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

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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 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 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 fall (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 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 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 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 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) from 2007 to 2015, with 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 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 (1:50000, 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 (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. 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).
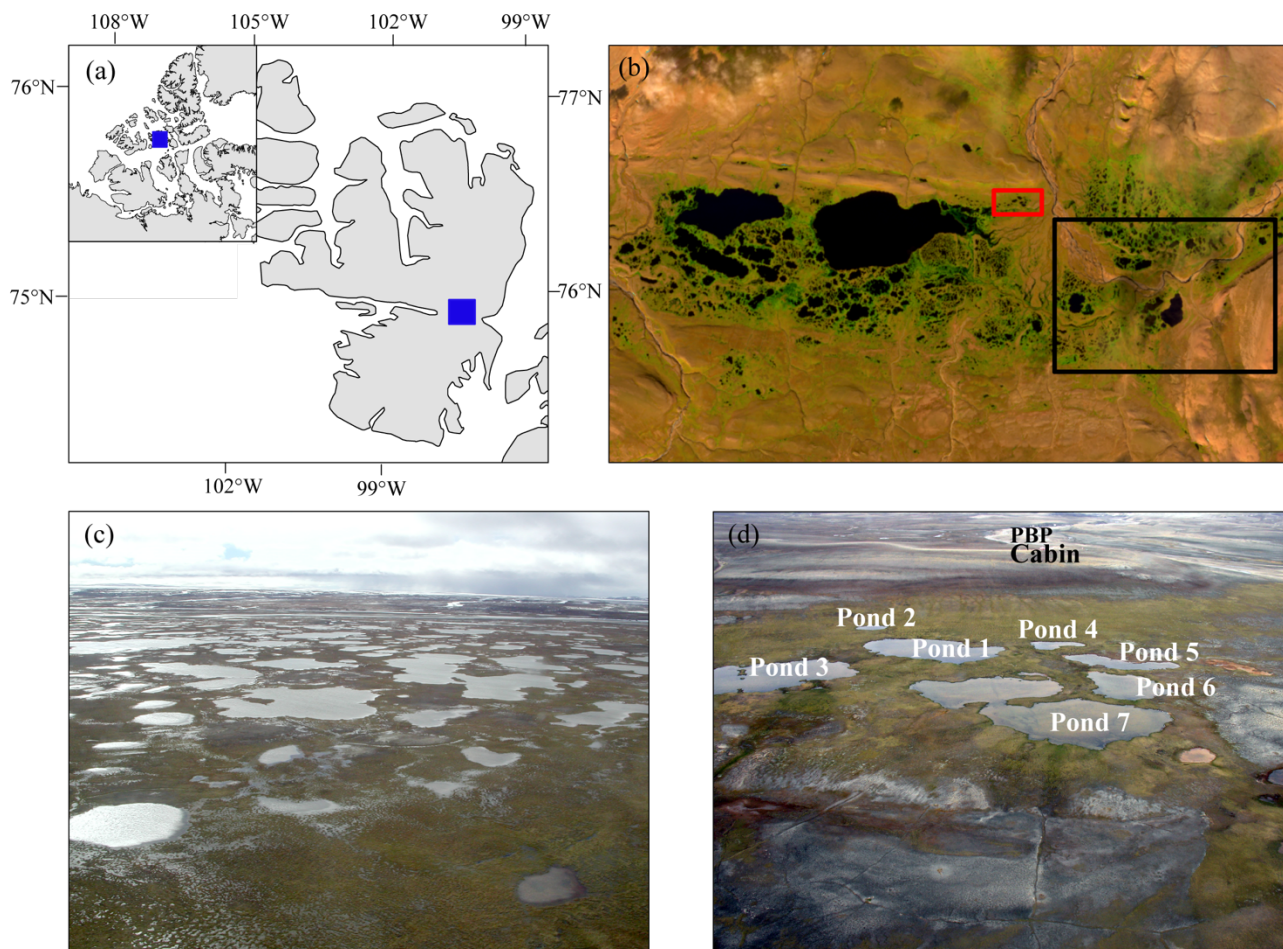
Figure 1. Location of the PBP catchment on Bathurst Island, Nunavut (a). Satellite imagery of the eastern and central lowland area (b), with an air photo showing the wetland with numerous ponds and upland areas (c) - the area indicated by black box in (b). Aerial photo of the central ponds (d) and general 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.

3 Methods

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 into them), whereas 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 substrate type varied: some pond bottoms were firm, light-coloured, while others had rocky or dark, soft organic beds (see Table S1, Fig. S1). 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, 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 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 $\geq 0º$ C (Johnson et al., 2014). To investigate inter-site correlations, water temperatures at Pond 1 were evaluated in relation to other ponds. 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

09 early in the season and then weekly once ground thaw slowed, providing a means of assessing active layer development and

10 re-freeze (i.e., 2008, 2009) (Abnizova et al., 2014). Climate data (e.g., air temperature) were obtained from the main automatic

11 weather station located near the PBP cabin situated on the plateau above the wetland (see Young and Labine, 2010; Young et

12 al., 2013; Miller and Young, 2016 for additional details on instrumentation, sensor siting, and frequency of monitoring). These

13 data allowed us to examine the air temperature-pond response, and to place our results in context of the variable spring and

14 summer conditions over several years at PBP, and in relation to the nearest government weather station at Resolute Bay

15 (Qausuittuq), Cornwallis Island, Nunavut (74.72º N 94.97º W) about 146 km to the southwest.

16 **4 Results**

17 **4.1 Seasonal thermal regime**

18 The seasonal regime of ponds at PBP over several years was explored using the detailed data from Pond 1 (Fig. 2: 2007-2015).

19 It is a medium-sized pond downslope of a wet meadow and lingering deep snowbed located in the lee of a hillslope (Young et

20 al., 2017). The diagram also illustrates the range of pond temperatures during two extreme years (2012-warm vs. 2013-cool).

21 In warm years (e.g., 2010, 2012), pond water temperatures warm rapidly by mid-June with peak pond temperatures reaching

22 about 15º C for extended periods. There is considerable variability from year-to-year, but the general trend is warming in June,

23 elevated temperatures in July and then falling temperatures in August. In context of Resolute air temperatures from 1948 to

24 2015 (Environment Canada (Resolute): weather.gc.ca), the 2012 JJA air temperature (4.6º C) was the 2nd highest on record,

25 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

26 68 years.

27 Figure 3 indicates that Pond 1 and the centrally located ponds show similar seasonal cycles. Pond temperatures (Tw)

28 are generally higher than the air temperature during the thaw season when temperatures are > 0º C, with most also trending

29 with the air temperature signal. This pattern suggests well mixed conditions as noted for shallow ponds elsewhere in the Arctic

30 (Dyke and Sladen, 2022). In 2009, Pond 1 Tw correlated well with all pond temperatures (r > 0.8 to > 0.9) including ones at

31 the periphery of PBP (east, west, and south). In 2008, a similar pattern between Pond 1 and the other ponds across the wetland

32 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,

33 elevated valley, and unlike most ponds, has deep residual snowbeds lying on the adjacent slopes. The nearby Pingo Pond is

34 not fed by the snowbeds. Meltwater from lingering snowbeds feeding the Meadow Pond ensures that pond temperatures are

35 dampened in comparison to more exposed and isolated wetland ponds. Others have observed this pattern on northeast

36 Ellesmere Island (e.g., Smol and Douglas, 2007).

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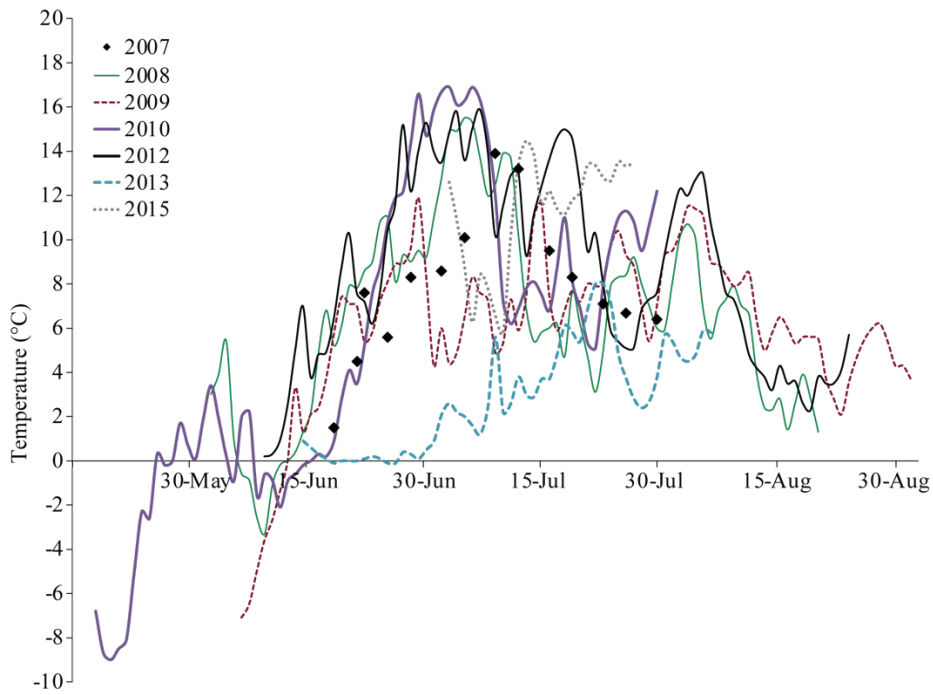
40 **Figure 2. Seasonal regime of water temperature (Tw) at Pond 1, PBP (2007-2015). Manual measurements for 2007 and daily averages**
41 **for 2008-2015 are plotted.**

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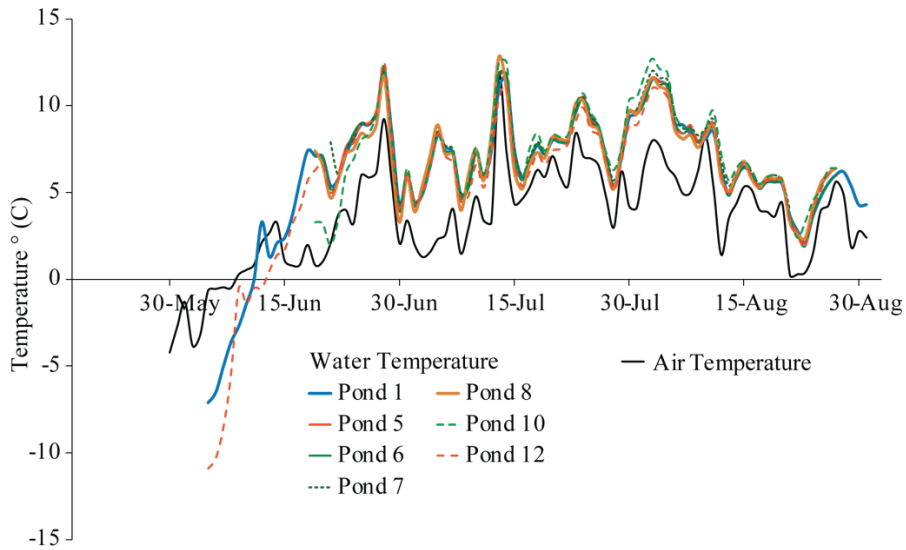
43 **Figure 3. Daily average water temperature of Pond 1 versus other centrally located ponds at PBP, 2009. The daily average air**
44 **temperature is also plotted.**

45

46   Figure 4 illustrates the seasonal rhythm (2007, 2008, and 2009) of medium-sized ponds across PBP. Here we select Pond 6 in

47   the central cluster of ponds as representative of a medium-sized pond. In 2007, by July 20, Pond 6 was slightly warmer than

48   other two ponds, though the rhythms – peaks and troughs of pond Tw remained similar. Warming is comparable to that seen

49   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.

50   Young and Labine (2010) found that environmental conditions were slightly cooler in the eastern part of PBP owing to

51   proximity to the Arctic Ocean, but the largest microclimatic discrepancies across PBP were related to differences in net

52   radiation (surface albedo) and ground heat flux (substrate, vegetation, etc.) (Young et al., 2010). A Student t-test (2-tailed, α

53   = 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

54   Pond (7.6º C ± 3.5, n=68) but it was different than West Medium Pond (6.6º C ± 4.5, n = 77). In 2009, both the East Medium

55   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

56   than Pond 6 (6.6º C ± 4.5, n=80).

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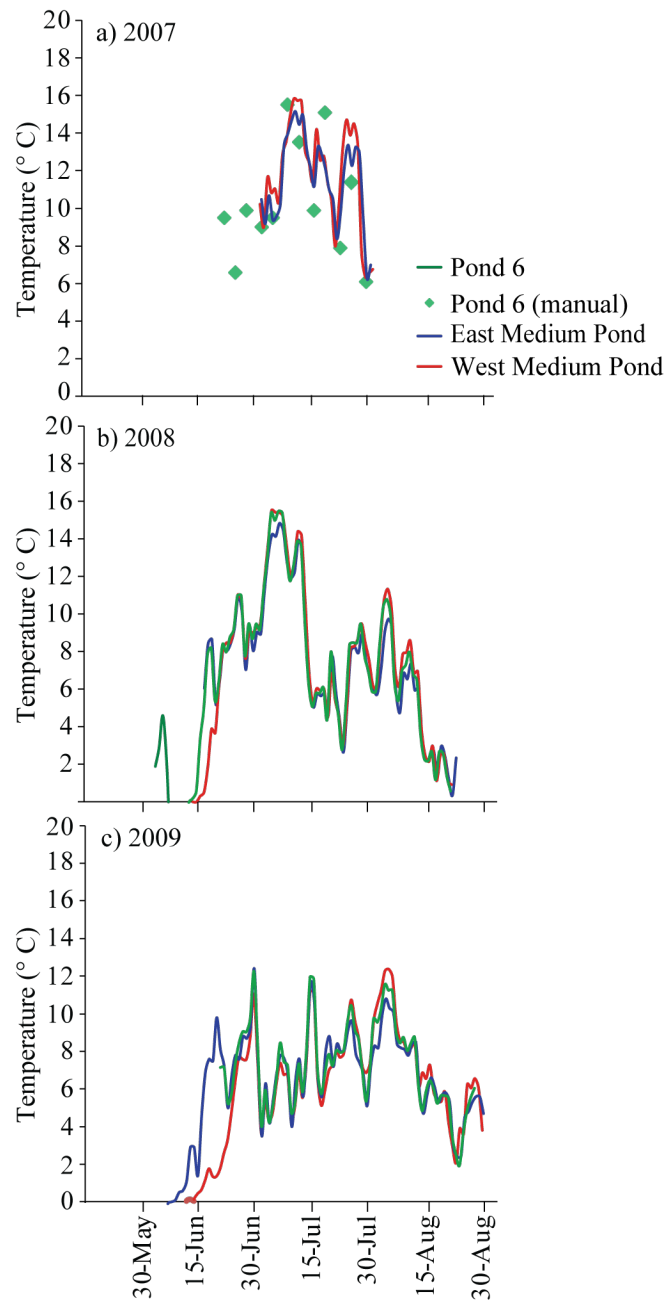
Figure 4. Seasonal temperature regime of medium-sized ponds across Polar Bear Pass (2007-2009) based on manual (dots) and continuous data (solid line) from 2007 (a), 2008 (b), and 2009 (c).

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4.2 Mean July temperature

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 plots the July mean temperatures of the central ponds at PBP, across the years. 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, 2011).
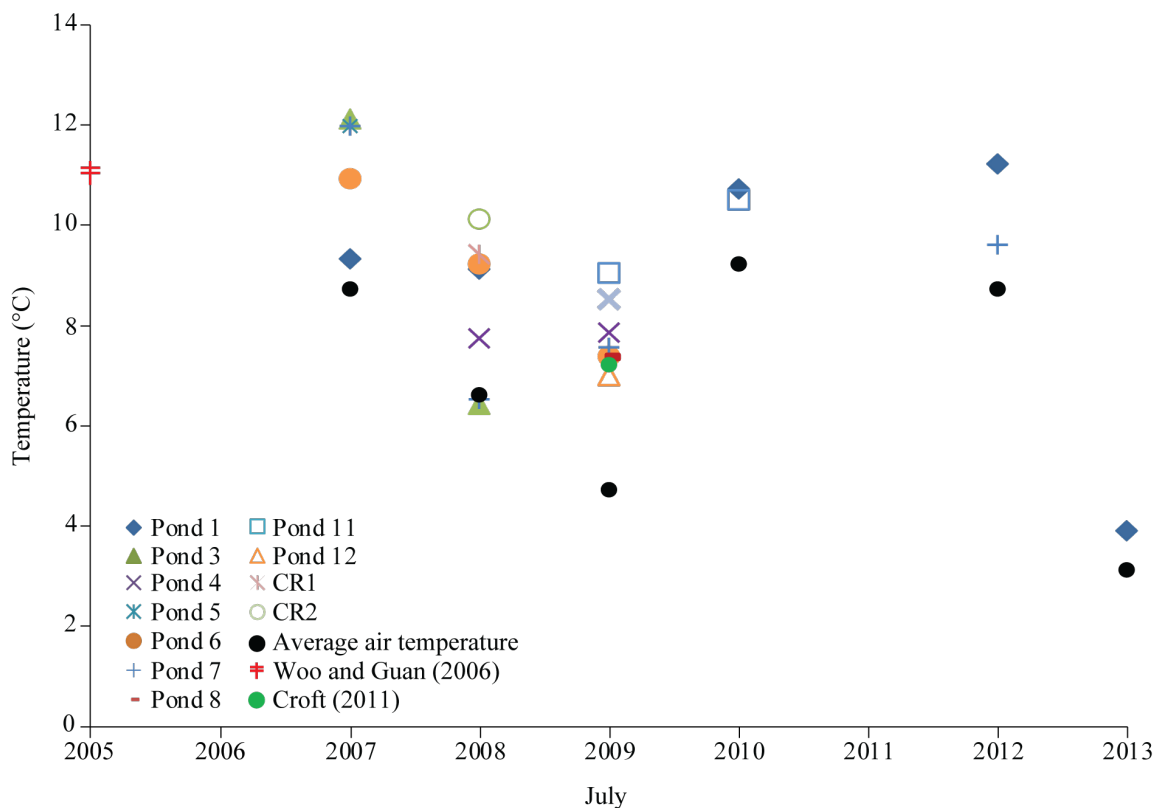
Figure 5. Average July pond temperatures at PBP ponds. Pond data from other Arctic studies are included here for comparison. Illness in 2011 prevented pond temperatures from being obtained at PBP.

4.3 Cumulative percentages and box plots of pond water temperatures

The cumulative percentages of Pond 1 from 2008 to 2013 (June 14 to July 30) based on continuous water temperature measurements is plotted in Figure 6 along with box plots. Comparable to Fig. 2, there is considerable variability from year-to-year. 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).
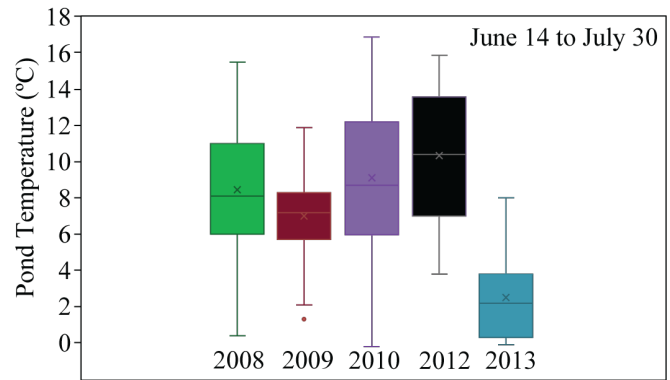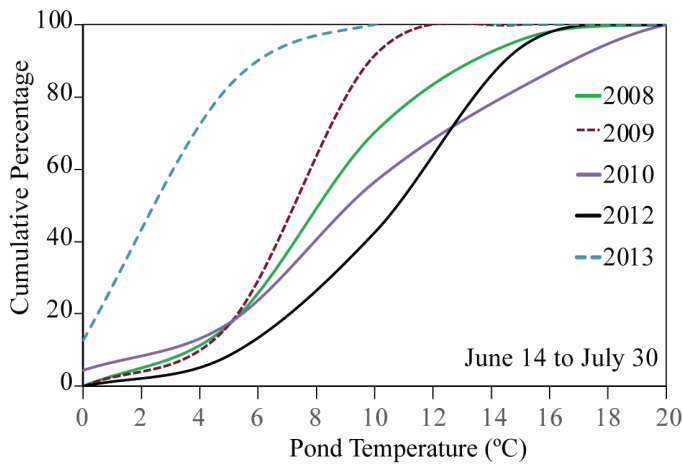
Figure 6. Cumulative percentages (left) and box plots of water temperatures (Tw) (right) in Pond 1, 2008 to 2013. The time frame selected for comparison is June 14 to July 30. Box plots show median (line in box), and x indicates the average temperature.

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.

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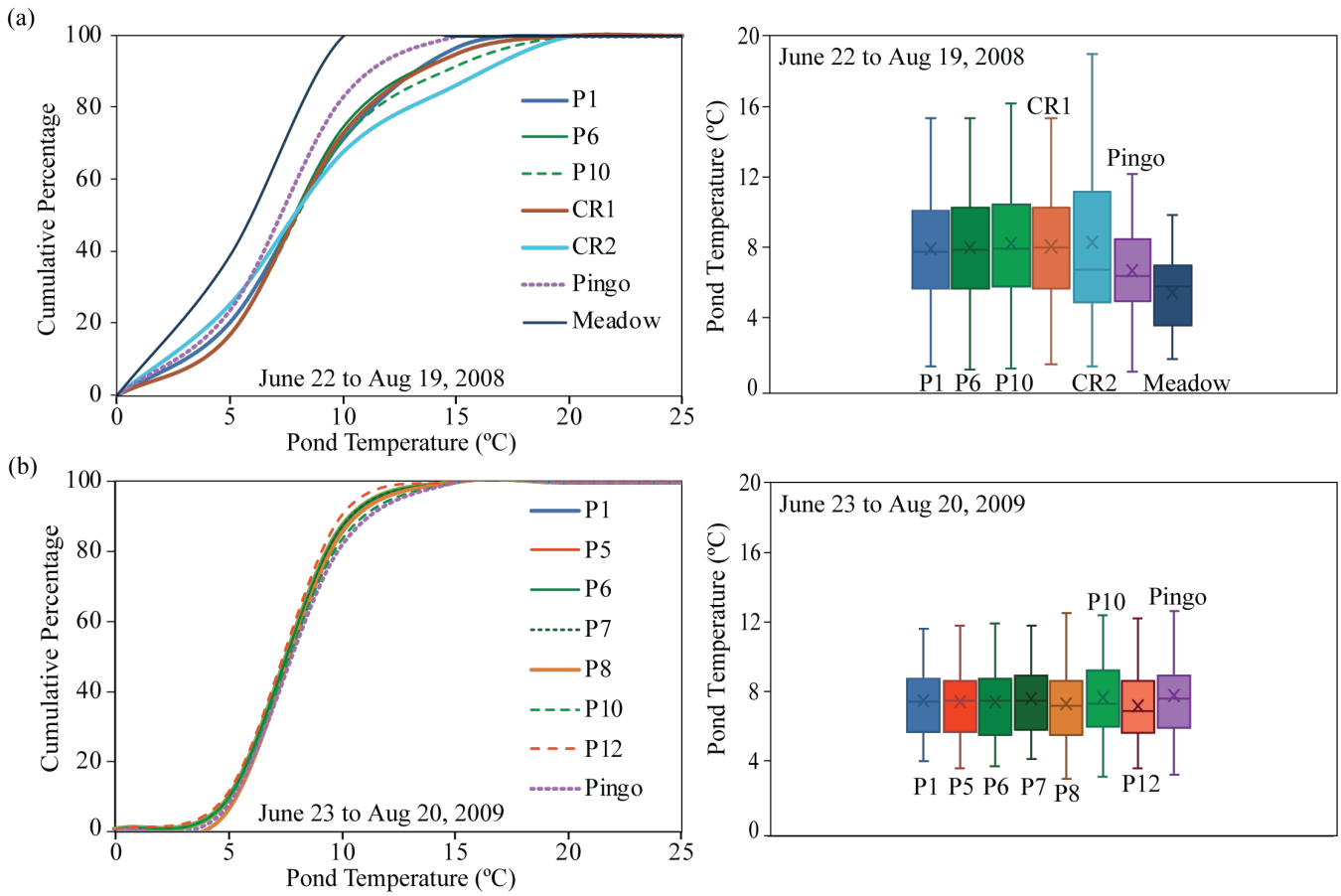


Figure 7. Cumulative percentages and box plots of temperatures (Tw) of Central ponds, 2008 (June 22 to Aug. 19) (a) and 2009 (June
23 to Aug. 20) (b) using continuous pond water temperatures.

(a)

(b)

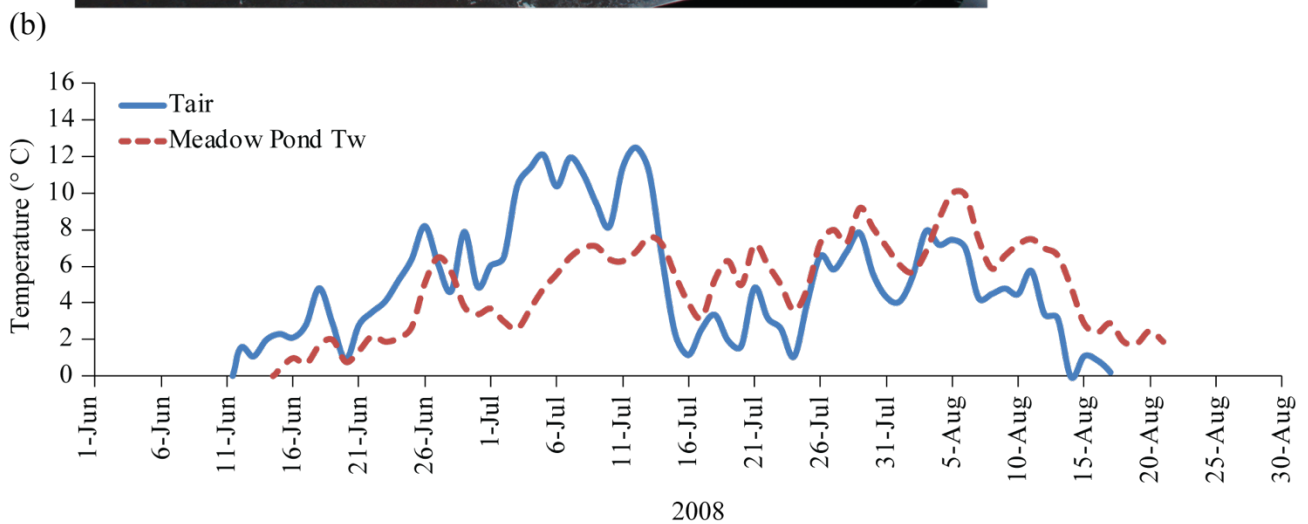
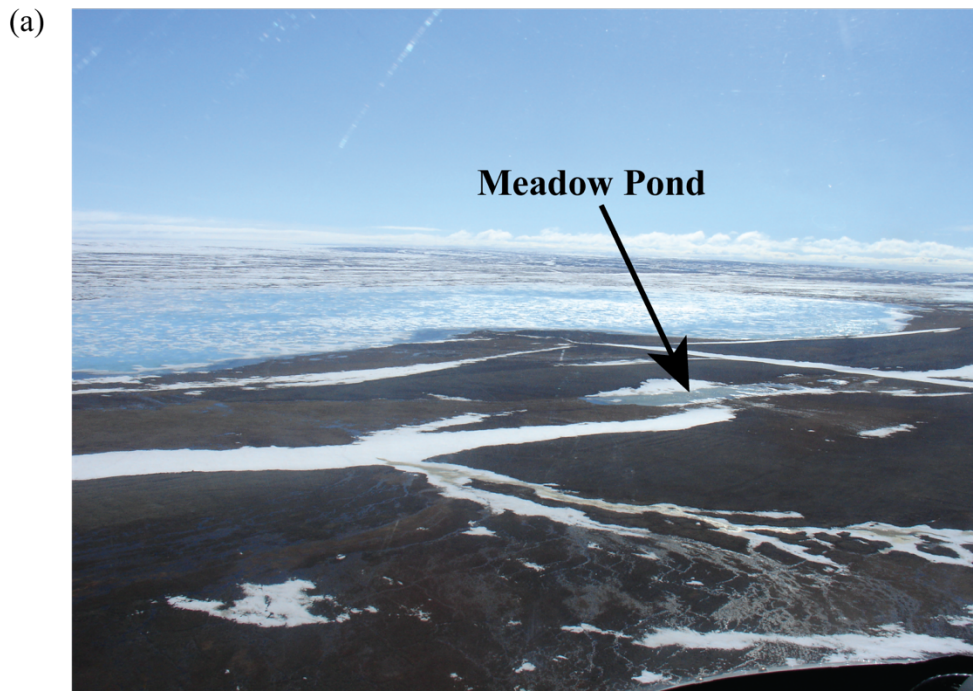



Figure 8. Photo of the Meadow Pond taken June 15, 2008, and air temperature versus pond water Tw (Meadow Pond) in 2008. Note the late-lying snowbeds adjacent to Meadow Pond.

4.4 Air temperature and pond water temperature response

Figure 9 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 Year). In 2008, the

99   relationship between air temperature and pond water temperature is strong, when temperatures are $> 0^\circ$ C. Here most ponds

00   show a correlation $r > 0.8$ or > 0.9. When points fall below the 1:1 line, it signals there was an initial lag in pond warming due

01   to ice-off (see Fig. 3). As mentioned earlier, the water temperature of Meadow Pond has a much weaker relationship with air

02   temperature. This is due to its location near melting late-lying snowbeds, which help to delay pond warming (see Figure 8).

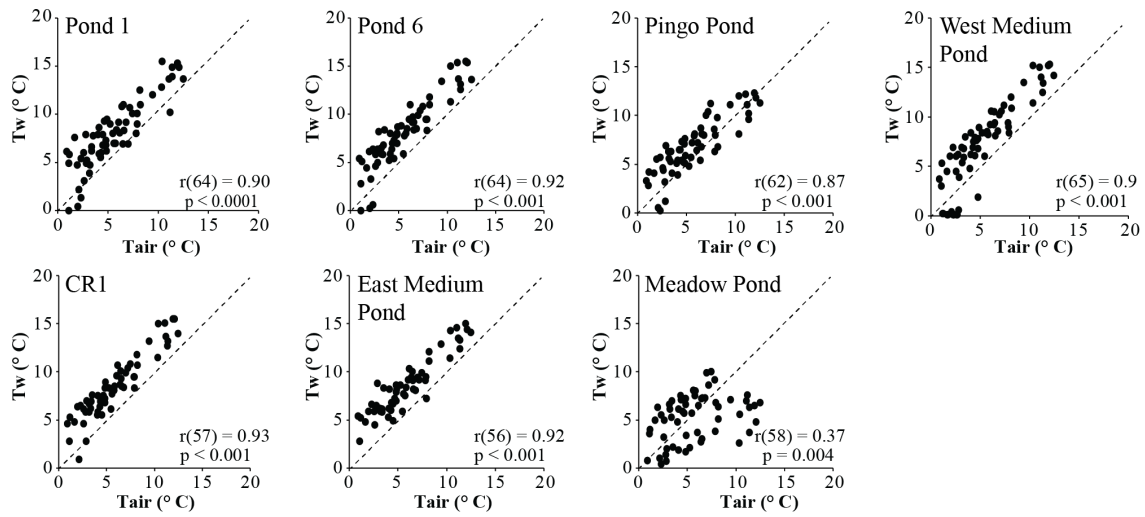
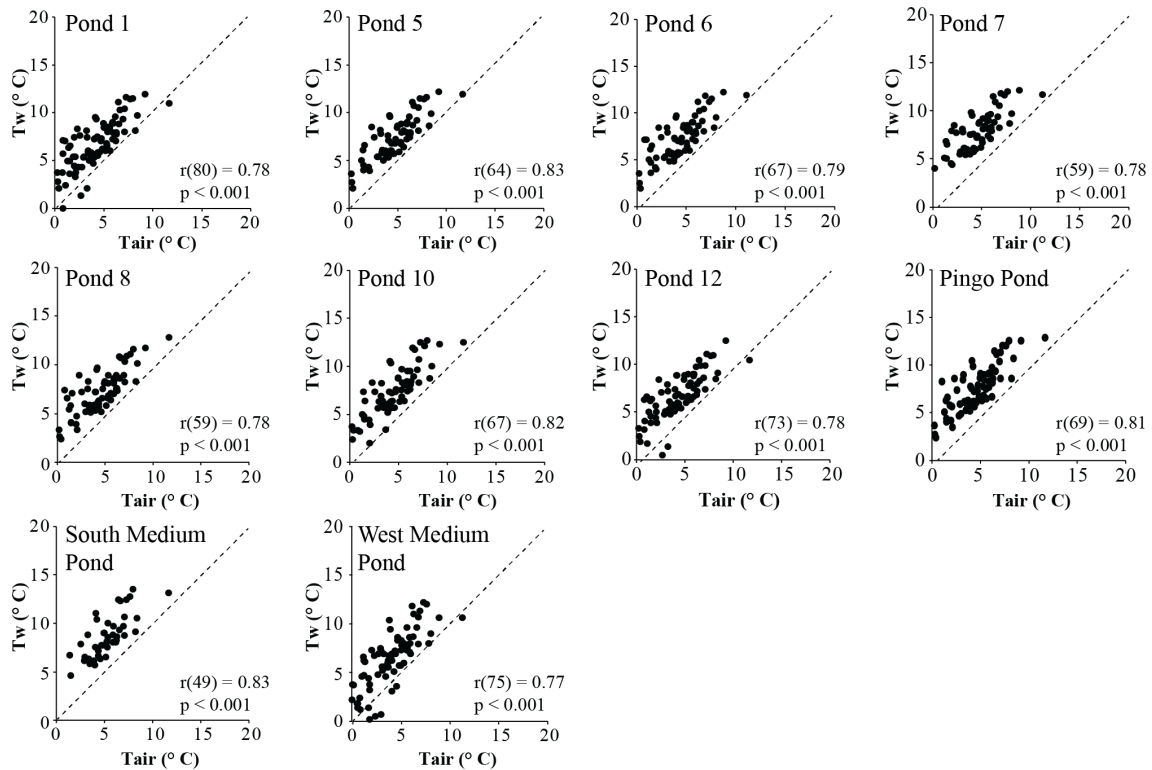



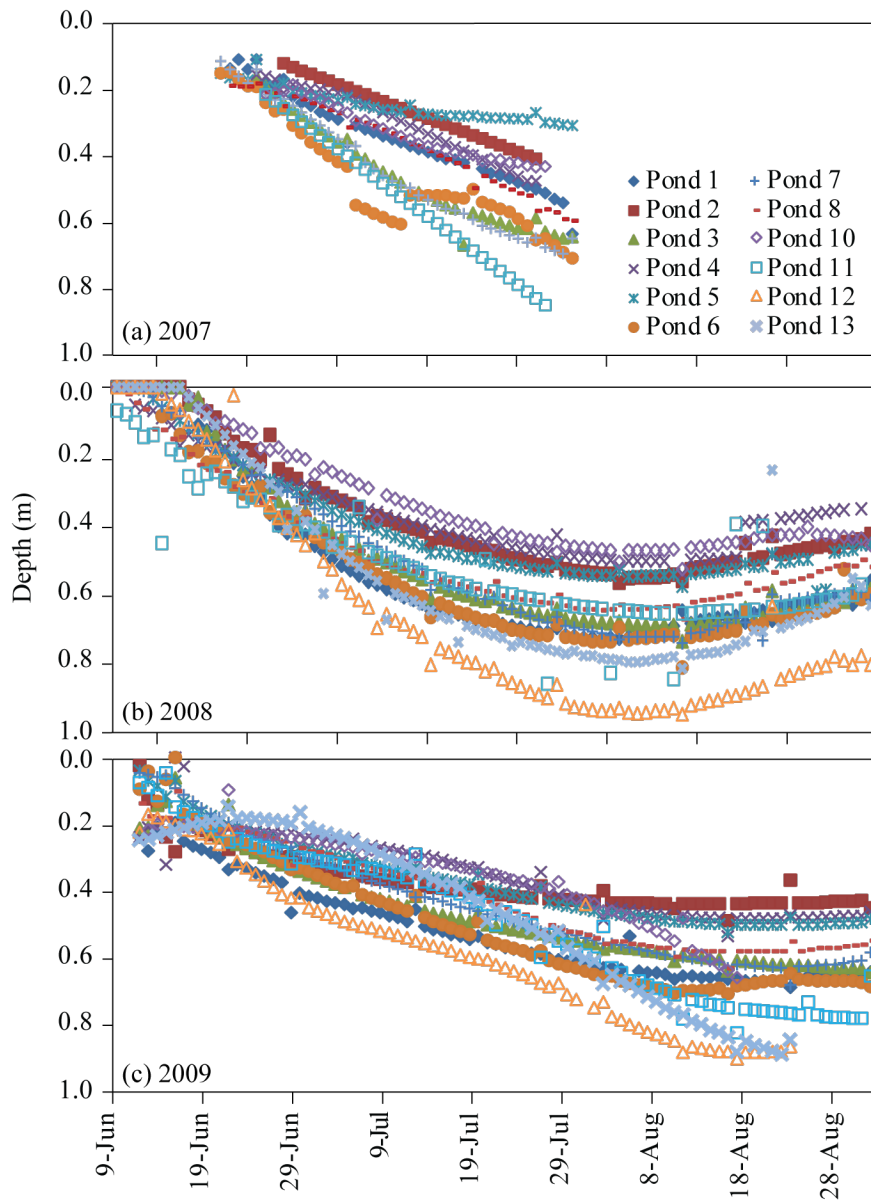
Figure 9. Correlations between Plateau daily air temperatures and Pond water temperatures (Tw > 0º C) for ponds 2008 (a) and 2009 (b), using continuous water temperature data. The black dashed line in the plots is the 1:1 line.

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 10a). Pond 5 had a mucky organic bottom, which might be indicative of high ice content that restrains ground thaw. Pond 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 $T_a = 7.4^\circ$ C).

Frost table measurements continued until the end of August in both 2008 and 2009 (see Figures 10b, c). Maximum frost table depths occurred around July 28 in 2008 and slightly later in 2009 (Aug 23). 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 . The thaw pattern of ponds is similar in early 2009, but then pond thaw show variable depths by July 29, 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).

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

27   **4.4.2 Pond water conductivity** (µS/cm)

28   There is considerable variation between ponds throughout the 2008 season and the conductivity levels rise from ~100 µS/cm

29   to most ponds exceeding 250 µS/cm (Figure 11a). Like water temperatures, meltwater from the nearby late-lying snowbed

30   adjacent to the Meadow Pond causes dilution so the water conductivities are generally lower than other ponds. Pond 11, due

31   to its rocky, blue-green substrate and deep ground thaw exhibits the highest water conductivity, maintaining levels > 400

32   µS/cm by early July 2008 (Fig. 11a). A similar pattern emerges in 2009. Pond 11's water conductivity reaches > 400 µS/cm

near the end of June and about 500 μS/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. 11b).

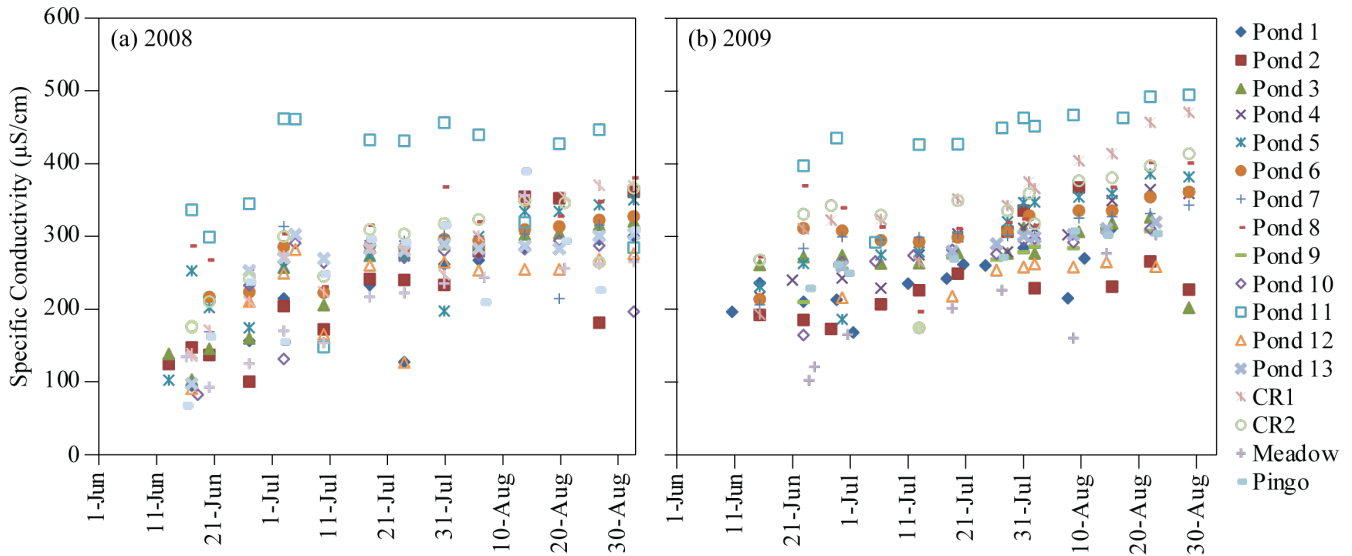



Figure 11. Spot measurements of specific conductivity (μS/cm) of ponds at PBP in (a) 2008 and (b) 2009.

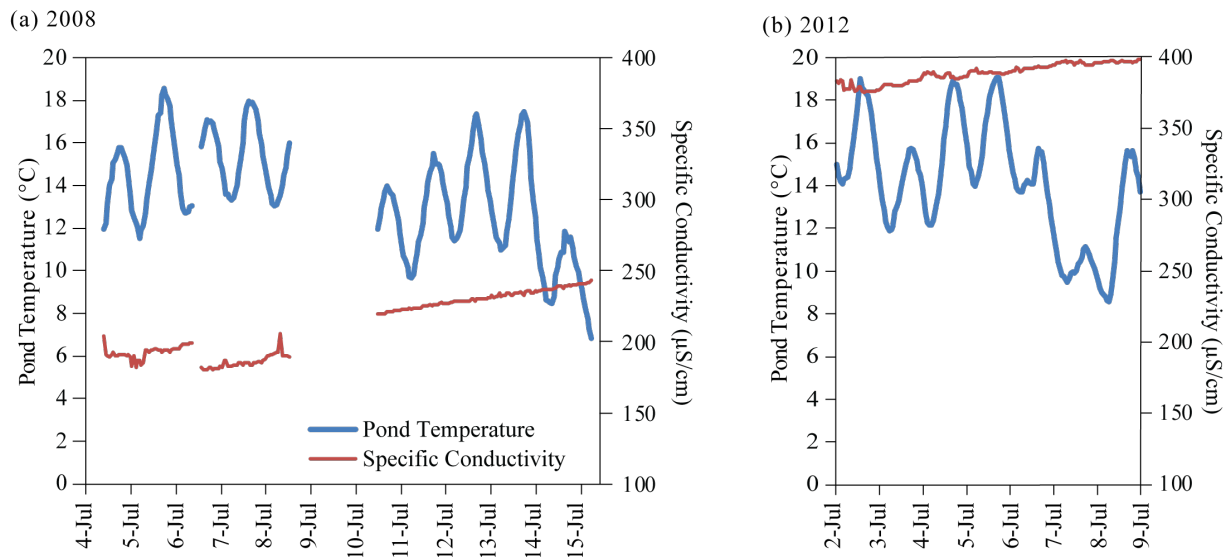
Figure 12 provides an illustration of the impact of a warm season on the conductivity of pond water as measured by a YSI 600 multiparameter sonde. Fig. 12a, shows the hourly water temperature and conductivity of Pond 1 in the early summer of 2008 versus the early summer in 2012. Pond temperatures do not vary that much in these two years during this time. Conductivity only reaches about 250 uS/cm in 2008 (mean Tair = 4.39 °C, 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.

(a) 2008 (b) 2012

Figure 12. Hourly estimates of pond temperature (blue line) and specific conductivity (µS/cm) (red line) of Pond 1 in 2008 (a) and in 2012 (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. 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 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 PBP. 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, 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 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. Figure 2 indicates that there is still much variability in climate and pond temperature response at PBP 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

The 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 level can drop. 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 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.

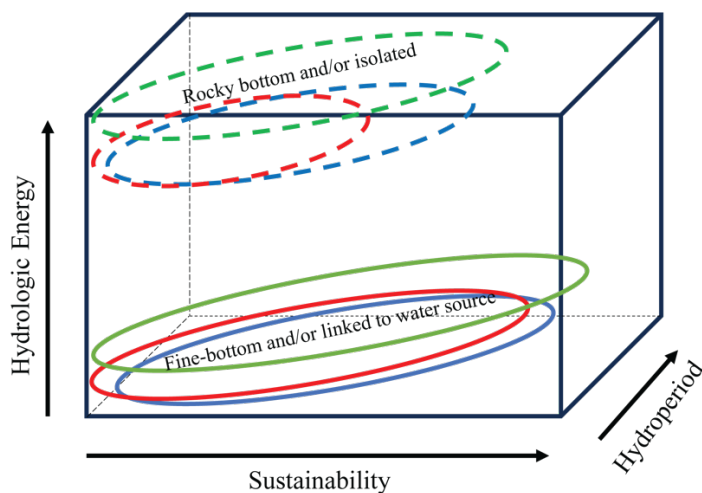
While pond temperatures are generally similar across PBP but vary due to climatic conditions (cool versus warm years), there are considerable differences in the ground thaw rates, which can be attributed to the physical characteristics of the sediments (coarser vs. finer) and colour. Some ponds have 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 to enhanced vertical pond seepage due to an increase in the active layer storage capacity. This process most likely contributed to drying and pond shrinkage (Young and Abnizova, 2011). Pond thaw rates differ from pond-to-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

04 with thawing soil materials. Figure 12 also confirms that pond conductivities can rise substantially in the same pond from one
05 year to another in response to warmer air temperatures and deeper ground thaw.

06   In the Old Crow Flats, Yukon, Roy-Leveillee and Burn (2017) found that near-shore taliks could develop in shallow
07 (often less than 20 cm) lake pond water when warm summers increased the thawing degree days. Deep and early snowpacks
08 near the shoreline also helped to keep lake bed temperatures above 0° C, preventing permafrost aggradation.

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

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

22
23 **Figure 13. Schematic showing the functional integrity of PBP ponds. Blue lines (solid/dashed) represent 'present'conditions; red**
24 **lines (solid/dashed) represent pond response to 'future warm/dry' conditions and green lines (solid/dashed) represent response to**
25 **future 'warm/wet' conditions. Hydrologic energy refers to the degree of fluctuations in water level, hydroperiod refers to the length**
26 **of time that the pond contains water over the season (diagram adapted after Young and Abnizova, 2011).**

28   It is likely that hillslope streams, which now provide some ponds with a source of water for an extended time during

29   the thaw season may not do so for as long (Young, 2019) and that ponds buffered now from elevated Tw and higher

30   conductivities by lingering meltwater contributions from late-lying snowbeds will cease to do so (Woo and Young, 2014). In

31   the high Andes, ponds and wet meadows are now being sustained by meltwaters from melting glaciers but they are predicted

32   to diminish and disappear by the end of the century. These ponds and wet meadows will then dry out and ultimately disappear

33   (Dangle et al., 2017). Moonmaw et al. (2018) also indicate that permafrost thaw can dramatically affect hydrology and that

34   fen-like systems are vulnerable as they rely on terrestrial water inputs (e.g., groundwater and streamflow). As these external

35   water sources change or cease to exist like the rapid loss of late-lying snowbeds at PBP and elsewhere across the Arctic islands

36   (Woo and Young, 2014), wetlands will be impacted. At PBP, many irregular shaped and shallow ponds (e.g., Ponds 8, 11)

37   have already been observed to dry out over summer seasons with vascular plants encroaching, suggesting that in the long-term

38   certain ponds may transition into wet or dry meadow features (see Fig. 14), which may eventually alter greenhouse gas

39   emissions (Rehder et al., 2023), snowcover receipt, and evapotranspiration rates as shifts in vegetation have done elsewhere

40   (Morison et al. 2023).

41   Strong correlations between air temperature and pond Tw will persist but departures will grow as pond water become

42   warmer than the air temperatures, especially shallow ponds with dark, rocky substrates (e.g., Pond 11). Lougheed et al. (2011)

43   observed that establishing a direct relationship between air and water temperatures is complicated by wind, water depth, ice

44   cover, and other physical processes that determine temperature in small tundra ponds < 0.5 m at the International Biological

45   Program (IBP) site, Barrow, Alaska. They noted that variability in temperature is higher in both the early and late part of the

46   season, a pattern emerging for PBP ponds as well (see Figs. 2, 3).

47

48   **Figure 14. Desiccated pond (Pond 8) July 23, 2007 (left) and Pond 8, August 19, 2010 (right), showing how *Eriophorum scheuchzeri***
49   **-White Cottongrass are encroaching.**

50

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

58   **6 Conclusions**

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

65   Ground thaw is variable in ponds owing to substrate type, water depth and ground ice content. In the future, an earlier
66   start to ground thaw and deepening of frost tables may drain some shallow ponds, while others due to deep waters and abundant
67   ground ice will be sustained. Like frost table patterns, the water chemistry (i.e., specific conductivity), which reflects evapo-
68   concentration processes, groundwater flow varied amongst these ponds. The rapid and sizeable increases in water conductivity
69   at Pond 1 in an extremely warm season (2012) highlight the large shifts in environmental responses that these ponds are now
70   undergoing. Uncertainties about fall precipitation exist for High Arctic regions. If pond storage deficits persist for several years
71   and cannot be augmented by seasonal snowmelt or linkages to other water sources (i.e., late-lying snowbeds and streams),
72   more ponds will disappear at PBP and may be replaced by larger wet/dry meadows. This will potentially have an impact on
73   greenhouse gases and the feeding patterns of migratory birds. Finally, future research efforts should focus on the response of
74   other large wetland areas in the Canadian High Arctic including Alison Inlet (southwest coast of Bathurst) and Truelove
75   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.

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