Spatial variation in the thermal regime of Mackenzie Delta lakes and channels

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ABSTRACT
The Mackenzie Delta, Northwest Territories, is an alluvial plain with approximately 40% aerial coverage of lakes and distributary channels. Tundra and taiga ecozones create two distinct terrestrial permafrost environments within the delta. Continuous temperature measurements made in 27 delta water bodies during 2009 indicate little spatial variation in the summer thermal regime of channels and lakes. Low spatial variation is also expected on an annual basis.

RÉSUMÉ
Le Delta du Mackenzie, dans les Territoires du Nord-Ouest, est un plan alluvial couvert à 40 pour cent par des lacs et des chenaux. Les regions de toundra et taïga créent deux environments distinctifs de pergélisol terrestre dans le delta. Des mesures continues de temperature dans 27 nappes d'eau du delta, prisent en 2009, indiquent qu'il n'y a pas beaucoup de variation spatiale pendant l'été dans le régime thermal des chenaux et lacs du delta. Une faible variation spatiale est aussi prévue sur une base annuelle.

1 INTRODUCTION

The purpose of this research is to understand the spatial variation in thermal regime, or temperature cycle of lakes and channels in the Mackenzie Delta, Northwest Territories (Fig. 1). The temperatures of water bodies constitute an important influence on ground temperature and hence permafrost distribution (Smith, 1976; Burn 2002). An understanding of permafrost configuration around water bodies can assist in predicting impacts of warming on the stability of shorelines (Kokelj et al 2009) and is therefore essential for appropriate development of infrastructure in the vicinity of lakes and channels.

This paper presents measurements of basal temperature made between June and August 2009 at 15 lake and 12 channel sites covering the geographic extent of the Mackenzie Delta. Spatial and temporal variation in thermal regime is examined, and estimates of mean annual lake and channel bottom temperature are derived.

2 BACKGROUND

2.1 Thermal Regime of Northern Lakes and Rivers

There is limited information available on the thermal characteristics of northern water bodies. Lakes in the Mackenzie Delta typically do not freeze completely to the bottom, and maximum ice thickness is generally 0.6 - 1.5 m (Marsh 1998). Maximum temperature for NRC Lake in the eastern delta near Inuvik (Fig. 1) was measured at ~ 22°C in late July by Marsh and Bigras (1988). Water at the lakebed in the central pool of Todd Lake, Richards Island, ranges from 12°C in late July to approximately 2°C in mid winter (Burn 2002). Water at the margins of lakes may freeze to the bottom.

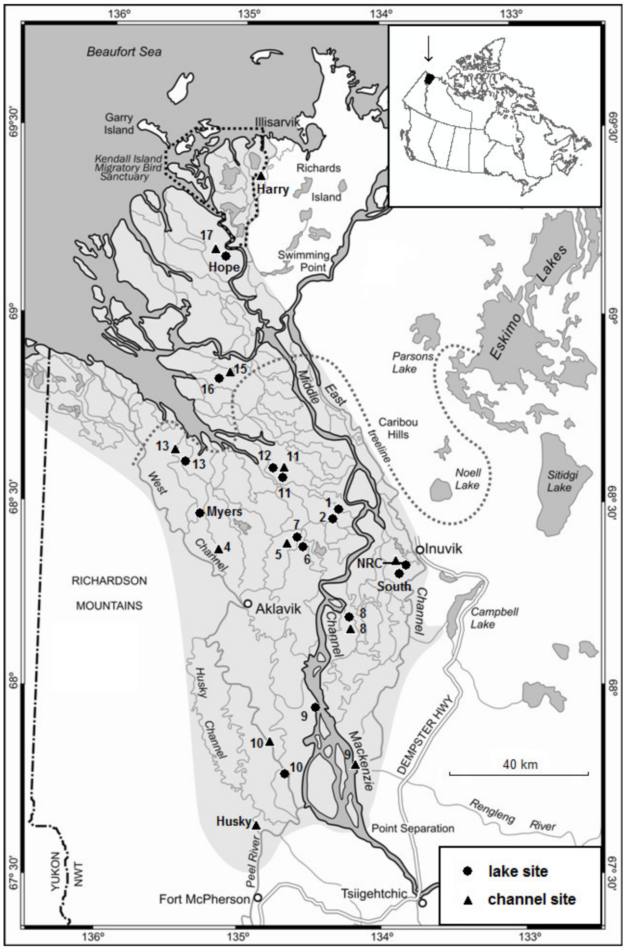

Figure 1. Mackenzie Delta region with study sites.

Channels in the delta generally have an ice cover between mid October and late May, and shallow channels may freeze completely to the bottom (Burn 1995; Burn and Kokelj 2009). Many channels do not freeze to the bottom, and water temperature likely remains close to 0°C for much of the winter. Basal water of a major channel in the northeastern delta was approximately 0°C from November to April, each year from 1967 to1970 (Smith 1976).

2.2 Ground Thermal Regime

When mean annual water temperature (MAWT) is above 0°C, water bodies in permafrost regions maintain a talik beneath them. Talik configuration is controlled by the size, bathymetry, and MAWT of the channel or lake. Burn (2002, Fig. 11) determined talik configuration beneath a tundra lake in the outer Mackenzie delta area by field measurement and geothermal modeling.

Steady-state models, presented by several authors, enable estimates of the ground temperature field and talik configuration when mean annual ground temperature and MAWT are known (Smith 1976; Burn 2002).

3 THE MACKENZIE DELTA

The Mackenzie Delta is the world's second-largest Arctic delta, with an area of over 13,000 km^2, and is bordered by the Richardson Mountains to the west and rolling tundra uplands to the east. Treeline crosses the delta, with subarctic boreal forest in the south and low-shrub tundra and sedge wetlands at the coast (Fig. 1).

The delta is a postglacial feature consisting of sediment derived from the Mackenzie and Peel River basins. The delta contains over 49,000 lakes and a complex network of channels (Emmerton et al. 2007). Most of these water bodies, which cover 40% of the delta surface and have a MAWT above 0°C, alter the configuration of permafrost from what would be expected in this region (Kanigan et al., 2008).

Permafrost is continuous in the delta (Nguyen et al., 2009), though it is typically less than 100 m thick due to abundant surface water and the shifting of channels (Smith 1976). This is in contrast to prevailing conditions in the region: permafrost thickness may exceed 100 m beneath adjacent uplands, and may reach 500 m beneath portions of the outer delta unglaciated during the Pleistocene (Burn and Kokelj 2009). Mean annual ground temperature in the Mackenzie Delta ranges between -1.5 and -3°C, south of treeline, and from -3 to -5°C north of treeline (Burn and Kokelj 2009).

4 METHODS

Twelve channel sites and 15 lakes from across the delta (Fig. 1, Table 1) were selected for instrumentation using National Topographic Series maps and 1:30,000 aerial photographs taken in August 2004. Examination of lake water clarity on aerial photographs helped to distinguish study lakes connected to and disconnected from the

Table 1. Summary statistics for instrumented Mackenzie Delta lakes and channels, summer (26 June–10 August) 2009. 'C' and 'P' refer to 'Connected' and 'Perched' lakes, respectively. 'Delta Region' refers to the Eastern, Western, Northern, or Southern delta.

Site	C/P	Perimeter (km)	Area (ha)	Depth (m)	Delta Region	Record (mm/dd)
Lakes						
NRC	P	1.0	7.2	2.0	E	06/09-08/10
South	C	4.3	34.2	3.2	E	06/09-08/10
L1	C	1.7	13.0	2.5	E	06/13-08/12
L2	P	1.3	8.01	2.5	E	06/13-08/12
Myers	C	10.6	88.7	2.3	W	06/25-08/18
L6	C	9.5	87.2	1.6	E	06/14-08/12
L7	P	2.1	25.0	1.3	E	06/14-08/12
L8	P	3.6	35.9	2.8	E	06/17-08/12
L9	P	1.6	9.6	4.5	S	06/17-08/14
L10	P	1.6	5.5	5.3	S	06/14-08/14
L11	P	0.8	4.6	2.4	E	06/17-08/15

L12	C	6.4	115.0	3.7	E	06/15-08/15
L13	C	3.2	49.6	1.1	W	06/25-08/18
L16	C	4.4	114.0	2.1	N	06/24-08/18
Hope	C	6.8	276.0	9.2	N	06/24-08/22
Mean	--	*3.9*	*55.0*	*2.9*	--	--
Channels						
Harry				1.2	N	06/24-08/21
Husky				10.1	S	17/24-08/14
C4 (Nikoluk)				7.7	W	06/25-08/18
C9 (East)				4.0	S	06/18-08/14
C11 (Pederson)				5.2	E	06/23-08/15
C13 (Leland at Jamieson)				12.0	W	06/26-08/18
C5 (Schooner)				8.4	E	06/14-08/12
C17				2.3	N	06/24-08/22
NRC				3.6	E	06/09-08-10
C8				10.8	E	06/17-08/12
C10 (Peel)				5.6	S	06/17-08/14
C15				3.7	N	06/24-08/18
Mean				*6.2*	--	--

channel network (the latter type referred to as 'perched').

Miniature data loggers were submerged in each channel and lake bed at the deepest location possible in mid June 2009 and fixed to shore by cable for retrieval. A
bathymetric survey was conducted at each site at the time of logger deployment. Temperature profiles were measured vertically in lakes, and both vertically and across the bed at each channel site to assess variability in thermal conditions. In mid August, channel logger installations were modified to withstand winter ice formation and spring breakup.

For comparison with water temperature series, summer 2009 wind speed and air temperature data sets were obtained for Inuvik from Environment Canada (http://www.climate.weatheroffice.ec.gc.ca/climateData/ canada_e.html) and for Harry Channel from Indian and Northern Affairs Canada.

Table 2. Mean temperature (℃) for Mackenzie Delta study lakes and channels, by region, for summer 2009. The number of study sites is given in (). 'St.Dev.' is standard deviation among mean summer temperatures for all water bodies in the region[1] or of the type[2] specified. MAWT estimates are explained in the Discussion.

	Northern Delta	Southern Delta	Eastern Delta	Western Delta	Mean ± St.Dev.[2]	Est. MAWT
Channels	14.6 (3)	15.0 (3)	15.3 (4)	15.1 (2)	15.0 ± 0.4 (12)	4.1 (12)
Perched Lakes	No Data	13.6 (2)	15.7 (5)	No Data	15.0 ± 1.4 (7)	3.4 (15)
Connected Lakes	13.8 (2)	No Data	13.5 (4)	15.2 (2)	14.0 ± 1.7 (8)	
Mean ± St.Dev.[1]	14.3 ± 0.5 (5)	14.5 ± 1.1 (5)	14.9 ± 1.6 (13)	15.2 ± 0.2 (4)	14.7 ± 1.3 (27)	3.8 (27)

5 RESULTS

Summary data including connectivity, delta region, depth, geometry, and period of temperature record are presented for lakes and channel sites in Table 1.

Temperature measurements made across channel beds indicated variability ≤0.1℃ at each study site, and therefore isothermal conditions. Temperature profiles taken in mid June following spring turnover indicated that study lakes were vertically isothermal at that time.

Mean lake and channel bed temperatures for the summer period (26 June to 10 Aug., 2009) were 14.5℃ and 15.0℃, respectively. Perched and connected lakes showed mean temperatures of 15.0℃ and 14.0℃, respectively, for the entire delta (Table 2). Perched lakes in the eastern delta averaged over 2℃ warmer than connected lakes in this region. Unfortunately, region-controlled comparisons of mean temperature between lake types were not possible elsewhere in the delta.

Daily variability among channel temperatures remained relatively low and consistent (standard deviation ~1℃) through the summer (Fig. 2a). Standard deviation of summer mean channel temperatures was lower (0.4℃; Table 2). In contrast, lakebed temperatures converged (Fig. 2b), with initial and final standard deviations of ~4℃ and ~1℃, respectively. The series of mean, maximum and minimum temperatures amongst all channels and lakes is presented in Figure 2. NRC Lake and South Lake represented the extremes of lake temperature until the beginning of August. These converged from 17.6℃ (NRC) and 3.7℃ (South) on 26 June to 18.6℃ and 18.1℃, respectively, on 6 August.

As shown in Figure 2, lake bed and channel thalweg temperatures exhibited a synchronous trend through the study period. Mean temperature among connected lakes peaked (19.1℃) on 30 July, while peak mean temperature for perched lakes (17.7℃) and channels (20.1℃) occurred on 31 July.

As shown in Figure 3, average basal temperature on 26 June appears inversely related to lake depth. By the end of summer, no relation is apparent. The same pattern holds true for both perched and connected lakes when considered separately. Figure 4 compares NRC Lake water temperature with Inuvik air temperature for summer. Figure 5 shows NRC Lake bottom temperature from August 2005 to August 2009. Temperature cycles from near 0℃ in late winter to >20℃ in late July, and rises and falls sharply between summer maxima and the limits of the ice-on period. NRC lake MAWT was 6.1℃, 5.7℃, and 5.1℃ for 2006, 2007, and 2008, respectively.

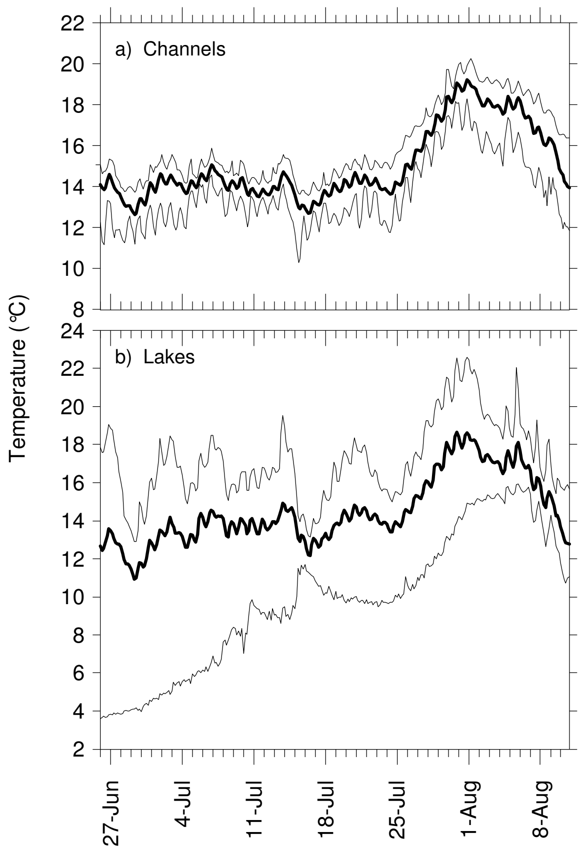

Figure 2. Summer 2009 maximum, mean, and minimum water temperatures among (a) 12 Mackenzie Delta channel sites and (b) 15 lakes.

6 DISCUSSION

Mean summer temperature difference between the lakes and channels studied was small (Table 2), and variability among lakes and channels was low. Connectivity to the Mackenzie River likely explains the low spatial variability in channel temperature. The apparent spatial consistency of lakewater temperature delta may be a result of spatially consistent forcings from solar insolation and air temperature, particularly across-delta. Burn (2005) has demonstrated that small lakes in the outer delta are well-mixed during summer. If the convectional and radiative heating of surface waters is similar throughout the delta,

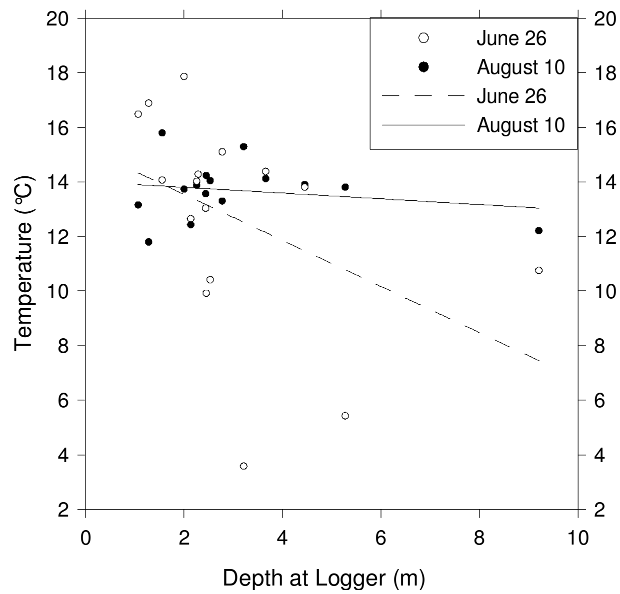

Figure 3. Depth of temperature logger vs. 26 June and 10 August temperature for 15 Mackenzie Delta lakes.

wind-induced mixing of lakes and inherent turbulence in channel waters may transmit these effects to the bottom. Mixing is likely stronger in shallow or well-exposed lakes.

Air temperature is likely an important driver of lake temperature. Marsh and Bigras (1988, Fig. 3) provide a time series of NRC lake temperature where peaks closely resemble and lag (~3 days) those of air temperature. Peaks in air temperature (measured at Inuvik airport) and NRC Lake water temperature exhibit a similar correspondence and lag over summer 2009 (Fig. 4).

Mean summer basal temperature for southern delta study lakes is only 0.2°C greater than that of northern delta lakes (Table 2). One might expect southern delta lake temperatures to exceed those of the north by a greater margin, as mean monthly air temperature in Fort McPherson (southern delta region) exceeds that of Tuktoyaktuk (northern delta region.) by approximately 7, 4, and 3°C during June, July, and August, respectively, for 2000-2006 (Environment Canada, 2009). The small observed difference in mean basal temperature may be a result of small sample size in the northern and southern delta region (n = 2 lakes in each region), and the significantly greater average depth of the southern delta study lakes than the overall mean (4.9 m and 2.9 m, respectively). Both southern study lakes are perched.

The reduction in temperature variability among study lakes over the summer study period (Fig. 2b) may occur in response to the negative water balance exhibited by lakes this season and typical for the delta (Bigras 1990, Emmerton et al. 2007). This increase in the ratio of lake surface area to volume likely strengthens the dependence of lake bottom temperature on air and lake surface temperature, leading to greater spatial consistency of basal temperatures in the late summer.

The consistency in the date and time of peak summer temperature among study lakes may result from a strong

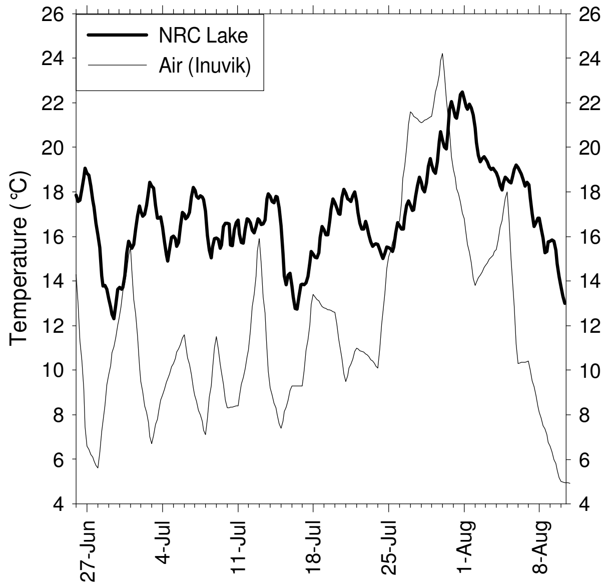

Figure 4. Summer 2009 NRC Lake bottom temperature and air temperature at Inuvik airport.

dependence on air temperature, or factors associated with conditions when air temperature is high. The steep rise in air temperature observed between 24 and 27 July, prior to the 30 July peak in air temperature (Fig. 3) may induce the steady increase in channel and lake temperature observed between 24 and 31 July. The second peak in mean water temperature, observed on 5 Aug. for lakes and channels, may occur due to the simultaneous peak in air temperature.

Figure 2b) reveals a 'bottleneck' in lake temperature variability between 16 and 17 July. At this time, temperatures at most sites agree closely. On 15 July, the strongest winds of the study period were observed at Inuvik (41 km/h sustained 11:00-12:00, max. gust 65 km/h) and in the northern delta ~10 km south of the Harry study site (25 km/h average of 24 hours). It is likely that these winds provided sufficient mixing to remove some existing stratification, bringing lake-bottom temperatures closer to those of surface waters already more spatially uniform due to insolation and air temperature.

Lake ice is generally present between 15 Oct. and 1 June, and channel ice formation and breakup usually occur ~1.5 weeks later in spring and ~2 weeks earlier in fall (Burn 1995). If lake and channel water is assumed to be 0°C while ice cover exists (25 Oct. to 16 May for channels), and the temperature transition between initial and final measured values and the ice-on period is assumed linear, mean annual temperature estimates are possible. Using 2009 summer data, MAWT at delta lake and channel beds was estimated at 3.4°C and 4.1°C, respectively. For a study area ~50 km north of Inuvik, Smith (1976) reported mean annual temperatures of 3.5°C and 3.0°C (1968, 1969) for lakes, and 3.7°C, 4.0°C, 3.8°C, and 4.2°C (1967-1970) for channels.

The assumption of lakewater at ~0°C for the entire ice-on period likely underestimates MAWT, given the observed increase in basal temperature each fall after ice

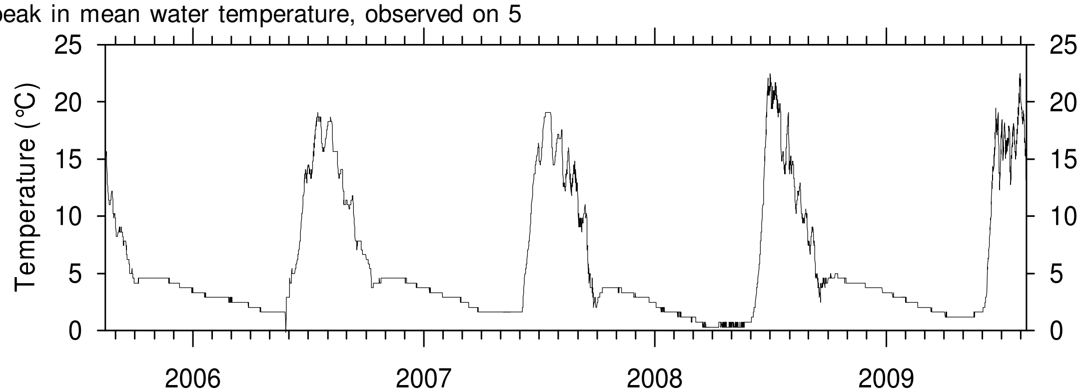

Figure 5: NRC Lake bottom temperature, Aug. 2005—Aug. 2009.

formation at NRC Lake (Fig. 5). This results from heat emission from lake sediments, and heating by solar insolation through clear ice prior to snow accumulation (Brewer 1958). This reinforces the importance of year-round temperature monitoring to verify MAWT.

7 CONCLUSION

Spatial variability in the summer thermal regime of Mackenzie Delta water bodies is low. While channels are isothermal at all study sites, depth is a likely source of variation in thermal regime between lakes. Spatial consistency of lake and channel-bed temperature during winter has yet to be determined, but sources of variation – namely air temperature – present during summer are not expected to influence water thermal regime appreciably beneath the ice and snow cover. It is likely that the limited summer thermal variability therefore represents the greatest annual spatial variability in Mackenzie Delta channels and lakes.

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