Thermal Regime of High Arctic Tundra Ponds, Nanuit Itillinga (Polar Bear Pass), Nunavut, Canada

Kathy L. Young[1], Laura C. Brown[2]

[1]Faculty of Environmental & Urban Change, York University, Toronto, Ontario, M9C 4A4, CANADA
[2]Department of Geography, Geomatics and Environment, University of Toronto, Mississauga, L5L 1C6, CANADA

Correspondence to: Laura C. Brown (lc.brown@utoronto.ca)

Abstract. This study evaluates the seasonal and inter-seasonal temperature regime of small tundra ponds ubiquitous to an extensive low-gradient wetland in the Canadian High Arctic. Pond temperatures can modify evaporation and ground thaw rates, losses of greenhouse gases, and control the timing and emergence of insects and larvae critical for migratory bird feeding habits. We focus our study on thaw ponds with a range of hydrologic linkages and sizes across Nanuit Itillinga, formerly known as Polar Bear Pass (PBP), Bathurst Island, and ~~whenever possible,~~ compare their thermal signals to other Arctic ponds. Pond temperatures and water levels were evaluated using temperature water level loggers and verified by regular manual measurements. Other environmental data collected included microclimate, frost table depths, and water conductivity. Our results show that there is much variability in pond thermal regimes over seasons, years, and space. Cumulative relative pond temperatures were similar across years, with ponds normally reaching 10-15° C for short to longer periods except in 2013, a cold summer season when pond temperatures never exceeded 5º C. Pond frost tables and water conductivities respond to variable substrate conditions and pond thermal patterns. This study contributes to the ongoing discussion of climate warming and its impact on Arctic landscapes.

1 Introduction

Arctic landscapes are warming faster than temperate locations (e.g., Linderholm et al., 2018; Sim et al., 2019; Kreplin et al., 2021; McCrystall et al., 2021; Webb et al., 2022), specifically, up to four times faster than the global average~~e (global average?)~~ since 1979 (Rantanen et al., 2022). This rapid warming has implications for thawing of permafrost, the alteration of hydrologic regimes (snow on/off, ice-free duration, runoff), changes in hydrologic pathways, and a suite of other environmental and ecosystem impacts (e.g., Webb et al., 2022). There is an expectation that the Arctic will transition from a snow-dominated to a rainfall-dominated regime, especially with an occurrence of higher rainfall in the f~~F~~all (McCrystall et al., 2021), and some suggest that it will occur earlier than initially modelled (McCrystall et al., 2021).

Recently, there has also been a suite of studies and literature reviews evaluating the warming of water bodies (e.g., ponds, lakes, and streams) across arctic landscapes (e.g., Dranga et al., 2017; Lehnherr et al., 2018; McEwen and Butler, 2018;

Saros et al., 2023) and elsewhere (e.g., small ponds in Alaska — Andresen and Lougheed, 2015; wetlands in the high Andes — Dangles et al., 2017; ponds/lakes in W. Greenland — Higgens et al., 2019). Saros et al. (2023) remark that "knowing temperatures and thermal structure within lakes and flowing waters at present and predicting their changes in the future is critical for understanding how aquatic ecosystems will undergo future changes". Other~~s~~ researchers, particularly in the subarctic, are concerned with deepening talik development (unfrozen ground) and lake expansion due to the interactions of shoreline erosion, rising lake bottom temperatures and the occurrence of deep snow near lake/pond shorelines (Roy-Leveillee and Burn, 2017).

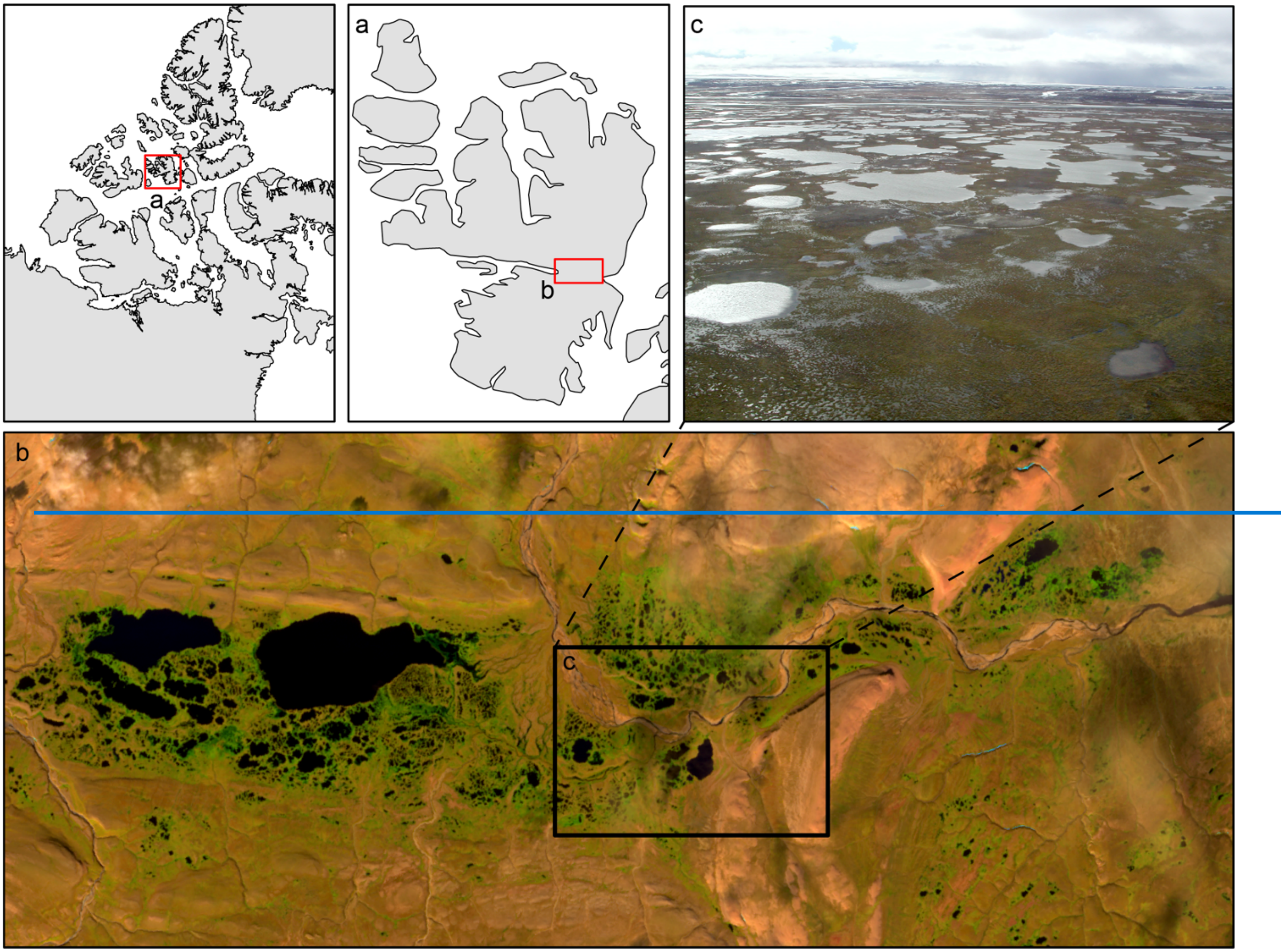
In the Eastern Canadian Arctic, warming has been especially prominent since 2000, with growing loss of glacier ice, permafrost thaw, disappearance of late-lying snowbeds, and the drying of small, patchy wetlands (Woo and Young, 2014). There has been a growing interest in how climate warming will affect northern wetlands here, because~~as~~ temperature increases can enhance evaporation rates, thaw permafrost, drain ponds, or initiate the development of new ponds. Warmer substrates can increase the thaw depth of water bodies~~,~~ and temperature has an impact on vegetation growth and~~,~~ greenhouse gases, including water vapour, methane and carbon dioxide (Negandhi et al., 2013; Andresen and Lougheed, 2015; Wrona et al., 2016; Zandt et al., 2020; Kreplin et al., 2021; Dyke and Sladen, 2022, Miner et al., 2022; Rheder et al., 2023).

This study of pond thermal regimes at PBP adds to this body of literature by evaluating the seasonal and inter-seasonal temperature regime of small tundra ponds ubiquitous to an extensive low-gradient wetland in the Canadian High Arctic spanning warm and cool spring/summers.

First, we examine the spatial and temporal variability of pond temperatures across PBP, highlighting variations in pond location, hydrological linkages, and response to climate variability on a seasonal and annual basis. We then evaluate whether July average pond temperatures vary across ponds at PBP and in relation to other Arctic sites. This study also examines the air-pond temperature relationship~~,~~ and we explore the impact of pond temperatures on the local environment in terms of pond ground thaw and water chemistry (i.e., specific conductivity), given that~~as~~ others have reported deeper thaw in warmer water bodies and higher nutrient loads (e.g., Saros et al., 2023). Finally, we place our results in the context of other studies and discuss how these ponds are ~~being~~ affected by both cool and warm seasons, and what can be expected in the future for these ponds and the ecosystems that depend on them.

2 Study Area

The study took place at the extensive low-lying wetland, Nanuit Itillinga - Polar Bear Pass (~~-~~PBP) Bathurst Island, Nunavut (75. 72º N 98.67º W) ~~NTD: are you not referring to PBP by the Inuk name?~~ from 2007 to 2015, with ~~focused~~ detailed pond studies occurring in 2008 and 2009. PBP is a National Wildlife Area and a Ramsar wetland site of international importance (Baker et al., 2021). The wetland itself is about 20 km long and 5 km ~~wide, and~~wide and is boarded by low-lying hills ranging upwards of 160 m to the north, and 170 m to the south (Caledonian River, District of Franklin, NWT, 1985 topographic map (1:50~~,~~000~~)~~, 68H/11, edition 1)). The low-lying wetland encompasses two small lakes and a myriad of ponds (small to large) exhibiting uniform or irregular shapes ~~(isn't it just irregular? How can something be uniform or irregular?)~~ (Fig. 1). Detailed characteristics of the PBP watershed and study ponds can be found elsewhere (e.g., Abnizova, 2013; Abnizova et al., 2014; Young et al., 2017), however we do provide a summary of the study ponds including location, pond area, water, and frost table depths and details on pond substrate where available (Supplementary Table S1, Supplementary Fig.~~ure~~ S1). Overall,~~-~~ we had 17 study ponds in 2007,~~;~~ 25 in 2008,~~;~~ 23 ponds in 2009,~~;~~ 25 ponds in 2010,~~;~~ 2 ponds in 2012, and only 1 pond in 2013 and 2015. No pond work was carried out in 2011 owing to medical issues. Pond surface areas varied from approximately 275 to 31,400 m^2 and water levels fell between 60 to 359 mm (Table S1). Where available, pond substrates ranged from grey to dark greyish brown and consisted of fines to coarse sand. Soil tests in 2009 did not fully capture the rocky substrate that existed for some ponds (e.g., Pond 11) (see Table S1, Fig. S1).


a
a
b
c
b
c

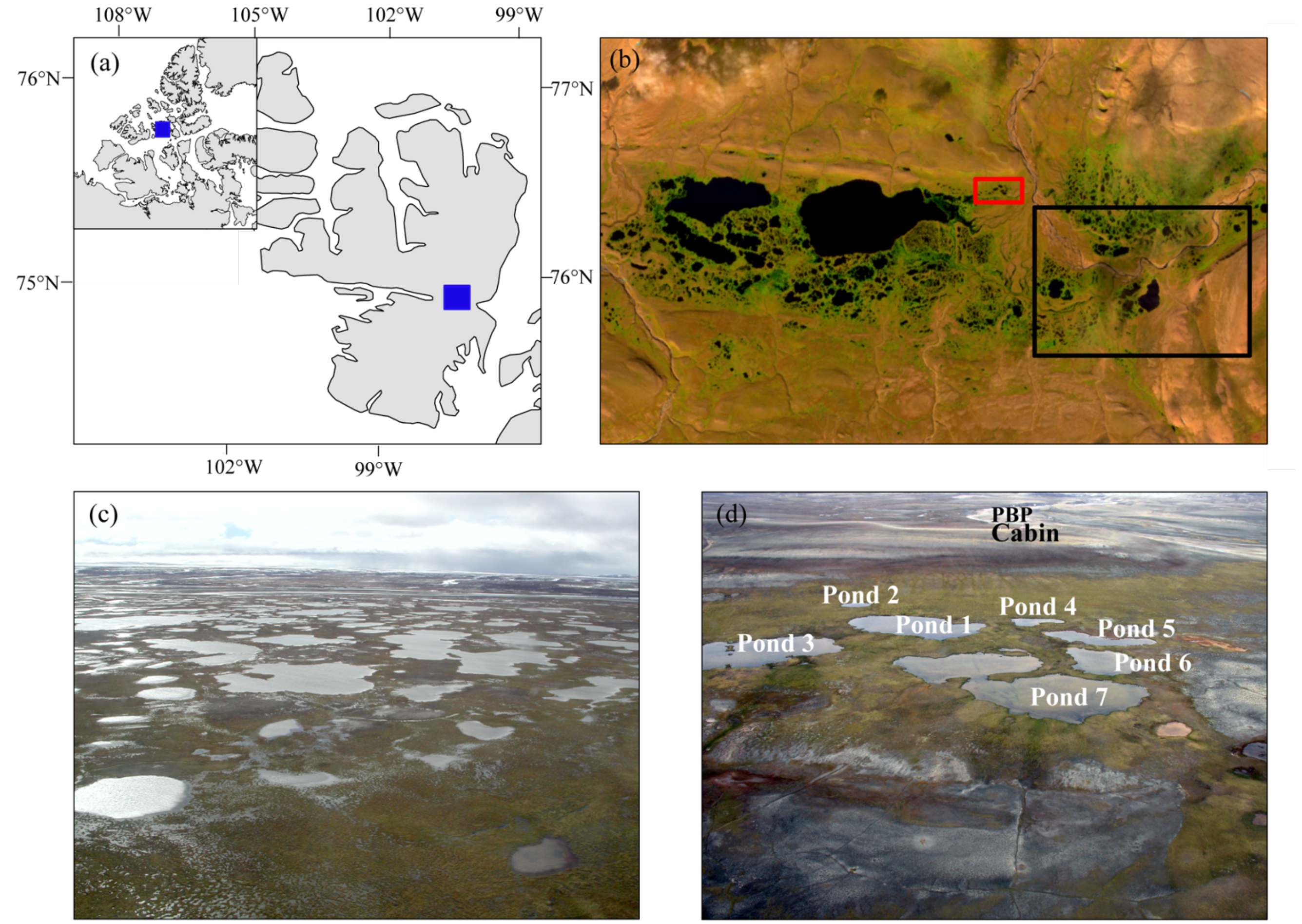


Figure 1. Location of the PBP catchment on Bathurst Island, Nunavut (a). Satellite imagery of the eastern and central lowland area (b), with an air photo showing the wetland with numerous ponds and upland areas (c) - the area indicated by black box in (b). Aerial photo of the central ponds (d) and general area indicated by red box in (b). Photo image (c) was taken on July 10, 2009, and (d) on July 16, 2008. Satellite imagery obtained through EOS Landviewer (eos.com): Sentinel-2 Level2A, Bands 11, 8A, 02, September 6, 2022.

~~**Figure 1: Location of the PBP catchment on Bathurst Island, Nunavut (a,b) and satellite imagery of the eastern and central lowland area with an air photo inset showing the wetland with numerous ponds and upland areas (b,c). Photo image was taken on July 10, 2009. Satellite imagery obtained through EOS Landviewer (eos.com): Sentinel-2 Level2A, Bands 11, 8A, 02, September 6, 2022.**~~

3 Methods

~~In this paper, we focus on describing~~We describe the thermal regime of selected ponds (small to large) across PBP –~~;~~ ones centrally located, and others situated at the eastern, western, and southern edges of the wetland. Some ponds are isolated (i.e., no apparent water sources feed~~ing~~ into them), whereas~~hile~~ other ponds are connected or temporarily connected to small creeks, other ponds, and/or meltwater from nearby late-lying snowbeds (Abnizova et al., 2014). Ponds at PBP are defined as having a maximum water depth of < 2.0 m (National Wetland Working Group, 1997; Woo, 2012). Pond s~~S~~ubstrate type varied~~ across the ponds~~: some pond bottoms were firm, light-coloured, while others had rocky~~ pond bottoms~~ or dark, soft organic beds (see Table S1, Fig. S1~~1, Supplementary Figure 1~~). Water levels in the ponds were continuously monitored with Ecotone water level recorders (Remote Data Systems Inc., ± 2.54 mm) or with HOBO water level sensors (± 3 mm), which also measured temperature (± 0.2º C) on an hourly basis. These sensors were typically placed in the centre of the pond in perforated, screened water wells (5.1 to 7.6 cm dia.)~~,~~ open to the atmosphere and secured into frozen ground. In ponds which were difficult to access due to a soft substrate, water wells and HOBO sensors were placed near the shoreline~~,~~ and occasionally these sensors were placed on the pond bed, ~~especially~~ particularly in remote ponds. HOBO water level sensors were also placed in dry wells dug into wet meadow areas to monitor the atmospheric pressure. The difference in the pressure determined by HOBO water level sensors in the ponds and the atmosphere allowed pond water levels (mm) to be derived (see Rosenberry and Hayashi, 2013). Like other shallow arctic ponds, the study ponds were generally well-mixed negating any concern about significant differences in temperatures of the bed and the water column (Dyke and Sladen, 2022).

Manual measurements of water levels at centrally located ponds were made on a regular basis, usually every one to two days, with a measuring tape (± 5 mm) to verify continuous measurements. Less frequent manual measurements ~~while manual estimates~~ were made at distant ponds. Small HOBO temperature sensors (± 0.1º C) were also deployed in ponds to track hourly temperatures. Manual estimates of temperature and conductivity were made with a YSI conductivity meter (± 0.2º C, ±1 μS/cm), while a Hanna pH meter provided an additional check on temperature (± 0.2º C) along with water pH (± 0.2). In 2008, hourly estimates over several days were made of water chemistry in the selected ponds, including water level (m), temperature (± 0.15º C), conductivity (± 1.0 μS/cm), dissolved oxygen (%), and pH (± 0.2), using a YSI 600 Multiparameter Sonde (Abnizova et al., 2014). In 2009, the YSI sonde was also used to obtain manual estimates of water chemistry in several centrally located ponds, and in 2012 pH and conductivity were monitored in Pond 1 on an hourly interval over several days.

To examine generalized patterns of spatial and temporal trends between air and pond temperatures, Pearson correlations (r) of pond to air temperatures (2008, 2009) were determined for daily mean temperatures ≥ 0º C~~, avoiding the flattening of data at low and high temperatures~~ (Johnson et al., 2014). To investigate inter-site correlations, water temperatures at Pond 1 were evaluated in relation to other ponds.~~ Prior to correlation analysis, air and pond temperature data were checked for normalcy using the Shapiro Wilk test, $\alpha = 0.05$. Like others (e.g., Johnson et al., 2014), the Durbin-Watson test was used as a diagnostic of autocorrelation in regression model residuals. Given that autocorrelation did exist amongst the data (k-1) and is commonly found when comparing air to water temperatures (Johnson et al., 2014), no further work was carried out to develop a predictive model between air temperature and pond water.~~ A Student-t test ($\alpha = 0.05$) was used to compare means of pond water temperature (Tw) when appropriate in the study (Bluman, 2006). We also utilize cumulative percentage diagrams and box plots to provide insights into the overall distribution, concentration and variation of pond thermal data (see https://www150.statcan.gc.ca/n1/edu/power-pouvoir/ch10/5214864-eng.htm).

Changes in ground thaw can alter drainage patterns and water storage in ponds (Young and Woo, 2003; Rehder et al., 2023). Thaw depth in ponds was measured by probing the ground with a metal rod (± 10 mm) twice a week near water wells early in the season and then weekly once ground thaw slowed, providing a means of assessing active layer development and re-freeze (i.e., 2008, 2009) (Abnizova et al., 2014). Climate data (e.g., air temperature) were obtained from the main automatic weather station located near the PBP cabin situated on the plateau above the wetland (see Young and Labine, 2010; Young et al., 2013; Miller and Young, 2016 for additional details on instrumentation, sensor siting, and frequency of monitoring). These data allowed us to examine the air temperature-pond response, and to place our results in context of the variable spring and summer conditions over several years at PBP, and in relation to the nearest government weather station at Resolute Bay (Qausuittuq), Cornwallis Island, Nunavut (74.72º N 94.97º W) about 146 km to the southwest.

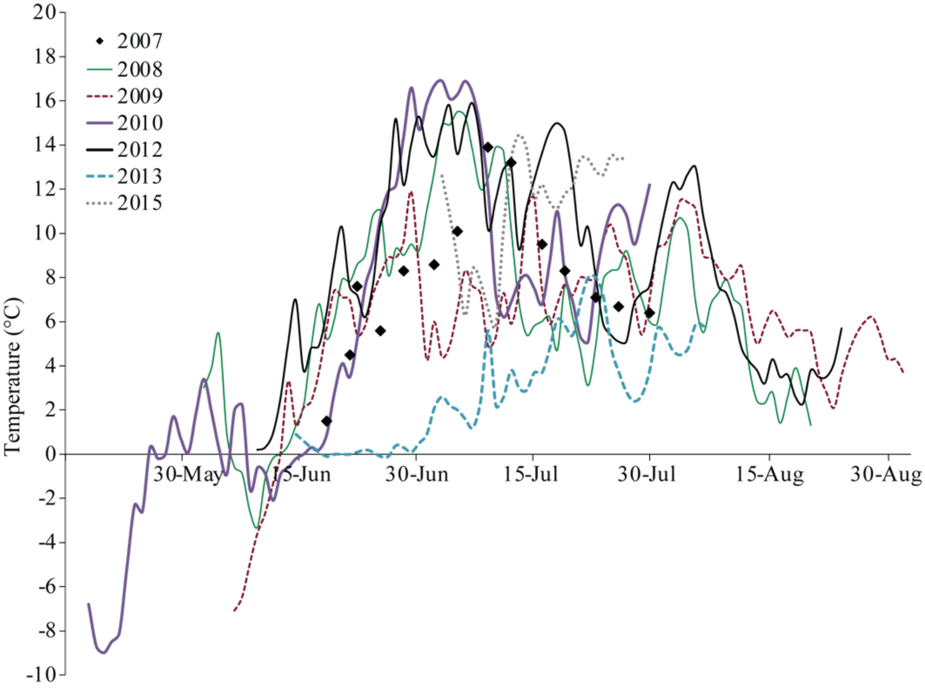
4 Results

4.1 Seasonal thermal regime

The seasonal regime of ponds at PBP over ~~a number of~~several years was explored using the detailed data from Pond 1 (Fig. 2: 2007-2015). It is a medium-sized pond downslope of a wet meadow and lingering deep snowbed located in the lee of a hillslope (Young et al., 2017). The ~~inset~~ diagram also illustrates the range of pond temperatures during two extreme years (2012-warm vs. 2013-cool). In warm years (e.g., 2010, 2012) ~~[I thought 2010 was a cold year I think you mean 2009]~~, pond water temperatures warm rapidly by mid-June with peak pond temperatures reaching about 15º C for extended periods. There is considerable variability from year-to-year, but the general trend is warming in June, elevated temperatures in July and then falling temperatures in August. In context of Resolute air temperatures from 1948 to 2015 (Environment Canada (Resolute): weather.gc.ca), the 2012 JJA air temperature (4.6º C) was the 2nd highest on record, while the 2013 JJA average (0.9º C) was one of the coolest (ranked 11th coolest, along with three other years) over a period of 68 years. ~~The anomalously warm summer 2012 and cool summer 2013 were a result of opposing NAO phases. The summer of 2012 had a very negative NAO (resulting in warm temperatures and substantial snow and sea ice melt) (Overland et al., 2013), while the summer of 2013 had a positive NAO with anomalously low spring and summer temperatures through the Canadian North, dipping 1-3°C cooler in the High Arctic relative to 2007 – 2012 (Overland et al., 2014).~~

Figure 3 ~~shows a similar response between~~indicates that Pond 1 and the centrally located ponds show similar seasonal cycles. Pond temperatures (Tw) are generally higher than the air temperature during the thaw season when temperatures are > 0º C, with most also trending with the air temperature signal. This pattern suggests well mixed conditions as noted for shallow ponds elsewhere in the Arctic (Dyke and Sladen, 2022). In 2009, Pond 1 Tw correlated well with all pond temperatures (r > 0.8 to > 0.9) including ones at the periphery of ~~the Pass~~PBP (east, west, and south). In 2008, a similar pattern between Pond 1 and the other ponds across the wetland emerged (r > 0.8 to > 0.9), except for the Meadow Pond (r (66) = 0.34, p = 0.005). The Meadow Pond is located in a small, elevated valley, and unlike most ponds, has deep residual snowbeds lying on the adjacent slopes. The nearby Pingo Pond is not fed by the snowbeds. Meltwater from lingering snowbeds feeding the

Meadow Pond ensures that pond temperatures are dampened in comparison to more exposed and isolated wetland ponds. Others have observed this pattern on northeast Ellesmere Island (e.g., Smol and Douglas, 2007).


2007
2008
2009
2010
2012
2013
2015
Temperature (°C)
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
30-May
15-Jun
30-Jun
15-Jul
30-Jul
15-Aug
30-Aug

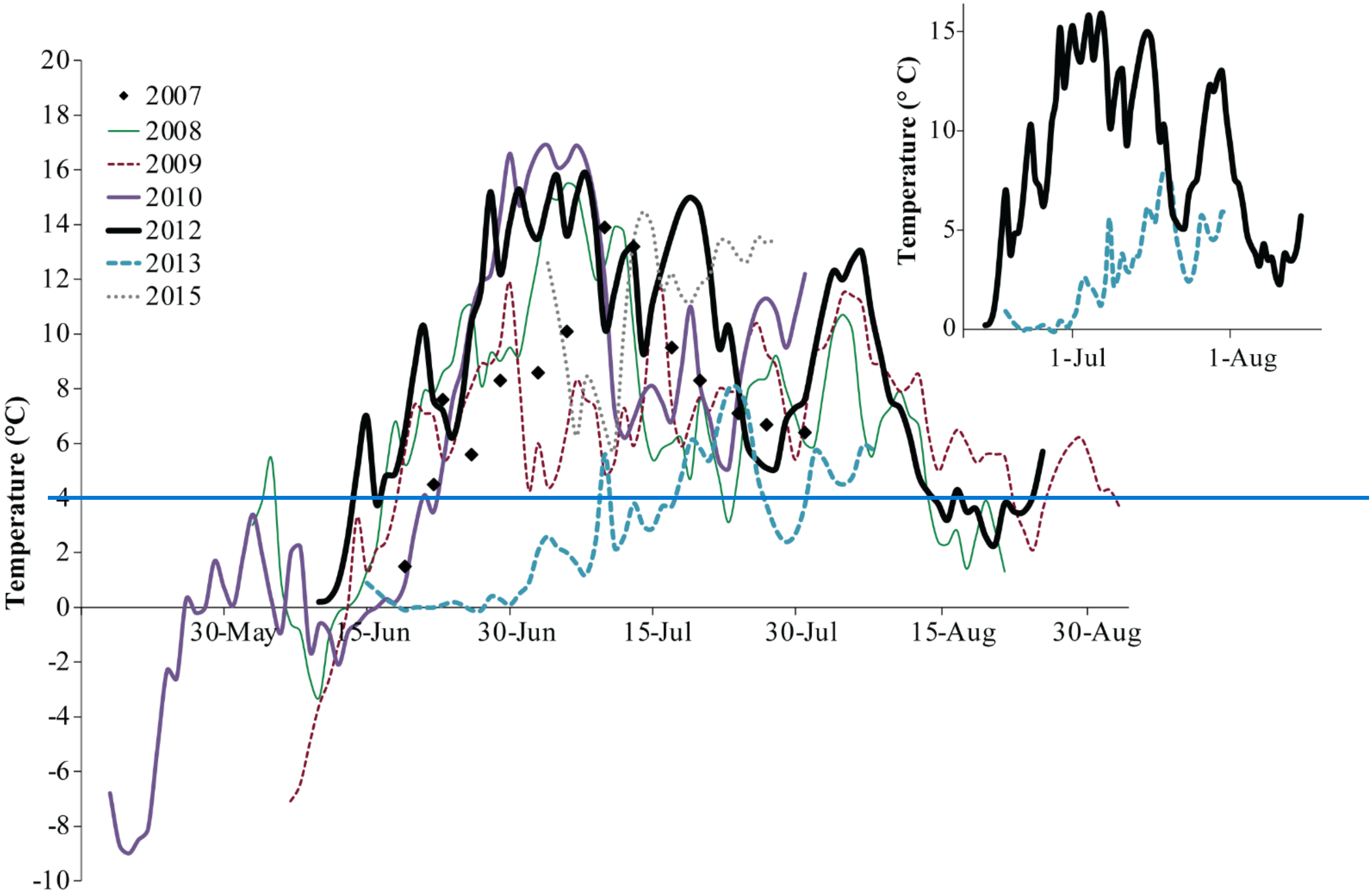
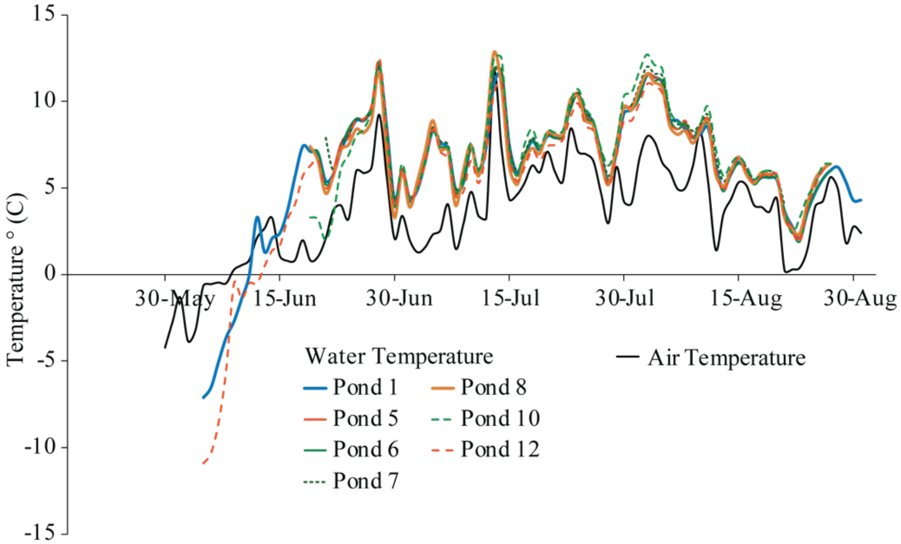


Figure 2.~~:~~ Seasonal regime of water temperature (Tw) at Pond 1, PBP (2007-2015). Manual measurements for 2007 and daily averages for ~~2009~~2008-2015 are plotted. ~~The inset diagram highlights the variability in Tw for two different seasons: 2012-warm and 2013-cool.~~



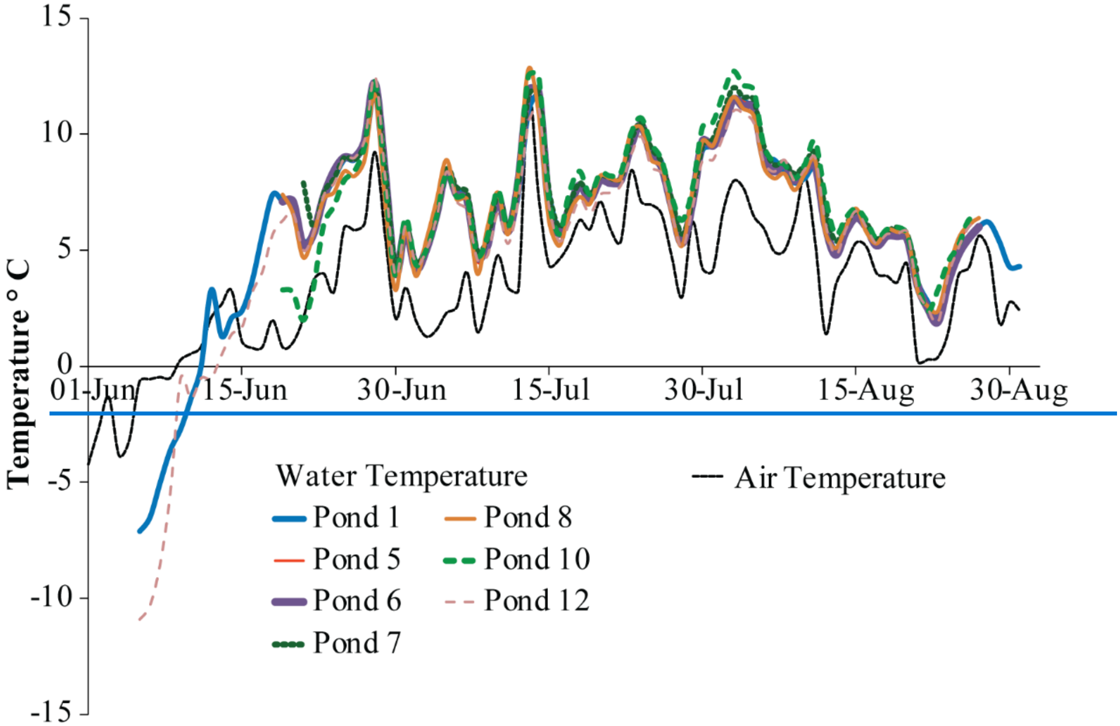
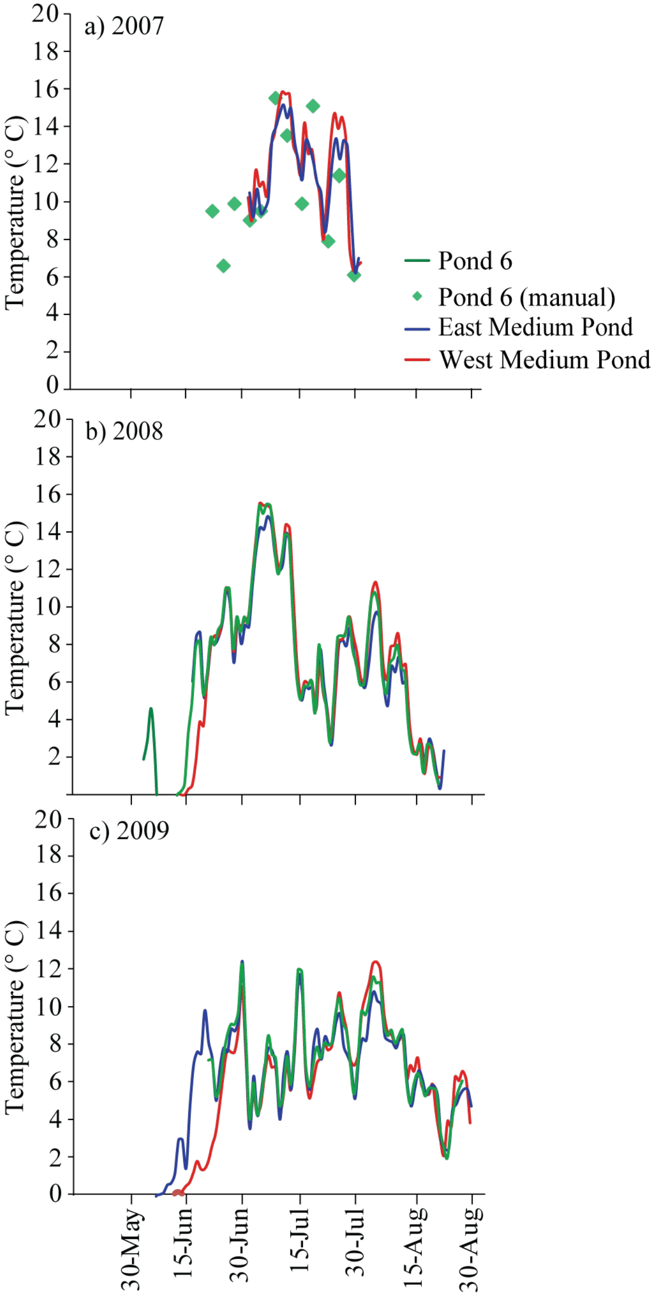


Figure 3.: Daily average water temperature of Pond 1 versus other centrally located ponds at PBP, 2009. The daily average air temperature is also plotted.

Figure 4 illustrates the seasonal rhythm (2007, 2008, and 2009) of medium-sized ponds across PBP. Here we select Pond 6 in the central cluster of ponds as representative of a medium-sized pond. In 2007, by July 20, Pond 6 was slightly warmer than other two ponds, though the rhythms – peaks and troughs of pond Tw remained similar. Warming is comparable to that seen to Fig. 2, where there is some variation in Tw from year-to-year, though these ponds do not exceed 15º C for prolonged periods. Young and Labine (2010) found that environmental conditions were slightly cooler in the eastern part of PBP owing to ~~nearness~~ proximity to the Arctic Ocean, but the largest microclimatic discrepancies across PBP were related to differences in net radiation (surface albedo) and ground heat flux (substrate, vegetation, etc.) (Young et al., 2010). A Student t-test (2-tailed, α = 0.05) reveals that in 2008, Pond 6's mean Tw (7.3º C ± 2.3, n = 69) was not significantly different than the East Medium Pond (7.6º C ± 3.5, n=68) but it was different than~~for the~~ West Medium Pond (6.6º C ± 4.5, n = 77). In 2009, both the East Medium Pond (5.7º C ± 3.8, n=95) and West Medium (4.3º C ± 5.5, n = 94) ponds had significantly different mean water temperatures than Pond 6 (6.6º C ± 4.5, n=80).


a) 2007
b) 2008
c) 2009
Temperature (° C)
0
2
4
6
8
10
12
14
16
18
20
Pond 6
Pond 6 (manual)
East Medium Pond
West Medium Pond
30-May
15-Jun
30-Jun
15-Jul
30-Jul
15-Aug
30-Aug

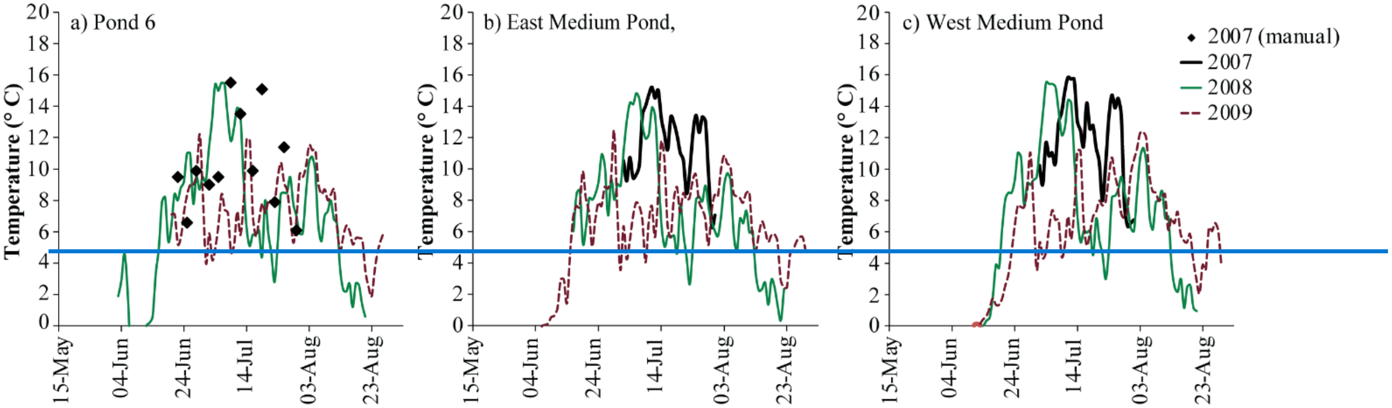


Figure 4.~~:~~ Seasonal temperature regime of medium-sized ponds across Polar Bear Pass (2007-2009) based on manual (~~dashed line~~dots) and continuous data (solid line) from ~~Pond 6~~2007 (a), 2008~~East Medium Pond~~ (b), and 2009~~d the West Medium Pond~~ (c).

4.2 Mean July~~July mean~~ temperature~~s~~

Overall, the pond temperatures at PBP fall in the range found by these other Arctic studies, except it was much cooler in 2013 due to a late spring and cold summer.

~~Benyahaya et al. (2007) and others (e.g., Morison et al., 2023) indicate that water temperature is one of the most important parameters in ecosystem studies as it can influence both chemical and biological processes.~~ Figure 5 plots the July mean temperatures of the central ponds at PBP, across the years. ~~The July average temperature of ponds (8.5º C ±3.9) lying across the Canadian Arctic and boreal regions of Northern Canada with data collected from 1979-2009 are plotted for comparison (see Dranga et al., 2018).~~ In addition, we also include July pond temperature data (11º C, 2005) from Eastwind Lake, Ellesmere Island (Woo and Guan, 2006) and from Cape Bounty, Melville Island (7.2º C, 2009 – Croft, ~~2013~~2011). ~~Overall, the pond temperatures at PBP fall in the range found by these other Arctic studies, except it was much cooler in 2013 due to a late spring and cold summer.~~

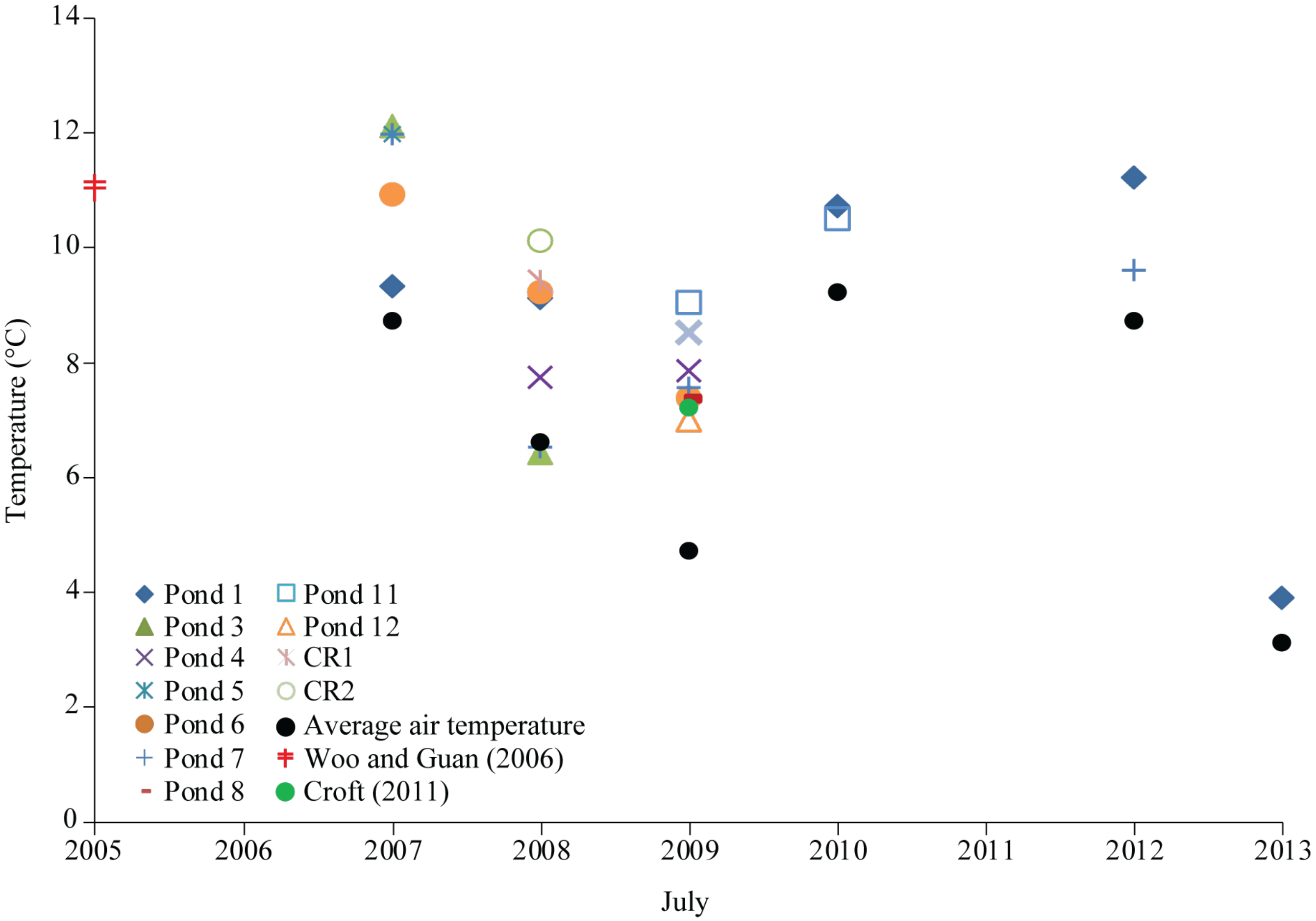


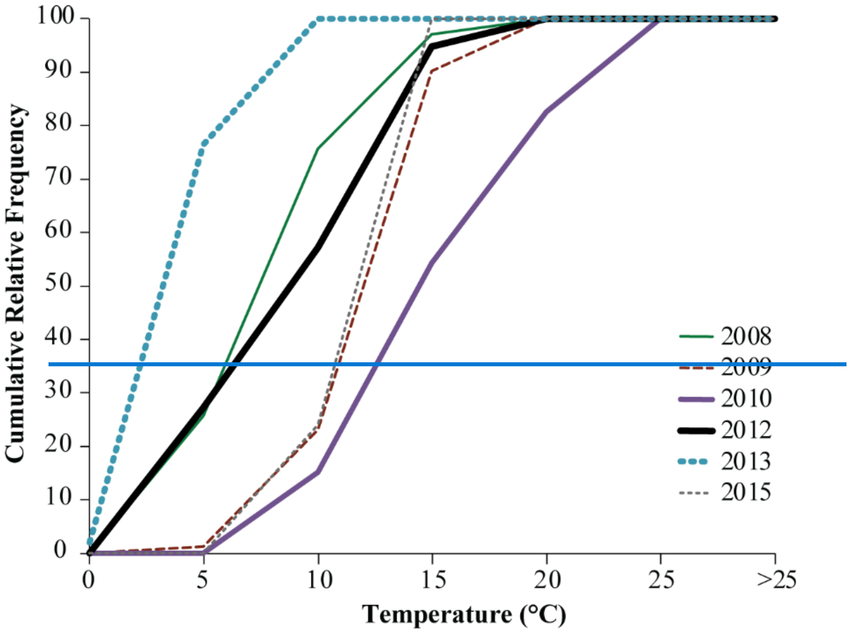
Figure 5.~~:~~ Average July pond temperatures at PBP ponds. Pond data from other Arctic studies are included here for comparison. Illness in 2011 prevented pond temperatures from being obtained at PBP.

4.3 Cumulative ~~relative frequency~~percentages and box plots of pond water temperatures

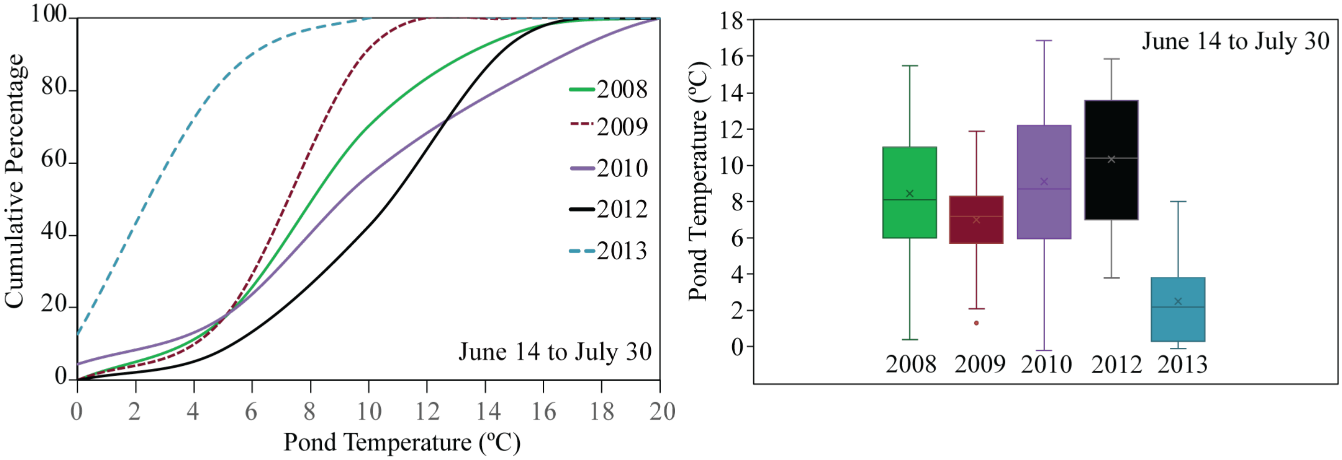
The cumulative ~~relative frequency~~percentages of Pond 1 from 2008 to ~~2015~~ 2013 (June 14 to July 30) based on continuous water temperature measurements is plotted in Figure ~~ure~~ 6 along with box plots. Comparable to Fig.~~ure~~ 2, there is considerable variability from year-to-year. ~~In 2010, approximately 30% of Tw exceeded 20° C but in 2013, pond waters never reached this threshold. Only about 5% of the time did Tw reach 10° C.~~

~~While 2012 was considered a warm season, Tw in Pond 1 only exceeded 15° C 20% of the time. It should be noted that the time frame of the study period in each year can impact these results. For instance, only 2008 and 2009 had a long record of pond water temperatures extending until the end of August. In 2008, Pond 1 exceeded 10° C about 20 % of the time. However, in 2009, Pond 1 was slightly warmer, >15° C, 20 % of the time.~~ In 2012, a warm season, pond Tw exceeded 11° C about 50%

of the time and 14° C about 15% of the time, but in 2013, a cool year, pond Tw only exceeds 2.5° C about 50% of the time and remains below 10 °C. Amongst the three years (2008, 2009, 2010), Pond 1 was the warmest in 2010 but showed the greatest variation according to the box plots (see Fig. 6).



~~**Figure 6: Cumulative relative frequency of water temperatures (Tw) in Pond 1, 2008 to 2015.**~~

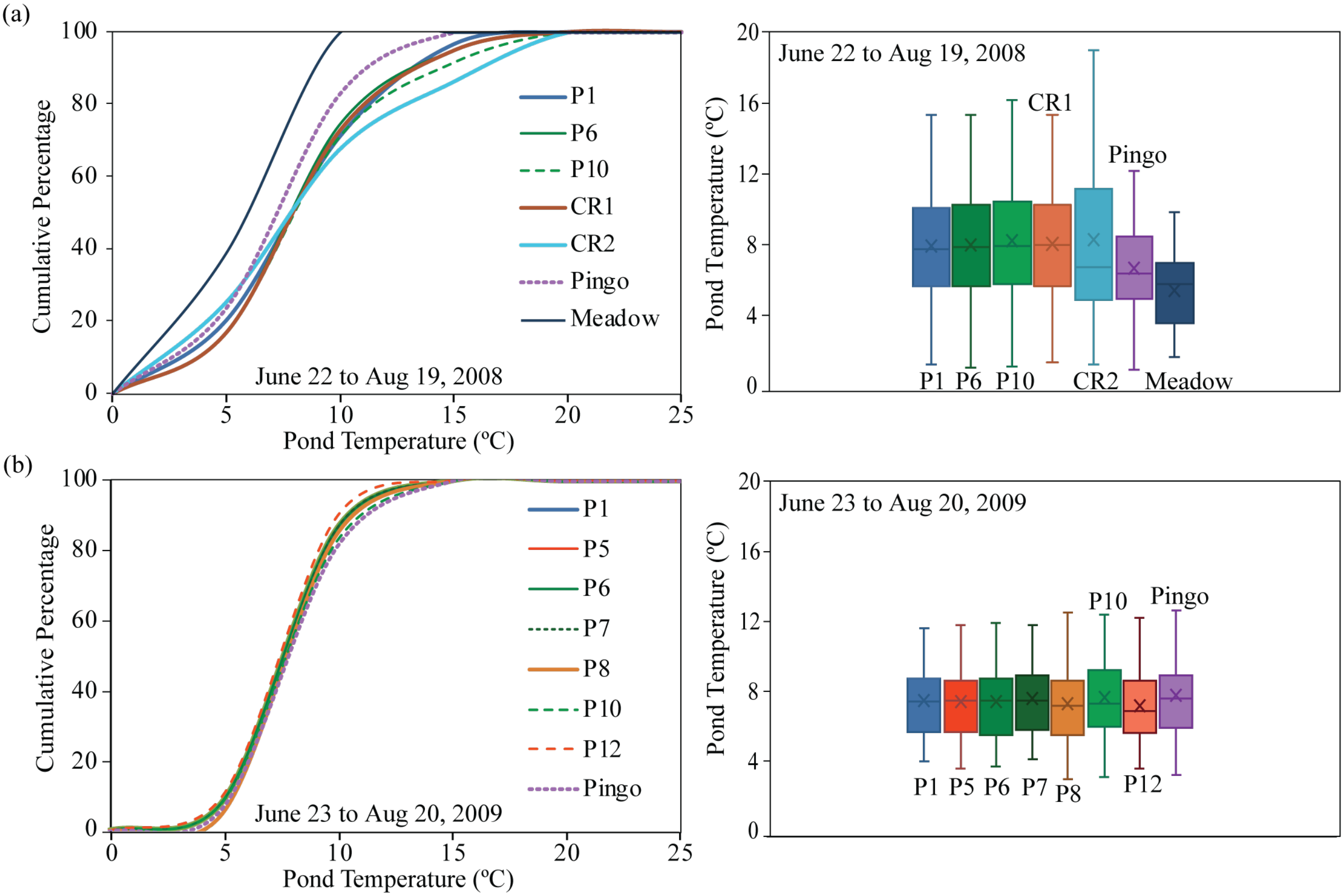


~~Figure 7, based on continuous daily mean data, shows the cumulative relative frequency of the central ponds. The pattern of ponds in a year are similar to Pond 1 (see Fig. 6), but variability from year-to-year and occasionally from pond-to-pond does exist (e.g., Ponds 2, 6). Differences in pond water depth, and water sources can impact water temperatures not just air temperature. For instance, the Meadow Pond plot varies from the others, as it remains cooler for a longer duration. About 80%~~

~~of the time, the Tw here never exceeds 10ºC. As mentioned earlier, this is due to its location nestled in a small valley with adjacent late-lying snowbeds that supply cool meltwater to it, for a protracted time (see Figure 8a, b). The Meadow Pond Tw does not increase until after the late-lying snowbed disappears.~~

Figure 6. Cumulative percentages (left) and box plots of water temperatures (Tw) (right) in Pond 1, 2008 to 2013~~5~~. The time frame selected for comparison is June 14 to July 30. Box plots show median (line in box), and x indicates the average temperature.

Figure 7, based on continuous daily mean data in 2008 (June 22 to Aug. 19) and 2009 (June 23 to Aug. 20), shows the cumulative percentages of water temperature of the central ponds and box plots. The pattern of ponds in a year are similar to Pond 1 (see Fig. 6), but variability from year-to-year and occasionally from pond-to-pond does exist (e.g., Ponds 2, 6). Differences in pond water depth, and water sources can impact water temperatures not just air temperature. For instance, the Meadow Pond plot varies from the others, as it remains cooler for a longer duration. About 80% of the time~~,~~ the Tw here never exceeds 10ºC. As mentioned earlier, this is due to its location nestled in a small valley with adjacent late-lying snowbeds that supply cool meltwater to it~~,~~ for a protracted time (see Figures 8a, b). The Meadow Pond Tw does not increase until after the late-lying snowbed disappears. Median temperatures capture this effect as well.


(a)
100
80
60
40
20
0
Cumulative Percentage
0
5
10
15
20
25
Pond Temperature (ºC)
P1
P6
P10
CR1
CR2
Pingo
Meadow
June 22 to Aug 19, 2008
20
16
12
8
4
0
Pond Temperature (ºC)
June 22 to Aug 19, 2008
CR1
Pingo
P1
P6
P10
CR2
Meadow
(b)
100
80
60
40
20
0
Cumulative Percentage
0
5
10
15
20
25
Pond Temperature (ºC)
P1
P5
P6
P7
P8
P10
P12
Pingo
June 23 to Aug 20, 2009
20
16
12
8
4
0
Pond Temperature (ºC)
June 23 to Aug 20, 2009
P10
Pingo
P1
P5
P6
P7
P8
P12

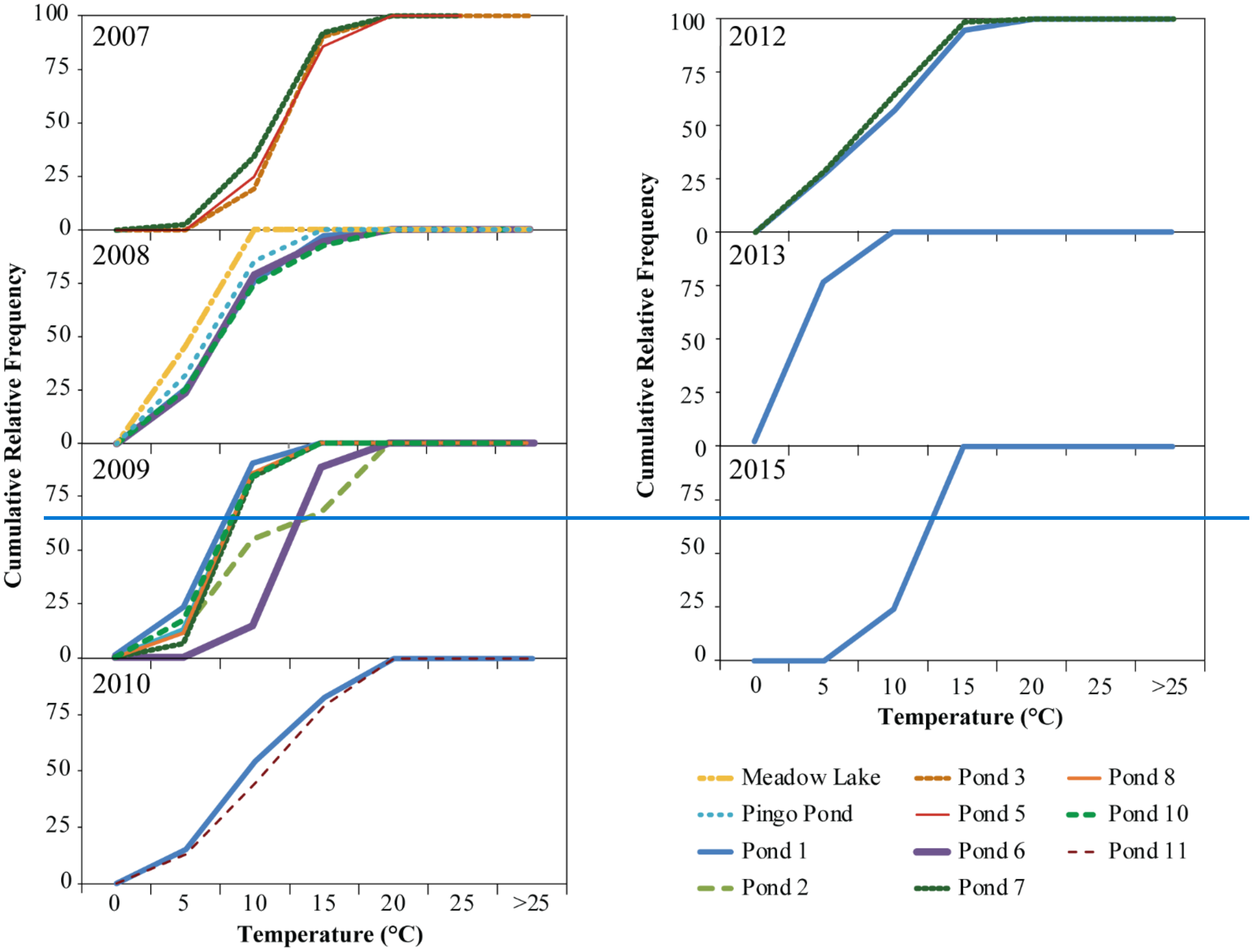
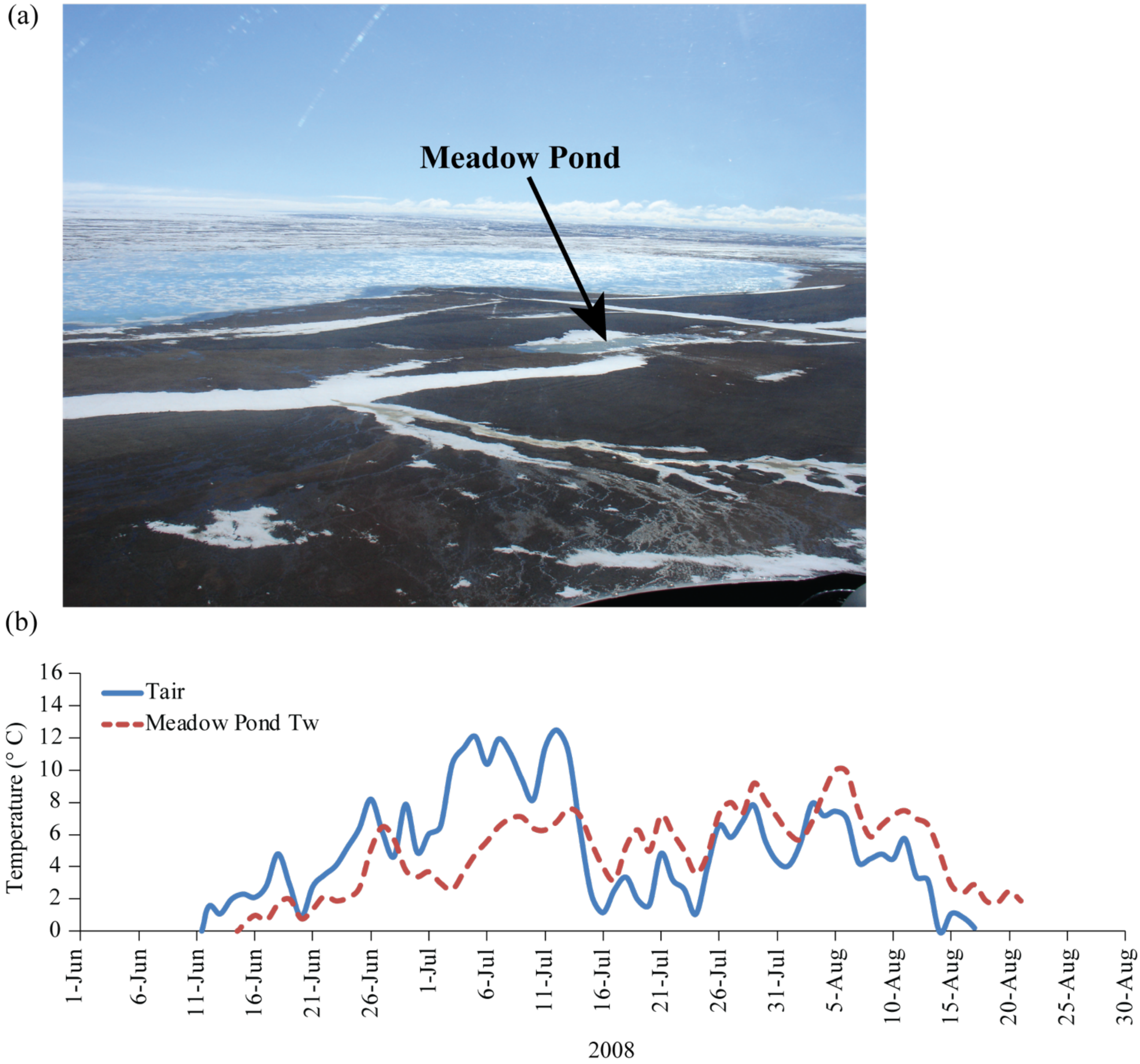


Figure 7.~~:~~ Cumulative ~~relative frequencies~~ percentages and box plots of~~ pond~~ temperatures (Tw) of Central ~~Ponds~~ponds, 2008 (June 22 to Aug. 19) (a) and 2009 (June 23 to Aug. 20) (b)~~7~~ using continuous pond water temperatures. ~~to 2015.~~


(a)
Meadow Pond
(b)
Tair
Meadow Pond Tw
Temperature (° C)
16
14
12
10
8
6
4
2
0
1-Jun
6-Jun
11-Jun
16-Jun
21-Jun
26-Jun
1-Jul
6-Jul
11-Jul
16-Jul
21-Jul
26-Jul
31-Jul
5-Aug
10-Aug
15-Aug
20-Aug
25-Aug
30-Aug
2008

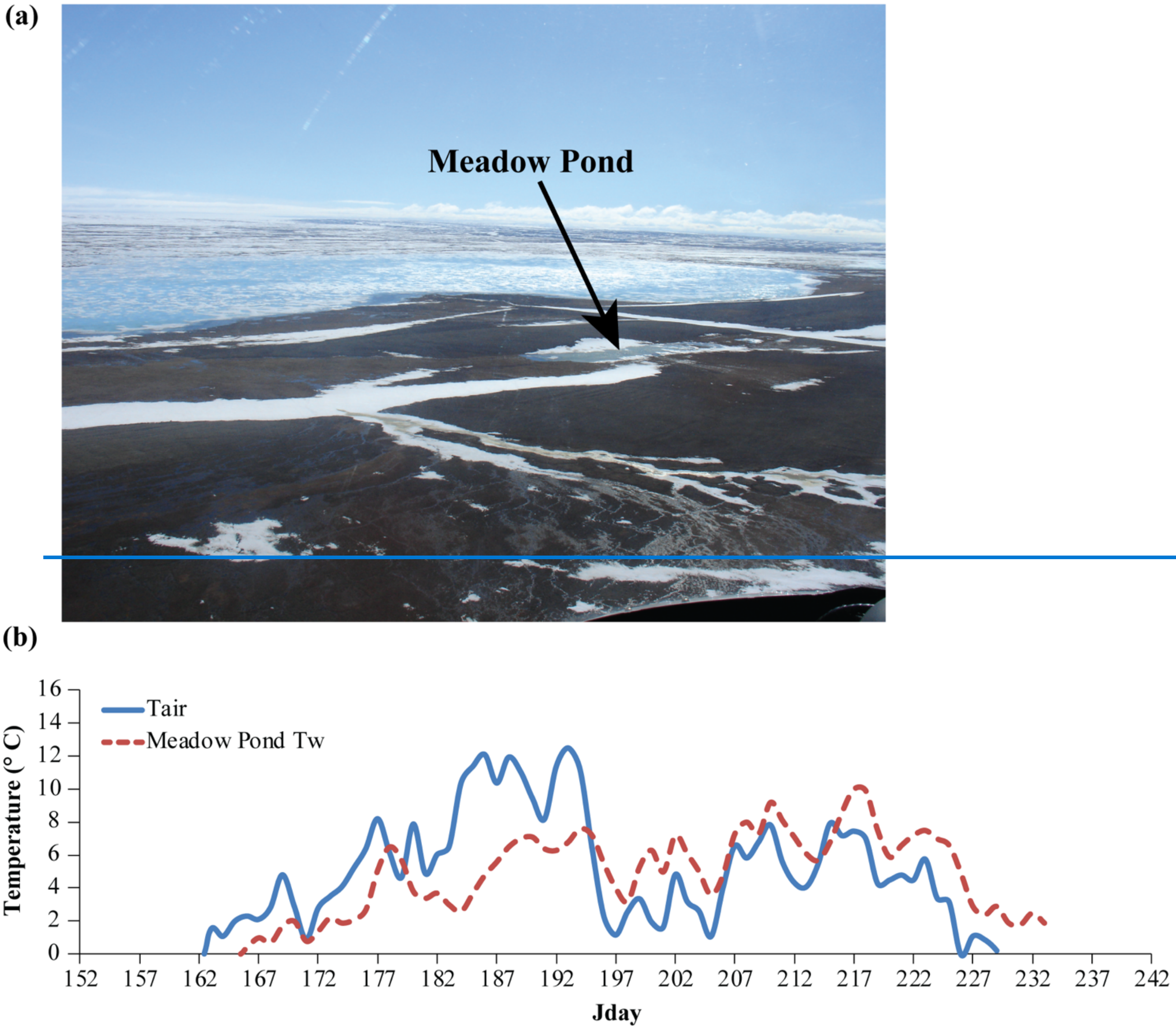
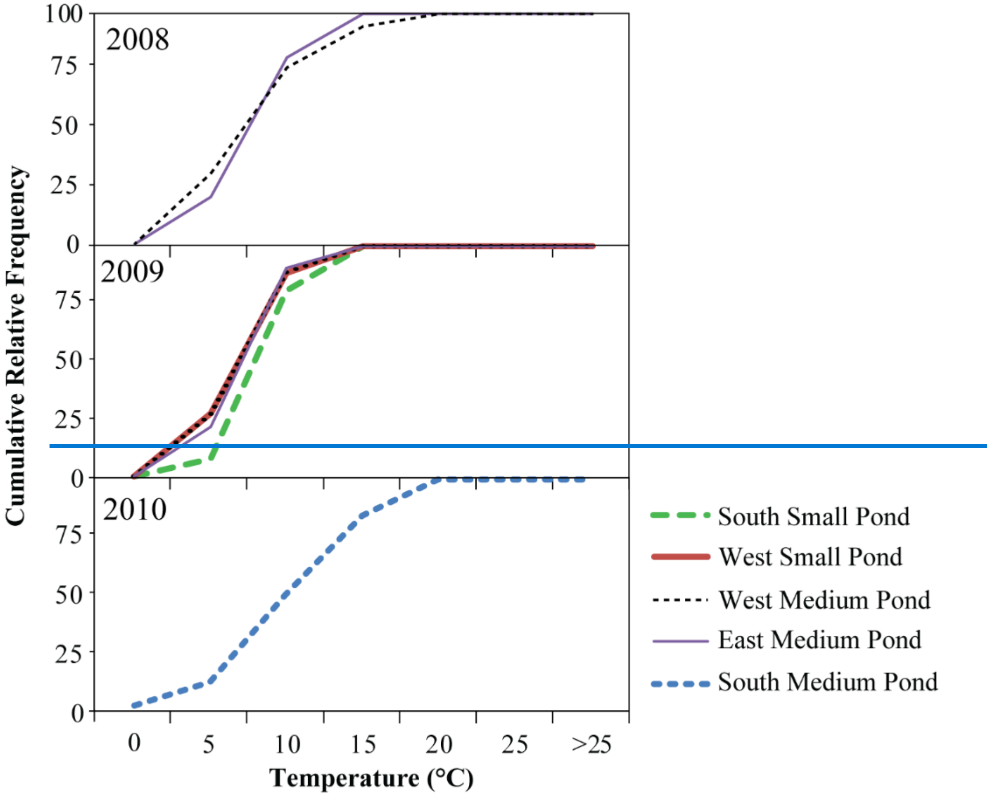


Figure 8.~~:~~ Photo of the Meadow Pond taken June 15, 2008, ~~(a)~~ and air temperature versus pond water Tw (Meadow Pond) in 2008 ~~(b)~~. Note the late-lying snowbeds adjacent to Meadow Pond.

~~Figure 9 shows the cumulative relative frequency of periphery ponds across PBP over several years. There is no significant difference in the pattern for these ponds, including size across PBP. The South Small Pond is shifted to the right in 2009 relative to other ponds, suggesting that it is warmer than the other ponds, but measurements did not start here until July 7 in 2009, which is generally the period when warmer air/water temperatures are reached. Steep temperature gradients can~~

~~accelerate warming similar to rapid thawing and warming of frozen ground released later in the season (early July) from below melting late-lying snowbeds (Woo and Young 2003). Given that the southern part of PBP (north-facing) is last to melt out (Young et al. 2018), the ponds would generally lag in thawing and warming in comparison to the other ponds lying in the northern part of PBP.~~

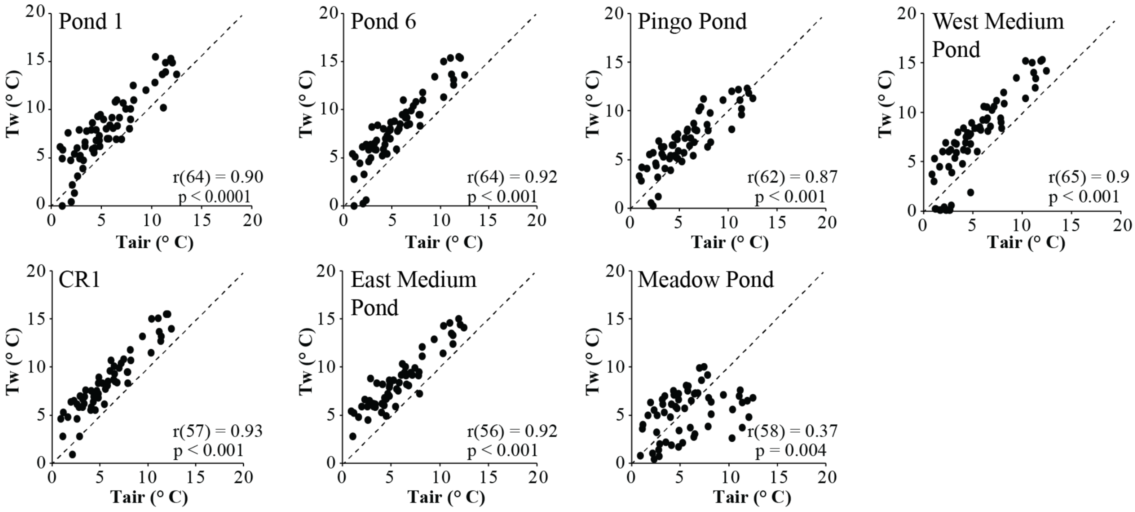


~~**Figure 9: Cumulative relative frequencies of pond temperatures (Tw) of periphery ponds at PBP, 2008 to 2010.**~~

4.4 Air temperature and pond water temperature response

Figure ~~10~~ 9 ~~provides an overview of~~shows the correlations between Plateau air temperatures and pond water temperatures in 2008 (a) and 2009 (b); the two years when continuous measurements were made until the end of August (International Polar Years)~~NTD: why does it matter if these are "International Polar Years" and what does that mean?~~. In 2008, the relationship between air temperature and pond water temperature is strong, when temperatures are > 0º C. Here most ponds show a correlation r > 0.8 or > 0.9~~,~~. When points fall below the 1:1 line, it signals ~~though pond temperatures are consistently warmer than the air temperature~~ there was an initial lag in pond warming due to ice-off (see Fig. 3). As mentioned earlier, the water temperature of Meadow Pond has a much weaker relationship with air temperature. This is due to its location near melting late-lying snowbeds, which help to delay pond warming (see Figure 8).

a) 2008



b) 2009

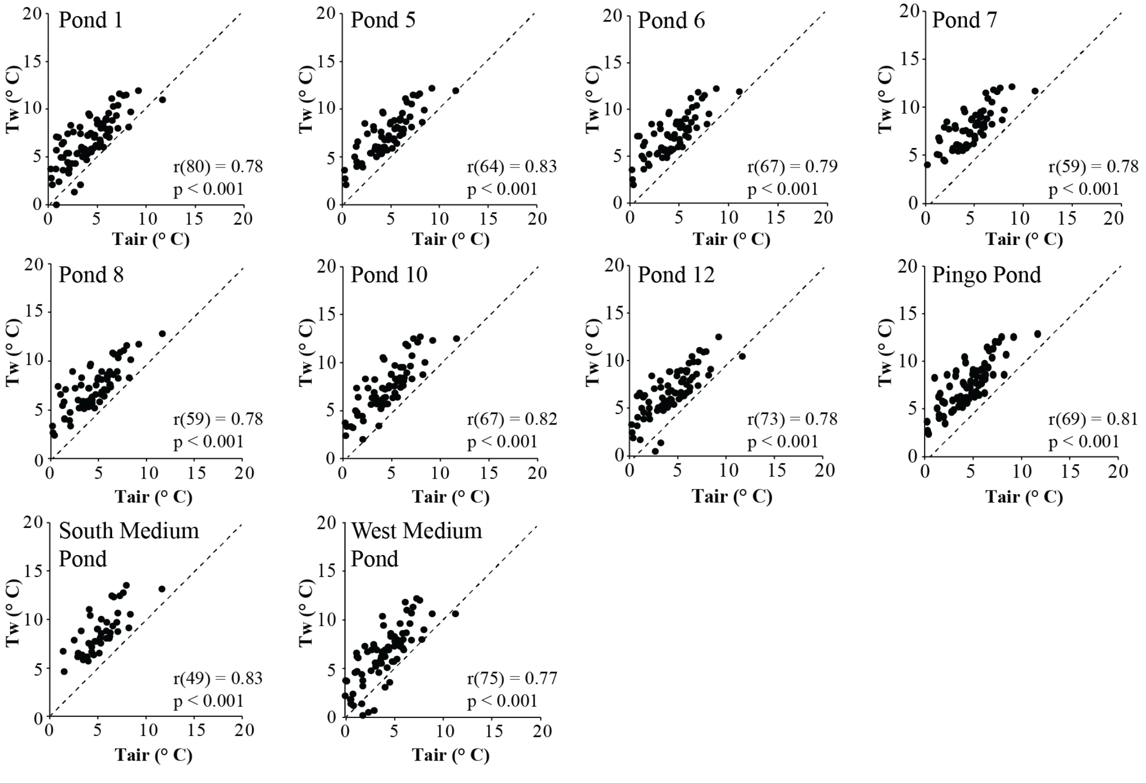


Figure 9~~10~~. ~~:~~Correlations between Plateau daily air temperatures and Pond water temperatures (Tw > 0º C) for ponds 2008 (a) and 2009 (b), using continuous water temperature data. The black dashed line in the plots is the 1:1 line.

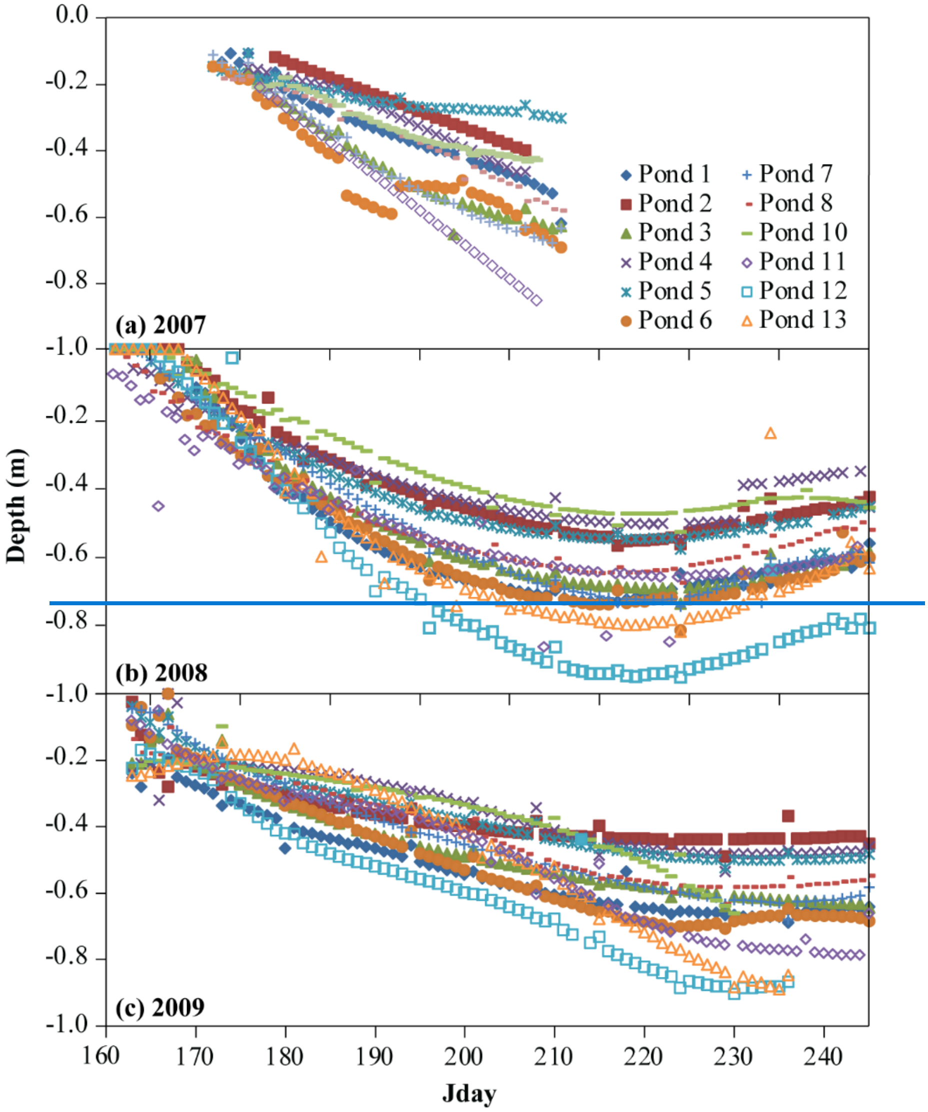
4.4 Other environmental responses

4.4.1 Ground thaw

In 2007, it can be observed that there is considerable variation in pond thaw depth (0.3 m to > 0.7 m) (Figure ~~11a~~10a). Pond 5 had a mucky organic bottom, which might be indicative of high ice content- that restrains ~~and/or?~~ , ~~dampening~~ ground thaw. Pond ~~11~~ 10 exhibited a deep thaw > 0.6 m. It was a shallow pond with a rocky, blue-green algae (dark colour substrate) (see Table S1), which would be effective in absorbing incoming radiation and accelerating ground thaw (Young and Woo, 2003; Young and Abnizova, 2011). Rapid thawing in the month of July can also be attributed to warm air temperatures (average Ta = 7.4° C).

Frost table measurements continued until the end of August in both 2008 and 2009 (see Figures ~~11b~~10b, c). Maximum frost table depths occurred around July 28~~JD 210~~ in 2008 and slightly later in 2009 (Aug 23~~JD 235~~). In 2008, the maximum depth reached in the ponds ranged from about 0.45 to 0.95 m, and in 2009, it was similar (0.42 to 0.95 m), with Pond 12 exhibiting the deepest thaw in both years. The rate of frost table decline amongst ponds is similar in the early part of the 2008 season but then a wider range in thaw develops with -the maximum spread emerging around -July 18 – 23rd ~~JD 200 to 225 in 2008~~. The thaw pattern of ponds is similar in early 2009, but then pond thaw show variable depths by ~~J~~July 29, ~~D 210,~~ which continues for the rest of the thaw period.

The well-defined freeze-back pattern is not as clear in 2009 as in 2008. While the rate and maximum frost table thaw in ponds might be different between the years owing to varying meteorological conditions, the thaw pattern of ponds is consistent; typically, Pond 5 exhibits a shallow thaw versus Pond 11, which can reach deep thaw, particularly in 2007 and 2009, and sporadically in 2008. This regular pattern in frost table depths amongst the ponds was replicated in 2010 as well (data not shown here).


0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Depth (m)
(a) 2007
(b) 2008
(c) 2009
◆ Pond 1
■ Pond 2
▲ Pond 3
× Pond 4
✱ Pond 5
● Pond 6
+ Pond 7
- Pond 8
— Pond 10
◇ Pond 11
□ Pond 12
△ Pond 13
160
170
180
190
200
210
220
230
240
Jday

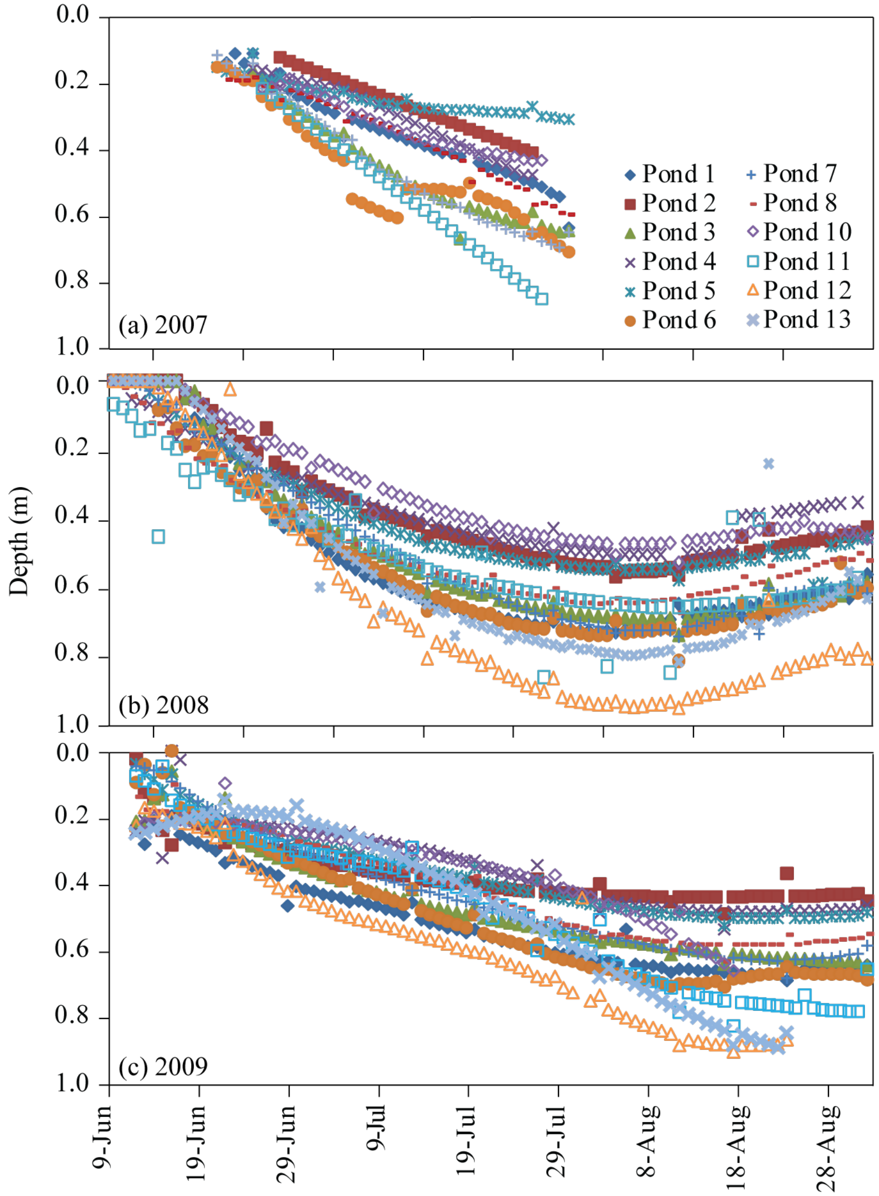
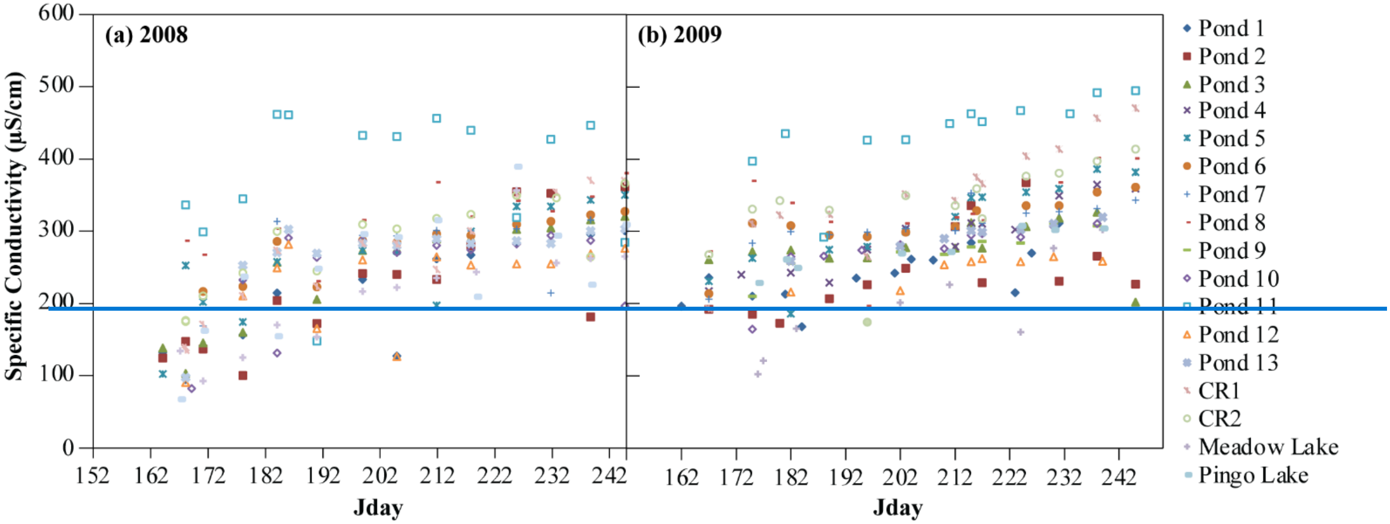


Figure ~~11~~10. ~~:~~ Frost table development in ponds at PBP in 2007 (a)~~,~~ 2008 (b), and ~~and~~ 2009 (c).

4.4.2 Pond water conductivity (µS/cm)

~~Figure 12 provides the spot measurements of specific water conductivity of ponds over the 2008 and 2009 seasons.~~ There is considerable variation between ponds throughout the 2008 season and the conductivity levels rise from ~100 µS/cm to most ponds exceeding 250 µS/cm (Figure 11~~2~~a). Like water temperatures, meltwater from the nearby late-lying snowbed adjacent to the Meadow Pond causes dilution~~helps to dilute it~~ so the water conductivities are generally lower than other ponds. Pond

11, due to its rocky, blue-green substrate and deep ground thaw exhibits the highest water conductivity, maintaining levels ~~higher~~ > 400 µS/cm by early July 2008 (Fig.~~ure~~ 11~~2~~a). A similar pattern emerges in 2009. Pond 11's water conductivity reaches > 400 µS/cm near the end of June and about 500 µ~~u~~S/cm at the end of August. Pond 11 is an irregular shaped pond with a dark substrate. It was prone to drying as was Pond 8. Like 2008, the Meadow Pond in early 2009 has a lower water conductivity signal than other ponds. Later in the season, water conductivity levels start to rise at the Meadow Pond arising from the loss of meltwater from the nearby late-lying snowbed (Fig. 11~~2~~b).



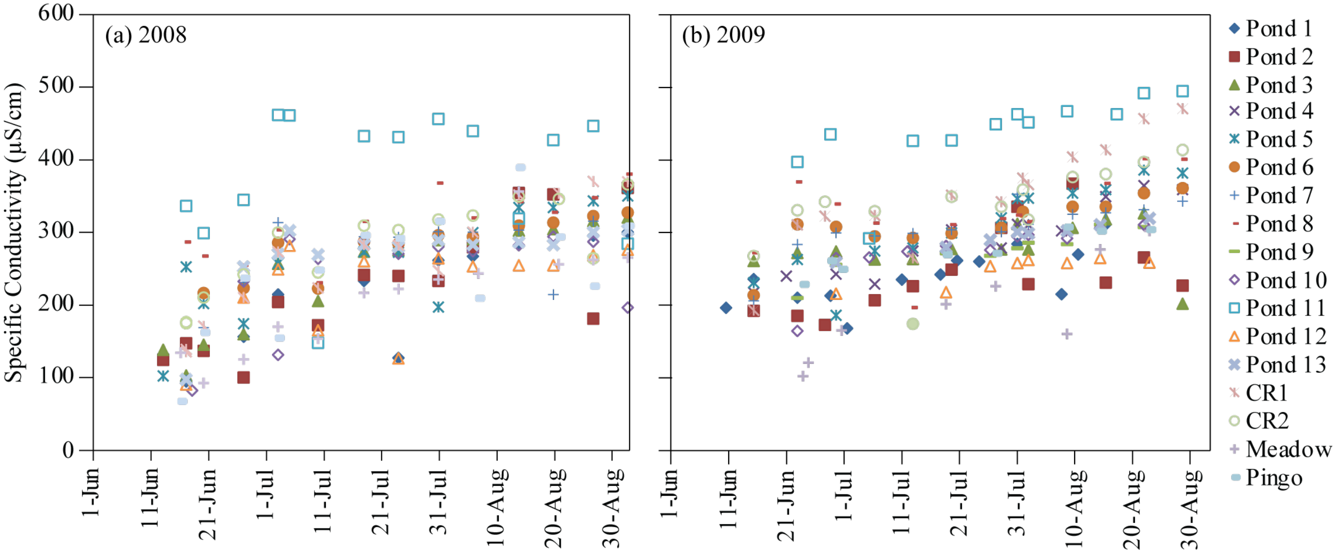
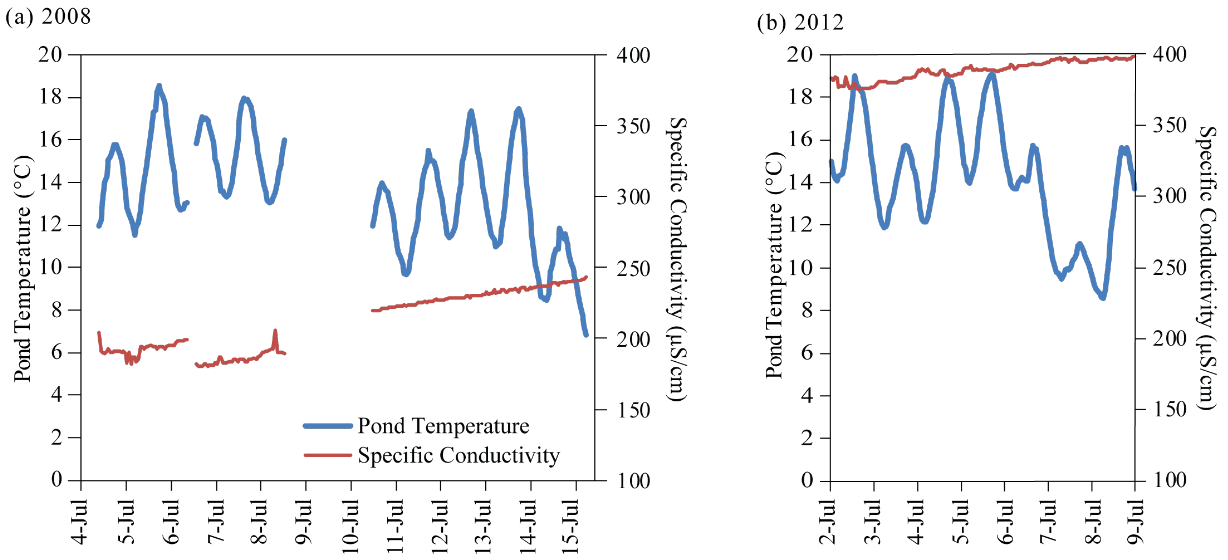


Figure 11~~2~~.~~:~~ Spot measurements of specific conductivity (µS/cm) of ponds at PBP in (a) 2008 and (b) 2009.

Figure 12~~3~~ provides an illustration of the impact of a warm season on the conductivity of pond water as measured by a YSI 600 multiparameter sonde. Fig.~~ure~~ 12~~3~~a, shows the hourly water temperature and conductivity of Pond 1~~,~~ in the early summer of 2008 versus the early summer in 2012. Pond temperatures do not vary that much in these two years during this time. ~~, but c~~Conductivity only reaches about 250 uS/cm in 2008 (mean Tair = 4.39 °C, ~~a cool season~~June 1- July 31)~~)~~ but exceeds 400 uS/cm in 2012, ~~(~~a warmer ~~-~~season (mean Tair = 6.43 °C, June 1-July 31). Due to the warmer air temperatures in 2012, frost tables reached upwards of -0.45 m in the wet meadow upslope of Pond 1 by June 27, 2012 (field notes). In 2008, on June 27, frost table of the wet meadow well adjacent to Pond 1 was only -0.172 m while the pond's frost table depth was 0.369 m. It was also drier in 2012, only 10.8 mm of rainfall was received by the end of June at PBP, while in 2008 ~19.5 mm was recorded by then, followed by 44.1 mm in July. Rainfall measured at Resolute in July 2012 was 30.7 mm.



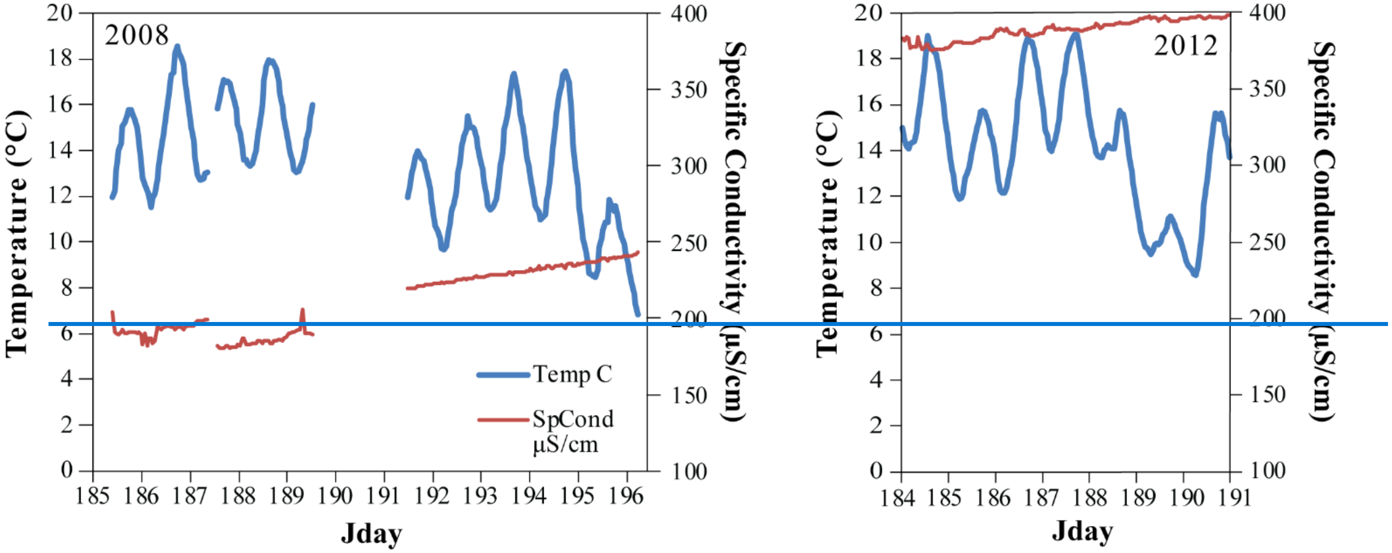


Figure 12~~3.:~~ Hourly estimates of pond temperature (blue line) and specific conductivity (µS/cm) (red line) of Pond 1 in 2008 (a) ~~(a)~~ and in 2012 (b). ~~(b).~~

5 Discussion

5.1 Pond temperatures

Benyahaya et al. (2007) and others (e.g., Dranga et al. 2017; Morison et al., 2023) indicate that water temperature is one of the most important parameters in ecosystem studies as it can influence both chemical and biological processes. ~~McEwan and Butler (2018) examined air temperature and water temperatures in an Arctic pond over 40 years in Alaska's Arctic Coastal~~

~~plain. They documented a 2.2º C increase over a 42-year period or roughly 0.5º C per decade. They found that the average thaw temperature of the pond increased during the first 30 days of the growing season from 1971 to 2012, and that the pond was warmer in the early spring. They found that temperatures in this study pond also correlated well across nearby and distant ponds (r= 0.93 – 0.99) suggesting that all the ponds extending over the coastal plain had undergone a significant change in their thermal dynamics over the past four decades.~~

At PBP, limited monitoring of the thermal regime of ponds indicates that most ponds show a rapid warming in the spring following snowmelt with most peaking in July. Then, pond water starts to cool in August. Average July temperatures are consistent with other pond studies across the Canadian High Arctic including~~; from the subarctic (Dangles et al., 2017) to~~ polar oasis regions (Woo and Guan, 2006). Like McEwan and Butler's (2018) study in northern Alaska, temperatures in central ponds all correlate well with each other and, for the most part, with ponds across~~ the~~ PBP~~ass~~. This indicates that these ponds are all responding to similar climatic conditions (warming temperatures), which is also supported by strong correlations of pond temperatures with air temperature (> 0º C). In this study, 2008 correlations (pond Tw vs. Tair) were slightly higher than in 2009 (see Fig. 9). We~~.~~ do not have a good explanation for this difference. In addition~~,However~~, there are still slight differences in the ponds owing to their unique settings.~~.~~ The Meadow Pond remains cooler than the other ponds owing to lingering meltwater from late-lying snowbeds, a pattern noted by others (e.g., Northern Ellesmere Island — Smol and Douglas, 2007; Somerset Island — Young and Abnizova, 2011). The South Ponds are delayed in warming relative to other ponds due to a regular and persistent snowpack - the southern part of the PBP has a north-facing aspect ensuring later snowmelt and pond opening than the northern part of the PBP (Young et al., 2013; Young et al., 2018; Young, 2019) but once ice free, their pond temperatures quickly catch up to others (Fig. 9).~~.~~

McEwan and Butler (2018) examined air temperature and water temperatures in an a~~A~~rctic pond over 40 years in Alaska's Arctic Coastal plain. They documented a 2.2º C increase over a 42-year period or roughly 0.5º C per decade. They found that the average thaw temperature of the pond increased during the first 30 days of the growing season from 1971 to 2012. Figure 2 indicates that there is still much variability in climate and pond temperature response at PBP~~, and that the pond was warmer in the early spring. They found that temperatures in this study pond also correlated well across nearby and distant ponds (r= 0.93 – 0.99) suggesting that all the ponds extending over the coastal plain had undergone a significant change in their thermal dynamics over the past four decades.~~ from year-to-year (e.g. 2012-warm vs. 2013-cold). The anomalously warm summer 2012 and cool summer 2013 were a result of opposing NAO phases. The summer of 2012 had a very negative NAO (resulting in warm temperatures and substantial snow and sea ice melt) (Overland et al., 2013), while the summer of 2013 had a positive NAO with anomalously low spring and summer temperatures through the Canadian North, dipping 1-3°C cooler in the High Arctic relative to 2007 – 2012 (Overland et al., 2014).

5.2 Environmental response to pond warming

~~“Lougheed et al. (2011) indicates~~ T~~t~~he effects of warming and permafrost thaw on Arctic freshwater ecosystems remain poorly understood (Lougheed et al., 2011)~~”~~. Generally, permafrost and the seasonal frost table maintain water levels in wetlands and ponds near the surface but with an increase in thaw~~,~~ the water ~~table~~ level can drop~~s~~. As the permafrost thaws to deeper soil layers or is completely thawed, the perched water table may be lowered, resulting in drier surface soils, and then this can lead to substantial carbon loss. But in other areas, ground collapse can fill with water to form ponds and wetlands enhancing methane losses (Moonmaw et al., 2018; Rehder et al., 2023).

Pond sediments at PBP ~~depending on porosity characteristics can~~ have varying ice contents (small to large) depending on their texture and porosity characteristics (see Table S1, Fig. S1). This can influence pond thawing rates and maximum thaw depths. Permafrost degradation can also cause expansion or shrinkage of wetland areas and warming associated with permafrost thaw could also turn wetlands into sources of carbon that increases greenhouse gas emissions to the atmosphere (Moonmaw et al., 2018; Kreplin et al., 2021; Rehder et al., 2023). Wrona et al. (2016) argue that while temperature is a key driver in ecological processes in tundra ecosystems, it is hydrological interactions that mediate the climate responses of tundra ecosystems.

While pond temperatures are~~were~~ generally similar across PBP but vary~~ied~~ due to climatic conditions (cool versus warm years), ~~–~~there are~~is~~ considerable differences in the ground thaw rates, which can be attributed to the physical characteristics of the sediments (coarser vs. finer)~~,~~ and colour. Some ponds have~~d~~ darker substrates than others, which can lead to greater absorption of incoming solar radiation due to a lower albedo (Young and Abnizova, 2011). Warmer summers (e.g., 2007) versus cooler ones (e.g., 2008) did lead to higher rates of pond evaporation (Young and Labine, 2010) but deeper thaw in warm, dry years also contributed~~s~~ to enhanced vertical pond seepage due to an increase in the active layer storage capacity. This process most likely contributed to ~~and~~ drying and pond shrinkage (Young and Abnizova, 2011). Pond thaw rates differ from pond-to-~~pond~~pond, but they are consistent from one year to the next confirming the critical role played by the pond sediments (see Table S1, Fig. S1). ~~.~~

A similar pattern emerges when evaluating pond water conductivity. Ponds that are shallow and subject to drying tend to have the greatest water conductivities in both cool and warm years. Here, shallow pond waters are in greater contact with thawing soil materials. Figure 12 also confirms that pond conductivities can rise substantially in the same pond from one year to another in response to warmer air temperatures and deeper ground thaw.

In the Old Crow Flats, Yukon, Roy-Leveillee and Burn (2017) ~~studied the near-shore talik development beneath shallow water in expanding thermokarst lakes, Old Crow Flats, Yukon. They~~ found that near-shore taliks could develop in shallow ~~lake/pond water,~~ (~~-~~often less than 20 cm) lake pond water~~,~~ when warm summers increased the thawing degree days. Deep and early snowpacks near the shoreline also helped to keep lake bed temperatures above 0°C, preventing permafrost aggradation. ~~Roy-Leveillee and Burn (2017) argue that “further work must include extensive examinations of permafrost sustainability in near shore and beneath the center of shallow Arctic lakes in areas with varied climatic conditions, with~~

~~particular attention to the increasing frequency of warm years in circumpolar regions and to the effects of fluctuations in water levels resulting from changes in lake hydrological regimes".~~

5.3 Climate warming: What can we expect for PBP ponds?

Climate warming over the last century has been greatest in the Arctic and is projected to continue in the 21st century at a rate above the global average (Sim et al., 2019; Miner et al. 2022). Future hydrological changes, vegetation shifts and degradation of permafrost have been identified as key areas of uncertainty in the prediction of permafrost carbon dynamics (Sim et al., 2019). So~~,~~ what can we expect for PBP? We will likely see continued warming, and if 2012 (a warm/dry season) is any indication of future climate warming, we can expect early snowmelt, an earlier opening of ponds, a prolonged thaw season, and extended periods of time when pond temperatures exceed 15º C. We can expect ~~frost tables~~pond substrates ~~-~~to thaw earlier in the season and frost tables to ~~be~~ deepen~~r~~, and that together with increases in evaporation loss, we may see pond water levels dropping below ground with some ~~some~~ ponds drying out (see Figure 13 - general schematic of pond response at PBP). This ~~pattern~~ conclusion is supported by Dyke and Sladen (2022), whose modelling efforts notes deeper talik development under shallow ponds dotted on subarctic peat plateau landscapes.

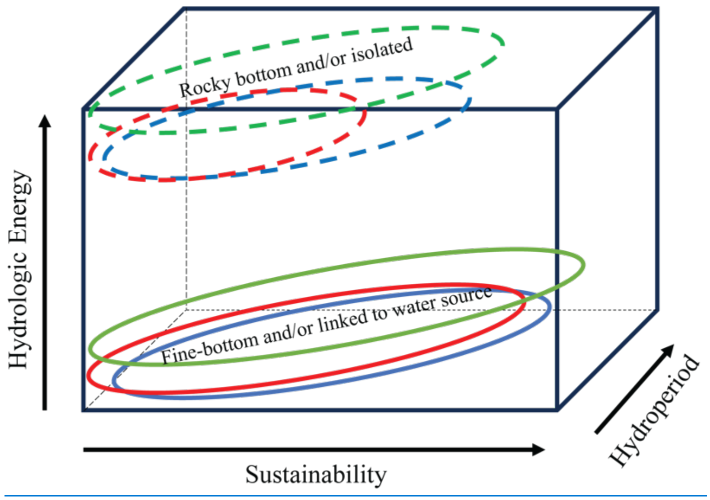


Figure 13. Schematic showing the functional integrity of PBP ponds. Blue lines (solid/dashed) represent 'present'conditions; red lines (solid/dashed) represent pond response to 'future warm/dry' conditions and green lines (solid/dashed) represent response to future 'warm/wet' conditions. Hydrologic energy refers to the degree of fluctuations in water level, hydroperiod refers to the length of time that the pond contains water over the season (diagram adapted after Young and Abnizova, 2011).

It is likely that hillslope streams, which now provide some ponds with a source of water for an extended time during the thaw season may not do so for as long (Young, 2019)~~,~~ and that ponds buffered now from elevated Tw and higher conductivities by lingering meltwater contributions from late-lying snowbeds will cease to do so (Woo and Young, 2014). In the high Andes, ponds and wet meadows are now being sustained by meltwaters from melting glaciers but they are predicted to diminish and disappear by the end of the century. These ponds and wet meadows will then dry out and ultimately disappear (Dangle et al., 2017). Moonmaw et al. (2018) also indicate that permafrost thaw can dramatically affect hydrology and that fen-like systems are vulnerable as they rely on terrestrial water inputs (e.g., groundwater and~~,~~ streamflow). As these external water sources change or cease to exist like the rapid loss of late-lying snowbeds at PBP and elsewhere across the Arctic islands (Woo and Young, 2014), wetlands will be impacted. At PBP, many irregular shaped and shallow ponds (e.g., Ponds 8, 11) have already been observed to dry out over summer seasons with vascular plants encroaching, suggesting that in the long-term~~,~~ certain ponds may ~~shift~~ transition into wet or dry meadow features (see Fig. ~~14~~14), which may eventually alter greenhouse gas emissions (Rehder et al., 2023), snowcover receipt, and evapotranspiration rates as shifts in vegetation have done elsewhere (Morison et al. 2023).

Strong correlations between air temperature and pond Tw will persist but departures will grow as pond water become warmer than the air temperatures, especially shallow ponds with dark, rocky substrates (e.g., Pond 11). Lougheed et al. (2011) observed that establishing a direct relationship between air and water temperatures is complicated by wind, water depth, ice cover, and other physical processes that determine temperature in small tundra ponds < 0.5 m at the International Biological Program (IBP) site, Barrow, Alaska. They noted that variability in temperature is higher in both the early and late part of the season, a pattern emerging for PBP ponds as well (see Figs.~~ures~~ 2, 3).

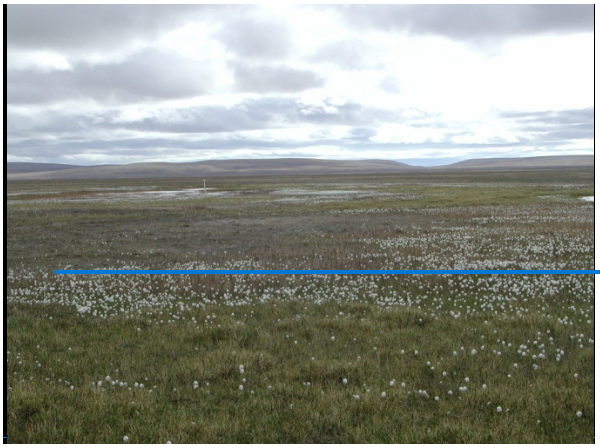


Figure 144. ~~:~~ Desiccated pond (Pond 8) July 23, ~~in~~ 2007 (left) and Pond 8, ~~July 15~~August 19, 2010 (right), showing how *Eriophorum scheuchzeri* -~~white~~ White C~~c~~ottongrass are encroaching.

Linderholm et al. (2018) indicate that reanalysis data show an increasing trend in Arctic precipitation over the 20th century, but changes are not homogeneous across seasons or space. Possible increases in 21st century Arctic late autumn and winter precipitation counter increased pond evaporation losses to some extent. However, large uncertainties remain in predicting future precipitation patterns (Sim et al., 2019). If there are a series of years where fall rainfall fails to replenish pond storage deficits, and little spring snowmelt occurs, then it is likely that these ponds, especially the irregular shaped and shallow ones will dry out permanently, and vascular plants will encroach as has happened to patchy wetlands on Cornwallis Island (Woo and Young, 2014) (see Fig. 14). ~~.~~

6 Conclusions

The thermal regime of High Arctic ponds was monitored over several years at Polar Bear Pass, a Ramsar wetland of international importance. Variability in pond temperatures occurs on a seasonal and inter-seasonal basis with ponds responding to warm and cool springs~~,~~ and summer seasons. There is little variation in pond temperatures across the PBP but linkages to other terrestrial sources besides rainfall and seasonal snowmelt remain important (e.g., Meadow Pond). Prolonged inputs of meltwater from late-lying snowpacks into adjacent ponds serves to dilute and dampen water temperatures for extended periods in the summer.

Ground thaw is variable in ponds owing to substrate type, water depth and ground ice content. In the f~~F~~uture, an earlier start to ground thaw and ~~enhances in~~deepening of frost tables~~pond thaw~~ may drain some shallow ponds, while others due to deep waters and abundant ground ice will be sustained. Like frost table patterns, the water chemistry (i.e., specific conductivity), which reflects evapo-concentration processes, groundwater flow varied amongst these ponds. The rapid and sizeable increases in water conductivity at Pond 1 in an extremely warm season (2012)~~,~~ highlight the large shifts in environmental responses that these ponds are now undergoing. Uncertainties about fall precipitation exist for High Arctic regions. If pond storage deficits persist for several years and cannot be augmented by seasonal snowmelt or linkages to other water sources (i.e., late-lying snowbeds and~~,~~ streams), more ponds will disappear at PBP and may be replaced by larger wet/dry meadows. This will potentially have an impact on greenhouse gases and the feeding patterns of migratory birds. Finally, future research efforts should focus on the response of other large wetland areas in the Canadian High Arctic including Alison Inlet (southwest coast of Bathurst) and Truelove Lowland, Devon Island in order to investigate the response of ponds to future fluctuations in climate.

Data Availability

The data that support the findings of this study are available at https://doi.org/10.5683/SP3/KGRQDO.

Author Contributions

Young carried out field work, analyzed the field data, and wrote the manuscript. Brown carried out field work, finalized diagrams, and helped to edit the manuscript.

Competing interests

Some authors are members of the guest editing team of the special issue in HESS.

Acknowledgments

First, we would like to thank the anonymous reviewers who took the time to read our paper and provided valuable advice and insight. You have all greatly improved the paper. Secondly, we~~We~~ would like to acknowledge sabbatical funding from York University to K. Young in 2021, which allowed these data to be analysed and a paper to be prepared. Since 2006 to 2015, the Canadian Government Agency, Polar Continental Shelf Program (PCSP) has provided exceptional logistical support ~~to~~ for our work at Polar Bear Pass. We are also grateful to the many undergraduate and graduate students who have worked at Polar Bear Pass to help ~~attain~~ obtain these environmental data. Jennifer Rausch, a wildlife ecologist with Environment Canada, kindly retrieved pond water temperature data in 2015. John R. Siferd, kindly corrected the grammar. ~~John R. Siferd graciously corrected the grammar in the manuscript.~~ Finally, K. Young presented some of these findings at the 23rd Northern Research Basins Symposium and Workshop held in Northern Sweden, August 20-25, 2023.

References

Abnizova A., Young, K.L., and Lafrenière, M.: Pond hydrology and dissolved carbon dynamics at Polar Bear Pass wetland, Bathurst Island, Nunvaut. Ecohydrol. **7**(1), 73–90, 201, 2014.

Abbott, B. W., Jones, J. B., Schuur, E. A. G., Chapin III, F. S., Bowden, W. B., Bret-Harte, M. S. et al.: Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: An expert assessment. Environ. Res. Lett. 11(3), 034014, 2016.

Abnizova, A.: Hydrology, Carbon Dynamics and Hydrochemical Properties of Ponds in an Extensive Low Gradient High Arctic Wetland, Polar Bear Pass, Bathurst Island, Nunvut, Canada. PhD thesis, Department of Geography, York University, Toronto, Ontario, Canada, 256 pp., 2013.

Andresen, C.G., and Lougheed, V.L.: Disappearing Arctic tundra ponds: Fine-scale analysis of surface hydrology in drained thaw lake basins over a 65-year period (1948-2013). J. Geophys. Res. Biogeosci. 120(3), 466-479, 2015.

Benyahya, L., Caissie, D., St-Hilaire, A., Ouarda, T.B.M.J., and Bobée, B.: A review of statistical water temperature models. Can. Water Res. J. 32(3), 179-192, 2007.

Baker, J., Dupont, D., and Vasseur, L.: Exploring Canadian Ramsar sites ecosystem governance and sustainability. Wetlands 41(6) https://doi.org/10.1007/s13157-021-01417-6, 2021.

Bluman, A.G.: Elementary Statistics. McGraw-Hill, 2006.

Croft, A.:   A L~~l~~ink between B~~b~~enthic M~~m~~acroinvertebrate D~~d~~iversity and the H~~h~~ydrology of High Arctic ponds in Polar Bear Pass, Bathurst Island, Nunavut and Cape Bounty, Melville Island, Nunavut. MSc thesis, Department of Geography, York University, Toronto, Ontario, Canada, 138 pp., 2011.

Dangles, O., Rabatel, A., Kraemer, M., Zeballos, G., Soruco, A., Jacobsen, D., and Antheime, F.: Ecosystems sentinels for climate change? Evidence of wetland cover changes over the last 30 years in the tropical Andes. PLoS ONE 12(5): 30175814. https://doi.org/10.1371/journal.pone.0175814, 2017.

Dranga, S.A., Hayles, S., and Gajewski, K.: Synthesis of limnological data from lakes and ponds across Arctic and Boreal Canada. Arctic Sci. 4, 167-185, 2017.

Dyke, L.D., and Sladen, W.D.: Modelling tundra ponds as initiators of peat plateau thaw, Northern Hudson Bay Lowland, Manitoba. Arctic, 75(3), 364-377, 2022.

Higgens, R.A.F., Chipman, J.W., Lutz, D.A., Culler, L.E., Virginia, R.A., and Ogden, L.A.: Changing lake dynamics indicate a drier Arctic in Western Greenland. J. Geophys, Res. Biogeosci. 124, 870-883. https://doi.org/10.1029/2019JG004879, 2019.

Johnston, M.F., Wilby, R.L., and Tonne, J.A.: Inferring air-water temperature relationships from river and catchment properties. Hydrol. Process. 28, 2912-2938, 2014.

Kreplin, H.N., Ferrerria, C.S.S., Destouni, G., Keesstra, S.D., Salvati, L., and Kalantari, Z.: Arctic wetland system dynamics under climate warming. Wires Water, https://doi.org/10.1002/wat2.1526, 2021.

Lehnherr, I., St. Louis, V.L., Sharp, M., Garner, A.S., Smol, J.P., Schiff, SL., Muir, D.C.G., and et al.: The world's largest High Arctic lake responds rapidly to climate warming. ~~, St. Louis, V., Sharp, M., and Garner, A. S.: Coupled terrestrial-aquatic climate impacts on High Arctic watersheds: Using the Lake Hazen Watershed as a sentinel for change.~~ Nature Comm. 9~~9~~:~~(1):~~ 1290, https://doi:~~.org/~~10.1038/s41467-018-0365-z, 2018.

Linderholm, H.W., Nicolle, M., Francus, P., Gajewski, K., Helama, S., Horhola, A., Solomina, O., and et al.: Arctic hydroclimate variability during the last 2000 years: current understanding and research challenges. Clim. Past. 14, 473-514, 2018.

Lougheed, V.L., Butler, M.G., McEwen, D.C., and Hobbie, J.E.: Changes in tundra pond limnology: Re-sampling Alaskan ponds after 40 years. Ambio 40, 589-599, 2011.

McCrystall M.M., Stroeve, J., Serrezze, M., Forbes, B.C., and Screen J.A.: New climate models reveal faster and larger increases in Arctic precipitation than previously projected. Nature Com. 12(6765), https://doi.org/10.1038/s41467-021-27031, 2021.

McEwen, D.C., and Butler, M.G.: Growing-season temperature change across four decades in an arctic tundra pond. Arctic 71(3), 281-291, 2018.

Miller, E.A., and Young, K.L.: Evaluation of the presence of streambed vegetation on storage and runoff in hillslope streams in a High Arctic environment. Ecohydrol. 9, 719-737, 2016.

Miner, K. R., Turetsky, M.R., Malina, E., Bartsch, A., Tamminen, J., McGuire, D., Fix, A., Sweeney, C., Elder, C.D., and Miller, C.E.: Permafrost carbon emissions in a changing Arctic. Nature Reviews Earth and Environ. 3, 55-67, 2022. https://doi.org/10.1038/S43017-021-00230-3.

Morison, M., Casson, N.J., Mamet, S., Davenport, J., Livingston, T., Fishback, L.A., White, H., and Windsor, A.: Snow, ponds, trees, and frogs: how environmental processes mediate climate change impacts on four subarctic terrestrial and freshwater ecosystems. FACETS 8, 1-15, 2023.

Moonmaw, W.R., Chmura, G.L., Davies, G.T., Finlayson, C.M., Middleton, B.A., Natali, S.M., Perry, J.E., Roulet, N., Sutton-Grier, A.E.: Wetlands in a changing climate: Science, policy and management. Wetlands 38, 183-205, 2018.

National Wetlands Working Group, The Canadian Wetland Classification System, Warner, B.G., Rubec, C.D.A. (Eds.), 2nd Edition. Wetlands Research Centre, University of Waterloo, Waterloo, ON, Canada, 68 pp., 1997.

Negandhi, K., Laurion, I., Whiticar, M.J., Galand, P.E., Xiu, X., and Lovejoy, C.: Small thaw ponds: An unaccounted source of methane in the Canadian High Arctic. PLoS ONE 8(11) e78204, 2013.

Overland J, Key J, Hanna E, I. Hanssen- Bauer I, Kim B.-M., Kim S.-J., Walsh J., –Wang M., Bhatt, U., Liu Y., Stone R., Cox C., and Walden, -V.: The lower atmosphere: air temperature, clouds and surface radiation [in "State of the Climate in 2013"]. Bull. Amer. Meteor. Soc., 95 (7), S115-120, 2014.

Overland J, Key J, Hanna E, I. Hanssen- Bauer I, Kim B.-M., Kim S.-J., Walsh J., -Wang M., Bhatt, U., Liu Y., Stone R., Cox C., and Walden, -V.: Air temperature, atmospheric circulation, and clouds [in "State of the Climate in 2012"]. Bull. Amer. Meteor. Soc., 94 (8), -S111–S113, 2013.

Qingbai, W., Yandong, H., Hanbo, Y., and Yongzhi, L.: Changes in active-layer thickness and near-surface permafrost between 2002 and 2012 in alpine ecosystems, Qinghai-Xizang (Tibet) Plateau, China. Global and Planet. Change 124, 149-155, 2015.

Rantanen, M., Karpenchko, A.Y., Lipponen, A., Nordling, K., Hyvarinen, O., Ruosteenoja, K., Vihamo, T., and Laaksonen, A.: The Arctic has warmed nearly four times faster than the globe since 1979. Nature Commun. Earth and Environ. 3:168 https://doi.org/10.1038/s43247-002-00498-3, 2022.

Rehder, Z., Kleinen, T., Kutzbach, Stepanenko, V., Langer, M., and Brovkin, V.: Simulated methane emissions from Arctic ponds are highly sensitive to warming. Biogeosci. 20, 2837-2855. https://doi.org/10.5194/bg-20-2837, 2023.

Roy-Leveillee, P., and Burn, C. R.: Near-shore talik development beneath shallow water in expanding thermokarst lakes, Old Crow Flats, Yukon. J. Geophys. Res. Earth Suf. 122, 1070-1089, http://doi.org/10.1002/2016JF004022, 2017.

Rosenberry, D.O., and Hayashi, M.: Assessing and measuring wetland hydrology. In: Anderson, J.T., and Davis, C.A. (eds). Wetland Technqiues, Foundations, Vol. 1. Springer Science, Dordrecht, pp. 87-225, 2013.

Saros, J.E., Arp, C.D., Bouchard, F., Comte, J. et al.: Sentinel responses of Arctic freshwater systems to climate: linkages, evidence, and a roadmap for future research. Arctic Science 00, 1-37, http://doi.org/10.1139/AS-2022-0021, 2023.

Sim, T.G., Swindles, G.T., Morris, P.J. Galka, M., Mullan, D., and Galloway, J.M.: Pathways for ecological change in Canadian High Arctic wetlands under rapid twentieth century warming. Geol. Res. Lett. 46(9), 4726-4737, 2019.

Smol, J.P., and Douglas, M.S.V.: Crossing the final ecological threshold in high Arctic ponds. Proceed. of the Nat. Acad. of Sci. 104, 12395–12397, 2007.

Webb, E.E., Liljedahl, A.K., Cordeiro, J.A., Loranty, M.M., Witharana, C., and Lichstein, J.W.: Permafrost thaw drives surface water decline across lake-rich regions of the Arctic. Nature Climate Change 12, 841-846. https;//doi.org/10.1038/s41558-022-01455-w, 2022.

Wrona, F.J., Johansson, M., Culp, J.M., Jenkins, A., Mård, J., Myers-Smith, I.H. Prowse, T.D., Vincent, W.F., and Wookey, P.A.: Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. J. Geophys. Res. Biogeosci. 121, 650-674, 2016.

Woo, M.K.: Hydrology of a drainage basin in the Canadian High Arctic. Annals of the Assoc. of Am. Geograph. 73, 577-596, 1983.

Woo, M.K.: Permafrost Hydrology. Springer, Heidelberg, 2012.

Woo, M.K., and Young, K.L.: Hydrogeomorphology of patchy wetlands in the High Arctic, polar desert environment. Wetlands 23(2), 291-309, 2003.

Woo, M.K., and Guan, X.J.: Hydrological connectivity and seasonal storage change in a polar oasis environment, Canadian High Arctic. Perm. and Perigl. Process. 17, 309-323, 2006.

Woo, M.K., and Young, K.L.: Disappearing semi-permanent snow in the High Arctic and its consequences. J. Glaciol. 60(219), 192-200, 2014.

Woolway, R.I., Sharma, S., and Smol, J.P.: Lakes in hot water: The impacts of a changing climate on aquatic ecosystems. Biosci. 72(11), https://doi.org/10.1093/biosci/biac052, 2022.

Young, K.L., and Woo, M.K.: Frost table development beneath patchy wetlands in a continuous permafrost, High Arctic setting. In Proc. of the 8th Inter. Conf. on Permafrost, Zurich, Switzerland, July 21-215, pp. 1265-1270, 2003.

Young, K.L., and Labine, C.: Summer hydroclimatology of an extensive low-gradient wetland: Polar Bear Pass, Bathurst Island, Nunavut, Canada. Hydrol. Res. 44(1-2), 2-20, 2010.

Young, K.L., and Abnizova, A.: Hydrologic thresholds of ponds in a polar desert wetland environment, Somerset Island, Nunavut, Canada. Wetlands 31(3), 535-549, 2011.

Young, K.L., Assini, J., Abnizova, A., and Miller, E.: Snowcover and melt characteristics of upland/lowland terrain: Polar Bear Pass, Bathurst Island, Nunavut, Canada. Hydrol. Res. 44(1-2), 2-20, 2013.

Young, K.L., Scheffel, H-A., Abnizova, A., and Siferd, J.: Spatial and temporal dynamics of groundwater flow across a wet meadow, Polar Bear Pass, Bathurst Island, Nunavut. Perm. and Perigl. Process. 28(2), 405-419, 2017.

Young, K.L., Brown, L., and Labine, C.: Snow cover variability at Polar Bear Pass, Nunavut. Arctic Sci. 4, 669-690, 2018.

Young, K.L.: Swings in runoff at Polar Bear Pass: An extensive low-gradient wetland, Bathurst Island, Canada. Hydrol. Res. 50.2, 778-792, 2019.

Zandt, M.H., Liebner, S. and Welte, C.U.: Roles of thermokarst lakes in a warming world. Trends in Microbiol. 28(9), 769-779, https://doi.org/10.1016/jtim.2020.04.002, 2020.