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# Hydrodynamic and climatic drivers of ice breakup in the lower Mackenzie River

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ABSTRACT

Ice breakup is a controlling factor in the hydrology of arctic deltas, including the Mackenzie River Delta, which is characterized by numerous channels and lakes. Ice jams that may form during the spring breakup often result in flooding, thus replenishing delta lakes with essential water, sediment and nutrients. These processes are primarily driven by the flow of the lower Mackenzie River. The present study, carried out under the auspices of the International Polar Year, examines how the ice cover of the lower Mackenzie River can break up while still retaining a significant portion of its mechanical strength. This is the so-called mechanical breakup, a necessary condition for occurrence of ice jams farther downstream. In most rivers, mechanical breakup can simply result from the rising freshet flow, but this is doubtful for the Lower Mackenzie, owing to the low water surface slope and thick winter ice cover. Analysis of extensive measurements obtained during the 2008 breakup event indicates that mechanical breakup can primarily result from javes, the sharp waves generated upon ice-jam release, which are known to amplify hydrodynamic forces. Further confirmation is provided by archived hydrometric station data for the period 2000–2011. The present results on the conditions of breakup initiation are consistent with past findings while indicating a lower base temperature for the accumulation of “thawing” degree-days. This difference is shown to be linked to water–ice heat exchanges and radiative fluxes. Recommendations for future research include upstream extension of the study reach to include the range of influence of releasing ice jams, and physics-based modeling of the decreasing ice competence during the pre-breakup period.

## 1. Introduction

The Mackenzie Delta, one of the world's largest Arctic deltas, contains over 49,000 lakes and covers 13,135 km$^2$ (Emmerton et al., 2007). This lake-rich environment is one of the most productive ecosystems in northern Canada (Squires et al., 2009), supporting large populations of birds, fish and mammals. The spring breakup of the ice cover and the ensuing ice jams are controlling factors in the hydroecology of the Mackenzie Delta (Marsh et al., 1994). Breakup ice jams can raise water levels to much higher elevations than do open-water floods (Beltaos, 2008a). The resulting replenishment of the higher-elevation Delta lakes with river water, sediment, and nutrients, plays a key role in the maintenance of their aquatic ecosystems. The main concerns addressed by the present study relate to the hydroecology of the Mackenzie Delta ecosystem (Marsh and Lesack, 1996; Prowse et al., 2006) and to potentially growing development resulting from oil and gas exploration and the proposed Mackenzie Valley pipeline. Ice jamming also modifies the temporal and spatial distribution of the flow entering the Delta (Mackenzie, Peel, and Arctic Red Rivers) and therefore has an effect on the fluxes of freshwater, sediment, and nutrients to the Arctic Ocean (Emmerton et al., 2008).

Delta ice processes in general, and breakup processes in particular, are driven primarily by the flow of the lower Mackenzie River; they have been qualitatively documented in some detail (e.g. Terroux et al., 1981), but there is little quantitative information. However, quantitative data are essential for advancing current understanding of hydrologic processes, and for developing mathematical models for use in environmental impact assessments and predictions of climate impacts on the long-term stability of Delta ecology. Under the auspices of the International Polar Year (IPY), and as a part of SCARF (Study of Canadian Arctic River Delta Fluxes; http://www.sfu.ca/ipy/), this gap is now being addressed via detailed field observations and measurements, specifically designed to collect quantitative data on delta ice breakup and jamming processes. A parallel study under SCARF aims to develop a multi-channel hydrodynamic flow model for the delta (Nafziger et al., 2009) in order to quantify flow distribution among delta channels under both open-water and ice breakup conditions. Data on ice processes can provide key validation and calibration information for such a model.

Beltaos et al. (2012) introduced the ice jam research component of IPY-SCARF and reported on resulting measurements of ice jams and their effects on water level and flow distribution in the delta channels. The focus herein is on the hydrodynamic conditions that are needed to trigger mechanical breakup events, which can lead to formation of sizeable ice jams and associated flooding. The word “mechanical” denotes that the ice cover retains significant mechanical strength when

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portions of it are dislodged, fractured into blocks, and come to jam against still-intact portions. By contrast, thermal breakup events occur under conditions of low runoff and advanced thermal decay of the ice cover, leading to negligible potential to form sizeable ice jams and cause flooding (Beltaos, 2003).

In general, mechanical breakup can be driven by the rising freshet flow, but this is not always the case. Beltaos (2007) examined breakup data for Peace River near the entrance to the Peace-Athabasca Delta and showed that occurrence of mechanical breakup requires the amplification of hydrodynamic forces that is generated by javes, i.e., waves that follow the release of an upstream ice jam. This finding was attributed to the fact that the lower reaches of Peace River are exceptionally flat. Considering that the Mackenzie River reach upstream of the Delta is also very flat, it is doubtful whether mechanical breakup can be triggered by the rising flow alone. The same applies to delta channels, given that slope decreases in the downstream direction (Beltaos et al., 2012).

Field measurements obtained during the 2007 and 2008 breakup events, along with archived hydrometric station data, have enabled quantification of the forces required to dislodge the ice cover and conclusively showed that such forces can only be generated by javes under nearly all flow and antecedent conditions. The first objective of this paper is to present the relevant field measurements and describe the results of the hydrodynamic jave analysis, which for the first time is being applied to a site where the slope of the water surface changes with discharge (Beltaos, 2011). A second objective is to quantify breakup onset conditions in the lower Mackenzie and compare them to previous findings in other rivers.

Following background information on the study reach and the associated ice breakup regime, quantitative knowledge on the triggers of breakup is outlined. Relevant measurements obtained during the mechanical 2008 breakup event are presented next, and the methodology for extracting hydrodynamic properties of javes from measured waveforms is described. This methodology is first illustrated with the 2008 jave and then applied to other recent events, using archived hydrometric data. The results are compared with previous findings in other rivers and gaps in current knowledge are discussed.

## 2. Background information

Breakup in the lower Mackenzie and the Delta usually starts in the second half of May and ends in the first half of June. It is primarily driven by the rising flow of the Mackenzie and secondarily of the Peel River. Fig. 1 shows the downstream-most reach of the Mackenzie River and the upper portions of the Mackenzie Delta, which begins at Point Separation. The Mackenzie River hydrograph entering the Delta is captured by the WSC (Water Survey of Canada) gauge located across the mouth of the Arctic Red River (Station No. 10LC014; Latitude 67°27′21″ N, Longitude 133°45′11″ W). This gauging station is named "Mackenzie River at Arctic Red River" (herein abbreviated as MARR) and located ~25 river km upstream of Point Separation.

An analysis of archived hydrometric gauge data, which were kindly provided to the writer by WSC, has indicated that the local ice cover consists primarily of a solid ice sheet, with only rare and limited accumulations of frazil slush under it. The seasonal growth of the ice cover is depicted in Fig. 2 where the thickness is seen to attain a maximum value of about 1.1 m in the second half of April.

Despite the considerable distance (over 200 km) to the Beaufort Sea, gauge hydraulic conditions are affected by the sea level so that the local water surface slope varies with flow discharge (Beltaos, 2011). A value of 0.025 was deduced for the bed Manning coefficient ($n_b$) from hydraulic surveys of the MARR gauge reach in June 2005 (measured slope = 0.029 m/km; discharge Q = 16,900 $m^3/s$, per WSC rating table for prevailing water level). Using limited bathymetric data, Parkinson and Holder (1982) applied a backwater model to the multi-channel delta reach and the lower Mackenzie River, starting at Beaufort Sea and ending above the confluence of Arctic Red River. For best agreement between computed and observed water levels, these authors deduced that $n_b$ should change from 0.027 at a flow of 7800 $m^3/s$ to 0.023 at 30,000 $m^3/s$. Though a decrease of $n_b$ with Q is plausible, these findings indicate that any variation within the MARR reach is likely to be small and not significantly affect hydraulic calculation. Therefore, a constant value of 0.025 has been assumed herein. The presence of an ice cover complicates the relationship between discharge, slope, and water level, leading to large uncertainty in the published discharge data for the pre-breakup and breakup periods (Beltaos, 2011, 2012a).

According to WSC "HiWater" reports (obtainable on request), which are issued daily during the spring freshet and ice breakup period, the average breakup level is between 8 and 9 m and occurring around May 18. Here, "level", means gauge height, which at this site is 0.03 m lower than the corresponding geodetic elevation. On the other hand, data presented by Goulding (2008) and Goulding et al. (2009) indicate that the breakup onset level can vary considerably (range ~6 to 13 m) and, with large scatter, increases with freezeup level. This kind of variability attests to the influence of additional factors, which are considered next.

## 3. Onset of breakup

The onset of breakup, that is, the dislodgment and sustained transport of the winter ice cover is controlled by numerous factors and therefore difficult to predict by simple regressions on relevant variables. A physics-based onset criterion relates the tractive force exerted on the ice cover to the width and curvature of the channel, as well as to the flexural strength and competence of the ice cover (Beltaos, 1997, 2008b):

$$\Phi_B \equiv \frac{8(W_B - W_i)\varpi_{iB} m^2}{(m-0.5)\eta_o} = \beta\sigma_{fo}\left(\frac{\sigma_f \eta}{\sigma_{fo}\eta_o}\right) \approx \beta\sigma_{fo} f(S_5) \qquad (1)$$

in which $\Phi_B$ is the multi-variable quantity on the LHS (left-hand-side) of the equation, and has units of stress (for brevity, $\Phi_B$ will be referred hereinafter as BOP, short for Breakup Onset Parameter); $W_B$ = water surface width at the stage at which the breakup is initiated; $W_i$ = width of ice cover = river width at the freezeup stage (peak 7-day average water level) minus side strips caused by hinge cracking prior to breakup; $\eta$, $\sigma_f$ = ice cover thickness and flexural strength, while the suffix o denotes initial values, just before thermal deterioration begins; m = radius of channel curvature divided by ice cover width; $\varpi_{iB}$ = tractive stress applied on the ice cover = downslope force per unit area, generated by cover's own weight and by flow shear, evaluated at the time of breakup initiation; and ß = dimensionless coefficient of unknown value but expected to fall in the range 0.3 to 1.5 based on the physics of the problem.

The ratio $\sigma_f\eta/\sigma_{fo}\eta_o$ quantifies the loss of ice "competence" due to thermal deterioration during the pre-breakup period. This process involves reductions in both ice thickness via top and bottom melt, and in strength via penetrating solar radiation and preferential melting at crystal boundaries (Ashton, 1985; Bulatov, 1972; Prowse et al., 1990). It is very difficult to predict such effects, however, owing to complexities introduced by the snow cover and its changing reflective/absorptive properties as melt advances (Prowse and Marsh, 1989). Consequently, the competence ratio has been expressed as an empirical function of the accumulated degree-days of thaw, referred to a base temperature of −5 °C. This function is denoted by $f(S_5)$ and by definition $f(0) = 1$. The choice of −5 °C, rather than 0 °C, derives from measurements of ice thickness decay in Alaskan and Canadian rivers (Bilello, 1980) and is in contrast to lake ice data indicating that a base of 0 °C is more appropriate. Bilello postulated that this reflects thermal erosion by the flowing water before air temperatures rise to the melting point: even a slightly positive water temperature can cause significant heat transfer to the ice, owing to the effect of velocity. Small positive temperatures under the winter ice cover are generated by such natural sources as tributary inflows, viscous dissipation by flow friction, heat transfer by bottom sediments and by groundwater; and, in usually negligible amounts, by