Monitoring Ice Break-Up on the Mackenzie River Using Remote Sensing

by

Pervaiz Muhammad

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Science

in

Geography

Waterloo, Ontario, Canada, 2014

Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The Mackenzie Basin is composed of eight sub-basins (North Mountains, Liard, Peace, Athabasca, Great Bear Low Plains, Great Slave and Arctic Red) and includes three large lakes (Great Bear Lake, Great Slave Lake, Lake Athabasca) and three deltas (Peace-Athabasca Delta, Slave Delta, Mackenzie Delta), one of which is the world's largest inland delta (Peace-Athabasca Delta). Annually, the Mackenzie River experiences freeze-up during the fall season and ice break-up in the spring, having an important influence on the basin hydrology Furthermore, the type of ice break-up event is dependent on the magnitude of hydrological and meteorological conditions present. In light of the decreasing network of ground-based stations operated by the Water Survey of Canada on the Mackenzie River, this study explored the use of satellite remote sensing data to improve monitoring capabilities during the ice break-up period.

MODIS Level 3 snow products (MOD/MYD10A1) and MODIS Level 1B radiance products (MOD/MYD02QKM) are used to monitor ice cover during the break-up period on the Mackenzie River, Canada, for 13 ice seasons (2001-2013). The initiation of the break-up period was observed to occur between days of year (DOY) 115-125 and end DOY 145-155, resulting in average melt durations of 30-40 days. Floating ice running northbound could therefore generate multiple periods of ice-on and ice-off observations at the same geographic location. At the headwaters of the Mackenzie River, ice break-up

was thermodynamically driven as opposed to dynamically, as observed downstream near the Mackenzie Delta. MODIS observations also revealed that ice runs were largely influenced by channel morphology (islands and bars, confluences and channel constriction). MODIS was found to be a powerful tool for monitoring ice break-up processes at multiple geographical locations simultaneously along the Mackenzie River. Finally, MODIS was found to be a viable tool for estimating river ice velocity where channel morphology least affected river flow. Ice run velocities north of 66° N ranged from 1.21-1.84 ms^{-1}.

Dedication

I dedicate my dissertation work to my family and many friends. I would also like to thank my parents for encouraging my academic endeavours. I dedicate this work and give special thanks to my loving wife Sarah. Thank you for being my number one fan.

Acknowledgement

To my supervisor, Prof. Claude Duguay, I would like to acknowledge the guidance and support that you have provided through my academic career. I have been extremely lucky to have a supervisor who cared so much about my work, and who responded to my questions and concerns so promptly.

I would also like to express my gratitude to Dr. Kevin Kang, for data handling and data processing support and for being a friend. Thank you to Dr. Laura Brown (University of Toronto, Mississauga) and Mr. Ross Brown (Environment Canada) for providing me with the ERA-Interim data used in Chapter 3 of the thesis. I would also like to thank Christina Surdu and Grant Gunn for providing support with image processing. Finally, I would like to thank the DUGUAY Research Group. It was nice to have the support of a family throughout the duration of this project.

This research was made possible with financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC). Data used in this thesis was provided by the National Aeronautics and Space Administration, the European Centre for Medium-Range Weather Forecasts and the Water Survey of Canada.

Table of Contents

List of Figures

List of Tables

Preface

In addition to the general introduction/conclusion, the thesis contains one paper manuscript. The paper, to be submitted to the international journal *Remote Sensing* in October 2014, evaluates the use high temporal resolution MODIS images (MODIS Snow Product and MODIS Level 1b) for monitoring ice cover during the break-up period on the Mackenzie River.

The paper is the result of direct collaboration with Prof. Claude Duguay and Dr. Kevin Kang. Prof. Claude Duguay provided expert advice and editorial assistance towards the completion of the paper. Dr. Kevin Kang provided aid in the design of the project and assisted with data handling.

Chapter 1

General Introduction

1.1 Introduction

The Mackenzie Basin (MB) is amongst the largest hydrologic systems in Canada, and 14^{th} largest total annual discharge in the world (Government of Canada, 2010a). The MB is composed of eight sub-basins (North Mountains, Liard, Peace, Athabasca, Great Bear Low Plains, Great Slave and Peel) and includes three large lakes (Great Bear Lake, Great Slave Lake, Lake Athabasca) and three deltas (Peace-Athabasca Delta [largest], Slave Delta, Mackenzie Delta), one of which is the worlds largest inland freshwater delta (Stewart et al., 1998; Woo and Thorne, 2003). These unique sub basins systems which feed the Mackenzie River Basin, like others such as the Yenissey, Ob', Lena drainage basins, are subject to important spring hydrologic processes specific to high latitude cold regions. More specifically the MB is amongst many systems within high latitudes where the direction of river flow courses from south to north. The MB experiences seasonal average temperatures of -25°C in the winter and 15°C in the summer (Stewart et al., 1998). Particularly, the snowmelt period initiates in the southern sub-basin followed by the later melt periods in the northern sub-basin ranging from April to June (Stewart et al., 1998). Of the main processes that takes place on the MB, snowmelt includes one of the mostly rapidly occurring processes contributing well over 50 percent of the annual runoff (Church, 1974; Marsh and Hey, 1994).

Furthermore, air temperature patterns control important in stream hydrologic processes. In the presence of below freezing air temperatures, the river can drop into a "super cooled" state forming frazil ice, which contains ice crystals typically a few mm in diameters and are suspended by fluid turbulence (Hicks, 2009). Conversely, the spring freshet initiates the break-up of river ice during the spring as result of snowmelt, which is derived from seasonal warmer air temperatures. However, recent studies over the northern river systems have shown significant changes in ice characteristics including maximum ice thickness and duration of ice cover with respect to increasing air temperatures in the fall (Shiklomanov and Lammers, 2014).

Rivers, which annually experience freeze-up during the winter season and ice break-up in the spring, also influence other processes such the local biota, sediment redistribution and, most importantly, seasonal water storage and redistribution. For example, the formation of frazil ice and hanging dams during the onset of the winter season have been known to adversely affect fish habitat, decreasing the amount of habitat space (Brown et al., 2000) and furthermore cause haemorrhaging during turbulent mountain streams (Brown et al., 1994). In addition, rivers such as the Mackenzie River have also been shown to be an important transportation corridor between land and oceans delivering organic matter and sediment (Goñi et al., 2000). Most importantly, river ice affects the MB's hydrology. Seasonally, the overwhelming majority of discharge is released during ice-free periods (Woo and Thorne, 2003a). Evidently, warm water discharge from the Mackenzie River in 2012 occupied an area of 316, 000 km^2 increasing the sea surface temperatures by 6.5°C during the break-up period (Nghiem et al., 2014). Furthermore, flooding during the ice break-up period experience water levels higher than those seen during open water conditions (Prowse and Beltaos, 2002). Therefore, water level under thick ice can increase 2-3 times the open water depth for the same discharge. Large north flowing drainage basins in the northern hemisphere experience earlier onset of ice break-up near the southern sub-basins as a result of peaked discharge from warmer regional air temperatures (Terroux et al., 1981). Most importantly, ice runs during the break-up period are commonly jammed from the presence of channel constrictions (MacKay and Mackay, 1973).

Within urban settings however, river ice floods are much more dangerous and frequently cause damage to infrastructure, including road, bridges, and buildings. Such flooding events have been most famous in regions adjacent to the Red River, which extends from Minnesota and North Dakota from the US and into Manitoba, Canada, as well as the Dawson River, Yukon. Historical ice jam floods on the Red River (e.g. 1997) have cost an estimated $180 million in damages, including loss of an estimated 1,000 homes. Over 7,000 military personnel were employed to help in the displacement of over 25,000 residents (Province of Manitoba, 2011). However, more recent reports have shown that the prevention of one spring flooding event in 2009 has prevented approximately $10 billion dollars in damages for cities located at proximity of the Red River (Province of Manitoba, 2011).

Given the important hydrologic processes described above, the study of cold region hydrology with respect to river ice has been generally understudied. Within the last decade and a half there has been an exponential push from science and engineering academic community to examine, monitor and influence flood risk management. However, there is a need for continued research focus concerning such hydrologic processes with the advent climate change (White et al., 2007). Continued research will be beneficial to both urban and remote communities, aiding in the transfer of new knowledge to conservation authorities, river and flood forecast centres and Indian and Northern Affairs offices.

1.2 Goal and Objectives

The goal of this research is to advance our current monitoring capabilities and understanding of ice hydrology during the break-up period on the Mackenzie River (MR).

Our current state of knowledge from long-term studies has heavily relied on water level, discharge and ice observations recorded by the Water Survey of Canada (WSC) hydrometric stations. In addition, point and multi-year point studies have been conducted in order to study local scale ice strength, ice break-up and morphological patterns. Research relying on WSC hydrometric data has become increasingly difficult as the continuity of stations, which have traditionally been operational for more than 10 years, have systemically been shutdown. As shown in Figure 1.1, the overall number of stations on the MB has remained at around 15-20 (as seen in the blue line) in the last 25 years or so.

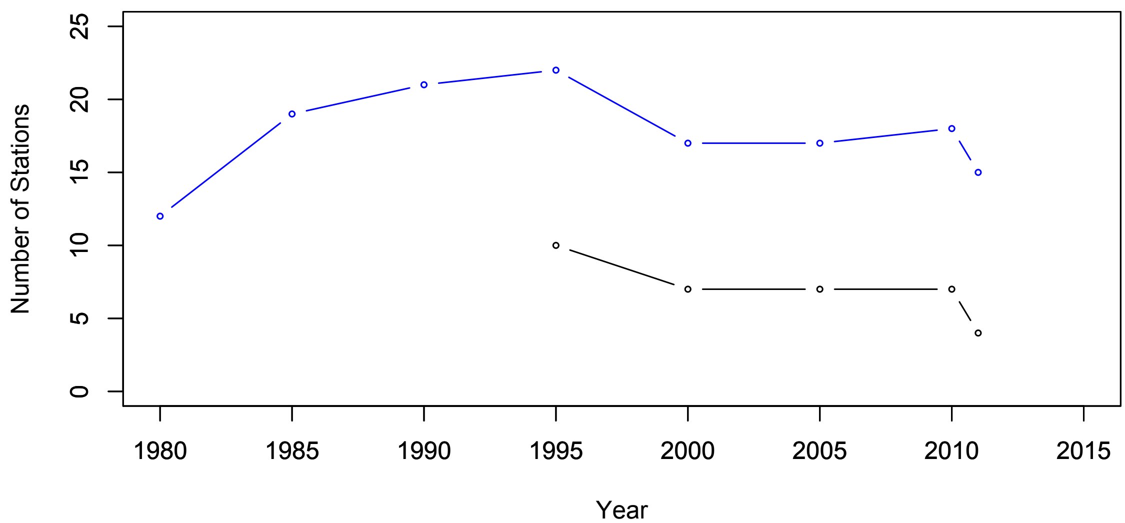


Figure 1.1: Evolution of the number of hydrometric stations operated by the Water Survey of Canada on the Mackenzie Basin (blue line) and the Mackenzie River (black line).

A closer look at Figure 1.1 reveals that, although the number of stations has remained relatively consistent on the MB, the number of operational stations on the Mackenzie River (as seen in the black line) has been dwindling and reallocated to the Mackenzie Delta. However, field-based monitoring in this area has proven to be expensive and logistically difficult. Harsh terrain, the lack of electricity and transportation of expensive field equipment to remote regions of the Arctic make river ice research challenging. As such there is a need to observe and monitor ice processes using new technologies that are economical and logistically simpler, and that can provide continuous monitoring of Arctic river systems. Satellite remote sensing is a viable technology for monitoring ice processes systematically over large stretches of Arctic rivers. It is with this in mind that the idea of the project described herein was developed.

The specific objectives of the thesis are therefore to: 1) develop an approach for monitoring river ice during the break-up period on the Mackenzie River with the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Aqua and Terra satellite platforms, but with potential for transferability to other large rivers of the Arctic; 2) compare the new ice break-up dataset derived from MODIS with the in situ record available from the traditional hydrometric network operated by the Water Survey of Canada; 3) document the spatial and temporal variability of ice break-up patterns over 13 ice seasons; and 4) identify some of the climatic and non-climatic controls that can help explain observed ice break-up patterns on the MR.

1.3 Thesis Structure

Chapter 2 provides a literature review of the current state of knowledge of cold regions hydrology and river ice studies, and related methods. It includes a description of important processes governing river ice freeze-up, river ice break-up and flooding. The chapter then briefly reviews field and remote sensing methods for river ice monitoring which have been implemented within the last two to three decades. Chapter 3 consists of a paper entitled "Monitoring Ice Break-up on the Mackenzie River, Canada, Using MODIS Aqua and Terra". Finally, Chapter 4 includes a conclusion and a description of some of the limitations of the thesis and areas for future work.

Chapter 2

Background

2.1 Overview

This chapter contains three main sections, which cover the state of knowledge of ice on rivers. The chapter begins with a review of river ice freeze-up and break-up processes. This is followed by an examination of the development and transition of methodologies and tools for river ice monitoring. The chapter then provides a description of the study area under investigation, including important sub-basins, climatic patterns and physiographical divisions.

2.2 River ice processes

2.2.1 River ice freeze-up

Seasonal river hydrology is marked by high and low flows relative to changes in precipitation patterns. The onset of winter seasons is therefore classified by experiencing low flows. River freeze-up is observed in tandem to the falling limb on a hydrograph (Prowse and Beltaos, 2002). As such, seasonally it is imperative to understand that river ice processes are not only affected by basin hydrology but basin hydrology is also affected by river ice processes (Woo, 2008).

During the fall freeze-up, the loss of sensible heat from within the water column continues until the temperature decreases fractionally below zero degrees Celsius forming ice (Hicks et al., 2008). This process is referred to as nucleation whereby the water molecules are supercooled forming frazil ice (Jasek et al., 2005). Of course the water column loses and gains sensible heats diurnally, which may not be enough to form ice in the water column, therefore a net loss of energy is required in order for river ice to form.

Frazil particles can remain suspended in river flow until by flocculation frazil ice freeze and stick together forming frazil slush. The formation of frazil slush ($H_2O_{(s)}$) sets a drop in the buoyancy of H_2O molecules; consequently the density of frazil decreases rising it to the surface of the water column (Hicks, 2009). The continuous freezing of water by latent heat flux loss can form pan ice or pancake ice, where ice has collected and frozen and has produced ice flows (Lock, 1990). Channel bridging may also occur where the accumulation of ice is sufficient enough such that there is enough ice to cover the river from bank to bank. Channel bridging may occur where flow velocities are sufficiently low enough for ice to accumulate, where channel constrictions occurs or near piers (Hicks, 2009). Although the initiation of ice formation is influenced by river flow, the formation of ice can then affect river flow. Channel bridging can obstruct passage of downstream flow (Prowse and Beltaos, 2002). When ice has formed over long stretches of a river upstream, forces (i.e. flow drag from underside of ice; weight of ice being pulled downhill) can push or shove ice downstream where ice can fracture, collapse and form above or below other ice pieces thickening the ice concentration within a column (Hicks, 2009). This results in a decreased water column occasioning a reduced discharge downstream and propagating water storage upstream due to increased frictional forces underneath the ice (Hicks et al., 2008). Flow transport of a channel reduces in proportion to the ice boundary roughness (Prowse, 1994). Such ice thickening events can often form ice jam floods during the freeze-up period, illustrating flood stages much higher and occurring more frequently than open water floods (Prowse and Beltaos, 2002). The highest stages are the result of thicker and rougher ice accumulation (Prowse and Beltaos, 2002).

The formation of frazil ice generally progresses on the falling limb of the hydrograph. Therefore, cooling air temperatures initiate the freezing of the watershed and flow is limited to few sources (i.e. ground water, icing/aufeis). The subarctic portions of the MRB derive groundwater flow from the zones of discontinuous permafrost continues throughout the winter as a result of unfrozen gravels (Prowse, 1994). However, northerly sections of the MRB experience decreased flows as the amount of frozen permafrost from the subsurface increases (Prowse, 1994). Cooling air temperatures are first observed in higher latitudes (68° N) and complete river freeze-over on the MRB begins in mid September. However, river ice formation in the lower latitudes (61° N) can continue until late October (Bonsal and Prowse, 2003). Therefore, large drainage basins such as the MRB illustrate north to south river freeze-over patterns.

2.2.2 River ice break-up

The beginning of the spring thaw is signalled by the spring freshet and increased air temperatures (Abdul Aziz and Burn, 2006). The input of heat in the spring initially serves to increase the temperatures of snow and ice on the river to 0^oC (Hicks et al., 2008). Such a process compromises the ice strength and promotes ice thinning from the bottom and top of the ice. This is a crucial step as the river ice break-up is dependant on the driving forces acting on the ice to displace it and the resistant forces working to keep it in place. The driving forces are a result of hydrodynamic forces that accompany the spring melt (discharge and water surface increase, slope, velocity) and/or rain on snow events (Beltaos and Prowse, 2009; Hicks et al., 2008). Resistance factors include ice cover thickness and strength.

Initially the resistance factors are greater than the driving factors and so the ice remains in place. After a point in time, the driving factors increase while the resistance factors decrease to the point where the ice is dislodged and transported down the river. In addition to the freshet driving forces, which are collected from snowmelt, water storage released from storage mobilized river ice can increase the spring freshet by an extra 25% (Prowse and Carter, 2002). This is significant as the initiation of ice break-up is characterized by the peak of a rising limb (stage) of a hydrograph as seen in the figure below (Beltaos, 1990; de Rham et al., 2008b; Scrimgeour et al., 1994) (Figure 2.1).

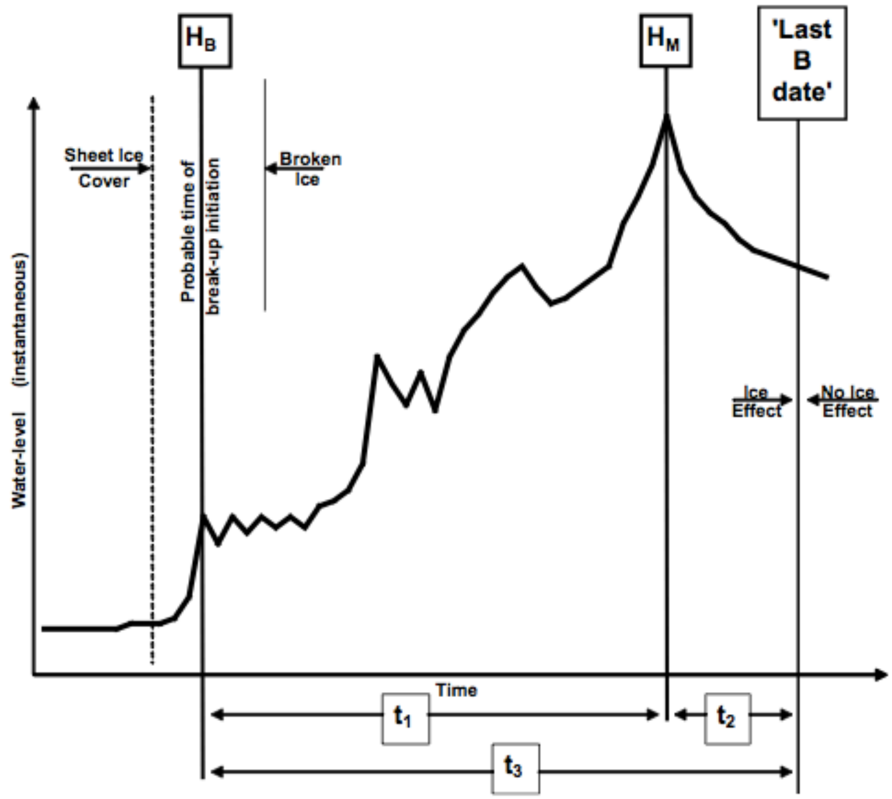


Figure 2.1: Illustration of water level increase during an ice break-up period adapted from de Rham et al. (2008b). Key terms include initiation of break-up (H_B); maximum instantaneous water-level during break-up (H_M); 'Last B date'; drive (t_1), wash (t_2), and duration (t_3).

Research has shown that the severity of peak stage break-up is most effected by upstream discharge and downstream ice conditions (Goulding et al., 2009b). The type of ice break-up events is dependent on the magnitude of hydrological and meteorological conditions present, and can be classified into two general types of break-up: (i) mechanical, pre-mature, non-thermal or dynamic and (ii) over-mature, thermal (Beltaos, 1997; Beltaos and Prowse, 2009; Prowse, 1994; Scrimgeour et al., 1994). In mechanical break-up, while temperatures remain cool and runoff remain high (spring flood wave), driving forces promote ice break-up. Increase of runoff from the overlying drainage basin increases discharge (Woo and Thorne, 2003a) within the river, thus causing a rise in water level within the river and therefore a rise in the floating ice. An excess of water pressure from increased discharge causes the formation of longitudinal fractures in ice known of hinge cracks. Formation of hinge cracks promotes excess heat transfer and ice melts on the ice edges, no longer longitudinally supported by the riverbanks. Therefore, once river ice runs downstream, the meandering river applies shear stress and causes transverse cracks once the ice is forced to bend. The opposite happens when resistance forces are high; the ice remains stationary and ice disintegration is the result of solar radiation, increasing air temperatures and heat transfer from flow beneath the ice. The equation below describes the ice decay process (Hicks et al., 2008):

$$E_m = E_{si} + E_{li} + E_{ei} + E_{hi} + E_{pi} + E_w \quad \text{(Joules/second [J/s] = Watts [W])}$$

where

E_m is the available net heat flux required to raise the temperature (positive) and later melt the ice floating ice;

E_{si} is the net solar radiation by the ice (positive);

E_{li} net longwave in exchange with the atmosphere and the ice surface (positive or negative);

E_{ei} is the heat gain (positive) by condensation or (negative) evaporation from the ice surface;

E_{hi} is the sensible heat transfer between ice and atmosphere (convective heat transfer, positive or negative);

E_{pi} is advected heat by rain (positive) or snow (negative);

E_w is convected heat from the water to the ice cover from under ice run (positive or zero).

When the sum of the variables is positive, the net heat flux (Joules/sec) is available to raise the temperature and eventually melt the ice pack. When there is snow on the ice, then E_m represents a heat flux that is directly supplied to the ice cover, otherwise heat is transferred to both the overlying snowpack and underlying river ice (Hicks et al., 1995). The temperature profile of river ice varies during spring thaw. At the ice-water interface the temperature is 0ºC and decreases as it approaches the ice-snow and increases again as it approaches the atmosphere (Hicks et al., 2008). The initiation of spring thaw is instigated by increased positive E_{si} in which surface melting begins. This causes the albedo of over ice to decrease due to snow/ice melt and therefore to increase solar radiation penetration in the river ice. This positive feedback loop continues until the ice has completely disintegrated.

2.2.3 Ice Jam Flooding

Another feature associated with the river ice break-up process is the ice jam generated wave (Jave). Upon the abrupt release of a jam negative and positive waves propagate upstream and downstream, respectively (Beltaos and Prowse, 2009). As an ice jam builds, water depth increases due to an increased subsurface surface roughness, thickened ice cover and low slope (Beltaos et al., 2011; Beltaos and Carter, 2009; Prowse and Beltaos, 2002, p. 2011; Shen and Liu, 2003). When upstream runoff factors increase above downstream ice resistance factors, ice jam releases create waves downstream as runoff raises water levels further amplifying flow velocities downstream (Shen and Liu, 2003). Observations of water levels on the St. John River have also captured the evolution of ice jam release waves at different cross sections of the river (Beltaos et al., 2011). In each case, the wave first increases and finally decreases water levels as the celerity attenuates downstream. This process has been observed to be dynamic as the stream pulse and downstream ice meet prematurely. Therefore, two types of ice jam releases have been identified (Kowalczyk Hutchison and Hicks, 2007). In type 1, ice jams created and released lead to the formation of additional ice jams downstream. In type 2, released jams attenuate downstream (Kowalczyk Hutchison and Hicks, 2007). In either case, javes create high sediment scouring depositing new sediments and nutrients over banks while simultaneously being detrimental to near stream communities, as javes have been recorded up to 7 metres above regular water levels (Beltaos et al., 2011).

2.3 River ice monitoring

2.3.1 Ground-based ice monitoring

Monitoring on the Mackenzie River and other high latitude rivers has been conducted using several approaches. The type and form of monitoring have also evolved over the last century. After World War II, there was a significant push by northern countries to establish ground-based monitoring networks so that freshwater ice and sea ice observations could be collected operationally (Lenormand et al., 2002). Some of countries included Canada, Russia, Finland, Sweden and the United States. Specifically for Canada, data collected and archived included ice thickness, freeze-up and break-up dates. In the 1970's and 1980's, Arctic field campaigns also contributed additional ice observations but these were limited mostly to seasonal and localized hydrology, modeling and thermal regime type studies (Allen, 1977; Beltaos, 1997; Bigras, 1990; MacKay and Mackay, 1973; Marsh and Prowse, 1987; Michel, 1992; Prowse and Marsh, 1989; Terroux et al., 1981). The harshness of the Arctic terrain, difficult mobility and inaccessibility to electricity made field research challenging. The operation of hydrometric stations by the Water Survey of Canada (WSC) also promoted long-term hydrologic studies across many sections of the MRB. Combined river ice datasets available from the WSC and the Canadian Ice Database (Lenormand et al., 2002) have allowed for the documentation of river ice river break-up and freeze-up from the early 1900s to the 1990s (Lacroix et al., 2005). However, monitoring stations from both sources peaked in the 1980s only to decline to a lamentable state by the late 1990s.

2.3.1.1 Water Survey of Canada (WSC)

The WSC is the national agency responsible for the collection of hydrologic data since the early 1900s, upon the recognition to protect Canada's sovereignty over water resources (Government of Canada, 2007a). Hydrometric datasets (HYDAT) are available to users and include metadata of stations, daily and monthly means of flow, water level and sediment concentration, including peak flows for some sites. The HYDAT stations can also be viewed using map layers to facilitate the graphical selection of the network of stations across Canada. Ice data is recorded using symbol measurements. The last 'B' day on a particular river signifies ice related backwater levels. The day following the last 'B' day implies the absence of ice effects on stage, including those which may occur downstream. Therefore, ice may not be present on a river section upstream, but the presence of downstream ice may have an adverse influence on rising backwater levels upstream. The day following the last measurement of ice on a river is usually marked with peak flows. Conversely, periods leading to last seasonal 'B' measurement do not have simultaneous flow measurements, as the river was probably frozen over. This 'B' measurement form WSC HYDAT (last ice day affecting stage) can be compared to MODIS estimates of last ice-on (or following ice-off) dates on the Mackenzie River. However, presence of ice downstream can influence a rise in backwater level upstream, therefore it would not be unusual to have delayed last 'B' day indications relative to estimates of initial MODIS ice-off dates.

2.3.1.2 Early River Ice Studies

Early ice research on the Mackenzie was largely influenced the eventuality of the building of a pipeline on or near the Mackenzie River and by the effects of water flow upon the creation of the W.A.C. Bennett dam. Observation by Terroux et al., 1981 describe ice break-up characteristics on the Mackenzie River as primarily initiated by rising water levels as observed in 1980. Typically, flood waves initiated from the Liard River (325 km) break-up ice on the Mackenzie River at sites downstream including Fort-Simpson (330 km, as seen in mid-May). Ice break-up rapidly progressed towards Norman Wells (890 km) near late-May. River sections at Fort Simpson and Arctic Red River were clear of ice on May 18 and 30, respectively. Average ice breakup date as measured between 1927-1974 is seen in Figure 2.2. Mean rates of ice clearance increased downstream ranging from 24 km/day and 29 km/day between Fort Simpson, Wrigley, NWT (570 km) and Fort Good Hope (1080 km), and 38 km/day downstream for Fort Goode Hope.

A technical report by MacKay and Mackay (1973) provides detailed observations of historical spring ice jamming on the Mackenzie River. The entrance of the Mackenzie River from Great Slave Lake to about 224 km downstream was assessed as having moderate ice jamming. Ices in the headwaters are driven by slow currents and wind processes causing moderate jamming. During the spring break-up period ice from the first 200 km of the Mackenzie River remain in place for extended periods of time. Therefore, the most important factors influencing ice melt is ground melting and melting due to increased air temperatures. An obvious jamming area at 270 km downstream was the result of river bends near the mouth of the Spence River. Ice jams are common where rock edges, boulders and constriction prevent free passage of ice within a channel. Other important ice jamming locations include the Liard-Mackenzie River junction. At 450 km downstream at the mouth of North Nahanni, river widening and shortening and a sharp bend at Camsell Bend (456 km) prevent ice runs downstream. The presence of the Ochre River at 600 km downstream causes ice jam by pushing ice to rise approximately 1 m above river level. Further downstream The Ramparts (1078-1090 km) constitute one of the largest geomorphic obstructions from the passage of ice downstream. Ice jams are an annual occurrence as ice has been reported to top the cliff on either side of the Mackenzie River.

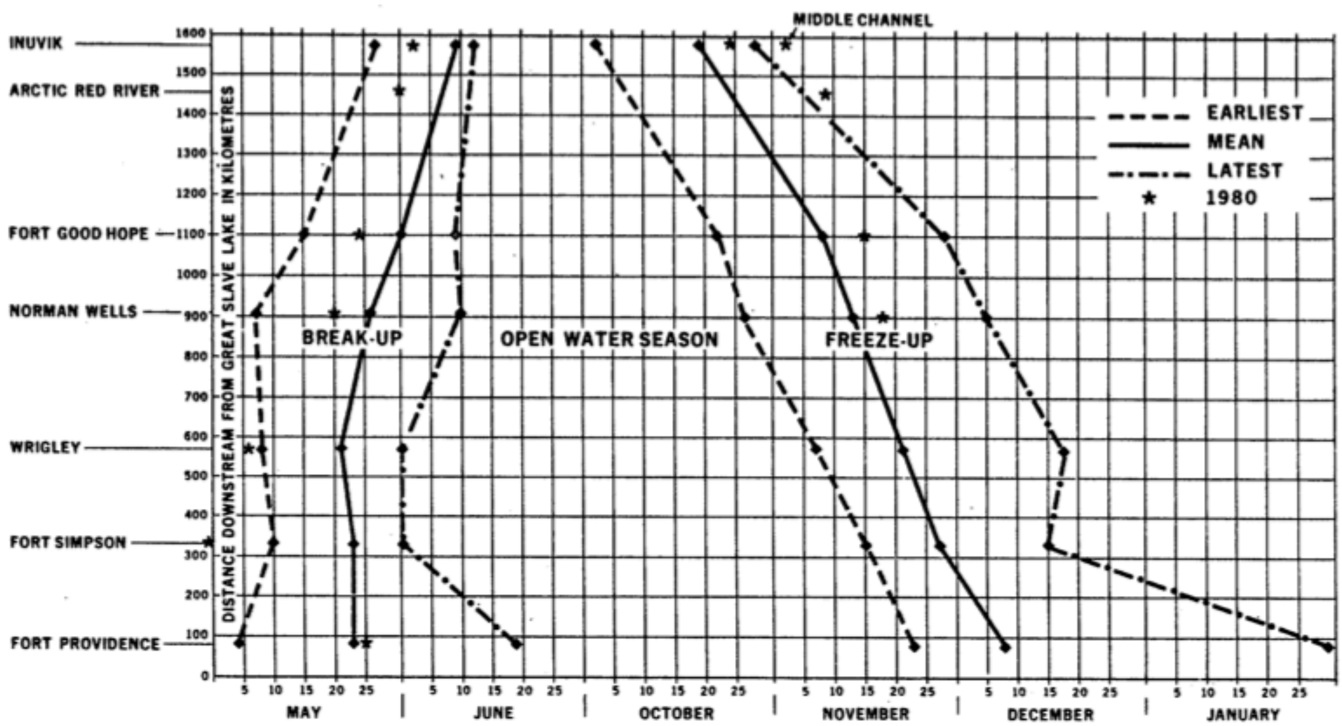


Figure 2.2: Average ice break-up dates measured from1927-1974 on the Mackenzie River (Terroux et al., 1981).

2.3.2 Ice Monitoring by Remote Sensing

Dey et al. (1977) conducted one of the first studies on the monitoring of river ice break-up dates using remote sensing. The study, conducted on Mackenzie River (MR), concluded that images from multiple satellites (NOAA VHRR, Landsat-MSS) could be used to monitor ice processes where hydrometrical data are not regularly collected. In another investigation, Dean et al. (1994) monitored discharge in the MRB and its effects on sea ice. Surface albedo and temperature was monitored using NOAA AVHRR data to specify the melt initiation process (and dates) from the MR, the Mackenzie Delta and the Beaufort Sea. In both of the above studies, data quality was limited due to poor spatial and/or temporal resolutions.

Remote sensing has become a useful tool for river ice research. River ice specialists are increasingly adopting remote sensing as a means to conduct investigations, which would otherwise rely on expensive field campaigns. Such directional move within the river ice research community is a significant step forward as satellite remote sensing provides the capability to monitor ice conditions routinely (Beltaos, 2007). For example, studies have investigated the influences of large Arctic drainage basins as a transporter of discharge and energy into areas like the Beaufort Sea and its impacts on sea ice melt (Beltaos and Kääb, 2014; Kääb et al., 2013; Nghiem et al., 2014). Other studies have focused on monitoring river ice processes in order to forecast hydrological events such as ice jams (Chaouch et al., 2012; Pavelsky and Smith, 2004; Unterschultz et al., 2009). Research has also attempted to map ice types and determine ice thickness on the Mackenzie River (Gauthier et al., 2003; Mermoz et al., 2014). Furthermore, studies have also been conducted river ice discharge and velocity in order to improve freshwater budget estimates (Beltaos and Kääb, 2014).

2.4 The Mackenzie River Basin

2.4.1 Physiography of the Mackenzie River Basin

The MRB is composed of many distinct drainage basins each of which hold unique hydrologic patterns. Physiographically, it is composed of the Mackenzie Delta, Western Cordillera, Interior Plains and Precambrian Shield (Figure 2.3). The regional vegetation varies with boreal in the south to alpine in its mountains, and Arctic tundra in the north (Stewart et al., 1998). The Mackenzie Drainage Basin occupies an area of 1.79 million km^2 stretching from mid-Alberta (~58° N) to the Beaufort Sea (Prowse, 1994). Furthermore, it encompasses seven major sub-basins, including: (1) Athabasca, (2) Peace, (3) Liard, (4) Great Slave, (5) Great Bear (6) North Mountain and (7) Peel. Of these, the Liard, Peace and Peele derive their flows from the Western Cordillera. The Athabasca, Great Slave and Great Bear basins regionally fall within the Interior Plains and Precambrian Shield, respectively.

2.4.2 Climate and break-up timing

Monthly average temperatures in winter range from -25°C to -30°C and 15°C in summer (Stewart et al., 1998). Rivers in the MB exhibit season flow patterns that include nival (snowmelt dominated), proglacial (glacier melt) and wetland and prolacustrine (large lakes). Mountainous sub-basins such as the Liard and Peace contribute about 60% of flow, which ends up in the Mackenzie River and interior plains and eastern Canadian Shield contribute about 25% (Woo and Thorne, 2003a).

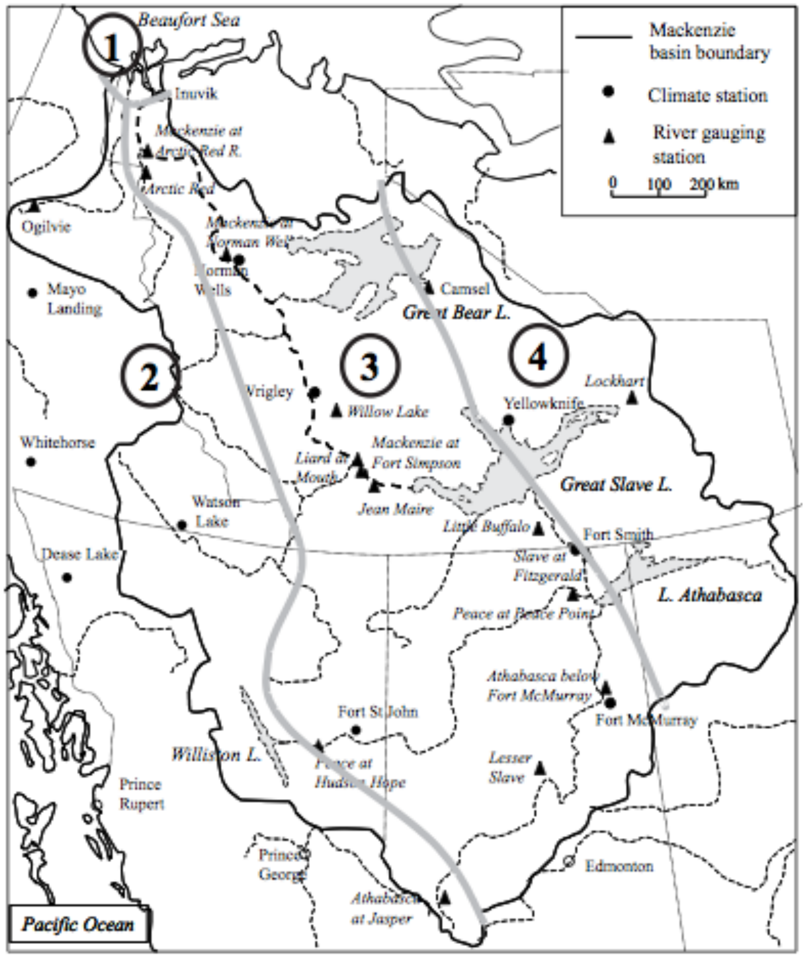


Figure 2.3: The Mackenzie Basin with it major physiographical divides. These include (1) Mackenzie Delta, (2) Western Cordillera, (3) Interior Plains and (4) Precambrian Shield (Woo and Thorne, 2003a).

The average spring 0◦C isotherm is located near northern Alberta on April 15 and continues northward towards the Mackenzie Delta by June 1 (Figure 2.4) (Bonsal and Prowse, 2003). Also, the rising limb of the hydrograph serves as a proxy for the first day of ice-off. The spring air isotherm fall on similar days to first day ice off as seen in Figure 2.5. The spring 0◦C isotherm date marks the beginning of the spring thaw and the initiation of the ice break-up period (Figure 2.5).

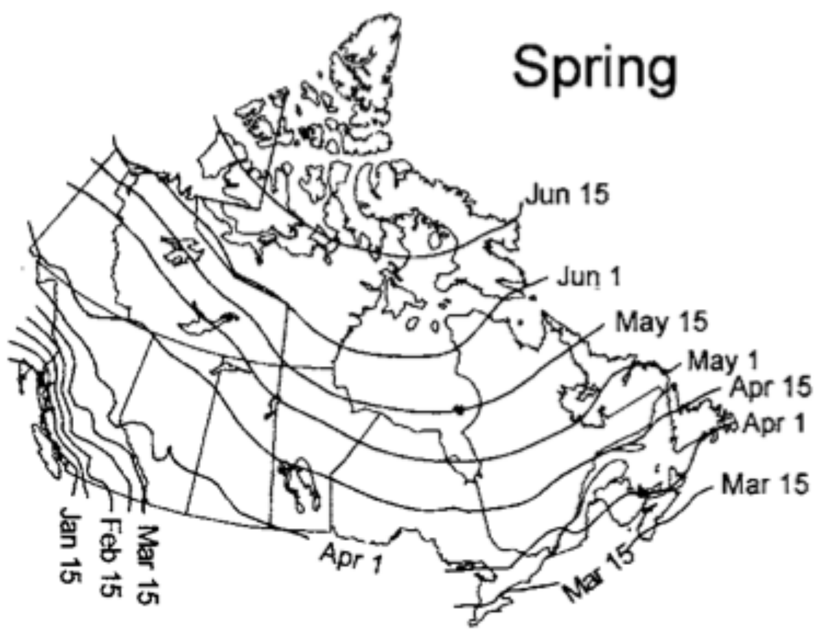


Figure 2.4: Mean dates of the spring 0◦C isotherm over Canada for the period 1961-1990 (Bonsal and Prowse, 2003).

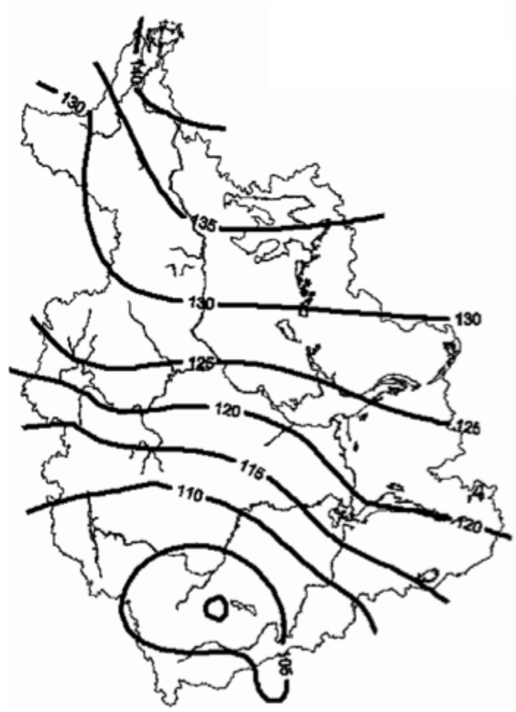


Figure 2.5: The Mackenzie River Basin isochrones of mean initiation of break-up timing. Day of Year 106=April 15 to Day of Year 140 = May 19 (de Rham et al., 2008).

2.5 Summary

River ice is an important hydrologic feature on the Mackenzie River Basin. The process of river ice freeze-up reduces discharge, propagating water storage on the Mackenzie River. Furthermore, river ice break-up is marked by an accelerating rise in seasonal water level (as seen on a hydrograph) promoting ice cleared rivers. Flooding also has an effect during the break-up period as javes promote new sediment deposition, while a build-up of backwater level works to reconnect lakes to the Mackenzie River, geochemically refreshing these systems. Research conducted in the 1970 and 1980s has identified important hydrologic and recurrent ice jamming events on the Mackenzie River. Hydrologic surges from the Mackenzie River adversely influence the rate of ice clearance and ice jamming further downstream. Unfortunately, the ground-based monitoring stations operated by the Water Survey of Canada have been systemically shutdown and relocated limiting the traditional mode of river ice monitoring.

Satellite remote sensing presents an interesting prospect for operational monitoring of ice cover on the Mackenzie River. The next chapter investigates how data from the MODIS instrument aboard the Aqua and Terra platforms can contribute to enhancing our monitoring capabilities and understanding of ice break-up from the largest river flowing into the Arctic Ocean from North America.

Chapter 3

Monitoring Ice Break-up on the Mackenzie River, Canada, Using MODIS Aqua and Terra Observations

Overview

This study involves the analysis of Moderate Resolution Imaging Spectroradiometer (MODIS) Level 3 500-m snow products (MOD/MYD10A1), complemented with 250-m Level 1B data (MOD/MYD02QKM), to monitor ice cover during the break-up period on the Mackenzie River, Canada. Results from the analysis of data for 13 ice seasons (2001-2013) show that first day ice-off dates is observed between days of year (DOY) 115-125 and end DOY 145-155, resulting in average melt durations of about 30-40 days. Floating ice transported northbound could therefore generate multiple periods of ice-on and ice-off observations at the same geographic location. During the ice break-up period, ice melt was initiated by *in situ* (thermodynamic) melt over the drainage basin especially between 61-61.8°

N (75-300 km). However, ice break-up process north of 61.8° N was more dynamically driven. Furthermore, years with earlier initiation of the ice break-up period correlated with above normal air temperatures and precipitation, whereas later ice break-up period was correlated with below normal precipitation and air temperatures. MODIS observations revealed that ice runs were largely influenced by channel morphology (islands and bars, confluences and channel constriction). It is concluded that the numerous MODIS daily overpasses possible with the Terra and Aqua polar orbiting satellites, provide a powerful means for monitoring ice break-up processes at multiple geographical locations simultaneously along the Mackenzie River.

3.1 Introduction

The Mackenzie River Basin (MRB) is the largest in Canada and is subject to one of the most important hydrologic events annually. River ice break-up on the Mackenzie River is a process by which upstream (lower latitude) ice is pushed downstream while intact ice resists movement downstream (higher latitude) (Beltaos and Prowse, 2009). Ice break-up is defined as a process with specific dates identifying key events in space and time between the onset of melt and the complete disappearance of ice in the river. This is the definition used in previously published literature and which will be applied in this paper. Break-up is often associated with flooding in north flowing systems and is thus an important hydrologic event with many environmental benefits (e.g. geochemical land deposition and lake and groundwater recharge) and detriments (e.g. infrastructure damage and lost economic activity) (Prowse, 2001; Kääb et al., 2013). Investigations of river regimes in high latitude countries including Canada, United States, Russia and Sweden and Finland, have a long history related to their ice monitoring (Lenormand et al., 2002). This is important as ice freeze-up and break-up records serve as climate proxies responding to changing air temperatures patterns (Magnuson et al., 2000). The ice break-up process is nonetheless under-monitored. There is therefore a gap in knowledge when attempting to understand all associated hydrologic parameters due to their highly dynamic nature (Beltaos et al., 2011).

The shortage of ice observations on the Mackenzie River and other rivers and lakes in Canada is partly the result of budget cuts, which have led to the closing of many operational hydrometric stations (Lenormand et al., 2002). Specifically, ice freeze-up and break-up observations peaked during the 1960-1990's and declined dramatically thereafter following budget cuts from the federal government (Lenormand et al., 2002). In the last decade only, the observational network of discharge and ice measurements on the MRB has declined from 65 to 15 stations. Satellite remote sensing is a viable tool for filling this observational gap. For example, Pavelsky and Smith (Pavelsky and Smith, 2004) were able to monitor ice jam floods and break-up events discontinuously over a 10-year period (1992–1993, 1995–1998, and 2000–2003) on major high-latitude north-flowing rivers at 500-m and 1-km spatial resolutions (the Lena, Ob', Yenisey and Mackenzie rivers) using MODIS and Advanced Very High Resolution Radiometer (AVHRR) imagery. Similarly, Chaouch *et al.* (2012) showed the potential of MODIS (0.25 and 1 km spatial resolutions) for monitoring ice cover on the Susquehanna River (40°-42° N), USA, from 2002-2010. Kääb and Prowse (2011) and Kääb *et al.* (2013) have also shown the effectiveness of remote sensing data acquired at 15-m, 2.5-m and 1-m spatial resolutions using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) and IKONOS, respectively, for estimating river ice velocities. However, these previous studies have been limited to spaceborne stereographic datasets capturing a few ideal (cloud-free) images a year and including revisit times ranging from 2-16 days, making detailed temporal studies difficult. Despite these recent advances, studies have yet to be conducted monitoring ice freeze-up and break-up processes by satellite remote sensing over longer periods (i.e. continuously over several years).

The aim of the present study was therefore to develop an approach to estimate key ice break-up dates (or events) on the Mackenzie River over more than a decade using Moderate Resolution Imaging Spectroradiometer (MODIS) data. The paper first provides a description of the procedure developed to monitor ice break-up on the MR. This is followed by a quantification of ice-off dates (spatially and temporally) provided by MODIS data. Next, average ice-off dates are compared for the last 13 years (2001-2013). Lastly, displacement of ice runs calculated with MODIS is used to estimate average ice velocity along sections of the MR.

3.2 Methodology

3.2.1 Study Area

The geographical area of this study focuses on the Mackenzie River extending from the western end of Great Slave Lake (61.36º N, 118.4º W) to the Mackenzie Delta (67.62º W, 134.15º W) (Figure 3.1). The study area encompasses the main channel and confluences of the river, including any smaller rivers that feed the Mackenzie. Currently, only 5 hydrometric stations measure water level and ice on the main channel (1,100 km long) of the Mackenzie River north of Great Slave Lake. The MRB forms the second largest basin in North America extending beyond the Northwest Territories at 1.8 x 10^6 km^2 (Government of Canada, 2007b). Approximately 75% of the MRB lies in the zones of continuous and discontinuous permafrost with many smaller sub-basins adding to flow at different time periods during the break-up season (Abdul Aziz and Burn, 2006). The MRB experiences monthly climatological (1990-2010) averages of -20 to -23 °C air temperature between the months of December to February, respectively (Brown and Derksen, 2013). Air temperature increases to an average of - 5 °C in April with the initiation of ice break-up near 61° N.

Air temperature plays an important role on the timing of spring freshet (Beltaos and Prowse, 2009; Goulding et al., 2009b; Prowse and Beltaos, 2002) in the MRB. It has therefore been associated with increased flow and the initiation of ice break-up in the basin as a result of snowmelt onset (Abdul Aziz and Burn, 2006). In thermal (over-mature) ice break-up, there is an absence of flow from the drainage basin earlier in the melt season, and the ice remains in place or is entrained in flow until incoming solar radiation disintegrates the river ice increasing water temperatures (Beltaos, 1997). This slow melting process causes a gentle rise in discharge on a hydrograph, with flooding found to be less frequent during that period (Goulding et al., 2009a). In dynamic (premature) ice break-up, the accumulation of snow on the drainage basin is higher and the stream pulse (or spring freshet) from snowmelt is characterized by a high slope on the rising limb of the hydrograph (Goulding et al., 2009b; Woo and Thorne, 2003a). In the presence of thick ice downstream, flow can be impeded causing a rise in backwater level and flooding upstream. However, when ice resistance is weak downstream, stress applied on the ice cover can rise with increasing water levels fracturing and dislodging ice from shorelines continuing downstream, eventually disintegrating downstream (Hicks, 2009). This process can continue until certain geometric constraints such as channel bends, narrow sections and islands can stop the ice run causing ice jams (Hicks, 2009). Here, the wide-channel jam is the most common of dynamic events which develops from the flow shear stress and the ice jams' own weight, which is formed by the collapse and shoving of ice floe accumulation and is resisted by the internal strength of the accumulation of ice flows (Beltaos, 2008). As the jam builds with ice rubble, the upstream runoff forces can increase above the downstream resistance releasing the jam and creating a wave downstream that raises water levels and amplifies flow velocities (Beltaos et al., 2012). Observations have shown an initial, increase and final decrease in water levels as wave celerity and amplitude attenuates downstream (Beltaos and Carter, 2009). In general, thermal decay and ice break-up process continue downstream after the ice jam release (Hicks, 2009). MODIS imagery has also shown the timing of spring flood and location of open water tributaries to have the most impact on ice break-up processes (Pavelsky and Smith, 2004)

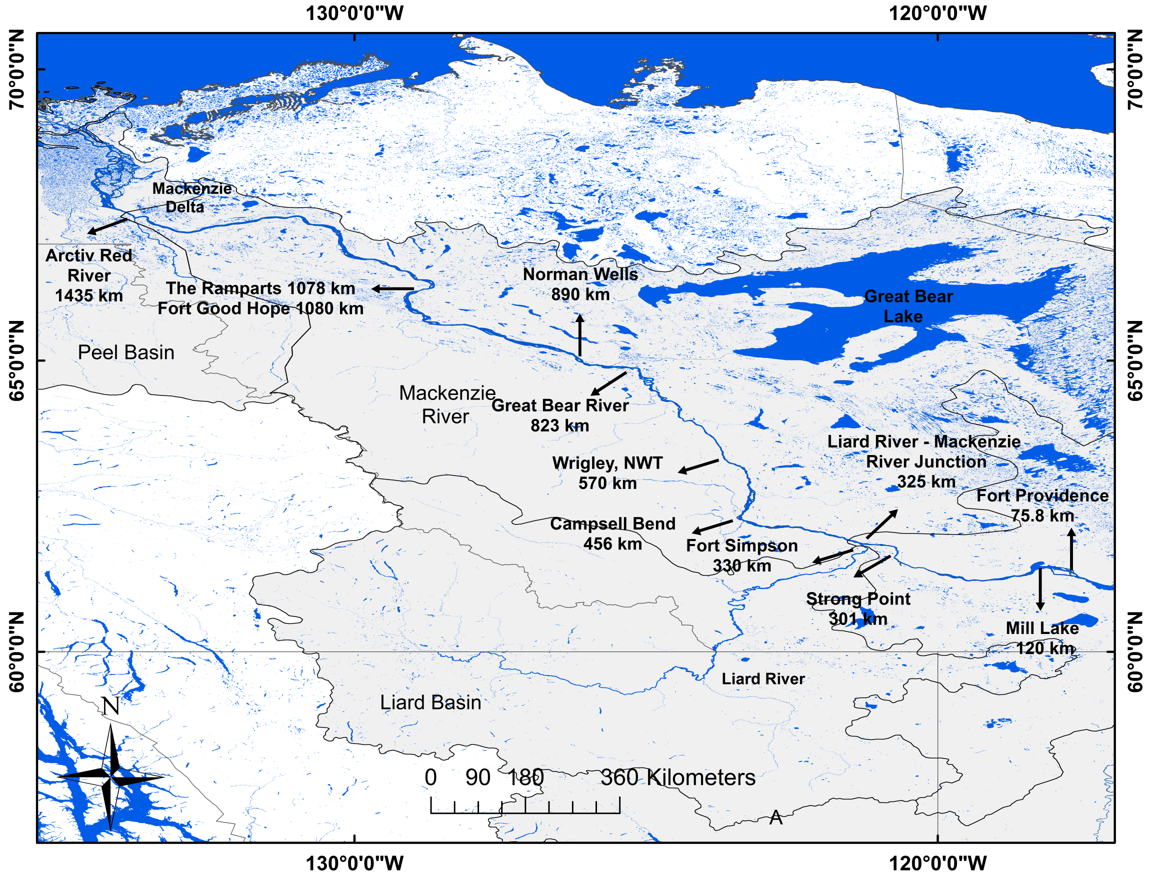


Figure 3.1: The Mackenzie River Basin (MRB), its sub-basins and major rivers and lakes. The MRB extends from 54° N to 68° N flowing from the southeast to northwest. The names of sub-basins and tributaries feeding into the Mackenzie River as well distances downstream (marked by arrows) from the mouth of the Mackenzie River are also shown.

3.2.2 MODIS Data

MODIS images, for the period from one week before to one week after the ice break-up period had ended over the MRB from 2001-2013, were downloaded from the National Aeronautic and Space Administration's (NASA) Earth observing System Data and Information System (EOSDIS) (http://reverb.echo.nasa.gov/reverb/) for processing. This study used 500-m (primary data) and 250-m (secondary data) spatial resolution MODIS data acquired from both the Aqua and Terra satellite platforms. More specifically, MODIS L1B (MYD02QKM/MOD02QKM) and MODIS Snow Product (L3) (MYD10A1/MOD10A1) datasets were retrieved for analysis. In this paper, the MODIS will generally be referred to as L3 and L1B. L3 and L1B images were processed using the MODIS reprojection tool swath and MODIS conversion toolkit respectively, using UTM projection and nearest neighbor resampling. RGB true-color composites and near-infrared band - MODIS Band 1 (250-m, 620-670 nm), Band 4 (500-m, 545-565 nm) and Band 3 (500-m, 459-479 nm) as well as Band 2 (250-m, 841-876 nm) from MODIS L1B were selected. In each of the L3 and L1B available image sets, daily swaths were mosaicked independently and automatically processed.

If cross-sections of a river were observed to be clear of ice from bank to bank using (Terra/Aqua) L3 Snow Product, then one observation would be made for the particular geographic location and time. However, cloud cover presence was one of the few incidences where image processing was limited. This has also been previously reported (Riggs et al., 2000) where cloud cover in the Arctic limited data acquisition from the study site. This, in combination with coarse-resolution cloud cover masks resulted in 5-10% of the images being omitted from analysis. Problems in snow detection arise when spectral characteristics important in the use of the normalized difference snow index (NDSI) make it difficult to discriminate between snow and specific cloud types (Hall et al., 2006). NDSI is insensitive to most clouds except when ice-containing clouds are present, exhibiting a similar spectral signature to snow. Hence, some MOD35/MYD35_L2 cloud mask images presented conservative over-masking of snow-cover on cloudy and foggy days (Hall et al., 2006).

To improve temporal coverage, ice-off observations were also carried out at varying overpass times (Chaouch et al., 2012) using MODIS L1B radiance products from both Aqua and Terra satellites, which do not include the MOD35/MYD35 cloud mask. If cloud cover was present in both L3 Terra and Aqua imagery, L1B images were used to make ice-off observations. Image sets from DOY 100 to 160 were analyzed to observe patterns over the entire ice break-up period ranging from 61° N to 68° N. Ice-off observations were recorded at latitudes where ice was present but subsequently absent from images the next Julian day. North flowing ice could generate multiple ice-on and ice-off dates at the same geographic location. Ice-off and ice-on dates are dynamic ice run events during the ice break-up period. Multiple ice-off dates observed by satellite imagery were referenced and compared to specific hydrometric stations from the Water Survey of Canada (WSC) along the Mackenzie River (Table 3.1).

Furthermore, river sections where land and river features were mixed within pixels of the 500-m MODIS products were included. To minimize the amount of excluded pixels due to cloud cover and pixel mixing, MOD L1B imagery at a higher spatial resolution (250-m) were also used.

Table 3.1: Description of Water Survey of Canada hydrometric stations on the Mackenzie River.

Station Name	Coordinates	Distance Downstream from Mouth of Mackenzie River
Mackenzie River at Fort Providence	61.27° N, 117.54° W	75.8 km
Mackenzie River at Strong Point	61.81° N, 120.79° W	301 km
Mackenzie River at Fort Simpson	61.86° N, 121.35° W	330 km
Mackenzie River at Norman Wells	65.27° N, 126.84° W	890 km
Mackenzie River at Arctic Red River	67.45° N, 133. 75° W	1435 km

A region of interest (ROI) was delineated over the Mackenzie River where ice break-up was observed. MODIS L3 and L1B are provided as scientific data set (SDS) values and digital number (DN) values, respectively (Table 3.2). The MODIS L3 SDS values are described in the “MODIS Snow Product User Guide Collection 5” (Hall et al., 2006). Matching SDS values on cloud free days were used to derive MODIS L1B DN threshold values.

Table 3.2: Integer values defining image cover on a ROI (Mackenzie River) from MODIS L1B and L3 images.

Image Cover	MOD/MYD L3 (SDS)	MOD/MYD L1B (DN)
	(500-m)	(250-m)
Cloud Cover	50	150 <
Snow	200	111-150
Ice (Snow Covered)	100	40-110
Open Water	37	30
Land	25	< 28

3.2.3 Ice Velocity

In addition to determining instances of ice break-up events with respect to location and time, this study also explored the use of MODIS as a tool for estimating velocity of ice flows. Ice velocity was observed and recorded on stretches of ice debris (>10 km) where ice and water demarcation was distinguishable. At the demarcations SDS values changed from 37 to 100 (open water to ice) at the leading edge and 100 to 37 (ice to open water) at the following edge of the north flowing river ice. Velocity was estimated by tracking the displacement of ice over time across multiple MODIS L3 and L1B swaths. Displacement estimates over time were made twice daily from Aqua and Terra satellites, although there is no way of telling that ice was moving within each MODIS image capture. Average velocities were recorded until ice debris could not longer be distinguished as a result of melt processes or when ice and open water were otherwise unobservable due to the presence of cloud cover. Ice velocities recorded also represent the lower limit of the ice flows, as the ice may not be moving at all times between image acquisitions. Therefore, the average velocities present time periods when the ice could be at rest and, therefore, the velocities measurements represent underestimation of the actual ice velocities. Ice debris movement was also referenced to WSC station provided that an operational station was on the route of the ice run.

3.3 Results

3.3.1 Thermal and Dynamic Ice Break-up

The use of L3 imagery from a single MODIS sensor (Aqua or Terra) limited the potential to acquire continuously ice break-up observations as a result of cloud cover conditions. In some years, this represented up to 40 percent of unusable imagery required to measure river ice-off dates. However, by using L3 product from both Aqua and Terra satellites across varying orbital tracks in combination with the L1B product greatly increased the number of observable events during ice break-up period, up to more than 90 percent of available images. MODIS acquisitions from both the Aqua and Terra satellites doubled the number of images available during clear-sky conditions. In addition, the availability of MODIS LIB data from Aqua and Terra further increased the number of available images for analysis (i.e. cases where ice could be seen under thin clouds).

Over the 13 years of analysis, the ice break-up period ranged from as early as DOY 115 and lasted as late as DOY 155. Most ice break-up over the 13-year period (2001-2013) began between DOY 115-125 and ended between DOY 145-155. River morphology acted as an important spatial control determining the type of ice break-up process and ice run. Ice break-up processes between years showed different overall patterns with respect to location, thus temporally the beginning, end and duration of ice break-up varied. For example, the initiation of ice break-up in 2002 (Fort Simpson-330 km) began 10-days later than the average date when ice would completely clear the river section. Compared to 2007, the initiation of ice break-up began 13 days earlier than the average ice-off date at 270 km (61.57° N). As seen in Figure 3.2, ice break-up initiates earliest at the headwaters (headwaters at 120 km, 61.43 ° N to 345 km, 61.92° N) between the Martin River and Mill Lake, and proceeds northward towards the Mackenzie Delta (see Figure 3.3).

The initiation of the ice break-up period on the Mackenzie River was generally observed at the Liard River (325 km). The beginning and end of ice-off observations were observed to take place sooner near the Liard River than upstream and downstream of this location (Figure 3.4). The confluence where the Mackenzie River and Liard River meet (61.82 ° N, 325 km) serves as a point where ice break-up proceeds dynamically northbound and thermodynamically southbound. South of 325 km, ice break-up was observed to be driven by a thermodynamic ice break-up regime (Figure 3.6). So, ice break-up advanced opposite to the direction of river flow, southbound towards Great Slave Lake. Interestingly, higher frequencies of observations were observed south of 325 km where thermodynamic ice break-up regime was prevalent. This ice break-up “reverse” to the river flow was observed to continue until it approached Mill Lake, where the ice break-up was simultaneously progressing in the direction of flow. The converging course continued until no ice remained south of Martin River (Figure 3.6).

As ice break-up proceeded northbound from the MR-Liard confluence, dynamic ice break-up flushed the ice downstream in a shorter period of time than the thermodynamic ice break-up south of the confluence (Figure 3.2 & 3.3). Generally, however, distances above 560 km (63.22° N) (Wrigley, NWT) on the Mackenzie River experienced later ice break-up dates over the 13 years studied (Figure 3.4).

Between 350-682 km (61.96-64° N) and north of the Mackenzie River and Liard River confluence, the average ice-off date for the study period was observed at DOY 130. The river width between 350-682 km was found to be smaller than reaches upstream (feeding ice into the main river channel) and downstream (letting ice exit the channel) as seen in Figure 3.5. Consequently, the movement of ice into this river reach was limited causing ice entering the channel to jam while ice exiting the channel present from the winter period cleared sooner. There is also the possibility that the release of ice javes (river waves generated from ice jam) at the entrance of the channel could give rise to the rapid clearance of downstream ice over 1-2 day period over this 230 km stretch of the Mackenzie River (Beltaos et al., 2011).

Downstream of 682 km (64° N), river sections showed diagonal ice-off observations as seen in Figures 3.2 and 3.3. These patterns are most visible in 2001, 2007-2009 and 2011-2012 observed between 860-1460 km (65-67.62° N). Observations of these diagonal events were the result of a second channel constriction at The Ramparts (1078 km, 66.19° N) as seen in Figure 3.5, preventing northerly ice run. Here, the river channel decreased from 4 km to less than 0.5 km in width. It is hypothesized that ice runs downstream of The Ramparts (as a result of an ice jam) gave rise to similar ice-off dates (estimated at the southern ice-water boundaries of these flows) to ice runs towards The Ramparts. It is estimated that ice jams due to sudden decreases in river width as seen in 2001, 2007-2009 and 2011-2012 gave rise to earlier ice-off dates for river sections north of the jam resulting in impeded ice run which would normally maintain ice-on condition. This phenomenon resulted in a sequence of ice-off observations that occur simultaneously at two different latitudes, north and south of the ice jam. This further outlines the important morphological controls on the Mackenzie River over ice runs.

Based on MODIS imagery, ice break-up began on average between DOY 115 and 125 and ended between DOY 145 and 155 (Figure 3.4). The standard deviation of estimated ice-off dates decreased with increasing latitude. MODIS derived dates showed highest deviations across river sections where thermodynamic ice break-up was prevalent. These patterns are similar to those seen from average break-up and standard deviations observed from the WSC. The 13-year average reveals similar ice conditions in the low, mid and high latitude of the Mackenzie River from MODIS and WSC data. There was an observed difference of 5 days between ice break-up observed from MODIS imagery and WSC. Also the respective standard deviations overlap across the similar periods. Ice break-up in general continued in a north to south direction over the ice break-up periods. Near Forth Simpson,(330 km, 61.85° N) it is worth mentioning that ice break-up was observed earlier than at more southern latitudes as illustrated by MODIS observations. This pattern is likewise visible from the WSC data.

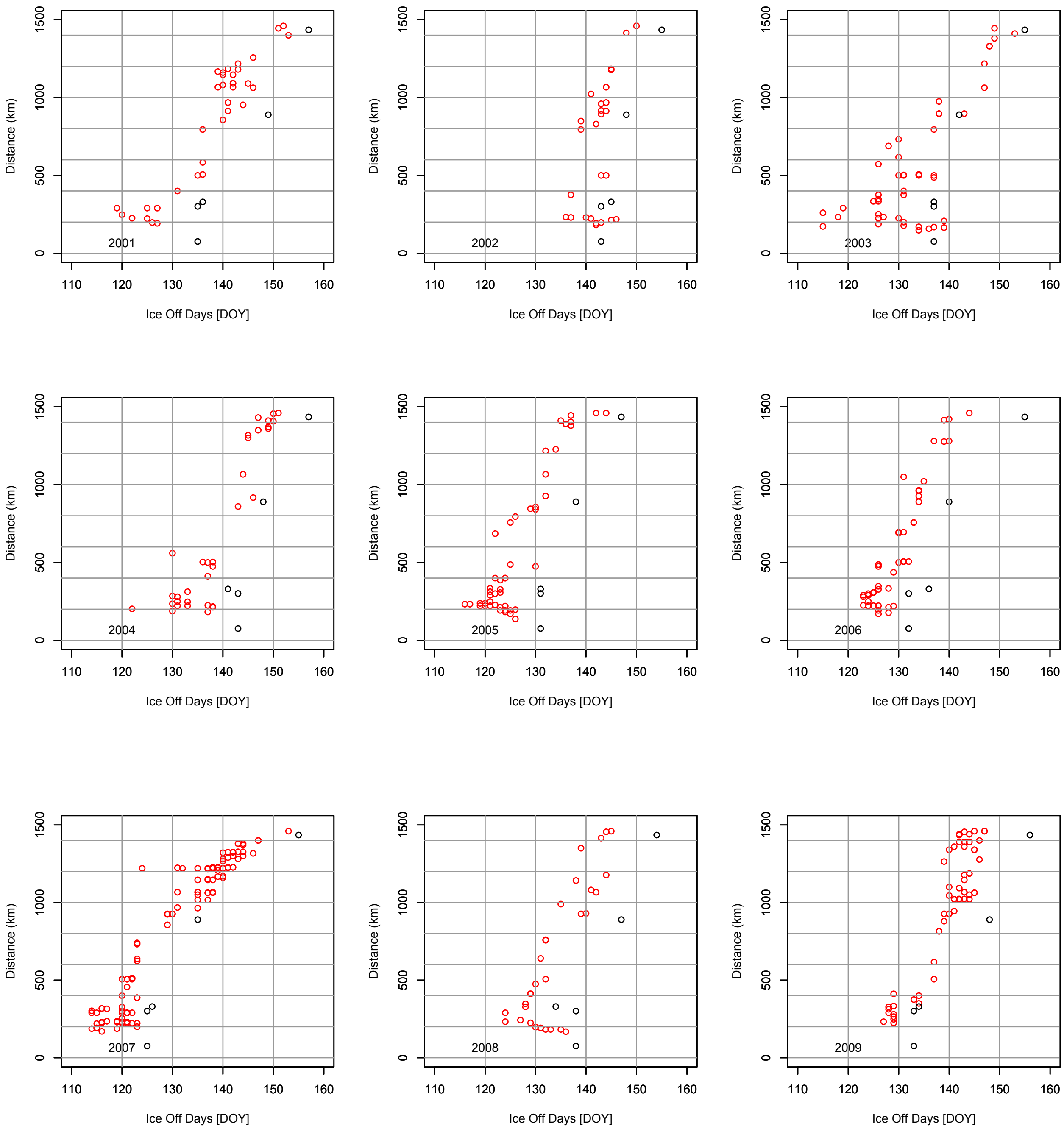
Inter-annual variability of estimated average ice-off dates can be contrasted against ERA-interim 2-m height air temperature and precipitation data available until 2011 only (Brown and Derksen, 2013). As seen in Figure 3.7, 2001, 2003, 2005-2007 and 2010 experienced earlier than normal (i.e. DOY 128) ice break-up dates. Furthermore in 2002, 2004, 2008-2009 and 2011 the average ice break-up date was estimated to be later than normal (DOY 128). Generally, years that experienced earlier than normal average ice break-up dates coincided with warmer (positive anomaly) than normal (-14.4^{o}C) air temperature or above normal (314 mm) precipitation (positive anomaly) or both from the preceding winter months (January to March). Conversely, later than normal ice break-up periods corresponded to below normal air temperatures (negative anomaly) and precipitation (negative anomaly) or both.

It is important to note that until 2010, five ground-based ice observation stations were operational on the MR. Following 2010, the hydrometric station on Mackenzie River at Fort Providence (61.27º N, 117.54º W, 75.8 km) was shutdown (Government of Canada, 2010b). Therefore, the WSC data was limited to 4 stations (Mackenzie River at Forth Simpson, Strong Point, Normans Wells, and Arctic Red River) in 2011 and 2012.

3.3.2 River Ice Velocity

Figures 3.8 and 3.9 illustrate ice movement from which ice velocities could be estimated over periods of 3-4 days following secondary channel constriction at 66° N. Here, ice runs that contained over 15 km of entrained ice were chosen to estimate average ice velocities. Only periods with at least three images with partial or no cloud cover were selected for velocity estimates.

In 2008, the open-water/ice boundary (leading end) was recorded beginning on DOY 143 (Figure 3.8). The open-water/ice (northern edge of ice) and ice/open-water (following end) boundaries were both visible from DOY 144. Finally, the ice/open-water boundary was last observed on DOY 145. The average ice run velocity between 1063-1210 km (66-66.95° N) over the three days was estimated to be at least 1.21 ms^{-1}. Likewise, in 2010 (Figure 3.9), open-water/ice (leading end) and ice/open-water (following end) was observed between DOY 138-141. The leading edge of the ice was first observed on DOY 138 and on DOY 139 when both the leading and following edges are visible. Finally, by DOY 141 the ice run has exited into the Mackenzie Delta. Across the 4-day period average ice run velocity was estimated to be at least 1.84 ms^{-1}.


2001
2002
2003
2004
2005
2006
2007
2008
2009
Distance (km)
Ice Off Days [DOY]
0
500
1000
1500
110
120
130
140
150
160

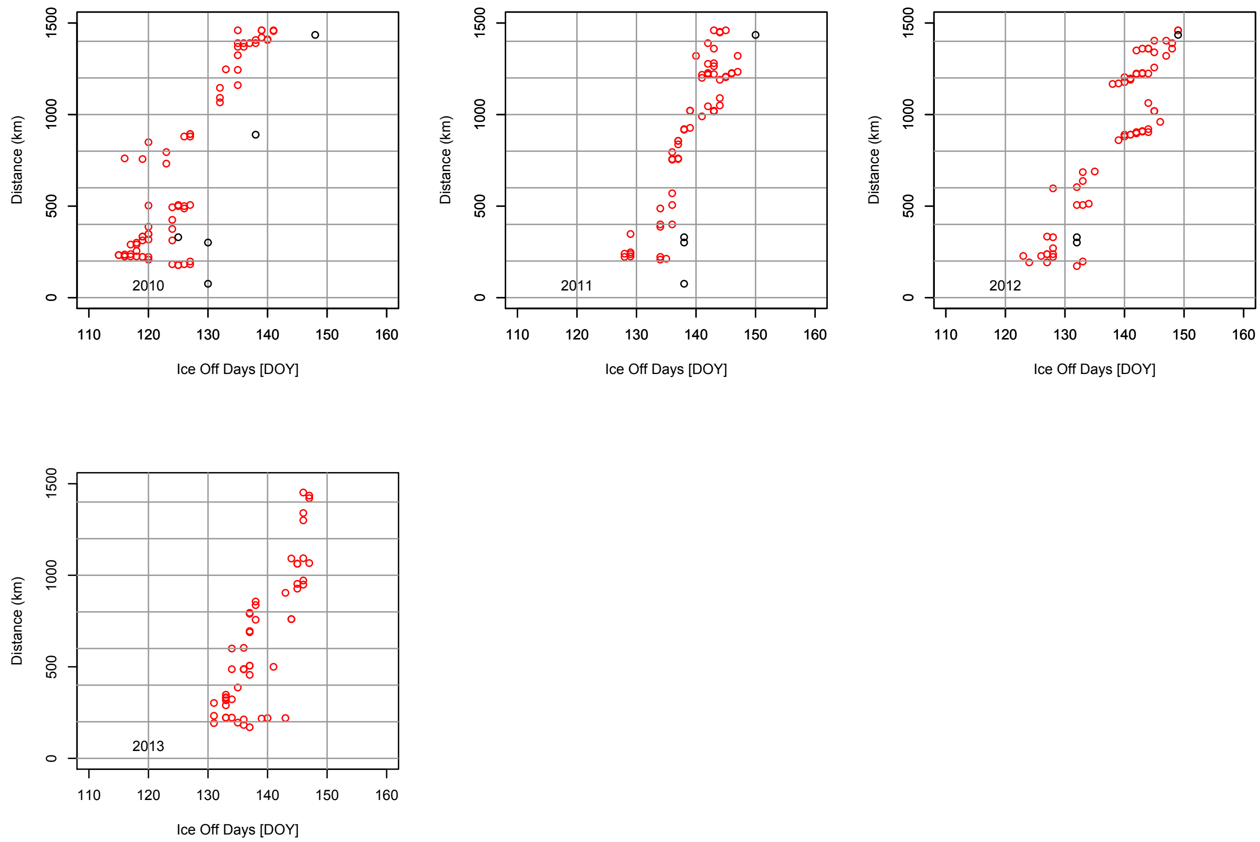


Figure 3.2: Estimated ice-off dates as illustrated by the red circles between 2001-2013 on the MR. Terra observations were made throughout the study period, while Aqua observations were available from 2003-onward. Black circles are indicative of WSC ice observation dates.

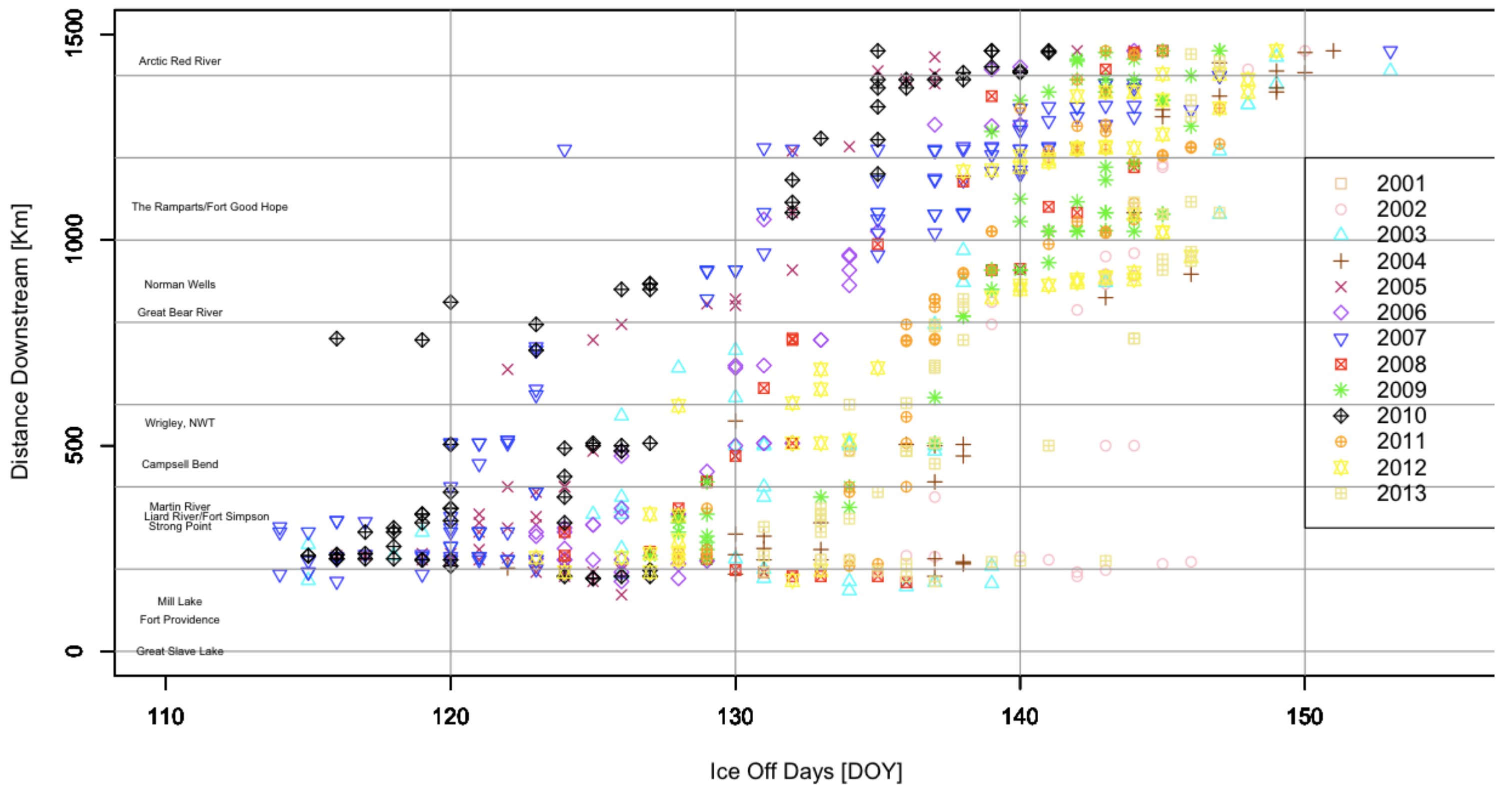


Figure 3.3: Compilation of all ice-off dates from 2001 to 2013 DOY [Day of Year] on the MR. First ice break-up dates generally began near 325 km. Ice break-up processes are more protracted just south of 325 km as seen with the higher density of measurements. Near 1078 km, a second channel constriction is present giving rise to two distinct ice-run patterns.

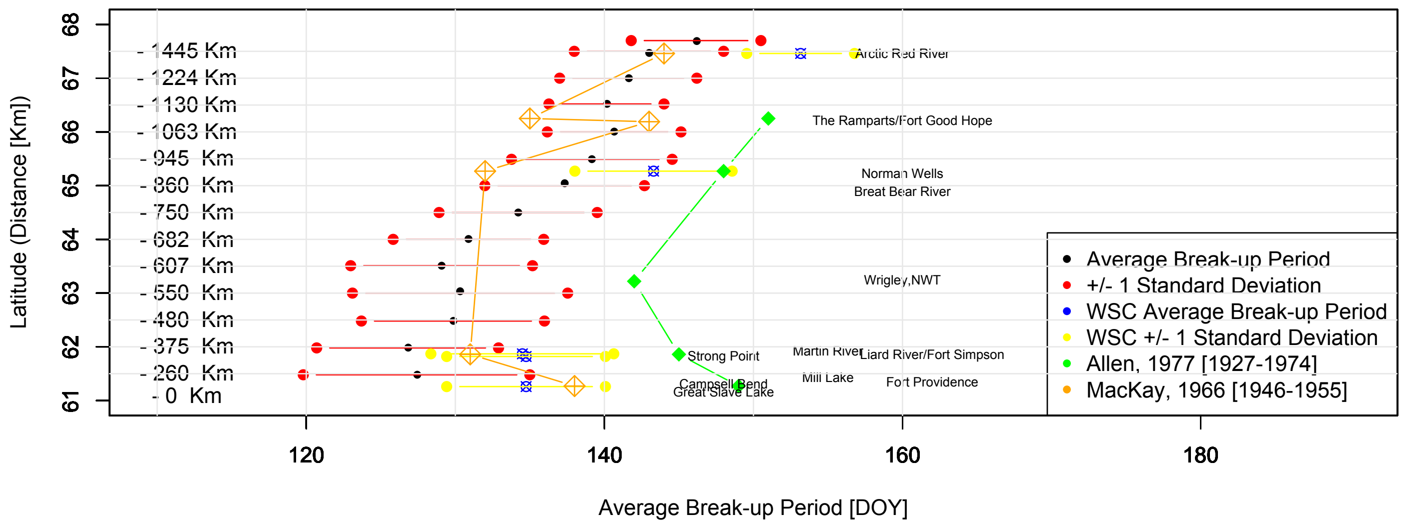


Figure 3.4: Average ice break-up dates estimated from MODIS (2001-2013) are given by the black dots, with ± one standard deviation showed with the red dots. The blue dots illustrate the WSC average ice break-up dates and the yellow dots ±one standard deviation. The green and orange dots represent average ice break-up dates from Allen (1977) from the time period of 1927 to 1975 and MacKay (1966) from the time period of 1946 to 1955, respectively.

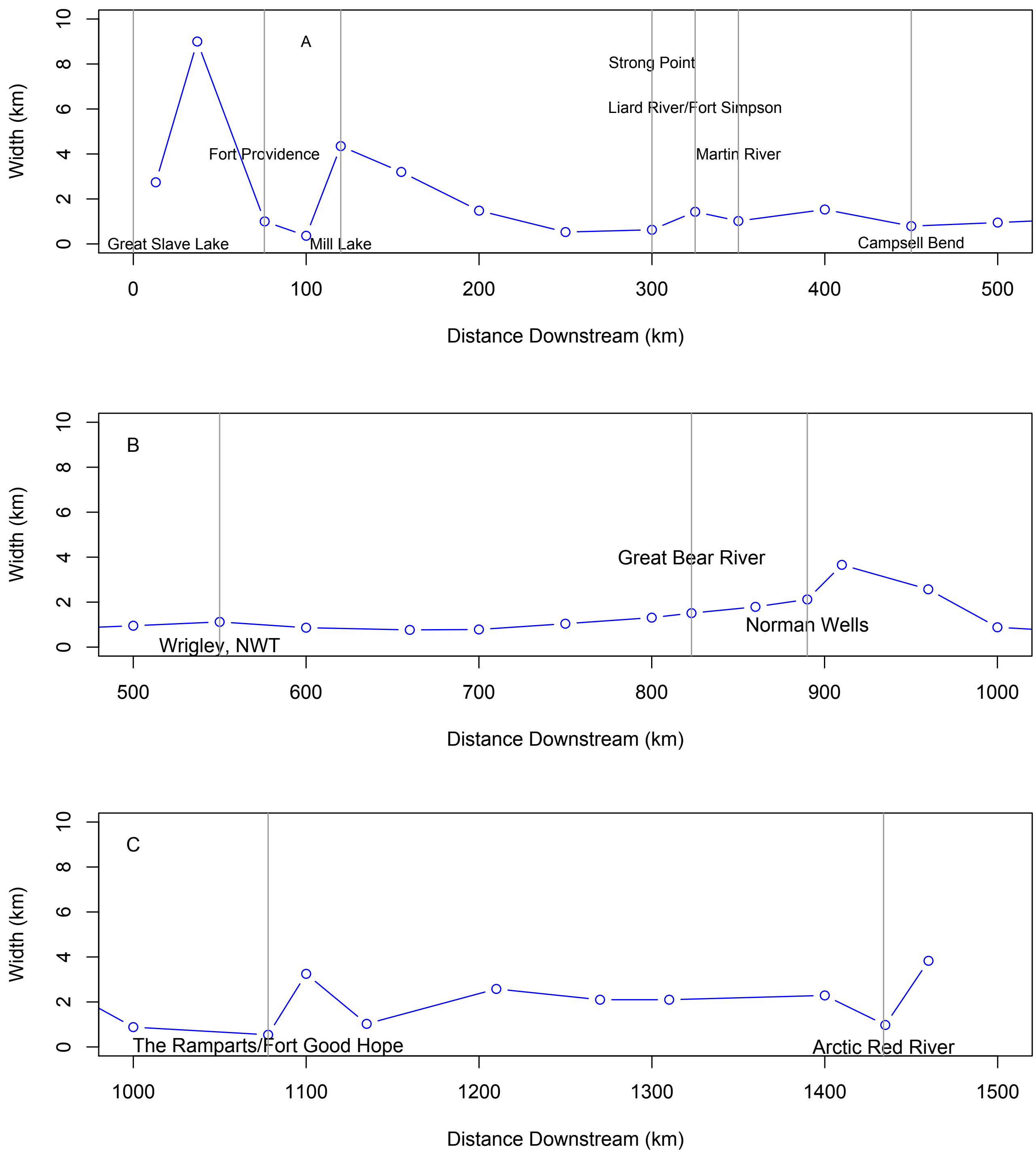
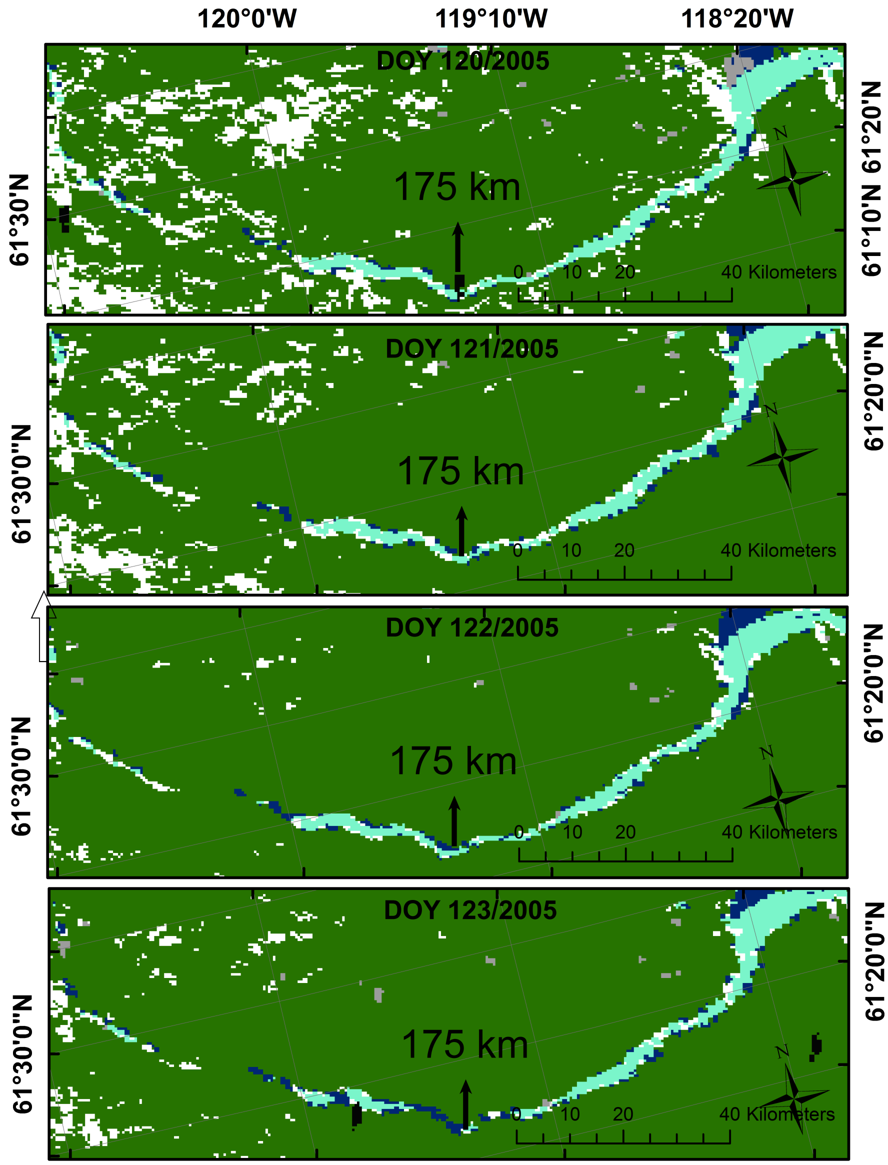


Figure 3.5: Observation of the change in channel width on the Mackenzie River, NWT as observed in A, B and C.



120°0'W
119°10'W
118°20'W
DOY 120/2005
175 km
0
10
20
40 Kilometers
61°30'N
61°10'N 61°20'N
DOY 121/2005
61°30'0"N
61°20'0"N
DOY 122/2005
DOY 123/2005

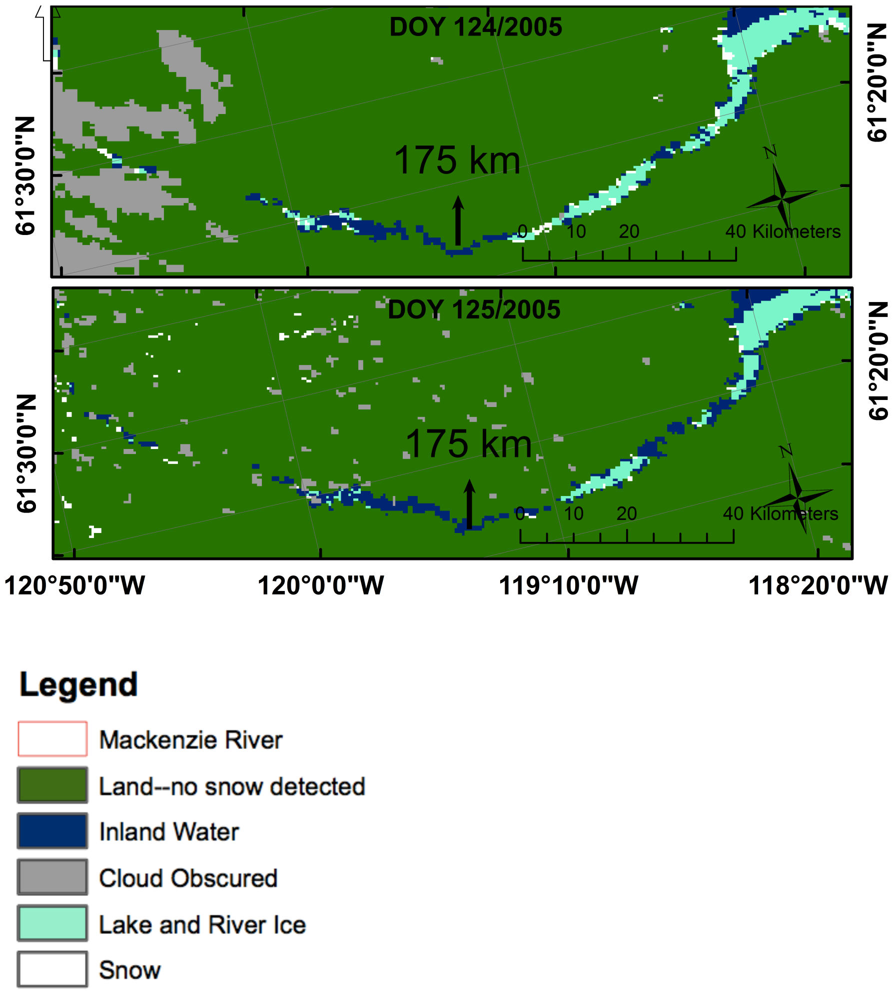


Figure 3.6: This example illustrates ice break-up at the headwaters of the Mackenzie River system in 2005 from DOY 120 - 125.

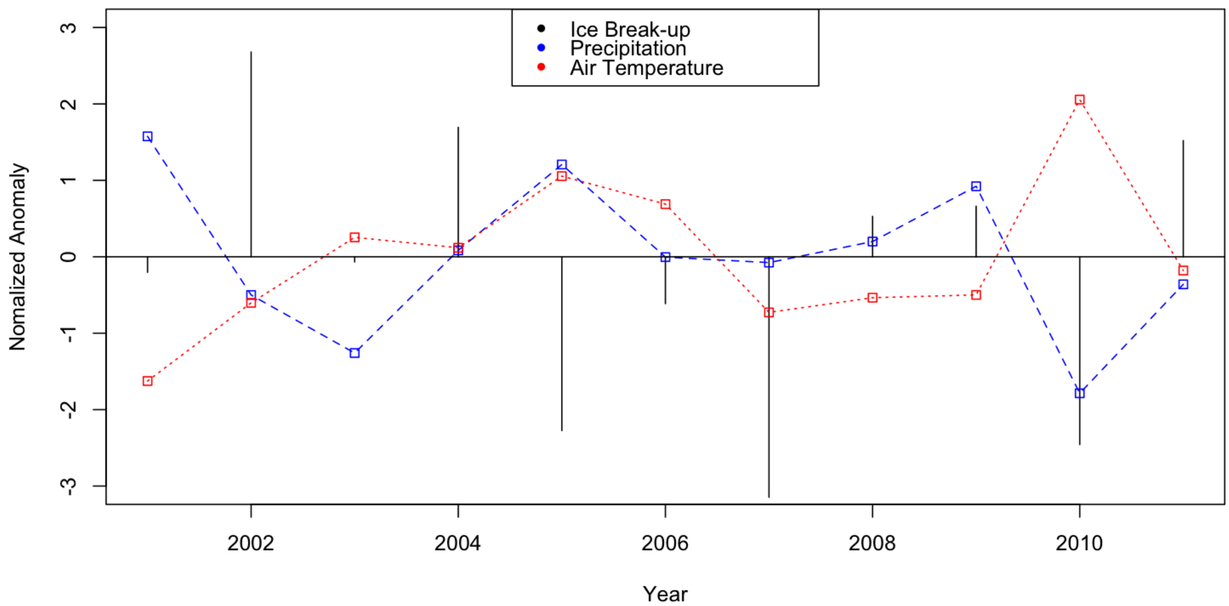


Figure 3.7: Normalized anomalies of ice break-up dates estimated with MODIS (black lines), together with precipitation (blue dots) and air temperature (red squares) determined from ERA monthly means (January to March) for the period 2001-2011. The average ice break-up date is DOY 128 at 62.5 °N, precipitation is 314.1 mm and air temperature is -14.4 °C.

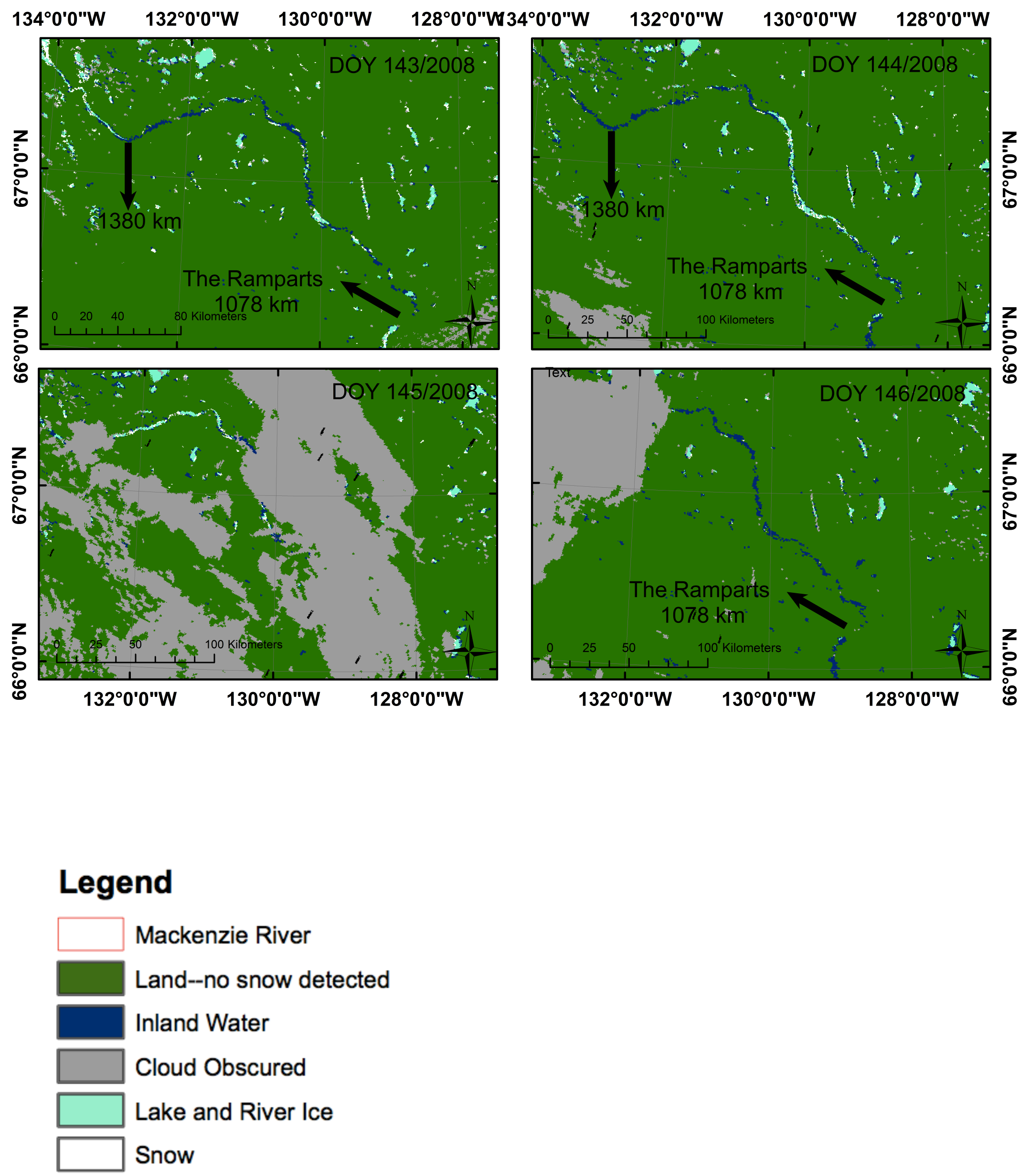


Figure 3.8: Ice flushing event recorded in 2008 between DOY 143-146.

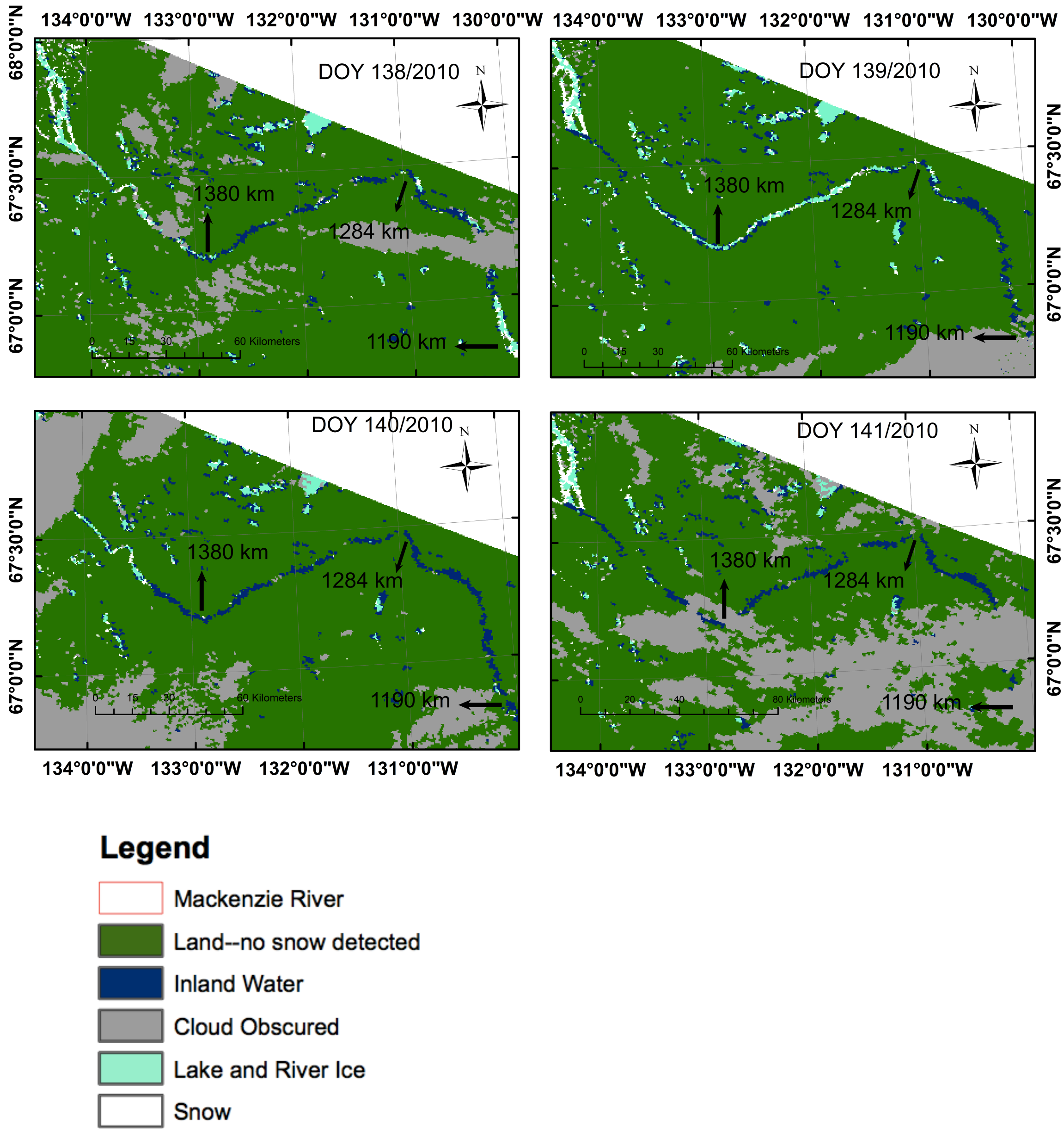
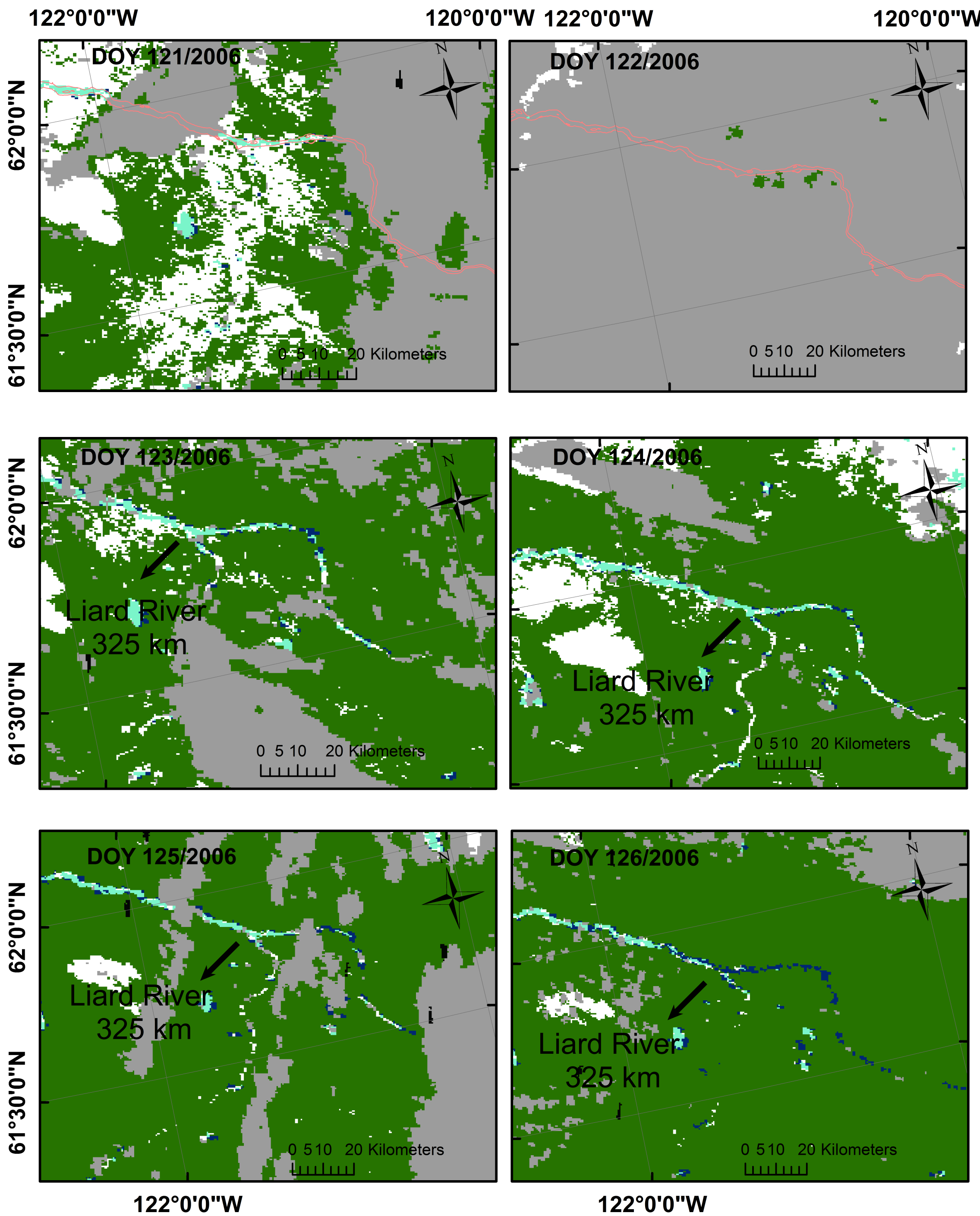


Figure 3.9: Ice flushing event recorded in 2010 between DOY 138-141. Here, on DOY141, the ice movement is last recorded after existing into the Mackenzie Delta.



122°0'0"W
120°0'0"W
62°0'0"N
61°30'0"N
DOY 121/2006
0 5 10 20 Kilometers
DOY 122/2006
DOY 123/2006
Liard River
325 km
DOY 124/2006
DOY 125/2006
DOY 126/2006
N

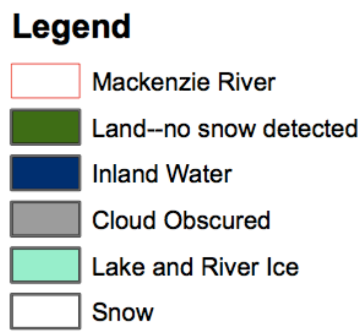
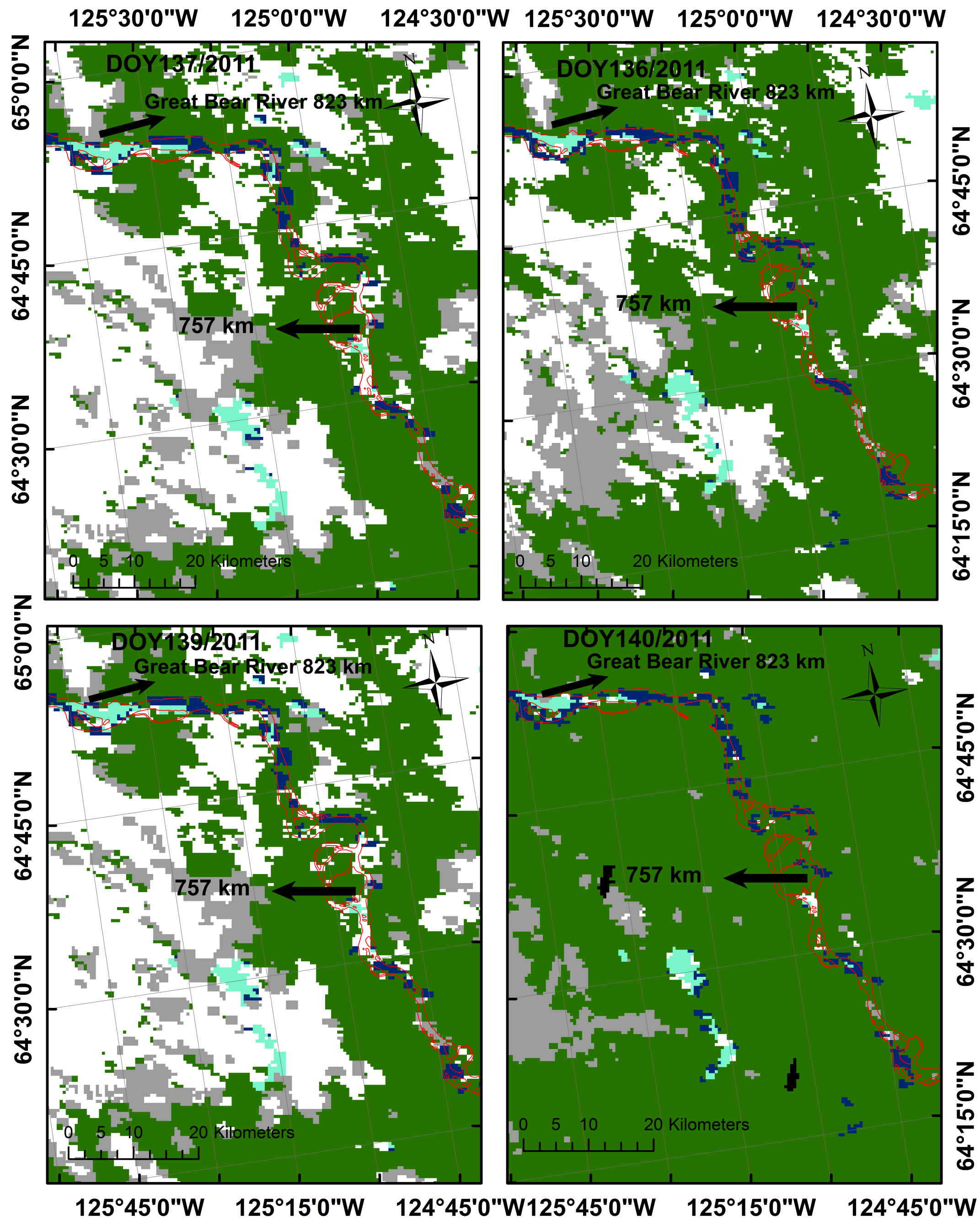


Figure 3.10: As example of thermodynamic break-up, where ice within the river requires an extra 2-3 days to be cleared after snow has melted over the immediate drainage basin. This example was observed in 2006 between DOY 121-126.


125°30'0"W
125°0'0"W
124°30'0"W
125°30'0"W
125°0'0"W
124°30'0"W
DOY137/2011
Great Bear River 823 km
757 km
0 5 10 20 Kilometers
DOY136/2011
Great Bear River 823 km
757 km
0 5 10 20 Kilometers
DOY139/2011
Great Bear River 823 km
757 km
0 5 10 20 Kilometers
DOY140/2011
Great Bear River 823 km
757 km
0 5 10 20 Kilometers
65°0'0"N
64°45'0"N
64°30'0"N
64°45'0"N
64°30'0"N
64°15'0"N
125°45'0"W
125°15'0"W
124°45'0"W
125°45'0"W
125°15'0"W
124°45'0"W

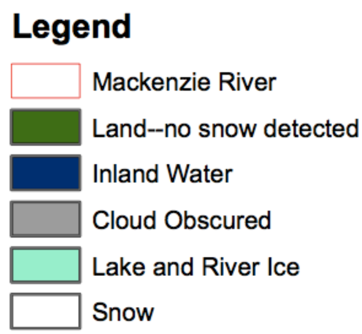
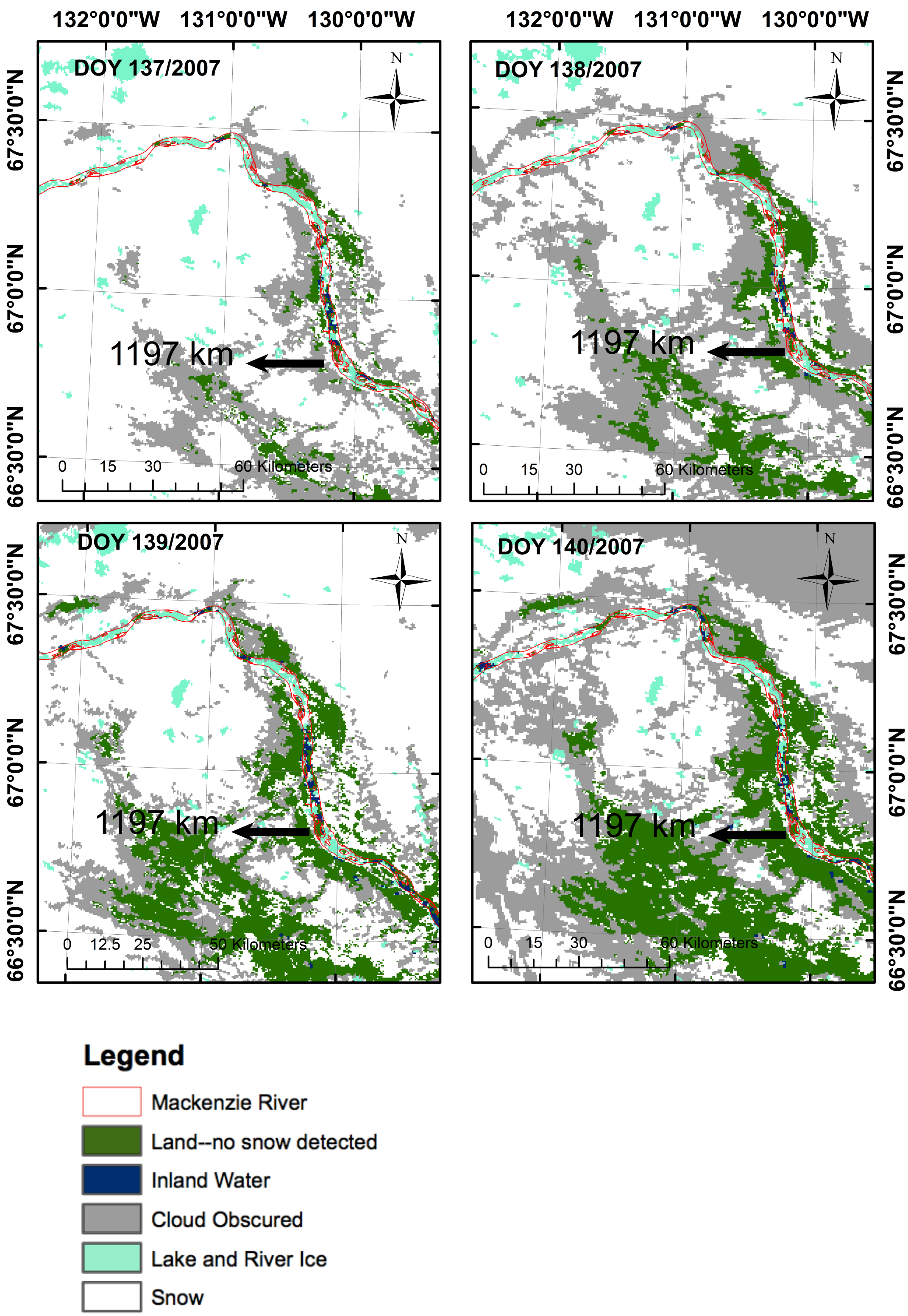


Figure 3.11: Snowmelt and ice run over the MRB in 2011 between the DOY 137-140. There is a 2-day lag between the complete clearance of snow on land and the clearance of ice on the Mackenzie River.



132°0'0"W
131°0'0"W
130°0'0"W
67°30'0"N
67°0'0"N
66°30'0"N
DOY 137/2007
DOY 138/2007
DOY 139/2007
DOY 140/2007
N
1197 km
0 15 30 60 Kilometers
0 12.5 25 50 Kilometers
Legend
Mackenzie River
Land--no snow detected
Inland Water
Cloud Obscured
Lake and River Ice
Snow

Figure 3.12: Observation of dynamic break-up over a section of the MRB, showing concurrent ice break-up and snowmelt over 6 days. This was observed in 2007 between DOY 137-142.

3.4 Discussion

3.4.1 Ice Break-up and Snowmelt Relations

In order to assess the relative timing of ice disappearance in relation to its surrounding sub-basin, the timing of river ice disappearance was qualitatively compared to the timing of near complete snow disappearance from the surrounding area. MODIS L3 imagery of different years was selected which clearly revealed ice-snow relations with respect to location, where cloud cover was a minimal issue. A similar methodology has also been completed previously (Chaouch et al., 2012), and supports the technique that it is possible to differentiate between ice-covered and ice-free pixels within a riverbed. Similarly the MODIS algorithm developed by Chaouch et al., [2012] was used over nine winter seasons and produced a probability of ice detection of 91% when compared to high resolution Landsat imagery.

Locations where thermodynamic ice disappearance was hypothesized (south of 61.8° N, 325 km) corresponded with patterns where ice disappeared much later than snow disappearance (Figure 3.6). For example, DOY 121/2006 (Figure 3.10) was observed to be the beginning of the snowmelt period at 290-487 km (61.75 ° N – 62.5 ° N) and this process ended when the snow had almost completely disappeared by DOY 125. However, with respect to the in-stream processes, DOY 125 and 126 was the initiation of ice break-up. This was not limited to 2006 so that snow generally disappeared sooner from surrounding sub-basins, followed by the initiation of ice-break-up.

At reaches north of the MR-Liard River confluence, ice break-up and snowmelt was observed to initiate in sync to one another. As seen in Figure 3.11, on DOY 136-137/2011, ice disappearance on the southern cross-section of the figure is marked by the near simultaneous disappearance of snow. In fact by DOY 140/2011 both ice and snow had completely disappeared analogous to each other. On sections of the Mackenzie River before it enters the Mackenzie Delta, estimated ice break-up and snow disappearance was again observed to occur almost simultaneous to one another (Figure 3.12). Over a 6-day period (DOY137-142/2007) ice break-up processes continued until ice completely disappeared from the channel. This process ensued sooner relative to complete snowmelt over the surrounding sub-basins. By DOY 142/2007 nearly one-third of the river was completely cleared of ice while most of the snow was still present over the MRB.

Principally, it was concluded that on the upper Mackenzie Basin snow cleared sooner than the initiation of ice break-up. In the mid-Mackenzie Basin (375-860 km, 62° N to 65° N), river ice cleared in-situ to snow clearance from the surrounding basin. In fact, ice cleared sooner in the mid basin than the upper Mackenzie Basin. Finally, in the lower Mackenzie Basin, river ice cleared sooner than the snow from the surrounding basin. This could be telling of a river continuum of the build-up of mechanical strength used to clear river ice within the Mackenzie River towards higher latitudes. The Liard River tributary accounts for one third of the total Mackenzie discharge (Woo and Thorne, 2003a), and so a rise in discharge in May initiates earlier ice break-up downstream as a result of increased stress induced on ice by a rise in river stage. Mechanical stress used to shove ice is continually magnified by the addition of small and large tributaries downstream of the Mackenzie River (Great Slave River, Arctic Red River).

Similar processes have also been observed on the Susquehanna River, USA, where an observed increase in discharge downstream foster earlier ice break-up while sections of upper river remain ice covered (Chaouch et al., 2012). The severity of ice break-up stage is therefore largely controlled by upstream discharge (Goulding et al., 2009b). Pavelsky and Smith (Pavelsky and Smith, 2004) also observed irregularities in ice break-up timing between years, particularly at 325 km (MR-Liard confluence) on the MR. Here, ice break-up began earlier at distances north of 325 km (61.8° N) than river sections south. Postponed ice break-up in the upper Mackenzie can result from the lack of discharge required to initiate ice break-up and so the ice is thermodynamically disintegrated.

3.4.2 Spatial and Temporal Ice Break-up Patterns

Over the 13-year period, the average estimated ice break-up dates were found to range between DOY 115-155 between distances 60 km and 1460 km. These estimates from MODIS are in agreement with break-up dates reported by the WSC ground-based network. Previous studies on the MR, between the late 1930's to 2002, have found the initiation of ice break-up to range DOY 123-140 between 0 km and 1217 km (de Rham et al., 2008a). Furthermore, it was reported by de Rham (2007) that the duration of average ice break-up ranged from 8-10 days over the entire basin. With respect to the findings reported in Figure 3.4, the observed ice-break-up patterns agree, such that the average observed break-up dates over the 13-year period ranged from DOY 128 ± 8 days at 61.5° N (260 km) to 145 ±4 days at 68° N (1460 km). Others have reported, using MODIS and AVHRR imagery acquired between 1992 and 2002, that ice break-up ranged between DOY 120 and 155 (Pavelsky and Smith, 2004). The earliest reports of mean ice break-up dates ranged from May 15 (DOY 135) to May 25 (145) (1946-1955 averages), from Fort Providence to Arctic Red River, respectively (MacKay, 1966). Furthermore, others have reported a range of ice break-up dates from May 22 (DOY 142) to May 31 (DOY 151) (1927-1974, Figure 2.2) from Fort Providence to Fort Good Hope, NWT, respectively (Allen, 1977).

In the headwaters of the Mackenzie River, ice break-up initiates the earliest between Mill Lake (120 km, 61.43° N) and Martin River (345 km, 61.92° N). As seen in Figures 3.2 - 3.4, ice break-up between 120-300 km initiated earlier as compared to other sites on the Mackenzie River, but ice cleared later than other for other river sections downstream. Here ice in the channel remains stagnant for extended periods of time as ice usually freezes to bed and is most susceptible to thermodynamic melt (MacKay and Mackay, 1973).

Furthermore, at the Liard River confluence (325 km, 61.84° N) it was found that the seasonal initiation of ice break-up began and cleared earliest at this central location where the Liard River converges into the MR. Others (Pavelsky and Smith, 2004) have noted that at the MR-Liard River confluence flooding is common between years, especially near channel junction. Ice break-up at the Liard River confluence occurs rapidly, as the flow contribution is of greater magnitude than the Mackenzie River (MacKay and Mackay, 1973). This causes a lifting of the river stage, exerting pressure on the ice cover resulting in ice jam downstream most attributed to presence of channel bending (Camsell Bend, 456 km) and channel constriction.

Channel morphology is therefore, a more important control on ice break-up patterns than previously believed. Both Pavelsky and Smith (Pavelsky and Smith, 2004) and de Rham et al. (de Rham et al., 2008a) alluded to the fact that channel morphology may exert influences on the patterns of ice break-up. In this study, it is determined that channel constriction at 350-682 km (61.96-64 ° N) and 1078 km (The Ramparts) is responsible for the delay of ice break-up timings upstream while promoting earlier ice break-up downstream. Upstream of the Liard River junction, river flow is stable. However, excessive discharge supplied by the Liard River causes earlier ice break-up and ice jamming downstream when the channel constricts between 350-682 km (MacKay and Mackay, 1973). Furthermore, excess supply of ice cover from the Great Bear River (821 km) into the Mackenzie River, causes the development of ice jamming at The Ramparts when the channel width decreases from over 3.5 km to less than 0.6 km (as seen in Figure 3.5) (MacKay and Mackay, 1973).

These processes gave rise to similar sequences of ice-off observations, which occurred in tandem at two different latitudes, north and south of the ice jam (as seen at The Rampart). Ice jams are therefore favorable where morphological features impede downstream ice passage (Beltaos, 1997). These ice jams are caused by channel constriction resulting from mid-channel islands and narrow reaches (Terroux et al., 1981). Channel braiding, constriction and changes in slope have also been reported to be important factors influencing ice break-up and flow regimes (de Rham et al., 2008a). In the context of our study, it was found that channel constrictions and bends represented localtions where ice runs were impeded. Hicks (2009) also reported that running ice may be stalled when geometric constraints such as tight bends, narrow sections and islands are present in rivers. In fact, it has been shown that ice debris flow drop to a velocity of zero in the presence of flow depths near channels islands and bars (Kääb et al., 2013). Lastly, Kääb and Prowse (2011), using ALOS PRISM stereo imagery on the

Mackenzie River determined that ice velocities decrease to zero in the presence of bars.

The estimated ice run events illustrated in Figures 3.7 and 3.8 may have been caused by ice jam releases (javes) initiated at The Rampart (1078 km, 66.19° N). Such processes may also be the reason why ice was estimated to be cleared at higher latitudes before the end of the snowmelt period. Accumulated stress with the rise of water levels behind the jam can result in sufficient kinetic energy to clear river ice downstream before the complete snowmelt overlying the surrounding sub-basins.

3.4.3 Ice Velocities

Ice run velocities are believed to be the highest where the ice is minimally effected by channel morphology; unconnected from incoming tributaries; and channel splitting which causes the formation of islands (Kääb et al., 2013). Amongst the variety of ice runs observed over the 13 years, ice velocities could be quantified in 2008 and 2010. Over 3-4 day period, average ice velocities were estimated to be 1.21 ms^{-1} and 1.84 ms^{-1}, respectively. More importantly, it is believed that the evolution of such velocities is a product of javes. Our measurements of ice run velocity in 2008 coincidently synchronize with other independent ice measurement by satellite and ground measurements. Extensive measurements of ice runs in 2008 around MR-Arctic Red River junction is believed to be generated by waves released from released ice-jams (Beltaos, 2013). This aligns with ice jams, which may form at The Rampart (1078 km, 66.19° N) as a result of channel constriction. The evolution of ice runs north of The Rampart (flowing past the Arctic Red River) observed over DOY 143-146/2008 (May 22-25 / 1.21 ms^{-1}) matches similar ground measurements (1.7 ms^{-1}) made by Beltaos et al. (2012). Across the same cross-section of the MR, Kääb and Prowse (with imagery acquired 1-2 days earlier in 2008) estimated a preceding ice run ranging from 0 - 3.2 ms^{-1}. The highest flow velocities were outlined where ice debris flow was most concentrated on the outside turn of the river bend. Finally, in another independent study, Beltaos and Kääb (2014) found ice debris velocities to range between 1-2 ms^{-1} using ALOS PRISM imagery in 2010. Again these high-resolution (2.5-m) image measurements compare quite well with our coarse (250-500 m) MODIS imagery. Additional, early investigations have reported that ice cleared at velocities of 0.27 ms^{-1} and 0.44 ms^{-1} at Fort Simpson and Fort Good Hope, respectively during the ice break-up season (Terroux et al., 1981).

MODIS was shown to be a viable tool to measure river ice velocities. However, this study found that certain preconditions are required to use MODIS to its fullest extent. With respect to the MR, ice velocities were only quantifiable above The Rampart. The presence of morphological controls and therefore river width shortening leading to impeded ice run prevented quantifying velocities, as leading river-ice demarcations were difficult to locate. However, it was possible to estimate the overall velocity by observing ice-open-water boundaries. Lastly, it was determined that in order to measure ice run velocities without major disturbance with impeded flows with respect to river morphology, estimates with MODIS should be made north of The Rampart. North of The Rampart river widths were generally observed to be largest with respect to other parts of the MR.

3.5 Conclusion

The aim of this study was to develop an approach to estimate ice break-up dates on the Mackenzie River over more than a decade using MODIS snow and radiance products. It was found that the initiation of ice break-up started on average between DOY 115-125 and ended DOY 145-155 over the 13 years analyzed. Thermal ice break-up was an important process driving ice break-up south of the Liard River. Conversely, north of he Liard, ice break-up was dynamically driven. The addition to discharge from the MR-Liard River confluence outlined a location where initial ice break-up began. Furthermore, morphological controls such as channel bars, river meandering and channel constriction were found to be important factors controlling ice runs and ice break-up.

MODIS is currently the most promising tool for near real-time monitoring of river ice processes as monitoring stations along the Mackenzie River are continuously being closed. Operating aboard of two satellites (Aqua and Terra), the MODIS sensor allows for multiple daily acquisitions simultaneously along extensive stretches of the MR. Furthermore, MODIS is proving to be a viable sensor for the monitoring of river ice as shown in this and other recent investigations (e.g. Chaouch et al., 2012). In this study, monitoring of ice break-up on the Mackenzie River with MODIS proved to be a robust approach when compared to WSC ground-based observations. MODIS observations also allowed for the analysis of basin level processes influencing ice break-up, including river morphology and snowmelt.

Finally, future research should focus on investigating river ice processes using a combination of ground-based and satellite-based sensors; particularly for examining relations between river morphology, ice strength and discharge. Data from these complementary technologies would be valuable in the context of an early warning system for municipalities where river ice break-up is an important spring event causing significant flood damage. As an example, the 2014 Canadian spring thaw witnessed a variety of river ice related infrastructure damages, including the dislodgement of a bridge on the Canaan River ("Covered bridge floats away," n.d.). Furthermore, a multi-sensor approach using both optical and synthetic aperture radar (SAR) data would be advantageous in order to monitor ice river processes and floods in near real-time. Satellite data from recent and upcoming SAR (Sentinel-1 and Radarsat Constellation) and optical (Sentinel-2 and Sentinel-3) satellite missions will make such monitoring possible in the near future.

Chapter 4

General Conclusion

4.1 Summary and Conclusion

The focus of this research was to advance our current monitoring capabilities of river ice break-up on the Mackenzie River using MODIS data acquired by both NASA's Aqua and Terra satellite platforms. The onset of winter seasons on the Mackenzie River is classified by the presence of low flows and freeze-over conditions. Input of heat during the spring period initially serves to increase the temperature of snow and ice on the river to $0^{o}C$ until ice strength is compromised, promoting ice thinning and eventually ice break-up. Break-up plays an important role influencing local biota, sediment redistribution and most importantly seasonal water storage and redistribution on the river. Unfortunately, the number of hydrometric stations operated by the Water Survey of Canada (WSC) has constantly been declining on the MR.

Data from MODIS provided the opportunity to examine the potential of satellite remote sensing with relatively high temporal frequency for monitoring spring break-up on a large northern river. Together, MODIS snow products

(MOD10A1/MYD10A1) and MODIS Level 1b radiance products proved to be valuable for ice monitoring. This was clearly demonstrated in Chapter 3, which involved the analysis of river ice break-up on the Mackenzie River from MODIS for a 13-year period (2001-2013). The study revealed that average ice-off dates were observed between DOY 115-125 and 145-155 for an average ice break-up period of 30-40 days. The approach developed in this thesis was robust in distinguishing between ice and ice-free pixels, as demonstrated through a comparison with WSC HYDAT 'B' observations. In addition to allowing for the determination of average ice break-up dates from 2001-2013, MODIS was also shown to be a viable tool for estimating river ice velocities and morphological controls on the MR.

4.2 Study Limitations

There are a few limitations that were identified during the course of this study. Cloud cover was the most important issue to deal with when trying to monitor ice processes. To limit this problem, MODIS images from both Aqua and Terra were used across the same area during the same day as to increase the number of possible ice observations on a daily basis.

4.3 Suggestions for Future Work

New and exciting opportunities exist to advance our current state of knowledge of river ice processes in Canada and elsewhere. In particular, several recent and upcoming satellite missions will permit to explore the synergy of data acquired by both optical and synthetic aperture radar (SAR) sensors for near real-time river ice monitoring. Data from MODIS and Radarsat-2 could already be explored for their synergy as both systems are currently in orbit. Future satellite missions, including the Radarsat Constellation Mission of the Canadian Space Agency (to be launched in 2018), the Sentinel missions of the European Space Agency (first satellite launched in April 2014 with several more to follow this decade), and the US/French Surface Water and Ocean Topography (SWOT) mission (to be launched in 2020) will offer endless opportunities for studying ice processes, hydrology and flooding on northern rivers.

References

Abdul Aziz, O.I., Burn, D.H., 2006. Trends and variability in the hydrological regime of the Mackenzie River Basin. J. Hydrol. 319, 282–294. doi:10.1016/j.jhydrol.2005.06.039

Allen, W.T.R., 1977. Freeze-up, Break-up and Ice Thickness in Canada -: Embâcle, Débâcle Et Épaisseur de la Glace Au Canada. Environnement atmosphérique.

Beltaos, S., 1990. Guidelines for extraction of ice-breakup data from hydrometric station records. Field Stud. Res. Needs Science Report No. 2,.

Beltaos, S., 1997. Onset of river ice breakup. Cold Reg. Sci. Technol. 25, 183–196. doi:10.1016/S0165-232X(96)00011-0

Beltaos, S., 2007. River ice breakup processes: recent advances and future directions. Can. J. Civ. Eng. 34, 703–716. doi:10.1139/l06-021

Beltaos, S., 2008. Progress in the study and management of river ice jams. Cold Reg. Sci. Technol. 51, 2–19.

Beltaos, S., 2013. Hydrodynamic characteristics and effects of river waves caused by ice jam releases. Cold Reg. Sci. Technol. 85, 42–55. doi:10.1016/j.coldregions.2012.08.003

Beltaos, S., Carter, T., 2009. Field studies of ice breakup and jamming in lower Peace River, Canada. Cold Reg. Sci. Technol. 56, 102–114. doi:10.1016/j.coldregions.2008.11.002

Beltaos, S., Carter, T., Rowsell, R., 2012. Measurements and analysis of ice breakup and jamming characteristics in the Mackenzie Delta, Canada. Cold Reg. Sci. Technol. 82, 110–123.

Beltaos, S., Kääb, A., 2014. Estimating river discharge during ice breakup from near-simultaneous satellite imagery. Cold Reg. Sci. Technol. 98, 35–46.

Beltaos, S., Prowse, T., 2009. River-ice hydrology in a shrinking cryosphere. Hydrol. Process. 23, 122–144. doi:10.1002/hyp.7165

Beltaos, S., Rowsell, R., Tang, P., 2011. Remote data collection on ice breakup dynamics: Saint John River case study. Cold Reg. Sci. Technol. 67, 135–145. doi:10.1016/j.coldregions.2011.03.005

Bigras, S.C., 1990. Hydrological Regime of Lakes in the Mackenzie Delta, Northwest Territories, Canada. Arct. Alp. Res. 22, 163. doi:10.2307/1551301

Bonsal, B.R., Prowse, T.D., 2003. Trends and variability in spring and autumn 0 °C-isotherm dates over Canada. Clim. Change 57, 341–358. doi:10.1023/A:1022810531237

Brown, R.D., Derksen, C., 2013. Is Eurasian October snow cover extent increasing? Environ. Res. Lett. 8, 024006. doi:10.1088/1748-9326/8/2/024006

Brown, R.S., Power, G., Beltaos, S., Beddow, T.A., 2000. Effects of hanging ice dams on winter movements and swimming activity of fish. J. Fish Biol. 57, 1150–1159. doi:10.1111/j.1095-8649.2000.tb00477.x

Brown, R.S., Stanislawski, S.S., Mackay, W.C., 1994. Effects of frazil ice on fish, in: Workshop on Environ. Aspects of River Ice, Saskatoon, Canada, Enir. Canada, National Hydrology Research Institute.

Chaouch, N., Temimi, M., Romanov, P., Cabrera, R., McKillop, G., Khanbilvardi, R., 2012. An automated algorithm for river ice monitoring over the Susquehanna River using the MODIS data. Hydrol. Process. n/a–n/a. doi:10.1002/hyp.9548

Church, M., 1974. Hydrology and permafrost: With reference to northern North America.

Covered bridge floats away [WWW Document], n.d. . CBCca Play. URL /player/News/Canada/NB/ID/2449841279/ (accessed 5.25.14).

Dean, K.G., Stringer, W.J., Ahlnäs, K., Searcy, C., Weingartner, T., 1994. The influence of river discharge on the thawing of sea ice, Mackenzie River Delta: albedo and temperature analyses. Polar Res. 13, 83–94. doi:10.3402/polar.v13i1.6683

De Rham, L.P., Prowse, T.D., Beltaos, S., Lacroix, M.P., 2008a. Assessment of annual high-water events for the Mackenzie River basin, Canada. Hydrol. Process. 22, 3864–3880. doi:10.1002/hyp.7016

De Rham, L.P., Prowse, T.D., Bonsal, B.R., 2008b. Temporal variations in river-ice break-up over the Mackenzie River Basin, Canada. J. Hydrol. 349, 441–454. doi:10.1016/j.jhydrol.2007.11.018

Gauthier, Y., El Battay, A., Bernier, M., Ouarda, T., 2003. An Approach Using Contextual Analysis to Monitor River Ice from RADARSAT Data, in: Eastern Snow Conference. p. 151.

Goñi, M.A., Yunker, M.B., Macdonald, R.W., Eglinton, T.I., 2000. Distribution and sources of organic biomarkers in arctic sediments from the Mackenzie River and Beaufort Shelf. Mar. Chem. 71, 23–51. doi:10.1016/S0304-4203(00)00037-2

Goulding, H.L., Prowse, T.D., Beltaos, S., 2009a. Spatial and temporal patterns of break-up and ice-jam flooding in the Mackenzie Delta, NWT. Hydrol. Process. 23, 2654–2670. doi:10.1002/hyp.7251

Goulding, H.L., Prowse, T.D., Bonsal, B., 2009b. Hydroclimatic controls on the occurrence of break-up and ice-jam flooding in the Mackenzie Delta, NWT, Canada. J. Hydrol. 379, 251–267. doi:10.1016/j.jhydrol.2009.10.006

Government of Canada, E.C., 2007a. Environment Canada - Water - About the Water Survey of Canada [WWW Document]. URL http://ec.gc.ca/rhc-wsc/default.asp?lang=En&n=EDA84EDA-1 (accessed 9.6.14).

Government of Canada, E.C., 2007b. Environment Canada - Water - Rivers [WWW Document]. URL http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=45BBB7B8-1 (accessed 6.7.14).

Government of Canada, E.C., 2010a. Environment Canada - Water - Environment Canada Data Explorer [WWW Document]. URL http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=0A47D72F-1 (accessed 3.27.13).
Government of Canada, E.C., 2010b. Environment Canada - Water - Environment Canada Data Explorer [WWW Document]. URL http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=0A47D72F-1 (accessed 3.27.13).
Hall, D.D.K., Riggs, D.G.A., Salomonson, D.V.V., 2006. MODIS Snow and Sea Ice Products, in: Qu, P.J.J., Gao, D.W., Kafatos, P.M., Murphy, D.R.E., Salomonson, D.V.V. (Eds.), Earth Science Satellite Remote Sensing. Springer Berlin Heidelberg, pp. 154–181.
Hicks, F., 2009. An overview of river ice problems: CRIPE07 guest editorial. Cold Reg. Sci. Technol. 55, 175–185.
Hicks, F., Cui, W., Ashton, G., 2008. River ice breakup: Chapter 4, Heat Transfer and ice cover decay. Water Resources Pubns, Highlands Ranch, Colorado.
Hicks, F.E., Cui, W., Andres, D.D., Territories, N., 1995. Forecasting breakup on the Mackenzie River at the Ft. Providence Ferry Crossing. University of Alberta.
Jasek, M., Marko, J., Fissel, D., Clarke, M., Buermans, J., Paslawski, K., 2005. Instrument for detecting freeze-up, mid-winter and break-up ice processes in rivers, in: Proc. 13th Workshop on River Ice. CGU-HS CRIPE, Hanover. pp. 151–183.
Kääb, A., Lamare, M., Abrams, M., 2013. River ice flux and water velocities along a 600 km long reach of Lena River, Siberia, from satellite stereo. Hydrol. Earth Syst. Sci. Discuss. 10, 9967–9997.
Kääb, A., Prowse, T., 2011. Cold-regions river flow observed from space. Geophys. Res. Lett. 38, L08403. doi:10.1029/2011GL047022
Kowalczyk Hutchison, T., Hicks, F.E., 2007. Observations of ice jam release waves on the Athabasca River near Fort Mcmurray, Alberta. Can. J. Civ. Eng. 34, 473–484.
Lacroix, M., Prowse, T., Bonsal, B., Duguay, C., Ménard, P., 2005. River ice trends in Canada. Proc. 13th Workshop Hydraul. Ice Cover. Rivers CGU HS Comm. River Ice Process. Environ. CRIPE Hanover N. H. 15–16.
Lenormand, F., Duguay, C.R., Gauthier, R., 2002. Development of a historical ice database for the study of climate change in Canada. Hydrol. Process. 16, 3707–3722.
Lock, G.S.H., 1990. The Growth and Decay of Ice. Cambridge University Press.
MacKay, D.K., 1966. Mackenzie River and Delta ice survey, 1965. Geogr. Bull. 8, 270–278.
MacKay, D.K., Mackay, J.R., 1973. Locations of Spring Ice Jamming on teh Mackenzie River, N.W.T. Environ.-Soc. Com. North. Pipelines Task Force North. Oil Dev. Rep. No 73-3 Technical Report 8.
Magnuson, J.J., Robertson, D.M., Benson, B.J., Wynne, R.H., Livingstone, D.M., Arai, T., Assel, R.A., Barry, R.G., Card, V., Kuusisto, E., Granin, N.G., Prowse, T.D., Stewart, K.M., Vuglinski, V.S., 2000. Historical trends in

lake and river Ice cover in the Northern Hemisphere. Science 289, 1743–1746. doi:10.1126/science.289.5485.1743

Marsh, P., Hey, M., 1994. Analysis of spring high water events in the Mackenzie Delta and implications for lake and terrestrial flooding. Geogr. Ann. Ser. Phys. Geogr. 76, 221–234.

Marsh, P., Prowse, T.D., 1987. Water temperature and heat flux at the base of river ice covers. Cold Reg. Sci. Technol. 14, 33–50. doi:10.1016/0165-232X(87)90042-5

Mermoz, S., Allain-Bailhache, S., Bernier, M., Pottier, E., Van Der Sanden, J.J., Chokmani, K., 2014. Retrieval of river Ice thickness from C-Band PolSAR data. IEEE Trans. Geosci. Remote Sens. 52, 3052–3062. doi:10.1109/TGRS.2013.2269014

Michel, B., 1992. Limit equilibrium of ice jams. Cold Reg. Sci. Technol. 20, 107–117.

Nghiem, S.V., Hall, D.K., Rigor, I.G., Li, P., Neumann, G., 2014. Effects of Mackenzie River discharge and bathymetry on sea ice in the Beaufort Sea. Geophys. Res. Lett.

Pavelsky, T.M., Smith, L.C., 2004. Spatial and temporal patterns in Arctic river ice breakup observed with MODIS and AVHRR time series. Remote Sens. Environ. 93, 328–338. doi:10.1016/j.rse.2004.07.018

Province of Manitoba, E.C., 2011. Manitoba - Flood Information [WWW Document]. URL http://www.gov.mb.ca/flooding/historical_facts.html (accessed 6.11.14).

Prowse, T., 2001. River-ice ecology. I: Hydrologic, geomorphic, and water-quality aspects. J. Cold Reg. Eng. 15, 1–16. doi:10.1061/(ASCE)0887-381X(2001)15:1(1)

Prowse, T. d., 1994. Environmental significance of ice to streamflow in cold regions. Freshw. Biol. 32, 241–259. doi:10.1111/j.1365-2427.1994.tb01124.x

Prowse, T.D., Beltaos, S., 2002. Climatic control of river-ice hydrology: a review. Hydrol. Process. 16, 805–822. doi:10.1002/hyp.369

Prowse, T.D., Carter, T., 2002. Significance of ice-induced storage to spring runoff: a case study of the Mackenzie River. Hydrol. Process. 16, 779–788. doi:10.1002/hyp.371

Prowse, T.D., Marsh, P., 1989. Thermal budget of river ice covers during breakup. Can. J. Civ. Eng. 16, 62–71. doi:10.1139/l89-008

Riggs, G.A., Barton, J.S., Casey, K.A., Hall, D.K., Salomonson, V.V., 2000. MODIS snow products users' guide. NASA GSFC.

Scrimgeour, G.J., Prowse, T.D., Culp, J.M., Chambers, P.A., 1994. Ecological effects of river ice break-up: a review and perspective. Freshw. Biol. 32, 261–275. doi:10.1111/j.1365-2427.1994.tb01125.x

Shen, H.T., Liu, L., 2003. Shokotsu River ice jam formation. Cold Reg. Sci. Technol. 37, 35–49. doi:10.1016/S0165-232X(03)00034-X

Shiklomanov, A.I., Lammers, R.B., 2014. River ice responses to a warming Arctic—recent evidence from Russian rivers. Environ. Res. Lett. 9, 035008. doi:10.1088/1748-9326/9/3/035008
Stewart, R.E., Crawford, R.W., Leighton, H.G., Marsh, P., Strong, G.S., Moore, G.W.K., Ritchie, H., Rouse, W.R., Soulis, E.D., Kochtubajda, B., 1998. The Mackenzie GEWEX Study: The water and energy cycles of a major North American river basin. Bull. Am. Meteorol. Soc. 79, 2665–2683.
Terroux, A.C.D., Sherstone, D.A., Kent, T.D., Anderson, J.C., Bigras, S.C., Kriwoken, L.A., 1981. Ice Regime of the Lower Mackenzie River and Mackenzie Delta. Environ. Can. Natl. Hydrol. Res. Inst.
Unterschultz, K.D., van der Sanden, J., Hicks, F.E., 2009. Potential of RADARSAT-1 for the monitoring of river ice: Results of a case study on the Athabasca River at Fort McMurray, Canada. Cold Reg. Sci. Technol. 55, 238–248. doi:10.1016/j.coldregions.2008.02.003
White, K.D., Hicks, F., Beltaos, S., Loss, G., 2007. Ice jam response and mitigation: the need for cooperative succession planning and knowledge transfer, in: Proc. 14th Workshop on River Ice. pp. 20–22.
Woo, M.-K., 2008. Cold region atmospheric and hydrologic studies the Mackenzie gewex experience. Springer.
Woo, M.-K., Thorne, R., 2003a. Streamflow in the Mackenzie Basin, Canada. ARCTIC 56, 328–340.
Woo, M.-K., Thorne, R., 2003b. Streamflow in the Mackenzie Basin, Canada. ARCTIC 56, 328–340.