Sensitivity of sediment bed temperatures to changes in on-ice snow thickness beneath near-shore zones of bottom-fast ice in the Mackenzie Delta

Christopher W. Stevens
Department of Geoscience, University of Calgary, Calgary, Alberta, Canada
Brian J. Moorman
Department of Geography, University of Calgary, Calgary, Alberta, Canada
Steve M. Solomon
Geological Survey of Canada, Dartmouth, Nova Scotia, Canada

ABSTRACT
This study examines the role that on-ice snow plays in regulating sediment bed temperatures beneath bottom-fast ice in the near-shore zone of the Mackenzie Delta. Field measurements indicate that mean winter sediment bed temperatures deviate up to 9.8°C (from -0.5°C to -10.3°C) in water ranging 10 cm to 100 cm deep. Intra-site variability in temperature over a two year period was as much as 4.7°C. Numerical thermal modeling confirms that the variability in sediment bed temperature is interrelated to the effects of snow on the duration of time ice is bottom-fast and the loss of heat from the underlying sediments.

RÉSUMÉ
Cette étude cherche à déterminer le rôle que joue la neige couvrant les étendues de glace dans la régularisation des températures du lit sédimentaire étant sous la glace de fond polaire situé à l'intérieur de la zone benthique littorale du Delta du Mackenzie. Des mesures prises sur le terrain indiquent que les températures hivernales moyennes du lit sédimentaire varient de 9.8 °C dans des eaux de 10 à 100 cm de profondeur. Une modélisation thermale confirme que la variabilité des températures est dépendante des effets des pertes de chaleur provenant des sédiments se trouvant sous cette glace.

1 INTRODUCTION

In the near-shore zone of the Mackenzie Delta, Canada (Figure 1a), the thermal condition of permafrost beneath shallow water (<2 m water depths) is related to the freezing of the ice column to the sediment bed (i.e. bottom-fast ice). Where ice is bottom fast, heat is readily conducted from the underlying sediments, which contributes to sustaining and aggrading permafrost beneath shallow water environments (e.g. Dallimore et al. 1988; Dyke, 1991; Dyke, 2000; Solomon et al. 2008). Key factors controlling heat loss from the sediments include the duration of time ice is bottom-fast and the thermal insulation of the overlying snow pack (Stevens et al. in press). These two main factors determine the thermal boundary conditions at the sediment bed and whether permafrost is within thermal equilibrium or disequilibrium with surface conditions.

Proposed plans for natural gas extraction make it important to understand permafrost within the near-shore zone of the Mackenzie Delta. Knowledge on the current state of permafrost, its distribution and potential response to climate change is essential for the safe and cost effective design and construction of coastal infrastructure related to oil and gas development. Such undertakings will require an understanding of ground thermal conditions and the ability to effectively model ground temperatures beneath various water depths.

In this study, we numerically model ground temperatures to determine the sensitivity of sediment bed temperatures to changes in on-ice snow thickness and ice growth. Field-based measurements at the sediment bed are also presented to demonstrate the natural variability in winter temperatures and to validate modeled results.

2 STUDY AREA

This study was conducted within the near-shore zone of the Mackenzie Delta, located within the western Canadian Arctic (Figure 1a). The delta lies within a zone of continuous permafrost (Nguyen et al. 2009), despite the thermal influence from numerous lakes and channels (Smith, 1976). Onshore terrestrial permafrost is < 100 m thick beneath the modern Holocene delta plain (Taylor et al. 1996).

Seaward of the delta front, the near-shore zone is characterized by a broad shallow water platform that consists of fine-grained sediments. Near-shore sedimentation results in localized progradation of sediment bars despite the delta undergoing a transgression (Jenner and Hill, 1998). Sea level rise is on the order of 2-3 mm a^{-1}, with shoreline retreat along the modern delta front averaging 1.8 m a^{-1} (Solomon, 2005).

Ice cover along the coast extends for ~8 months of the year, with freeze-up occurring in early to mid-October. Coastal ice thickness typically ranges from 160 cm to 180 cm by late March. This results in bottom-fast ice (BFI) occurring over large regions of the near-shore zone where water depths are less than seasonal ice growth. Ice break-up seaward of the delta front is thermally induced by air temperatures greater than 0 ^{o}C and over-ice flooding caused by the spring freshet that occurs in early June.

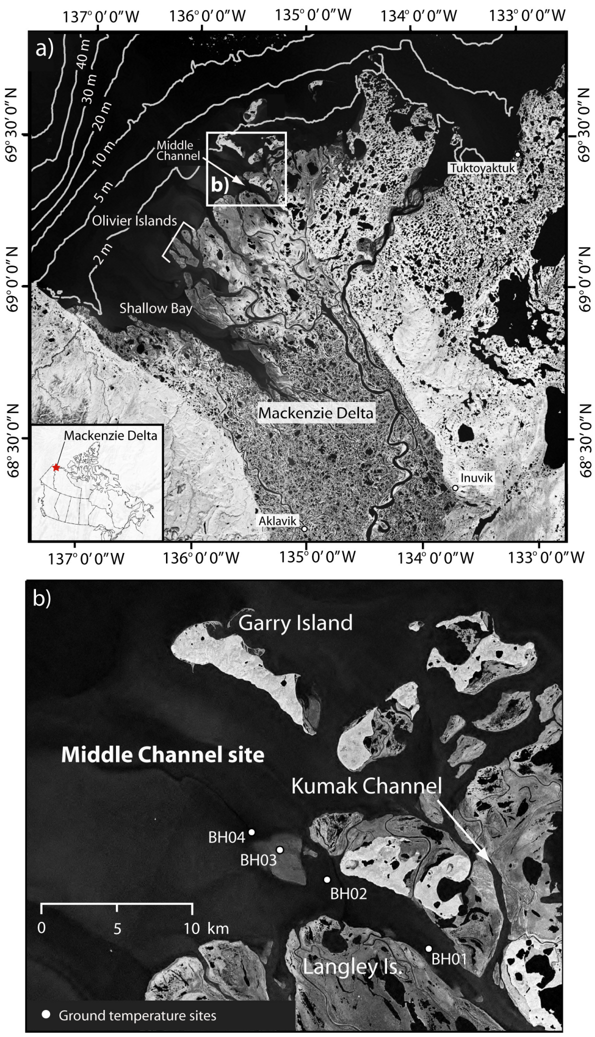

Figure 1. Location map of a) the Mackenzie Delta, NWT, Canada with water depth contours and b) the location of near-shore ground temperatures sites.

3 METHODS

3.1 Field-based measurements

Sediment bed temperatures were measured for two consecutive winters (2005-2006 and 2006-2007) at four BFI locations, which span water depths ranging from 10 cm to 100 cm. These sites extend along a seaward transect from the mouth of Middle Channel, located within the Mackenzie Delta (Figure 1b). Temperatures were measured with a Vemco^{TM} logger accurate to $\pm$0.3^{o}C.These ground temperature records have been previously presented (Solomon et al. 2008; Stevens et al. in press). Herein, we utilize this dataset to summarize differences in the mean winter sediment bed temperature (SBT_w) and to establish verification between measured and modeled temperatures.

3.2 Modeling approach

TEMP/W thermal modeling software was used to model SBT_w under varying thickness of on-ice snow. This model is based on a finite element solution of conductive heat transfer that accounts for temperature dependent thermal properties, sediment unfrozen water content and the distribution of latent heat (Geo-Slope International Ltd. 2007).

Model simulations were run at 10, 25, 50, 75, 100, 125, 150 cm water depths, with an average snow thickness of 10, 20, 30 and 40 cm. Average snow depths were used, since no continuous record exists for the study area and land-based records inaccurately capture snow accumulation and redistribution on ice (Hanesiak et al. 1999). Mean daily air temperature records from Tuktoyaktuk were used to simulate SBT_w (Environment Canada, 2008).

Sediment thermal properties were measured from intact cores and remolded sediments collected from the study sites using a KD2 Pro^{TM} dual needle probe. The temperature dependent thermal conductivity and heat capacity were expressed as a function of the unfrozen water content measured with TDR from 0^{o}C to -8^{o}C. The thermal properties of snow were based on a bulk average measured from on-ice snow in the Beaufort Sea (Strum et al. 2002). The thermal properties for sediment, ice and snow are shown in Table 1.

The initial timing of BFI for each water depth under the given snow thickness was defined by a simplified ice growth model (Woo and Heron, 1989)

$$\frac{\partial h_i}{\partial t} = \left(\frac{T_w - T_s}{\rho_i L_f}\right)\left(\frac{h_i}{k_i} + \frac{h_s}{k_s}\right)^{-1}$$
[1]

where $\partial h_i/\partial t$ is the rate of ice growth, T_w is the freezing point of water (^{o}C), T_s is the snow surface temperatures assumed to be equivalent to the air temperature (^{o}C), L_f is the latent heat of fusion (J kg^{-1}), ρ_i is the density of snow (kg m^{-3}), h_i and h_s are the ice and snow thickness (m), and k_i and k_s are the thermal conductivity of ice and snow. The ice growth model was validated against field measurements for the two consecutive winters of study, using the timing of BFI recorded at the ground temperature sites and the average ice thickness determined from drill measurements. The ice growth model does not account for local variability in ice growth caused by significant spatial difference in on-ice snow, sub-ice currents or more dynamic ice-related processes.

Table 1. Thermal properties of snow, ice and sediment used to model ground temperatures. Frozen and unfrozen sediment properties represent average values directly measured from cores and remolded sediment acquired from the study sites.

Property	Snow	Ice	Sediment
Unfrozen thermal conductivity	48 kJ/day/m/^{o}C	48 kJ/day/m/^{o}C	94 kJ/day/m/^{o}C
Frozen thermal conductivity	12 kJ/day/m/^{o}C	193 kJ/day/m/^{o}C	120 kJ/day/m/^{o}C
Unfrozen heat capacity	4187 kJ/m^3/^{o}C	4187 kJ/m^3/^{o}C	3130 kJ/m^3/^{o}C
Frozen heat capacity	735 kJ/m^3/^{o}C	1880 kJ/m^3/^{o}C	2929 kJ/m^3/^{o}C

4 RESULTS AND DISCUSSION

4.1 Thermal response at the sediment bed

Figure 2 shows the thermal response at the sediment bed for 30 and 100 cm water depths throughout the period of open water and ice-cover. During the period of open water, ground temperatures are consistently above 0^{o}C, until ice freeze-up when ground temperatures become isothermal around 0^{o}C. Following the onset of BFI, ground temperature measured at the sediment bed decrease rapidly due to conductive heat loss. In this case, the ice column forms a conductive link between cold winter air temperatures and the warmer underlying sediments.

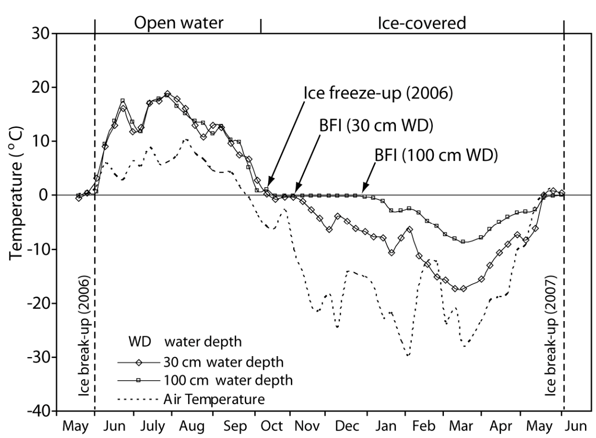

Figure 2. Sediment bed temperatures for 2006-2007 measured at 30 and 100 cm water depths and the Tuktoyaktuk air temperature record presented for the same period of time. The temperatures represent an average of five days for clarity. Note that sediment bed temperatures were recorded at different sites beneath the respective water depths.

The onset of BFI is dependent upon the rate of ice growth and the water depth at each site. As a result, deeper water depths exhibit shorter durations of ice contact and warmer ground temperatures throughout the freezing season. For example, in Figure 2, the two sites located beneath 30 and 100 cm water depths experience a 6.3^{o}C difference in SBT_w (from -4 to -10.3^{o}C).

Table 2 presents a summary of the SBT_w for each site over the winter of 2005-2006 and 2006-2007. Mean winter air temperatures over these two winters were similar (-18.4 and -18.9^{o}C). However, mean winter temperatures recorded at the sediment bed deviate by up to 9.8^{o}C (from -0.5 to -10.3^{o}C) beneath water depths ranging from 10 to 100 cm deep. Intra-site variability in temperature over the two winters was as much as 4.7 ^{o}C. The intra-site variability suggests that SBT_w does not directly correlate to water depth.

Instead, the variability in temperatures at the sediment bed can be explained by differences in on-ice snow depth, which altered the rate of ice growth, the duration of time ice was bottom-fast (i.e. the ice contact time) and the loss of heat from the ground (Stevens et al. in press).

In the winter of 2005-2006, average late winter ice thickness was 114 cm (n=41) compared to the following winter which averaged 160 cm (n=76). This difference in ice thickness was associated with an average on-ice snow depth of 20 and 10 cm, for the respective winters. This resulted in a slower rate of ice growth throughout the former winter, as inferred by the shorter durations of ice contact that occurred beneath deeper water sites (Table 2). The SBT_w were also considerably warmer in 2005-2006 (Table 2), which also reinforces the importance of snow on heat extraction from sub-ice sediments. As a result, both the ice contact time (ICT) and the on-ice snow depth for each water depth must be accounted for, in order to accurately model SBT_w.

Table 2. Water depth, mean winter sediment bed temperature (SBT_w) and ice contact time (ICT) measured at the near-shore ground temperature sites.

Site	BH01	BH02	BH03	BH04
Water depth (cm)	30	100	10	40
2005-2006				
SBT_w (°C)	-3	-0.5	-9.7	-6.1
ICT (days)	200	83	227	204
2006-2007				
SBT_w (°C)	-7.7	-2.6	--	-10.3
ICT (days)	206	154	--	213

4.2 Modeled ice contact times

The ICT can be defined as a function of the water depth (WD) and the rate of ice growth (ICT=f(WD, $\partial h_i/\partial t$)), where the timing of ice freeze-up and break-up are held to be constant over an area. Snow plays an important role in determining the ICT, as it restricts heat loss at the ice-water interface and thus decreases the rate of ice growth. Once the ice column becomes bottom-fast, snow limits heat loss from the underlying sediments. Where ICT=0, the ice does not become bottom-fast and SBT>0°C.

The modeled growth of ice, using Equation 1 confirms that the increase in on-ice snow exhibited in 2005-2006 contributed to a slower rate of ice growth (Figure 3). The modeled results also demonstrate that the rate of ice growth has a direct impact on the ICT, with the accumulated impacts being greater in late winter. This results in deeper water sites experiencing greater interannual variability in ICT when compared to shallow water sites.

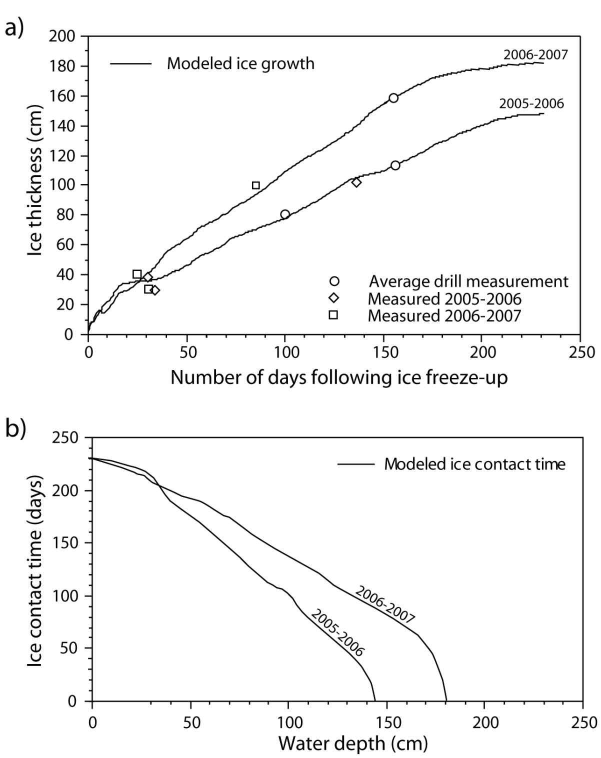

Figure 3. Modeled a) ice thickness and b) ice contact times for the winter of 2005-2006 and 2006-2007. Ice growth over these two winters is validated using average drill measurements of ice thickness and the timing of BFI recorded at ground temperatures sites.

4.3 Modeled sediment bed temperatures

Figure 4 shows the sediment bed temperatures modeled with snow depths ranging from 10-40 cm. The modeled data is based on results obtained from TEMP/W using full thermal conditions that integrate the release and consumption of latent heat and an ICT that has been corrected for ice growth using Equation 1. Six of the seven modeled sediment bed temperatures are within ±0.25°C of the measured values, which is within the accuracy of the Vemco™ loggers used to record SBT_w.

The relation between SBT_W and ICT is shown to be exponential, with increasing ICT and decreasing snow depth associated with colder temperatures (Figure 4). At a maximum ICT, the SBT_w changes by 8.5°C in response to snow varying from 10 to 40 cm. The thermal offset between different snow depth scenarios decreases where the ICT is of short duration, due in part to the release of latent heat from the freezing of the underlying saturated sediments.

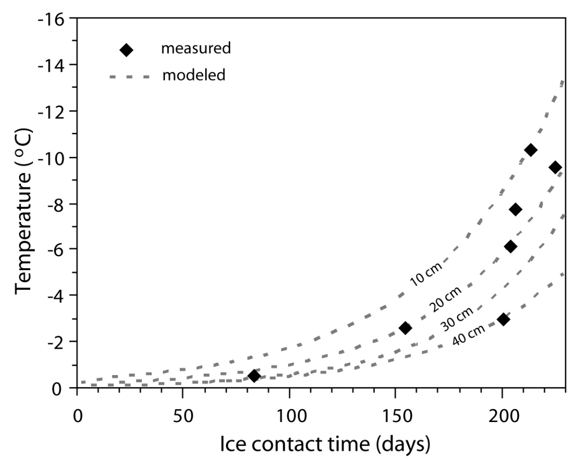

Figure 4. Modeled mean winter SBT for average on-ice snow depths ranging from 10-40 cm. Temperature exponentially increases with increasing duration of ice contact.

4.4 Changes to the ice contact time, mean sediment bed temperature and permafrost

In this study, SBT_w is shown to correlate to the ICT under different snow depths. The ICT is primarily controlled by the water depth which determines the amount of ice growth necessary to achieve BFI conditions. The influence of snow acts as a secondary control on the ICT, which contributes to variability in the rate of ice growth.

Based on Figure 3, the greatest variability in ICT caused by on-ice snow exists beneath deeper water. This results from the accumulated effects of snow on ice growth, which is greater with time. However, at shorter durations of ICT (i.e. deeper water depths), snow has less of an impact on SBT_w. Instead, the greatest thermal offset is associated with sites that have the longest duration of ice contact (i.e. the shallowest water sites). As a result, the greatest potential for change in the thermal conditions is caused by snow occurring over the shallowest water depths.

Given the importance of the snow depth and the ICT on SBT_w, the thermal response of permafrost within the near-shore zone of the Mackenzie Delta will not be solely dependent upon increasing air temperatures that are associated with climate change. Instead, an increase in on-ice snow accumulation alone could lead to a shift in the extent of permafrost and considerably warmer ground temperatures. As demonstrated by Solomon et al. (2008) permafrost beneath shallow water environments is often marginally below $0^{o}C$. This results in permafrost that is susceptible to thawing in response to changes in SBT_w.

Future thermal modeling beneath BFI will be required in the Mackenzie Delta to effectively engineer coastal infrastructure related to proposed oil and gas development. Establishing unique SBT_w for each water depth was previously a major challenge to modeling permafrost conditions beneath shallow water environments. However, the results presented by this study provide a more complete view of SBT_w across the spectrum of water depths influenced by BFI and its sensitivity to changes in on-ice snow. The strong correlation between the ICT and SBT_w suggests that the near-shore distribution of SBT_w can be reasonably estimated using remotely sensed data that defines the duration of time ice is bottom-fast.

5 CONCLUSIONS

The following conclusions can be drawn from this study.

1. Sediment bed temperatures are highly sensitive to changes in on-ice snow depth, due to its impact on the ICT and the transfer of heat from the ground.

2. Over the two winters of study, SBT_w varied by $9.8^{o}C$ for water depths ranging from 10 to 100 cm. Intra-site changes in SBT_w were as much as $4.7^{o}C$, due to differences in the ICT caused by changes in on-ice snow depth.

3. The SBT_w correlates to the ICT, which is defined as a function of T_s, WD and $\partial h_i/\partial t$ and snow depth. The correlation between these two parameters under various snow depth scenarios provides the means for accurate prediction of the spatial and temporal variability in SBT_w.

4. The greatest variability in ICT exists beneath deeper water, due to effects of snow on ice growth. However, snow creates the greatest thermal offset at sites that exhibit the shallowest water and longest duration of ice contact.

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