Field studies of ice breakup and jamming in the Mackenzie Delta

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Ice breakup is a controlling factor in the hydrology of arctic deltas, including the Mackenzie River Delta, which is characterized by a flat front and numerous channels and lakes. Ice jams forming during the spring breakup typically produce the highest water levels of the year. The resulting flooding of delta lakes provides essential replenishment with water, sediment and nutrients. Growing concerns about potential development and climate impacts have prompted a major study of delta hydroecology under the auspices of the International Polar Year. One component of this study aims to document breakup and jamming processes in the highly complex delta environment, and to gather essential quantitative data for calibration and application of numerical prediction models. Progress to date is described herein, with emphasis on first-time comprehensive measurements that were carried out during the 2007 and 2008 breakup events. Because of the extremely low slopes of the delta channels, mechanical breakup (2008 event) is driven by javes originating in the lower reaches of the Mackenzie River. Water level hydrographs and dynamic effects were recorded by means of numerous data loggers placed at key locations along the delta channels. Low-level oblique aerial photography was also used for additional water-level data and for shear wall heights, serving as rough indicators of jam thickness. To facilitate the analysis of the field data, numerous channel cross sections were also surveyed during open water conditions in 2007 and 2008. Examples of key data sets are presented and future research opportunities discussed.
1. Introduction
River ice breakup is a controlling factor in the hydroecology of the Mackenzie River Delta (Marsh et al., 1994). Breakup ice jams can raise water levels to much higher elevations than open-water floods. The resulting replenishment of delta lakes with river water, sediment, and nutrients, plays a key role in the maintenance of their aquatic ecosystems. Delta ice processes in general, and breakup processes in particular, have been documented in some detail (e.g. Terroux et al., 1981). Northern resource exploration and development is a primary issue motivating such research. More recently, the issue of climate change has added urgency to the need for improved understanding of ice processes in the Mackenzie Delta. Though much has already been learned, there is no quantitative ice-jam information, which could be used to calibrate numerical models for environmental impact assessments and prediction of climate change impacts on long-term stability of delta ecology. Under the auspices of the International Polar Year (IPY), this gap is now being addressed via detailed field observations and measurements, specifically designed to collect quantitative data on delta ice jams and related channel characteristics.

The objectives of this paper are to introduce the ice jam research program, and illustrate results that have been obtained to date. Following background information and description of the main components of the ice jam study, chronologies of the 2007 and 2008 breakup events are presented. Emphasis is placed on the 2008 event, which resulted in significant jamming and flooding, unlike the thermal breakup of 2007. Ice-jam data obtained in 2008 are presented next, and future research is outlined.

2. Background Information
Breakup in the delta usually starts in the second half of May and ends in the first half of June. It is generally driven by the rising flows of the Mackenzie and Peel Rivers (Fig. 1). The Peel and west-side tributaries rise earlier, and thus breakup develops more rapidly in the southwestern sector of the delta. However, the breakup in the central and eastern sectors is driven by the much larger flow of the Mackenzie River (e.g. Terroux et al., 1981).

Ice jams often form in Middle Channel between the entrance to the delta (Point Separation) and Horseshoe Bend (Bigras, 1988), diverting backwater and Mackenzie River ice into the Aklavik and Peel Channels (e.g. see review and extensive bibliography in Goulding, 2009). The community of Aklavik has a history of ice-jam flooding, most recently during the 2006 breakup, one of the most dynamic events on record. Relative to most rivers, delta channels have very mild slopes (~ 0.02 m/km or less; e.g. see Hill et al, 2001), which translates to low tractive forces being applied on the ice cover by the current. Coupled with the relatively large ice thickness, this feature leads to thermal breakup, unless tractive forces are amplified by javes, that is, waves generated by releases of upstream ice jams. This pattern has been identified and quantified in the Peace-Athabasca Delta, another major freshwater delta of northern Canada (Beltaos, 2007; Beltaos and Carter, 2009).

3. Description of Study
The present study is a part of a major IPY research program. Its main objectives are to document breakup and jamming processes in the highly complex delta environment, and to gather essential
quantitative data for calibration and application of numerical prediction models. Comprehensive observations and measurements have been carried out during the 2007 and 2008 breakup events. They included frequent aerial and ground reconnaissance, water level recordings at key locations, ice-jam water level profiling via oblique photography, and post-event documentation of shear wall heights. In addition, detailed surveys of channel bathymetry and slope have been carried out along reaches where ice jams are known to form. A scarcity of geodetic survey monuments in the delta has necessitated reliance on advanced GPS instrumentation and data processing. Temporary bench marks (TBM’s) were established using dual frequency survey grade GPS base stations with long/multiple occupations. Rapid static post processed differential GPS techniques established water level pins (WLP’s) at sites of interest within 10 km maximum baseline from at least one TBM. During post processing, NRCan’s PPP (Precise Point Positioning) service allowed correction of the TBM vertical data to centimetric (or better) levels; these positions were “fixed” and the WLP’s corrected. All vertical data were then converted using NRCan’s GPSH v2.1 to the CGG05 Geoid model. [NRCan = Natural Resources Canada; CGG05 = Canadian Gravimetric Geoid 2005].

4. 2007 Breakup

The 2007 breakup in the delta was a protracted thermal event, with relatively low flows and stages, as is illustrated in Fig. 2. The Water Survey of Canada (WSC) gauge on the Mackenzie River just below the mouth of Arctic Red River is the last hydrometric station (herein abbreviated as MARR) before the river enters the delta. It is located 25 km upstream of Point Separation (Fig. 1), across from the community of Tsiigehtchic, formerly known as Arctic Red River.

Major ice jamming developed in early May near Norman Wells, and a few days later at the “Ramparts”, respectively located 550 and 370 km upstream of the MARR gauge. Downstream of the Ramparts, the ice cover deteriorated over time, on occasion developing minor jams, which released, only to form new ones further downstream. The javes produced by such releases were subdued and hardly registered at the MARR gauge.

Within the delta, the ice cover on the various channels disintegrated gradually, as depicted in the photos of Fig. 3. Not captured in these few photos is a south-to-north improvement in ice conditions, which became evident as soon as decay effects appeared in the southern portions of the delta. By May 28, the upstream edge of the ice cover was past the mouth of Arctic Red River, arriving at the Middle-East Channel bifurcation on the 29th and advancing past Horseshoe Bend by the 31st. On the same day, the East channel ice cover moved out of the Inuvik area. A feature that is not often seen in rivers is the progressive disintegration of stationary delta ice covers into small individual blocks. Such blocks accumulate on the water surface creating tiny surface jams (Fig. 3e) that have very limited potential to raise the water level.

5. 2008 Breakup

In anticipation of the breakup event, a number of pressure and temperature data loggers were placed at selected locations along the lower Mackenzie River, Middle Channel, East Channel and the Peel-Middle confluence. Each logger was placed in sturdy protective casing and installed on
one of the channel banks, slightly below or slightly above the prevailing water level (Fig. 4). Logger elevations were “tied” to nearby temporary benchmarks for later survey.

Relatively fast runoff resulted in rapid rise of water levels in the lower Mackenzie River (Fig. 4) and the Peel River further west. On May 19, a 13 km jam was seen in Peel River above its confluence with Middle Channel, while on May 21st an ice run was observed by the first author from the commercial flight to Inuvik in the Mackenzie River. Its upstream end was located at ~ 200 km above the mouth of Arctic Red River (ARR), while its downstream end could not be seen because view of the river was lost at ~ 140 km above ARR. As shown in Fig. 5, the ice cover at ARR was very likely dislodged on May 20, at about the same time as the movement of the gauge orifice. Simultaneous readings by one of the pressure loggers enabled full reconstruction of the water level variation during the breakup event (Fig. 6). The sizeable jump that arrived at this site late on May 20 indicates that a major jam had released upstream, and that the ensuing ice run was the one that was observed on the following day.

Between 1300 and 1600 h on May 21, the delta and lower river were observed from the air [unless otherwise specified, quoted times are local, i.e. they represent Mountain Daylight Saving Time]. Ice cover decay appeared to be more advanced in the smaller channels. Ice in the larger channels, such Middle, East, and Peel Channel, was still in good condition though open-water side strips and transverse cracks were common. In Middle Channel, slightly above Horseshoe Bend, the ice cover had numerous fractures and ridges for a considerable distance upstream. The toe (Fig. 7) of a newly formed ice jam was seen at about 44 km downstream of Point Separation. The length of this jam was only ~ 8 km, but local water levels were already very high (Fig. 8a). The incoming ice run was very heavy and extended well above the ARR mouth (Fig. 8b). Rubble from this ice run had pushed its way into East Channel, causing a 12 km jam (Fig. 9). Similar jams had also formed in a few other channels that were connected to Middle Channel upstream of the toe of the main jam. Some of the channels forming the Peel-Middle confluence were open, while the May 19 jam in Peel River was now much shorter. A drive from Inuvik along the Dempster Highway to the MARR gauge site indicated that the ice run continued until at least 2100 h (Fig. 10).

By the next day, the head of the Middle Channel jam was at Point Separation, while more ice was arriving from upstream reaches (Fig. 11). Changes were also occurring in various other parts of the delta, with ice conditions generally improving in the northerly (downstream) direction. On the afternoon of May 23, more rubble from Middle Channel ran into East Channel, further raising water levels and sending floodwater and ice into connecting channels and nearby lakes. The East Channel jam appears to have released at this time (Fig. 12) but re-formed several km downstream. A similar movement occurred in the Middle Channel on May 24, with a new toe being established some 9 km downstream of the first location. This jam released on May 30, after becoming progressively shorter via thermal attrition at its head. The above events were “captured” by a logger that was located well downstream of the toe of the jam, as shown in Fig. 13. Jave 1 is the same wave that was recorded near the MARR gauge site (Fig. 6). Jave 2 is a minor wave produced by the brief release on May 24, while Jave 3 was produced by the final release on May 30, and followed by a major ice run. Figure 13 further suggests that, while the ice cover remained in place, the water temperature exhibited a diurnal variation, not exceeding a few tenths of a degree C. This was most likely the result of daytime heat transfer, which would have
been quickly dissipated by the proximity of the ice cover. Some time after the release of the jam, the temperature rose sharply, reflecting the end of the ice run and establishment of open-water conditions. By this time, most of the smaller channels in the upper delta were completely open. Ice cover was still in place, however, in the lower delta where it continued to decay by thermal attrition. The spring program was terminated in early June upon completion of post-event surveys of shear walls, as discussed later. No further jamming was observed.

During late August and early September, a field crew carried out comprehensive supplementary surveys, using boats for access and occasionally camping on the delta. This work consisted mainly of retrieval of loggers, GPS survey, identification and survey of ice jam levels from oblique photos, and survey of additional cross sections to complete a larger set that was obtained in the summer of 2007.

The water surface profile of an ice jam is a key data set for modelling and calibration purposes. In the Mackenzie Delta, lack of access necessitated use of low-level oblique photography. While the Middle Channel jam was in place, low-level flights were carried out to photograph the water-and/or ice-level against the channel bank, at numerous locations along the jam (Fig. 14). These photos were later used to identify and survey the elevations of the water surface. Of course, this approach can only provide crude elevations, but the large number of data points enhances confidence in defining an “average” profile (Fig. 15). More accurate data from nearby loggers are also plotted in Fig. 15 for comparison. Though not shown here, oblique-photo profiles were also obtained for May 21, 23, and 27, 2008.

When a jam releases, shear walls form along the river banks as the grounded portions of the rubble remain in place, while the main body of the jam is set in motion. The shear wall height provides a rough, but usually the only, indication of the thickness of the jam. Ordinarily, shear wall heights can be measured with optical instruments if there is access to the river. This is not an option in the Mackenzie Delta; therefore a photographic method was again utilized. Using a helicopter for access, 1 m long wooden stakes were dropped near the bottom of the shear wall to furnish scale in close-up photos (Fig. 16). The resulting shear wall heights are plotted along the river in Fig. 17. In the Middle Channel (distance > 25 km) the shear wall height varies between 3.3 m and 5.3 m, whereas it appears to be more variable along the Mackenzie River (distance < 25 km). Extreme values indicated by some of the “poor” data points in Fig. 17 (including two that exceed 10 m and are not shown) are due to the 1 m stake pointing towards, rather than being parallel to, the wall. For such data, an attempt will be made to apply scale corrections using simple geometrical relationships based on the apparent angle between the stake axis and the horizontal. Occasional ice pile ups on the river banks could also cause formation of very high shear walls, especially at bends. This aspect is presently being investigated.

6. Summary and Future Work
A two-year field research program has resulted in the first set of quantitative data on ice breakup and jamming in the Mackenzie Delta. Through a combination of spring and summer work, ice jam profiles along Middle Channel have been obtained, and supplemented by shear wall heights, channel cross sections, and detailed water level recordings at key locations in the upper delta. Both types of breakup were documented, a thermal event in 2007 and a mechanical event in
2008. Qualitative aspects of both events have been illustrated with numerous photographs, and key examples of quantitative data discussed.

Though the field component of the study has been completed, much more work remains. Completion of data acquisition and processing is the next step, including channel cross sections, ice jam profiles, shear wall heights, and archived data on channel flows and local weather conditions. Data analysis will comprise ice jam model calibration, at least for the Middle channel jam, and possibly for the jam in East Channel. Trend analysis on historical data sets containing hydrologic and climatic variables would also be of interest in view of evolving Arctic conditions. There are also good prospects for future collaborations, as the field data described herein could be of interest to other IPY study components.

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References


Figure 1. Plan view of Mackenzie River Delta and main delta channels.
Figure 2. Water surface variation during the 2007 breakup, as recorded by Water Survey of Canada. Mackenzie River at Arctic Red River (MARR) hydrometric station. Estimated peak water surface elevation = 9.45 m.

Figure 3a. May 17th: Ice conditions in western delta. Essentially intact ice cover with narrow side strips of open water.
Figure 3b. May 20th: Most delta channels still have intact ice covers but signs of deterioration appear in a few of them, especially the smaller ones.

Figure 3c. May 23rd: Ice cover in larger channels is still intact but many smaller channels now have fractured or disintegrating covers; a few (not shown) are completely open.
Figure 3d. May 25th: The ice cover of the larger channels is also beginning to fragment, while decay in the smaller channels is further advanced. The snow cover is starting to disappear.

Figure 3e. Advanced state of ice cover decay and disintegration into individual blocks.
Figure 4. Data logger in its protective casing (insert is a rear view). Total mass ~ 20 kg.

Figure 5. Water surface variation during the 2008 breakup, as recorded by Water Survey of Canada. Mackenzie River at Arctic Red River (MARR) hydrometric station. Estimated peak water surface elevation = 13.91 m.
Figure 6. Water surface variation during the 2008 breakup, as recorded by pressure logger near the MARR hydrometric station. (Geodetic elev. = gauge height + 0.03 m).

Figure 7. Toe of newly formed ice jam in Middle Channel, May 21, 2008, 1336 h. Flow is from left to right.
Figure 8a. Though relatively short, the May 21 jam in Middle Channel was causing very high water levels and localized ice piles. The water level was approaching, and occasionally exceeding, the tops of the banks. [Subtract 2 hours from all times indicated on photos to obtain local time].

Figure 8b. May 21, 2008, looking downstream: heavy ice run in Mackenzie River at its confluence with Arctic Red River (enters on left side).
Figure 9. Ice jam in East Channel, May 21. Looking upstream towards the head of East Channel, with rubble-laden Middle Channel in background.

Figure 10. Ice run near the MARR gauge site, May 21, 2007. Flow is from left to right.
Figure 11. Ice conditions in upper delta, ~ 1500 h, May 22, 2008.
Figure 12. Variation of water level and temperature in East Channel, 10.7 km downstream of Middle-East bifurcation.

Figure 13. Variation of water level and temperature in Middle Channel, 84 km downstream of Point Separation.
Figure 14. Example of low-level, oblique photo used to determine ice-jam elevation, May 22, 2008.

Figure 15. Water surface profile of Middle Channel jam, May 22, 2008. Elevations are referenced to the Canadian Gravimetric Geoid 2005 (CGG05).
Figure 16. Example of photograph used to determine shear wall height. June 3, 2008. The ends of the 1 m stakes were painted red to enhance visibility.

Figure 17. Shear wall heights along the Mackenzie River and Middle Channel. ("Turtle" is an unofficial name for the large complex of islands that begins just downstream of Point Separation – see Fig. 1).