover were estimated using aerial photographs from the Canadian National Air Photo Library (2), oblique photos from previous field expeditions (7), and Radarsat-1 and Radarsat-2 Synthetic Aperture Radar (SAR) imagery (25). Since the backscatter of perennial ice is much higher than first year ice [*Mueller et al*., 2009], the extent of different ice types was manually digitized from each midwinter SAR image, with validation from other visual sources when available. Ice thickness was assessed by drilling through the ice cover and measuring with a metal tape from the lower ice surface. We measured water temperature and conductivity (fine structure at centimeter-scale intervals) from 2010 onward, with all temperature measurements performed between 27 June and 1 July. Temperature and conductivity were also measured in water track inflows to the lake in 2011, and discharge was measured in 2013. Air temperature, snow depth, wind conditions, and incoming solar

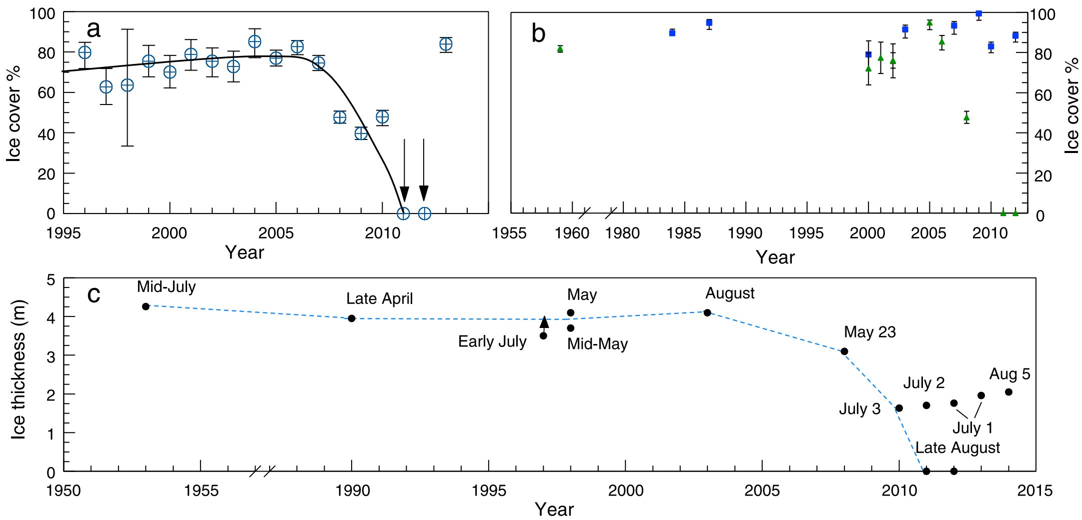

Figure 2. Ward Hunt Lake ice cover. (a) Ice cover extent at the end of each season; the arrows point to dates of complete disappearance. The values correspond to the "multiyear ice" type presented in the supporting information Table S1. The curve was fitted visually to the data. (b) Lake ice cover phenology during July and August; note the break in the *x* axis due to absence of data. Blue squares are July measurements, and green triangles are August measurements. The values used correspond to the "summer ice" type as presented in the supporting information Table S1. (c) Lake ice thickness, annotated with the date of measurement. Note the break in the *x* axis due to a lack of data; data for Figures 2b and 2c include unpublished and published data from *Antoniades et al.* [2007], *Hattersley-Smith et al.* [1955], L. King, E. Schmidt, and S. Becker (unpublished data, 1990), D. S. Lemmen, (personal communication, 1987), R. A. Wharton, D. T. Andersen, C. Cockell, R. Costello, and P. T. Doran (unpublished data, 1997).

radiation measurements were provided by Parks Canada and by the Centre for Northern Studies (Centre d'Études Nordiques; CEN) from a weather station located on the northern shore of WHI, 1 km from the lake [*CEN*, 2014].

In order to estimate grounded ice area and lake volume, the bathymetry of WHL was measured with ground penetrating radar surveys using 50 MHz antennas over the ice cover in early June 2013. Signals were calibrated on three auger holes in the ice and with a common midpoint survey [*Jol and Bristow*, 2003]. Measurements from a total of 14 transects were then spline interpolated to produce a digital elevation model of the lake bottom.

3. Results

3.1. Ice Cover History

Throughout all years of field observations, WHL remained fully ice covered for at least 9.5 months each year, with a moat of open water forming in late June along the northern, western, and southern shores, where slope runoff and near-surface inflows through water tracks spaced about 1 m apart were widespread (Figures 1a and 1b). At other parts of the shoreline, snowdrifts extended from the hillslopes onto the lake, strongly impeding the input of runoff and nearshore melting of lake ice for most of the melting season.

The percentage of ice cover remaining at the end of summer provides a measure corresponding to the perennial ice cover at the beginning of the next year (Figure 2a). While WHL was visited almost yearly from 1998 onward, there was no evidence suggesting extensive areas of open water prior to 2008, with perennial ice fluctuating around a mean of 74.8% of lake area. The lake ice cover percentage in summer months showed that there was >90% ice cover in July and >70% in August during much of the record (Figure 2b). The year with observations in both July and August (2000) showed only a slight decrease, from 79% to 72% over the 24 day period between 25 July and 18 August.

In 2008 and until 2010, there was a reduction to less than 50% perennial ice, followed by its complete melt out in summer 2011. This warm summer was also the time of extensive breakout of the thick land-fast ice of the Ward Hunt Ice Shelf, resulting in open seas around much of WHI for the first time in recorded history (Figure 1c versus 1d). Images from the automated camera installed on the western lake shore in 2012 revealed a second year of full melt out, with an absence of ice cover for 26 days, from

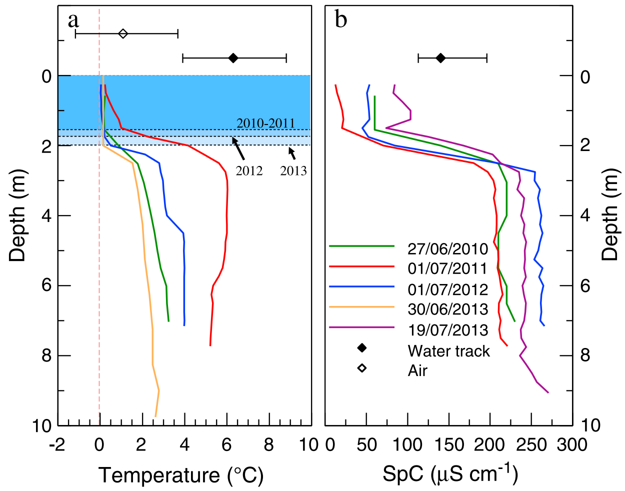

Figure 3. Water column profiles in WHL, in late summer 2010 to 2013. Blue areas show ice thickness at time of measurements. (a) Water temperature, blue bars represent ice thickness in 2010 and 2011, 2012, and 2013 in order from dark to pale. (b) Specific conductivity. Also shown are the temperature and specific conductivity of an inflowing water track, with maximum and minimum values (black diamonds and bars), and the corresponding air temperature range (open diamond and bars). The conductivity profile from 30 June 2013 could not be performed and was replaced by a profile from 19 July 2013.

11 August to 5 September (supporting information Figure S2). In contrast, 2013 saw the return of an ice cover lasting through the summer and of multiyear ice conditions.

The ice thickness records followed a similar trend to that of ice cover extent. For the decades following the first measurement in 1953, midsummer ice thickness varied between 3.7 and 4.26 m (Figure 2c). However, the records since 2008 showed thinning to values of 3.1 m, 1.63 m in 2010, and 1.76 m in 2011, until complete disappearance in August 2011. The ice thickness on 1 July was 1.88 m in 2012 and 1.99 m in 2013. Our measurements at three sampling sites in June 2013 (before the onset of melt) gave a mean thickness of 1.96 m. Ice was thinner (1.53 m) under a 0.55 m thick snow cover, consistent with the low 2010 thickness taken near that location, and thicker (2.30 m) where snow was absent.

3.2. Lake and Watershed Characteristics

Photointerpretation of the watershed of WHL provided an area estimate of 1.82 km^2 and a watershed to lake area ratio of 5.2:1. Snow banks in the watershed are the main water sources for the lake. Water flow paths include surface flow through overland flow and short rills (<30 m), and near-surface flow through snowmelt-fed water tracks up to a few hundred meters long (Figure 1). The lake drains to the sea through a channel 10 to 15 m wide and up to 0.1 m deep located at its southern shore.

The survey of WHL bathymetry (supporting information Figure S3) shows that the deepest part of the lake is on the northeastern side, with a maximum depth of 9.7 m, while the southeastern and western portions have extended shallows less than 3 m deep and a small ridge in the middle of the lake rises to less than 3 m depth. The hypsographic curve for the lake underscores the predominance of shallow waters (supporting information Figure S3); water volumes above the 4 and 2 m isobaths, corresponding to the thickness of perennial and seasonal ice respectively, represent 82% and 49% of total lake volume. A 4 m thick perennial ice cover on the lake results in ice being grounded and frozen to the bottom over 55% of the surface area of the lake, a value dropping to 21% under conditions of 2 m thick seasonal ice.

The lake temperature profiles showed large interannual variation (Figure 3a). All profiles were taken during a similar time period in late June to early July and, while the 2011 profile had temperatures up to 6°C, lake temperatures were usually less than 4°C in other years. Lake water temperatures were coldest in 2013, with a maximum of 2.8°C near the bottom, reflecting the low-cumulative melting degree days (MDD) at that moment in the season. Conductivity showed little variation throughout the water column of the lake, with values within the range 200–275 $\mu S\ cm^{-1}$ (Figure 3b).

Temperatures in the inflowing water tracks in 2011 reached up to 8.8°C, with a mean of 6.3°C (Figure 3a), and conductivities from 113 to 196 $\mu S\ cm^{-1}$, with a mean of 140 $\mu S\ cm^{-1}$ (Figure 3b). These temperatures exceeded air temperatures, which averaged 1.1°C during the same measurement period and never exceeded 3.6°C. In 2013, discharge measurements showed a median discharge of 8.18 (±0.52) × 10^{-5} $m^3\ s^{-1}$ (peak discharge of 3.71 (±0.10) × 10^{-4} $m^3\ s^{-1}$) in a water track over a 22 day period.

The air temperature data from WHI also showed a large amount of interannual variability: melting degree days (MDD, the sum of daily mean air temperature above 0°C) varied by up to a factor of 3 between recorded years (Table 1). The MDD values were particularly high in 2003 and in all years from 2008 to 2012. Warm

Table 1. Air Temperature in Degree Days and Incoming Solar Radiation in Summer at Ward Hunt Island, Nunavut

Month	1996	1997	1999	2001	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Mean
									Melting degree days [a]								
June	9.2	1.2	13.7	24.8	15.2	5.5	2.3	13.7	22.8	*56.5*	14.2	28.4	*56.7*	*46.8*	10	10.2	20.7
July	31.4	42	48.5	41.3	*91.3*	30	39	52.9	31	56.3	*69.8*	*77.5*	43.7	*72.8*	34.2	24.2	49.1
August	7	Inc.	Inc.	20.6	*48.2*	21.7	10.9	15.3	28.9	34.7	36.5	13.7	36.5	37.2	11	Inc.	24.8
Total	47.6	Inc.	Inc.	86.7	*154.7*	57.2	52.2	81.9	82.7	*147.5*	120.5	119.5	136.9	*156.8*	55.2	Inc.	100.0
									Freezing degree days [b]								
Total	6954	6779	6526	7175	6524	7040	6828	6316	6392	6769	6721	*5992*	*6083*	6647	6548	6308	6600
									Summer Incoming Solar Radiation (MW m^{-2}) [c]								
Total	-	-	-	-	-	-	-	1617	1754	1859	*1973*	1696	1862	*1542*	Inc.	Inc.	1758

[a]Italic values exceed the mean by more than 1 standard deviation.
[b]Totals are for the winter ending during the listed year. Italic values are below the mean by more than 1 standard deviation.
[c]Italic values exceed the range of 1 standard deviation from the mean. Missing years and Inc. indicate incomplete data, and dashes indicate no measurements.

episodes occurred in the month of June in 2008, 2011, and 2012, with maximum air temperatures >10°C in each of these years. In comparison, the amount of freezing degree days (the sum of daily mean air temperature below 0°C) varied between 5992 and 7175, with a mean of 6600, and reached lows in the winters of 2010 and 2011. Incoming solar radiation showed some year to year variability, with a mean of 1758 MW m^{-2} per summer, ranging between extreme values of 1542 and 1973 MW m^{-2} in 2012 and 2009, respectively. The amount of MDD did not covary significantly with incoming solar radiation on a daily, monthly, or yearly basis. A return to cold conditions in summer 2013 (55.2 MDD) resulted in an ice thickness of 2.1 m on July 17. Incomplete measurements (40.9 MDD on 8 August 2014) suggest that the 2014 summer should allow the 2.05 m thick ice cover to be maintained.

4. Discussion

The complete loss of perennial ice from WHL appears to be unprecedented for at least 60 years, but is consistent with other major changes that have recently taken place throughout the Arctic cryosphere. For example, record minimum extent of sea ice over the Arctic Ocean was observed in late summer 2012 [*Parkinson and Comiso*, 2013], which was also the time of prolonged ice-free conditions on WHL. Large expanses of open water were observed along the northern edge of High Arctic Canada in 2008, along with the collapse of certain ice shelves [*Mueller et al*., 2009]. This was also the year that the WHL ice cover detached from the eastern shore of the lake and then persisted during late summer as a floating ice pan of substantially reduced thickness relative to previous years (Figure 2).

The cooler summers at WHI had similar MDD values to certain summers of substantial perennial lake ice ablation in the McMurdo Dry Valleys, Antarctica; for example, in 2001 and 2002, above-average MDD were recorded at Lake Fryxell, Lake Hoare, and Lake Bonney: 53.9, 57.4, and 99.4 MDD [*Doran et al*., 2008], with ice cover ablation of 0.67 m, 1.62 m, and 0.59 m, respectively [*Dugan et al*., 2013]. WHI experienced a warm summer in 2003 but there was no apparent change in lake ice thickness. The large variability among these polar lakes and lack of correspondence with MDD values imply other factors in addition to air temperature are likely important in controlling ice melt. Among these factors are the timing of warm events and the repetition of warm summers. In contrast to 2003, the summers of 2008 and 2011 at WHI each began with warm episodes in June (max temperature >5°C), while 2012 had 10 days of unusual warming in early to mid-July, in which the maximum temperature reached 18°C. Such events corresponded to large reductions in measured ice cover. The combination of early summer warm events and a continuous sequence of warm summers is likely to have been pivotal in the WHL regime shift from perennial ice and limited moat development to seasonal ice and full open water conditions in summer. The effects of this combination are likely to result in increased surface ablation by sensible heat influx and increased melt at the ice-water interface due to warmer lake temperatures. Two factors that may influence the increase in lake temperatures other than variation in meteorological forcing are the bathymetry of the lake and its effect on the extent of grounded ice and the timing of moat development as controlled by the input of snowmelt water from the water tracks.

Adams et al. [1989], in a study of Colour Lake on Axel Heiberg Island, argued that similar to ice sheets, lake ice melts from the surface downward, and similarly *Dugan et al*. [2013] assumed bottom melt to be negligible when evaluating Antarctic lake ice reduction processes, an assumption also made in recent modeling of lake ice phenology and multiyear ice formation [*Nolan*, 2013]. Most of the melting of WHL ice cover likely occurs by surface ablation, and the absence of a clear link between ice melt and incoming solar radiation identifies atmospheric sensible heat flux (rather than radiative heating) as the dominant process in melting the ice cover.

Heron and Woo [1994] demonstrated through measurements and modeling of Small Lake (Cornwallis Island) that about 25% of melting occurred at the ice-water interface, and that the thermal gradient at this interface increased by an order of magnitude during the season, thereby accelerating the bottom melt process. In early July 2011 at WHL, much of the water column under the ice had already warmed to >5°C (Figure 3a), a temperature similar to those recorded in the water tracks. The temperature gradient at the ice-water interface (upper 0.05 m of the water column) at that time was 60.4°C m^{-1}. This value is similar to the highest values recorded in Small Lake, when bottom melt accounted for more than 1 cm d^{-1} of melt; applying this loss rate to WHL implies that at least 24% of the ice was lost by underice melting during the remaining 41 days of ice cover. At WHL, and possibly other extreme polar lakes with low air temperatures in summer, a substantial fraction of the ice melting likely occurs at the ice-water interface.

The bathymetric survey of WHL showed that 82% of the lake volume was at depths less than 4 m. This predominance of shallows means that much of the lake ice was grounded in the past inhibiting bottom water circulation and melting. The extensive grounded ice combined with the cooler early summer temperatures likely explains why WHL has maintained such a thick ice cover prior to 2008. The thinning of the ice from 4 m to 2 m exposed large areas of previously grounded ice cover to heat transfer from the lake water while also uncovering and exposing areas of the littoral zone to heating via direct solar radiation.

The rate at which air temperatures rise above freezing in early summer controls the timing and extent of moat development, which affect lake water temperature by allowing prolonged direct solar warming of the lake water, additional ice melt, and increased open water conditions. This explains the pronounced difference in water temperature between 2011 and 2012. An additional factor that likely affect moat development is the advection of heat from the catchment via the numerous shallow water inflows (rills and water tracks), which flow across dark, sunlight-absorbing soil crusts [*Steven et al*., 2013]. The water track thermal record (Figure 3) showed temperatures that were well above air and lake values, and greatest moat development in the lake occurred in the areas adjacent to these inflows. For a water track discharge of 8.2×10^{-5} m^3 s^{-1} and a maximum recorded water temperature in a flowing track of 8.8°C (4 July 2011), the heat advection to the lake is

$$q = Q{\cdot}\rho{\cdot}c_p{\cdot}\Delta T \quad (1)$$

where q is heat flux (W), Q is discharge (m^3 s^{-1}), ρ is water density (kg m^3), c_p is the heat capacity of water (J kg^{-1}°C^{-1}), and ΔT is the difference in temperature (°C). Assuming a lake temperature of 0°C, the maximum heat flux to the lake from a single water track is equal to 3.05 ± 0.19 kW. This is an order of magnitude higher than the maximum daily average incoming solar radiation flux per m^2 measured at Ward Hunt Island during these 4 days (0.376 kW). Heat advection has been recognized elsewhere as an important factor for ice decay [*Brown and Duguay*, 2010; *Williams*, 1965], and this calculation indicates the potential importance of water tracks for the inshore heat budget of the lake, particularly given their abundance along the western shore. The transition from thick perennial ice to a regime of thin seasonal ice cover with prolonged open water conditions will have many effects on the biophysical and biogeochemical properties of WHL, including greater light availability for primary production and increased nutrient entrainment from deeper waters by wind-induced mixing [*Veillette et al*., 2010]. The seasonal loss of ice cover will also lead to increased water temperatures and evaporation, which could result in the lake level falling below the shallow outflow sill and closure of the lake in late summer when inputs are limited.

The rapid disappearance of lake ice on WHL also raises questions about the fate of perennial ice elsewhere in polar regions. Some lakes in Greenland retain their ice throughout the year [*Perren et al*., 2012], and many Antarctic lakes, such as those in the McMurdo Dry Valleys, have thick perennial ice [*Chinn*, 1993; *Doran et al*., 1994]. Our observations from WHL at the northern terrestrial limit of the Canadian High Arctic show the precarious nature of perennial ice and its vulnerability to rapid disappearance through multiple feedback effects once air temperatures begin to warm. This effect may be reversible when summer conditions return to colder temperatures, as was observed at WHL in 2013, but the accumulation to ice thicknesses ≥4 m is unlikely under the current and projected regime of long-term warming.

5. Conclusions

WHL maintained a 4 m thick, perennial ice cover from at least the 1950s to the early 21st century. Rapid thinning was observed from 2008 onward, culminating in the complete disappearance of ice cover in the summers of 2011 and 2012. This was associated with recurring warm summer temperatures, elevated early summer air temperatures, warming of the water column beneath the ice, and warm water inflows from the watershed slopes. The shallow bathymetry of the lake results in a large change in area of ice freezing to the bottom of the lake and extensive open water shallows that likely accelerated ice melt. Most of the ice cover is now in contact with liquid water throughout the year and as a result may be more sensitive to interannual variations in climate. These observations underscore the vulnerability of thick perennial ice to rapid thinning and disappearance during periods of warming.

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