

ARTICLE

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Monitoring the freeze-up and ice cover progression of the Slave River¹

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Abstract: River ice is an important component to maintain traditional and cultural lifestyles for the peoples along the Slave River in the Northwest Territories. During the winter a stable ice cover provides a vital transportation link to hunting, trapping, and fishing areas along the river. However, little was known about the Slave River ice cover characteristics and behaviour during the freeze-up and ice cover progression period. RADARSAT-2 satellite and time-lapse camera imagery were used in this study to document the different types of ice and understand the mechanisms of ice cover formation progression along the river during the course of winter. Time-lapse images were analyzed to observe the frazil ice generation and patterns of stable ice cover formation of the Slave River near Fort Smith during freeze-up. RADARSAT-2 images acquired from the Slave River Delta areas captured ice cover flooding due to higher river flows in mid-winter. Field surveys along the river provided insights about the ice cover growth in various sections along the river. Air pockets and layers under the ice cover were also detected during the ice surveys. The variation of water flows during the winter has a great impact on the Slave River ice regime. Increases in discharge cause the ice cover to crack or dislodge from the river banks leading to water seeping onto the ice and flooding it, which has implications for muskrat and beaver populations.

Key words: Slave River, river ice freeze-up, RADARSAT-2 satellite imagery, time-lapse imagery.

Résumé : La glace de rivière est un élément essentiel au maintien des modes de vie traditionnels et culturels des populations vivant le long de la rivière des Esclaves, dans les Territoires du Nord-Ouest. Durant l'hiver, une couverture de glace stable fournit un lien de routier vital menant aux zones de chasse, de trappe et de pêche situées le long de la rivière. Cependant, on méconnaissait jusqu'ici les caractéristiques et le comportement de la couverture de glace de la rivière des Esclaves durant la période d'englacement et de formation de cette couverture. Les images fournies par le satellite RADARSAT-2 et à l'aide d'appareils de prise de vues en accéléré ont été utilisées dans la présente étude pour répertorier les différents types de glace et comprendre les mécanismes de formation et de progression de la couverture de glace le long de la rivière durant toute la période hivernale. Les images en accéléré ont été analysées et ont permis d'observer l'apparition du frasil et les motifs de formation de la couverture de glace stable sur la rivière des Esclaves à proximité de Fort Smith durant la période d'englacement. Les images de la région du delta de la rivière des Esclaves provenant du satellite RADARSAT-2 ont mis en évidence un débordement de la couverture de glace au-delà du lit de la rivière en raison des crues se produisant au milieu de l'hiver. Des études de terrains effectuées le long de la rivière ont permis de mieux comprendre la croissance de la couverture de glace dans différentes portions du cours d'eau. Des poches et couches d'air situées sous la couverture de glace ont été également repérées au cours des études de la glace. Les variations du débit de la rivière pendant l'hiver ont de fortes répercussions sur le régime des glaces de la rivière des Esclaves. En raison des augmentations de débit, la couverture de glace se fissure et se détache des rives, l'eau s'écoulant alors au-dessus de la glace et recouvrant celle-ci, ce qui a des conséquences sur les populations de rat musqué et de castor. [Traduit par le Rédaction]

Mots-clés : rivière des Esclaves, englacement de la rivière, images du satellite RADARSAT-2, images en accéléré.

Introduction

Ice constitutes an important control on the flow regime of a river in winter. Ice along northern rivers can be an important component to the traditional and cultural lifestyles of indigenous peoples as the ice provides transportation links to hunting, trapping, and fishing areas. Changes in the ice regime can impact and even alter these traditional lifestyles.

The construction of the W.A.C. Bennet Dam on the upper Peace River has significantly altered the flow regime of the Slave River by modulating the flow hydrograph over the course of a year (lower flood peaks in summer and higher discharges in winter). These changes in the flow regime have also imposed changes on the ice cover characteristics during winter. For example, air pockets underneath the ice cover and double ice layers, with air and water sandwiched between the top and bottom ice layers, can create a major hindrance to travel and fishing for the Slave River communities (AANDC and ENR 2012). Periodic winter kills of muskrat and beaver populations along the Slave River are also attributable to ice cover flooding since the additional ice layer on top of the ice cover can trap and drown the animals in their overwintering shelters. Open water sections on the river ice have also been observed, which were not common in the past (AANDC and ENR 2012). Little has been documented in the literature about the Slave River's more recent ice cover characteristics and behaviour. To

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understand and perhaps mitigate the impacts of ice cover changes on the livelihoods of residents along the river, it is important to monitor and understand the freeze-up processes along the Slave River. The manner in which the river freezes over often sets the stage for the ice cover conditions during the course of winter, right into breakup.

Hydraulic, geomorphologic and meteorological conditions and flow regulation affect the ice regime along the river. Flow regulation due to dam operations can change the thermal and flow conditions of a river and change the characteristics and behaviour of the river's ice cover, e.g., types of ice and timing of freeze-up (Beltaos 2013). Higher water discharges during the winter can maintain open water sections along the river (Vuyovich et al. 2009; Ghobrial et al. 2013). Also, fluctuating winter discharges may cause cracking or dislodgement of the ice cover causing pressurized water to seep onto and flood over the cover (Lindenschmidt and Davies 2014). The physical characteristics of the river can also be an important influential factor controlling the behaviour of ice during freezeup. For example, width constrictions in less steep river sections are potential areas for ice bridging that can accelerate the freeze over of a river (Lindenschmidt and Chun 2013). Steeper river sections with rapids may lead to a greater rate of frazil generation and entrainment of air into the flows (Gherboudj et al. 2007), which can lead to rapid freeze over and air bubble entrapment in the ice. The amount of snow on the ice cover immediately after freeze-up may also affect the rate of ice thickening in certain sections. Deeper snow may decrease the rate of ice thickening resulting in thinner ice covers (Woo et al. 2007). On the other hand, deeper snow may also increase the rate of ice thickening through the formation of snow ice.

RADARSAT-2 satellite images are extensively used for tracking the processes of river ice freeze-up and changes in winter ice cover characteristics along rivers (e.g., Van der Sanden et al. 2009; Lindenschmidt et al. 2011). RADARSAT-2 operates with a synthetic aperture radar (SAR) sensor that transmits and receives C-band microwaves to produce an image of the earth's surface (CCRS 2009). Differences in the strength of the received signal, also known as the radar backscatter, enable the detection of the location of the river ice cover front, the classification of ice types, and estimation of ice cover thicknesses (e.g., Lindenschmidt et al. 2010; Van der Sanden and Drouin 2011). There are two general scattering mechanisms involved in the interaction between river ice and radar signal — surface scattering and volume scattering. In surface scattering, a large proportion of the transmitted radar signal is scattered at the air-ice and ice-water interfaces, particularly if the interfaces have rough ice surfaces. In volume scattering radar signals transmitted throughout the thickness of the ice layer are scattered due to impurities in the ice volume, such as cracks, inclusions, and voids in the ice. (Unterschultz et al. 2009; Lindenschmidt et al. 2010). These scattering mechanisms of the river ice mainly depend on the physical properties of the ice, such as its structure and degree of wetness, the former being influenced by ice cover formation processes at freeze-up and the latter by air temperature. During freezing conditions, that is when the ice is free of liquid water, microwaves will penetrate the ice-air interface and scatter at the ice-water interface and (or) at dielectric discontinuities (cracks, air inclusions, bubbles, and impurities) within the ice volume. Microwaves that impinge on a smooth thermal ice-water interface will mostly reflect in the forward direction, i.e., away from the radar sensor. As a result thermal ice covers generate little backscatter and will appear dim in a satellite SAR image. Similar to thermal ice, open water typically appears dark in SAR images because it scatters the majority of incident microwaves in the forward direction. On the other hand, "white" ice covers with a relatively rough ice-water interface will scatter a significant portion of the incident signal back towards the sensor and will therefore show as bright areas in a SAR image (Unterschultz et al. 2009). The radar return signal of ice covers that include large amounts of dielectric discontinuities results primarilv as a result of so-called volume scattering. This type of scattering is known to generate relatively high backscatter signals that show as bright areas in radar images. For example, a consolidated ice cover produces relatively brighter images because this type of ice cover consists of the accumulation of frazil ice and ice pieces that increase the roughness and dielectric discontinuities within the ice cover. Therefore, increasing the roughness of the surface ice cover will increase the backscattered return signal. More dielectric discontinuities will also produce stronger volume scattering which returns a high proportion of signal to the satellite (Lindenschmidt et al. 2011). Increasing the concentration of more frazil ice or juxtaposing two or more different types of ice along the river can also lead to further increases in backscattering signal to generate corresponding brighter areas in the images (Gauthier et al. 2006). As frazil ice is known to be transported long distances under the ice (i) from observations of moving frazil slush appearing continuously in open leads located far distances downstream from open-water sections (Jasek et al. 2013) and (ii) from measurements using acoustic instruments (SWIPS) for long durations in the winter (Jasek et al. 2005)

Real-time imagery collected through time-lapse photography is also an effective way of tracking the changes in a river ice cover during freeze-up (Fjeldstad et al. 2002; Vuyovich et al. 2009). Timelapse cameras can be used for continuous monitoring of the river ice during the entire course of winter, especially for remote areas or where access to the river during winter is difficult (Vuyovich et al. 2009). Observations of the ice formation through time-lapse imagery can be used to validate the results obtained by other tools such as sonar measurements (Ghobrial et al. 2013) and RADARSAT satellite imagery.

The main purpose of this research is to describe the mechanism of ice cover formation along the Slave River, and document the different ice types using RADARSAT-2 satellite and time-lapse imagery. The impacts of flow changes on the ice cover are also investigated.

Methods

Study area

The Slave River (Fig. 1) is a large transboundary river flowing from Alberta to the Northwest Territories (NWT). The 440 kilometres (km) long river conveys flows in a northerly direction from the Peace River, Athabasca River, and Lake Athabasca to Great Slave Lake, with more than half of its total volume stemming from the Peace River. Its bed drops approximately 35 m between Fort Fitzgerald and Fort Smith, over a series of four rapids: Cassette Rapids, Pelican Rapids, Mountain Rapids, and Rapids of the Drowned. The river eventually drains into Great Slave Lake near Fort Resolution at the Slave River Delta (AAN DC and ENR 2012).

The Slave River Delta, located on the southeastern side of Great Slave Lake, is a source of food and subsistence income for the Fort Resolution community. The delta encompasses an area of approximately 640 square kilometres and is interwoven with several active channels, the main ones being: Steamboat Channel, Resdelta Channel, Middle Channel, Eastern Channel, and Nagle Channel (Fig. 1). Additional water is diverted from the Slave River via the Jean River to empty into Great Slave Lake.

Since the commencement of the W.A.C Bennet Dam operations on the upper Peace River winter discharges have significantly increased along the Slave River. A significant decreasing trend was observed in the fall and summer discharge between the 1960s and 2000s (Fig. 2). The annual total volume of water flowing in the Slave River has remained unchanged, despite the seasonal variation in the flows. This flow regulation by the Bennet Dam operations may be altering the quality of the ice cover of the Slave River.

Field data

Two study areas were selected along the Slave River for the field sampling program: Evans' cabin and the Slave River Delta. Evans'

Fig. 1. Slave River and Slave River Delta.



Fig. 2. Discharge at Fitzgerald averaged over 10 years for each day of the year (data source: Water Survey of Canada, gauge No. 07NB001).



cabin (Fig. 1) is situated approximately 40 km downstream from the Rapids of the Drowned. The study sites in the Slave River Delta extend for approximately 16 km from the Jean River to the Steamboat Channel. In total, three areas were selected in the delta for surveying: at the confluence of Jean River (S1), between the Nagle and Steamboat channels (S2), and between the Steamboat and Middle channels (S3) (Fig. 1).

Ice surveys were carried out during the entire course of winter, from December 2013 to March 2014, and included transects of measurements of total ice thickness, snow ice thickness, and the depth of snow overlying the ice cover. An auger was used to drill holes into the ice and a measuring staff was implemented to measure ice thicknesses and snow depths. A total of 24 holes were drilled along the transect at Evans' cabin to measure the depth of snow ice and total ice thicknesses. Using the staff, snow depths were measured from the top surface of the snow to the snow-ice interface. Snow ice thicknesses of the cover were determined in partially drilled holes, which were dry to detect the transition from white ice to black ice in the cover. The measuring staff had a L-bracket at the end which, when lowered through a hole completely augured through the ice, could be hooked on the underside of the ice cover to determine the cover's thickness. This direct field measurement of the ice thicknesses and snow depths is reliable, accurate and provides a systematic measurement. Due to the remoteness of the studied sites and time constraints (≈6 h of sunlight per day) only a few holes were drilled along each transect of the delta, however an amount deemed sufficient for understanding the development of the ice cover along the river.

For a more detailed analysis near Fort Smith the transect at Evans' cabin was qualitatively divided into three sections according to the amount of flow. The "slow flow" section extended from the left shoreline to the middle portion of the channel (augered holes 1 to 8), the "fast flow" section was in the middle of the channel (augered holes 9 to 18), and the "medium flow" section was near the right shoreline (augered holes 19 to 24). These categories may help us to determine if ice thicknesses along the river are impacted by different flow velocities. Qualitative observations were also made during the field sampling program such as the different types of ice, air pockets underneath of the ice, and double layers of ice. Several air pocket holes were punctured and venting of air from the ice cover observed during the surveys. The observation of this air through the puncture hole also captured in a video that helped us to further analyze this phenomenon. The surveyed data and observations were used to analyze the ice quality and understand the ice regime along the Slave River.

RADARSAT-2 imagery

Canada's RADARSAT-2 synthetic aperture radar (SAR) satellite was tasked to track ice cover changes along the Slave River from November 2013 to March 2014. As shown in Table 1, a combination of wide fine mode (F0W3) and wide standard quad-polarization (SQ21W) was acquired. The F0W3 images comprise two channels each, that is, one corresponding to the HH-polarization and the other to the HVpolarization. On the other hand, the SQ21W images comprise four channels corresponding to the HH-, HV-, VH-, and VV-polarization. These are the different combinations of microwave transmit-receive polarization configurations for the RADARSAT-2 sensor: HH, horizontal transmit - horizontal receive (co-polarized); HV, horizontal transmit - vertical receive (cross-polarized); VH, vertical transmit horizontal receive (cross-polarized); and VV, vertical transmit - vertical receive (co-polarized). These polarizations can be used to extract different information about river ice characteristics (Lindenschmidt et al. 2011), e.g., co-polarization configurations of the radar signals can easily detect rough ice surfaces (Lindenschmidt et al. 2010), whereas cross-polarization can be useful to pinpoint finer features in

Table 1. RADARSAT-2 images attained during the freeze-up over the

 Slave River, near Fort Smith and Slave River Delta.

RADARSAT-2 image	Date	Beam (incidence angles)
Slave River Delta	21 November 2013	F0W3 (38.7°-45.3°)
	15 December 2013	F0W3 (38.7°-45.3°)
	08 January 2014	F0W3 (38.7°-45.3°)
	01 February 2014	F0W3 (38.7°-45.3°)
	25 February 2014	F0W3 (38.7°-45.3°)
Fort Smith	04 November 2013	SQ21 (40.2°-41.6°)
	28 November 2013	SQ21 (40.2°-41.6°)
	22 December 2013	SQ21 (40.2°-41.6°)

the ice cover (Sandven and Johannesen 2006) and produce better contrast between level ice and ice ridges (Mäkynen 2007).

The images were converted to the TIFF format for subsequent processing using ArcGIS 10.2 Arctool (http://www.arcgis.com) modules and ET GeoWizard from ET Spatial Techniques (http://www. ian-ko.com). A centerline was constructed for the Slave River along which points were added every 100 m. Circular buffers of 100 m in diameter were applied to the centerline points to which the Arctool "Zonal Statistics" was applied to extract the mean backscatter intensity values. A visual analysis and backscattering values of the RADARSAT-2 imagery were used to determine the different types of ice along the river. Significantly lower backscattering values ranging from -18 to -22 dB, produced darker sections in the satellite imagery and were considered to be open water sections along the river. Dark sections with relatively higher backscattering values between -15 and -18 dB counted as predominantly thermal ice. Comparatively brighter sections with return signals ranging from -12 to -15 dB were considered to be juxtaposed ice covers. Return values greater than -12 dB were considered to stem from thick consolidated ice covers along the Slave River Delta.

However, in the case of RADARSAT-2 imagery at Fort Smith, visual analysis and qualitative analysis of backscattering values were used to determine different types of ice along the river. Open water sections appear black with very low backscattering values; low backscattering values of reddish color were considered to be thermal or skim ice along the river. Comparatively higher back-scattering signals from juxtaposed or consolidated ice cover produced brighter images along those river sections in the images.

Time-lapse camera imagery

Several time-lapse cameras were installed to monitor the ice conditions along the Slave River during the winter 2013-2014. Three time-lapse cameras near Fort Smith, at Bell Rock Landing, the boat launch, and immediately below the Rapids of the Drowned helped track freeze-up in this area. One time-lapse camera in the Slave River Delta tracked the freeze-up at the start of the Resdelta Channel. This study used Moultrie D-333 7 megapixel waterproof outdoor cameras with different photo capture modes such as time lapse, hybrid, and motion detection. These cameras are capable of capturing photos and video, day and night and able to take 30 000 images on 6 alkaline C-cell batteries (Fig. 3). The cameras are also suitable for extreme weather conditions and are able to stamp the moon phase, air temperature, time, date, and camera ID onto the imagery. All cameras were mounted on trees (Fig. 3) and were programmed to take three pictures per day. The captured images were stored on 16 GB internal SD memory card inserted in the cameras. More than 300 pictures were analyzed to determine the changes of ice conditions during freeze-up.

Meteorological and hydrometric data

Daily air temperature data was retrieved from Environment Canada's weather station at Fort Smith, from which accumulated freezing degree days (AFDD) were calculated. The Stefan equation





was used to express the ice thicknesses as a function of the accumulation degree days of freezing ADDF:

(1)
$$h = a \sqrt{\text{ADDI}}$$

where h is the ice thickness and a is the slope.

Water flows were obtained from the real-time gauging station on the Slave River at Fitzgerald, (No. 07NB001) operated by Water Survey of Canada (WSC).

Results

Ice regimes along the Slave River

Frazil ice generation along the Slave River typically begins during the second week of November when air temperatures are consistently below 0° C and the discharges along the Slave River have gradually reduced. A steep stretch of the river between Fitzgerald and Fort Smith is open all winter and significant turbulence in the super-cooled water is a source of frazil ice throughout the winter. Frazil ice coalesces to form ice floes that are transported downstream until their flow is arrested at an ice bridge or a constriction of a river. Frazil ice is also deposited under an existing ice cover along the river. A juxtaposed ice cover begins at the Slave River Delta and extends upstream along the Slave River. Ice bridging in many sections along the river create additional juxtaposing ice covers to create backwater staging and areas of thermal "black" ice. The ice regime along the Slave River depends greatly on the local climate conditions and the hydraulics and geomorphology of the river reaches.

Winter 2013-2014

Ice regime along the Slave River near Fort Smith

Time series of average daily air temperature, discharge and water level conditions along the Slave River during the winter 2013–2014 are shown in Figs. 4 and 5. Air temperatures began to decrease to freezing during the third week of October 2013 and consistently remained below freezing from 28 October 2013 onwards (Fig. 4). During this time, flow along the Slave River progressively decreased and the water level increased gradually as the ice cover formed (Fig. 5). Freezing air temperatures and low flow conditions initiated frazil pans along the Slave River and the first frazil pans were detected by the time-lapse cameras near Fort Smith on 7 November 2013. During the second week of November, air temperatures dropped below –10 °C and fluctuated between –10 °C and –26 °C until 23 November 2013. During this time the number of ice floes along the river increased significantly and

border ice progressed from both shorelines of the river toward the middle of the channel (Fig. 6). Also, ice bridging occurred at different locations along the river arresting ice floes to form a stable ice cover that progressed in the upstream direction. The backwater effects (Fig. 5) due to stable ice cover formation was recorded at the Fitzgerald gauge station. A solid ice cover was observed immediately downstream of the Rapids of the Drowned on 20 November 2013, although there were still many open water sections along the river. For example, an open water section was captured by time-lapse imagery from the camera at Bell Rock Landing near Fort Smith until 2 December 2013, which was finally frozen over by 4 December 2013 (see Fig. 6).

The process of freeze-up along the Slave River at the Fort Smith area could also be tracked by RADARSAT-2 images acquired 28 November and 22 December 2013 (Fig. 7). The color-composites shown in Fig. 7 represent a combination of the HH-, HV-, and VV-polarization shown in red, green, and blue, respectively. In the first satellite image several open water and ice bridging sections along the Slave River can be detected. An ice bridging section formed approximately 8 km downstream from the Rapids of the Drowned to develop a juxtaposed ice cover as the flow of ice pans was arrested at this bridging location (Fig. 7). Another ice bridging section was also observed just downstream of Bell Rock Landing where ice pans formed a consolidated ice cover. Numerous thermal (skim) ice sections along the river are also depicted in the satellite imagery created by the backup of water upstream of ice bridging sections.

By 22 December the river was mostly dominated by a consolidated ice cover and several thermal ice sections can be observed in the RADARSAT-2 image along the river. Low backscattering signals (reddish color) reveals the thin layers of thermal ice with air layers on the ice cover along the Slave River. Several air layers underneath of the ice cover were observed at approximately 20 km downstream of Fort Smith during the field ice surveys. The staging reduced flow velocities to allow a thermal ice cover to form. This spatial pattern of intermittent consolidated "white" ice and thermal "black" ice sections extends approximately 80 km along the river reach downstream of the Rapids of the Drowned.

A stationary ice cover has formed along the Slave River during the first week of December 2013 and the first field surveys at Evans' cabin were carried out on 16 December 2013. The average ice thickness along the river transect was approximately 0.36 m and the average snow depth was about 0.12 m. Several air pockets underneath of the ice cover were observed near the banks of the river. Compressed air and water were released through holes punctured in the ice cover along the river transect, videos





Fig. 5. Discharge and water level condition during the winter 2013–2014 at the gauge station at Fitzgerald (data source: Water Survey of Canada, gauge No. 07NB001).



Fig. 6. River ice conditions along the Slave River during freeze-up at the Fort Smith study sites: (*a*) border ice progressing toward the middle of the channel at the Rapids of the Drowned on 17 November 2013 and (*b*) open water section observed at Bell Rock Landing on 1 December 2013.



Fig. 7. Color-composites of RADARSAT–2 SQ21W images along the Slave River, extending from Rapids of the Drowned to approximately 80 Km downstream of the river. Image acquired on 28 November 2013 (*a*) and 22 December 2013 (*b*). Red = HH, Green = HV, and Blue = VV (RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd (2013) — All Rights Reserved. RADARSAT is an official trademark of the Canadian Space Agency).



of which can be found at http://youtu.be/ITy5OVRe5cA and http:// youtu.be/uc2QEntaeG0, respectively.

A second survey was carried out at Evans' cabin on 14 January 2014 with a total number of 24 holes augured (approximately 25 m distance between two drilling holes) along the river transect. The average ice thickness was 0.57 m and snow depth varied from 0.2 m to 0.9 m. Air bubbles and pockets underneath the ice cover were observed along the middle section of the channel at holes 16 and 18 and a double layer of ice was identified at holes 14 and 19.

Two surveys were undertaken during the first and third weeks of February 2014. By 2 February 2014, the ice cover along the Slave River near Fort Smith had significantly thickened. The average ice thickness at Evans' cabin was measured to be 0.96 m and the snow depths ranged from 0.29 m to 0.54 m. On 17 February 2014 the average ice thickness had increased by 27% to 1.22 m and the snow depths varied between 0.31 m and 0.70 m. Also a 0.20 m thick air pocket was augured through in the ice cover. A final ice field survey was carried out at Evans' cabin on 18 March 2014. Warmer **Fig. 8.** Profile of ice cover progression (*a*) and summary of average ice thickness (*b*) along the Slave River at the Fort Smith study site (Evans' cabin) during the winter 2013–2014.



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air temperatures during this month led to decreasing ice cover thicknesses, measured to be 0.78 m, approximately 36% less than the previous February survey. A summary of average ice thicknesses and profile of ice cover progression along the transect is shown in Fig. 8. Although, there are no significant differences between the ice cover thicknesses in terms of flow categories along the river, other factors such as changes of water temperature or accumulative freezing degree day (AFDD) can play a major role to ice cover thickening along the river.

Ice regime at the Slave River Delta

The freeze-up along the Slave River at the Slave River Delta is different compared to that near Fort Smith. A comparatively milder sloping river bed and low turbulence along this river reach led to the formation of a thicker layer of columnar ice after freeze-up. During the freeze-up ice floes from upstream of the river continuously juxtaposed to develop an initial ice cover at the delta, unless they are arrested at an ice bridging section or any river constriction (Fig. 9). Frazil ice from as far upstream as the rapids was also continuously deposited under the ice cover throughout the winter. Air pockets and layers were also formed particularly at the upstream end of the delta, just downstream of the Jean River, which was evident in the "brightening" of ice cover areas in the satellite imagery acquired during the winter. Longitudinal profiles of backscatter return signal (HH polarization) were extracted from five RADARSAT-2 satellite images acquired between November 2013 and February 2014 to understand patterns of the ice cover progression along the main Slave River Delta channel (Fig. 10). On 21 November 2013 most of the river sections at the Slave River Delta were ice covered. An ice bridging occurred at Big Eddy located approximately 5 km downstream of the Jean River from which a consistent consolidated ice cover extended in the upstream direction (Fig. 11a). An ice cover had already formed at the river's mouth at Great Slave Lake which extended 2 km upstream from the lake along the Resdelta Channel. Lower backscatter values ranging from -12 to -22 dB were recorded in the lower portion of Slave River Delta channel indicative of ice layers ranged from juxtaposed, thermal ice, and open water along the channel.

Ice thickening and deposition of frazil ice underneath of the ice cover resulted in a large increase in the backscattering values extracted from the image acquired on 15 December 2013. However, low backscattering (approximately –18 dB) between Big Eddy and Nagle Channel (approximately 23 km upstream from Great Slave Lake) reveal the persistence of open water or a thin thermal ice cover on the water surface. During this time the river between Nagle Channel and Steamboat Channel was dominated mostly by

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Fig. 9. River ice condition along the Slave River Delta at the Resolution Delta Channel on 06 November 2013.



Fig. 10. RADARSAT-2 backscattering profile along the Slave River at the Slave River Delta (about 91 km long sections along the Slave River Delta, from McConnell Island to Great Slave Lake.



thermal "black" ice (Fig. 11b). By 08 January 2014 thickening ice increased backscattering slightly along all ice covers in the delta. Low backscattering signals (reddish and black color) between the Nagle and Middle Channels indicate the predominance of thermal ice along the Slave River (Fig. 11c). Several areas of relatively thin ice with underlying air pockets and layers were observed along this area during the ice field surveys.

At the end of January and throughout February 2014, there was a moderate fluctuation in the Slave River flows, between 1600 m³/s and 3100 m³/s. Discharge of the river at the end of January 2014 increased from below 2000 m³/s to about 2780 m³/s and by the second week of February 2014 flows increased to 3000 m³/s and remained so until the following week (Fig. 5). These flow fluctuations led to ice cover changes along the Slave River Delta between February and March 2014. Increasing discharges along the river increased the water pressure underneath of the ice cover resulting in cracking of the ice and dislodgement of the ice cover from the banks allowing water to seep onto and flood over the cover.

On 1 February 2014 the level of backscatter recorded by the satellite imagery was reduced significantly due to the scattering of microwaves incident on flooded areas in the forward direction, i.e., away from the sensor. Numerous dark areas indicative of flood water were also depicted in the satellite image (Fig. 12). For example, many flooded areas (dark) approximately 36, 39, and 57 km upstream from Great Slave Lake (Fig. 12) reduced the backscatter values to less than –11 dB by 1 February 2014 (Fig. 10). By

Fig. 11. RADARSAT-2 F0W3 (HH + HV composite) imagery covering the area from Great Slave Lake to approximately 20 km upstream of the Slave River Delta, images acquired on 21 November 2013 (*a*), 15 December 2013 (*b*), and 08 January 2014 (*c*). (RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd (2013) — All Rights Reserved. RADARSAT is an official trademark of the Canadian Space Agency).



25 February 2014 more flooded areas (black color) were observed in the imagery along the river at the Slave River Delta (Fig. 12). A high water discharge during mid-February exacerbated water seepage to flood more areas along the river banks.

Ice surveys along the Slave River Delta were carried out between February and April 2014. The first ice surveys were taken at the entrance to the Jean River and between the Nagle and Steamboat channels on 01 February 2014. At this time the ice cover along the delta's main channel was not uniform and total ice thicknesses varied between 0.44 m and 0.75 m. The average ice thickness near the Jean River was measured to be about 0.50 m and approximately 0.71 m near the Nagle Channel. Average snow depths at the Jean River site were significantly higher (about 0.38 m) than those near the Nagle Channel sites (about 0.19 m). Deeper snow may have insulated the ice cover to slow the ice thickening rate along the river. Thin ice layers of air bubbles and pockets underneath the ice were also observed between the Nagle Channel and Old Steamboat Channels.

On 3 March 2014 an additional site near Middle Channel was added to the ice surveying program. The total ice thickness at the Jean River increased, albeit the ice thicknesses were less than the other two sites. The average ice thickness at the Jean River was approximately 0.61 m and near the Nagle and Middle channels were about 0.87 m and 0.77 m, respectively. Also average snow depths at the Jean River site were higher, averaging 0.32 m Das et al.

Fig. 12. RADARSAT-2 satellite images indicating ice cover flooding (black color on the ice cover) in the lower reach of the Slave River on 1 February 2014 (*a*) and 25 February 2014 (*b*), numbers indicating the km distance of the specific reaches along the river from Great Slave Lake. (RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd (2013) — All Rights Reserved. RADARSAT is an official trademark of the Canadian Space Agency).



Fig. 13. Ice thickness and snow depth at the Slave River Delta between February and April 2014.



compared to 0.25 and 0.30 m at the Nagle and Middle Channels sites, respectively.

The final ice surveys in the Slave River Delta were undertaken on 2 April 2014. Though ice cover thicknesses decreased at the confluence of the Jean River, ice thicknesses increased near the Nagle and Middle channels of the river. The average ice thickness at the confluence of Jean River was 0.48 m while average ice thicknesses near the Nagle and Middle channels were approximately 1 m and 0.81 m, respectively. The average snow depth at the start of the Jean River was 0.39 m, significantly higher than at Nagle and Middle channels, respectively 0.18 m and 0.23 m. Deeper snow may have decreased the rate of ice thickening at the Jean River along the river. Air bubbles and slush underneath of the ice cover were also observed along several sections of the channel. A summary of field surveys data are provided in Fig. 13.

Ice thickness data acquired at Evans' cabin and the delta are plotted against the square root of ADDF in Fig. 14. Ice thickening at Evans' cabin significantly increased between January and February 2014. During the field surveys between December 2013 and January 2014 air was bled out from under the ice cover allowing the ice cover to come in contact with the underlying water and increase the ice thickening rate. In contrast, ice thicknesses in the Fig. 14. Ice thickness versus the square root of the accumulated degree days of freezing (ADDF) with linear regressions according to the Stefan equation.



Slave River Delta were thinner than at Evans' cabin. Ice covers in the delta area, such as at Nagle Channel and Middle Channel were comparatively thicker than those at the Jean River site. In the delta, lower density of air pockets allowed for thicker ice than areas with higher air pocket density (Jean River). During April 2014 ice thicknesses at Jean River had already decreased but an increasing trend of ice cover thicknesses was still observed between the Nagle and Middle channels. Therefore, the insulating effect of the air pockets can inhibit the rate of ice thicknesing along the river.

Discussion and conclusion

There are various patterns of ice formation along different sections of the Slave River. The most upstream portion of our study site, extending from the rapids to at least 80 km downstream, has a pattern of intermittent sections of consolidated and thermal ice covers, since this section is narrower than the downstream reach. Also several open water areas formed immediately downstream of those ice bridging sections. Therefore, ice cover formation processes are a reflection of the different geomorphological characteristics along the river. Studies have found that various geomorphologic parameters can influence the formation of different types of ice covers along rivers (Lindenschmidt and Chun 2013; Chao et al. 2014). Narrower and sinuous sections are potential areas for ice bridging along the river. Once an ice bridging is formed, ice floes can be arrested at that section leading to a juxtaposed ice cover to finally form a consolidated ice cover upstream of the bridging (Beltaos 2013). The ice covers in the Slave River Delta are thicker and consist of more thermal ice than the upstream Slave River due to the influence of Great Slave Lake. An ice bridging approximately 5 km downstream along the river led to the formations of a juxtaposing and consolidated ice cover during the course of winter 2013-2014. There are indications from observations and satellite imagery that frazil ice generated at the rapids can be transported for long distances along the river before it is deposited under the ice cover.

An increase in the mid-winter discharge caused the ice cover to form cracks or to dislodge from the river banks to allow water to spill onto the ice surface and flood large sections of the ice cover. Water level fluctuations in winter can cause the ice cover to crack and cause flooding of the top surface of ice covers (Lindenschmidt and Davies 2014). The subsequent freezing of this flood water can trap and drown muskrats and beavers as was witnessed along the Jean River in the previous winter.

A number of studies have used satellite imagery to understand river freeze up and to document different types of ice along the river (e.g., Jasek et al. 2013; Lindenschmidt and Chun 2013; Lindenschmidt et al. 2011; Van der Sanden and Drouin 2011; Unterschultz et al. 2009). In this study we analyzed a series of RADARSAT-2 images to identify dominant ice types along the river near Fort Smith and in the Slave River Delta. Ice cover progression and their changes along the delta are also described using backscattering values of RADARSAT-2 satellite imagery acquired from this study. Backscattering profiles of RADARSAT images were also used elsewhere to map the ice cover formation (Gauthier et al. 2006) and in determining the ice cover thicknesses along a river (Lindenschmidt et al. 2010; Jasek et al. 2003). Remote sensing is a useful technique to map the ice cover progression and to classify different types of ice along the river, particularly in remote areas such as the Slave River. It is very difficult to observe the ice cover conditions during the winter because of limited access to most places along the Slave River from the shorelines. Also, the ice cover is not always safe to travel on due to numerous open water sections and many air pockets concealed under the snow cover. Pockets of compressed air along the underside of the ice cover keep the ice thin and unstable. Therefore, taking in situ ice measurement or sample collections by individuals is not always possible. However, puncturing the pockets to release the air and allowing water to fill the void increases the ice thickening rates. Air pockets and layers were found along the entire course of the studied river stretch.

Since the ice regime of the Slave River can change due to variability of flows and different meteorological conditions from year to year, it is difficult to attain a complete understanding of the ice regime from one year of observations and measurements. Hence, further research with additional sampling techniques is necessary to extend our knowledge of the river's ice cover behaviour and characteristics. For example, extracting ice core samples using a core barrel will help to further our understanding of the complexity of the air pocket formation phenomenon. Also, ice maps of the river's ice cover extracted from satellite imagery during the course of winter may be a good means to communicate changes in ice cover characteristics to the local communities. Hazards to winter travel along the river, e.g., locations of high air pocket densities and areas of

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flooding, could be revealed. The findings of this study can help local residents to identify safe routes to trap lines and fishing areas. Finally this study will provide future guidelines for researchers to increase their predictability of river ice cover formation and progression along the Slave River.

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