NA DONG

BORDER ICE PROCESSES ON THE SAINT LAWRENCE RIVER

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Abstract

Border ice is one of many ice freeze-up processes, but it is discussed only to a limited extent in the literature. Border ice formation can be a precursor for ice jam formation that may restrict navigation and lead to flooding. This master's thesis is mainly devoted to the research on the border ice on the Saint Lawrence River from Montréal to Québec City. This reach stays artificially open all winter because commercial ships are continuously preventing a full ice cover to form. The traffic also limits the extent of border ice.

This study provides key information on ice formation and decay. Through analysis of Environment Canada's historical data (ice charts from 2004 to 2009), the areal coverage of border ice is analyzed during freeze-up, winter and breakup periods. The historical information of ice coverage is collected in order to find out the factors which influence its formation and its spatial limits. Border ice growth and decay rates are also discussed.

The thesis shows that border ice coverage has three stages including the rapid growth period at the beginning of the winter, the relatively stable period in the mid-winter and the breakup period as March progresses. During the mid-winter period, the border ice coverage sometimes drops sharply if the air temperature rises above 0 °C and/or if there is some rain. It was also found that the maximum border ice spatial limits are quite similar over the five winter seasons.

Based on the analysis of the ice charts, a number of empirical laws regarding the formation and decay of border ice are proposed. Along the river flowing direction, the border ice is formed easily when there are obstacles particularly at the downstream end. The obstacles could include river bends, ice booms, shoals, artificial islands, bridge piers and so on. Thus,

the obstacle influences the flow velocity, which is an important factor for ice formation and also provides an object against which the ice can become fast and initiate its formation.

On average, border ice reaches 20% of its maximum coverage when the accumulated freezing degree days (AFDD) reaches 124 °C-D. This is followed by a rapid growth period that ends when the ice cover reaches about 80% of its maximum cover corresponding to AFDD equal to 247 °C-D. Border ice coverage usually reaches the maximum value when the average AFDD is 551 °C-D corresponding to the end of January.

The winter period is characterised by a stable ice cover (>90% of max) upstream of Trois-Rivières except in the event of a mid-winter thaw. Downstream of Trois-Rivières there is no stable period as the decay begins very soon after the ice reaches its maximum value.

Breakup is a gradual process that normally begins on about Feb. 15th downstream of Trois-Rivières and about March 1st upstream. Most ice has normally gone by March 31st.

Moreover, the river flow velocity, river depth and Froude number along the limits of border ice once it reaches its maximal areal coverage are evaluated and analyzed. The flow velocity is almost always less than 1.0 m/s; the maximum Froude number is normally 0.1 at Lake Saint-Pierre and 0.2 in the Montréal to Sorel reach; river depth at the ice edge can vary widely.

Through numerical modelling, it was found that border ice increased the current velocity by 0.1 m/s in the Lake Saint-Pierre reach and raised water levels by 14 cm in the Montréal to Sorel reach.

Résumé

La glace de rive est un des nombreux processus de formation des couverts de glace sur les rivières. Cependant peu d'articles dans la littérature traitent de ce sujet malgré que la formation de la glace de rive peut-être un précurseur de l'apparition d'embâcles qui peuvent entrainer des inondations.

Ce mémoire de Maitrise porte sur l'étude de la glace de rive le long de la portion du fleuve Saint-Laurent allant de Montréal à Québec. Du fait qu'il y a de la navigation commerciale toute l'année, le fleuve reste ouvert (libre d'un couvert de glace entier) artificiellement pendant tout l'hiver. Ce trafic limite aussi l'extension de la glace de rive.

Cette étude fournit des informations clés sur la formation et la désagrégation de la glace de rive. À partir des données historiques d'Environnement Canada (cartes des glaces de 2004 à 2009), la répartition superficielle de la glace de rive est analysée pour les périodes de formation, de stabilité et de rupture de la glace. Les informations historiques sur les couvertures de glace sont collectées afin de déterminer les paramètres qui influencent la formation et les limites spatiales de ce type de glace. Les taux de croissance et de décomposition de la glace de rive sont aussi abordés.

Il est montré que l'évolution de la structure propre à la couverture de la glace de rive se fait en trois étapes. Une période de formation rapide (début hiver), suivie d'une période stable (milieu d'hiver) et enfin une période de rupture (pendant le moi de mars). Pendant la période stable, la glace de rive se rompt partiellement parfois lorsque la température de l'air monte au dessus de zéro °C et surtout lorsque le redoux est accompagné de pluie. Il a été trouvé aussi que les limites spatiales maximales des glaces de rive sont très semblables sur 5 hivers de la période d'étude.

À partir de l'analyse des cartes des glaces, un certain nombre de relations empiriques sont proposées. Ces relations caractérisent la formation et la désagrégation des glaces de rive. Le long de la direction de l'écoulement la glace de rive est formée facilement en présence d'obstacles, et particulièrement lorsqu'elles sont à l'extrémité aval. Parmi ces obstacles on peut citer les méandres de rivière, les bancs, les estacades, les iles artificielles, les piliers de ponts. Ainsi, les obstacles influencent la vitesse d'écoulement qui est un paramètre important dans la formation de la glace et peut aussi effectuer un apport d'objets sur lesquels la glace peut s'attacher et initier son accroissement.

En moyenne la glace de rive atteint 20% de sa couverture maximale lorsque son le nombre de degrés jours accumulés (DJA) atteint 124 °C-j. Ceci est suivi d'une période d'accroissement rapide qui prend fin lorsque la couverture de glace atteint 80% de son maximum qui correspond à un DJA de 247 °C-j. La couverture de glace de rive atteint son maximum lorsque le DJA atteint 551 °C-j; ce qui correspond normalement à la période de fin janvier.

La période d'hiver est caractérisée par une couverture de glace stable (supérieure à 90% de son maximum) en amont de Trois-Rivières, sauf pendant les périodes de dégel mi hivernales. À l'aval de Trois-Rivières, il n'y a pas de période stable, vu que la désagrégation commence très tôt après que la glace ait cru à son étendu maximal.

La rupture est un processus graduel qui normalement commence vers le 15 février en aval de Trois-Rivières et vers le premier mars en amont. La grande majorité de la glace disparait généralement avant le 31 mars.

Par ailleurs, la vitesse d'écoulement de la rivière, ainsi que sa profondeur et son nombre de Froude le long des limites de la glace de rive sont évalués. Ceci dans la condition où la glace de rive a atteint sa répartition superficielle maximale. La vitesse est presque toujours inférieure à 1 m/s, le nombre de Froude maximal est normalement de 0,1 au dans le Lac St

Pierre et de 0,2 sur le tronçon Montréal-Sorel. La profondeur de la rivière à la limite de la glace peut varier largement.

À partir d'une modélisation numérique, il a été calculé que la glace de rive cause une augmentation de la vitesse de 0,1 m/s dans le chenal maritime du Lac St Pierre et du niveau d'eau de 14 cm dans le tronçon Montréal-Sorel.

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Abbreviations

AFDD: Accumulated Freezing Degree Days (°C-D)

ANN: Artificial Neural Network

AP: Accumulated Precipitation (mm)

CCG: Canadian Coast Guard

CSI: Canadian Ice Service

DD: Degree Days (°C-D)

DFO: Department of Fisheries and Oceans

EC: Environment Canada

FDD: Freezing Degree Days (°C-D)

NRC: Natural Resources Canada

NWSFO: National Weather Service Forecast Office

PWGSC: Public Works and Government Services Canada

SLC: St. Lawrence Centre

SLGO: St. Lawrence Global Observatory

UTM: Universal Transverse Mercator coordinate system

Chapter 1
Introduction

1.1 Thesis motivation and objectives

Border ice is one of the least known phenomena in river ice formation (Michel, 1980). Due to the lack of knowledge of border ice existence, ship transport might be affected on the navigation channel in the Saint Lawrence River. Border ice formation can be a precursor for ice jam formation that may restrict navigation and lead to flooding. Border ice also affects water levels, currents, sediment transport, ecology and fish habitat. This project was carried out at the specific request of Environment Canada (Morin, personal communication, 2008) in order to help them create an operational hydrodynamic model of the St. Lawrence that would be valid for winter conditions. The study was also useful in assessing vessel squat in winter conditions (Morse, 2011) and to assess the likelihood of UXO transportation by ice out of the Firing Range of Lake St. Pierre (Morse et al., 2010).

Thus motivated, we examine border ice and collect historical information of ice coverage in order to find out the factors influencing its formation and its limits.

The main objectives of this thesis are in the following:

- To analyze the areal coverage of border ice during freeze-up and breakup periods;
- To determine speed of its formation and of its decay;
- To further the understanding of the border ice limits and influencing factors;

- To document flow velocity and river depth along the maximal areal coverage border ice limits;
- To compare influencing factors of border ice formation through statistics methods on historical data;
- To attempt to model border ice formation in Saint Lawrence River using quantitative historical data;

1.2 General description of the study area

The study area of this thesis is the Saint Lawrence River from Montréal (45°30' N, 73°33'W) to Québec City (46°48'N, 71°15'W) having a length of approximately 256 km. For this study, Lake Saint-Pierre is the most important reach in this section. It is a wide shallow reach located in midway between Montréal and Québec (Figure 1.1).

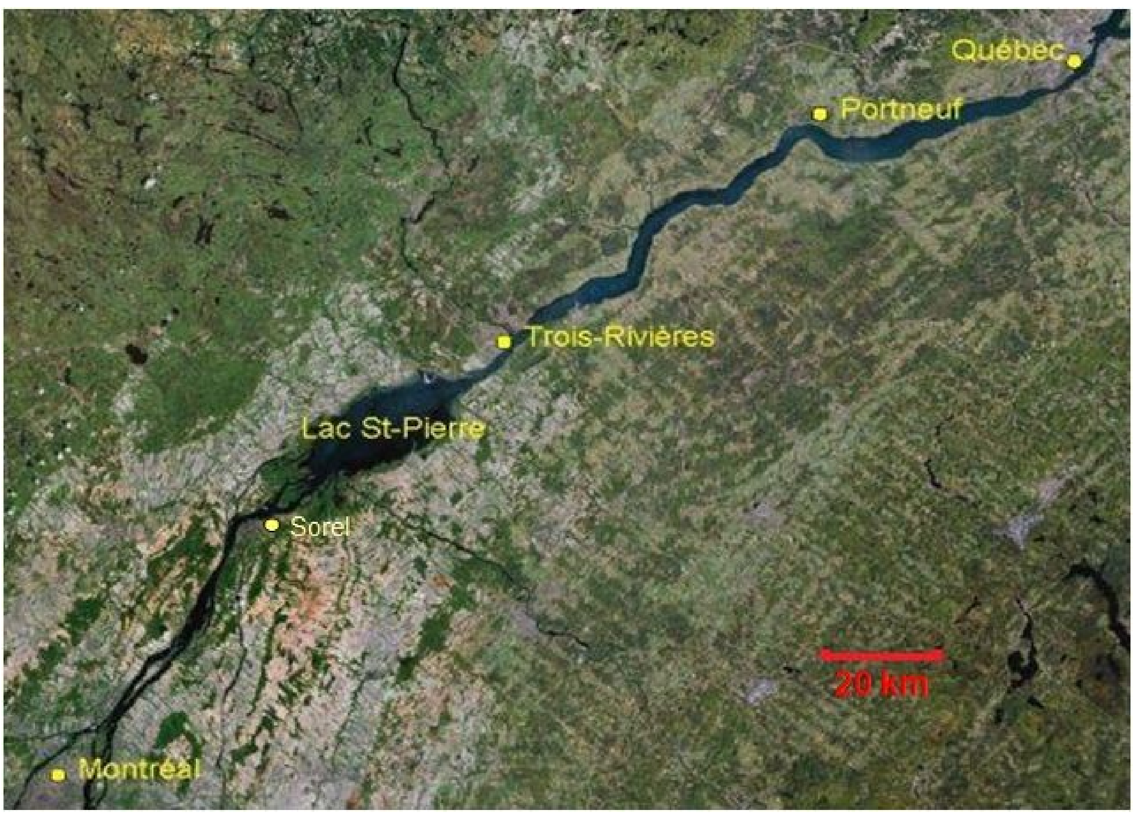

Figure 1. 1 Saint Lawrence River from Montréal to Québec City (Google Earth)

Lake Saint-Pierre is a natural open-water widening whose surface area is large enough that it can be considered as a lake, but whose flow is typical of rivers. Hence, it is termed a fluvial lake. It is also the last of the three fluvial lakes of the fluvial Saint Lawrence River in the Québec portion, with the other two, Lake Saint-François and Lake Saint-Louis, occurring just before the river becomes an estuary. (EC, 2010)

Lake Saint-Pierre (See Figure 1.2) is a wide segment of the Saint Lawrence River located downriver of Montréal, and bounded by the towns of Sorel to the west and Trois-Rivières to the east. There are a number of tributaries entering it.

Lake Saint-Pierre constitutes one of the major components of the St. Lawrence ecosystem. The farthest upstream of all freshwater basins of the St. Lawrence, Lake Saint-Pierre is bordered by the most expansive freshwater floodplain in Québec, such that its area grows by more than 600 km^2 during periods of high water. Except for the ship channel, with has an average depth of 11 m, Lake Saint-Pierre is characterized by its shallowness (less than three meters deep). (EC, 2010)

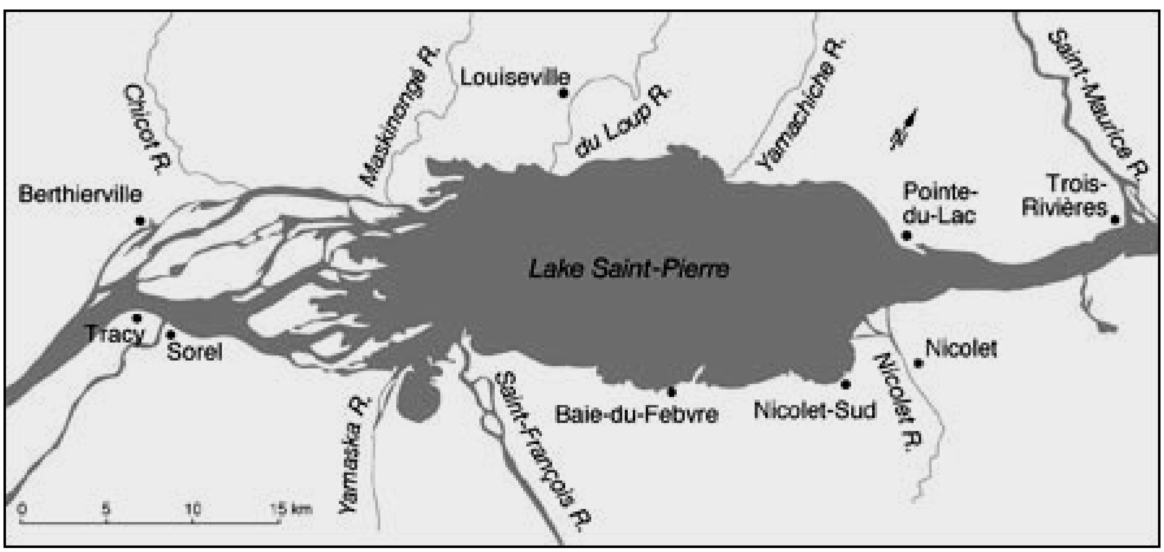

Figure 1. 2 Lake Saint-Pierre (EC, 2010)

- Location - 120 km downstream of Montréal Island
- Length - 35 km
- Width - 15 km

- Surface area - 500 km^2
- Mean depth - 3 m
- Volume - 1.5 km^3
- Mean discharge - 10 000 m^3/s

1.3 Data and methodology of the thesis

1.3.1 Data

The Saint Lawrence River is a well monitored river. For our study, the climate data can be obtained from the Environment Canada website (www.climate.weatheroffice.gc.ca). Environment Canada (EC) and the Department of Fisheries and Oceans (DFO) cooperate to produce ice charts, which are published online (www.marinfo.gc.ca). Ice charts are drawn directly on a computer screen using GIS software. Ice reconnaissance carried out from a helicopter. Those ice charts give good information about the areal coverage of border ice. Meanwhile, we obtain the database including the flow velocities, river depths and Froude numbers of 192744 nodes when the river covers the maximal border ice on 29th Jan., 2005 (as well as data for summer conditions) from the output of the 2-D numerical simulation work of Environment Canada. 2-D modeling of the St. Lawrence can be summed up as the process of integrating information and knowledge about the physical and biological aspects of the river into numerical models that simulate hydrodynamics (water level, flow, water depth), waves (height, direction, energy), distribution of aquatic vegetation (species), wildlife (species), etc (Morin et Champoux, 2006).

1.3.2 Methodology

Environment Canada's historical ice charts of locations of the Saint Lawrence River for five winter seasons (i.e. 2004-2009) were chosen for analysis. The methodology is herein presented as follows:

1. Download the ice charts of Saint Lawrence River in the reach from Montréal to Québec City from 2004 to 2009 from Canadian Coast Guard website, and then import them into a MATLAB environment. Using an overlay with Google maps, obtain scaling and offset factors to determine position of each river section.

2. Assess the regularity and determine the influencing factors of the existence of border ice on Saint Lawrence River.

3. Perform a statistic analysis of AFDD (Accumulated Freezing Degree Day) and key dates for each of the nine river sections. Calculate and compare the maximal border ice coverage, AFDD and AP (Accumulated Precipitation) on Lake Saint-Pierre and one reach upstream and downstream separately.

4. Perform a separate analysis of 'mid-winter' breakup events in order to identify environmental conditions leading up to a loss of areal coverage (i.e., temperatures above zero with or without a rainfall event). Find out the regularity of loss of percentage of border ice on Lake Saint-Pierre and one reach upstream and downstream separately via statistic work in 5 winter seasons.

5. Compare flow velocity and river depth with ice and without ice of Saint Lawrence River in the reach from Montréal to Trois-Rivières.

6. For each location (each map) and for each date that a map was available, using criteria that we designed for that purpose, have MATLAB recognize and delineate border ice areas on ice charts. Calculate the areal coverage of border ice using MATLAB. Present areas in tabular and graphical fashion as a function of date. Also, in order to provide additional insights, present the data as tables and figures as a function of the AFDD and precipitation (in the case of rain or snow, expressed in equivalent mm of water where 'AP' corresponds to the accumulated precipitation from December 1st and is also expressed in mm of water).

Analyze figures and identify periods of (1) border ice cover growth – normally rapid initially to a first peak near 75-85% coverage that is followed by a slow growth up to and beyond 90% coverage; (2) a relatively stable mid-winter period when ice is normally above 90% coverage; and (3) a breakup period when ice coverage gradually diminishes.

Obtain and compare the trends in areal coverage for all locations for both freeze-up and breakup periods during these 5 winter seasons.

7. In view of its variability and, given its specific importance, calculate and compare the limits of border ice of Lake Saint-Pierre which correspond to the ice areal coverage are around 30%, 60% and maximal from each winter season, respectively. Particularly, we pay more attention to the limits of border ice on the south side of Lake Saint-Pierre reach (in order to answer specific needs related to Morse et al. study, 2010) which correspond to the ice areal coverage are 40%, 80% and maximal from each winter season, respectively.

8. For conditions corresponding to the maximum mid-winter ice coverage, mine the Environment Canada 2-D model simulation database (192744 nodes) to obtain the flow velocities, river depths and Froude numbers at locations of interest (i.e., nodes corresponding to the location of the border ice limit). The 2-D simulation is of the river reach from Montréal to Trois-Rivières corresponding to discharge, tide and ice conditions on 29th January 2005. This date was chosen as it corresponds to date for which the border ice areal coverage of this river region is at a maximum. Generate relevant figures and tables of associated data in order to determine and summarize findings with regards to flow velocity, river depth and Froude number criteria at the border ice limit.

9. Calculate the border ice growth velocity (while the ice limit goes from the smallest to the maximal coverage). Utilise a contour function in MATLAB to plot the graphs of

growth speed and growth direction as a function of location and AFDD (expressed in degree Celsius days).

Note that to analyze the relationship between air temperature and ice areal coverage, we chose the air temperature measured at Montréal for ice charts upstream of Sorel; the air temperature measured at Trois-Rivières for charts between Sorel and Grondines; and the air temperature measured at Québec City for the remaining charts downstream of Grondines.

10. Synthesize results, make conclusions and discussion.

Chapter 2
Literature review

Ice that is formed along and fastened to the shore is called border ice. Since border ice does not extend across the entire width of the river, we also call it shore ice (Figure 2.1 and 2.2). In general, border ice is the first type of ice formed on a river. As it grows laterally towards the mid-stream, it grows (thickens) vertically as well. There are several characteristics of border ice bellows (National Weather Service Forecast Office (NWSFO)):

- forming along and attached to river banks;
- occasionally attached to other obstacles such as islands, rocks and structures such as bridge piers;
- calm water flow provides best conditions for growth;
- water level changes or surface waves can fracture existing border ice or detach it from the shore.

Figure 2. 1 Border Ice, photo New Brunswick Ice Manual

Figure 2. 2 Border Ice forming along mid-channel ledges, photo Dennis Kalma

2.1 River ice processes

River ice processes can normally be classified as either freeze-up or breakup. In freeze-up process, border ice forms and develops. Border ice is one of many elements making up the ice freeze-up processes, but it is discussed only to a limited extent in the literature. Since border ice is a very transitory phenomenon, most researches did not attach too much importance to it. In general, there is not much in the literature on the topic of the freeze-up of border ice. Since there is almost no literature on breakup of border ice, here we only introduce the breakup of river ice.

Freezing degree days (FDD) and accumulated freezing degree days (AFDD) are two parameters commonly used to estimate ice cover thickness. AFDD is a scientific method to measure the cold level and its duration. It is the sum of the daily computed degree days (DD) since the beginning of winter where AFDD is always greater or equal to zero. DD is simply the difference between the daily mean temperature and zero degrees C; DD is greater than zero when the air temperature is below zero. The value of AFDD (in °C-D) for day k is given as:

$$\mathrm{AFDD}\ \mathrm{k}\ = \sum_{\mathrm{j=1}}^{\mathrm{j=k}} \mathrm{DD}\ \geq 0$$

Where j = 1 is the first day of winter (i.e., T less than zero) and the temperature T is expressed in degrees C.

In general, AFDD stays unchanged or increases somewhat during the breakup period. In the case of a naturally occurring breakup, this is a sign that AFDD (calculated from a reference value of zero degrees C) is not a very suitable indicator as it is more or less constant over the breakup period. A modified Accumulated Melting Degree Days $\mathrm{AMDD}\ \mathrm{k} = \sum_{\mathrm{j=1}}^{\mathrm{j=k}}(\mathrm{T_j} + 10) \geq 0$ (Where j = 1 is March 1st of each winter and the temperature T is expressed in degrees C.)

2.1.1 Freeze-up of border ice

In a river, the freeze-up usually starts with the formation of border ice along the banks and in low velocity zones (Svensson et al., 1989). Since there is less movement of water there, and the temperature in the shallow water along the bank drops faster in a cold night than in the middle of the stream. Border ice can develop either in a static thermal mode from skim ice or from lateral accumulation of moving surface ice floes along river banks or the edge of existing border ice. The latter might be viewed as border ice growth by hydraulic accumulation (Shen, 2010). This process may already start when the bulk temperature of the river is one or two degrees above 0 °C (Svensson et al., 1989). As long as flow and temperature conditions permit, ice crystals will continue to spread out over the adjacent water surface. After that, border ice grows gradually towards the center until the river freezes over. The growth of the width of border ice is dependent upon the stability of the surface ice floes and ice edge contact; meanwhile, it is affected by the density of the floating ice. Generally speaking, the width of border ice grows proportionally to the density of surface ice floes (Michel et al., 1982).

At the sites where the velocity is smaller than 0.2 m/s, border ice will rapidly grow in shallow areas. If the entire river section has low velocities and depths, within a few days only, the entire river may become covered with fast ice. The cover can be formed by a closure of the ever-decreasing open water area and ice floes coming from upstream. At other sites, where the channel is deep such as on the Saint Lawrence River, border ice may extend to a local depth of 2 m or so. The rest of the river may stay open all year round. In steep gravelly rivers, border ice may form as a result of lateral processes, as well as the vertical growth of anchor ice and the presence of frazil ice (Turcotte and Morse, 2011). Boulders often play a key role. In steep rapids, the river may only temporarily close during extremely cold weather particularly if upstream of the rapids, an ice cover cuts off the supply of frazil ice. However, in most rivers, border ice grows out a certain distance, and then, through longitudinal processes the cover eventually forms across the whole river width (Morse et al. 2006).

Based observations of river ice condition of Ste. Anne River, QC, Michel et al. (1982) proposed that there are five factors influencing the formation and width of border ice. They are: heat exchange, velocity at the edge of border ice, concentration of frazil produced, geometry of the river reach and depth of river reach. (See Table 2.1) They also present empirical formula for the progression rate of border ice until the progression stops when the average velocity exceeds a critical value. Matousek et al. (1984) presented the regularity of border ice formation using a theoretical experimental method. Svensson et al. (1989) studied two-dimensional mathematical models about formation and growth of border ice, and made a comparison with the in-situ measurement data. Finally, they proposed empirical formula. Hanley and Michel (1977) reported a laboratory study of border and frazil ice. Matousek (1990) derived the relation for the border ice spreading rate based on model experiments.

Table 2. 1 Factors influencing the formation of border ice (Michel et al., 1982)

	Beginning of formation (early winter)	**Intermediate and final periods**
Heat exchange	-initiates the formation in low velocity zones near the bank -produces a back and forth process, allowing the particles to freeze on the edge during the night and to melt during the day -forms distinct banks of ice	-first-order importance -directly related to the progression of the ice edge
Velocity at the edge	-small importance when <0.2 m/s	-very important as ice progresses toward higher velocity zones (>0.35 m/s) -determining factors as it is directly related to the erosive process and to the ability of frazil to adhere. No progression for v>1.2 m/s
Frazil ice concentration	-speeds up the process by accumulating in irregularities in the banks	-importance decreases with the percentage produced and with the higher velocities zones reached
Geometry of the reach	-helps the frazil to agglomerate in curves -increases or decreases the rate of progression of thermally grown ice (contraction or enlargement of section)	-plays a role when the maximum velocity is not attained
Depth	-important in broader variations (very shallow to very deep)	- of less importance

Through literature review, all numerical ice analysts have used and modified existing equations proposed by Michel, Newbury or Matousek. These three empirical equations are introduced as follows:

1. Newbury (1969) proposed an equation that relates border ice growth to the mean channel velocity and to air temperature:

$$W = \frac{mn}{2}\Sigma \quad \ldots (1)$$

where:

W - Border ice width (m)

ΣΦ - Heat loss during time of border ice formation (W/m^2)

n - number of faces where growth occurs

m - calibration coefficient related to frazil adhesion

where:

$$m = \frac{a}{(AS_F)^b} \quad \ldots (1b)$$

where:

A - water surface area free of ice (m^2)

S_F - local water slope (-)

a and b - empirical coefficients

Based on their observations of a 7.5-km long reach of gravel-bed river in New England, Calkins and Gooch (1982) proposed a modified form of the Newbury equation:

$$\Delta W = a_1 V^{b_1} \Delta T \quad \ldots (2)$$

where :

ΔW Border ice growth rate (m/day)

ΔT (Water – Air) Temperature (°C)

a_1 Calibration coefficient

b_1 Calibration coefficient

V Local velocity (m/s)

Based on data presented by Newbury and their own field study, they plotted a best fit line corresponding to $a_1 = 0.1$ and $b_1 = -1.19$. Later when doing the numerical modelling of the same reach, they found that the coefficients could be a function of the local depth. For depths less than 0.6 m and V < 0.7 m/s, they propose values of 0.08 and -0.7 respectively. For depths greater than 0.6 m, they propose values of 0.4 and -0.7 respectively when V < 0.7 m/s; and 0.1 and -2.81 respectively when V > 0.7 m/s.

Carson (1991) also proposed an integrated version of Newbury to be used in RIVICE:

$$W = a_1 V^{b_1} DD \; \ldots \; (3)$$

where :

W	Total border ice width (m)
a_1	$a_1 = 0.054$
DD	Number of degree-days (°C-d)
b_1	$b_1 = -1.5$ for a Northern Manitoba River
V	Average channel velocity (m/s)

One should probably use this equation within reasonable limits of DD since there is probably no supporting data for DD > 200 °C-d.

2. Matousek (1984) calculated a critical velocity (V_c) based on local meteorological conditions (air and water temperature and wind speed).

$$V_c = \frac{\phi_e}{1130(-0.1 - T_W)} - \frac{b_2 U_2}{1130} \; \ldots. \; (4)$$

where:

V_c	Critical vertically integrated mean velocity (m/s) beyond which no border ice grows
Φ_e	Unit heat flux to the atmosphere (W/m^2)
T_a	Air temperature (°C)

Where the local velocity is less than the critical velocity, border ice will form.

If $0 > T_a > -12°C$: $\Phi_e = -81+12T_a+3.2(0.8T_a-0.1)U_2+0.1(318+4.6T_a)$ ... (4b)

If $T_a < -12°C$: $\Phi_e = -96+11T_a+3.2(0.7T_a-0.9)U_2+0.1(326+4.6T_a)$ … (4c)

where :

T_w	Water temperature (°C)
b_2	coefficient
	= -0.9+5.8log(open top width between border ice (m))

U_2 Wind speed 2 m above water surface (m/s)

The interesting aspect of the Matousek equation is that it incorporates the open top width. Presumably, this is to account for bridging processes. Also of interest is that the growth is assumed to act instantaneously for all areas less than V_c.

3. Michel (1982) also evaluated border ice growth based on a critical velocity and local meteorological conditions. However, he also added the effect of the local ice concentration.

$$\Delta W = \frac{\Delta \phi}{\rho_w \cdot L} 14.1 \cdot (\frac{V}{V_c})^{-0.93} \cdot N^{1.08} \quad \ldots (5)$$

where:

- $\Delta\Phi$ Heat per unit area extracted from water for the same period (K cal/m^2)
- P_w The specific gravity of water 1000 kg/m^3
- L Latent heat of fusion of ice 80 K cal/kg
- V Depth integrated mean local velocity adjacent to the border ice (m/s)
- V_c The maximum observed velocity for adherence of frazil, 1.2 m/s

where:

$$N = \frac{Q_i^S}{V \cdot t_i \cdot T} \quad \ldots (5b)$$

where:

- N Ice concentration (dimensionless): Note if $N < 0.1$, set $N = 0.1$
- Q_i^S Frazil ice transport rate (m^3/s)
- V Depth integrated mean local velocity adjacent to the border ice (m/s)
- t_i Mean frazil ice pan thickness (m)
- T Open top width (m)

Where Michel uses $V_c = 1.2$ m/s. Note that equation 5 does not calculate a value for V_c and therefore the equation only uses the concept of a critical velocity.

Morse et al. (2006) included an evaluation of Newbury and Michel's model and evaluated a new model proposed by Morse and a simple model based only on DD information. Experimental equations are calibrated using Michel's database of 67 time periods in straight and curve river sections on the Ste. Anne River. The available data are the following:

- W Width of border ice over a given period of time (m)
- V Open surface water velocity adjacent to the border ice (m/s)
- DD Number of degree-day of freezing during the period (°C-D)
- N Frazil concentration (-)

Table 2.2 presents the results of curve fitting using eight different equations to model the 67 border ice growth data. The table presents the optimized values obtained for the curve-fitting parameters (a, b and c). It also presents the resulting correlation coefficients (CC) and root mean square errors (RMSE). The process used for calibration is a multidimensional unconstrained nonlinear minimization of the total square error. The critical frazil concentration (N_c) value used in all the equations is 1.1. This value was validated using statistical methods.

Table 2. 2 Results of the border ice growth equations calibrations

Name	**Equation**	**a**	**b**	**c**	**CC**	**RMSE (m)**
Simple 1	$W = aDD$	0.0316	-	-	0.782	0.99
Simple 2	$W = aDD^b$	0.0162	1.1471	-	0.784	0.98
Newbury	$W = aV^b DD$	0.0241	-0.4700	-	0.806	0.95
Michel	$W = aV^b N^c$	6.1288	-0.1888	1.1421	0.887	1.28
Morse 1	$W = aV^b DD/(N_c-N)$	0.0179	-0.4968	-	0.913	0.65
Morse 2	$W = aV^b DD^c/(N_c-N)$	0.0053	-0.6573	1.2492	0.922	0.61
Morse 3	$W = aDD/(N_c-N)$	0.0239	-	-	0.894	0.71
Morse 4	$W = aDD^b/(N_c-N)$	0.0112	1.1677	-	0.898	0.69

Table 2.2 shows that all Morse's equations give the best results corresponding to a correlation coefficient around 0.9 and a RMSE value around 0.65 m. The equation that describes best the growth of border ice is Morse 2 since it gives the highest correlation (0.92) and the lowest RMSE (0.61 m).

2.1.2 Breakup of river ice

The main processes taking place during the so-called breakup period are the decay, fracture, transport and eventual clearance of the ice from a river. Breakup is triggered by warmer weather and is of particular interest because major ice jams with serious potential for damage often occur (Environment Canada New Brunswick).

When the air temperature rises, particularly the higher daytime temperatures, snow and ice surface begins to melt. Ice breakup on rivers usually happens very quickly, mainly at night, and it is practically impossible to make measurements on the fast-moving water and ice. Thus, it is one of the least known natural ice process phenomena.

Breakup is characterized by the formation of ice jams, and numerous icy floods (Michel, 1971). If there are constrictions in the river, such as where bridge abutments have been placed out into the river, the breakup ice may jam the river and cause flooding (River ice). A conceptual model of the breakup process is developed and discussed as a means of addressing short-term forecasting problems (Beltaos, 1984).

The breakup of a river is divided into three phases, although one or two of them may not fully occur in certain cases. These phases are the pre-breakup period, the drive and the wash.

During the pre-breakup period, even before air temperatures rise above freezing, snow on the river ice cover and on land begins to melt under the influence of solar radiation. At the drive period, firstly, it is mechanical process of destruction by the action of hydrodynamic forces acting on the ice cover. The next movement of the ice cover depends on the possible combinations of river discharge and strength of the ice sheet. Finally, with ever-increasing discharge and the ice cover weakening by thermal effects, one of the bigger jams gives way and is impact carries all others along its course, freeing the river of ice in a matter of hours. At the wash period, the vertical walls attest to the shearing action of the ice pack and maximum levels attained by the ice. The spring flood comes and cleans the ice floes left over on the banks and bordering lowland (Michel, 1971).

Figure 2. 3 Thermal breakup (left) and Mechanical breakup (right) (NWSFO)

River ice cover breakup is usually the result of hydrothermal and hydromechanical processes, the relative importance of each being largely dependent on meteorological conditions (Davar et al., 1996). Warm weather normally melts the snow pack and weakens the ice cover. In addition, longitudinal and transverse cracks further reduce the strength of the cover. These two main types of breakup of ice cover are shown in Figure 2.3.

For thermal breakup, weather is the most important factor, including warmer air and water temperature and reflectance of the ice surface. Surface color influences absorption of sunlight. Also, direct sunlight plays a large role. Water on ice decreases reflection, may promote melting. Development of open water allows more heat to enter the flow, melting ice from below. (NWSFO)

For Mechanical breakup, ice cover is pushed higher or lower, causing it to break into pieces. Hydrodynamic forces act on ice cover exceed cover strength. Physical factors are quite important. The rate of the snowmelt and rainfall and the subsequent runoff are the major factors affecting the breakup process. A high rate of snowmelt and rainfall, and consequently a rapid increase in river flows, normally results in an early breakup of a relatively strong ice cover. This form of breakup may occur in mid-winter or early spring and generally causes the worst flooding (Environment Canada New Brunswick). On the other hand, slow snowmelt causes a gradual increase of the river flow and a gradual decay of the ice cover resulting in significantly lower peak water levels. Beltaos (1990) introduced the concept of the formation of longitudinal and transverse cracks. He also indicated boundary constraint leads to a breakup forecasting criterion. This explains that the past empirical findings and identifies the factors influencing various empirical coefficients.

We have accumulated a good understanding on phases and types of the breakup process. However, a concise method to predict the occurrence of ice cover breakup is still needs development. In particular, the rate and magnitude of the rise of discharge that can trigger a dynamic break up on a controlled or uncontrolled river need to be determined. Beltaos (2003) suggested that a breakup ice run would occur when the water level rises above that of a preceding freeze-up by a specific amount proportional to the end-of-winter cover thickness. Such a site-specific threshold criterion is of great practical value. A joint effort from the ice engineering community could help to improve and generalize this criterion. For example, a coordinated monitoring program on breakup conditions during the peaking of hydropower facilities and other natural rivers could lead to a useful database for this purpose.

The lake ice first starts to melt on the shore. Because more heat comes from the adjoining ground surface and cracks formed there due to changes in water level and thermal ice expansion. A free water surface appears along the shoreline leaving the main body of ice floating free. At that time the ice cover still has considerable strength (Michel, 1971).

In some areas of Canada, during winter, from mid-November to the end of May, icebreaking services provide on the Labrador Coast, East Coast, Gulf of St. Lawrence, the St. Lawrence and Saguenay Rivers and in the Great Lakes. The objectives of icebreaking conclude: to facilitate the safe and timely movement of maritime traffic through or around ice-covered waters; to minimize the effect of flooding caused by ice jams on the Saint Lawrence River; to assist in the re-supply of northern communities for which there are no commercial services (CCG).

An icebreaker is a special-purpose ship or boat designed to move and navigate through ice-covered waters. An icebreaker requires three traits that most normal ships lack: a strengthened hull, an ice-clearing shape, and the power to push through ice-covered waters. The hovercraft (Figure 2.4) has been in service for over 20 years in Trois-Rivières and Québec (Public Works and Government Services Canada (PWGSC)).

Figure 2. 4 The Canadian Coast Guard's new Hoverwork AP1-88/400 *Mamilossa* (PWGSC)

Ship transport occurs throughout the winter season in some channels including the Saint Lawrence River. It has led to the catastrophic breakup of the ice sheet close to shore in the past, and the spalling of large ice floes into the navigation channel. Stander et al. (2005) describe the results of a field program carried out for the Canadian Coast Guard in 1995. They defined some of the possible parameters responsible for foe ice failure, and laid a foundation for a theoretical study on ice sheet flexure in a kinematic environment.

2.2 Introduction of Saint Lawrence River

The Saint Lawrence River is the second longest river in Canada, originates at the outflow of Lake Ontario. It traverses an international section (Ontario and USA) and then Québec.

The river includes river reaches and fluvial lakes including Lake Saint-Louis, Lake Saint Francis and Lake Saint-Pierre. The River runs 3,058 km from the furthest headwater to the mouth and 1,197 km from the outflow of Lake Ontario. Its watershed is 1,344,200 km^2, of which 839,200 km^2 is in Canada and 505,000 km^2 is in the United States. The basin covers the provinces of Ontario and Québec, and the states of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, Vermont, and Wisconsin. (Natural Resources Canada (NRC))

Moreover, the St. Lawrence hydrographic system, including the Great Lakes, with a surface area of 1.6 million km^2, is the third largest drainage basin in North America, (See Figure 2.5) after the Mississippi and Mackenzie rivers. It drains more than 25% of the Earth's freshwater reserves and influences the environmental processes of the entire North American continent. Over 30 million Americans and 15 million Canadians live in this immense basin. The major hydrographic divisions of the Saint Lawrence River include the Fluvial Section, the Fluvial Estuary, the Upper Estuary and Saguenay River, and the Lower Estuary and Gulf. (EC)

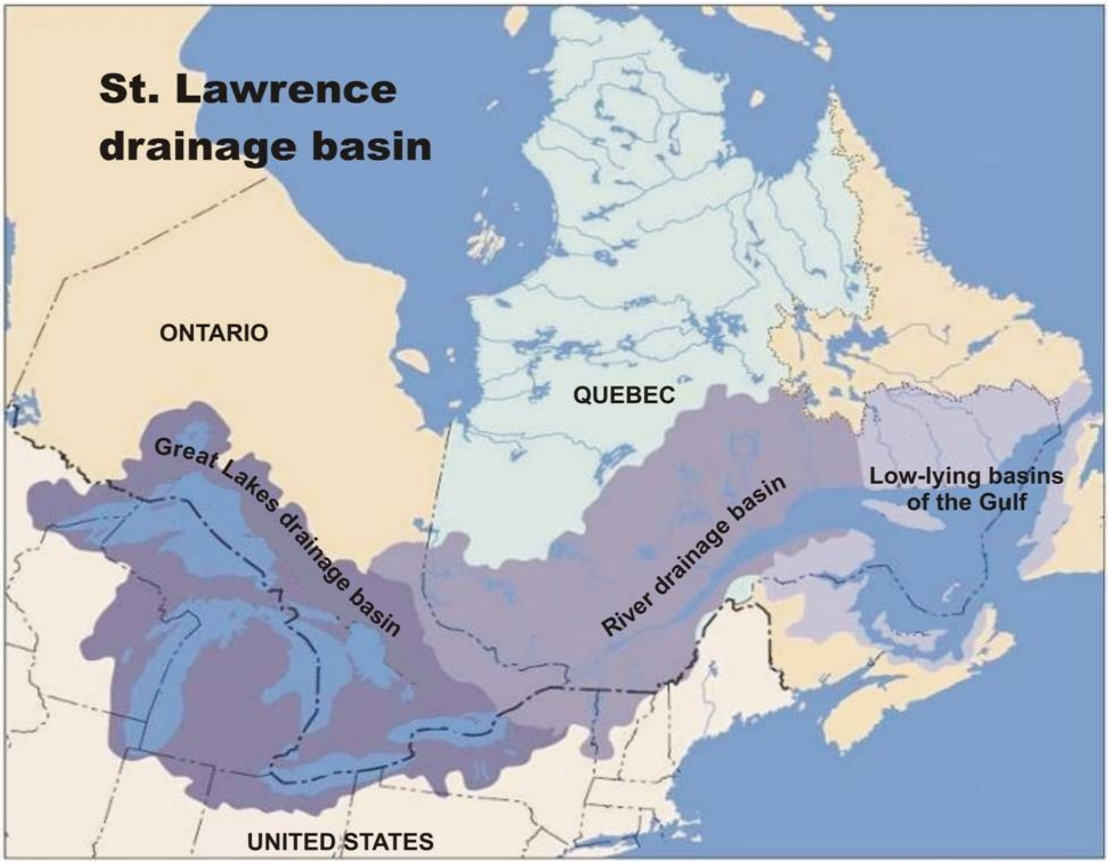

Figure 2. 5 St. Lawrence/Great Lakes drainage basin (EC, 2011)

On the other hand, the geographic position of the St. Lawrence and its physical characteristics make it a significant socio-economic asset for Québec, Canada, and the industrial heartland of the United States. The St. Lawrence links the Atlantic Ocean with the Great Lakes and is among the world's most important commercial waterways.

2.3 Existing documentation on Saint Lawrence River

In the last decades, a large number of researches have been devoted to investigate the Saint Lawrence River. The St. Lawrence Centre (SLC) is a research center attached to Environment Canada (EC), with a focus on the Saint Lawrence River's ecosystem. Specifically, it conduct a multitude of studies and research programs aimed at more sufficiently understanding how the ecosystems of the Saint Lawrence River function and at keeping this knowledge up-to-date. The St. Lawrence Global Observatory (SLGO) is also focus on the St. Lawrence global ecosystem, which is an initiative to provide integrated access to data and information from a network of governmental, academic and community organizations. Moreover, there are other organizations work with a wide variety of research and survey for Saint Lawrence River such like Canadian Coast Guard (CCG), and Canadian Ice Service (CSI) who publishes the ice distribution in Saint Lawrence River. As well as the Saint Lawrence River Institute of Environmental Sciences, a non-governmental organization located in Cornwall, Ontario. Its mandate is research, education and community action relating to large river systems, with various individuals, groups, agencies and communities to fulfill its environmental mission of the Saint Lawrence River ecosystem.

Recently, some researches on the ice processes in the Saint Lawrence River have been published. For the study of ice on Saint Lawrence River, Morse et al. (2003a) summarized the characteristics of brash ice in the Saint Lawrence River downstream of Montréal. Richard and Morse (2007) presented the results of a field study of multiple frazil ice blockages of a municipal water intake located on the north shore of the Saint Lawrence River at Québec City, Canada. Adams (1976) estimated water temperatures and time of ice formation on the Saint Lawrence River. Specifically, monthly mean losses from the surface of the river during the fall-winter cooling period were determined by an empirical heat budget which incorporated the processes of radiation, conduction, convection and precipitation. Shen et al. (1981) reported the flow and ice conditions in the upper Saint Lawrence River.

For river ice monitoring and prediction, Emond et al. (2009) reported on the field campaign to develop the use of infrared thermography as a means of river ice monitoring. Shen et al. (1984) developed a computer model for simulating the formation of ice cover in the Upper Saint Lawrence River. For Saint Lawrence River freeze-up forecast, Foltyn et al. (1986) developed a method for making long-range forecasts of freeze-up dates in rivers. Through the study, the water temperature response parameters can be either estimated from the surface heat exchange coefficient and the average flow depth or determined empirically from recorded air and water temperature data. As for other research methods to predict the ice characteristics, Morse et al. (2003b) evaluated the potential of using artificial neural networks (ANNs) to model ice parameters related to ice jams in the Saint Lawrence River navigation channel through lake St. Pierre.

Also, research on the ice boom on Saint Lawrence River, Cornett et al. (1998) presented an analysis of the loads measured in ice control booms deployed at three locations during the winters of 1994 to 1997. Morse (2001a, 2001b) presented generic equations and the results of measured ice forces on three booms along the Saint Lawrence River downstream of Montréal.

Chapter 3
Statistical results and analysis

In this chapter, we first obtain a general idea of border ice location and existence conditions. Then, we analyze the factors influencing border ice formation and decay.

Based on an analysis of ice charts, we identify which conditions are beneficial to the existence of border ice. We also track and quantify the loss of the border ice areal coverage.

More specifically, we note the date and calculate the Degree Days required for the ice areal coverage to reach to 20% of the maximum; to reach the end of the rapid growth period (i.e., ‘Plateau 1’); and to reach its maximum coverage each winter. Finally, a comparison of the river flow velocity and depth in the River with ice and without ice is presented.

3.1 Existence of the border ice on Saint Lawrence River

This section is devoted to find out what elements are required for the existence of border ice on Saint Lawrence River. On the ice charts, the gray area indicates the presence of the fast border ice which is the subject of our study.

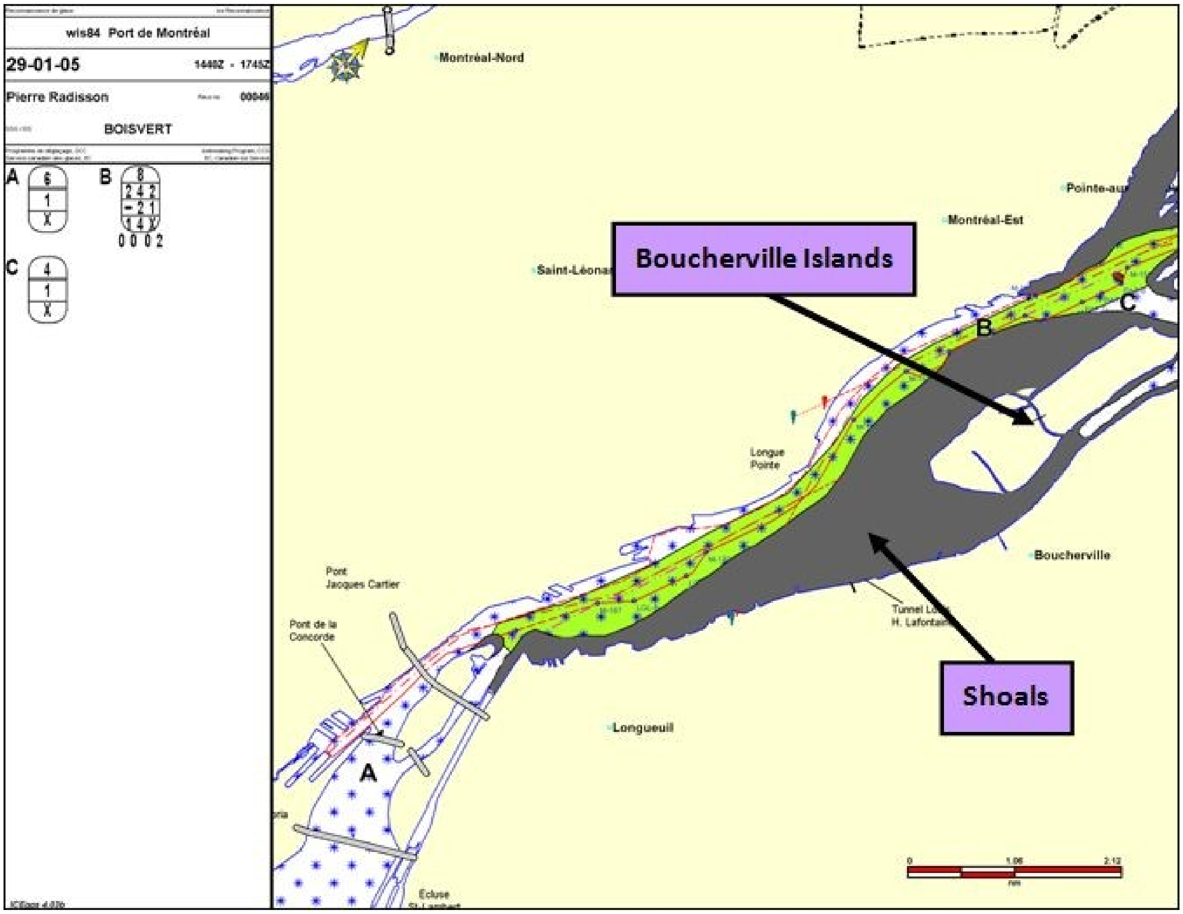

Figure 3. 1 ‘Port of Montréal’ reach of Saint Lawrence River on 29th Jan. 2005

As shown in Figure 3.1, there are several shoals and ‘Boucherville Islands’ near the south side of the river in ‘Port of Montréal’ reach on Jan. 29th, 2005. These shoals are obstacle to river flow. Thus, the flow velocity of river will decrease when river water flows through these shoals. This is beneficial to ice formation. Also, the Boucherville Islands divide the river into two parts. The secondary channel located on the south side of the river nearly has full ice coverage. The navigation channel (located in the main channel) operates 365 days a year. It is difficult to form ice there as commercial navigation is continuously breaking it.

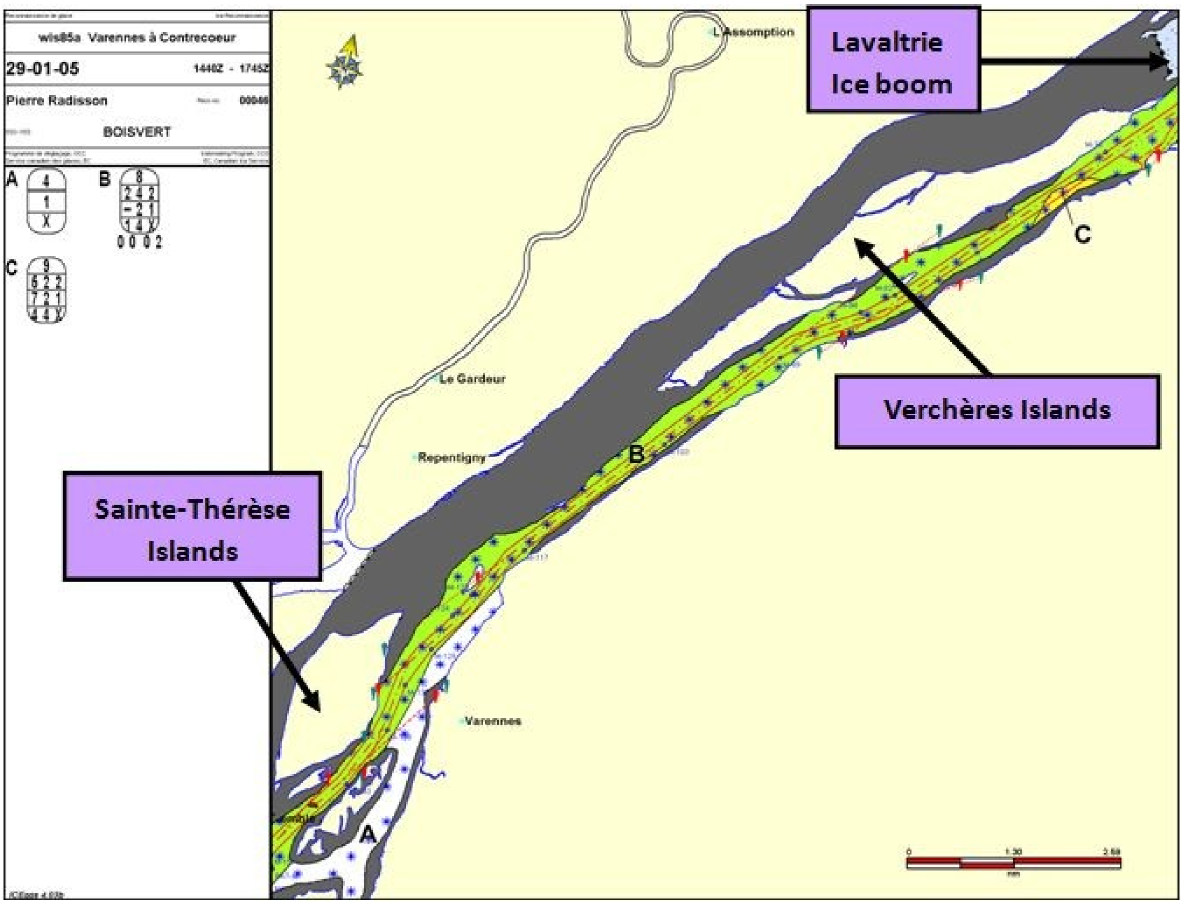

Figure 3. 2 'Varennes to Contrecoeur' reach of Saint Lawrence River on 29th Jan. 2005

Figure 3.2 presents the 'Varennes to Contrecoeur' reach on Jan. 29th, 2005 wherein there are the 'Sainte-Thérèse Islands', the 'Verchères Islands' and 'Lavaltrie Ice Boom'. Due to the length of the islands, the river is divided into two channels. The secondary channel (north of the islands) is shallow and narrow and easily forms an ice cover thanks to the presence of the booms downstream. The ice cover continues upstream of the Verchères islands where it turns into border ice before finally reaching the Sainte-Thérèse Islands where once again it forms a fast ice cover between two banks. In our analysis, we included the full areal extent of all this ice knowing full well that it is only border ice on those portions where there are no islands. The main navigation channel to the south is open 365 days a years, so it does not form a full ice cover.

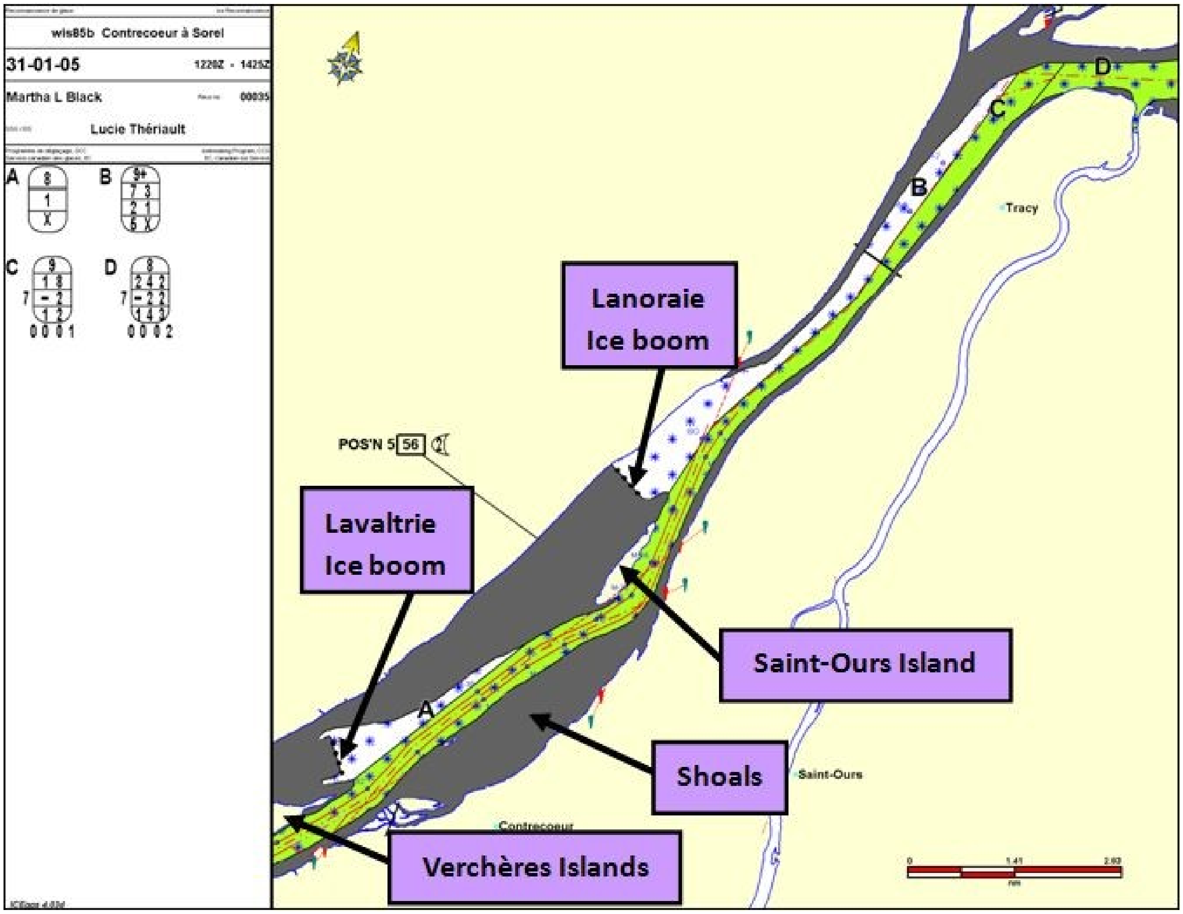

Figure 3. 3 'Contrecoeur to Sorel' reach of Saint Lawrence River on 31st Jan. 2005

In Figure 3.3, there are two ice booms i.e., Lavaltrie ice boom and Lanoraie ice boom on the north side of the river in 'Contrecoeur to Sorel' reach. The upstream boom (Lavaltrie) and the ice formed there have been discussed in the previous paragraph. The downstream (Lanoraie) boom is located between the north bank and 'Saint-Ours Island', and a full ice cover is easily formed upstream of it between the north bank and the island. Then, the ice cover continues upstream (without the help of the island) and becomes border ice until it reaches the Lavaltrie boom. We can observe that at the downstream of ice booms there is nearly no ice. When the river flow passes under the ice boom, the water is 0 °C. The water then needs to lose heat to form ice. That will occur after a certain distance that depends on the speed of the river current and if the ice has a place to lodge downstream. Also, there are several islands and shoals on south side of this river reach near Contrecoeur. Border ice is easily formed around in this area.

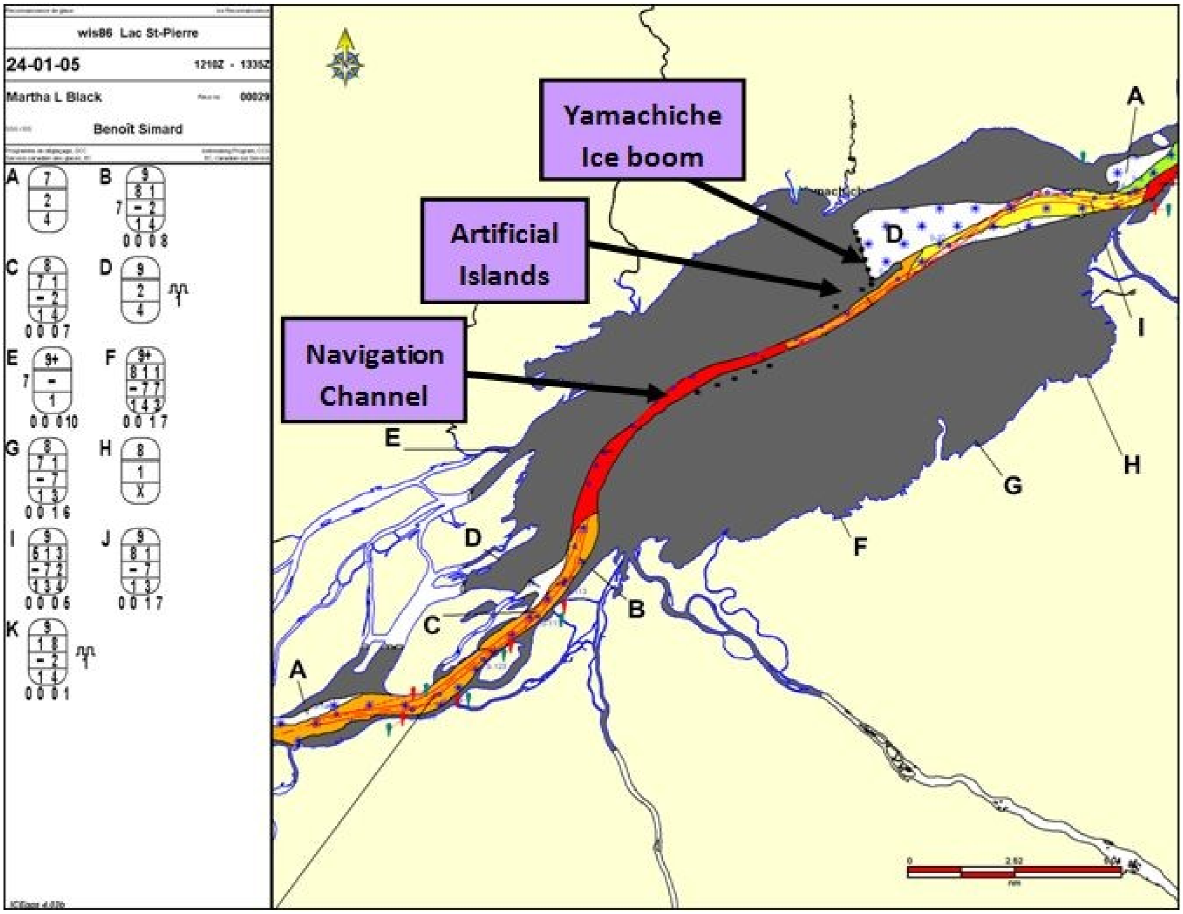

Figure 3. 4 ‘Lake Saint-Pierre’ reach of Saint Lawrence River on 24th Jan. 2005

Figure 3.4 depicts the ice chart of ‘Lake Saint-Pierre’ reach on Jan. 24th, 2005. We see that there is Yamachiche ice boom on north side of the lake, and at the upstream of ice boom, border ice is easily formed. A series of artificial islands and navigation lights at both sides of the channel make the border ice more stable, and prevent the ice sheet from breaking away and drifting into the navigation channel. Moreover, there is nearly no border ice at the downstream of the ice boom. The reason is the same as at Lavaltrie and Lanoraie ice booms discussed in the previous paragraph.

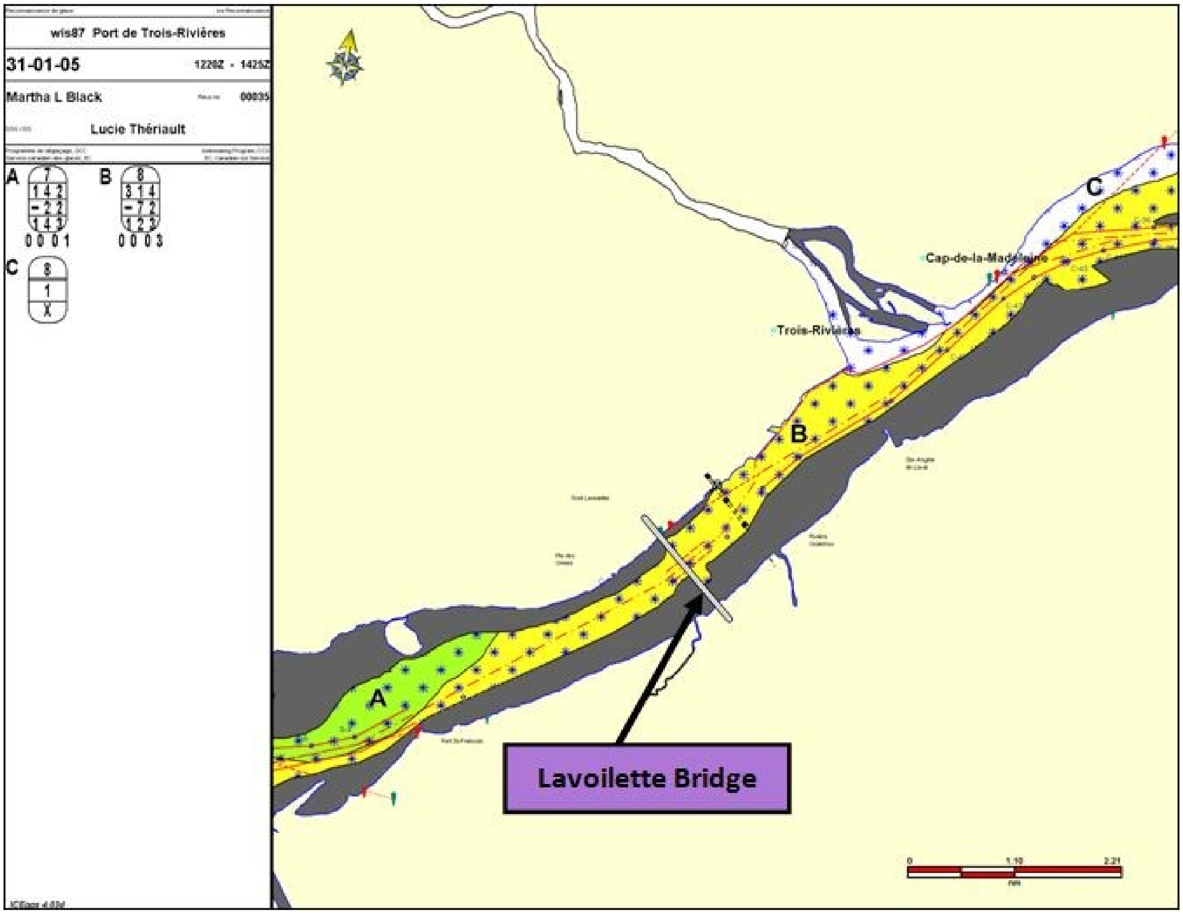

Figure 3. 5 ‘Port of Trois-Rivières’ reach of Saint Lawrence River on 31st Jan. 2005

As shown in Figure 3.5, ‘Laviolette bridge’ is located in ‘Port of Trois-Rivières’ reach as depicted on the ice chart of Jan. 31st, 2005. The width of border ice upstream bridge is obviously wider than that downstream bridge. This is because the bridge piers are obstacles to river flow at the upstream side and offer a place for the ice to be arrested. This is beneficial to ice formation there.

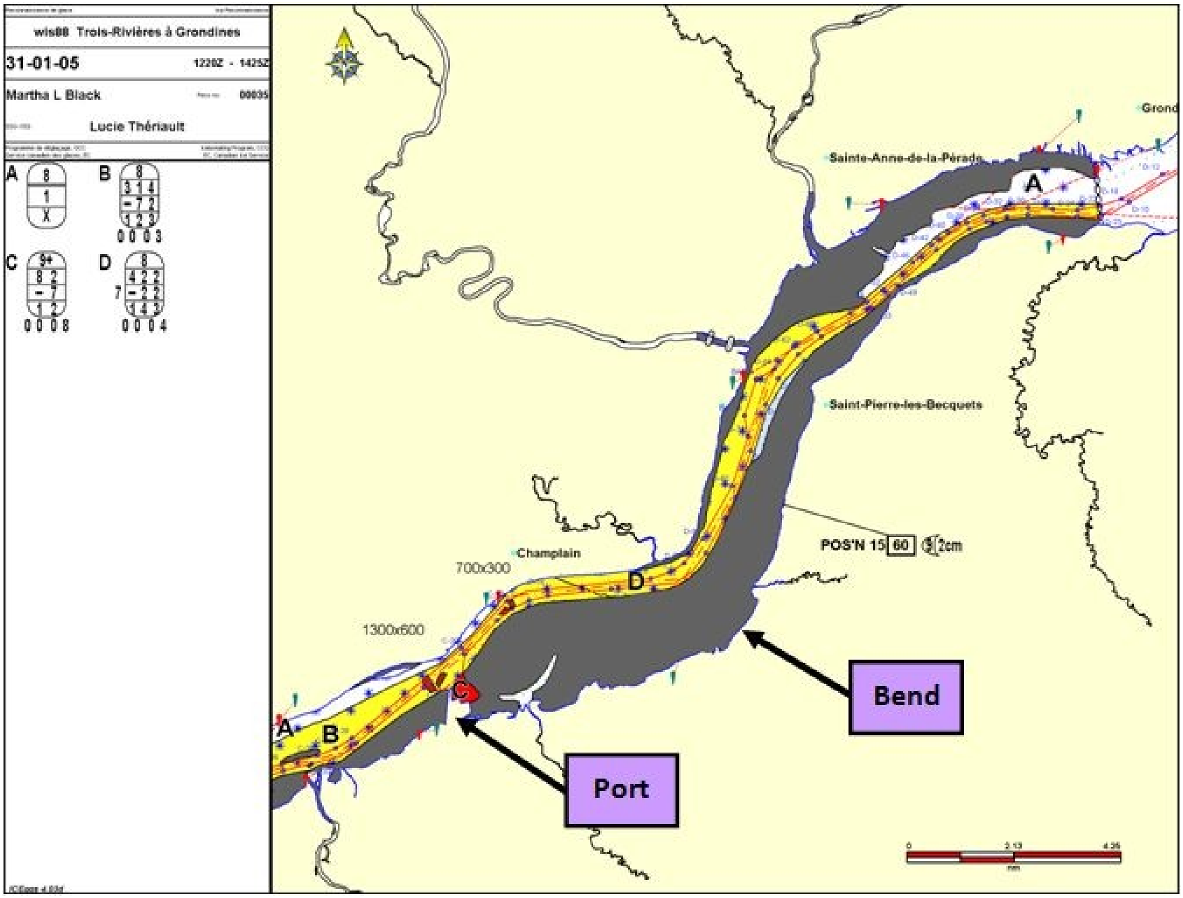

Figure 3. 6 'Trois-Rivières to Grondines' reach of Saint Lawrence River on 31st Jan. 2005

As shown in Figure 3.6, the border ice coverage reached the maximum on Jan. 31st, 2005. It is clearly seen that the border ice is easily formed at the bend of riverbank. The bend of river makes an obstacle to the river flow. This obstacle encourages the ice to freeze there and affects the flow velocity and makes it slow. Therefore, border ice is more easily formed at the curve location than normal locations. Also, there is a port located in this reach. At the port, the boats come into or sail out of the port that will make ice breakup. Meanwhile, the boats calling at the port is not beneficial to ice formation. At upstream port, the border ice is fast to the port and towards upstream direction the ice is easily formed.

Though analyzing these ice charts, we summarize the general laws where it is beneficial to existence of border ice. There are usually differences in border ice coverage related to the local river geometry. Along the river flowing direction, the border ice is formed easily when there are obstacles. The obstacles could include river bends, ice booms, shoals, artificial islands, bridge piers and so on. The obstacle influences the flow velocity, which is an important factor for ice formation and also provides an object against which the ice can become fast. The formed ice fastens to the obstacle and the ice forms gradually towards the upstream direction.

Border ice forms thermally from the river banks, as the water loses heat to the surrounding air, and grows outwards where the velocities are low enough to permit it. As a result, its formation is greatest on the inside of river bends as well as around large boulders and bridge piers. The amount of this ice that is created is highly dependent on the flow conditions and geometry of the river.

3.2 Analysis of loss of border ice coverage

In Figure 3.7, the border ice areal coverage is presented during winter season 2008-2009 on Lake Saint-Pierre. The values are obtained using the MATLAB image recognition and scaling software. During the mid-winter, the border ice coverage normally keeps a relatively stable areal coverage. As shown in Figure 3.7, the beginning of this period is ‘Plateau 1’ and the end is ‘Plateau 2’. From this figure, we could also discover that there are some dates (from 26th Dec. 2008 to 30th Dec. 2008) during which the areal coverage of border ice coverage dropped sharply. To investigate the reason why this phenomenon happens, we select one reach upstream and one reach downstream of Lake Saint-Pierre separately and Lake Saint-Pierre as our study area from Montréal to Québec of Saint Lawrence River.

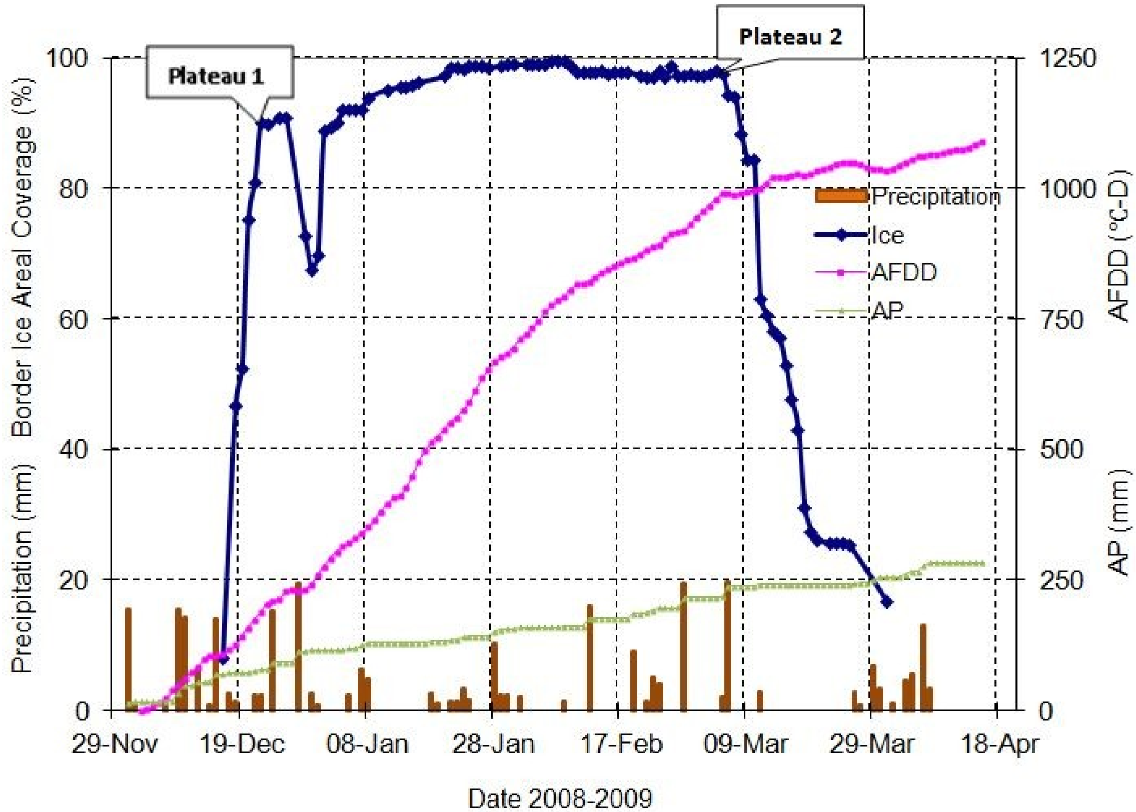

Figure 3. 7 Border ice areal coverage during 2008-2009 winter at Lake Saint-Pierre

3.2.1 Varennes to Contrecoeur

In Table 3.1, weather information and border ice coverage of 'Varennes to Contrecoeur' reach are given. We see that there are sharp drops in coverage marked with gray shading in the winter of 2005-2006, 2006-2007 and 2007-2008, respectively. The losses of areas are all higher than 10%. Especially in January 2008, the loss was 83% over 7 days (from 3^{rd} Jan. 2008 to 10^{th} Jan. 2008). The loss occurred because of a warm spell when temperatures from 6^{th} Jan. to 10^{th} Jan. are all higher than freezing point and the highest temperature was 11.3 °C on 9^{th} Jan. 2008.

Table 3. 1 Weather information and border ice coverage at Varennes to Contrecoeur

Varennes to Contrecoeur (upstream)	Date of ice loss	T_{max} (°C)	T_{mean} (°C)	Precipitation (mm)	Ice coverage (%)	Loss of coverage (%)
2004-2005	none					
2005-2006	2005/12/22	0.5	-8.2	0.6	29	
	2005/12/23	2.7	1.2	8.6		
	2005/12/24	2.6	1.5	0.4		
	2005/12/25	2	0.5	7.3		
	2005/12/26	-1	-3	4.2		
	2005/12/27	-4.1	-7.3	0	11	**17**
2006-2007	2007/03/12	6.6	2.7	0	66	
	2007/03/13	7.1	4.3	1		
	2007/03/14	8.6	6.3	6.6		
	2007/03/15	6.6	-0.7	0.4		
	2007/03/16	-5.8	-8.2	5.6	56	**10**
2007-2008	2007/12/20	-6.3	-7.5	1	99	
	2007/12/21	-2.4	-4.6	0		
	2007/12/22	1.7	-0.6	0		
	2007/12/23	8.7	4.8	5.6		
	2007/12/24	1	-1.7	0	86	**13**
	2008/01/03	-14.4	-19.7	0	90	
	2008/01/04	-1.7	-8.1	1.6		
	2008/01/05	-0.3	-2.2	0		
	2008/01/06	3.4	1.6	0		
	2008/01/07	6	4	18		
	2008/01/08	9.8	6.7	3		
	2008/01/09	11.3	7.3	0.2		
	2008/01/10	3.4	1.1	0	7	**83**
2008-2009	none					

3.2.2 Lake Saint-Pierre

In Table 3.2, we observe that the weather information and border ice coverage at 'Lake Saint-Pierre' reach. Without exception, there exists some maximum air temperature above 0 °C. The loss of border ice coverage marked with grey shading is 25%, 43% and 23% in the winter of 2005-2006, 2007-2008 and 2008-2009, respectively. With the high air temperature, there is sometimes large precipitation (20.3 mm on 5th Feb. 2006 and 19.5 mm on 28th Dec. 2008). However, the air temperature is still the most important factor for ice cover stability.

Table 3. 2 Weather information and border ice coverage at Lake Saint-Pierre

*: estimated

Lake Saint-Pierre	date	T_{max} (°C)	T_{mean} (°C)	Precipitation (mm)	Ice coverage (%)	Loss of coverage (%)
2004-2005	none					
2005-2006	2006-02-04	3.4	2.1	4.3	90	
	2006/02/05	2.5	1.7	20.3		
	2006/02/06	0.8	-3.2	0	66	**25**
2006-2007	none					
2007-2008	2008/01/06	2.9	1.3	0	97	
	2008/01/07	3.5	2	7.4		
	2008/01/08	6	3.4	5.4		
	2008/01/09	8.9*	5.3*	0*		
	2008/01/10	2.8*	-0.5*	0*	54	**43**
2008-2009	2008/12/26	-8.4	-14	0	91	
	2008/12/27	-0.4	-4.4	0		
	2008/12/28	6.4	2.9	19.5		
	2008/12/29	1.8	-1.6	0	73	
	2008/12/30	-3.3	-9.9	2.6	68	**23**

3.2.3 Grondines to Portneuf

Table 3.3 shows the weather information and the border ice coverage at 'Grondines to Portneuf' reach. There are all sharp temperature drops during these five winters. This reach is located downstream of Lake Saint-Pierre. We find that the loss of coverage condition of this reach is complicated, and there are always several times of sharp drops in every winter. That means that the border ice coverage is easily influenced and unstable. Unusually, in winter 2006-2007, there are seldom air temperatures above 0 °C and with little precipitation, but there are still several sharp drops of ice coverage.

Table 3. 3 Weather information and border ice coverage at Grondines to Portneuf

Grondines to Portneuf (downstream)	date	T_{max} (°C)	T_{mean} (°C)	Preciptation (mm)	Ice coverage (%)	Loss of coverage (%)
2004-2005	2004/12/21	-17.4	-22	0.2	77	
	2004/12/22	-4.8	-11.1	6.3		
	2004/12/23	6.5	0.8	30.9		
	2004/12/24	-3.4	-11.4	0	42	**36**
	2005/01/27	-15.5	-20.4	0	100	
	2005/01/28	-15	-20.9	0	96	
	2005/01/29	-9.2	-14.8	0	96	
	2005/01/30	-0.2	-6.9	0	93	
	2005/01/31	-7.1	-12.2	0	88	
	2005/02/01	-5.9	-12.2	0		
	2005/02/02	-2.7	-10.6	0		
	2005/02/03	0.7	-6.1	0		
	2005/02/04	3.6	-4.3	0	83	
	2005/02/05	1.5	-4.7	0	75	
	2005/02/06	0.7	-2.7	0	75	
	2005/02/07	6.6	-0.3	1.5	73	
	2005/02/08	3.7	2.1	1		
	2005/02/09	1.4	-1.6	0	69	
	2005/02/10	-4.6	-5.5	0.4	62	**38**
2005-2006	2005/12/23	0	-4	2.1	50	
	2005/12/24	-2.5	-3.7	2.2	43	
	2005/12/25	-2.6	-3.5	6.3		
	2005/12/26	-2.1	-3.9	4.3		
	2005/12/27	-5	-9.5	0.1	32	**18**
	2006/01/08	-7.5	-13.5	1	68	
	2006/01/09	-4.7	-6.2	2.3		
	2006/01/10	-2.3	-6.3	0	50	
	2006/01/11	0.4	-4.7	5.8	46	
	2006/01/12	2.4	1.1	7.7		
	2006/01/13	7.2	3.5	0		
	2006/01/14	3.7	-1.8	26.4	33	
	2006/01/15	-7.3	-12.7	0.1	29	**39**
	2006/02/03	3.1	-0.1	20.2	33	
	2006/02/04	3	1.4	0.6	26	
	2006/02/05	1.4	0.3	28.3	22	
	2006/02/06	-0.6	-4.9	0.1	17	**17**

2006-2007	2007/01/19	-2.4	-6.4	0.1	37	
	2007/01/20	-5.9	-12.3	0	18	**20**
	2007/01/23	-7.5	-13.5	0.1	43	
	2007/01/24	-6.1	-11.8	2.9	36	
	2007/01/25	-14.6	-19.8	0	21	**22**
	01/23/07	-7.5	-13.5	0.1	43	
	01/24/07	-6.1	-11.8	2.9	36	
	01/25/07	-14.6	-19.8	0	21	**22**
	02/25/07	-3.4	-7.6	0	82	
	02/26/07	-4.1	-11.2	0	68	
	02/27/07	2.7	-4.8	0	69	
	02/28/07	-2.1	-6.6	0	66	
	03/01/07	-5.8	-11.8	0	59	**23**
2007-2008	12/10/07	-9	-14.6	0.5	36	
	12/11/07	-5.3	-9.7	7.2		
	12/12/07	-2.5	-9	2.2	25	
	12/13/07	-11.9	-16.8	0.1	16	**20**
	12/24/07	2.9	-0.6	0.6	81	
	12/25/07	-1	-4.4	0.1	78	
	12/26/07	-0.1	-2.4	0.1	60	
	12/27/07	-1.2	-2.7	2.5	49	
	12/28/07	-1.5	-3.2	1.6	50	
	12/29/07	1.9	-1.2	4.5	54	
	12/30/07	-1.8	-6.3	0.1	50	
	12/31/07	-6.1	-8.3	3	48	
	01/01/08	-4.5	-6.8	0.2	36	**46**
	01/05/08	-1.8	-3.4	0.1	84	
	01/06/08	1.1	-1.2	2.8		
	01/07/08	3.4	1.8	3.3	57	
	01/08/08	5.6	3.1	15.8		
	01/09/08	6.4	3.2	7.1	35	
	01/10/08	2.1	-2	0.1	23	
	01/11/08	-0.5	-3.5	9.8		
	01/12/08	2.8	-2.7	0.8	20	
	01/13/08	-6.6	-9.9	0	18	
	01/14/08	-5.7	-6.7	0.1	10	**74**
	03/17/08	0.2	-5.3	0	42	
	03/18/08	2	-5.3	0	33	
	03/19/08	-0.3	-2.1	12.2		
	03/20/08	-0.6	-3.1	15.7	22	**20**
2008-2009	12/25/08	4.1	-7.9	6.2	68	

	12/26/08	-8.8	-16	0.2	49	
	12/27/08	-1.9	-5.4	2.4		
	12/28/08	7.4	2.8	11.5		
	12/29/08	1.7	-3.9	0.4	41	**27**
	02/25/09	-3.9	-9.7	0.1	59	
	02/26/09	-1.1	-5.3	0.8	54	
	02/27/09	7.7	0.2	14.4	46	
	02/28/09	-7.2	-12.7	0.4	41	**18**

Through the observation of all loss events for all these river reaches, there are always some dates with air temperatures above 0 °C and/or some rain in the periods when the ice coverage drops sharply.

3.3 Degree Days

3.3.1 Initial border ice areal coverage

At the beginning of winter, air temperature is quite an important factor. Ice is easily formed when the water temperature is at or slightly below the freezing point 0 °C. As presented above, we calculated border ice areal coverage through analyzing the ice charts posted on Environmental Canada website. The border ice areal coverage of ice chart of the first day in one winter has already reached a certain value. In the purpose of comparison, we select 20% of maximum border ice areal coverage as the initial value. For some mappings, some years for some locations, the very first border ice coverage exceeds 20%. In this case, we are obliged to extrapolate back in time to estimate when the 20% value occurred.

We calculate AFDD for the 20% coverage In Table 3.4, we note that the AFDD value of 2006-2007 in ‘Port of Montréal’ reach is very small (only 3 °C-D). Through observing mean air temperature at the beginning winter of this year, we found there are a large number of days with temperature above 0 °C. For this reason, the AFDD remained at a relatively low level despite many cold days. Table 3.4 shows that the AFDD required to reach a 20% coverage varies from one year to the next and from one location to the next. However, on average, most AFDD values are around 124 °C-D.

Table 3. 4 AFDD when the border ice covers 20% of the maximal coverage

(Unit: °C-D)	04-05	05-06	06-07	07-08	08-09	Average	Standard Deviation
Port MTL	94	115	**3**	112	121	**89**	**49**
V to C	150	212	123	114	119	**144**	**41**
C to S	120	81	N/A	105	N/A	**102**	**20**
Lac SP	149	81	79	62	113	**97**	**35**
Port 3R	146	94	106	73	N/A	**105**	**31**
3R to G	N/A	N/A	82	60	N/A	**71**	**16**
G to P	183	161	151	91	157	**149**	**34**
P to SN	181	143	281	64	110	**156**	**82**
Port QC	N/A	135	279	N/A	151	**188**	**79**
Average	**146**	**128**	**138**	**85**	**129**	**124**	
Standard Deviation	**32**	**45**	**98**	**23**	**20**		

Note: Port MTL = Port of Montréal; V = Varennes; C = Contrecoeur; S = Sorel; Lac SP = Lac Saint-Pierre; Port 3R = Port de Trois-Rivières; G = Grondines; P = Portneuf; SN = Saint-Nicolas; Port QC = Port de Québec. The values are around the average value marked with underline.

3.3.2 Border ice areal coverage at 'Plateau 1'

The mappings of border ice areal coverage (Annex B) show that the border ice grows quickly initially and reaches its first local maximal coverage ('Plateau 1') at the beginning of winter. (An example of the time corresponding to 'Plateau 1' is provided in Figure 3.7. 'Plateau 1' defines the end of the rapid growth period. It normally occurs when ice coverage reaches values greater than 80%.) After 'Plateau 1', the border ice grows slowly or stagnates. In Table 3.5, we can see that the AFDD when the border ice coverage reaches their 'Plateau 1' in a winter season during 2004-2005 to 2008-2009. The majority of AFDD values are around 247 °C-D.

Table 3. 5 AFDD when border ice area reaches to first local maximal coverage

(Unit: °C-D)	04-05	05-06	06-07	07-08	08-09	Average	Standard Deviation
Port MTL	210	442	414	191	190	**289**	**127**
V to C	210	281	224	159	181	**211**	**47**
C to S	210	152	N/A	183	164	**177**	**25**
Lac SP	242	189	313	241	188	**234**	**51**
Port 3R	211	150	313	232	230	**227**	**58**
3R to G	242	129	198	225	204	**200**	**43**
G to P	203	197	397	201	221	**244**	**86**
P to SN	369	291	469	219	370	**343**	**94**
Port QC	286	225	450	254	221	**287**	**95**
Average	**242**	**228**	**347**	**205**	**197**	**247**	
Standard Deviation	**54**	**98**	**102**	**30**	**61**		

3.3.3 The maximal border ice areal coverage

The AFDD values when border ice reaches to the maximal coverage in one winter season during 2004-2005 to 2008-2009 are given in Table 3.6. The average AFDD value of these 9 reaches generally increases for reaches downstream. The average AFDD value of these 9 reaches is 551 °C-D during 2004-2005 to 2008-2009. Compared with the average, the 251 °C-D for 2007-2008 is very low and shows that under the right conditions, the river can freeze-up quickly and thereafter stagnate or decline in coverage.

Table 3. 6 AFDD when border ice reaches to maximal coverage

(Unit: °C-D)	04-05	05-06	06-07	07-08	08-09	Average	Standard Deviation
Port MTL	556	539	518	191	595	**480**	**164**
V to C	556	500	490	159	595	**460**	**174**
C to S	572	500	490	191	789	**508**	**214**
Lac SP	568	338	583	330	776	**519**	**188**
Port 3R	989	584	583	232	677	**613**	**270**
3R to G	677	581	583	225	636	**540**	**181**
G to P	707	669	659	338	585	**592**	**148**
P to SN	707	669	765	254	601	**599**	**202**
Port QC	727	762	699	338	713	**648**	**175**
Average	**673**	**571**	**597**	**251**	**663**	**551**	
Standard Deviation	**139**	**123**	**95**	**69**	**80**		

3.4 Dates

The dates when border ice reaches to the maximal coverage in one winter are summarized and given in Table 3.7. In different reaches, the dates are similar in a winter season except the dates indicated in bold. Border ice coverage usually reaches the maximal value at the end of January or at the beginning of February. Also, the border ice coverage reaches peak value in early winter 2007-2008, and this average date of 9 reaches is just 25 December 2007. Otherwise, through the calculation of the average date of one reach in 5 years, the dates are always at the end of January or at the beginning of February.

Table 3. 7 Date when border ice reaches to the maximal coverage

yyyy-mm-dd	04-05	05-06	06-07	07-08	08-09	Average (mm-dd)	Standard Deviation
Port MTL	2005-01-29	2006-03-03	2007-02-22	2007-12-20	2009-01-29	**02-01**	**28**
V to C	2005-01-29	2006-02-27	2007-02-19	2007-12-17	2009-01-29	**01-30**	**28**
C to S	2005-01-31	2006-02-27	2007-02-19	2007-12-20	**2009-02-24**	**02-05**	**29**
Lac SP	2005-01-24	**2006-02-01**	2007-02-19	2008-01-04	2009-02-06	**01-29**	**17**
Port 3R	**2005-03-10**	2006-03-04	2007-02-19	2007-12-20	2009-01-29	**02-08**	**32**
3R to G	2005-01-31	2006-03-03	2007-02-19	2007-12-19	2009-01-26	**01-31**	**28**
G to P	2005-01-27	2006-02-21	2007-02-13	2008-01-05	2009-01-19	**01-29**	**19**
P to SN	2005-01-27	2006-02-21	2007-02-21	2007-12-22	2009-01-20	**01-28**	**25**
Port QC	2005-01-28	2006-02-28	2007-02-16	2008-01-05	2009-01-26	**02-01**	**21**
Average	**2005-02-01**	**2006-02-24**	**2007-02-18**	**2007-12-25**	**2009-01-30**	**01-31**	
Standard Deviation	**14**	**10**	**3**	**8**	**11**		

3.5 Maximal border ice coverage, AFDD and AP

This part, we discuss maximal border ice coverage in terms of actual surface area. We also present AFDD and AP values. Table 3.8 provides data for Lake Saint-Pierre as well as a representative upstream reach (Varennes to Contrecoeur) and a representative downstream reach (Grondines to Portneuf) for the five winters studied.

Areal coverage shows that border ice on Lake Saint-Pierre is about 6 to 8 times greater than the chosen upstream and downstream reaches hence its importance to hydraulic conditions on the St. Lawrence and its specific interest to CCG and EC. Typically, areal coverage on the lake is between 249 and 273 km^2. Border ice coverage from Varennes to Contrecoeur varied between 30 and 38 km^2. Coverage in the downstream reach varied between 34 and 44 km^2. Typically (although not precisely) the lowest areal extent of the border ice coverage in all reaches occurred during the mildest winter and the greatest coverage occurred during the coldest winters.

AFDD varies from one region to the next since upstream air temperatures (measured at Montréal) are warmer than those measured downstream (at Trois-Rivières and Québec). The coldest winter was 2008-2009. The warmest was 2005-2006.

Montréal seems to get the most snow of any region reaching a maximum of 442 mm equivalent of water during the 2007-2008 winter season. The least precipitation during the period was measured at Québec during 2004-2005 when only 208 mm were recorded. Note that the AP value does not seem to have a great effect on the maximal border ice coverage.

Table 3. 8 Maximal border ice area, AFDD and AP from 1st Dec. until 31st Mar. during winter season from 2004-2005 to 2008-2009

	04-05	05-06	06-07	07-08	08-09	Average	Standard Deviation
	Maximal border ice area (km^2)						
Varennes to	38	32	30	37	36	**35**	**3**
Lake Saint-Pierre	267	249	265	273	272	**265**	**10**
Grondines to Portneuf	44	34	40	37	40	**39**	**4**
	Maximal value of AFDD for each winter (°C-D)						
Montréal	780	582	683	745	875	**733**	**109**
Trois-Rivières	1044	612	810	923	1050	**888**	**183**
Québec	1147	862	1002	1087	1183	**1056**	**128**
	Total accumulated precipitation (AP) Dec. 1 to Mar. 31 (mm)						
Montréal	279	324	287	442	352	**337**	**66**
Trois-Rivières	220	297	181	311	255	**253**	**54**
Québec	208	344	249	342	324	**293**	**61**

3.6 Comparisons of flow velocity and river depth

In this section, we compare the flow velocity between the River with ice and the River without ice. The study area that we chose is located at Saint Lawrence River from Montréal to Trois-Rivières.

We obtain the database including the flow velocities, river depths and Froude numbers of 192744 nodes when the river covers maximal border ice and no ice separately via the simulation work of Environment Canada. Flow velocity difference is calculated by the flow velocity when the river with ice minus the flow velocity when the river without ice. Then, we generate the Figure 3.8 via MATLAB to demonstrate that their difference is between -0.1m/s to 0.1m/s. In the navigation channel, the flow velocity difference is always over 0 m/s; this means that the flow velocity when river with ice is higher than that when river without ice. Specially, the difference value in the navigation channel is always around 0.1m/s at Lake Saint-Pierre. However, velocities are diminished outside the navigation channel, under the border ice.

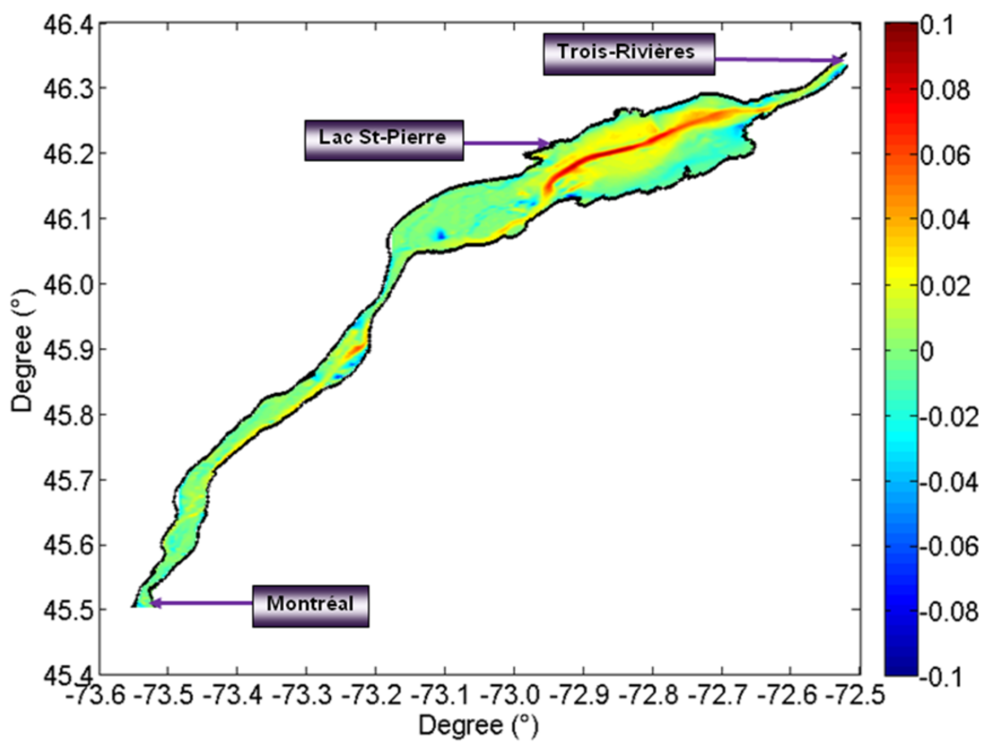

Figure 3. 8 Difference of flow velocity between the river with ice and without ice

The difference value of river depth is distributed in 0 m to +0.14 m, which is shown in

Figure 3.9. In general, the difference increases from Trois-Rivières to Montréal as the accumulated effect of the extra resistance to flow in the presence of border ice is felt.

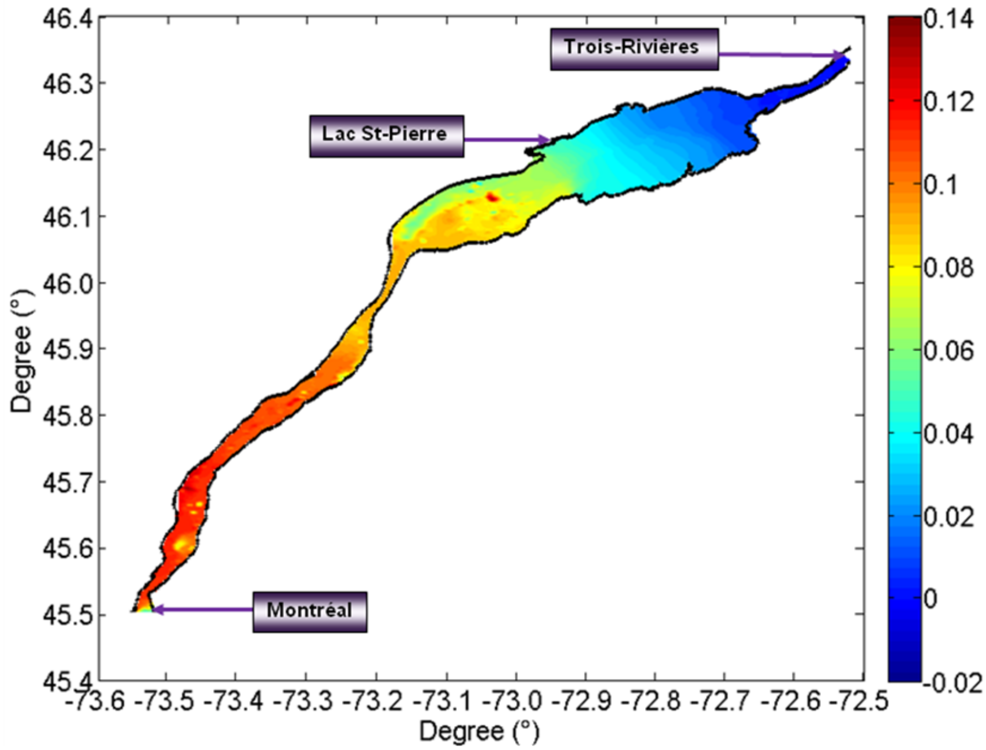

Figure 3. 9 Difference of depth between the river with ice and without ice

3.7 Conclusions

In this chapter, some heuristic analyses were made that allowed us to identify where border ice is likely to form: Upstream of bends, islands, shoals and hydraulic structures such as wharves and ice booms and other locations where currents are slow and ship traffic is not too close.

Through analyzing the existence and the loss of border ice coverage, we have a general idea of border ice and propose some general laws for ice formation and decay. We note that 20% coverage occurs, on average, after 124 °C-D and the ice finishes its rapid growth period after about 247 °C-D. We also note that the loss of border ice always occurs during a warming period that is usually accompanied by some rain.

We note that the presence of border ice generally augments velocities by about 10 cm/s in the main navigation channel of Lake Saint-Pierre while flow velocities under the ice sheets can be reduced by almost the same amount. The increase in water depth at Montréal incurred by the presence of border ice is about 14 cm.

In the following chapters, more detailed analyses are made of specific reaches.

Chapter 4
Results and analysis of border ice limit on Lake Saint-Pierre

In the following 3 chapters, we present the quantitative analyses of border ice growth on the Saint Lawrence River from Montréal to Québec. In particular, we will examine the downstream boundary conditions and time-dependent meteorological conditions required to conditions to initiate growth. Typical seasonal patterns as a function of location will be quantified.

The study area contains 9 sections each corresponding to a unique ice mapping produced by Environment Canada from Montréal to Québec City of Saint Lawrence River. They are: Port of Montréal, Varennes to Contrecoeur, Contrecoeur to Sorel, Lake Saint-Pierre, Port of Trois-Rivières, Trois-Rivières to Grondines, Grondines to Portneuf, Portneuf to Saint-Nicolas and Port of Québec. The results of 'Lake Saint-Pierre' section is illustrated and analysed as an example in this chapter. The results of other reaches are presented in Annexes A through C.

Lake Saint-Pierre is discussed through several aspects such as the border ice areal coverage, the growth rate of the border ice limit, particular with respect to the south side of the lake, as a function of AFDD. The river flow velocity, depth and Froude number along the limit of border ice once it reaches its maximal areal coverage are also presented. Both freeze-up and breakup periods are analyzed though more attention is on freeze-up period since this process is natural whereas breakup depends on the ice-breaking activities of the CCG.

4.1 Border ice areal coverage

In term of all these 9 sections between Montréal and Québec City, 2726 ice charts were downloaded and analyzed covering five winters. All the graphs of border ice areal coverage are given in Annex B of which a sample has been selected for a more detailed presentation below.

On the ice charts, the gray area indicates the presence of the fast border ice which is the subject of this study. Through programming in MATLAB, we find out the gray colour that we are interested in and get the position of each pixel, then we transfer to UTM coordinate (MATLAB program in Annex A). Based on the UTM coordinate, the area of the border ice could be calculated.

Figure 4.1 presents a selected example of Lake Saint-Pierre for the 2008-2009 winter season. In Figure 4.1 (bottom), the original EC ice charts for three individual dates are reproduced. The first chart (18th December, 2008) corresponds to conditions at freeze-up; the second (6th February, 2009) presents the maximal coverage during mid-winter; and the third (22nd March, 2009) shows conditions during the breakup period. The percentage of border ice areal coverage presented in Figure 4.1 (top) expresses the border ice areal coverage on any given day divided by maximal areal coverage of border ice that was observed for all five winter seasons (2004-2009). The values presented in Figure 4.1 (top) are obtained using the MATLAB image recognition and scaling software: During freeze-up period, the extent of border ice areal coverage of Lake Saint-Pierre grows rapidly. We observe that the area of border ice grew from 8% at the time of the very first ice chart (16th December 2008 – not shown in Figure 4.1. bottom) to 90% on 22rd December (i.e., in only 6 days). The mean air temperatures during this period were -12 °C representing 188 AFDD. During border ice coverage keeping relatively stable period, the beginning is 'Plateau1' and the end is 'Plateau 2' as shown in Figure 4.1 (top).

Then, on December 28th, temperatures rose to 2.9 °C above zero accompanied by a heavy rain of 19.5 mm. Hence, the areal coverage of border ice drops sharply down to 73%. When air temperatures drop anew, the lost area is quickly recovered. Then from very slowly climbs in surface area until the end of January and stays at relatively full stable coverage until March 5th. Note that, even at the height of winter, there is always an open area on the north side of the Lake just downstream of the Yamachiche ice boom. This open area is always found downstream of ice booms as the water (at zero °C coming from under the ice cover upstream of the boom) takes a certain time (i.e., distance) before cooling sufficiently to produce ice.

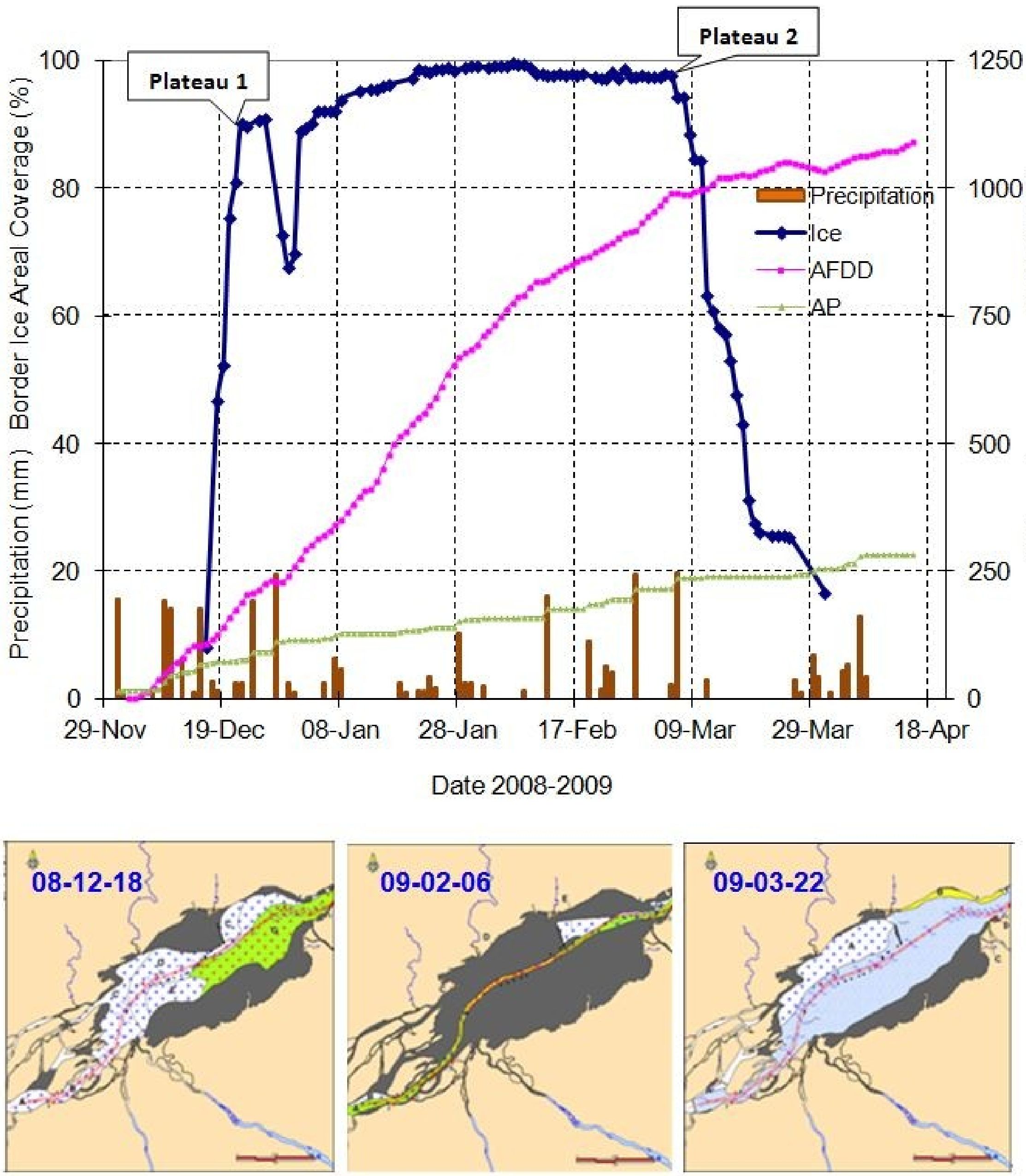

Figure 4. 1 Top: Border ice areal coverage during 2008-2009 winter at Lake Saint-Pierre

Bottom: Ice charts from Environment Canada 2008-2009

As March progresses, air temperatures rise and occasionally hit positive values. The areal extent of the ice continues to fall rapidly during that period. This is not an only natural process but rather, it is primarily the result of the effective and extensive ice breaking activities carried out by the Canadian Coast Guard (CCG) hovercrafts. This ice breaking into small pieces ensures that large pieces of border ice do not naturally break off and flow downstream where they may present a danger to commercial navigation. Once the extent of the ice is reduced to less than 20%, ice breaking is no longer necessary because the residual areas lose all strength before ice pieces naturally break off from the fast ice. The residual sheet then typically breaks into small pieces having no strength and, as such, presents no danger to ships navigating downstream. This explains why there is still 18% coverage present on the last ice chart taken on March 31st.

4.2 Freeze-up of border ice on Lake Saint-Pierre

4.2.1 Growth rate of border ice

In Figure 4.2, we observe four ice charts of the 'Lake Saint-Pierre' reach at the beginning of 2004-2005 winter which cover 21%, 59%, 81% and 93% border ice areal coverage on Dec. 20th, Dec. 24th, Dec. 25th and Dec. 27th, 2004 respectively. We see clearly that the freeze-up starts with the formation of border ice close to the river banks.

From the Figure 4.2, the ice chart upper left shows the ice coverage is 21% on Dec. 20th with the temperature of -8.8 °C. In 4 days, the ice coverage increases to 59% as shown on the ice chart upper right. Observing this ice chart, it is easily to form the border ice upstream. On the contrary, the border ice forms hardly at the downstream ice boom. In the following day, the ice coverage increases rapidly to 81% on Dec. 25th with temperature of -16 °C and reaches the maximum coverage as shown in ice chart bottom left. In the ice chart bottom right, it shows the border ice coverage reaches to maximum in 2004-2005 winter. From all these ice charts, we can observe clearly the change of the border ice coverage. In only 7 days, the border ice coverage grows quickly from 21% to 93%.

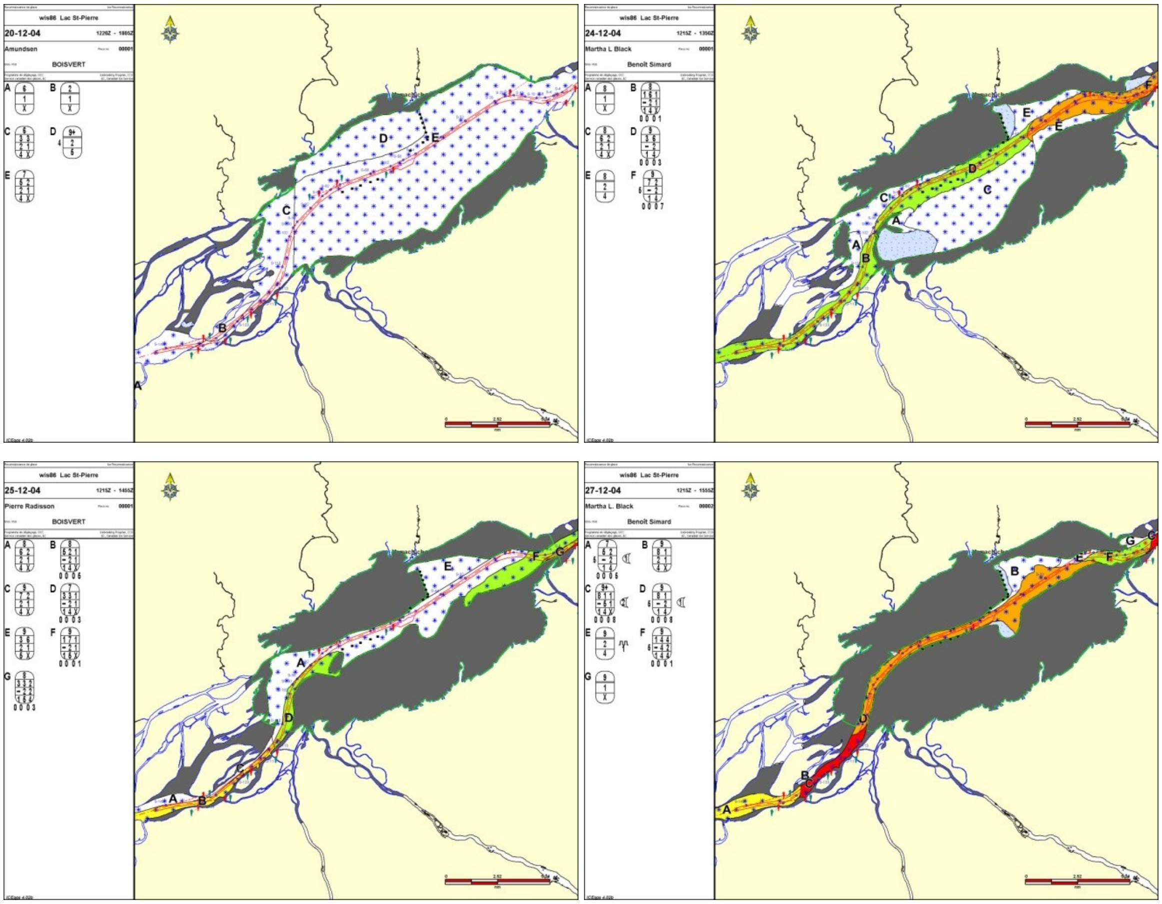

Figure 4. 2 Ice charts of Lake Saint-Pierre on 20th Dec., 24th Dec., 25th Dec. and 27th Dec. 2004

Figure 4.3 presents the Lake Saint-Pierre border ice freeze-up periods for all five winters. Based on a linear regression, growth trend lines are determined for freeze-up occurring during the areal coverage from 20% to 80%. This represents the initial ‘rapid’ growth stage. The lower limit (20%) was chosen as ice charts are normally unavailable for values lower than 20% ice coverage. The upper limit (80%) was chosen because in some years (e.g., 2005 and 2006) the rate slows significantly once the ice sheet reaches about 80% (although, admittedly, the ‘rapid’ growth can continue beyond the 80% value as in years 2004, 2007 and 2008). The regressions were made as a function of AFDD as that is the normal parameter used to estimate ice thickness.

Note that the 20% ice coverage value is reached when 80 < AFDD < 150 and the nominal 80% value is reached for 140 < AFDD < 220. This represents an increase of 60% (i.e. from

20% to 80%) in about 60 AFDD corresponding to an average increase of 1% per DD. (In fact the average value over the 5-year period was found to be 0.8% per DD). More specific values are presented in Figure 4.3. The rate of border ice growth in 2008-2009 is 0.96% per DD, which is the fastest among this 5-year period. By contrast, the rate of border ice growth in 2007-2008 is the slowest with a rate of 0.64% per DD although if only those data greater than 120 AFDD are taken, the slope of the line is very similar to those of other years.

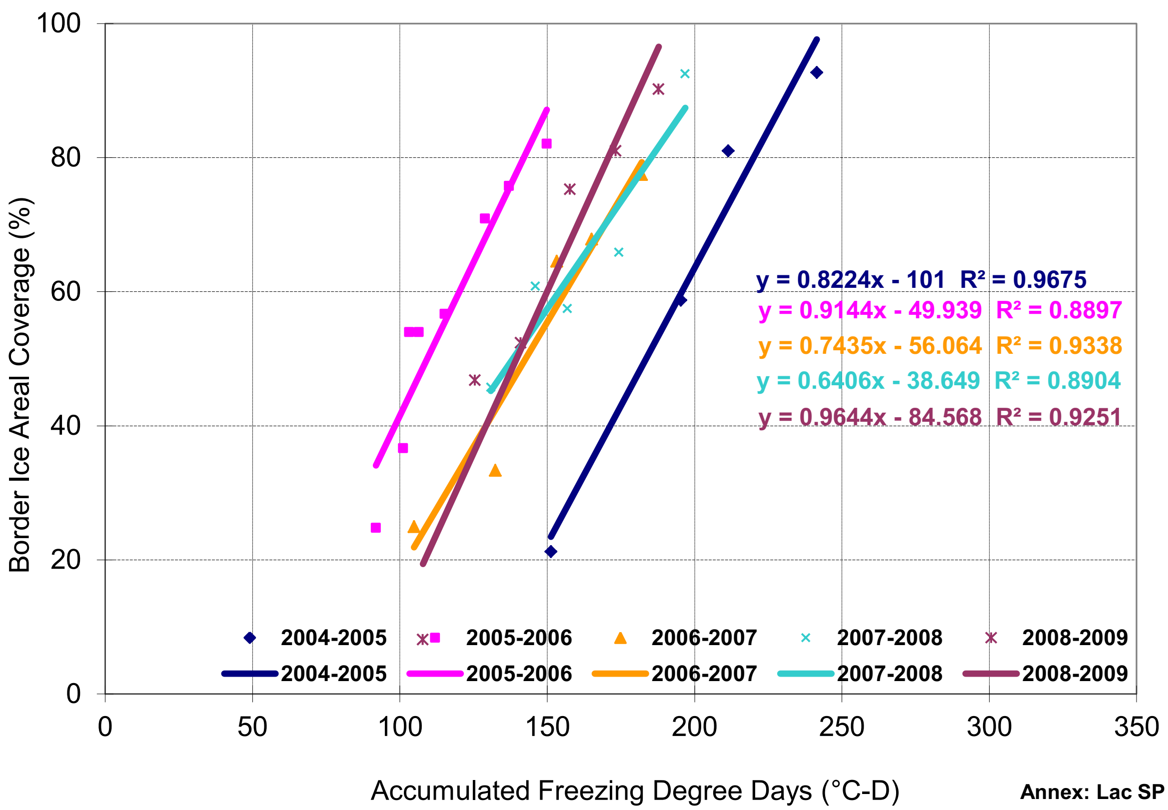

Figure 4. 3 Trend lines of ice coverage as a function of AFDD at Lake Saint-Pierre during freeze-up period

For the very fast growth (20% to 55%) and the relatively fast growth (55% to the beginning of the slow growth period – i.e., 'Plateau 1') periods, the growth rates are calculated as a function of AFDD and simply as a function of the number of days. These rates are presented in Figures 4.4 and 4.5.

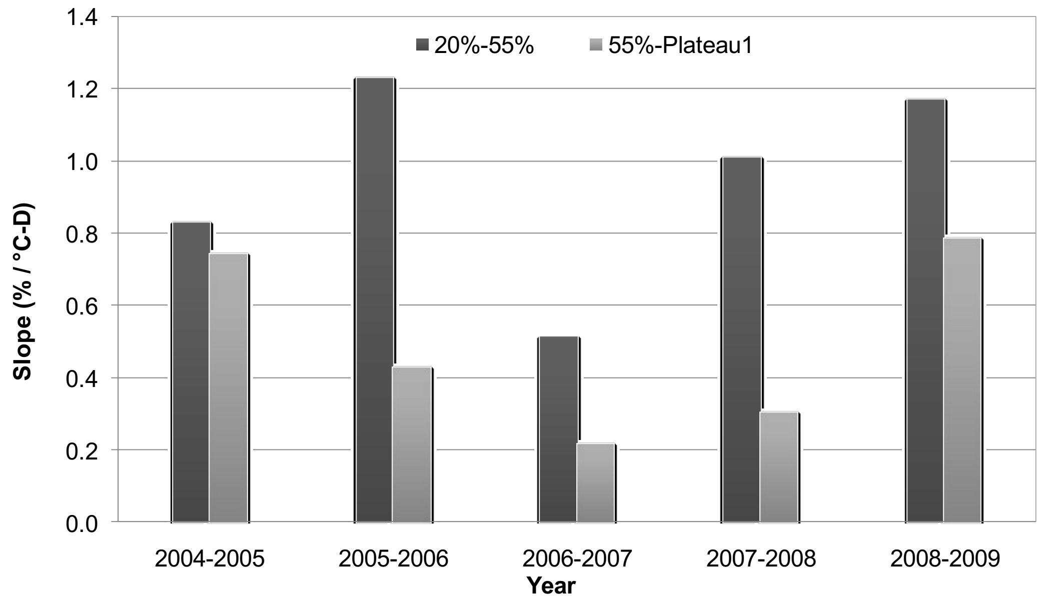

Figure 4. 4 Rate of border ice areal coverage growth per degree-day at Lake Saint-Pierre

In Figure 4.4, the rates are presented as a function of AFDD ($Slope_1$ = Increase in % / DD during the period). The black columns represent the $Slope_1$ when the border ice coverage grows from 20% to 55%. The grey columns represent the $Slope_1$ when the border ice coverage grows from 55% to 'Plateau 1'. The $Slope_1$ of 20% to 55% is higher than that of 55% to 'Plateau 1'. We can see that the $Slope_1$ in 2006-2007 winter is lower than that in other years at 0.5%/DD. Through observing the weather condition, we find that there are always some days with temperature above 0 °C during that year. The maximum value is 1.2%/DD. In other words, the variability of the rate from one year to the next is about 2.4 (i.e. = 1.2 / 0.5).

During the second part of the rapid growth period, rates vary from 0.2%/DD to 0.8%/DD representing a variability factor of about 4. Note that the correlation between the two growth periods. Generally (although not always true), if the first is fast (as in 2008-2009) the second is too whereas if the first period is slow (2006-2007), the second is too.

In Figure 4.5, growth is expressed as a function of the number of days rather than as a function of DD. The black and gray columns represent the $Slope_2$ (=Increase in % / Days during the period) for the two rapid freeze-up sub-periods. For the first sub-period, the growth rate varies from 2.5%/D in 2006-2007 to 14%/D in 2008-2009 representing a variability factor of 6. For the second sub-period, the growth rate varies from 2.5%/D to 12%/D representing a variability factor of 5. As expected, these variability factors are greater than those based on AFDD. We can conclude that AFDD is therefore a better growth predictor than simply time itself. The white columns represent the $Slope_2$ during the breakup period. Because the ice coverage decreases as time goes by during the breakup period. To obtain a positive value, we create the opposite value of $Slope_2$ during the breakup period, which is shown in Figure 4.5.

Note also, that, once again, trends in the two sub-period growth rates are fairly well correlated.

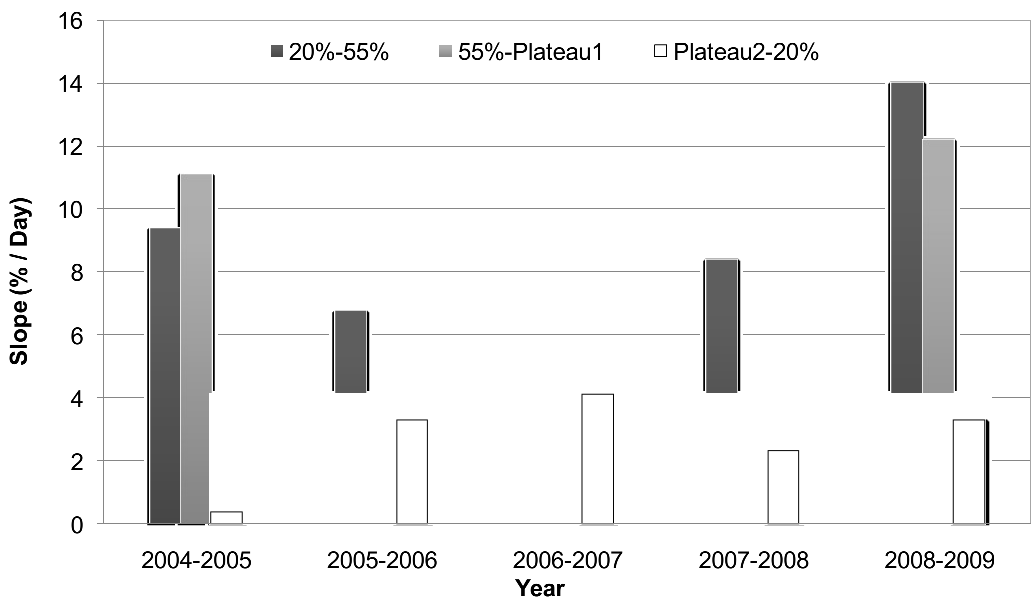

Figure 4. 5 Rate of border ice areal coverage growth per day at Lake Saint-Pierre

An analysis was also made of the direction of growth of border ice. Normally one would expect it to be roughly perpendicular to the shoreline. The length of Lake Saint-Pierre is approximate 26 km. In these 5 winter seasons, the maximum border ice coverage is 273 km^2. The distance of ice growth is roughly estimated through the area divided by the approximate length along the shore (i.e., 26 km). Thus, the maximum width of border ice on the south side of Lake Saint-Pierre is approximately equal to 5.5 km.

Accordingly, rate of border ice distance growth per degree-day for Lake Saint-Pierre is given in Table 4.1. We calculate the growing distance and AFDD values when the ice area grows from 20% coverage to 55% coverage and from 55% coverage to 'Plateau 1', respectively. As shown in Table 4.1, the growth speed from 20% coverage to 55% coverage is higher than from 55% coverage to 'Plateau 1'. This is because the growth speed of border ice is very fast once the air temperature drops below freezing at the beginning of the winter. But as the areal coverage increasing, the speed of growth tends to slow.

Table 4. 1 Rate of border ice growth distance per degree-day at Lake Saint-Pierre

(Unit: km/DD)	**04-05**	**05-06**	**06-07**	**07-08**	**08-09**
20%---55%	9	13	5	11	12
55%---Plateau 1	8	5	2	3	8

4.2.2 A detailed comparison of border ice limit on Lake Saint-Pierre

The Lake Saint-Pierre ice charts were examined in order to quantify the variability of the border ice extent (limit). The navigation channel passing through the Lake is very important for transportation between Montréal and Québec City and is vulnerable to ice jamming. The extent of border ice affects the effective navigation channel width.

For both freeze-up and breakup periods, we identified 3 ice charts corresponding to around 30%, 60% and maximal border ice areal coverage for each year, respectively. Then, we compared 30% 60% and maximal coverage in a winter season during freeze-up and breakup period. Figure 4.6 shows the limits of border ice while areal coverage is around 30%, 60% and maximal coverage during freeze-up period of winter season 2004-2005. The yellow line stands for the limit of 21% coverage. The green line is the limit of 59% ice coverage. The red line in the middle of the river is the limit of maximal ice coverage. We can see clearly the border ice grows from river banks towards the center of the Lake. During the freeze-up period, it is easy to form border ice upstream of Yamachiche ice boom whereas it takes more time for the border ice coverage to form on the south side of the Lake.

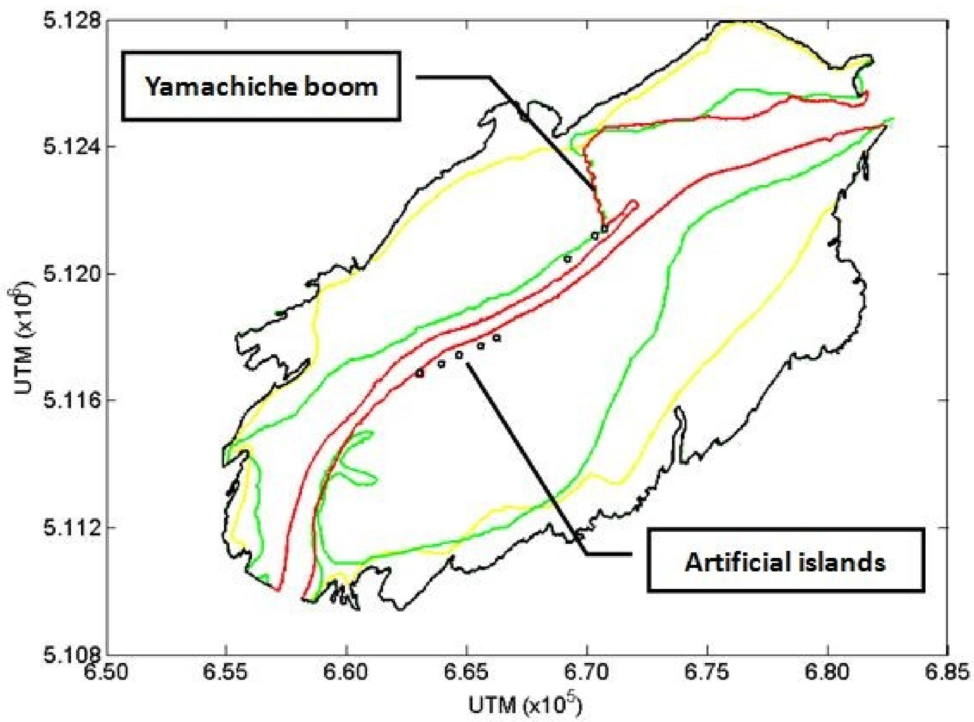

Figure 4. 6 Lake Saint-Pierre border ice limits when areal coverage is around 30%, 60% and maximal respectively during freeze-up period in winter season 2004-2005

Morse (2001b) presented the ice formation at Yamachiche ice boom (Figure 4.7) located on the north side of the Lake. Upstream of the boom (west side), border ice forms quickly and freezes into the north bank forming fast border ice. To hold the north cover fast there are a series of artificial islands and navigation lights along the navigation channel that prevent the ice sheet from breaking away and drifting into the navigation channel. The cover, formed in the area upstream of the boom, eventually (after a few weeks) freezes into these artificial islands. The cover therefore is bound on the north side as border ice right from the beginning of winter and is only eventually bound on the south side onto the artificial islands (Figure 4.7). The upstream end of the subject area (20 km upstream of the boom) is the Sorel archipelago (commonly known as the Sorel delta), which freezes early in the season. Therefore, most incoming ice to the boom consists of large sheets of thin (2-6 cm) columnar ice generated locally at the upstream end of the Lake.

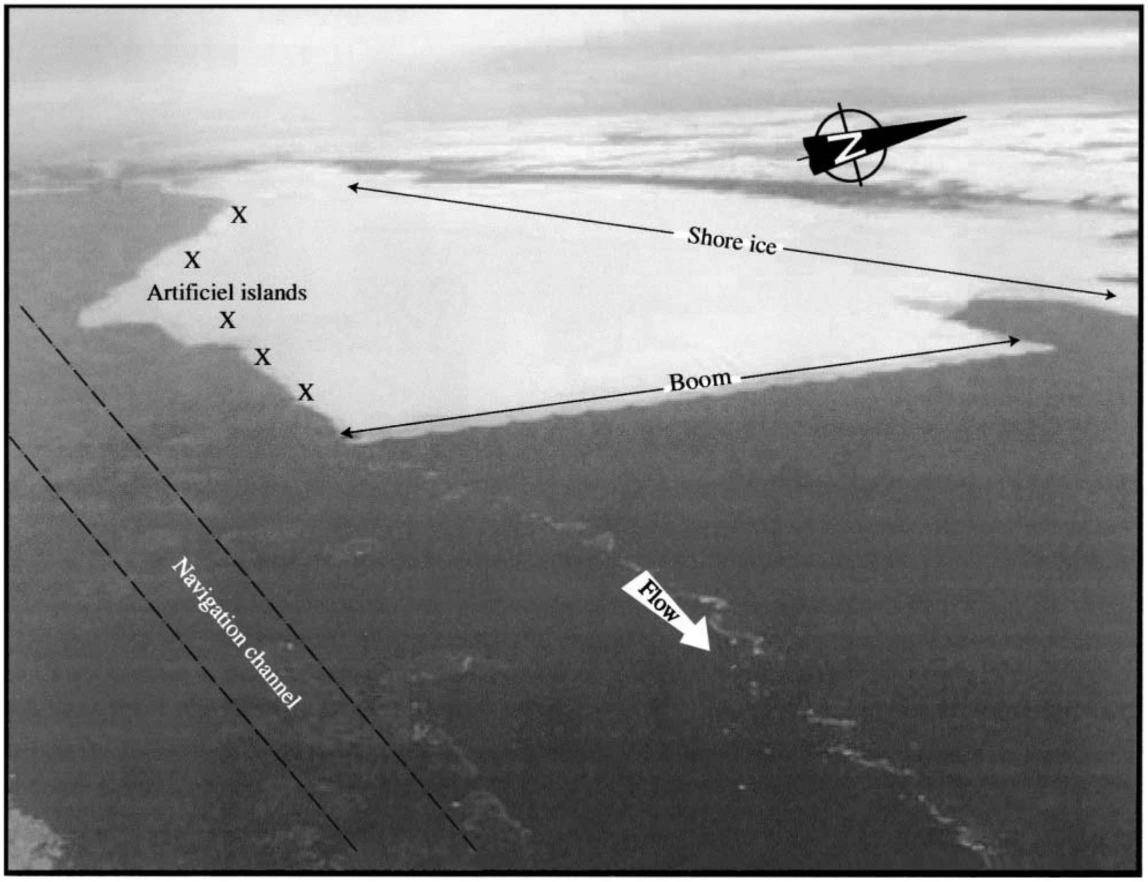

Figure 4. 7 Yamachiche boom on Lake Saint-Pierre with a fully developed ice cover upstream of it (Morse, 2001b)

The ice boom installed in 1995 at Yamachiche has greatly improved the stability of the fast ice cover along the north side of the lake. However, degradation of the cover still occurs as a result of ship transport through the St. Lawrence navigation channel. Waves generated by passing ships commonly break floes off the leading limit of the ice sheet, and have been known to produce large open leads in the vicinity of the shoreline (Stander et al., 2005).

Figure 4.8 presents the maximum border ice limits for the five winter seasons of this study.

We can see that the border ice limit follows a continuous line and the limits of maximum border ice areal coverage are similar during these five winters. The dates to reach the maximum ice coverage are all around the end of January or the beginning of February.

The main difference is the amount of encroachment downstream of Yamachiche from the border ice sheet on the south side towards the navigation channel. The reason for the variability here is that there are no artificial islands stabilising the cover in this area. It is therefore vulnerable to the forces of nature (waves, wind and current) and ships' wakes. Sometimes it stays intact right up to the navigation channel limit while at other times, it does not form close to the channel or, if it does, it subsequently gets broken away. The stability of the area has been the subject of risk to navigation studies performed by the Canadian Coast Guard. While some studies recommended the construction of additional artificial islands to stabilize the cover here, they were never considered to be of sufficient priority to warrant action (Morse, personal communication, 2011).

In Annex C, we present border ice limits for Lake Saint-Pierre corresponding to around 30%, 60% and maximal border ice areal coverage during both freeze-up and breakup periods in all these 5 winter seasons.

In Figure 4.8, the Lake shore is in black. Blue line is border ice limit in 2004-2005. Red line is border ice limit in 2005-2006. Green line is border ice limit in 2006-2007. Pink line is border ice limit in 2007-2008. Yellow line is border ice limit in 2008-2009. (In Figure 4.10, 4.11 and 4.12, the limits and southern Lake shore in 5 winters are also presented with the same colours.)

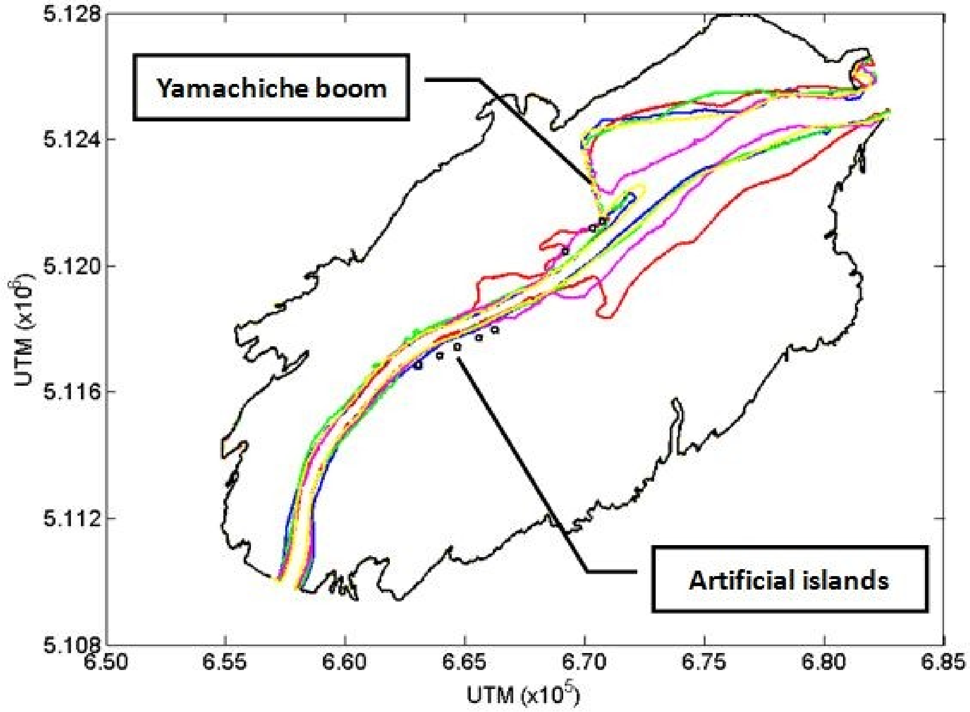

Figure 4. 8 Border ice limits of maximal areal coverage of Lake Saint-Pierre during 5 winter seasons

In Figure 4.9, we check the maximal border ice limit on 29th Jan. 2005 interpolated onto Google Earth via MATLAB. The border ice limit and the lake bank are quite suitable. It is shown that the limit location is corresponding to that in Figure 4.8.

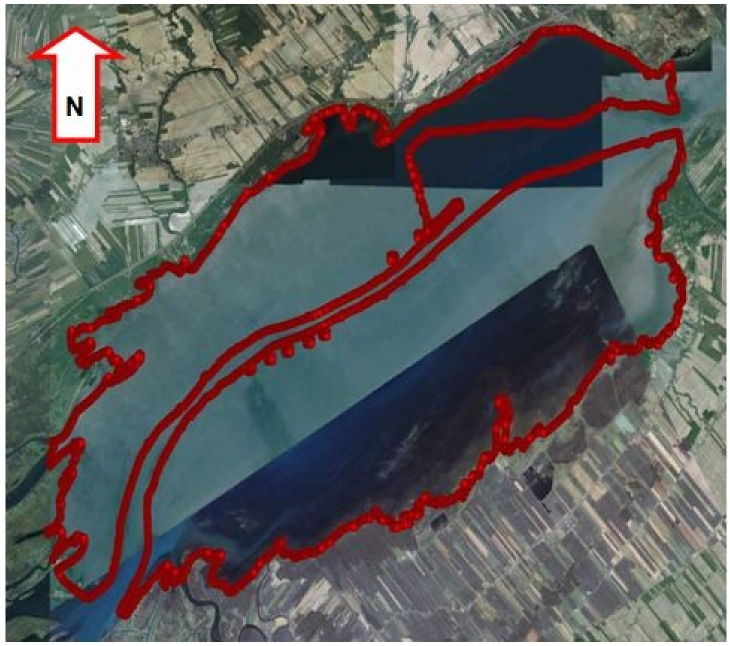

Figure 4. 9 Border ice limits of maximal areal coverage of Lake Saint-Pierre on 29th Jan. 2005

Because ice growth on the south side of the Lake is of special interest and because its growth is quite variable (Brochu, 2008), a special analysis was made of its growth. We selected to examine its areal distribution when it was at exact 40% (Figure 4.9), 80% (Figure 4.10) and 100% (Figure 4.11) via interpolating between 2 limits beside the coverage percentage we need.

In Figure 4.10, the border ice limits are presented for 5 winters when the ice coverage is 40%. The values presented are interpolations of observed ice conditions during each year. The limits of these 5 winter seasons are not very similar. At the beginning of the winter, the formation of border ice is greatly influenced by the air temperature and other meteorology conditions. The variability of the growth pattern may well be due to a combination of hydraulic, temperature, precipitation and especially wind effects.

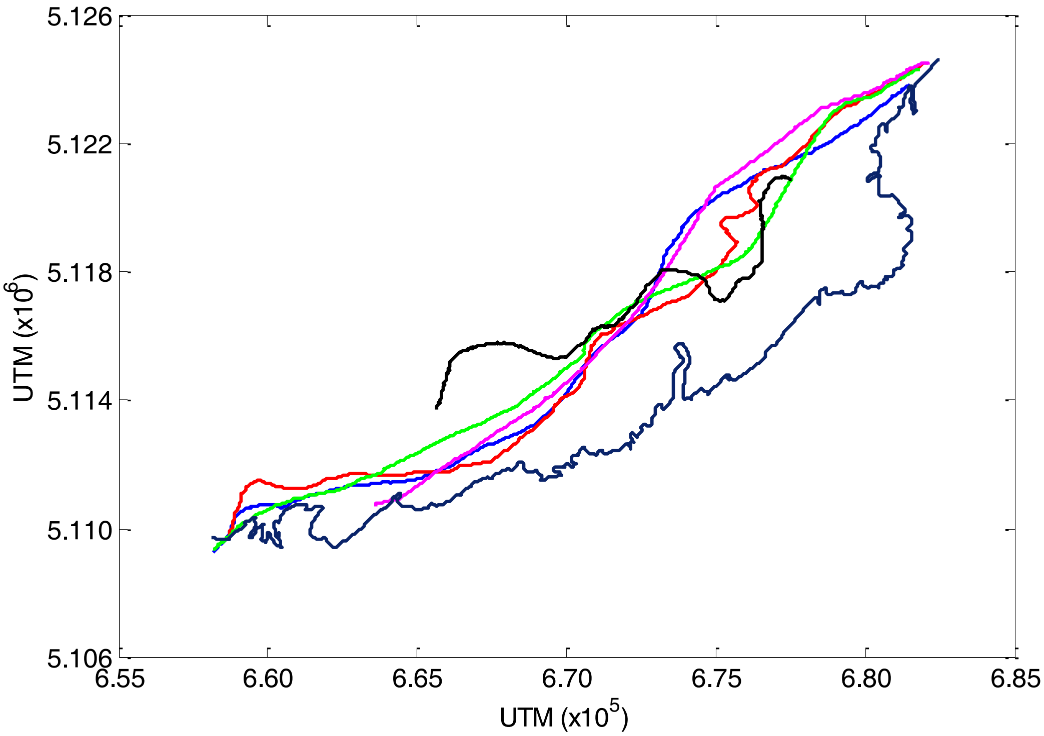

Figure 4. 10 Border ice limits when south side coverage is 40%

In Figure 4.11, we draw the limits when the area of border ice is 80%. In this case, there is some similarity between the limits in 5 winters. During this period, the air temperature is normally below 0 °C, and the border ice is solid enough. Once the border ice is formed, it is difficult to melt.

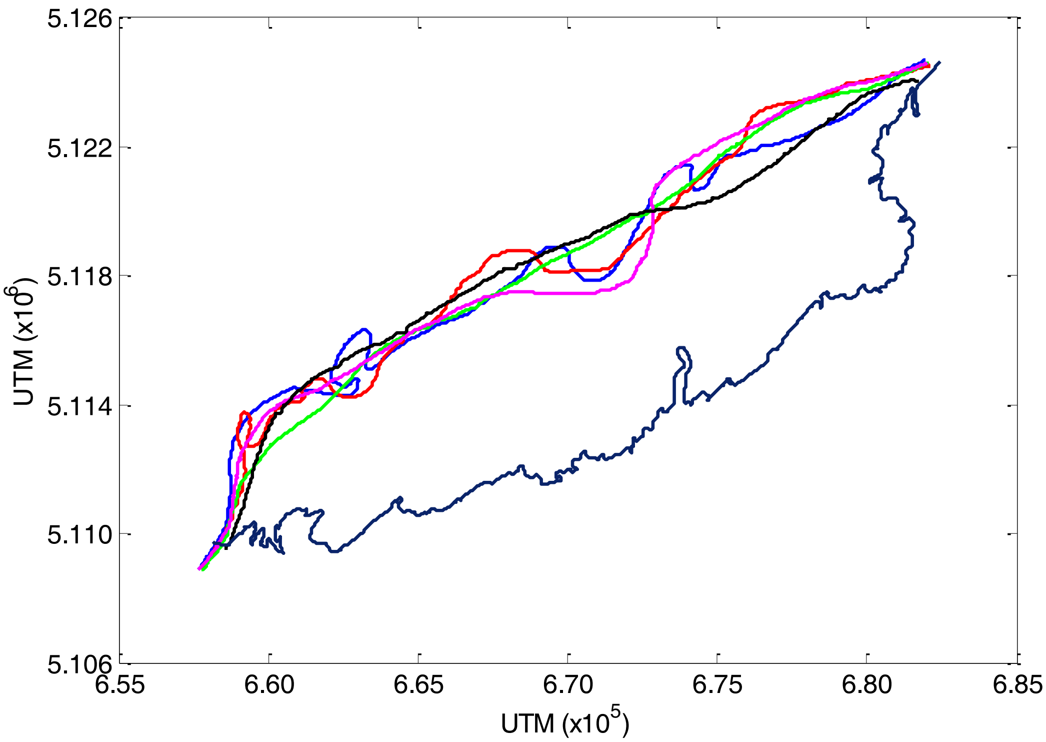

Figure 4. 11 Border ice limits when south side ice coverage is 80%

In Figure 4.12, we draw the limits when the coverage of border ice is maximal in each winter. We can see the limits of these 5 winter seasons are almost the same, especially for the upstream portion of the Lake. It is often the coldest period in one winter. The border ice is very firm. As explained above, because of vulnerability to ships waves and the absence of artificial islands, there is some variability of ice coverage over the downstream portion. Waves generated by passing ships break floes off the leading limit of the ice sheet.

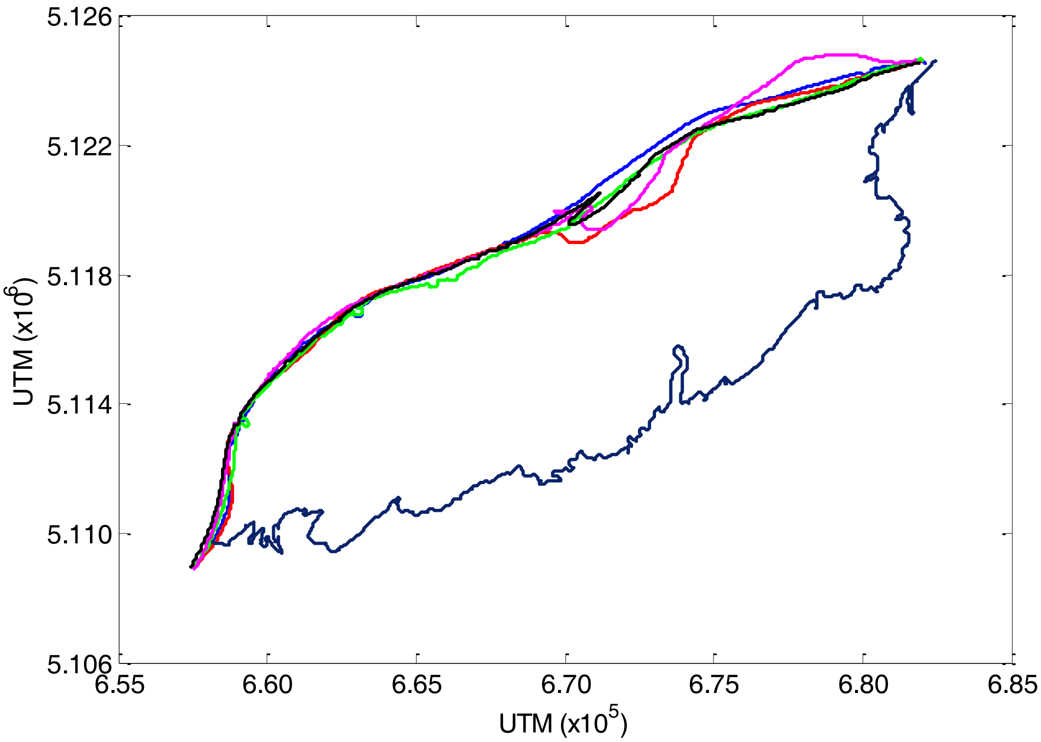

Figure 4. 12 Border ice limits when south side ice coverage is maximal

We calculated the AFDD when the border ice coverage is 40%, 80% and maximal. The results are presented in Table 4.2. AFDD values are not very similar during these 5 winter seasons. When the ice coverage grows from 40% to 80%, it only needs around 30 degree-days. It often needs less than 100 degree-days to reach maximal coverage from 80% coverage. That means the formation of border ice is rapid at the beginning of the winter, and this period is referred to as the freeze-up period.

Table 4. 2 AFDD when border ice reaches 40%, 80% and maximal coverage

(Unit: °C-D)	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009
40%	181	101	121	84	126
80%	210	137	149	183	163
maximum	293	236	198	241	188

4.2.3 Velocity contour lines on Lake Saint-Pierre

In this section, we analyze the south side of Lake Saint-Pierre border ice growth velocity (i.e., speed and direction) during the freeze-up period. We utilize contour function in MATLAB to generate contour lines representing isovels and iso-directions. We focus on the freeze-up period in 2004-2005 winter season. The graphs of other winter seasons are shown in Annex D.

4.2.3.1 Growth speed

First, for each ice mapping, each border ice limit is divided equally into 500 points when border ice goes from initial to the maximal coverage. We then calculate the growth speed through the distance of the corresponding points divided by the time. In Figure 4.13, the growth speed is low at the beginning of the freeze-up period. The speed becomes faster presumably because the water is colder and all heat exchange can be converted into surface ice. When the limit approaches to the center of the lake, it reaches the maximal line so that the speed reduces to zero. We can see the biggest growth speed is around 250 meters per hour.

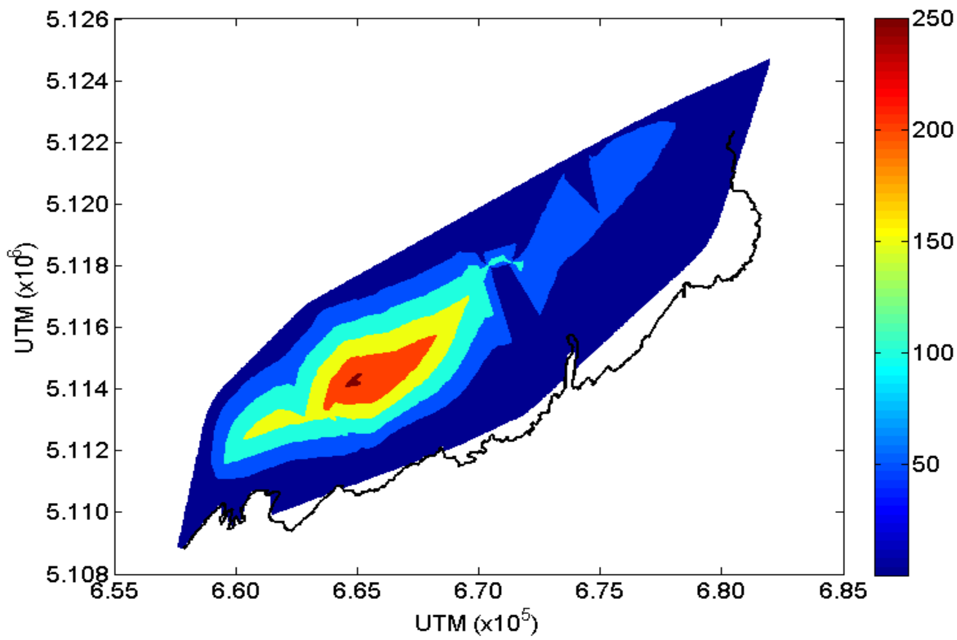

Figure 4. 13 Contour lines of growth speed (m/h) in 2004-2005

4.2.3.2 Growth direction

Like the calculation of the growth speed presented previously, we divide each border ice limit into 500 points when border ice goes from initial to maximal coverage on south side of Lake Saint-Pierre. The growth direction is perpendicular to the border ice edge. The flow direction is arbitrarily set to 0 degrees when it is 30° East of North corresponding to the general direction of the shoreline. That means the angle is 90° when the angle is perpendicular to the general flow direction. Therefore, one would expect most growth to be near an angle of 90°. Figure 4.14 shows the growth direction. The yellow color represents the expected 90° value.

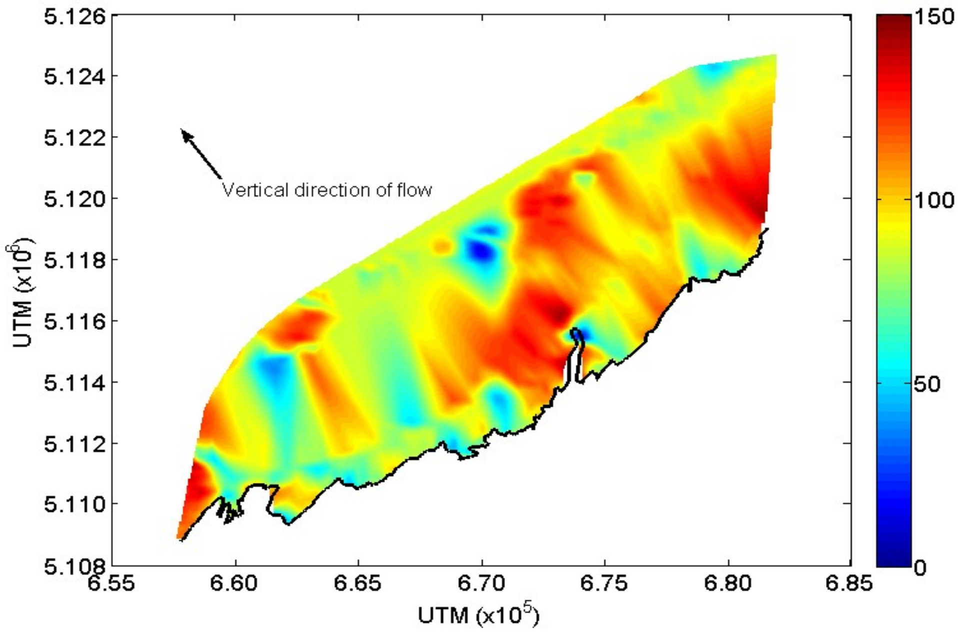

Figure 4. 14 Contour lines of growth direction (°) in 2004-2005

(yellow represents the expected 90° value)

4.2.3.3 Growth speed as a function of AFDD

Based on the discussion previously, we know that the AFDD is a very important factor to form border ice. Thus, we also generate the rate of growth contour lines as a function of AFDD (Figure 4.15) using the following ratio: Δd/ΔAFDD (m/°C-D) to compare the relationship of growth speed in relation to the cold intensity (AFDD). Similarly, we calculate the value which is corresponding to 500 points on each border ice limit during the freeze-up period.

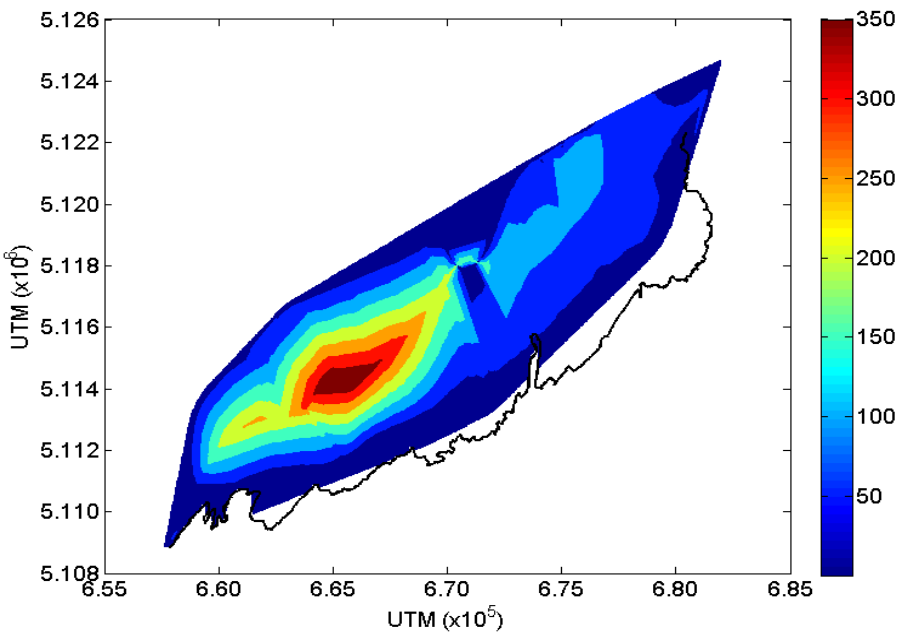

Figure 4. 15 Contour lines of function f=Δd/ΔAFDD (m/DD) in 2004-2005

4.3 Breakup of border ice on Lake Saint-Pierre

4.3.1 Decay rate of border ice

The breakup period is presented in Figure 4.16 for Lake Saint-Pierre. Ice areal coverage diminution is presented as a function of AFDD and the trend lines based on a linear regression are included. In Figure 4.17, areal ice cover diminution is presented as a function of AMDD and the trend lines based on a linear regression are included. AMDD (in °C-D) would probably be more representative as sunlight plays an important role and melting typically occurs in the spring when temperatures are higher than -10 °C.

However, no conclusion should be drawn from Figure 4.16 or 4.17 as the ice breakup rate is essentially a function of when and how fast the CCG hovercraft can work. Depending on the weather and the mechanical state of the crafts, it typically takes the CCG crew about three weeks to clear the Lake of most of the fast ice. Ice breaking operations typically begin in mid-March but will depend on the CCG ice bureau officer’s assessment of the risk that large pieces of ice could break off because of forecasted climate or rainy weather.

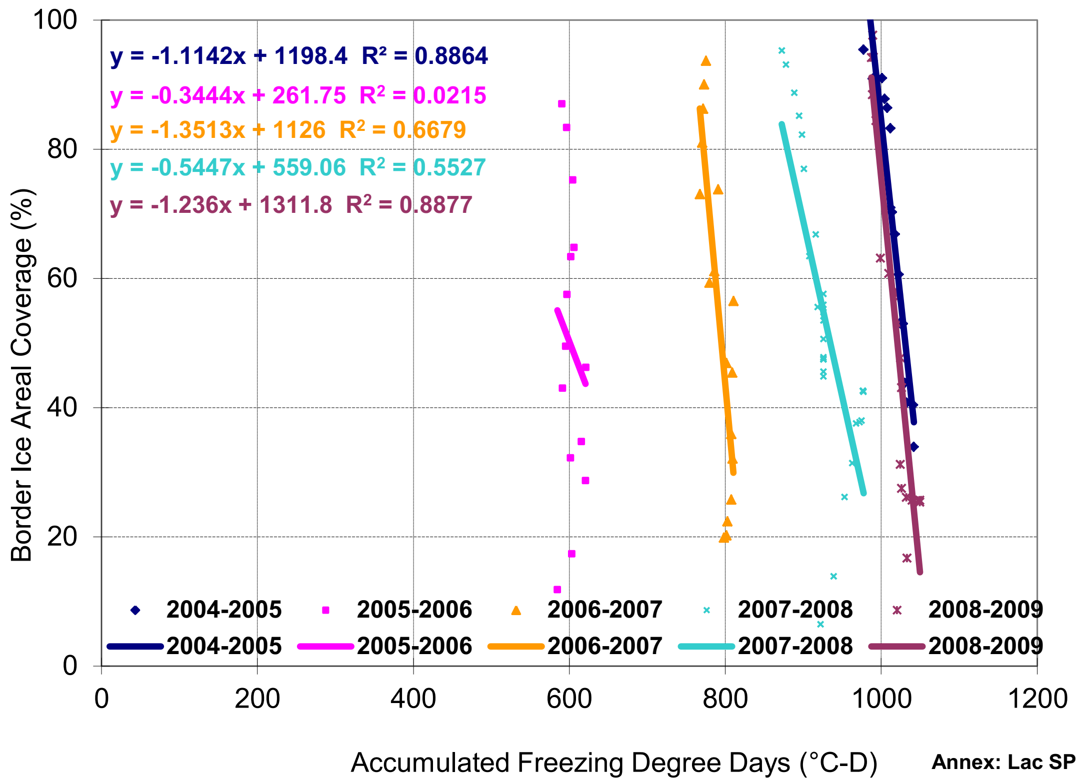

Figure 4. 16 Trend lines of ice coverage as a function of AFDD at Lake Saint-Pierre during breakup period

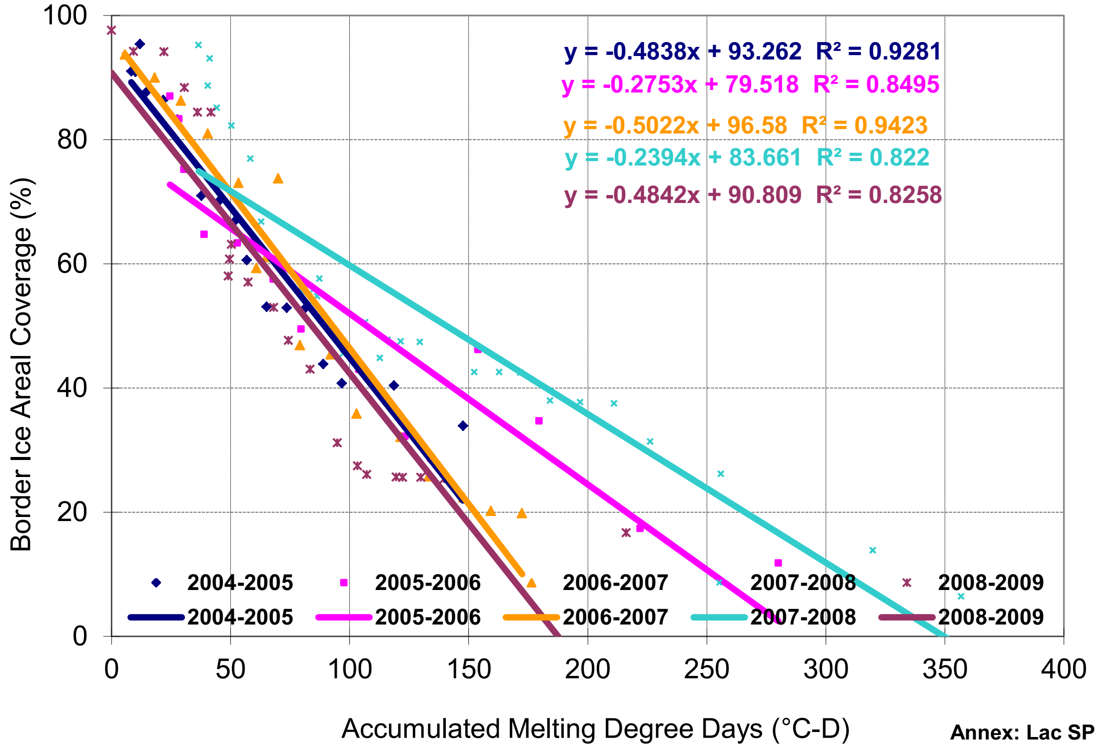

Figure 4. 17 Trend lines of ice coverage as a function of AMDD at Lake Saint-Pierre during breakup period

The breakup period is also presented in Figure 4.18 for Lake Saint-Pierre. Ice areal coverage decrease is presented as a function of number of days and the trend lines based on a linear regression. Number of days begins from March 1st each year. From the figure, we observe that the breakup usually begins the March 5th-10th. In 30 days, the Ice will totally melt. But this is not only the nature force but also a function of how fast the CCG hovercraft can work.

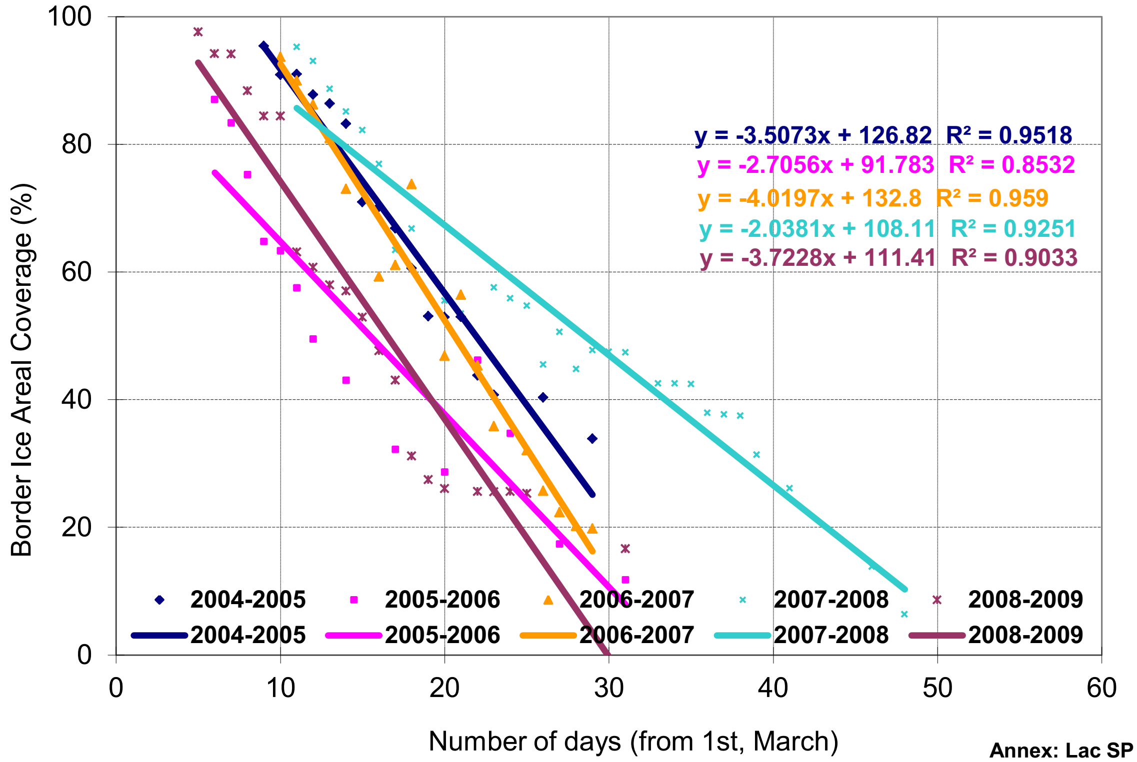

Figure 4. 18 Trend lines of ice coverage as a function of number of days at Lake Saint-Pierre during breakup period

4.3.2 A detailed comparison of border ice limit on Lake Saint-Pierre

For the breakup period, Figure 4.19 presents Lake Saint-Pierre border ice limits when areal coverage is around 30%, 60% and maximal respectively during breakup period in winter season 2004-2005. The yellow line stands for the limit of 34% coverage. The green line is the limit of 61% ice coverage. The red line in the middle of the river is the limit of maximal ice coverage. The limit of 61% ice coverage differs significantly from the 59% demarcation during the freeze-up period (Figure 4.6). The most important reason is ice breaking program that follows a pattern than is different than that used by Mother Nature during ice formation.

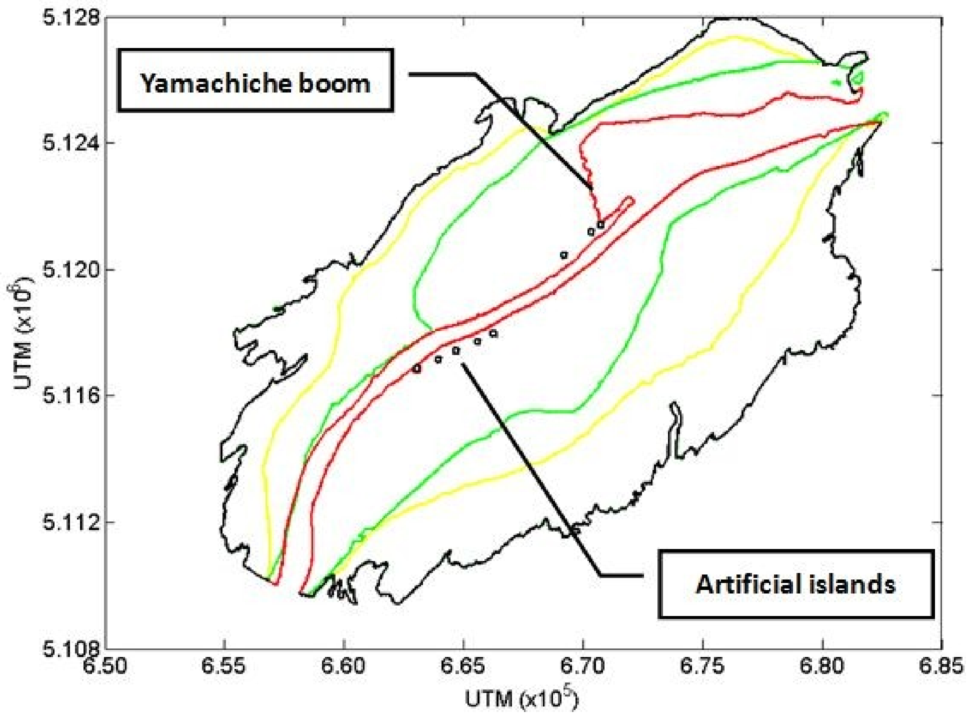

Figure 4. 19 Lake Saint-Pierre border ice limits when areal coverage is around 30%, 60% and maximal respectively during breakup period in winter season 2004-2005

4.4 Flow velocity, river depth and Froude number when the limit of border ice reaches to maximal areal coverage

When modeling the border ice growth, it is convenient to have some criteria that can be used to estimate the maximum extent that border ice can reach. Thus, we present and discuss flow velocity, river depth and Froude number that are present at the limit of border ice when the areal coverage reaches maximum in this section. We have previously presented (in Section 4.2.2) evidence that the limit of border ice is very similar from one winter to the next. Therefore, we only focus on the 2004-2005 winter season and will consider the results representative of all five years.

We first obtained the database of flow velocities, river depths and Froude numbers for 192744 nodes as provided from the 2-D numerical simulation of the River by Environment Canada (Morin et al., 2000). The simulation of all these nodes was carried out on the river section from Montréal to Trois-Rivières on 29th January 2005 conditions during which time, border ice areal coverage was at its maximum (Champoux, personal communication, 2011). From the database, using MATLAB, we culled the values corresponding to the location of border ice limit. From Montréal to Trois-Rivières, there are four reaches including the Port of Montréal; Varennes to Contrecoeur; Contrecoeur to Sorel and Lake Saint-Pierre. In the following, these reaches will be discussed individually.

4.4.1 Upstream of Lake Saint-Pierre

This part will be introduced in chapter 5.

4.4.2 Lake Saint-Pierre

The ice chart of Lake Saint-Pierre on 29th January 2005 is shown in Figure 4.20. This is when border ice areal coverage reaches the maximum on the Lake. Note that there are two ice limits that are adjacent to the navigation channel (i.e., 'limit 1' and 'limit 2').There is an ice boom located on the north side of the Lake that defines part of 'limit 1'.

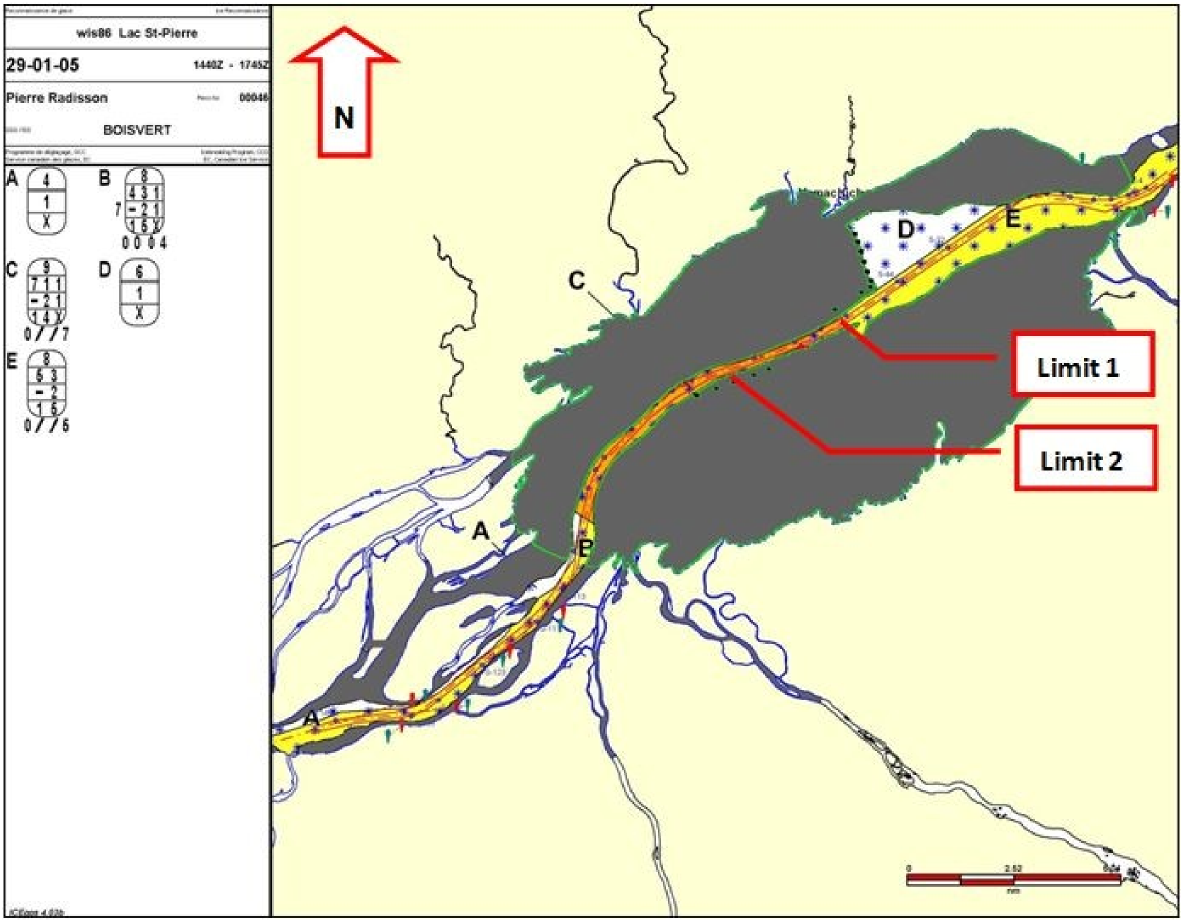

Figure 4. 20 Ice chart of Lake Saint-Pierre on 29th Jan. 2005

Figure 4.21 shows the flow velocities of nodes along these limits of maximal border ice areal coverage. All the nodes are in a range of 0-1.0 m/s. First, we observe the flow velocity along 'limit 1'. The Yamachiche ice boom locates near the longitude of -72.8º. Note that the flow velocity is relatively small next to the boom. Downstream of the boom, the flow velocity is even smaller, in the order of 0.2m/s where the ice limit is very close to the north bank. Thereafter, as border ice increases in width, so do the flow velocities along its limit, reaching an extreme value of 0.75 m/s near the downstream end of the Lake. Table 4.3 shows that along 'limit 1', 17% nodes are in a range of 0.2-0.4 m/s; 79% nodes are in a range of 0.4-0.8 m/s.

Secondly, we observe the flow velocity along 'limit 2', near longitude of -72.9º to -72.85º, there are several artificial islands and navigation lights located there to stabilize the ice cover. In this region, some flow velocities are quite small; as low as 0.05 m/s. And the flow velocities keep at 0.4-0.5 m/s near the artificial islands at the longitude of -72.9º to -72.8º. Along 'limit 2', around 90% of the nodes are in a range of 0.4-0.8 m/s. There are no nodes that exceed 0.8 m/s, which is the maximal flow velocity value along the edge of this southern ice limit (Table 4.3).

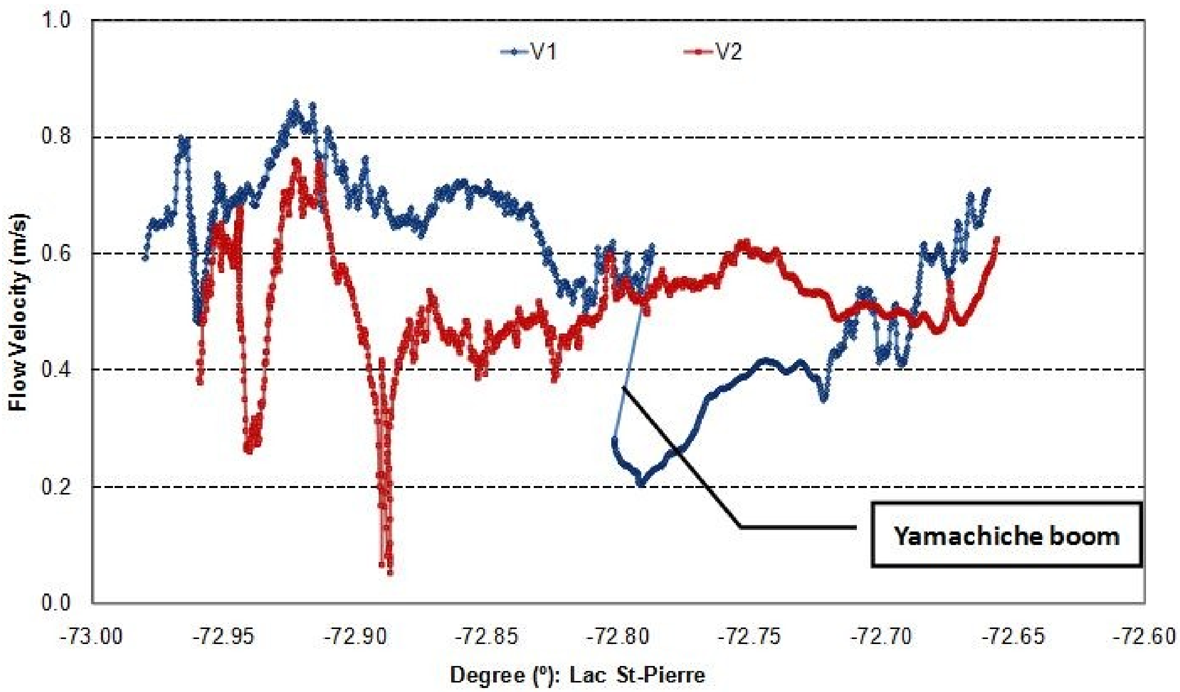

Figure 4. 21 Flow velocities along the limits of maximal ice coverage at Lake Saint-Pierre

Table 4. 3 Distribution of flow velocities along the limits at Lake Saint-Pierre on 29th Jan. 2005

Unit: %	0-0.2 m/s	0.2-0.4 m/s	0.4-0.6 m/s	0.6-0.8 m/s	0.8-1.0 m/s	>1.0 m/s
Along limit 1	0	17	**32**	**47**	4	0
Along limit 2	2	8	**72**	18	0	0

Figure 4.22 presents river depths of nodes along the limits of maximal border ice areal coverage on Lake Saint-Pierre. In the figure, we can see that all river depths stay at a range of 0-16 m. For limit 1, the water depth drops quickly close to the ice boom. The river depth decreases to 4 m reached to ice boom near the longitude of -72.8º. Downstream of the ice

boom, the minimal river depth is lower than 2 m. The river depth along the ice edge then ascends after passing through the ice boom. For limit 2, at artificial islands location, the river depth is also quite low at 2-4 m, even reaches 0 m. Table 4.4 shows 85% nodes are in a range of 0-8 m along 'limit 1' and 95% nodes are in a range of 0-8 m along 'limit 2'. There are no nodes exceed 16 m on both limits. Note that the large depths imply that the cover has reached over top of the dredged deep navigation channel.

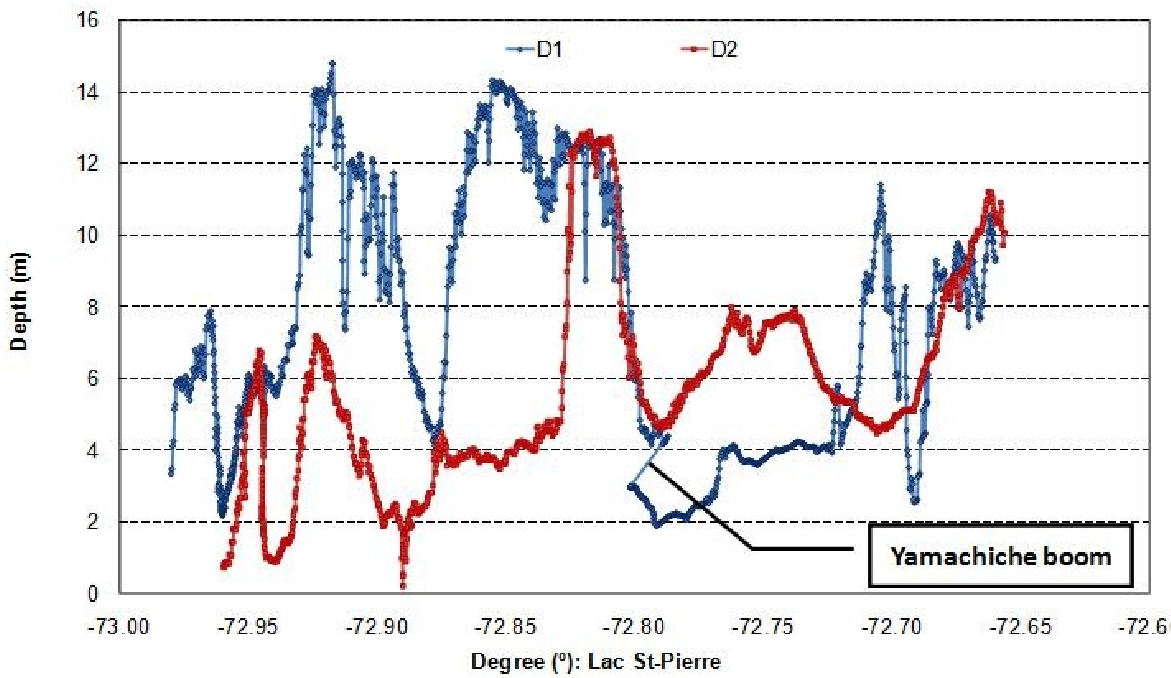

Figure 4. 22 River depths along the limits of maximal ice coverage at Lake Saint-Pierre

Table 4. 4 Distribution of river depths along the limits at Lake Saint-Pierre on 29th Jan. 2005

Unit: %	0-4 m	4-8 m	8-12 m	12-16 m	>16 m
Along limit 1	**24**	**37**	**25**	15	0
Along limit 2	**31**	**56**	8	5	0

A similar analysis was carried out of the Froude numbers along the ice limits. Figure 4.23 shows the Froude numbers along the limits of maximal border ice areal coverage on Lake Saint-Pierre. Compared with flow velocity and river depth, the Froude number is less variable. In Figure 4.23, we see that the most of Froude Numbers are in a range of 0.05-0.10. Table 4.5 shows that 84% nodes are in this range along 'limit 1' and 78% along 'limit 2'.

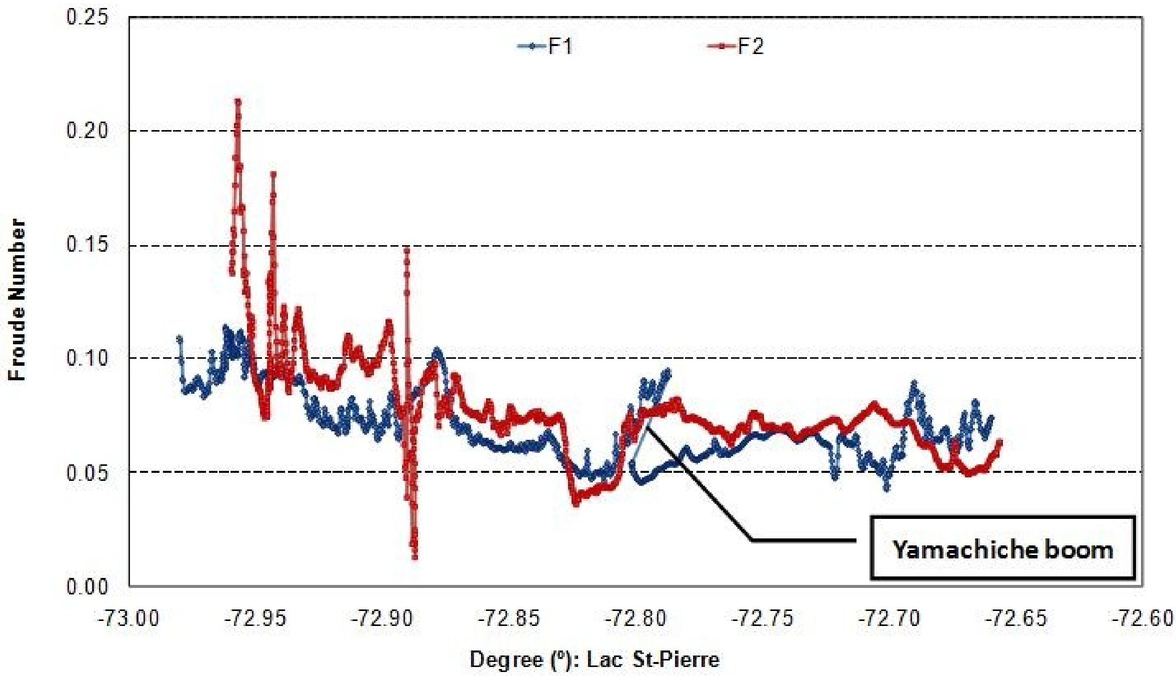

Figure 4. 23 Froude Numbers along the limits of maximal ice coverage at Lake Saint-Pierre

Table 4. 5 Distribution of Froude numbers along the limits at Lake Saint-Pierre on 29th Jan. 2005

Unit: %	**0-0.05**	**0.05-0.10**	**0.10-0.15**	**0.15-0.20**	**0.20-0.25**	**>0.25**
Along limit 1	5	**84**	11	0	0	0
Along limit 2	8	**78**	12	1.6	0.3	0

Recently, several researchers have discussed the critical flow velocity for border ice formation. For the Sainte-Anne River, the critical velocity V_c was found to be equal to 1.2 m/ s (Michel et al. 1982). Moreover, for the upper Saint Lawrence River, the V_c value is about 0.4 m/ s (Shen et al. 1984). Matousek et al. (1984) mentioned that the range of critical velocity is 0.4-0.6 m/s by Soviet authors. Obviously, the value of V_c varies with the change of the flow and ice conditions. Lal et al. (1991) mentioned V_c is determined by the stability of surface ice elements that are in contact with the limit of an existing border ice. The stability of an ice element is governed by the drag force acting on it including the component of the gravity force along the water surface and the hydrodynamic drag, which is resisted by the friction at the contact.

Based on the above discussion of our study, I summarize the conclusion of border ice limit criteria. At the maximum border ice limit of Lake Saint-Pierre, the velocity is under 0.8 m/s. This value is different from other researchers. Since in our study, we focus on the Lake Saint-Pierre, although it is a fluvial lake. Hence, the flow rate is not the same as that of the river. The river depth along the border ice limits looks not regular. The range is from 0 to 14 m. The Froude number is steady compared with the flow velocity and the river depth. The Froude number is usually under 0.1.

Chapter 5
Results and analysis of border ice limit from Montréal to Sorel

In chapter 4, we analyzed and discussed several aspects of border ice limit of Lake Saint-Pierre in detail. In this chapter, we continue to research on the border ice limit in the upstream reach of Lake Saint-Pierre from Montréal to Sorel. This reach includes Port of Montréal, Varennes to Contrecoeur and Contrecoeur to Sorel.

5.1 Border ice areal coverage

For analysing the border ice areal coverage of this reach, we select a graph of the Varennes to Contrecoeur sub-reach for a detailed presentation. Figure 5.1 presents a selected example for the 2008-2009 winter season. In Figure 5.1 (bottom), the original EC ice charts for three individual dates are reproduced. In chapter 3, we have introduced that the ice coverage in this reach is not all border ice. Between the north bank and Verchères islands the ice is full ice coverage. The cover is initiated at the downstream end by the deployment of the Lavaltrie ice boom. The ice cover continues upstream of the Verchères islands where it turns into border ice before finally reaching the Sainte-Thérèse islands where once again it forms a fast ice cover between two banks. The islands divide the river into two parts. The ice cover in the secondary channel located north side of the river is easily formed. The main navigation channel located south side of the river operates 365 days a year. Thus, the ice in navigation channel is difficult to form.

The first chart (22^{nd} December, 2008) corresponds to conditions at freeze-up and the ice coverage is 66%; the second (29^{th} January, 2009) presents the maximal coverage 86% during mid-winter;

and the third (16^{th} March, 2009) shows conditions during the breakup period and the ice coverage is 39%.

The percentage of border ice areal coverage presented in Figure 5.1 (top) expresses the border ice areal coverage on any given day divided by maximal areal coverage of border ice that was observed for all five winter seasons (2004-2009). The values presented in Figure 5.1 (top) are obtained using the MATLAB image recognition and scaling software: During freeze-up period, the extent of border ice areal coverage of Varennes to Contrecoeur grows rapidly. We observe that the area of border ice grew from 2% on 18^{th} December 2008 to 74% on 25^{th} December (i.e, in only 7 days). The mean air temperature during this period was -10 °C.

Then, on December 28^{th}, temperatures rose to +6.4 °C. Hence, 75% border ice coverage (29^{th} December, 2008) drops sharply down to 67% (2^{nd} January, 2009). When air temperatures drop anew, the lost area is quickly recovered. The ice coverage climbs until the end of January and then drops slowly until beginning of March.

As March progresses, air temperatures rise and occasionally hit positive values. The areal extent of the ice continues to fall rapidly during that period. On March 31^{st}, there is only 0.5% border ice coverage. Compared with Lake Saint-Pierre, the breakup period of Varennes to Contrecoeur is more natural without the icebreaking activities carried out by the Canadian Coast Guard.

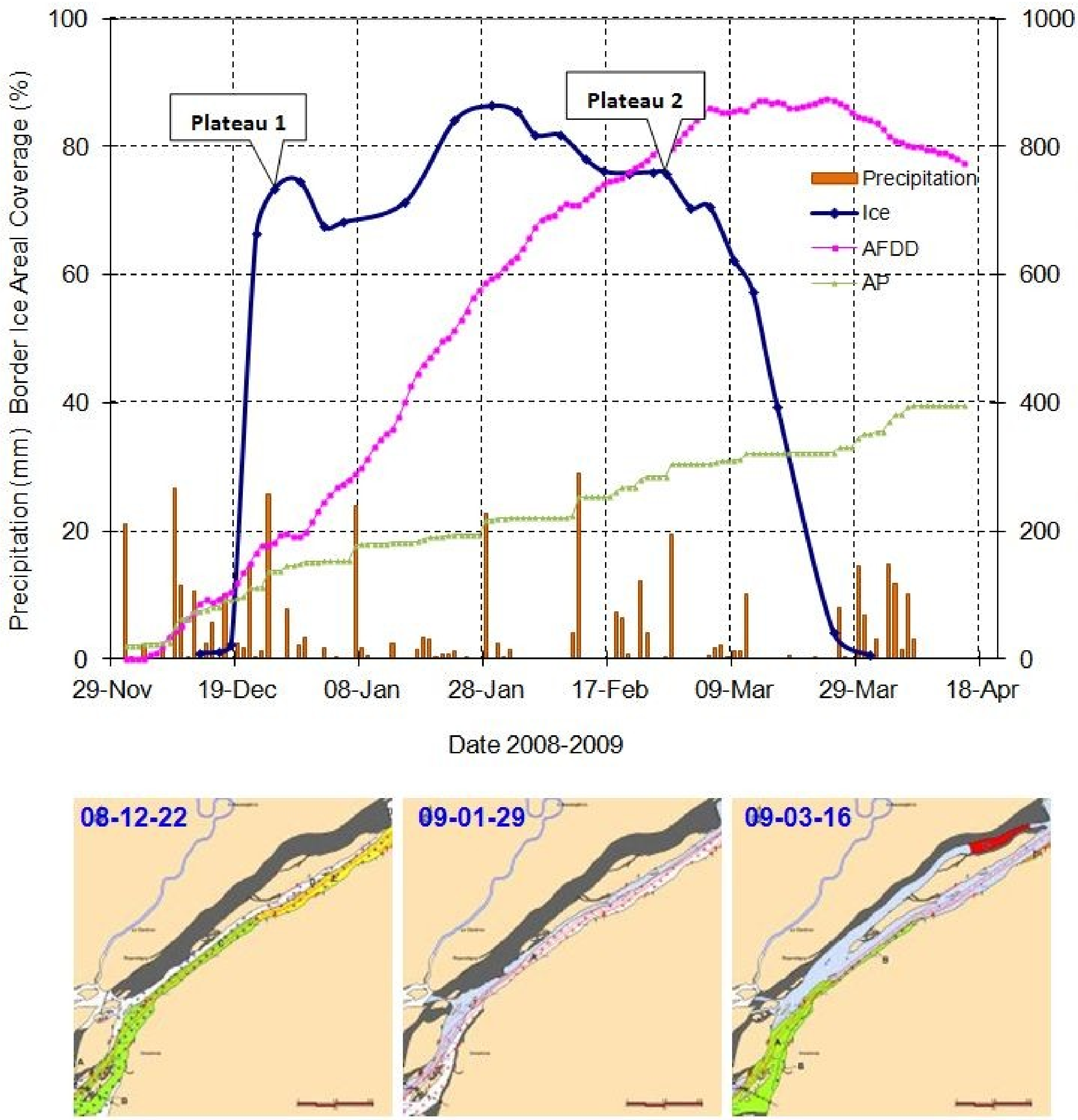

Figure 5. 1 Top: Border ice areal coverage during 2008-2009 winter at Varennes to Contrecoeur

Bottom: Ice charts from Environment Canada 2008-2009

5. 2 Freeze-up and breakup period

5.2.1 Growth rate of border ice

We choose 'Varennes to Contrecoeur' reach as an example to present the growth speed of ice cover. Figure 5.2 presents the ice cover of the reach during freeze-up periods for all five winters.

Based on a linear regression, growth trend lines are determined for freeze-up occurring during the areal coverage from beginning of the winter to 'Plateau 1'. This represents the initial 'rapid' growth stage. The lower limit was usually chosen under 10% at the very beginning of the winter. The reason for choosing 'Plateau 1' as upper limit is that the rate slows significantly once the ice sheet reaches 'Plateau 1'. In the years 2005-2006 and 2006-2007 the 'Plateau 1' begins around 60%. In the years 2004-2005 and 2008-2009 the 'Plateau 1' begins around 80%. In 2007-2008, the ice coverage grows quickly to 100%. The regressions were made as a function of AFDD as that is the normal parameter used to estimate ice thickness.

Note that the 10% ice coverage value is reached when $80 < \text{AFDD} < 180$ and the nominal 60% value is reached for $130 < \text{AFDD} < 280$. This represents an increase of 50% (i.e. from 10% to 60%) in about 50 to 100 AFDD corresponding to an average increase of 1% to 0.5% per DD. (The average value over the five year period was 0.7% per DD). More specific values are presented in Figure 5.2. The rate of border ice growth in 2007-2008 is 0.94% per DD, which is the fastest among this 5-year period. By contrast, the rate of border ice growth in 2006-2007 is the slowest with a rate of 0.4% per DD.

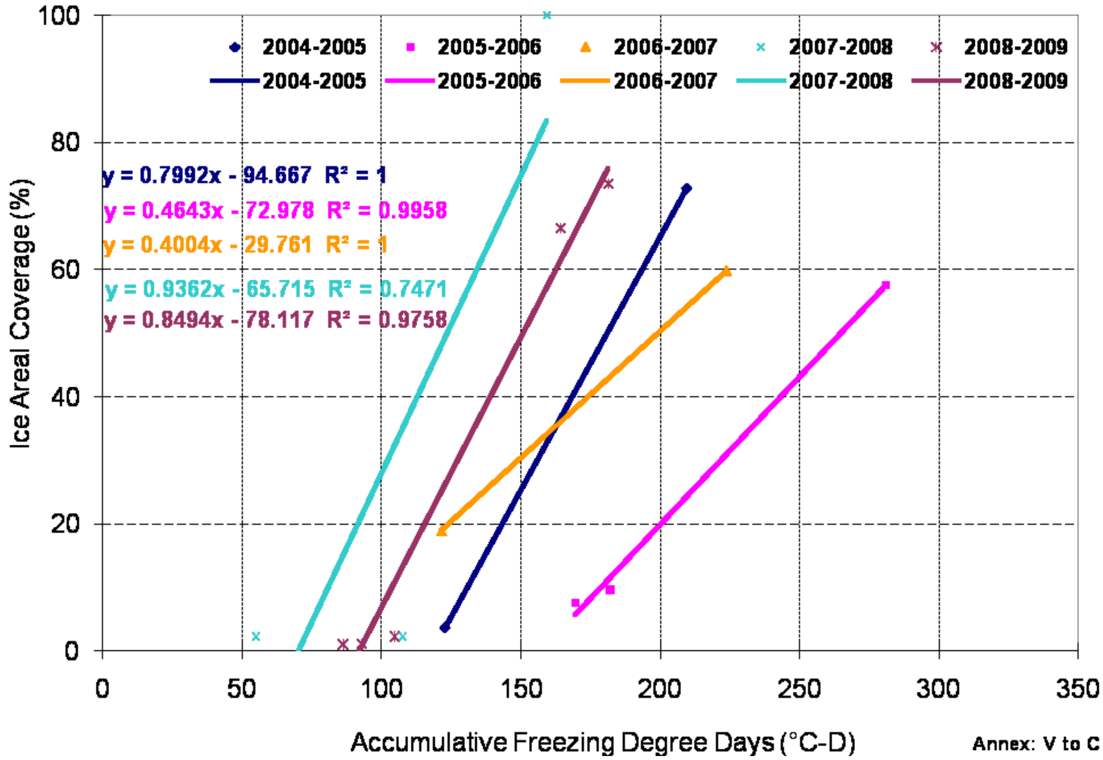

Figure 5. 2 Trend lines of ice coverage as a function of AFDD at Varennes to Contrecoeur during freeze-up period

For the very fast growth (20% to 55%) and the relatively fast growth (55% to the beginning of the slow growth period – i.e., 'plateau 1') periods, the growth rates are calculated as a function of AFDD and simply as a function of the number of days. These rates are presented in Figures 5.3 and 5.4.

In 2007-2008 winter season, there are twice obvious fast growth periods (refer to Annex B: Figure B.9). We show slopes of the first fast growth with 2007-2008 and the second slopes with 2007-2008*.

In figure 5.3, the rates are presented as a function of AFDD ($Slope_1$ = Increase in % / DD during the period). The black columns represent the $Slope_1$ when the border ice coverage grows from 20% to 55%. The grey columns represent the $Slope_1$ when the border ice coverage grows from 55% to 'Plateau 1'. The $Slope_1$ of 20% to 55% is usually higher than that of 55% to 'Plateau 1'. Especially in 2007-2008, at the very beginning of the winter, the border ice coverage grows very quickly to 100% on 17th December 2007. But the ice coverage decreases to 7% on 10th January 2008. Until 24th January 2008 the ice coverage recovered to 66%. And then the ice keeps a relative stable coverage.

Figure 5.3 shows that the $Slope_1$ in 2006-2007 winter is lower than that in other years at 0.4%/DD. Through observing the weather condition, we find that there are always some days with temperature above 0 °C during that year. The maximum value is 1.6%/DD in 2007-2008. In other words, the variability of the rate from one year to the next is about 4 (i.e. = 1.6 / 0.4).

During the second part of the rapid growth period, rates vary from 0.1%/DD to 1.9%/DD. Note that the correlation between the two growth periods. Generally (although not always true), if the first is fast (as in 2004-2005) the second is also; whereas if the first period is slow (as in 2006-2007), the second is also.

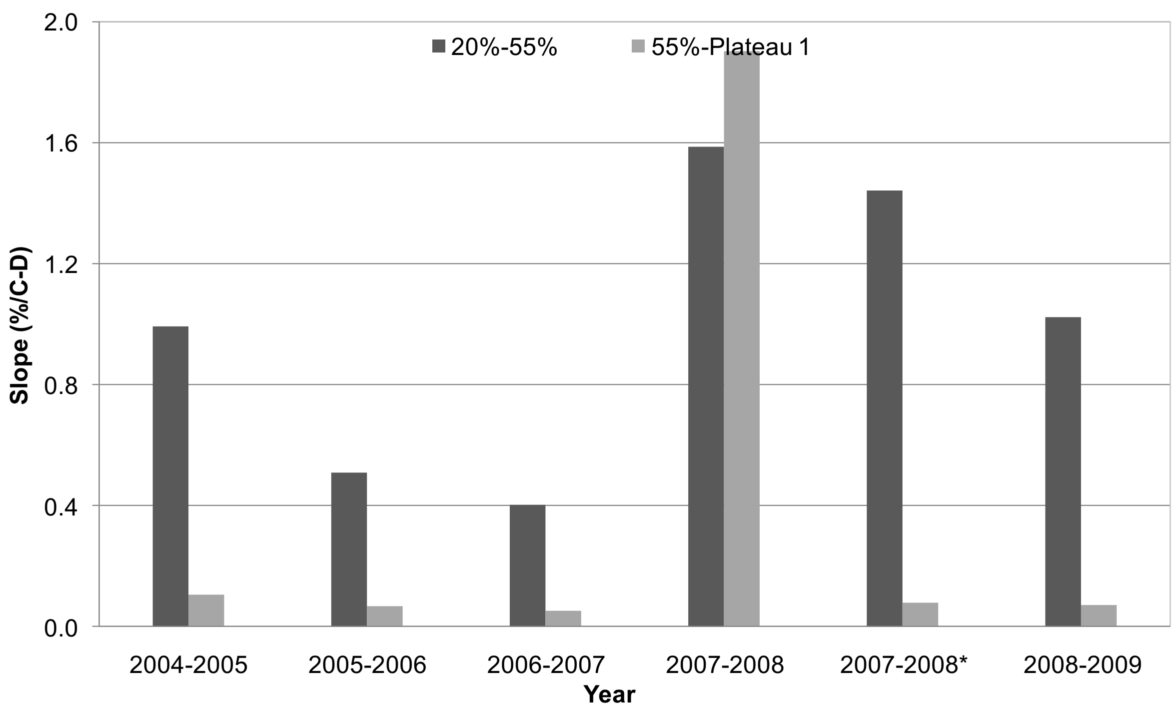

Figure 5. 3 Rate of border ice areal coverage growth per degree-day at Varennes to Contrecoeur

In figure 5.4, growth is expressed as a function of the number of days rather than as a function of AFDD. The black and gray columns represent the $Slope_2$ (=Increase in % / Days during the period) for the two rapid freeze-up sub-periods. For the first sub-period, the growth rate varies from 2.5%/D in 2006-2007 to 24%/D in 2008-2009 representing a variability factor of 10. For the second sub-period, the growth rate varies from 0.4%/D to 14%/D representing a variability factor of 35. As expected, these variability factors are greater than those based on AFDD. We can conclude that AFDD is therefore a better growth predictor than simply time itself. The white columns represent the $Slope_2$ during the breakup period. Because the ice coverage decreases as time goes by during the breakup period. To obtain a positive value, we create the opposite value of $Slope_2$ during the breakup period, which is shown in Figure 5.4.

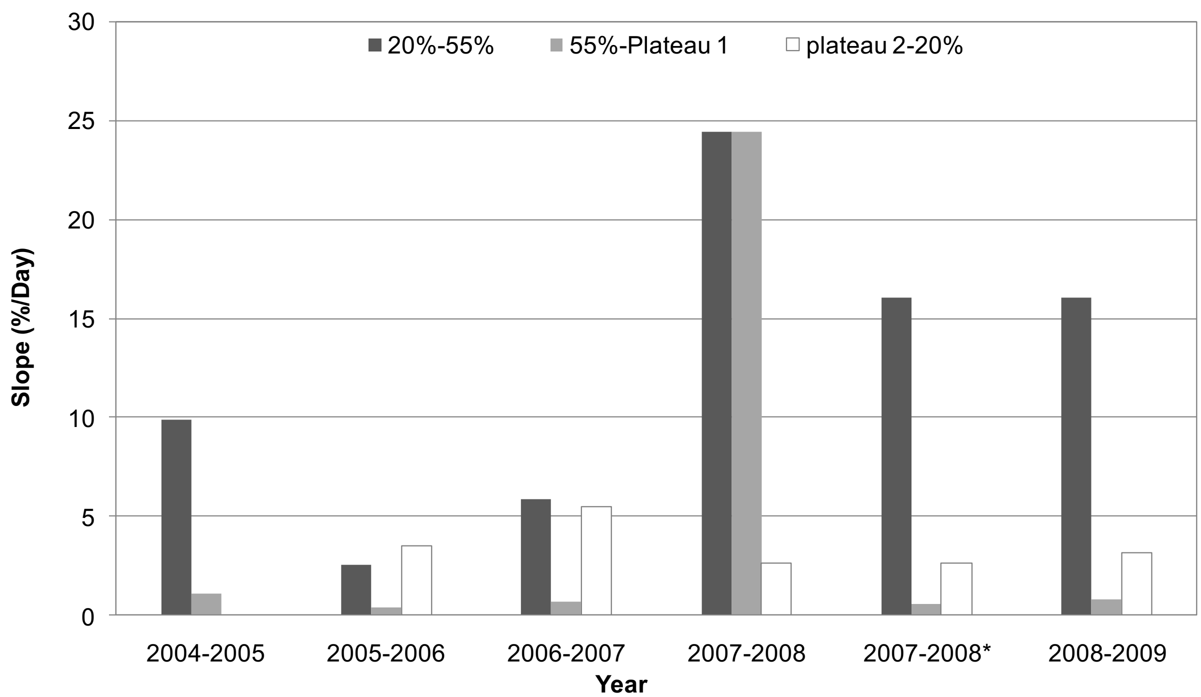

Figure 5. 4 Rate of border ice areal coverage growth per day at Varennes to Contrecoeur

5.2.2 Decay rate of border ice

The breakup period of Varennes to Contrecoeur is presented in Figure 5.5 and Figure 5.6. In Figure 5.5, areal ice cover diminution is presented as a function of AFDD and trend lines based on a linear regression are included. In general, AFDD is positive during the breakup period (only in 2006-2007, AFDD is negative). In the case of a naturally occurring breakup, this is a sign that AFDD (calculated from a reference value of zero degrees C) is not a very suitable indicator as it is more or less constant over the breakup period.

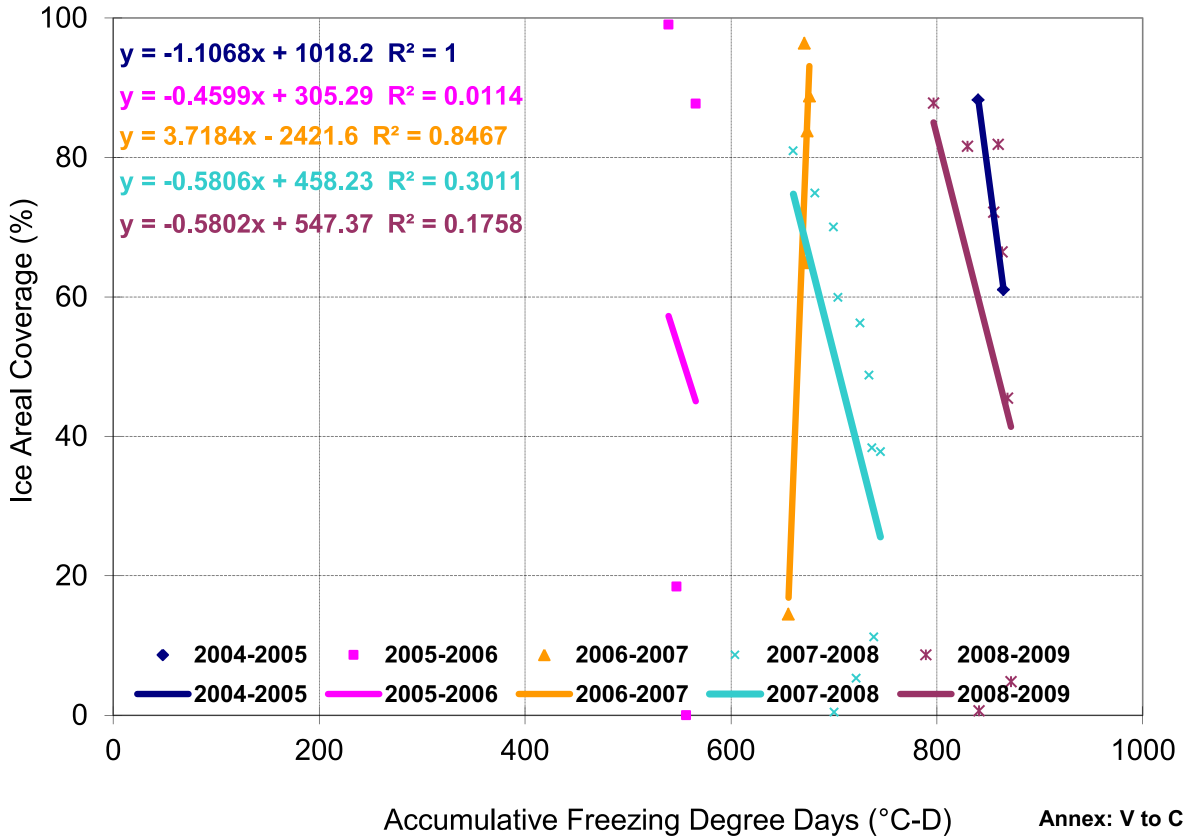

Figure 5. 5 Trend lines of ice coverage as a function of AFDD at Varennes to Contrecoeur during breakup period

In Figure 5.6, areal ice cover diminution is presented as a function of AMDD. AMDD would be more representative as sunlight plays an important role and melting typically occurs in the spring when temperatures are higher than -10 °C. Note that the 80% ice coverage value is reached when 10< AMDD < 110 and the ice coverage melts totally when 210 < AMDD < 290 in the 5 winters. This represents a decrease of 80% (i.e. from 80% to 0%) in about 200 AMDD corresponding to an average decrease of -0.4% per DD. (In fact the average value over the five year period was found to be -0.5% per DD). Compared with the condition of Lake Saint-Pierre, the change of border ice coverage at breakup period is more complicated. This is because the breakup process of these reaches is more natural without ice breaking program.

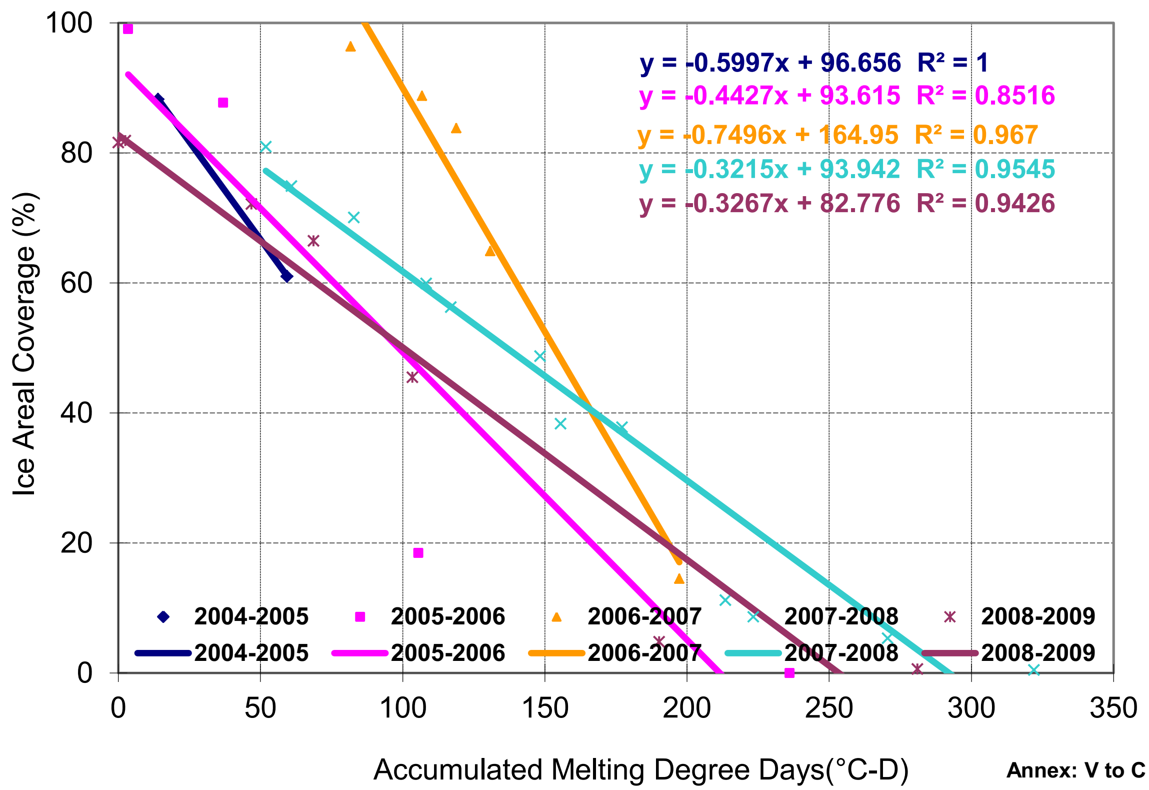

Figure 5. 6 Trend lines of ice coverage as a function of AMDD at Varennes to Contrecoeur during breakup period

5.3 Flow velocity, river depth and Froude number when the limit of border ice reaches to maximal areal coverage

We have introduced the data obtainment, method and objective to study on the flow velocity, river depth and Froude number when the limit of border ice reaches to maximal areal coverage in chapter 4. In this part we continue to focus on the results for the Port of Montréal, Varennes to Contrecoeur and Contrecoeur to Sorel separately.

5.3.1 Port of Montréal

Ice chart of 'Port of Montréal' reach on 29th January 2005 is shown in Figure 5.7. We rotate the chart to make the vertical upward direction north. There are 2 border ice edges (limits): One for the west side and one for the east side of the river. Obviously, the 'Limit 1' and 'Limit 2' are not terminational in this ice chart. They will continue to the next reach. The magnified figure on the right is from ice chart of 'Varennes to Contrecoeur' reach. The red lines in the magnified figure make the limits completed.

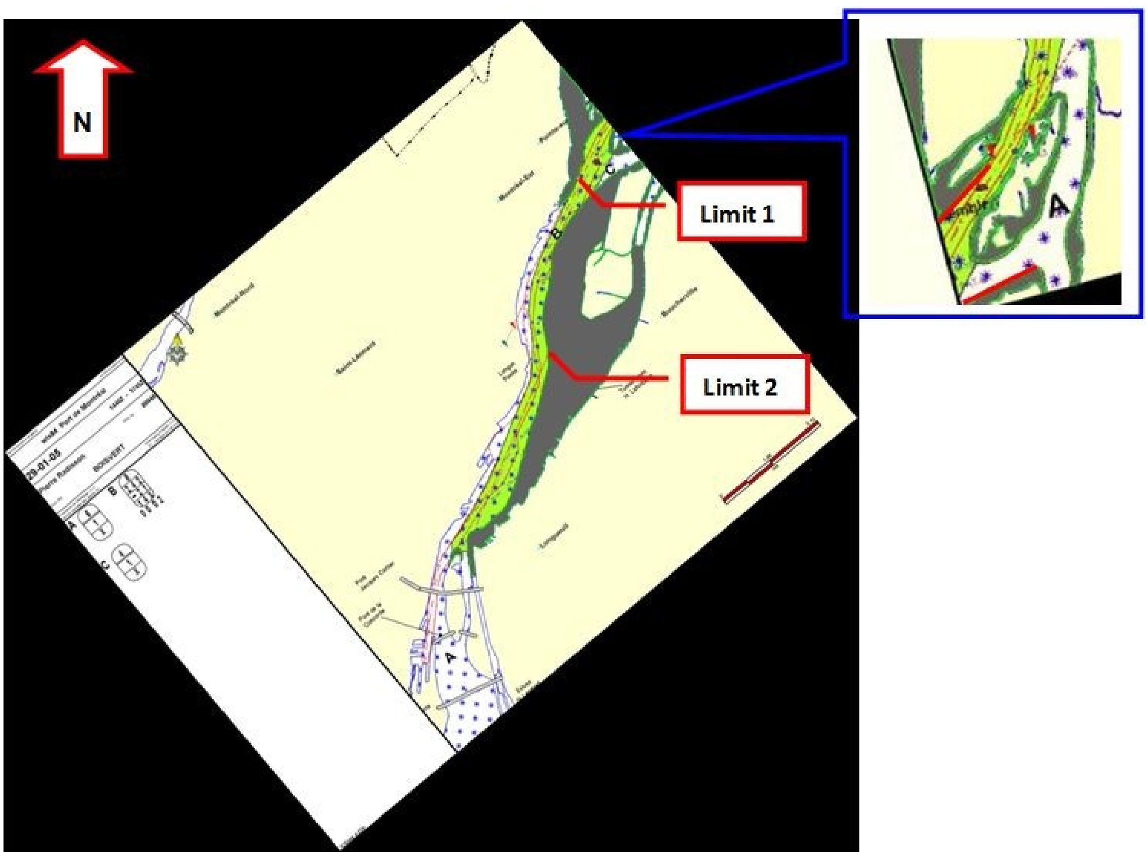

Figure 5. 7 Ice chart of Port of Montréal on 29th Jan. 2005

Figure 5.8 shows the flow velocities of nodes along these limits of maximal border ice areal coverage in Port of Montréal reach. Most nodes stay in a range of 0.4 m/s to 1.0 m/s. First, we observe the flow velocity along 'limit 1'. An island locates near the longitude of -73.48º and the flow velocity decreases there. The flow velocity increase when the river flows pass the island. Then, we observe the flow velocity along 'limit 2'. There is a series of islands located from the longitude of -73.49º to -73.455º. We can observe a continuous fall of flow velocity at this location. For these 2 limits, 1.0 m/s is the approximate maximal value.

To explain more clearly, we refer to Table 5.1 where the distribution of flow velocity along the border ice limits at Port of Montréal is quantified. Along 'limit 1', more than 70% nodes are in a range of 0.4-0.8 m/s. Along 'limit 2', more than 70% nodes are in a range of 0.6-1.0 m/s. Very few nodes exceed 1.0 m/s.

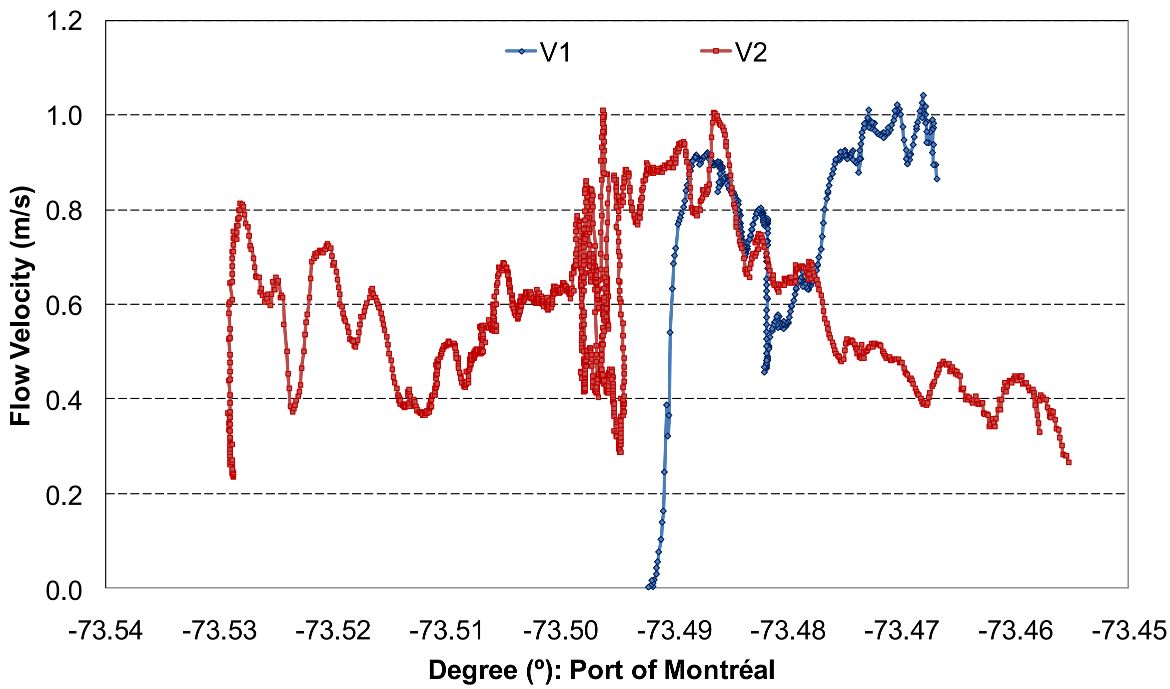

Figure 5. 8 Flow velocities along the limits of maximal ice coverage at Port of Montréal

Table 5. 1 Distribution of flow velocities along the limits at Port of Montréal on 29th Jan. 2005

Unit: %	0-0.2m/s	0.2-0.4 m/s	0.4-0.6 m/s	0.6-0.8 m/s	0.8-1.0 m/s	>1.0 m/s
Along Limit 1	0	12	**41**	**34**	13	0.3
Along Limit 2	4	1	17	**41**	**36**	0

Figure 5.9 shows river depths of nodes along the limits of maximal border ice areal coverage on

Port of Montréal. The river depths vary from 0 to 14 m (where the river depth is low near the island).

To understand more clearly, relevant statistical calculation is presented in Table 5.2. Along these 2 limits, more than 70% nodes are in a range of 0-8 m, and nearly 20% nodes are in a range of 8-12 m.

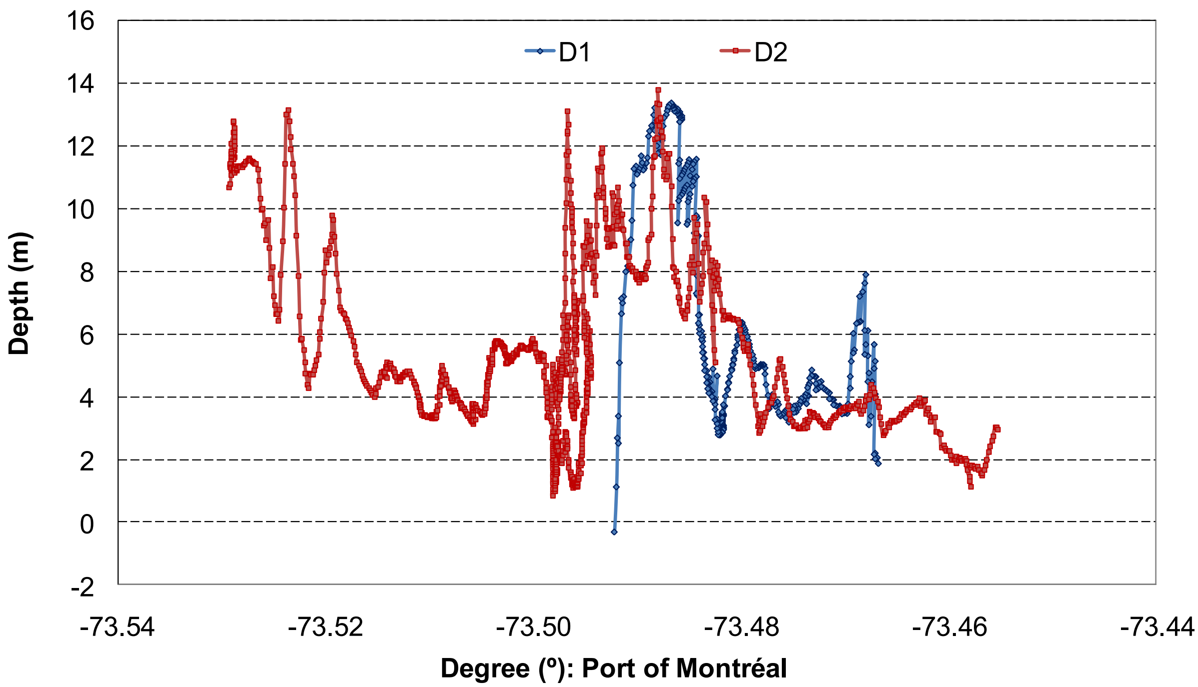

Figure 5. 9 River depths along the limits of maximal ice coverage at Port of Montréal

Table 5. 2 Distribution of river depths along the limits at Port of Montréal on 29th Jan. 2005

Unit:%	**0-4 m**	**4-8 m**	**8-12 m**	**12-16 m**	**> 16 m**
Along Limit 1	**37**	**44**	17	2	0
Along Limit 2	**35**	**33**	19	13	0

Figure 5.10 shows Froude numbers of nodes along the limits of maximal border ice areal coverage on Port of Montréal reach. It directly shows that most of nodes are in a range of 0.05-0.15. In table 5.3, we make a statistical calculation and obtain 89% nodes are in this range along 'limit 1' and 83% nodes are in this range along 'limit 2'.In particular, more than 60% nodes are in a range of 0.05-0.10. No nodes exceed 0.25.

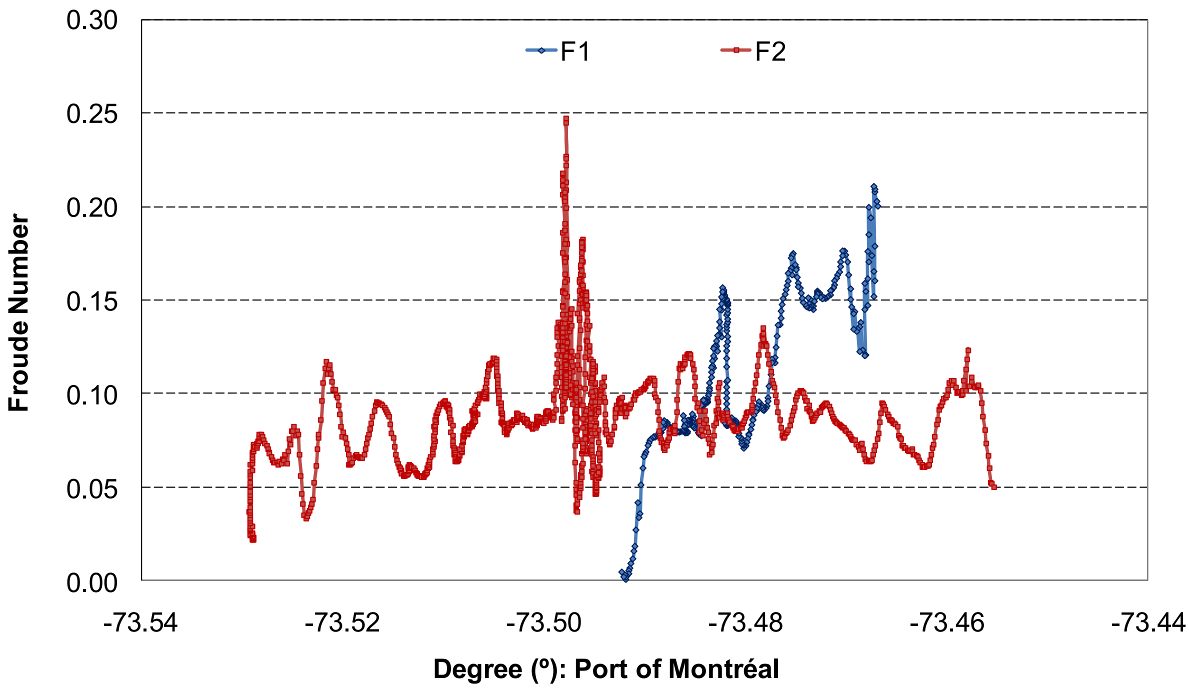

Figure 5. 10 Froude Numbers along the limits of maximal ice coverage at Port of Montréal

Table 5. 3 Distribution of Froude numbers along the limits at Port of Montréal on 29th Jan. 2005

Unit:%	0-0.05	0.05-0.10	0.10-0.15	0.15-0.20	0.20-0.25	> 0.25
Along Limit 1	6	**66**	**23**	4	1	0
Along Limit 2	5	**60**	**23**	12	0	0

5.3.2 Varennes to Contrecoeur

The ice chart of ‘Varennes to Contrecoeur’ reach on 29th January 2005 is shown in Figure 5.11. We also rotate the chart to make the vertical upward direction north. There are 5 limits (edges) when border ice areal coverage reaches the maximum on this reach. The ‘limit 1’ and ‘limit 2’ belong to the north-west shore. The other limits belong to the south-east shore.

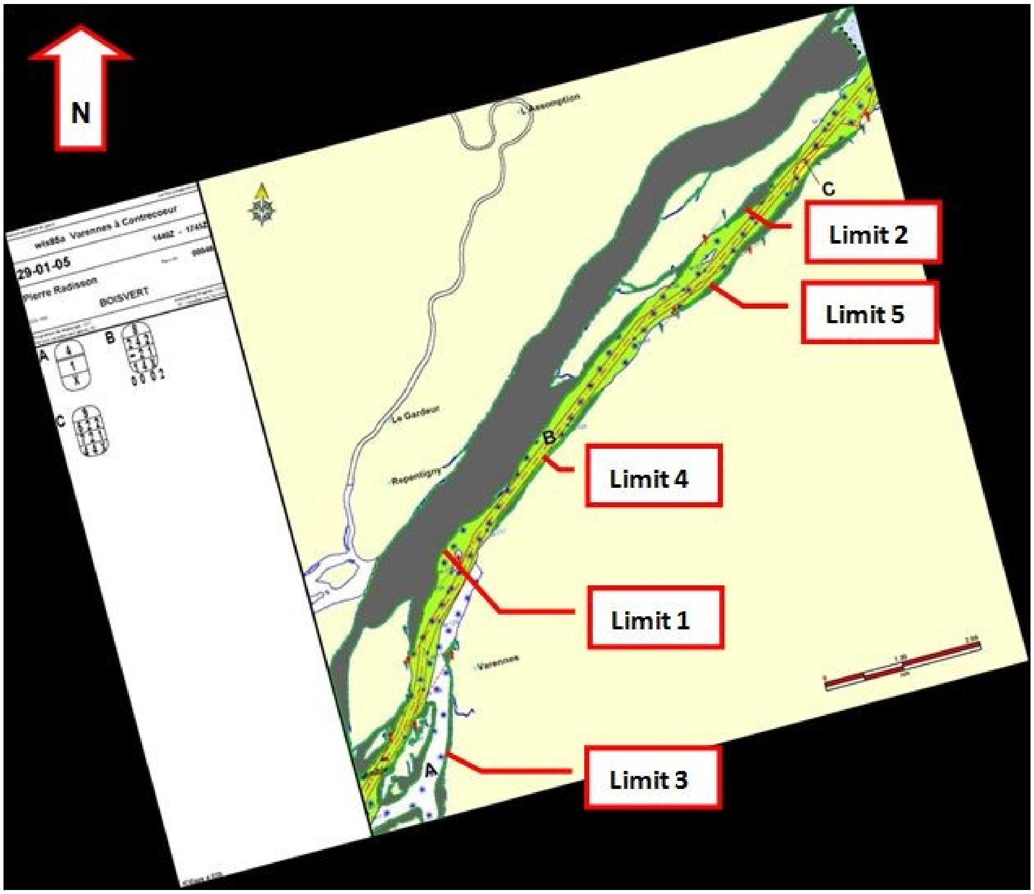

Figure 5. 11 Ice chart of Varennes to Contrecoeur on 29th Jan. 2005

Figure 5.12 shows flow velocities of nodes along the limits of maximal border ice areal coverage on Varennes to Contrecoeur reach. First, we observe the flow velocity along ‘limit 1’. There is a sharp drop near the longitude of -73.42 º where there is an island located closed to the limit. From the figure, we can see all the nodes stay in a range of 0-1.0 m/s. In table 5.4, we can see directly the distribution of flow velocities. It does not seem very regular but no nodes exceed 1.0 m/s.

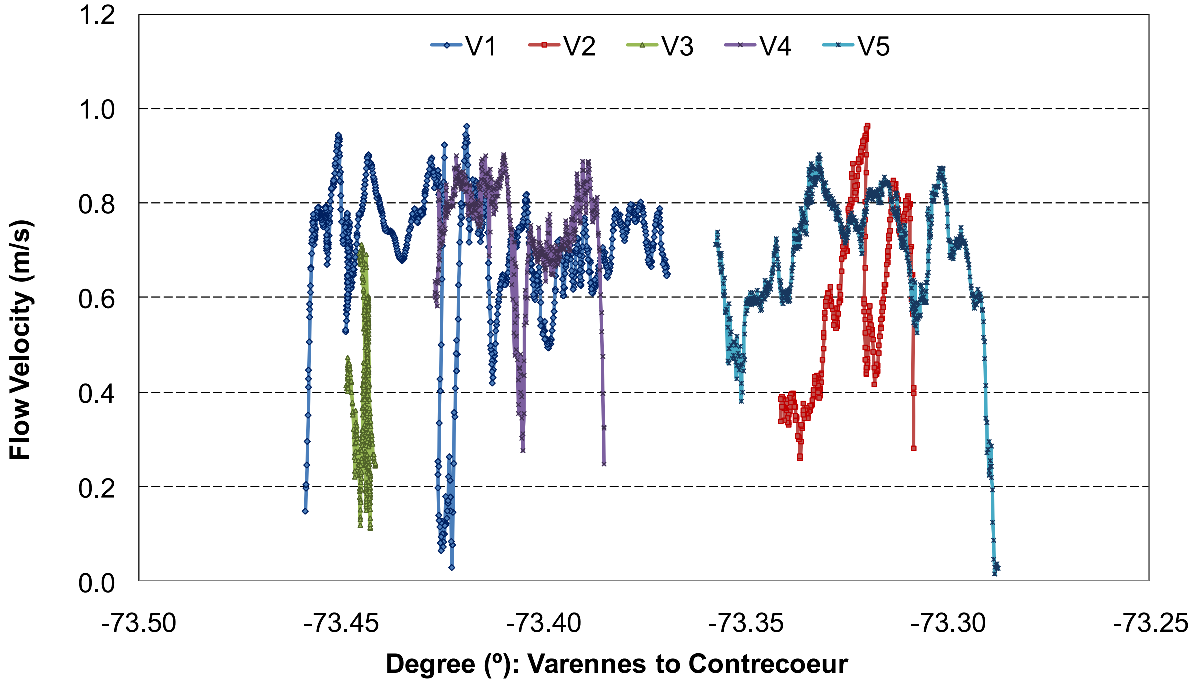

Figure 5. 12 Flow velocities along the limits of maximal ice coverage at Varennes to Contrecoeur

Table 5. 4 Distribution of flow velocities along the limits at Varennes to Contrecoeur on 29th Jan. 2005

Unit: %	0-0.2 m/s	0.2-0.4 m/s	0.4-0.6 m/s	0.6-0.8 m/s	0.8-1.0 m/s	>1.0 m/s
Along Limit 1	3	1	9	**71**	16	0
Along Limit 2	0	**23**	**33**	**27**	18	0
Along Limit 3	11	**36**	**42**	11	0	0
Along Limit 4	0	3	6	**56**	**35**	0
Along Limit 5	2	2	19	**51**	**26**	0

Figure 5.13 shows river depths of nodes along the limits of maximal border ice areal coverage on Varennes to Contrecoeur reach. We see that the most river depths stay in a range of 0-12 m. Table 5.5 shows more than 90% nodes are in a range of 0-8 m along almost all the limits. On this reach, only 0.2% nodes of ‘limit 1’ exceed 12 m.

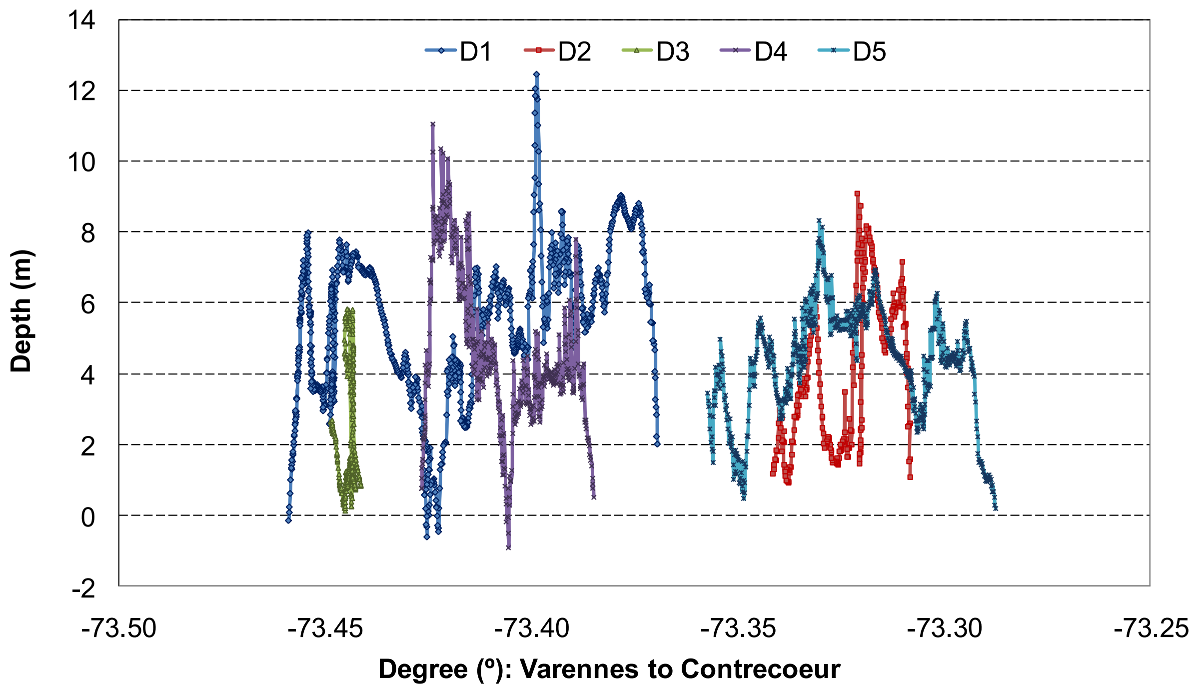

Figure 5. 13 River depths along the limits of maximal ice coverage at Varennes to Contrecoeur

Table 5. 5 Distribution of river depths along the limits at Varennes to Contrecoeur on 29th Jan. 2005

Unit: %	**0-4 m**	**4-8 m**	**8-12 m**	**12-16 m**	**>16 m**
Along Limit 1	**27**	**64**	9	0.2	0
Along Limit 2	**51**	**46**	3	0	0
Along Limit 3	**81**	**19**	0	0	0
Along Limit 4	**46**	**41**	11	0	0
Along Limit 5	**34**	**66**	0.3	0	0

Froude numbers of nodes along the limits of maximal border ice areal coverage on Varennes to Contrecoeur reach is shown in Figure 5.14. It is observed that the Froude Numbers along ‘limit 5’ reaches 0.35 and those along other limits are below 0.25. In Table 5.6, it is noted that 1% nodes are in excess of 0.25 along ‘limit 5’. Except 20% nodes are in a range of 0.15-0.20 along ‘limit 2’, most nodes are in a range of 0.05-0.15. Through statistical calculation we obtain 88% nodes along ‘limit 1’, 77% nodes along ‘limit 2’, 92% nodes along ‘limit 3’, 94% nodes along ‘limit 4’ and 94% nodes along ‘limit 5’ are in this range.

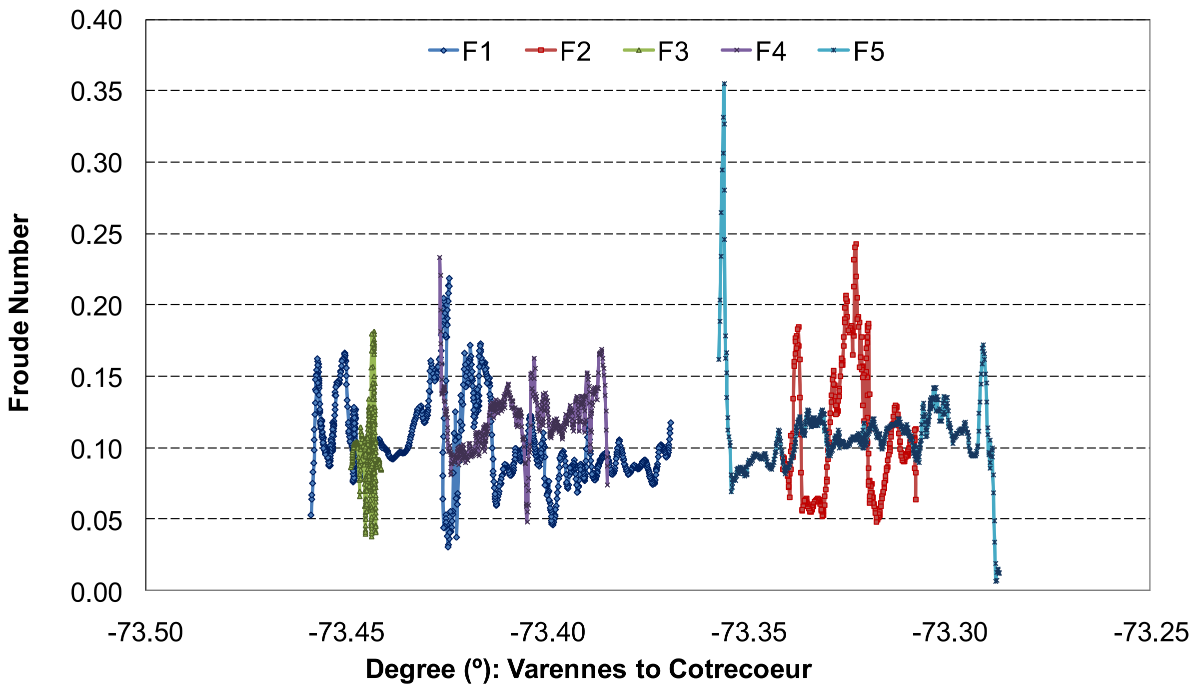

Figure 5. 14 Froude Numbers along the limits of maximal ice coverage at Varennes to Contrecoeur

Table 5. 6 Distribution of Froude numbers along the limits at Varennes to Contrecoeur on 29th Jan. 2005

Unit: %	0-0.05	0.05-0.10	0.10-0.15	0.15-0.20	0.20-0.25	>0.25
Along Limit 1	2	**53**	**35**	10	0.8	0
Along Limit 2	0.7	**49**	**28**	**20**	3	0
Along Limit 3	4	**59**	**33**	4	0	0
Along Limit 4	0.2	**20**	**74**	5	0.5	0
Along Limit 5	2	**27**	**67**	2	0.5	1

5.3.3 Contrecoeur to Sorel

The ice chart of 'Contrecoeur to Sorel' reach on 29th January 2005 is shown in Figure 5.15. As the previous method, we rotate the figure to calibrate the vertical upward direction north. There are 3 limits when border ice areal coverage reaches the maximum in this reach. The 'limit 1' and 'limit 2' belong to the north shore, and 'limit 3' belongs to the south shore. There are 2 ice booms located on north-west side of the river.

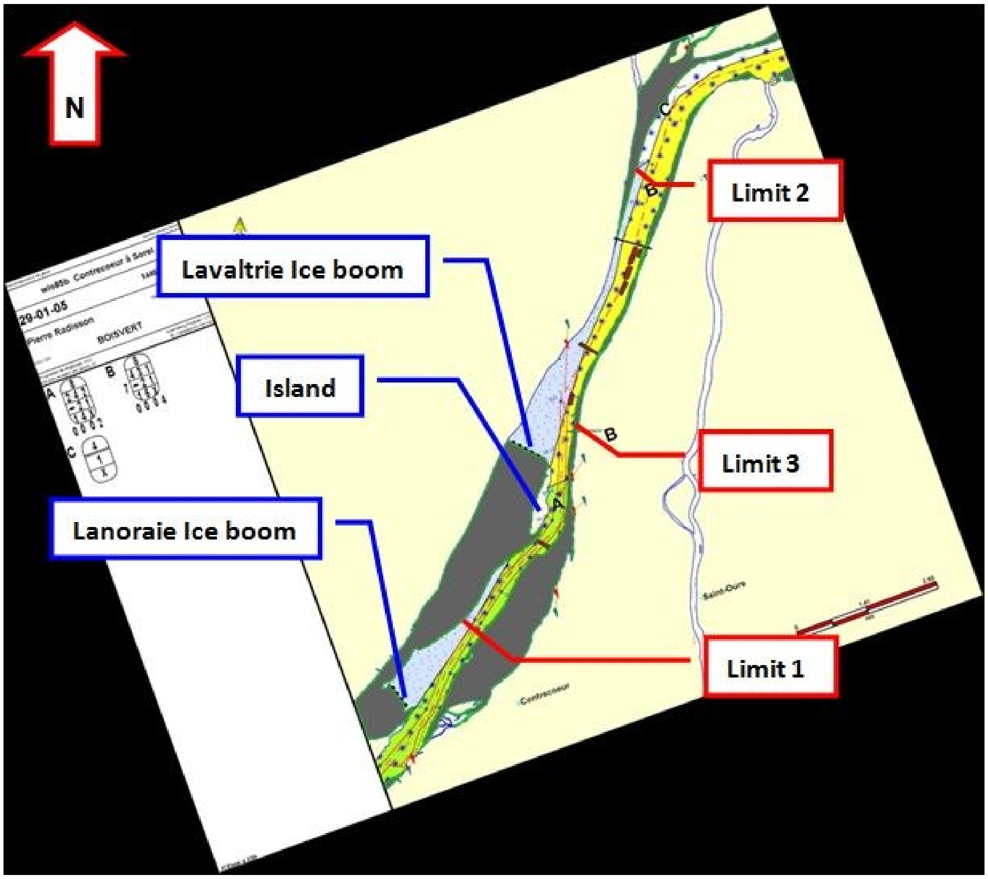

Figure 5. 15 Ice chart of Contrecoeur to Sorel on 29th Jan. 2005

Figure 5.16 shows that flow velocities of nodes along the limits of maximal border ice areal coverage on Contrecoeur to Sorel reach. Similar as other reaches, all the nodes stay in a range of 0-1.0 m/s. There are 2 ice booms located on the two sides of 'limit 1'.

At Lavaltrie ice boom location, the flow velocity is very small. The ice grabs the boom and island, and the ice accumulated. The ice builds up to Lanoraie ice boom. Near the upstream 'limit 3', there are several shoals existing. The flow velocity decreases occasionally when the water close to the shoals.

Through observation, the flow velocities stay at small values on both sides of 'limit 1'. There are 29% nodes in a range of 0-0.2m/s along 'limit 1' in Table 5.7. Most other nodes are in a range of 0.4-1.0 m/s. At south side of the lake, 80% nodes along 'limit 3' are in a range of 0.6-1.0 m/s. There are no nodes exceeding 1.0 m/s, so that 1.0 m/s is the maximum value.

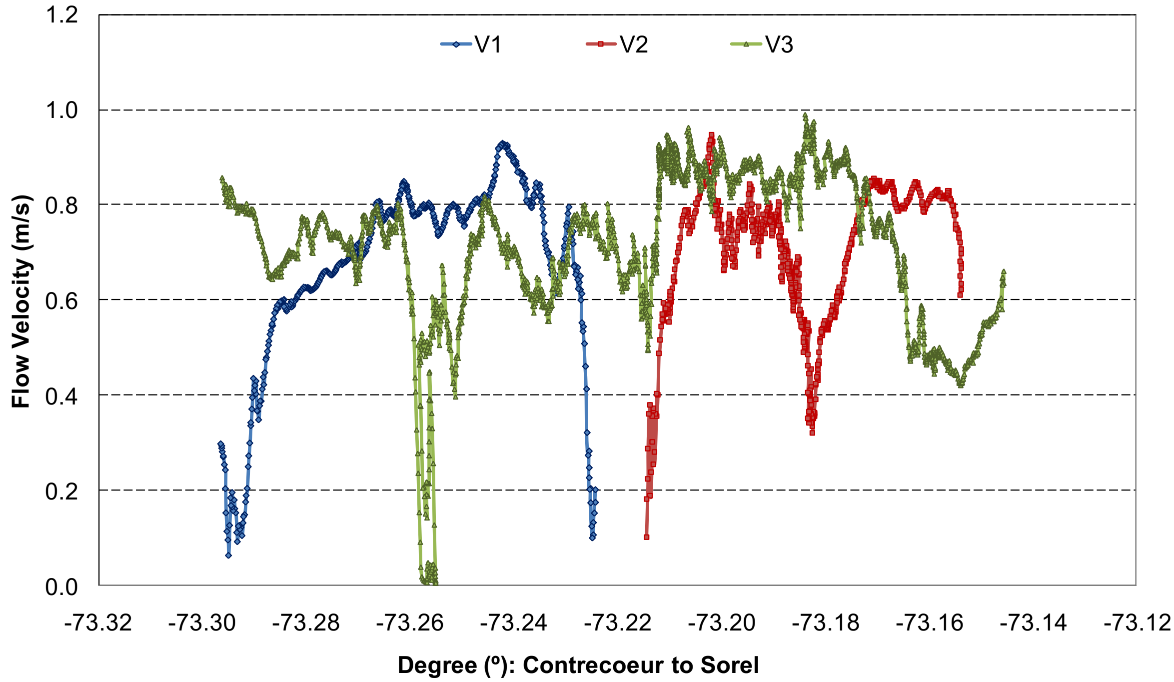

Figure 5. 16 Flow velocities along the limits of maximal ice coverage at Contrecoeur to Sorel

Table 5. 7 Distribution of flow velocities along the limits at Contrecoeur to Sorel on 29th Jan. 2005

Unit: %	**0-0.2 m/s (%)**	**0.2-0.4 m/s (%)**	**0.4-0.6 m/s (%)**	**0.6-0.8 m/s (%)**	**0.8-1.0 m/s (%)**	**>1.0 m/s (%)**
Along Limit 1	**29**	15	**19**	**27**	10	0
Along Limit 2	0.4	5	**20**	**50**	**26**	0
Along Limit 3	2	1	18	**39**	**41**	0

Figure 5.17 presents river depths of nodes along the limits of the maximal border ice areal coverage on Contrecoeur to Sorel reach. We can see most river depths stay in a range of 0-16 m. As we discussed above, near ice booms location the river depths are also shallow and nearly reach to 0 m. Table 5.8 shows more than 90% nodes are in a range of 0-12 m along all the limits. Along 'limit 3', 8% nodes are in a range of 12-16 m, and also 0.2% nodes exceed 16m.

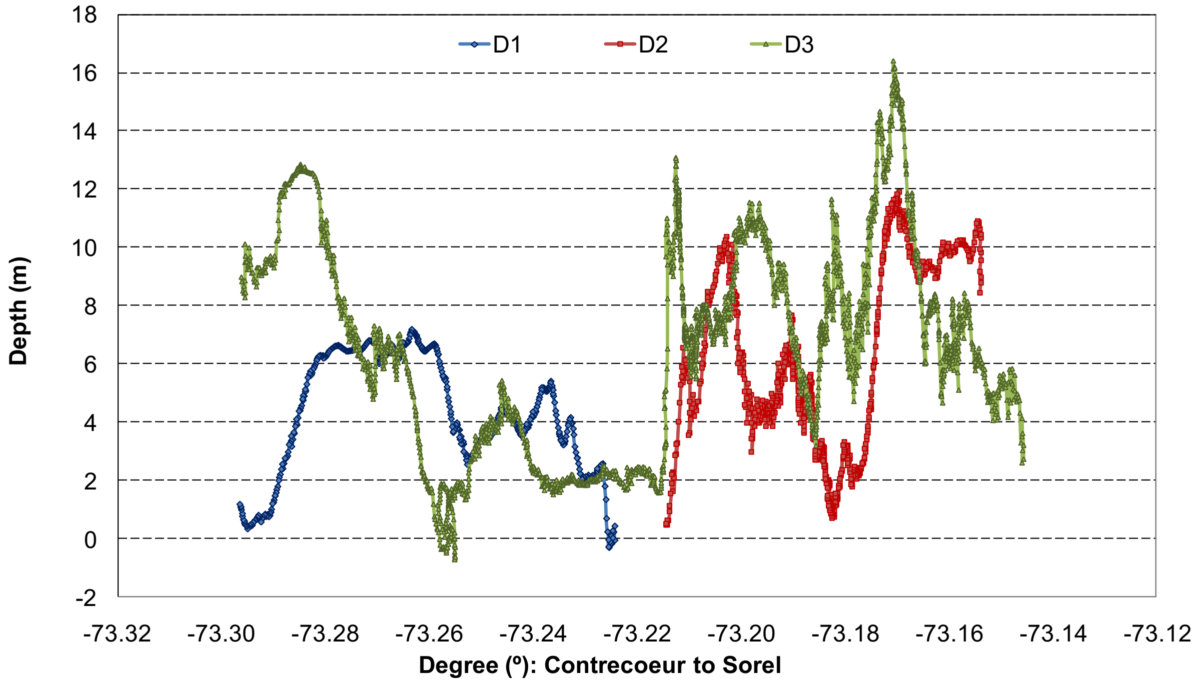

Figure 5. 17 River depths along the limits of maximal ice coverage at Contrecoeur to Sorel

Table 5. 8 Distribution of river depths along the limits at Contrecoeur to Sorel on 29th Jan. 2005

Unit: %	0-4 m	4-8 m	8-12 m	12-16 m	>16 m
Along Limit 1	**57**	**32**	0	0	0
Along Limit 2	**31**	**37**	**32**	0	0
Along Limit 3	**22**	**43**	**26**	8	0.2

Figure 5.18 shows Froude numbers of nodes along the limits of maximal border ice areal coverage on Contrecoeur to Sorel reach. We can see that the all Froude Numbers are below 0.25. From Table 5.9, 21% nodes are in a range of 0-0.05, since ice booms located at 'limit 1'. More than 70% nodes are in a range of 0.05-0.15. Along 'limit2' and 'limit 3', around 90% nodes are in a range of 0.05-0.15.

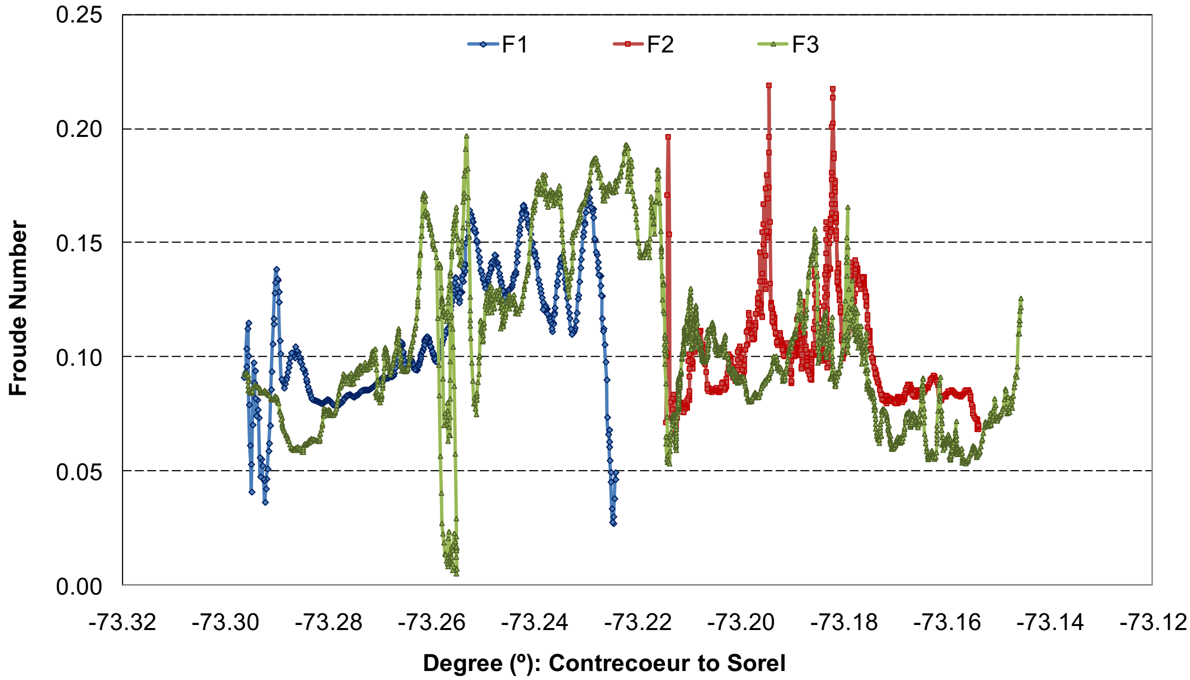

Figure 5. 18 Froude Numbers along the limits of maximal ice coverage at Contrecoeur to Sorel

Table 5. 9 Distribution of Froude numbers along the limits at Contrecoeur to Sorel on 29th Jan. 2005

Unit: %	0-0.05	0.05-0.10	0.10-0.15	0.15-0.20	0.20-0.25	>0.25
Along Limit 1	**21**	**43**	**30**	6	0	0
Along Limit 2	0	**48**	**46**	6	0.6	0
Along Limit 3	2	**52**	**35**	11	0	0

In this part, the flow velocity, river depth and Froude number along border ice limits when the ice coverage is maximal is presented. Generally, it is found that along the limits corresponds to a maximum flow velocity of under 0.8 to 1 m/s. The depth along the border ice limits is highly variable, ranging from 0 to 14 m. The maximum Froude number is usually found to be under 0.2. These results are similar to those found for Lake Saint-Pierre reach presented in Chapter 4. The main difference is that the maximum Froude number is bigger in this reach (~ 0.2) than that found for Lake Saint-Pierre (~ 0.1).

Chapter 6
Results and analysis of border ice limit from Trois-Rivières to Québec

In chapter 5, we analyzed and discussed the border ice limits of upstream Lake Saint-Pierre. In this chapter, we research the downstream border ice limits from Trois-Rivières to Québec City reach including Port of Trois-Rivières, Trois-Rivières to Grondines, Grondines to Portneuf, Portneuf to Saint-Nicolas and Port of Québec.

6.1 Border ice areal coverage

For analysing the border ice areal coverage of downstream Lake Saint-Pierre, we select a graph of the Grondines to Portneuf reach as a sample to make a detailed presentation.

Figure 6.1 presents a selected example for the 2008-2009 winter season. In Figure 6.1 (bottom), the original EC ice charts for three individual dates are reproduced. The first chart (8th December, 2008) corresponds to conditions at freeze-up and the areal coverage is 24%; the second (19th January, 2009) presents the maximal coverage (91%) during mid-winter; and the third (13th March, 2009) shows conditions during the breakup period and the areal coverage is 38%.

The percentage of border ice areal coverage presented in Figure 6.1 (top) expresses the border ice areal coverage on any given day divided by maximal areal coverage of border ice that was observed for all five winter seasons (2004-2009). During freeze-up period, the extent of border ice areal coverage of Grondines to Portneuf grows rapidly. We observe that the area of border ice grew from 2% on 13th December 2008 to 68% on 23rd December (i.e, in only 10 days). The mean air temperature during this period was -12 °C.

Then, on December 28th, temperatures rose to 2.8 °C above zero. Hence, the areal coverage of border ice dropped sharply down to 48% (26th December, 2008) and then to 41% (29th December, 2008). When air temperatures become cold again, the lost area is quickly recovered to 61% (3rd January, 2009). Then, the ice coverage climbs slowly to the maximal value 91% (19th January, 2009) and keeps a short relative stable period above 80% until 6th February, 2009. Then, the ice coverage drops sharply to 48% (20th February, 2009). After a little recovery to 58% (21st February, 2009), the ice drops until the end of March.

Compared with Lake Saint-Pierre and Varennes to Contrecoeur reach, the annual border ice cycle is different. There isn't an obvious 'Plateau' period. From 6th February, 2009, the ice coverage continuously drops up to the end of winter despite it being relatively cold. On March 26th, there is only 4% border ice coverage. In this reach, the breakup process is not totally natural without the icebreaking activities carried out by the Canadian Coast Guard if the activities are finished on Lake Saint-Pierre.

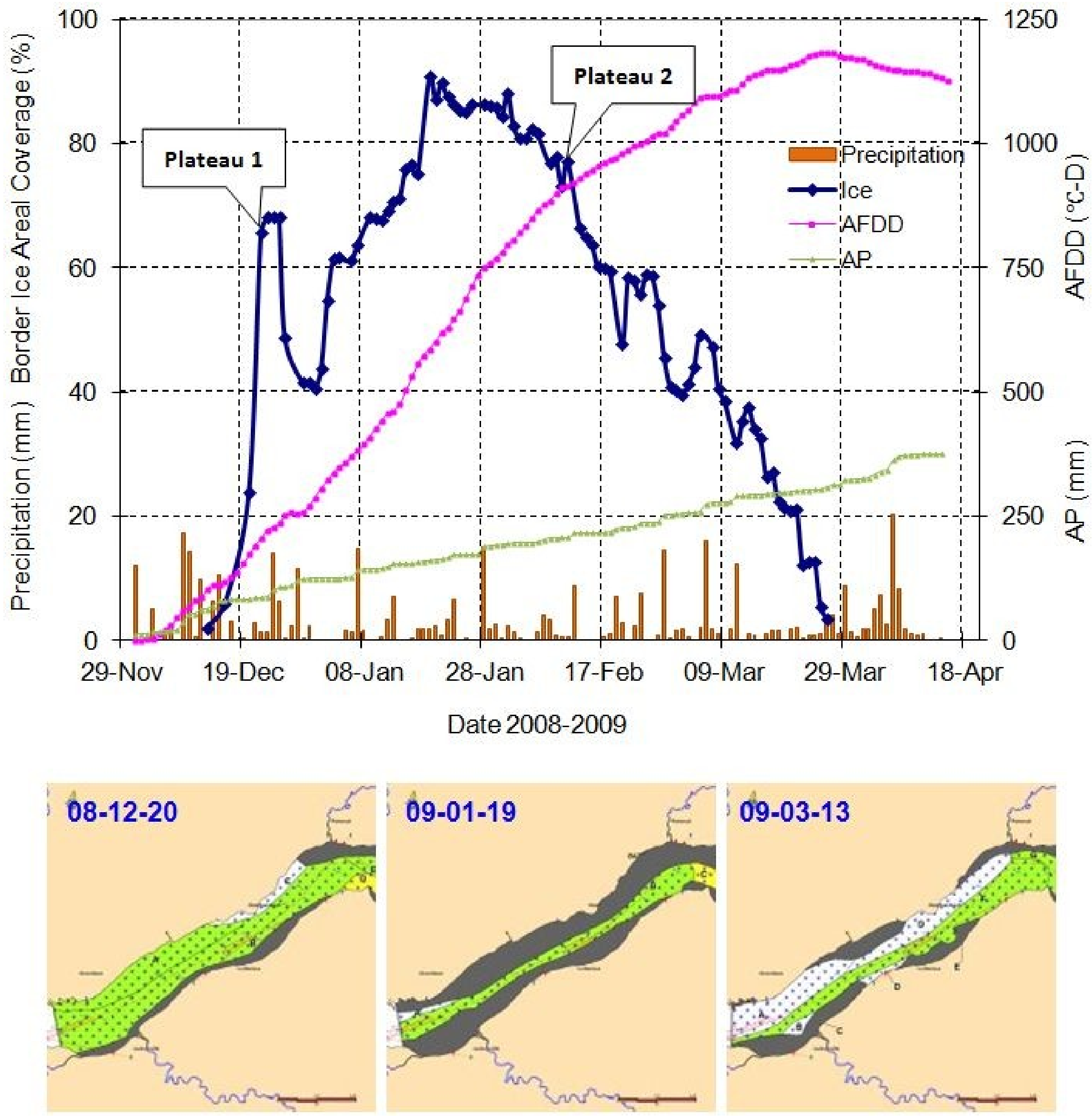

Figure 6. 1 Top: Border ice areal coverage during 2008-2009 winter at Grondines to Portneuf

Bottom: Ice charts from Environment Canada 2008-2009

6. 2 Freeze-up and breakup of Trois-Rivières to Québec

6.2.1 Growth rate of border ice

For presenting the growth rate of border ice downstream Lake Saint-Pierre, we also choose Grondines to Portneuf reach as an example. Figure 6.2 presents the border ice of Grondines to

Portneuf reach during freeze-up periods for all five winters. Based on a linear regression, growth trend lines are determined for freeze-up occurring during the areal coverage from beginning of the winter to 'Plateau 1' (sometimes the plateau period is not obvious). This represents the initial 'rapid' growth stage. The lower limit was chosen under 10% (usually from the first ice chart) at the very beginning of the winter.

In 2006-2007, the 'Plateau 1' begins around 40%. That because after this value there are several values stay at around 40% and there are even drops to 20% (Annex B: Figure B.33 Border ice areal coverage during 2006-2007 winter at Grondines to Portneuf). In the years 2004-2005 and 2008-2009 the 'Plateau 1' begins around 70%. In the years 2005-2006 and 2007-2008, the 'Plateau 1' begins around 50%. The regressions were made as a function of AFDD as we introduced in previous chapters.

Note that the 20% ice coverage value is reached when $100 < AFDD < 180$ and the nominal 40% value is reached when $160 < AFDD < 280$. This represents an increase of 20% (i.e. from 20% to 40%) in about 60 to 100 AFDD corresponding to an average increase of 0.33% to 0.2% per DD (The value of 2004-2005 was an exception at 3% per DD).

More specific values are presented in Figure 6.2. The rate of border ice growth in 2004-2005 is 3% per DD, which is the fastest among this 5-year period. By contrast, the rate of border ice growth in 2006-2007 is the slowest (same as Varennes to Contrecoeur) with a rate of 0.2% per DD.

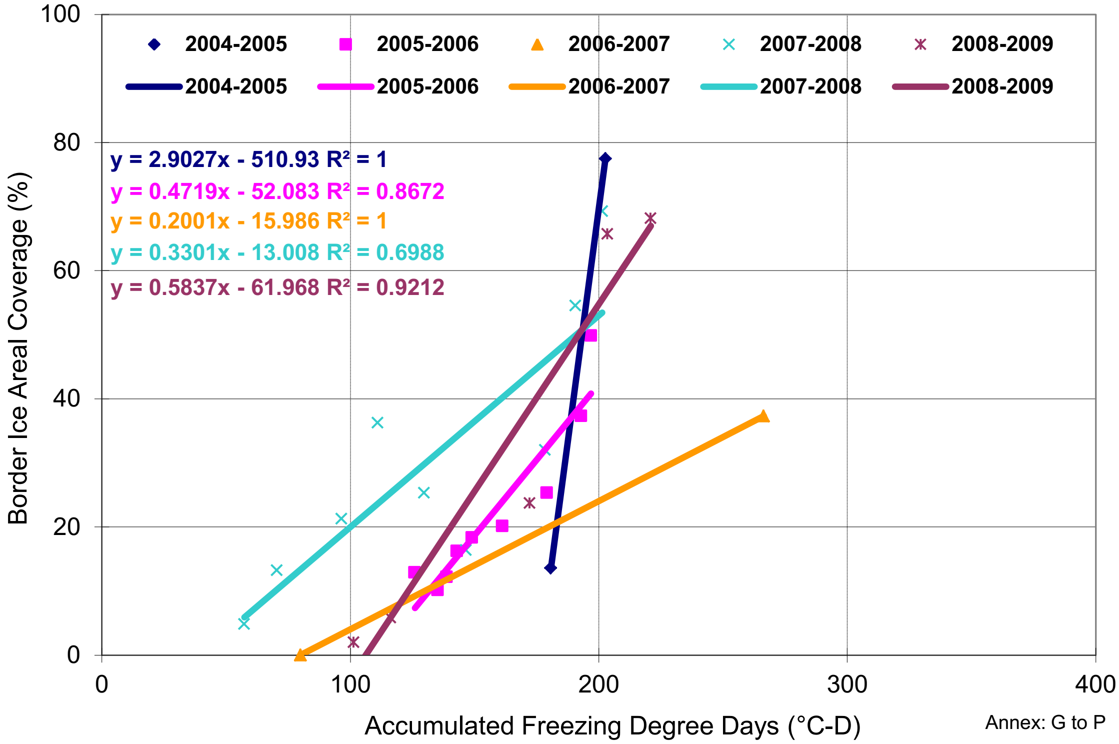

Figure 6. 2 Trend lines of ice coverage as a function of AFDD at Grondines to Portneuf during freeze-up period

In this reach, the 'Plateau' period sometimes is not obvious as Figure 6.1 (top). So for the second growth period we don't choose 55% to 'Plateau 1' as Lake Saint-Pierre, and we choose maximal value instead. For the very fast growth (20% to 55%) and the relatively fast growth (55% to maximal value in one year) periods, the growth rates are calculated as a function of AFDD and simply as a function of the number of calendar days. These rates are presented in Figures 6.3 and 6.4.

In Figure 6.3, the rates are presented as a function of AFDD ($Slope_1$ = Increase in % / DD during the period). The black columns represent the $Slope_1$ when the border ice coverage grows from 20% to 55%. The grey columns represent the $Slope_1$ when the border ice coverage grows from 55% to 'Max'. The $Slope_1$ of 20% to 55% is usually higher than that of 55% to 'Max'.

First, we observe the $Slope_1$ of 20% to 55%. We can see that the $Slope_1$ in 2006-2007 winter is lower than that in other years at 0.15%/DD. Through observing the weather condition, we find that there are always some days with temperature above 0 °C during that year. The maximum value is 2.9%/DD in 2004-2005. In other words, the variability of the rate from one year to the next is about 19 (i.e. = 2.9 / 0.15).

During the second part of the rapid growth period, rates vary from 0.07%/DD to 0.2%/DD representing a variability factor of 3. Note that the correlation between the two growth periods. At Lake Saint-Pierre and Varennes to Contrecoeur, we make a conclusion that if the first period is fast the second is too whereas if the first period is slow, the second is too. But in this reach, the result is not the same. The reason is after first fast growth period, it is slow to reach the maximal value in the year. (Refer to Annex B: Border ice areal coverage figure). That makes the slope of second growth small.

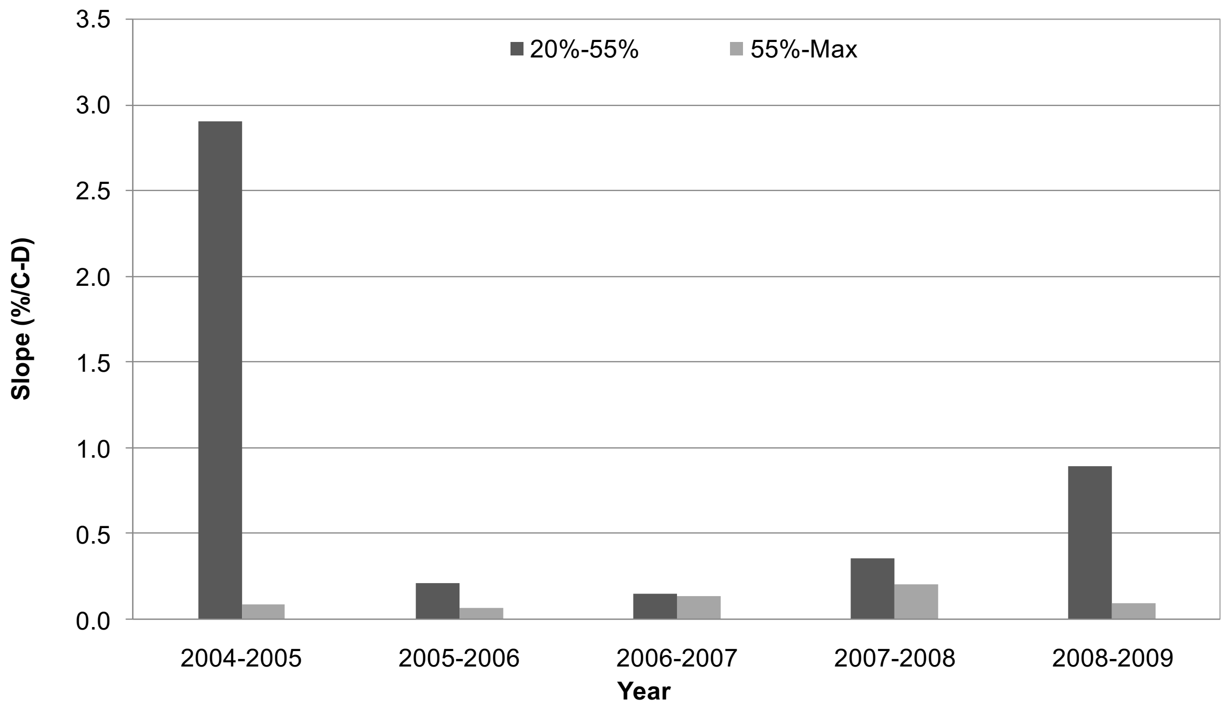

Figure 6. 3 Rate of border ice areal growth per degree-day at Grondines to Portneuf

In Figure 6.4, growth is expressed as a function of the number of days rather than as a function of AFDD. The black and gray columns represent the $Slope_2$ (=Increase in % / Days during the period) for the two rapid freeze-up sub-periods. For the first sub-period, the growth rate varies from 2%/D in 2006 to 64%/D in 2008 representing a variability factor of 32. For the second sub-period, the growth rate varies from 0.5%/D to 2%/D representing a variability factor of 4. As expected, these variability factors are greater than those based on AFDD. We can conclude that AFDD is therefore a better growth predictor than simply time itself. The white columns represent the $Slope_2$ during the breakup period. Because the ice coverage decreases as time goes by during the breakup period. To obtain a positive value, we create the opposite value of $Slope_2$ during the breakup period, which is also shown in Figure 6.4. The value is from 0.3%/D to 3.3%/D. In Figure 6.4, one value is so large that we cannot see the other values clearly. So we make Table 6.1 to show the values.

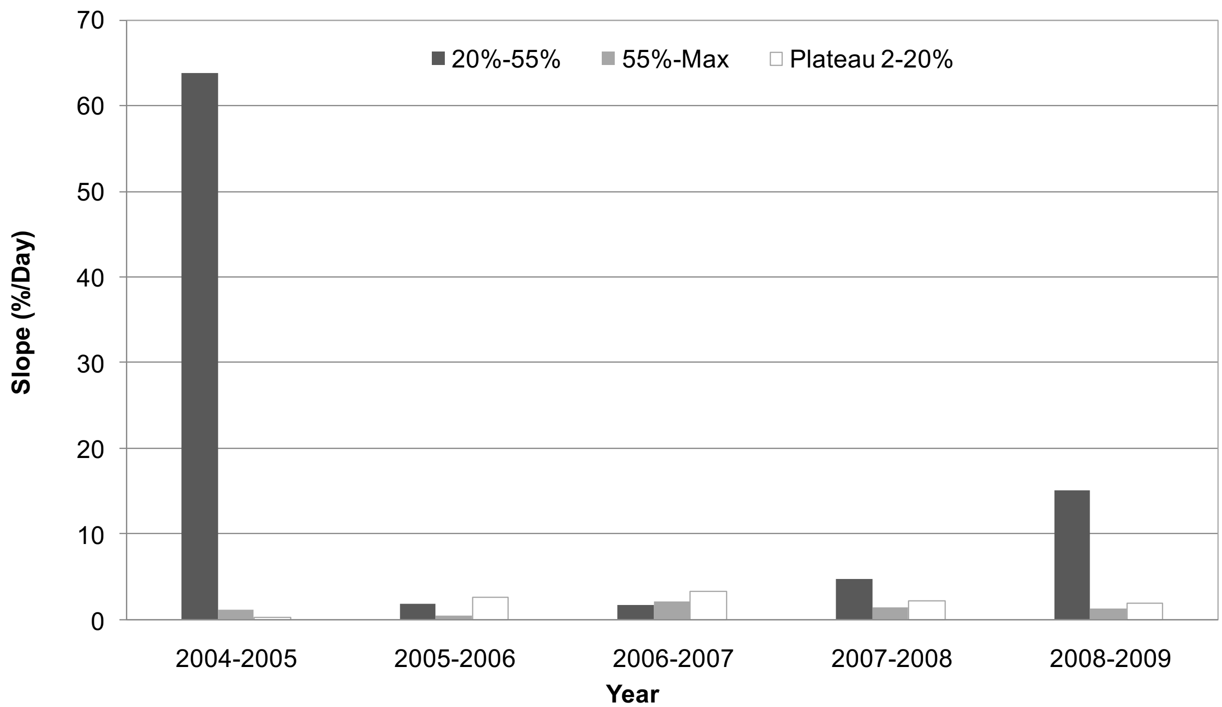

Figure 6. 4 Rate of border ice areal growth per day at Grondines to Portneuf

Table 6. 1 Rate of border ice areal coverage growth per day at Grondines to Portneuf

	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009
20%-55%	63.9	1.9	1.7	4.8	15.1
55%-Max	1.2	0.5	2.1	1.5	1.3
Plateau 2-20%	0.3	2.6	3.3	2.1	1.9

6.2.2 Decay rate of border ice

The breakup period of Grondines to Portneuf is presented in Figure 6.5 and Figure 6.6. Areal ice cover diminution is presented as a function of AFDD and trend lines based on a linear regression are included in Figure 6.5. In general, AFDD is positive during the breakup period.

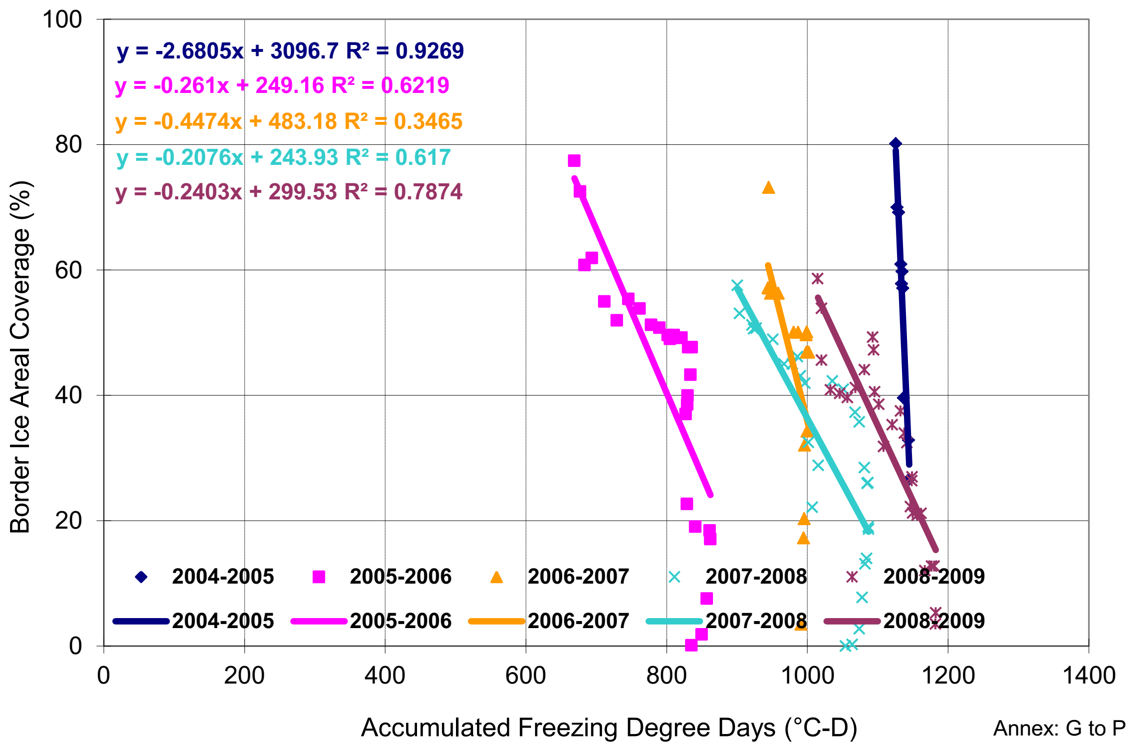

Figure 6. 5 Trend lines of ice coverage as a function of AFDD at Grondines to Portneuf during breakup period

In Figure 6.6, areal ice cover diminution is presented as a function of AMDD. As we introduced before, AMDD would be more representative as sunlight plays an important role and melting typically occurs in the spring when temperatures are higher than -10 °C. Note that the 40% ice coverage value is reached when 20< AMDD < 100 and the ice coverage melts totally when 150 < AMDD < 230 in the 5 winters. This represents a decrease of 40% (i.e. from 40% to 0%) in about 130 AMDD corresponding to an average decrease of -0.3% per DD. (In fact the average value over the five year period was also found to be -0.3% per DD).

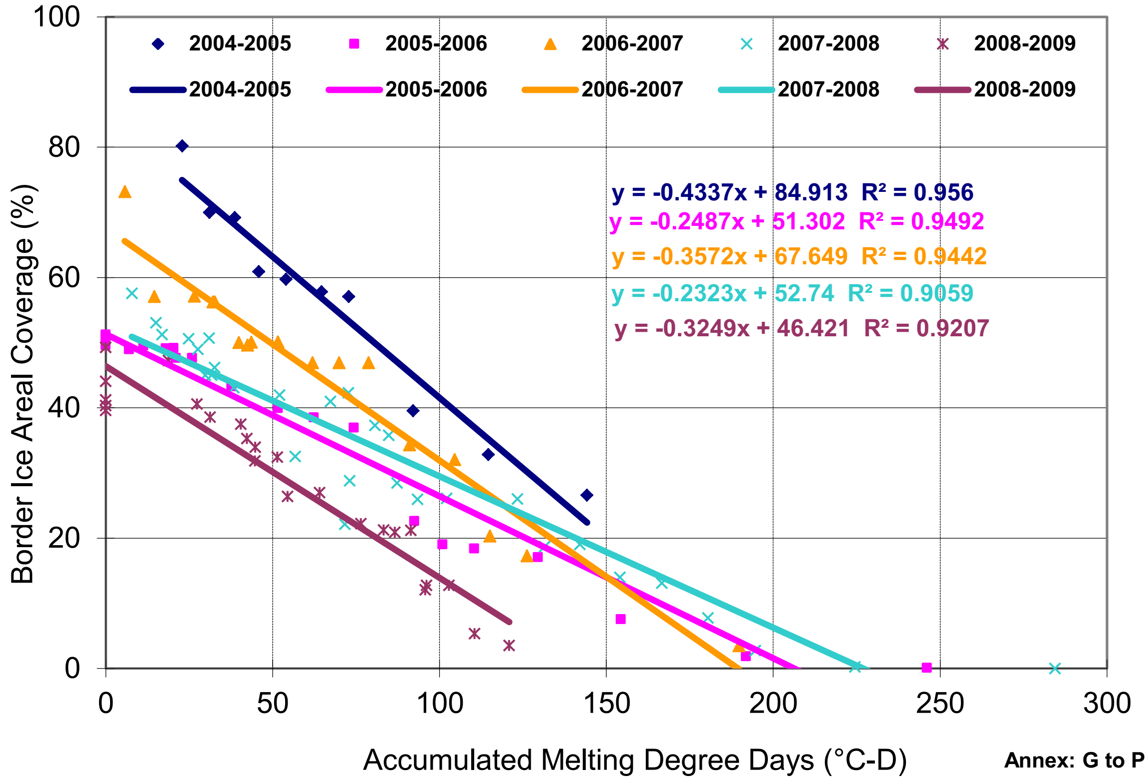

Figure 6. 6 Trend lines of ice coverage as a function of AMDD of Grondines to Portneuf during breakup period

Compared with the condition of Lake Saint-Pierre, the change of border ice coverage downstream at breakup period is more complicated. The CCG ice breaking program will operate on downstream Lake St. Pierre once it finish the work on Lake St. Pierre. As we have introduced, in Figure 6.1 (top), sometimes the 'Plateau' period is not very obvious, and the breakup period starts early and sometimes accompanies with a little recovery because of the temperature, precipitation or other reasons.

Chapter 7
Conclusions and discussion

In this thesis, a statistical analysis of border ice behavior on Saint Lawrence River from Montréal to Québec City is presented in considerable detail. In keeping with the objectives, the criteria for border ice formation and decay are established. The conclusions and discussion of this thesis are summarized in this chapter.

7.1 Findings

For freeze-up, existing border ice equations proposed by Michel, Newbury and Matousek identify that AFDD is a dominant factor influencing the ice formation and growth. Local velocity, Froude no. and depth are also identified.

This analysis shows that obstacles (river bends, ice booms, shoals, artificial islands, bridge piers and so on) play a very important role on the Saint Lawrence River. They influence flow velocity and provide an object against which the ice can become fast and initiate its formation.

7.1.1 Border ice coverage

The analyses presented in this thesis are centered on the amount of areal border ice coverage. For this purpose, MATLAB is applied to recognize and delineate border ice areal coverage of the Environment Canada ice mappings over five winters. The results are presented in tabular and graphical fashion as a function of AFDD, date and precipitation.

During a winter season, there are three stages of ice coverage. First, the growth rate of the border ice at the beginning of the winter is usually very quick once the water cools sufficiently. After that, upstream of Trois-Rivières, ice coverage will stay at a relatively stable status as long as no warm/rainy spell occurs. At last, border ice begins to breakup as March progresses. Since the ice breaking activities are carried out by the Canadian Coast Guard hovercrafts, the breakup is not natural in some locations (particularly for Lake Saint-Pierre).

Moreover, several general laws are proposed through analyzing the loss of border ice coverage in mid-winter. In our study, winter breakup usually occurs during the late December and early January period. For all events over the 5-year study period, there were mid-winter events only when air temperatures rose above 0 °C. This was often associated with a rain event. The rain results in a high rate of snowmelt and consequently, high river flows. As a result, increased downstream forces are exerted on the ice cover causing localized breakup as it looses strength and thermally expands (causing internal stresses) as it warms up.

7.1.2 Border ice growth and decay

Through the method of statistical analysis, several factors (AFDD and dates) which influence border ice formation and melting are discussed. Although the AFDD and dates seem not very similar when the border ice reaches certain coverage, there still exist several similarities.

The statistical analyses of nine reaches extending over five winters revealed that the border ice reaches 20% of the maximum coverage when the AFDD reaches, on average, 124 °C-D. The border ice reaches to 'Plateau 1' (i.e., the end of the rapid growth period) when AFDD reaches about 247 °C-D. On average, border ice reaches maximal coverage when AFDD reaches 551 °C-D.

Border ice usually reaches to maximal coverage at the end of January except the average date for 2007-2008 was 25th Dec. 2007.

To better understand the freeze-up process, the south side of Lake Saint-Pierre was examined in some detail as this is the most important area of interest. Border ice growth velocity (i.e., speed and direction) was analyzed, as well as the growth function $f = \Delta d/DD$ (where Δd is the increase in ice width (m) and DD are degree-days (°C-D). Contour lines are plotted using interpolations made by MATLAB. The growth velocity is modest at the very beginning of the winter and then accelerates. When the ice coverage is near the maximum, the growth slows down. With respect to direction, most growth is perpendicular to the general direction of the shoreline but can significantly change directions on occasion.

For the border ice decay, the breakup rate is essentially a function of when and how fast the CCG hovercraft can work. Depending on the weather and the mechanical state of the crafts, it typically takes the CCG crew about three weeks to clear most of the fast ice (especially for Lake Saint-Pierre). Ice breaking operations typically begin in mid-March but will depend on the CCG ice bureau officer's assessment of the risks to commercial navigation.

7.1.3 Border ice limits

Since it is the most important reach, a detailed comparison of border ice limits was conducted for Lake Saint-Pierre. There are a series of artificial islands and navigation lights to catch hold of the border ice along the channel. For this reason, it is found that the maximum border ice limit is quite similar over these five winter seasons.

Along the ice edge in Lake Saint-Pierre, the flow velocity is under 0.8 m/s along the maximum border ice limits. The Froude number is relatively stable compared with flow velocity and river depth. The Froude number is usually under 0.1. The depth along the border ice limit is irregular, ranging from 0 to 14 m.

In the Montréal to Sorel reach, the velocity is always under 1.0 m/s; the maximum Froude number is around 0.1 to 0.2; and the river depth is also irregular, but is less than 12 m (corresponding to the maximum river depth). On the whole, maximum river velocity and the Froude number along the ice edge are regular and fall within a narrow range whereas the river depth can vary widely.

7.1.4 Comparison of flow velocity and water surface elevation with ice and without ice

A comparison of flow velocity and water surface elevation with ice and without ice is conducted for the Montreal to Trois-Rivières reach by subtracting EC's numerical solution of one simulation from the other. The flow velocity difference is between -0.1 m/s to 0.1m/s. In the navigation channel, the flow velocity is always faster in winter and is generally equal to 0.1 m/s. On the other hand, velocities are diminished outside the navigation channel, under the border ice where water currents in shallow areas are very small in winter.

The change in water surface elevation due to border ice increases in the upstream direction starting at 0 for Trois-Rivières and increasing to +0.14 m at Montréal.

7.2 Discussion

There are many detailed considerations and there are specific ice events that occur on the River. However, in very general terms, this study showed that border ice growth on the Saint Lawrence River generally behaves in a predictable manner. It reaches 20% of its maximum growth when AFDD reaches about 124 °C-D. Thereafter it grows rapidly (about 0.8% per DD) until reaches a plateau (that varies between 75% and 85%) after which time it gradually climbs to its maximum spatial coverage near January 31st. If, at any time, there is a winter thaw/rain event, there is a certain portion of ice that is lost that may or may not be quickly recovered. Otherwise, upstream of Trois-Rivières, the spatial coverage stays within 15% of its maximum value until the beginning of March after which time it gradually diminishes. Downstream of Trois-Rivières, the peak coverage is not maintained for as long a period. Area is lost starting at the beginning of February and continues into April.

The location of the border ice is highly dependent on channel geometry. Border ice generally starts from a downstream starting point (a wharf, an ice boom, bridge piers, shallows, etc,). It can also grow out from the bank and from that point into flow rarely exceeding 0.8 m/s and Froude numbers rarely exceeding 0.1 to 0.2.

It is clear that the results found here are specific to the Saint Lawrence River as there is winter navigation all year whereby the ship traffic artificially keeps the river open all year long and whose ship wakes regularly keep border ice at a distance from the navigation channel. Although the findings are certainly useful for the understanding of this very important River, they should be exported to other rivers with great caution.

Border ice is an important element that influences all eco-thermo-sediment-vegetative-hydraulic processes. In general, it increases the water velocity in the main channel through Lake Saint-Pierre by 0.1 m/s and reduces it significantly in shallow area covered by border ice.

7.3 Conclusions

In conclusion, the maximum spatial extent of border ice on the Saint Lawrence River depends on the proximity of the ships, the local Froude no. and velocity and on the presence of obstacles that secure the ice. The maximum spatial coverage is fairly uniform from one year to the next. Border ice goes through the following stages: initiation (20% coverage for AFDD = 124°C-D); rapid growth to about 80% at AFDD = 247°C-D; slow growth to maximum value near the end of January (AFDD = 551°C-D); a stable period upstream of Trois-Rivières where coverage is usually above 90% from beginning of January to beginning of March; a period of decay that begins in mid-Febuary downstream of Trois-Rivières and begins early March upstream usually ending at the end of March. The decay rate on Lake Saint-Pierre depends on ice breaking activities by CCG and is highly correlated to the Accumulated Melting Degree Days (with a base temperature of -10 °C). Usually, there is no mid-winter stable period for border ice downstream of Trois-Rivières as tides play a very important factor in border ice stability.

This study was undertaken at the request of Environment Canada and will probably be useful for its implementation of an operational model of the River. It is our hope that the findings presented in this thesis will be helpful for that endeavor.

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Annex A: MATLAB program

```
 function B = FindBorderIce( ImageFileName,Where,Show )
% FINDBORDERICE - Finds the border ice within the provided image
%
% DESCRIPTION: Within an ice charts from the Canadian Ice Service, the function automatically locates
all places where border ice was reported.
%
% INPUTS
% ImageFileName: File name of the image to be analyzed
% ImageFileName = '20080417131412_wis86c_cgqb.gif';).
% Where: location of the map. Choices are: 'Lake Saint-Pierre'
%                                           '...'
% Show (opt)   : Flag (1 or 0) to show the images within the process
% (Default value==0).
%
% OUTPUTS
% B: Cell (n x 1) containing the boundaries of all the border
% ice 'objects' that have been found. Each cell is defined as [i j ; ...].
% USAGE
% EX.:
% ImageFileName = '20080417131412_wis86_cgqb.gif';
% Where = 'Lake Saint-Pierre';
% Show = 1;
% B = FindBorderIce( ImageFileName,Where,Show );


close all;
warning off;
% Inputs check
try; info = imfinfo(ImageFileName); catch; error('Input image file name is wrong or image is not defined');
return; end;
switch Where
    case 'Lake Saint-Pierre'
    case 'Port of Montreal'
    case 'Port of Trois-Rivieres'
    case 'Varennes to Contrecoeur'
    case 'Contrecoeur to Sorel'
    case 'Potrneuf to Saint-Nicolas'
    case 'Trois-Rivieres to Grondines'
```

```
    case 'Port of Quebec'
    case 'Grondines to Portneuf'

    otherwise
        error('Specified location of the image is unknown');
        return;
end
if nargin<2|nargin>3; error('Wrong number of entries'); return; end;
if nargin<3; Show=0; end;
% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

% Read image
info = imfinfo(ImageFileName);
I = imread(ImageFileName);
% Convert to rgb according to file format
switch info.Format
    case 'GIF'
        Irgb = ind2rgb(I,info.ColorTable);
    case 'jpg'
        Irgb = I;
end
switch Where
    case 'Port of Montreal'
        Irgb = imrotate(Irgb,40);
end
switch Where
    case 'Port of Trois-Rivieres'
        Irgb = imrotate(Irgb,10);
end
switch Where
    case 'Varennes to Contrecoeur'
        Irgb = imrotate(Irgb,15);
end
switch Where
     case 'Contrecoeur to Sorel'
        Irgb = imrotate(Irgb,20);
end
switch Where
    case 'Potrneuf to Saint-Nicolas'
        Irgb = imrotate(Irgb,-15);
end
```

```
switch Where
   case 'Port of Quebec'
       Irgb = imrotate(Irgb,-2);
end
switch Where
   case 'Grondines to Portneuf'
    Irgb = imrotate(Irgb,10);
end
% show image if wanted
if Show; figure; imshow(Irgb); end
% determine if image is a colored one (RGB) or gray scaled one (indexed)
if size(info.ColorTable,1)==256
   ImType = 'c';   % colored image
elseif size(info.ColorTable,1)==16
   ImType = 'g';   % gray scaled image
else
   error('Image type is unknown. Please check the image type.');
   return;
end
% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

% Manipulate image according to the format and location specified
% Create object image to work on
Iobject = zeros( size(Irgb,1),size(Irgb,2),1 ); % totally black image
% find all border ice 'objects' from their color
if strcmp(ImType,'c')
   % colored image -> border ice == 0.384
   indBorderIce = Irgb(:,:,1)>0.383 & Irgb(:,:,1)<0.385;
elseif strcmp(ImType,'g')
   % gray scaledimage -> border ice == 0.502
   indBorderIce = Irgb(:,:,1)>0.5 & Irgb(:,:,1)<0.52;
end
Iobject(indBorderIce) = 1;    % impose white where there may be border ice

% get rid of the points outside the interested zone
[i2check j2check] = find(indBorderIce); % define coord. to check
switch Where
   case 'Lake Saint-Pierre'
         load('LacStPierrePolygonIN.mat') % load polygon of the interested zone
         xin = x; yin = y;
% load('LacStPierrePolygonOUT.mat') % load polygon of the interested zone
```

```
%xout = x; yout = y;
    case 'Port of Montreal'
        load('PortofMIN.mat')
        xin = x; yin = y;
    case 'Port of Trois-Rivieres'
        load('TRIN.mat')
        xin = x; yin = y;
    case 'Varennes to Contrecoeur'
         load('VtoC.mat')
          xin = x; yin = y;
    case 'Contrecoeur to Sorel'
         load('CtoS.mat')
          xin = x; yin = y;
    case 'Potrneuf to Saint-Nicolas'
        load('PtoS.mat')
        xin = x; yin = y;
    case 'Trois-Rivieres to Grondines'
        load('TRtoGIN.mat')
        xin = x; yin = y;
    case 'Port of Quebec'
        load('PofQ.mat')
        xin = x; yin = y;
    case 'Grondines to Portneuf'
        load('GtoP.mat')
        xin = x; yin = y;
end
if ~exist('xin');
      IN1 = ones(numel(i2check),1);
      IN2 = inpolygon( j2check,i2check, xout,yout );
elseif ~exist('xout');
      IN1 = inpolygon( j2check,i2check, xin,yin );
      IN2 = zeros(numel(i2check),1);
elseif (exist('xin')&exist('xout'));
      IN1 = inpolygon( j2check,i2check, xin,yin );
      IN2 = inpolygon( j2check,i2check, xout,yout );
end
ind = ~IN1 | IN2;
% turn points to black for each pixel where we are not interested
for i = 1:numel(ind)
    if ind(i)==1; Iobject( i2check(i),j2check(i) ) = 0; end
end
```

```
% show image if wanted
if Show; figure; imshow(Iobject); end

% find all objects within the bw image
[B L] = bwboundaries(Iobject);  % Find all the boundaries of white objects
ind = [];   % initialise indices to keep in B
if Show; figure; imshow(Irgb); hold on; end
% Impose the minimum area to disregard object
if strcmp(ImType,'c')
   areaCrit = 50;
elseif strcmp(ImType,'g')
   areaCrit = 100;
end
% loop over all boundaries found
for k = 1:length(B)
   boundary = B{k};
   area = bwarea(boundary);    % compute inside area found
   % disregard if too small to be intersting
   if area > areaCrit
      ind(end+1,1) = k;   % Big enough, keep in memory
      if Show; plot(boundary(:,2), boundary(:,1), 'g', 'LineWidth', 2); end
   end
end
% Define the cell containing all the boundaries that have been kept
if isempty(ind)
   newB = [];
else
   for i = 1:numel(ind)
      newB{i,1} = B{ind(i)};
   end
end
B = newB;
% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

switch Where
   case 'Lake Saint-Pierre'
      UTMcoord=cell(numel(B),1);
      for i=1:numel(B)
         data = B{i};
         UTM = [];
         UTM(:,1) = (1700-data(:,1)-1)/1699 * (5133240.269-5095026.696) + 5095026.696;
```

```
        UTM(:,2) = (data(:,2)-1)/2199 * (684433.210-632365.049) + 632365.049;
        UTMcoord{i,1} = UTM;
    end
  case 'Port of Montreal'
    UTMcoord=cell(numel(B),1);
    for i=1:numel(B)
        data = B{i};
        UTM = [];
        UTM(:,1) = (2781-data(:,1)-1)/2780 * (5059816.0297-5033832.9906) +5033832.9906;
        UTM(:,2) = (data(:,2)-1)/2716 * (627420.2963-599853.7354) +599853.7354;
        UTMcoord{i,1} = UTM;
    end
  case 'Port of Trois-Rivieres'
    UTMcoord=cell(numel(B),1);
    for i=1:numel(B)
        data = B{i};
        UTM = [];
        UTM(:,1) = (2057-data(:,1)-1)/2056 * (5142868.329-5122622.476) + 5122622.476;
        UTM(:,2) = (data(:,2)-1)/2464 * (698754.4557-672484.5121) +672484.5121;
        UTMcoord{i,1} = UTM;
    end
  case 'Varennes to Contrecoeur'
    UTMcoord=cell(numel(B),1);
    for i=1:numel(B)
        data = B{i};
        UTM = [];
        UTM(:,1) = (2213-data(:,1)-1)/2212 * (5079604.4654-5053911.4674) +5053911.4674;
        UTM(:,2) = (data(:,2)-1)/2564 * (638663.9032-607588.1502) + 607588.1502;
        UTMcoord{i,1} = UTM;
    end
  case 'Contrecoeur to Sorel'
    UTMcoord=cell(numel(B),1);
    for i=1:numel(B)
        data = B{i};
        UTM = [];
        UTM(:,1) = (2353-data(:,1)-1)/2352 * (5103134.3320-5073162.4171) + 5073162.4171;
        UTM(:,2) = (data(:,2)-1)/2648 * (653725.2290-618565.7043) + 618565.7043;
        UTMcoord{i,1} = UTM;
    end
  case 'Potrneuf to Saint-Nicolas'
    UTMcoord=cell(numel(B),1);
```

```
    for i=1:numel(B)
        data = B{i};
        UTM = [];
        UTM(:,1) = (2213-data(:,1)-1)/2212* (5196865.0584-5146676.3389) + 5146676.3389;
        UTM(:,2) = (data(:,2)-1)/2564 * (820230.5782-722344.8503) +722344.8503;
        UTMcoord{i,1} = UTM;
    end
  case 'Trois-Rivieres to Grondines'
    UTMcoord=cell(numel(B),1);
    for i=1:numel(B)
        data = B{i};
        UTM = [];
        UTM(:,1) = (1700-data(:,1)-1)/1699 * (5167479.0192-5135378.2094) + 5135378.2094;
        UTM(:,2) = (data(:,2)-1)/2199 * (728561.0642-684031.9617) + 684031.9617;
        UTMcoord{i,1} = UTM;
    end
   case 'Port of Quebec'
    UTMcoord=cell(numel(B),1);
    for i=1:numel(B)
        data = B{i};
        UTM = [];
        UTM(:,1) = (1777-data(:,1)-1)/1776 * (5198451.8478-5173084.1538) +5173084.1538;
        UTM(:,2) = (data(:,2)-1)/2260 * (343488.4134-344172.2993) +344172.2993;
        UTMcoord{i,1} = UTM;
    end
  case 'Grondines to Portneuf'
     Degreecoord=cell(numel(B),1);
    for i=1:numel(B)
        data = B{i};
        UTM = [];
        UTM(:,1) = (2057-data(:,1)-1)/2056 * (46.7245-46.5168) + 46.5168;
        UTM(:,2) = (data(:,2)-1)/2464 * (-71.8085+72.175) -72.175;
       Degreecoord{i,1} = UTM;
    end
end
save( [ImageFileName(1:end-2),'.mat'],'UTMcoord','B' );
imwrite( Irgb2 , ['New_',ImageFileName(1:end-2),'.jpg']);
```

Annex B: Border ice areal coverage figures from 2004-2005 to 2008-2009

Location 1: Port of Montreal

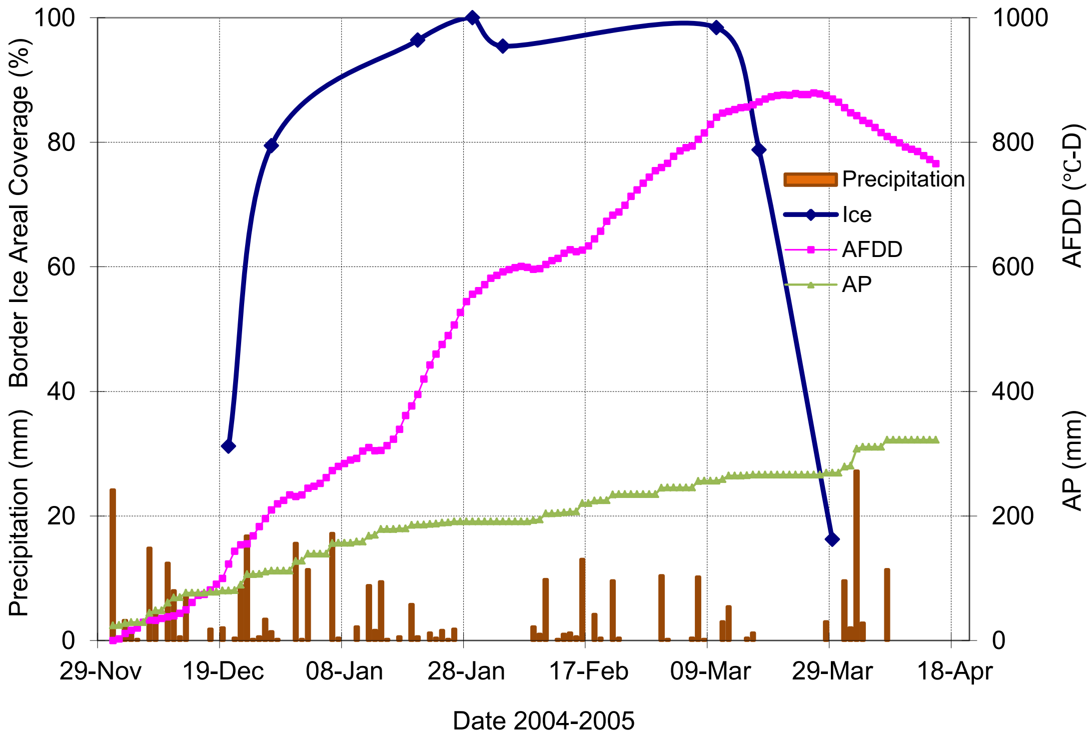

Figure B.1: Border ice areal coverage during 2004-2005 at Port of Montreal

Note: AP = Accumulated precipitation in water equivalent;
AFDD = Accumulated Freezing Degree Days

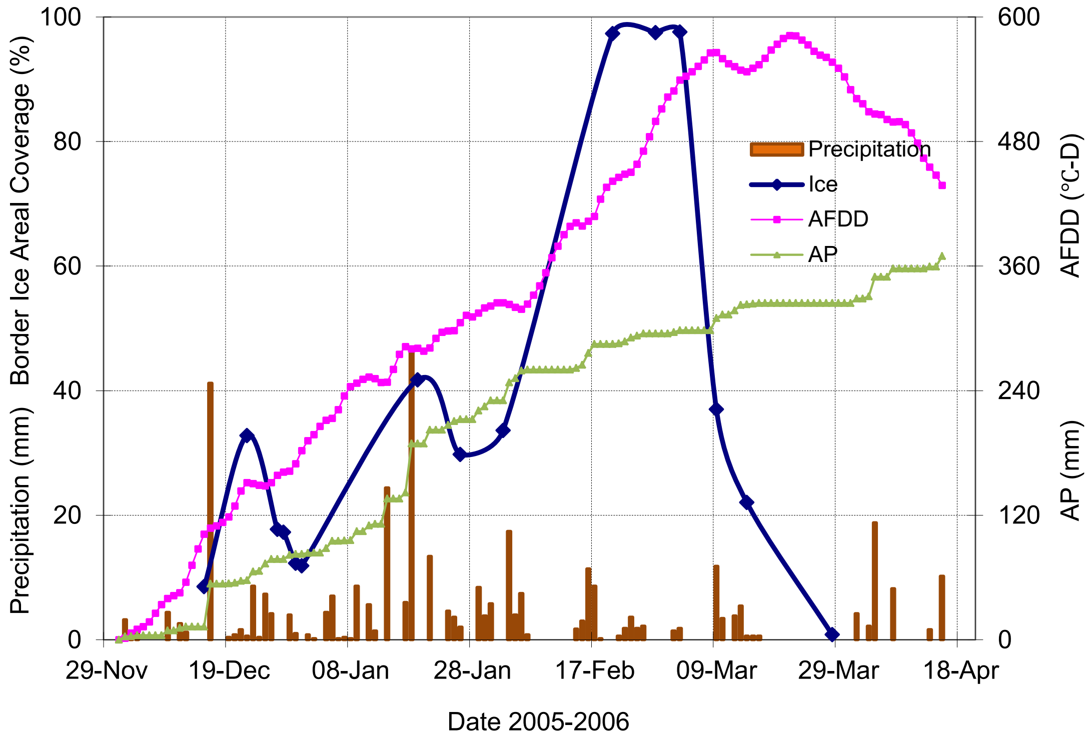

Figure B.2: Border ice areal coverage during 2005-2006 at Port of Montreal

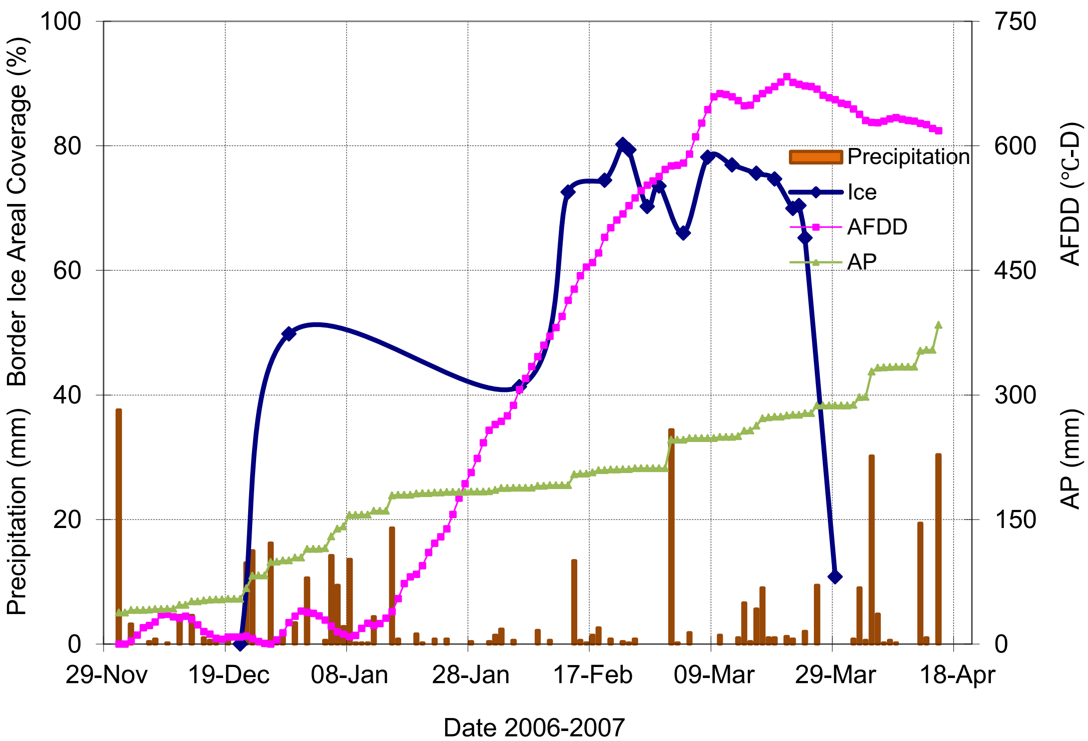

Figure B.3: Border ice areal coverage during 2006-2007 at Port of Montreal

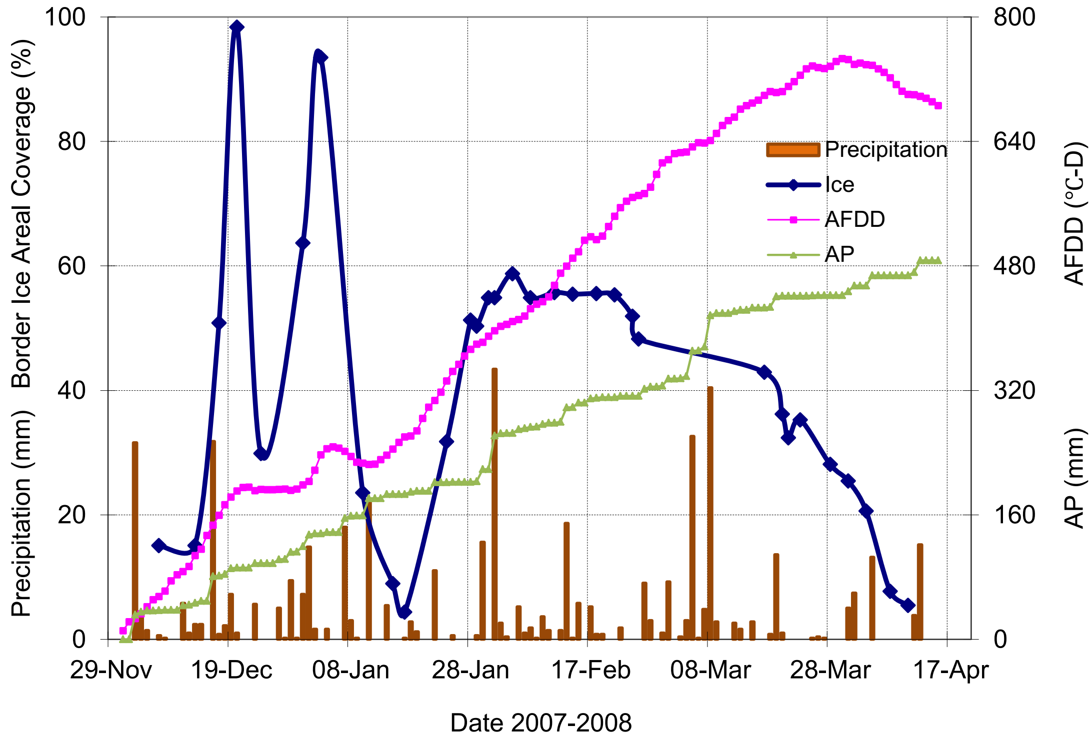

Figure B.4: Border ice areal coverage during 2007-2008 at Port of Montreal

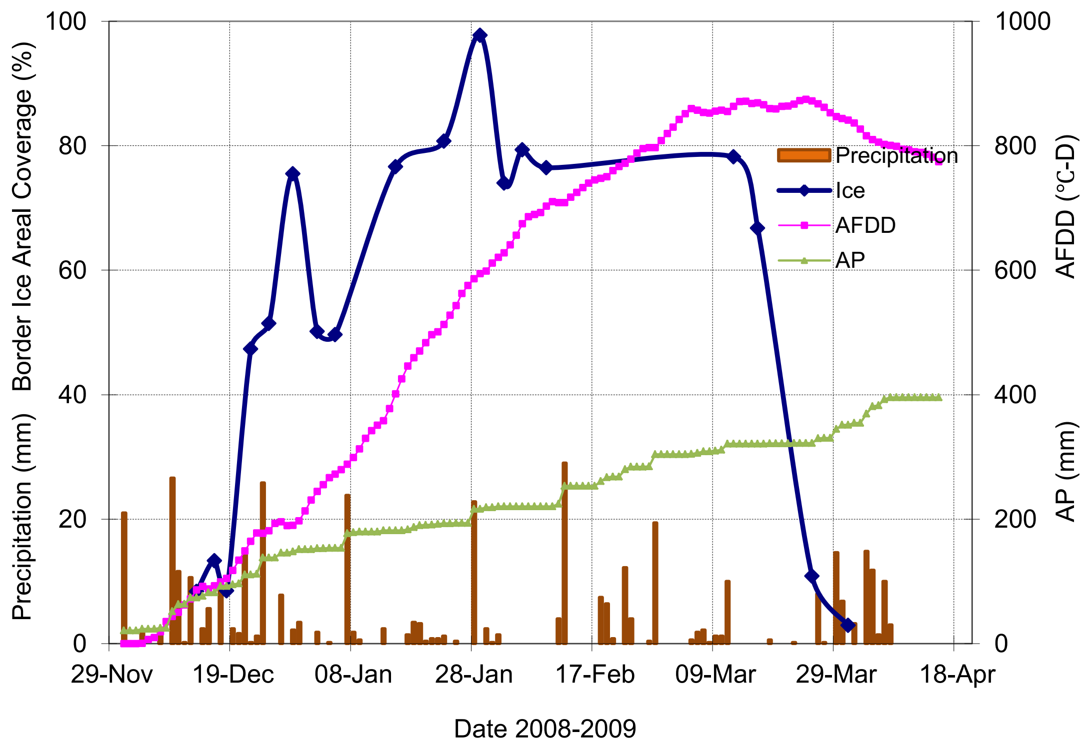

Figure B.5: Border ice areal coverage during 2008-2009 at Port of Montreal

Location 2: Varennes to Contrecoeur

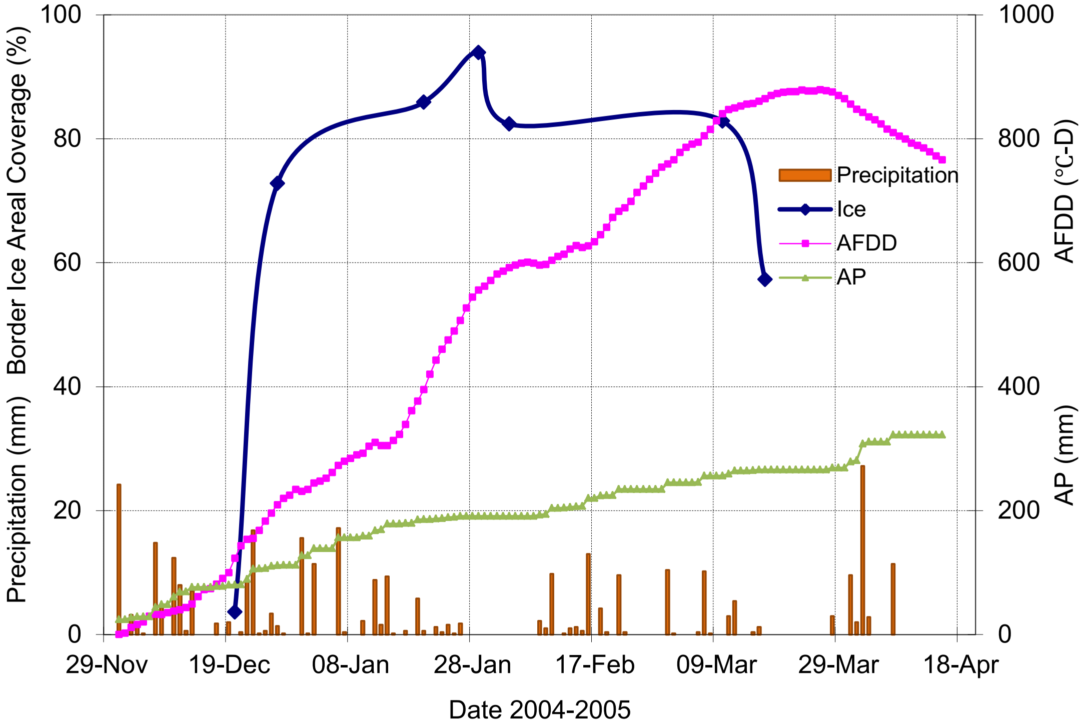

Figure B.6: Border ice areal coverage during 2004-2005 at Varennes to Contrecoeur

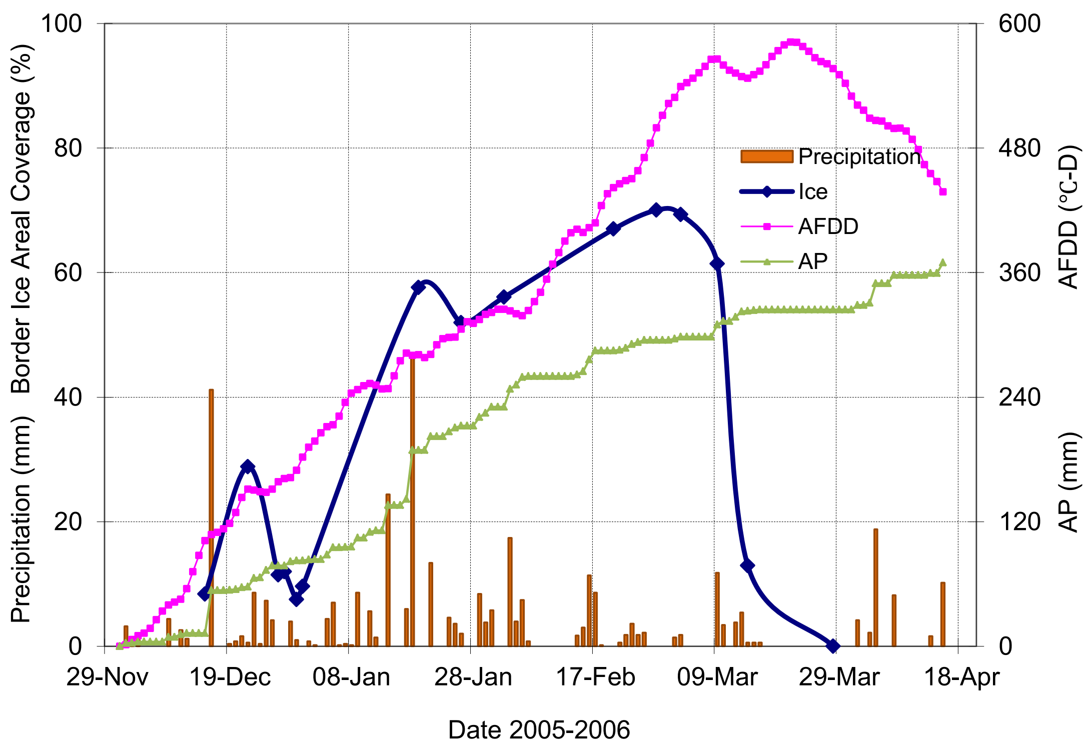

Figure B.7: Border ice areal coverage during 2005-2006 at Varennes to Contrecoeur

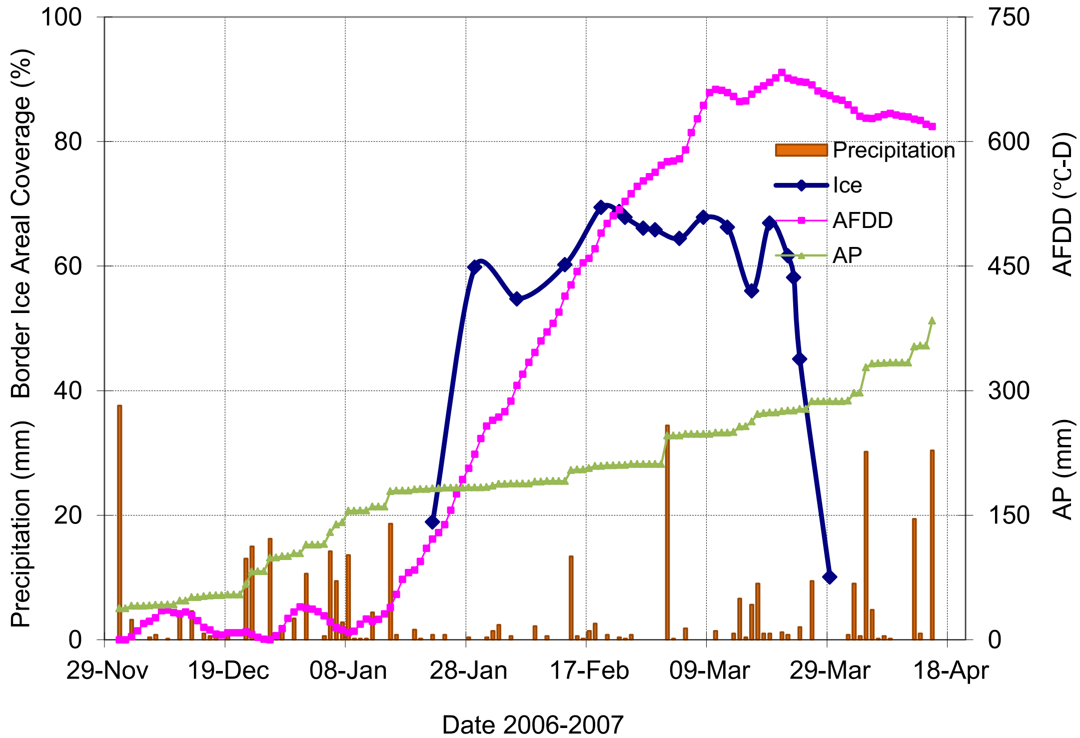

Figure B.8: Border ice areal coverage during 2006-2007 at Varennes to Contrecoeur

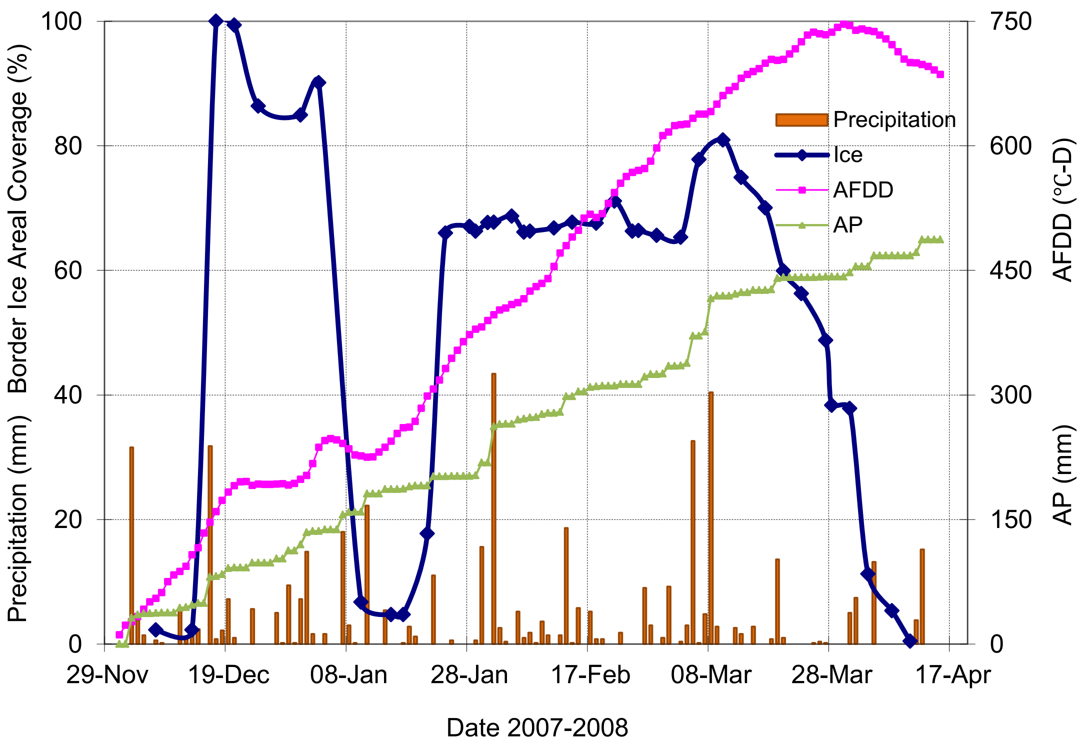

Figure B.9: Border ice areal coverage during 2007-2008 at Varennes to Contrecoeur

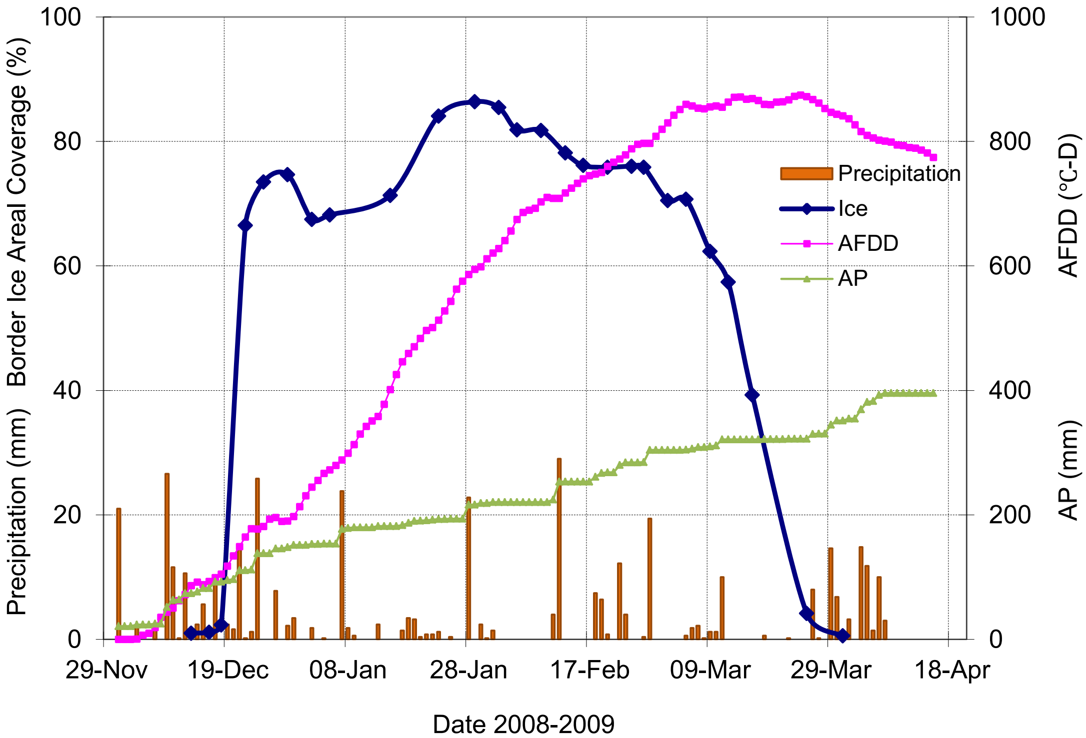

Figure B.10: Border ice areal coverage during 2008-2009 at Varennes to Contrecoeur

Location 3: Contrecoeur to Sorel

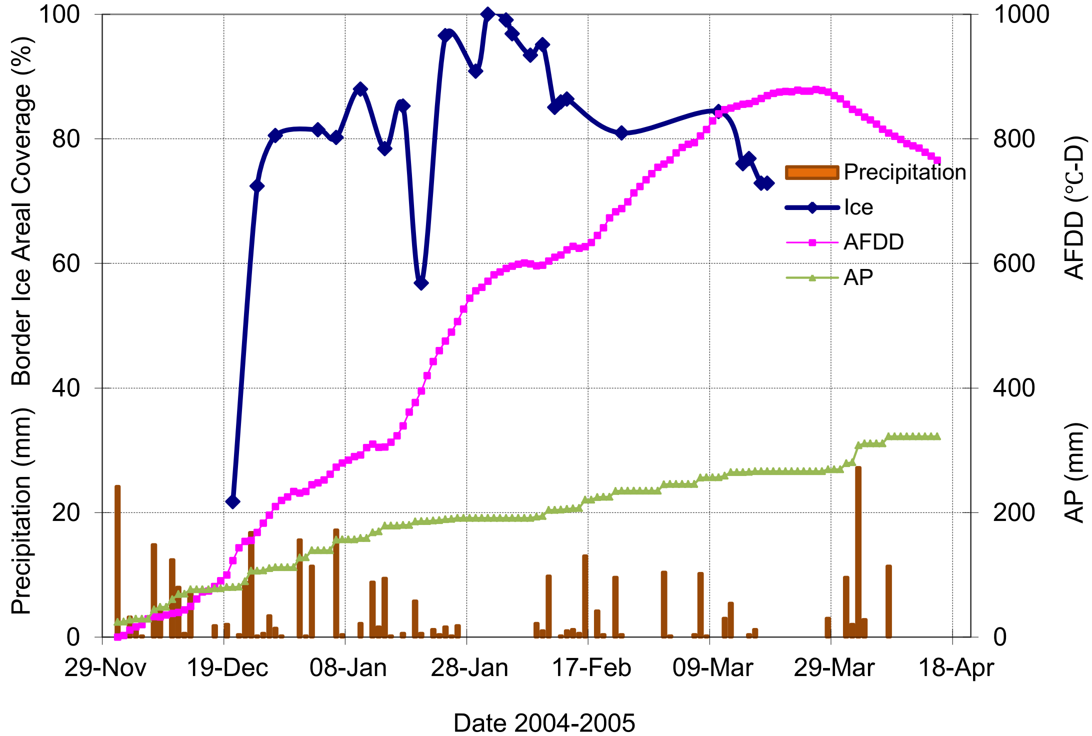

Figure B.11: Border ice areal coverage during 2004-2005 at Contrecoeur to Sorel

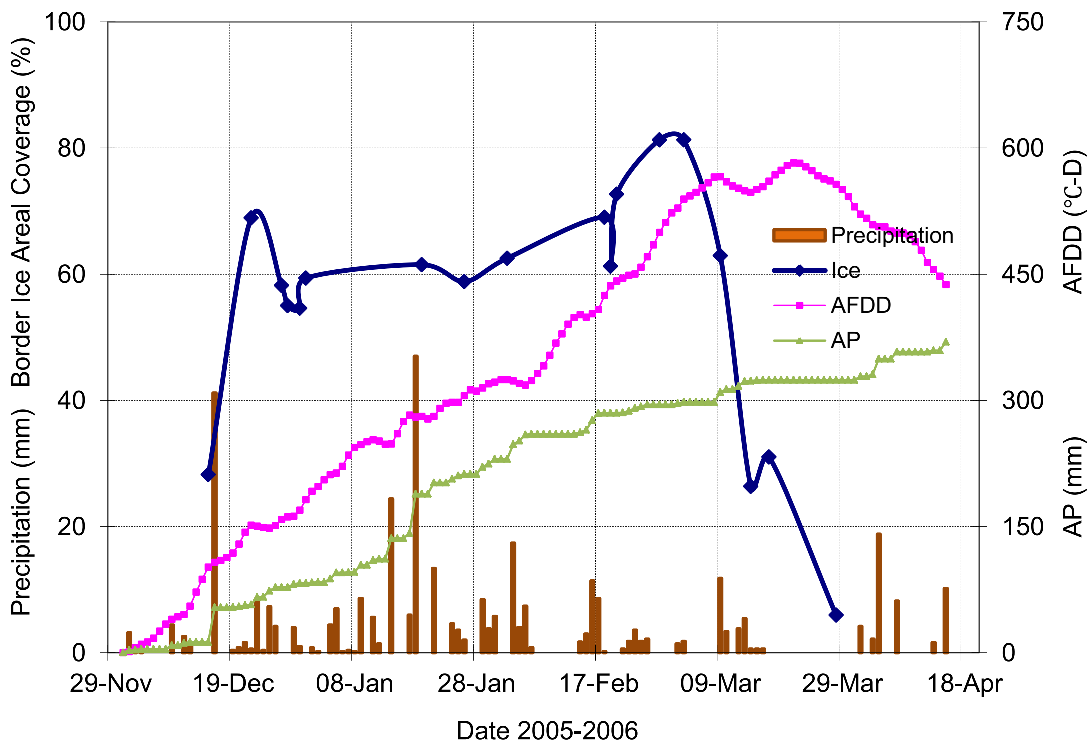

Figure B.12: Border ice areal coverage during 2005-2006 at Contrecoeur to Sorel

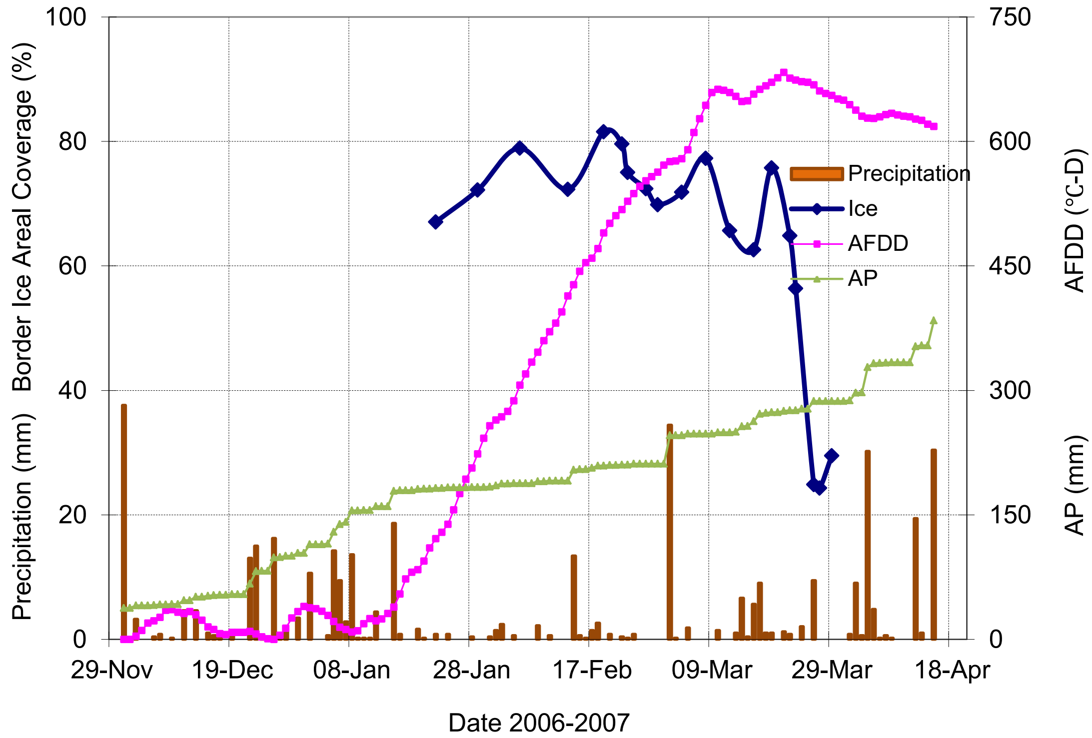

Figure B.13: Border ice areal coverage during 2006-2007 at Contrecoeur to Sorel

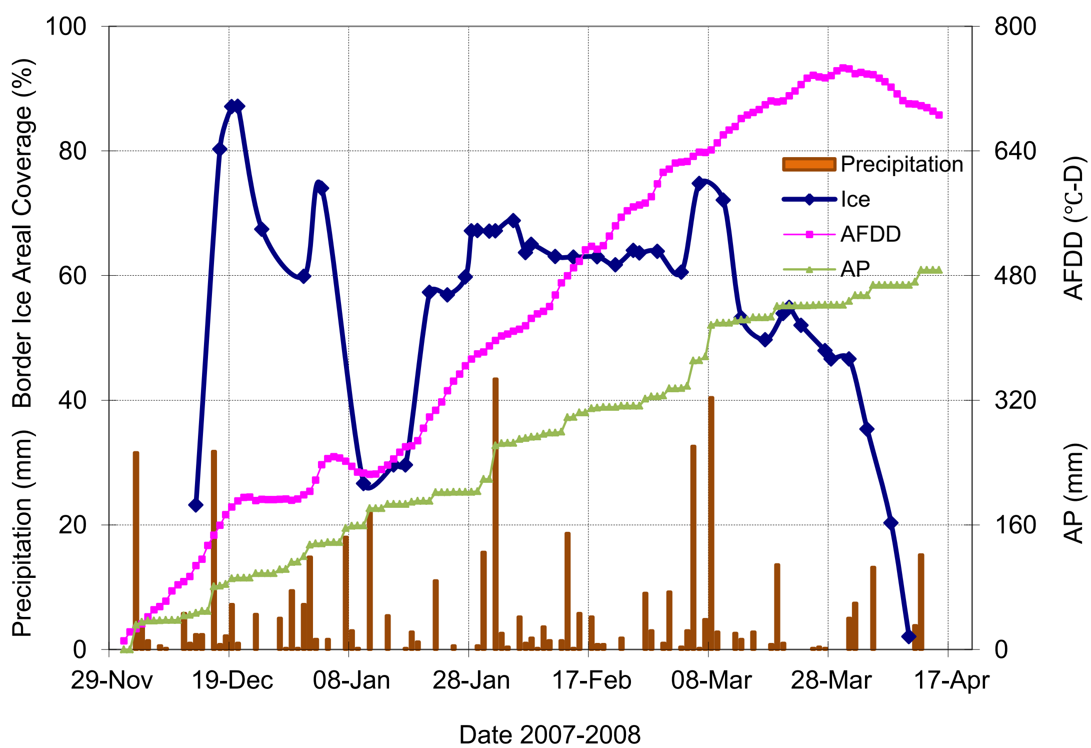

Figure B.14: Border ice areal coverage during 2007-2008 at Contrecoeur to Sorel

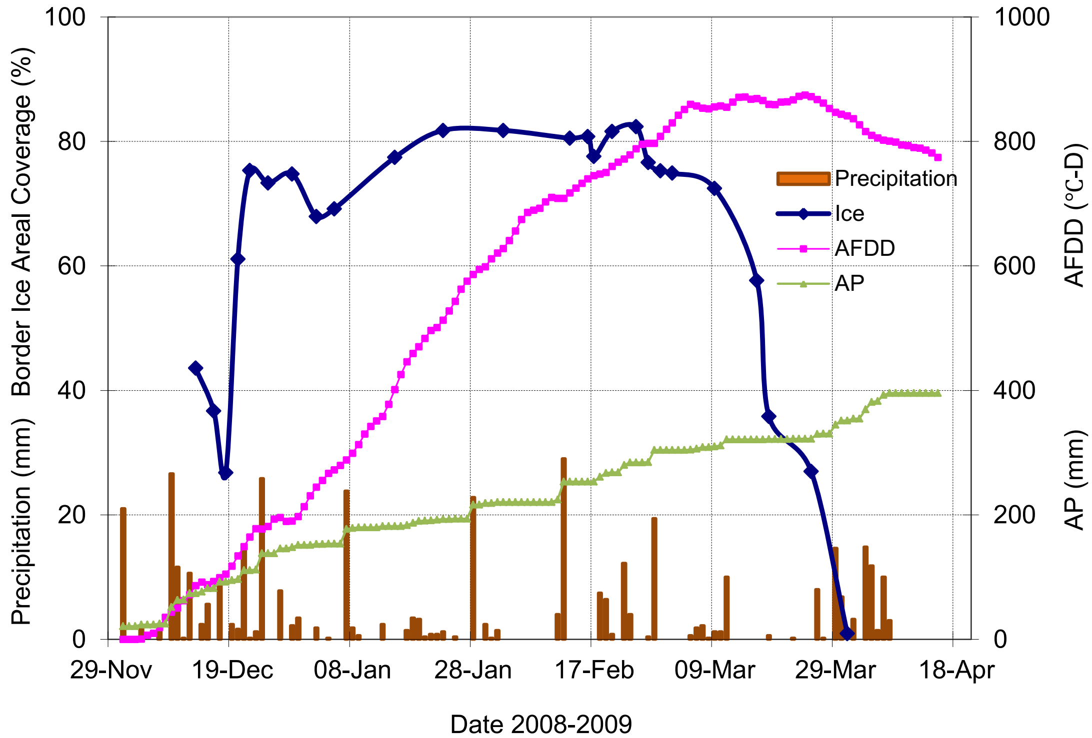

Figure B.15: Border ice areal coverage during 2008-2009 at Contrecoeur to Sorel

Location 4: Lake Saint-Pierre

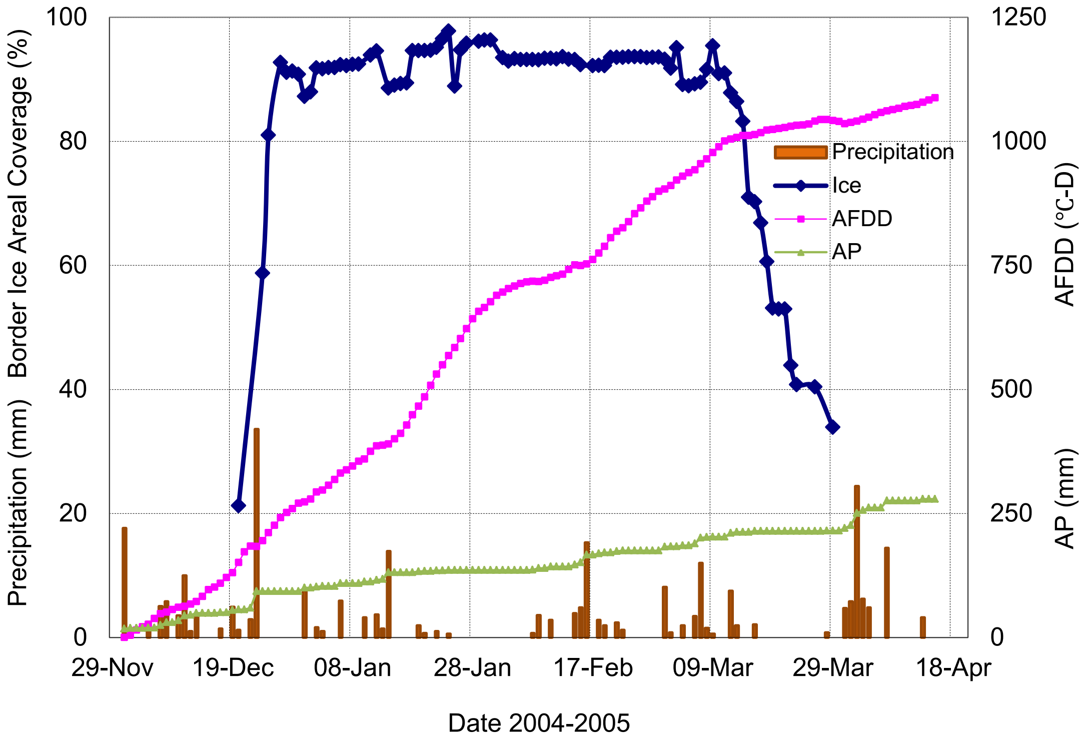

Figure B.16: Border ice areal coverage during 2004-2005 at Lake Saint-Pierre

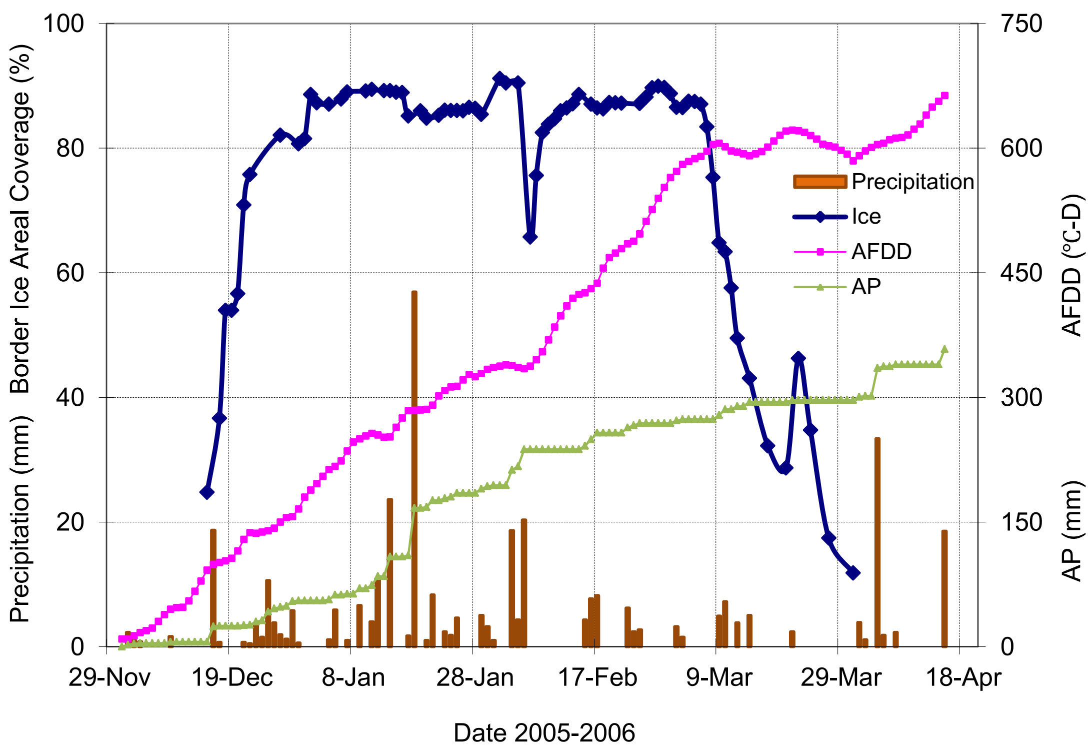

Figure B.17: Border ice areal coverage during 2005-2006 at Lake Saint-Pierre

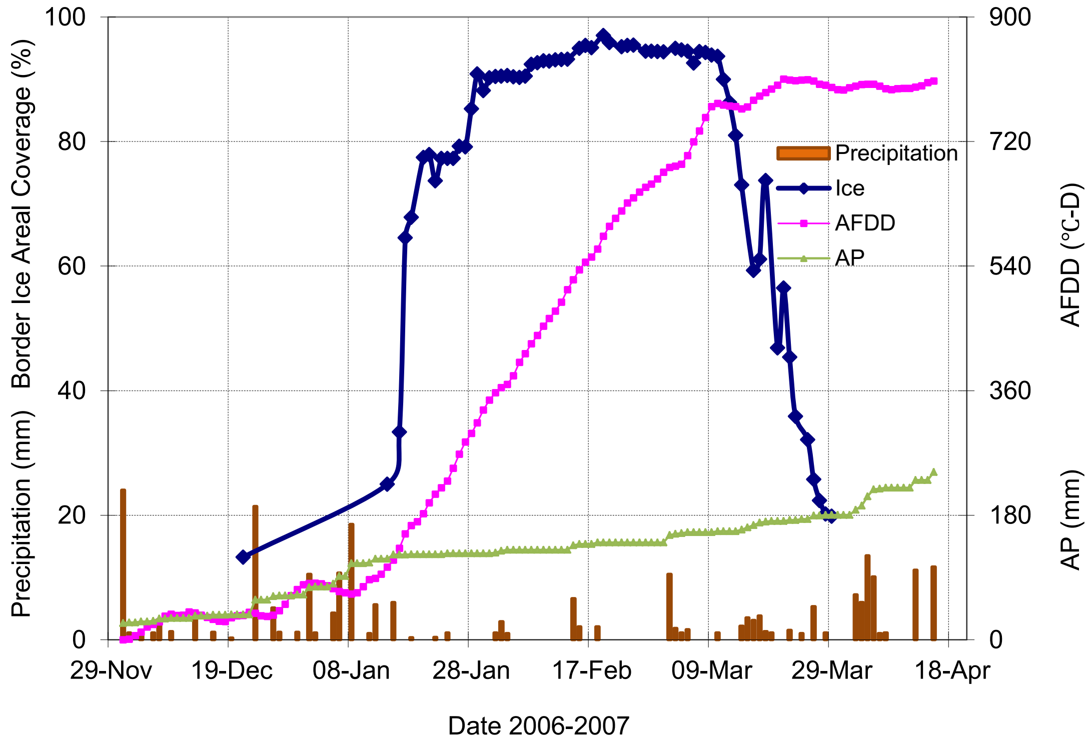

Figure B.18: Border ice areal coverage during 2006-2007 at Lake Saint-Pierre

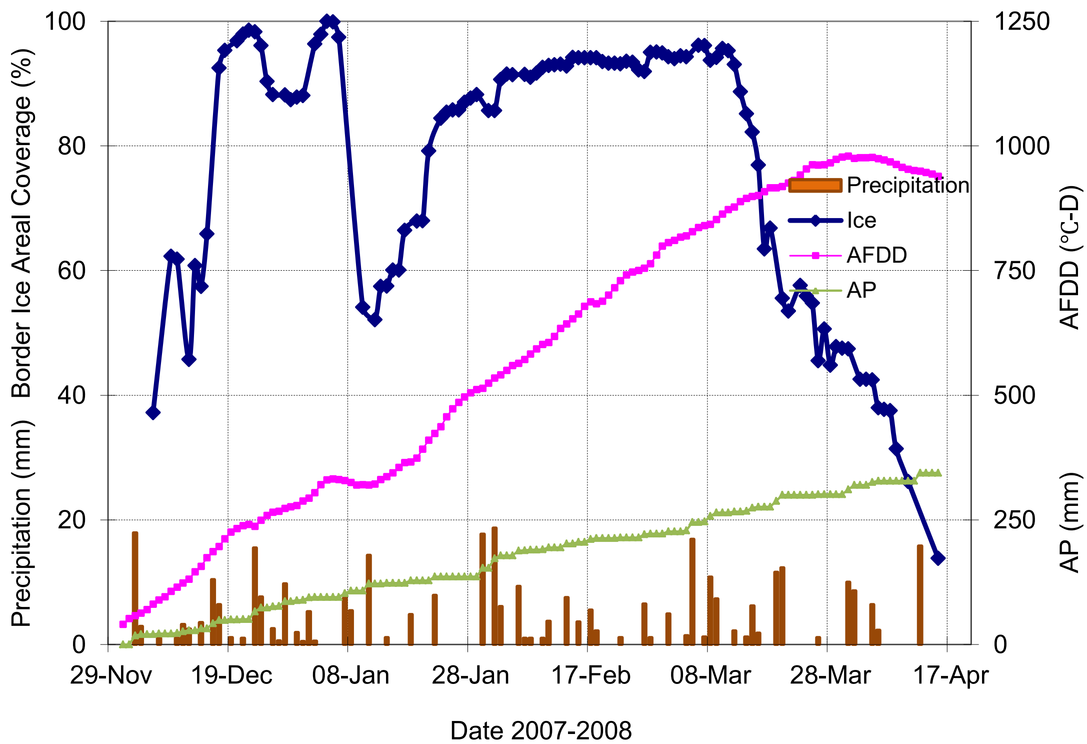

Figure B.19: Border ice areal coverage during 2007-2008 at Lake Saint-Pierre

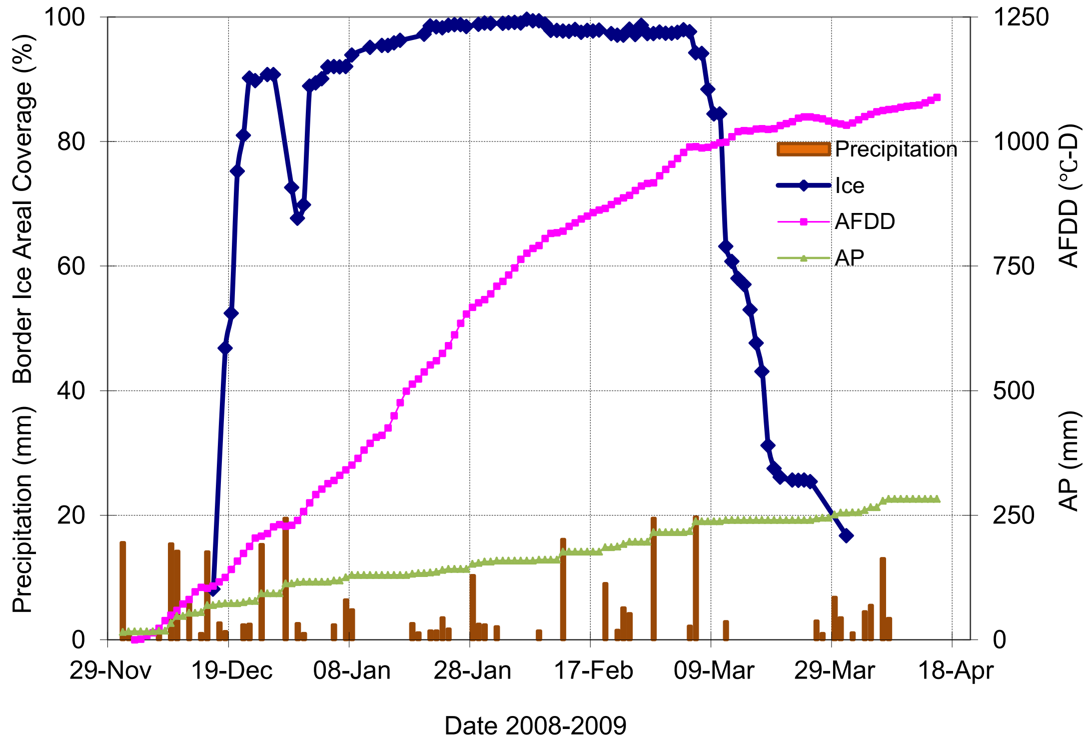

Figure B.20: Border ice areal coverage during 2008-2009 at Lake Saint-Pierre

Location 5: Port of Trois-Riviere

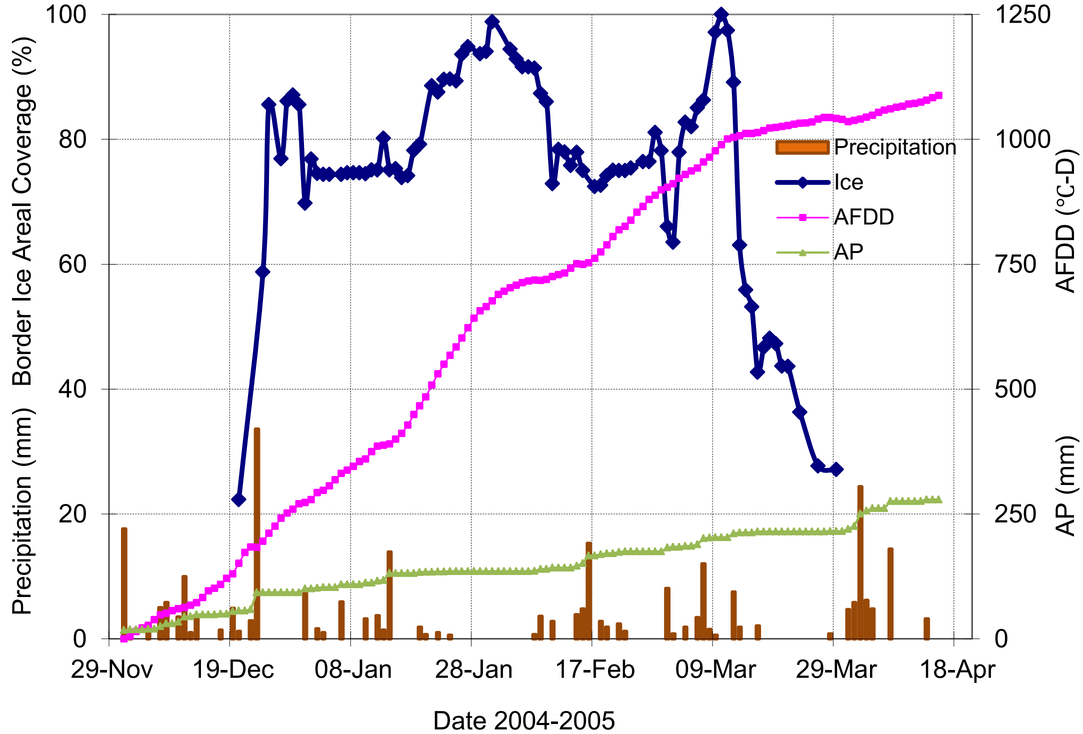

Figure B.21: Border ice areal coverage during 2004-2005 at Port of Trois-Riviere

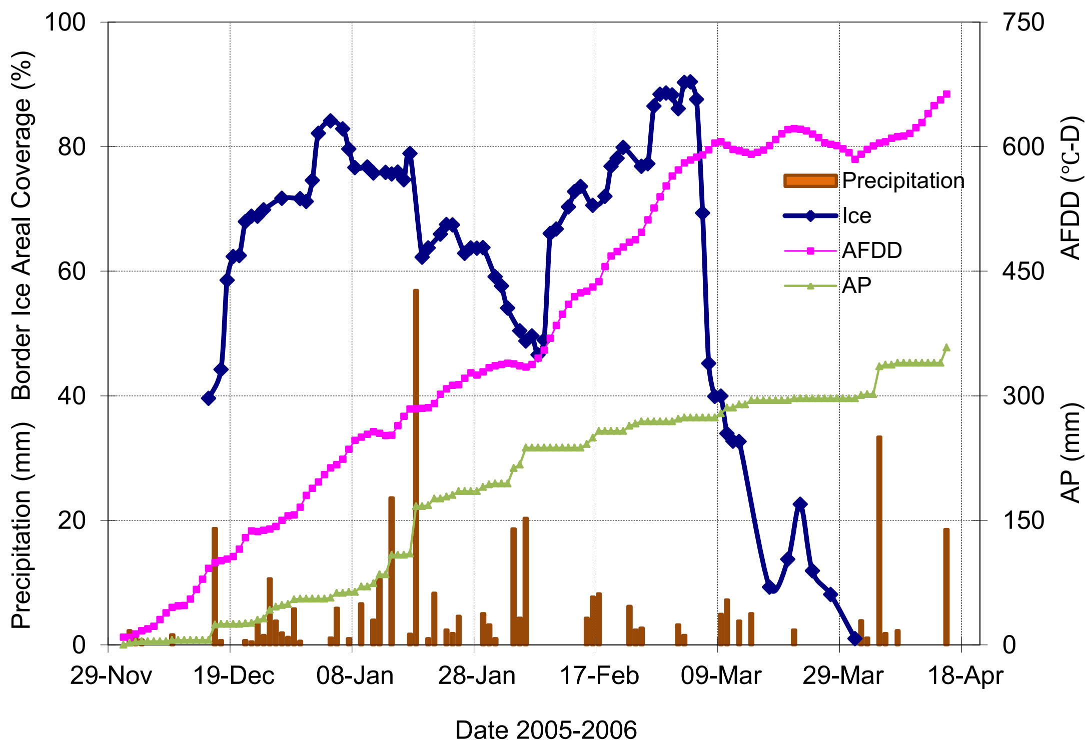

Figure B.22: Border ice areal coverage during 2005-2006 at Port of Trois-Riviere

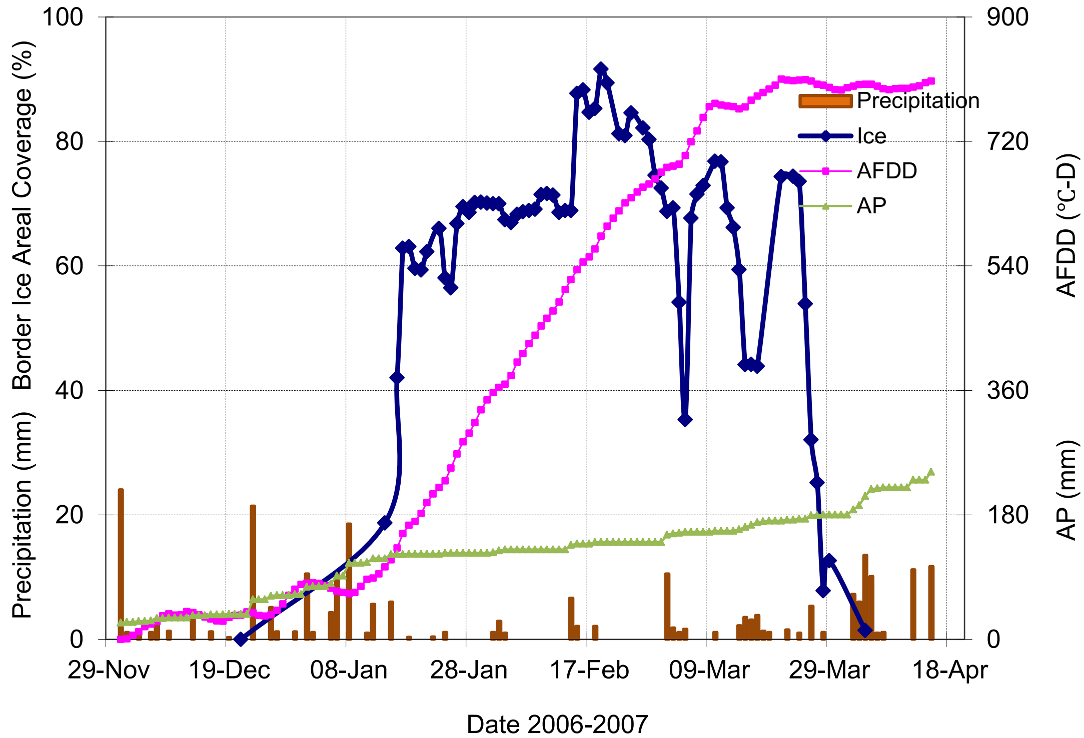

Figure B.23: Border ice areal coverage during 2006-2007 at Port of Trois-Riviere

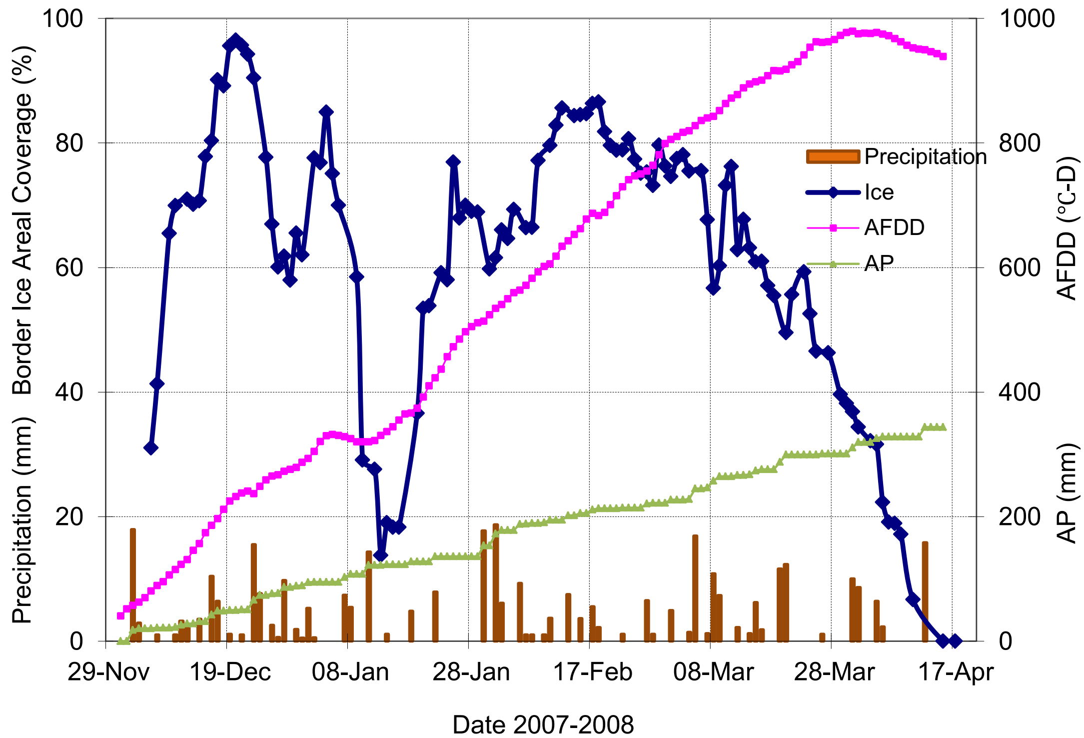

Figure B.24: Border ice areal coverage during 2007-2008 at Port of Trois-Riviere

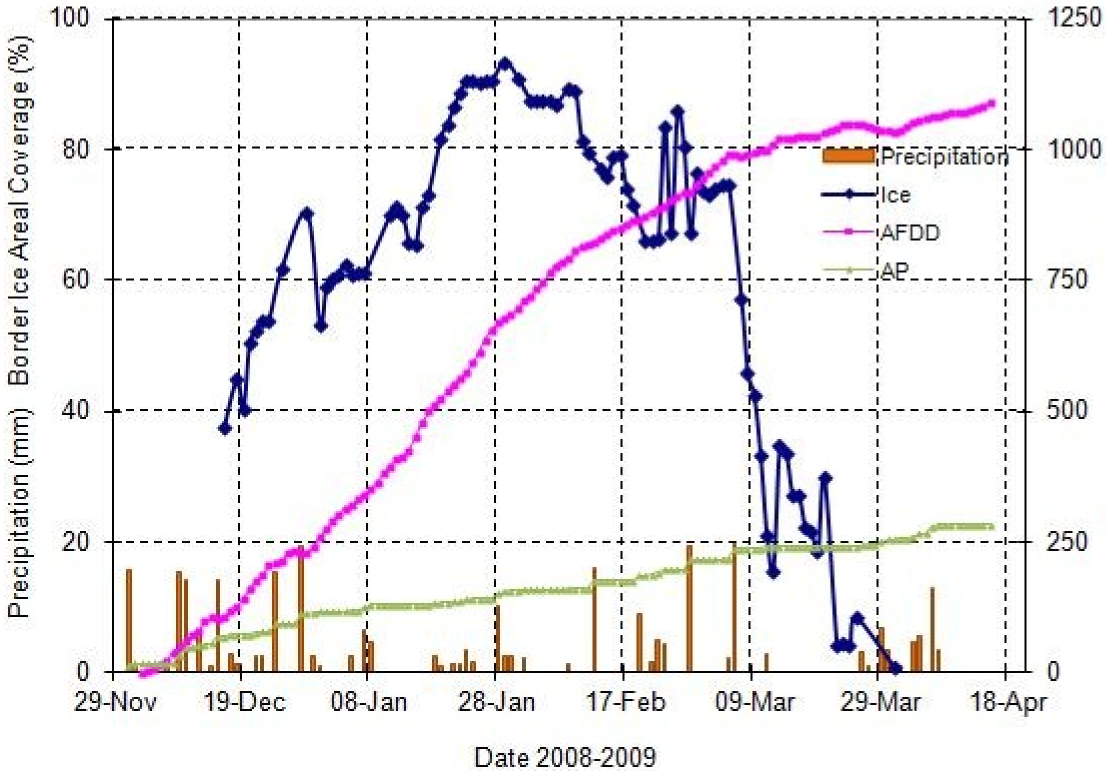

Figure B.25: Border ice areal coverage during 2008-2009 at Port of Trois-Riviere

Location 6: Trois-Rivières to Grondines

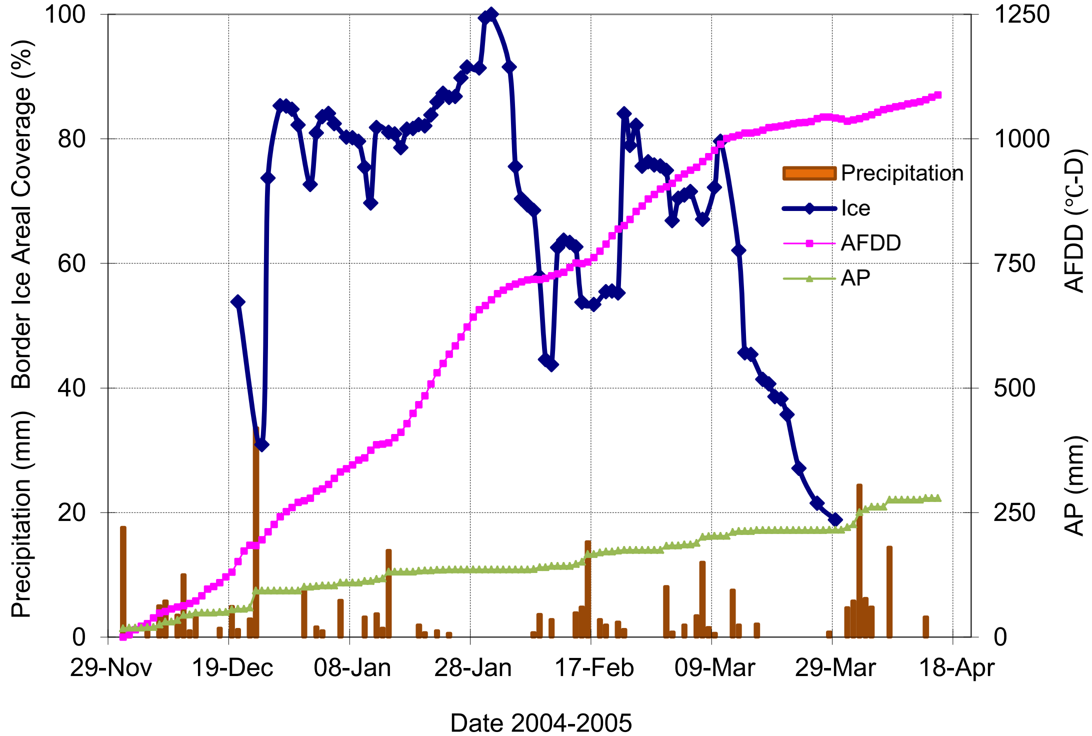

Figure B.26: Border ice areal coverage during 2004-2005 at Trois-Rivières to Grondines

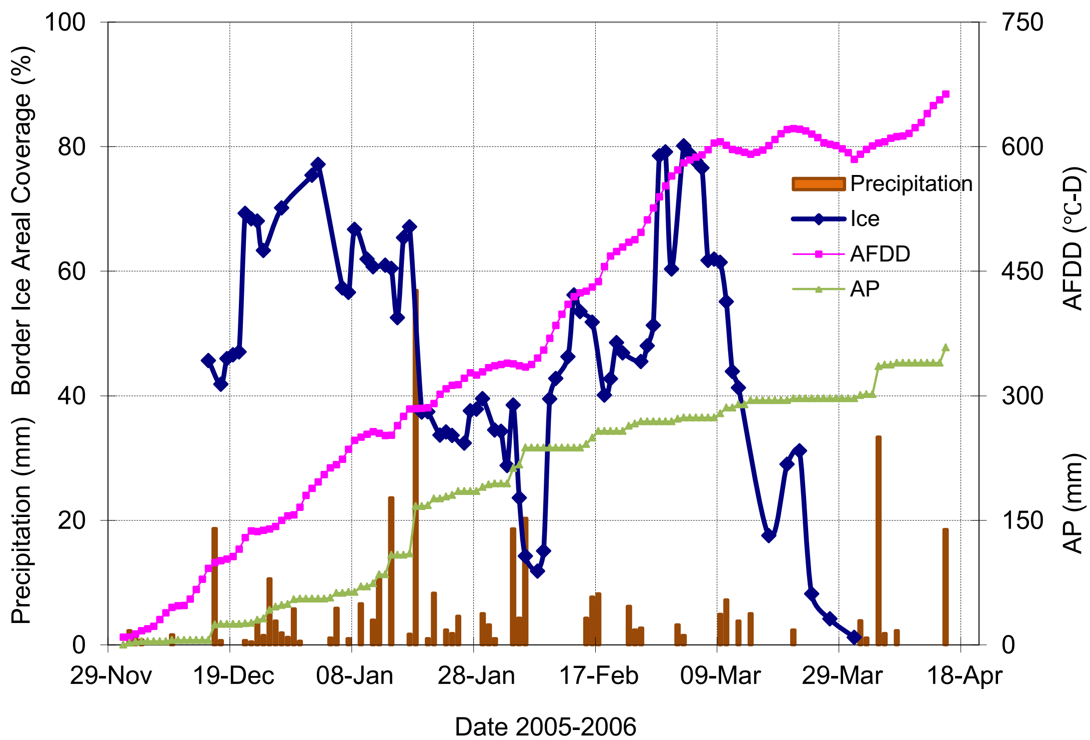

Figure B.27: Border ice areal coverage during 2005-2006 at Trois-Rivières to Grondines

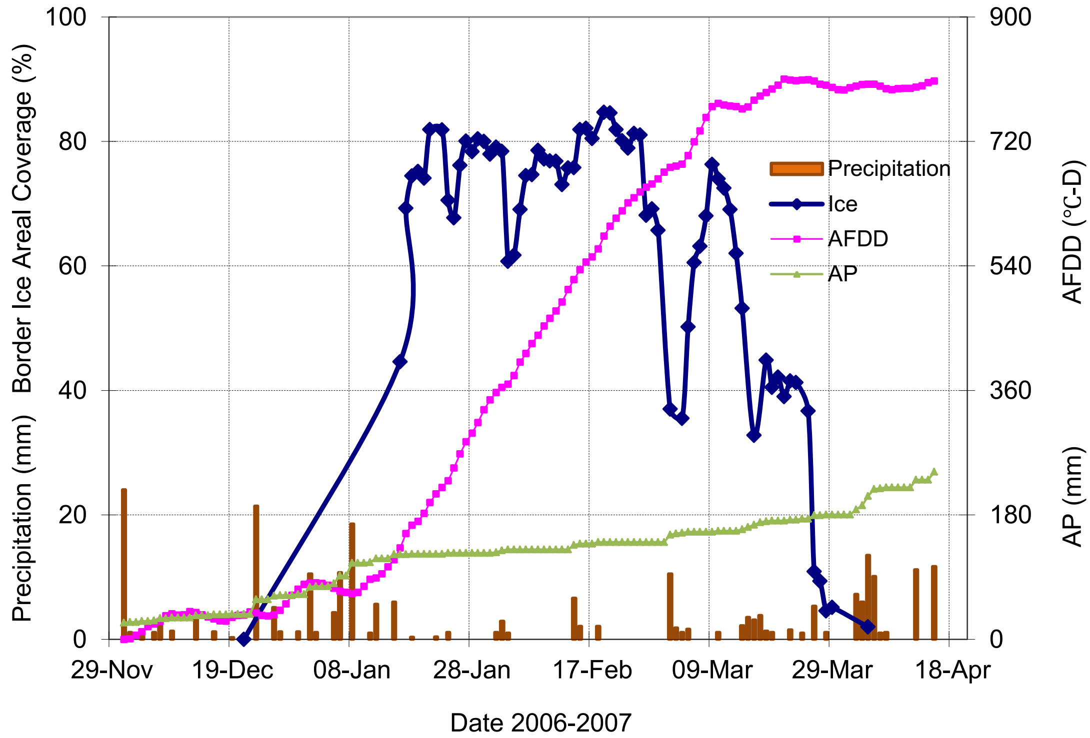

Figure B.28: Border ice areal coverage during 2006-2007 at Trois-Rivières to Grondines

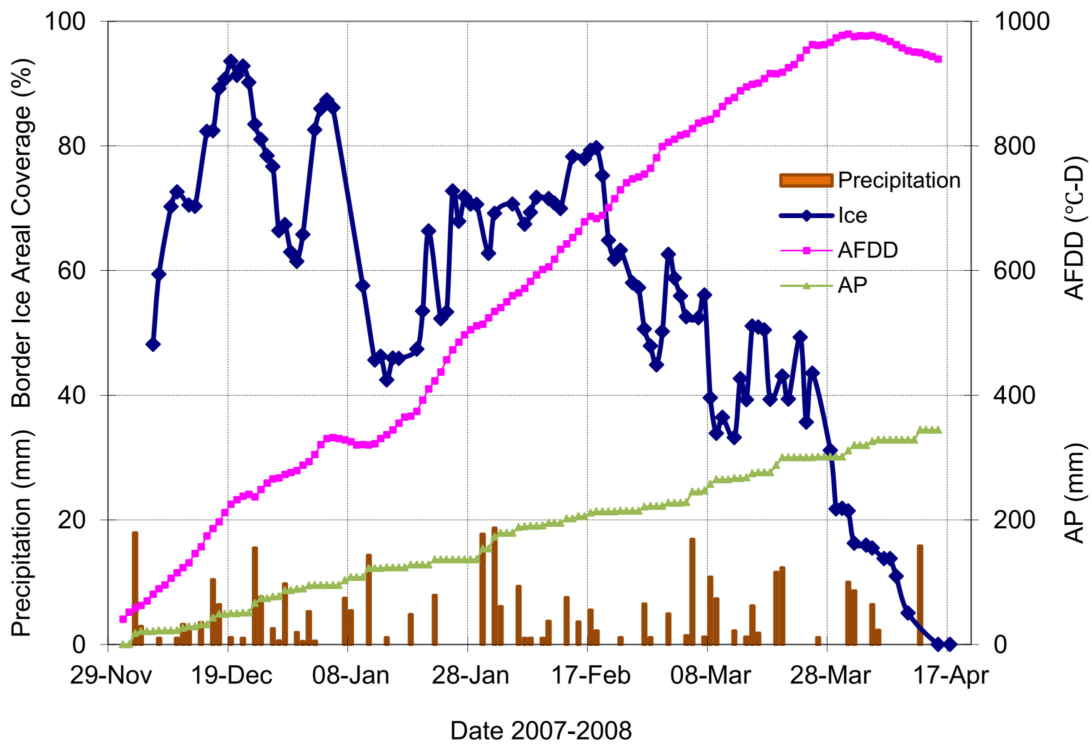

Figure B.29: Border ice areal coverage during 2007-2008 at Trois-Rivières to Grondines

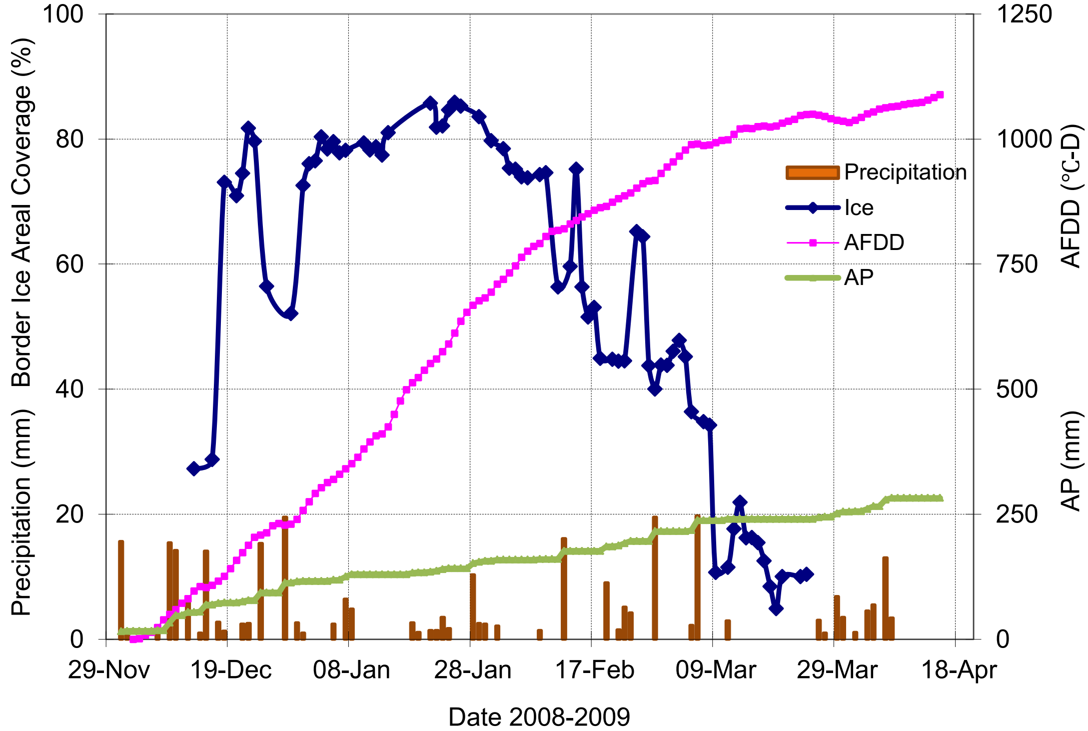

Figure B.30: Border ice areal coverage during 2008-2009 at Trois-Rivières to Grondines

Location 7 : Grondines to Portneuf

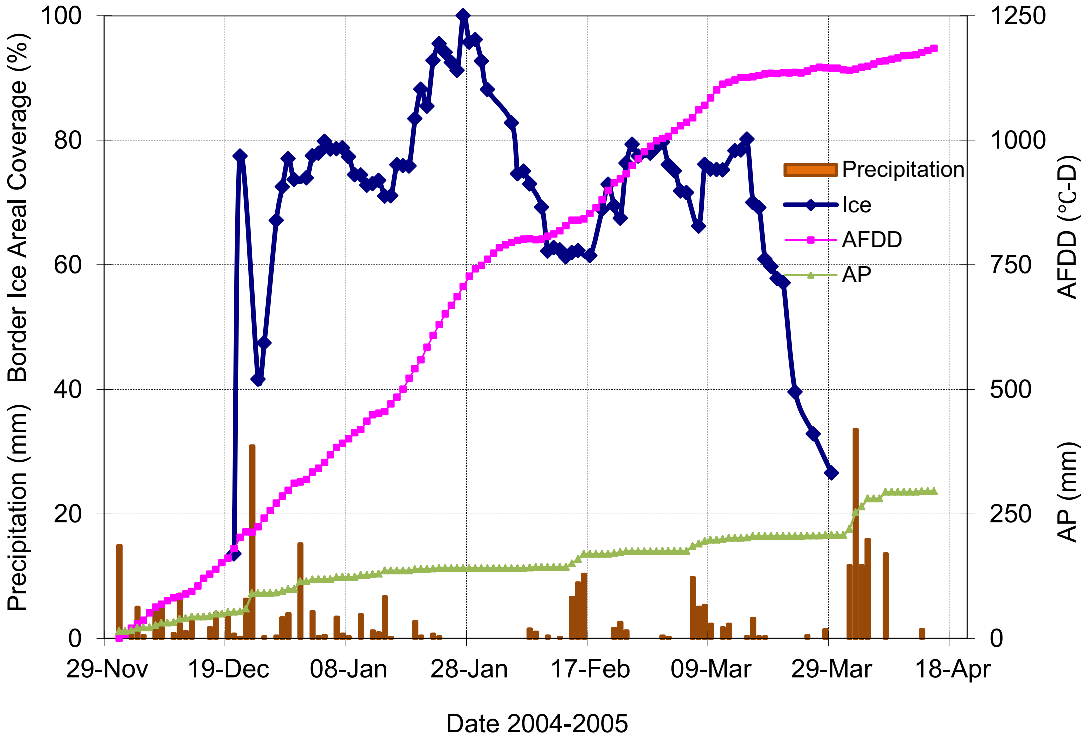

Figure B.31: Border ice areal coverage during 2004-2005 at Grondines to Portneuf

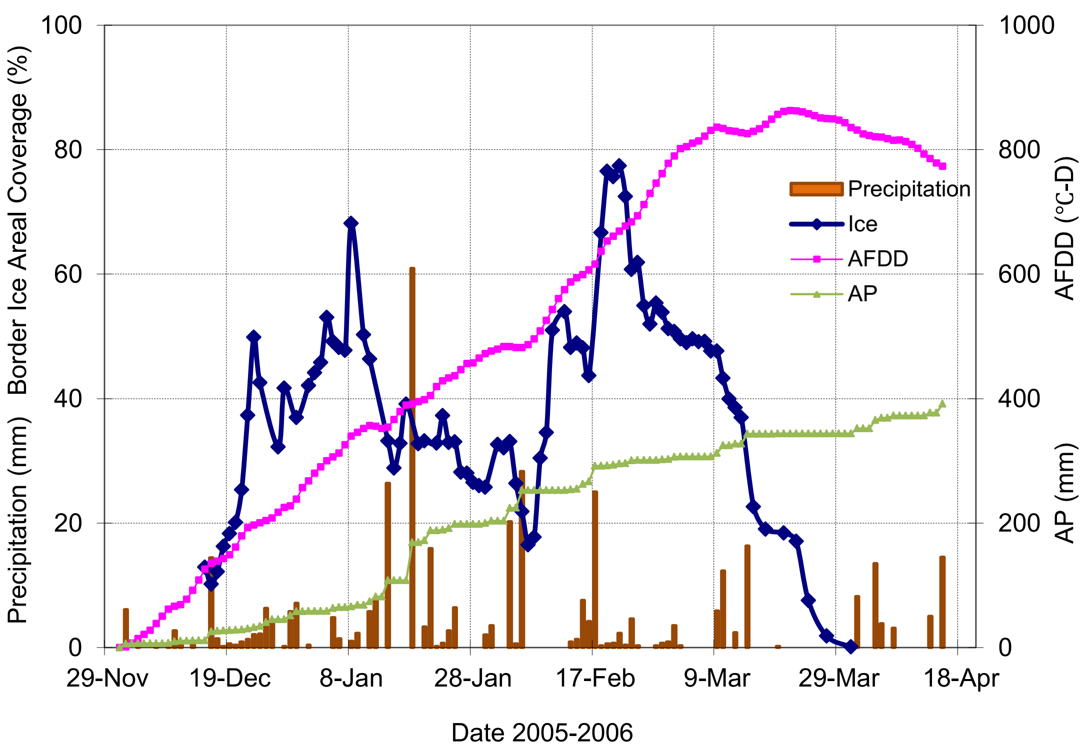

Figure B.32: Border ice areal coverage during 2005-2006 at Grondines to Portneuf

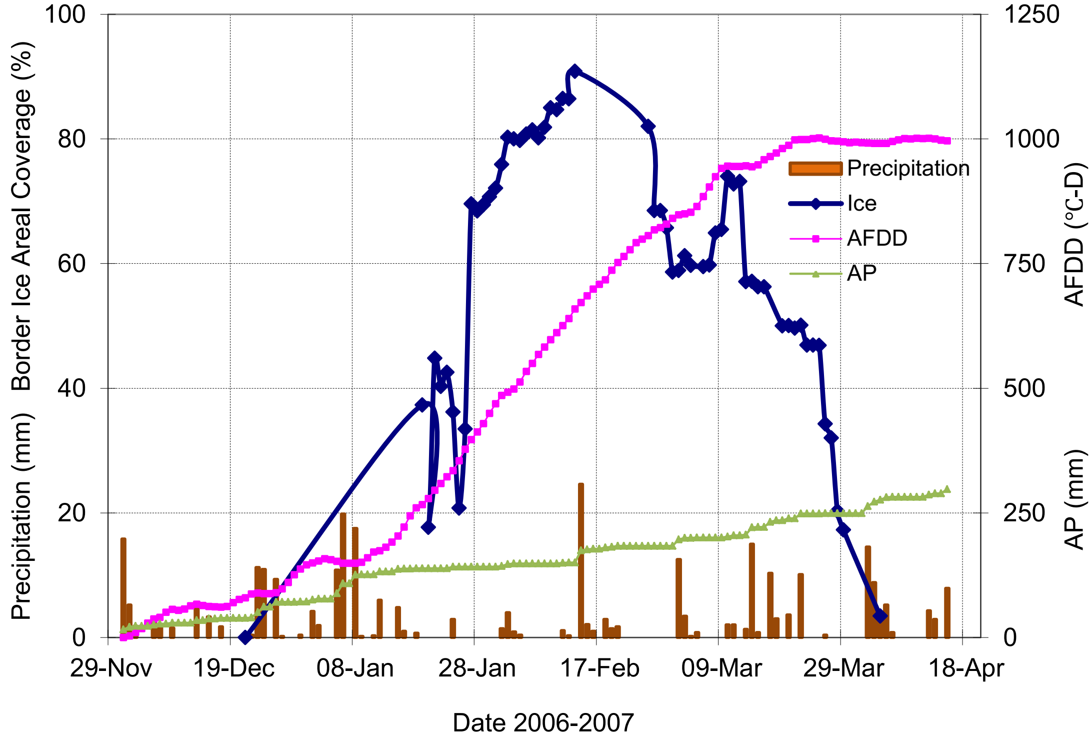

Figure B.33: Border ice areal coverage during 2006-2007 at Grondines to Portneuf

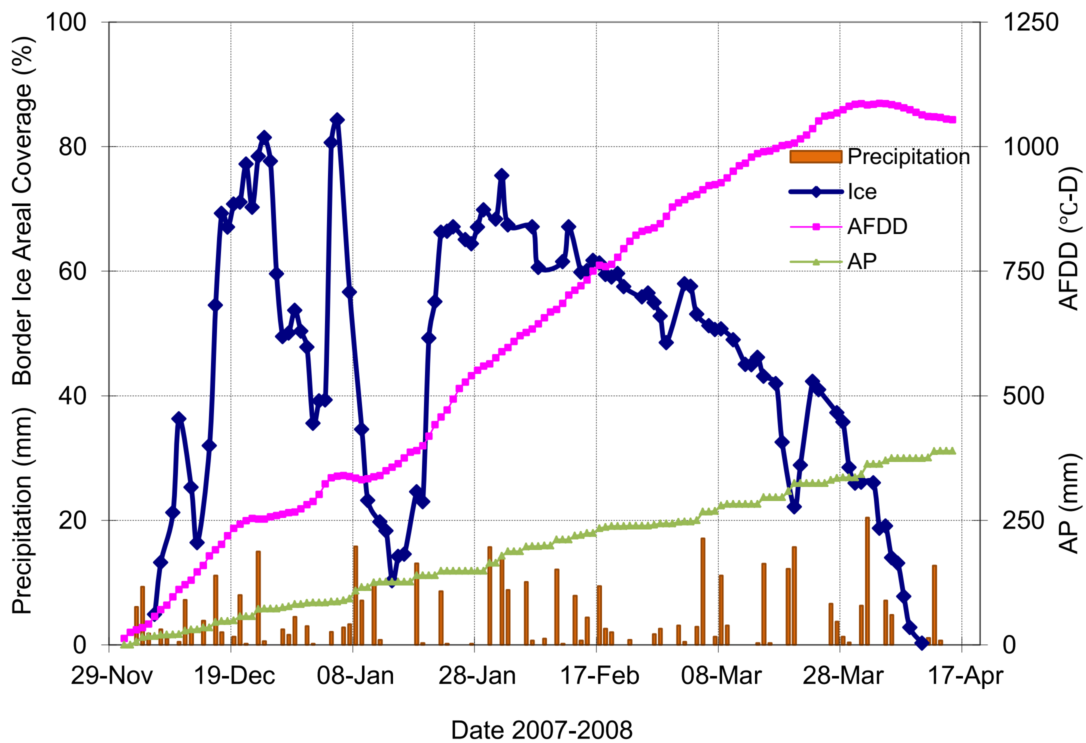

Figure B.34: Border ice areal coverage during 2007-2008 at Grondines to Portneuf

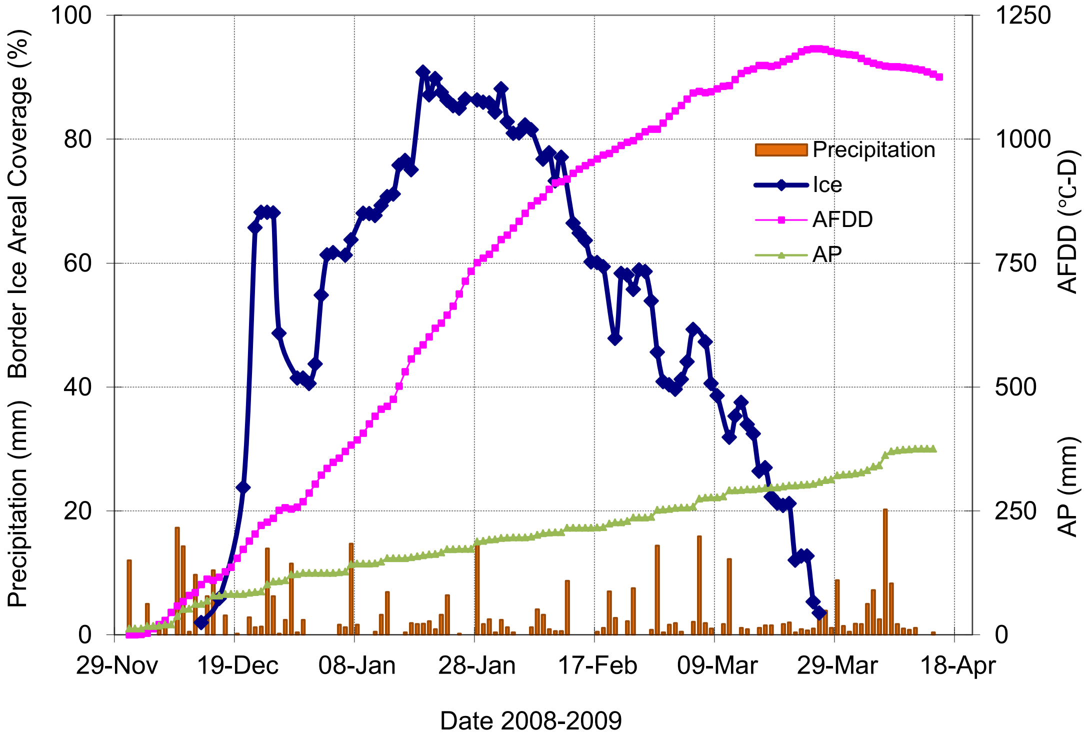

Figure B.35: Border ice areal coverage during 2008-2009 at Grondines to Portneuf

Location 8: Portneuf to St-Nicolas

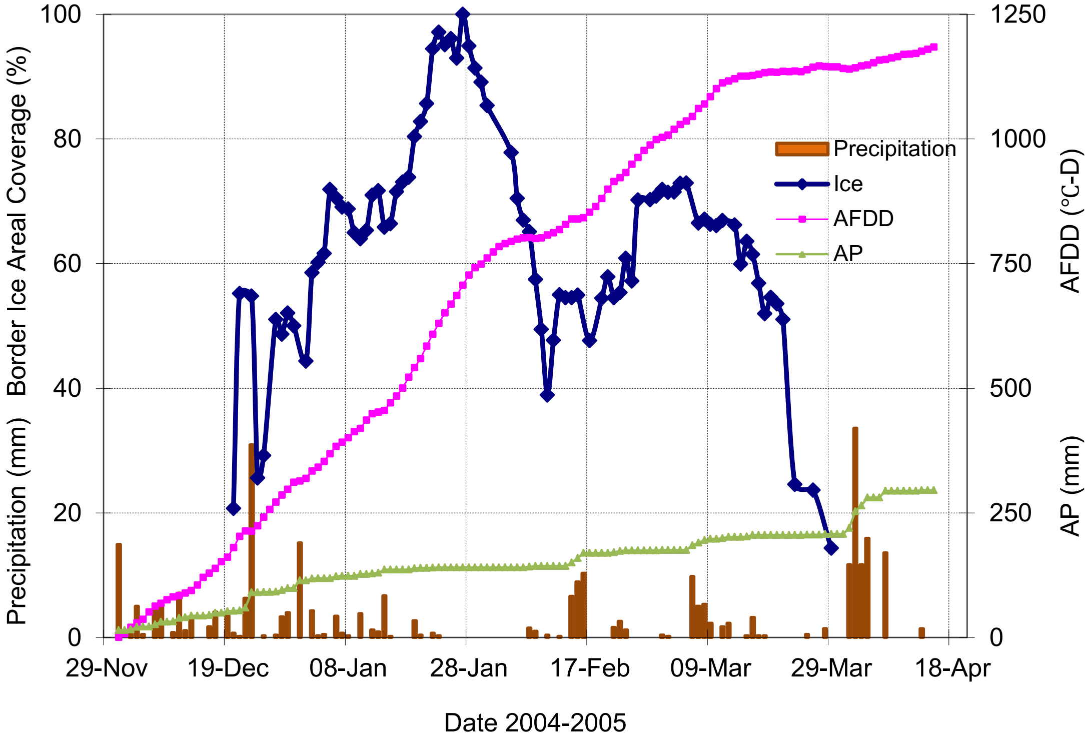

Figure B.36: Border ice areal coverage during 2004-2005 at Portneuf to St-Nicolas

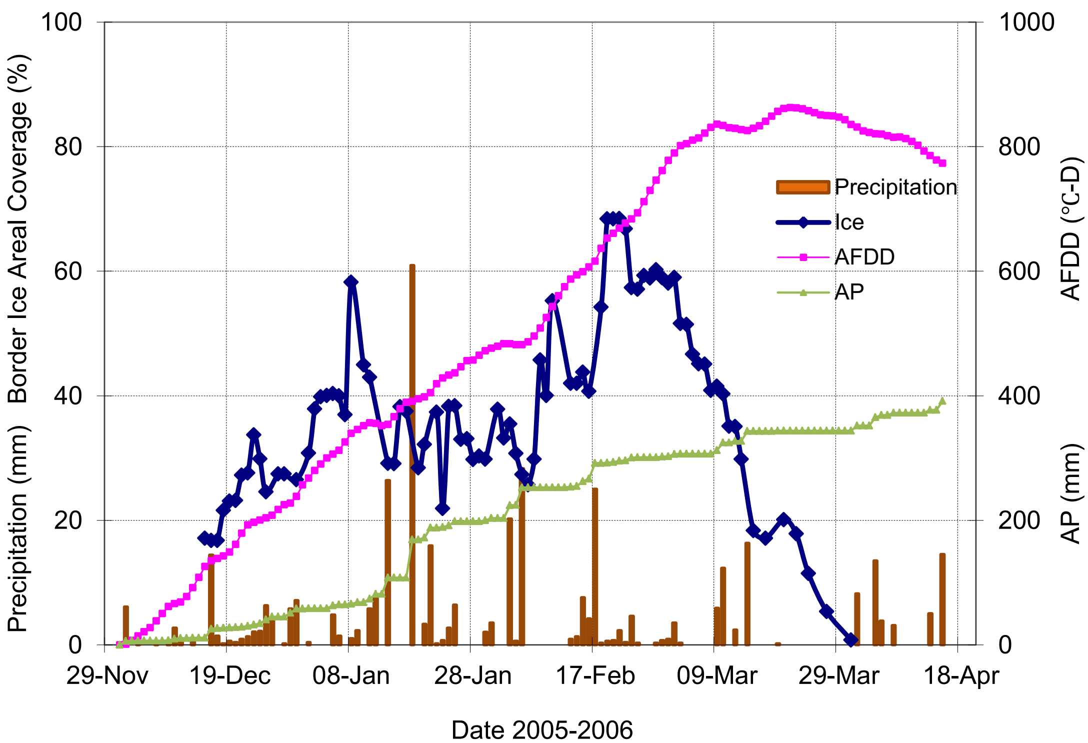

Figure B.37: Border ice areal coverage during 2005-2006 at Portneuf to St-Nicolas

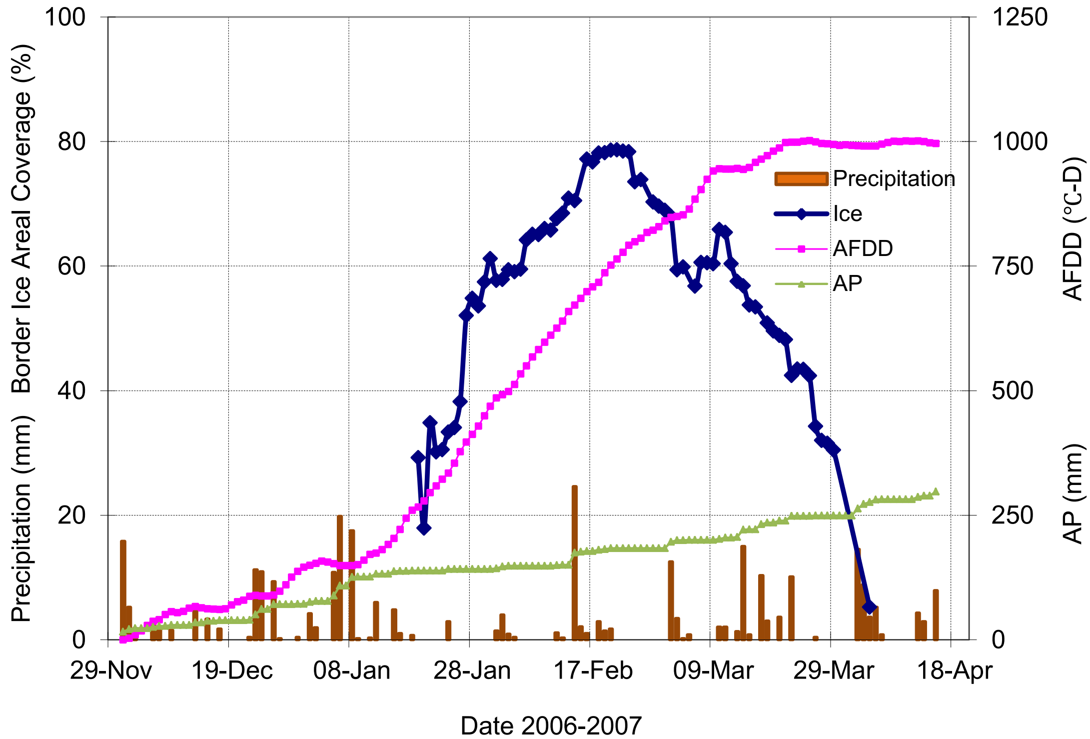

Figure B.38: Border ice areal coverage during 2006-2007 at Portneuf to St-Nicolas

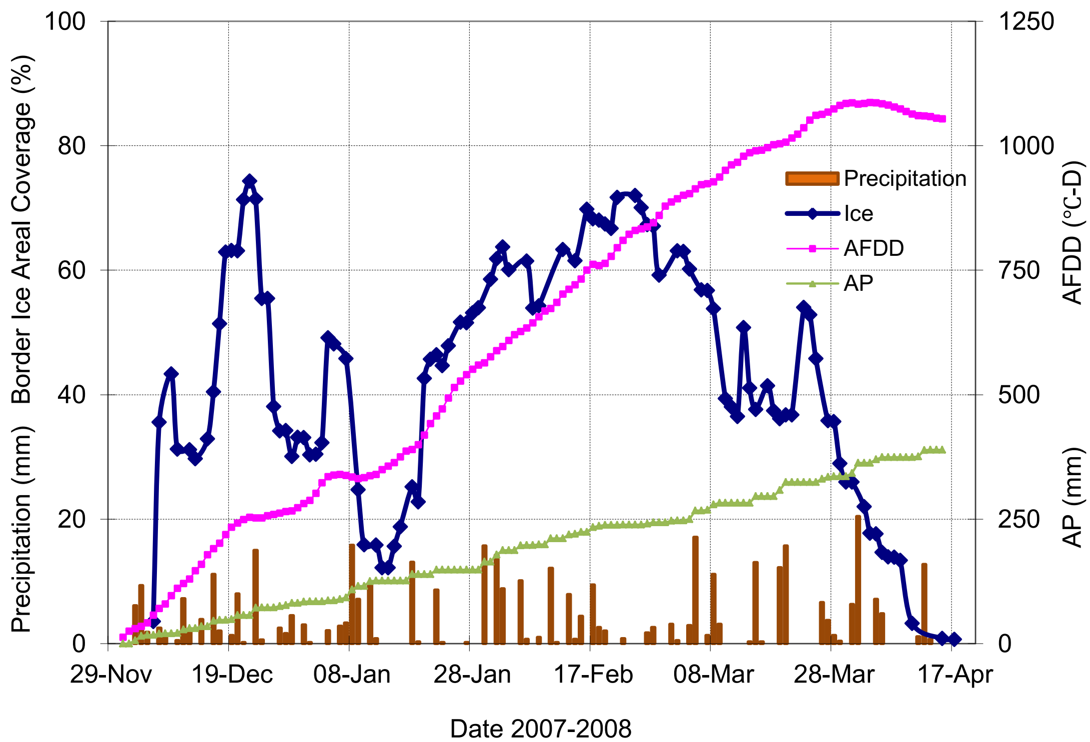

Figure B.39: Border ice areal coverage during 2007-2008 at Portneuf to St-Nicolas

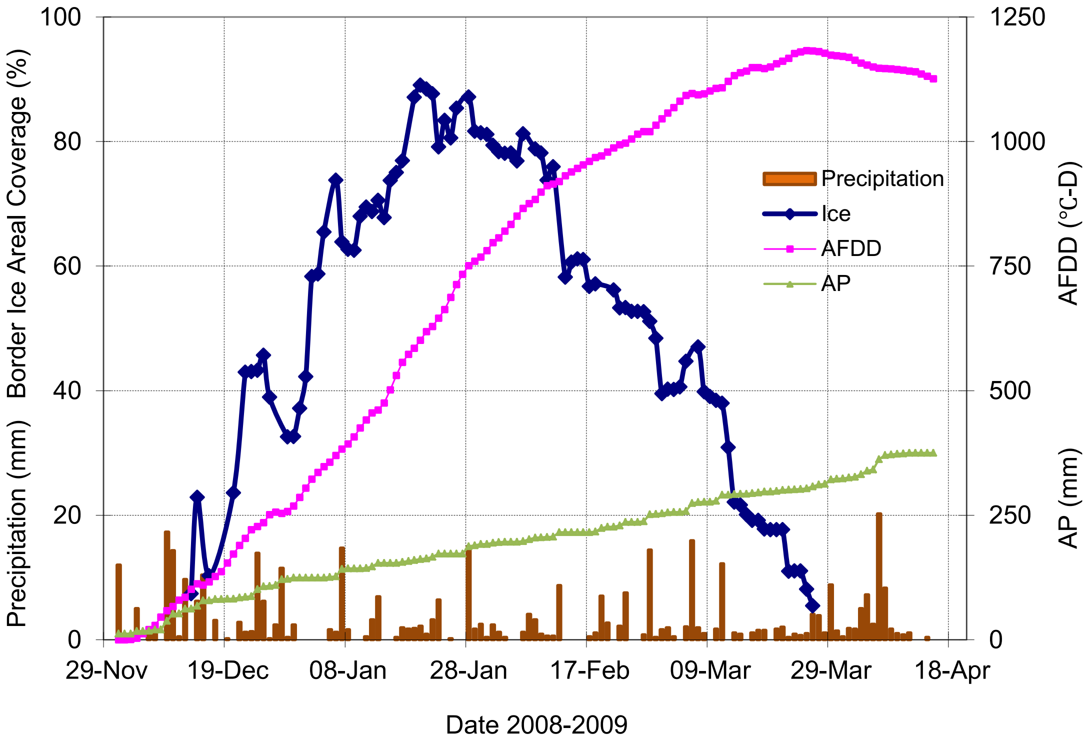

Figure B.40: Border ice areal coverage during 2008-2009 at Portneuf to St-Nicolas

Location 9: Port of Quebec

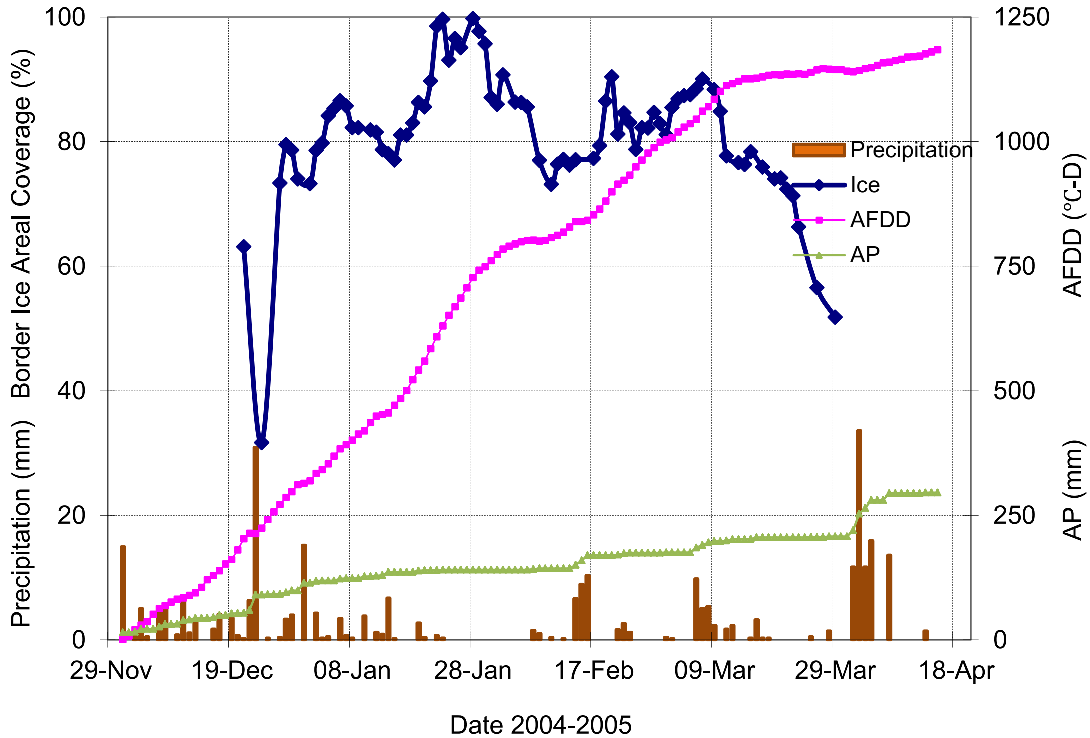

Figure B.41: Border ice areal coverage during 2004-2005 at Port of Quebec

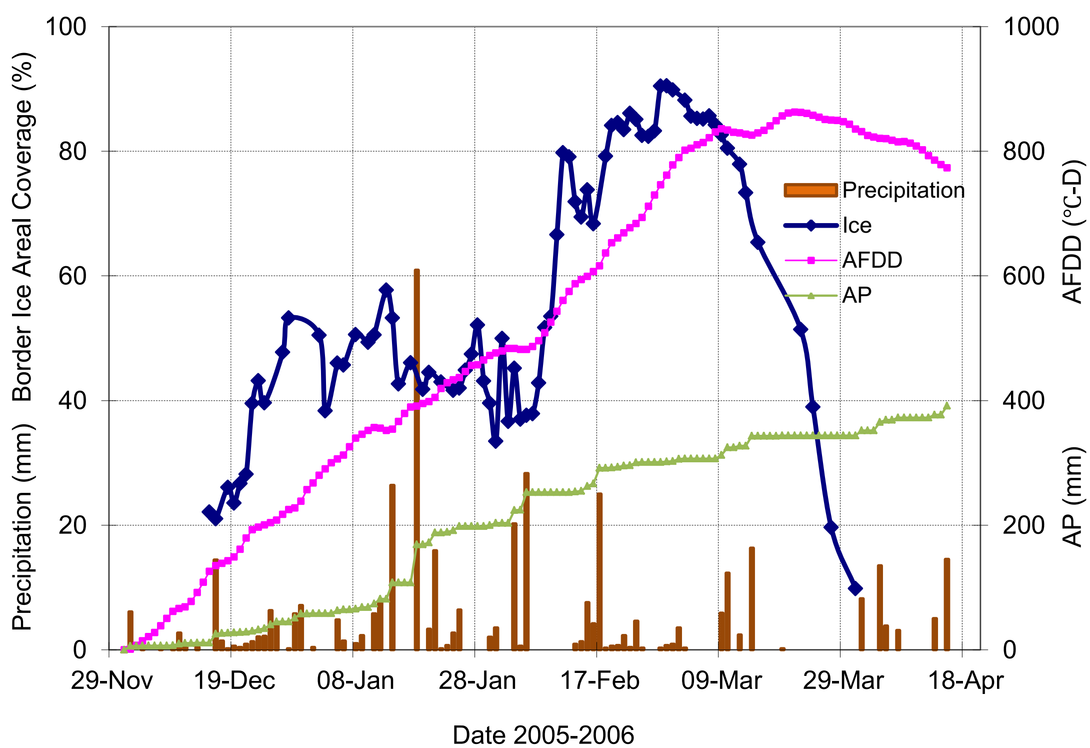

Figure B.42: Border ice areal coverage during 2005-2006 at Port of Quebec

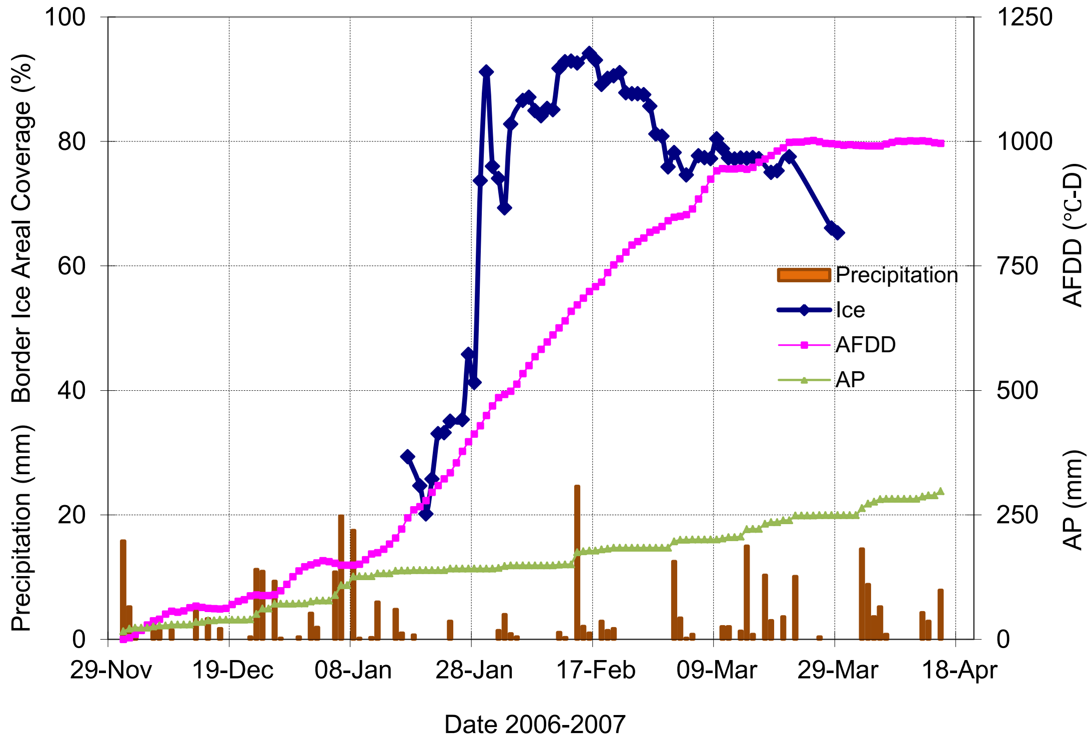

Figure B.43: Border ice areal coverage during 2006-2007 at Port of Quebec

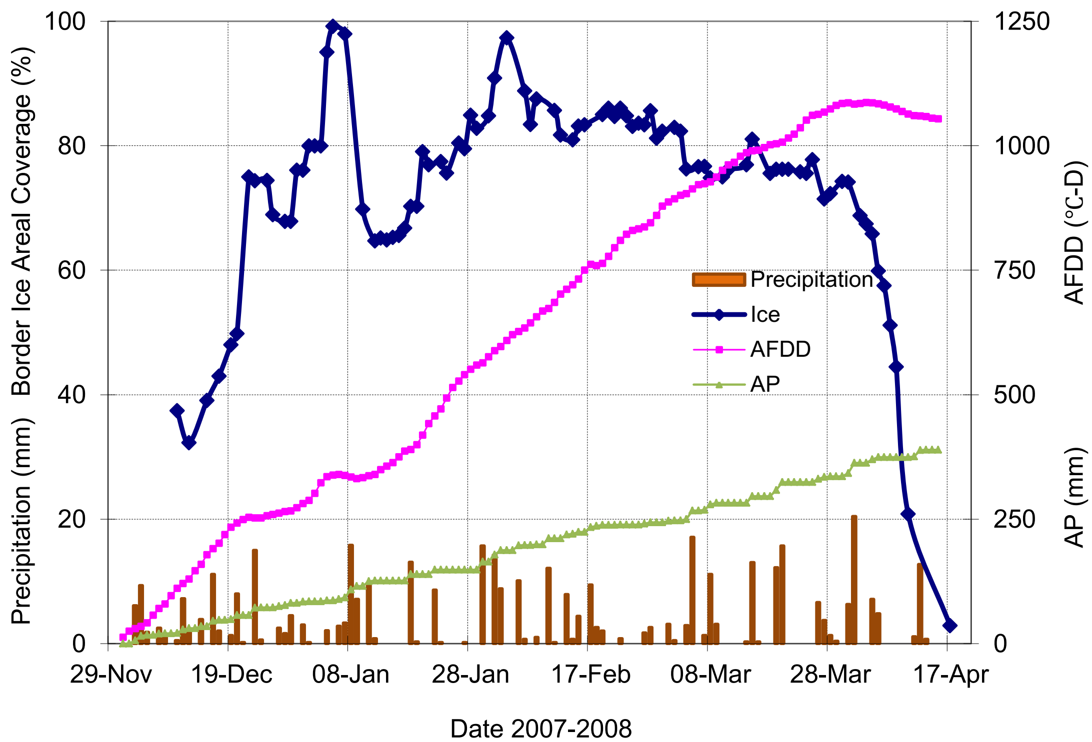

Figure B.44: Border ice areal coverage during 2007-2008 at Port of Quebec

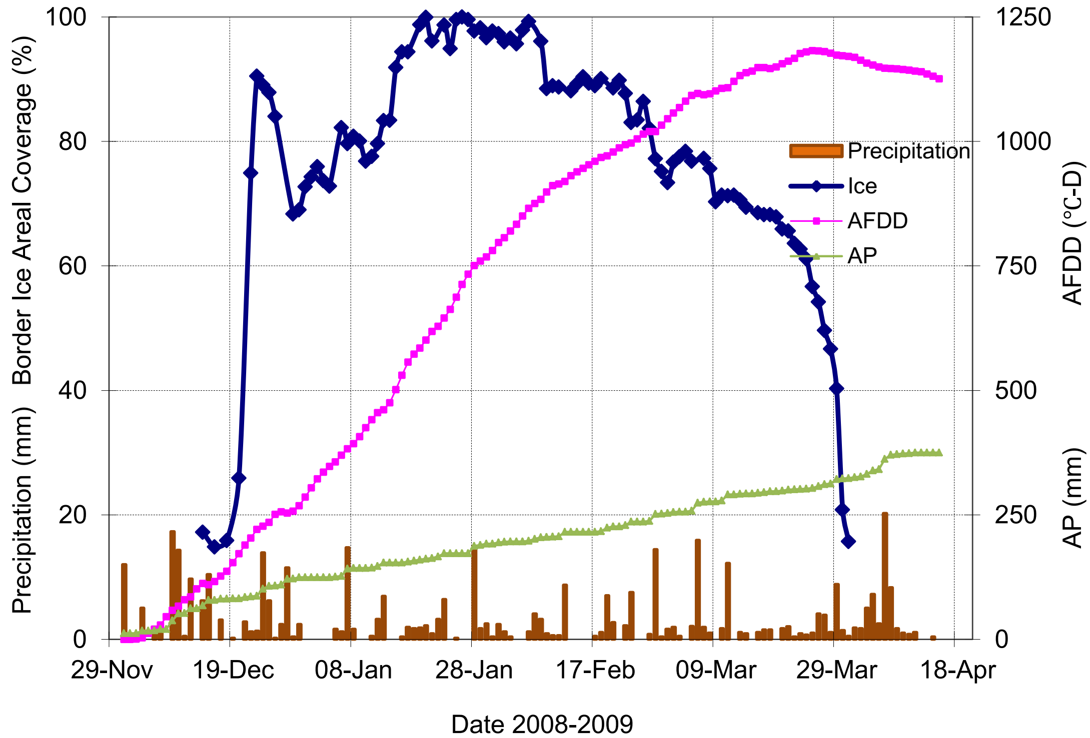

Figure B.45: Border ice areal coverage during 2008-2009 at Port of Quebec

Annex C: The edge of the border ice at Lake Saint-Pierre from 2004-2005 to 2008-2009

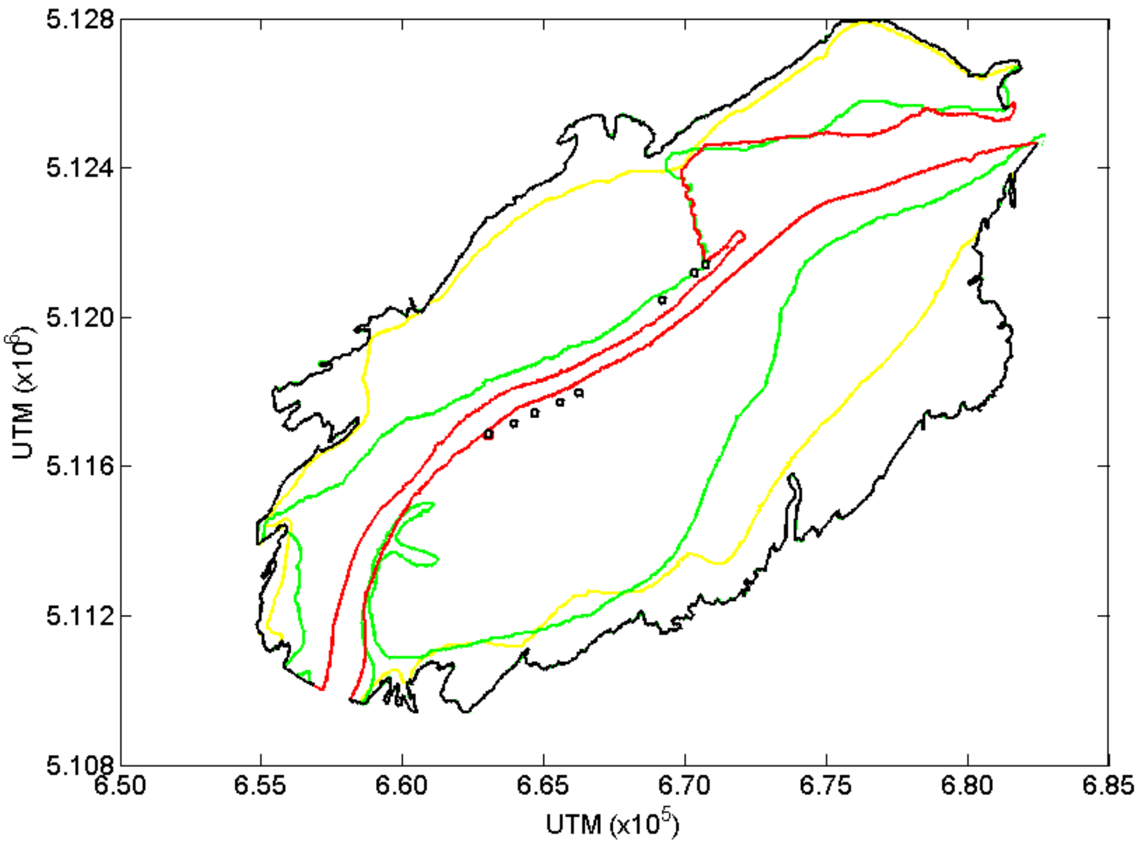

Figure C.1: The edge of the border ice at freeze-up period of 2004-2005

Yellow:	**2004-12-20**	**21.23%**
Green:	**2004-12-24**	**58.71%**
Red:	**2005-01-24**	**97.76%**

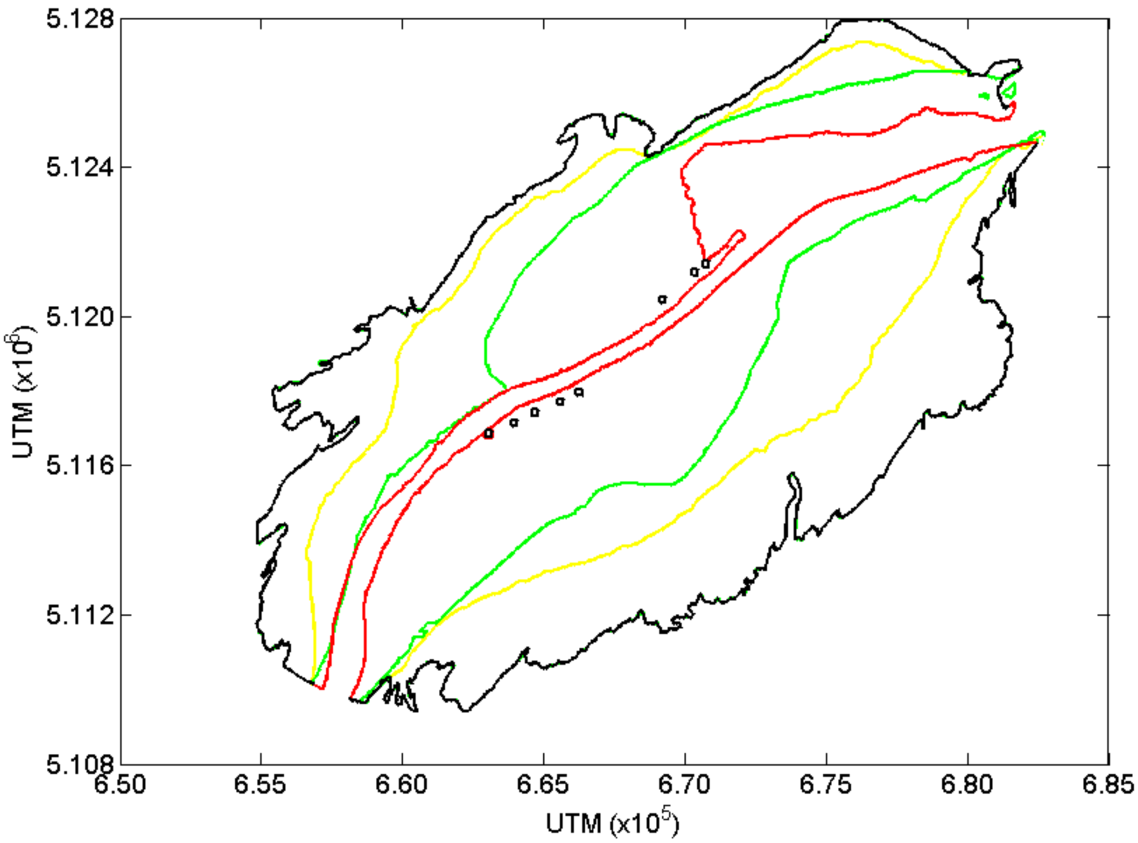

Figure C.2: The edge of the border ice at break-up period of 2004-2005

Yellow:	**2005-03-29**	**33.90%**
Green:	**2005-03-18**	**60.60%**
Red:	**2005-01-24**	**97.76%**

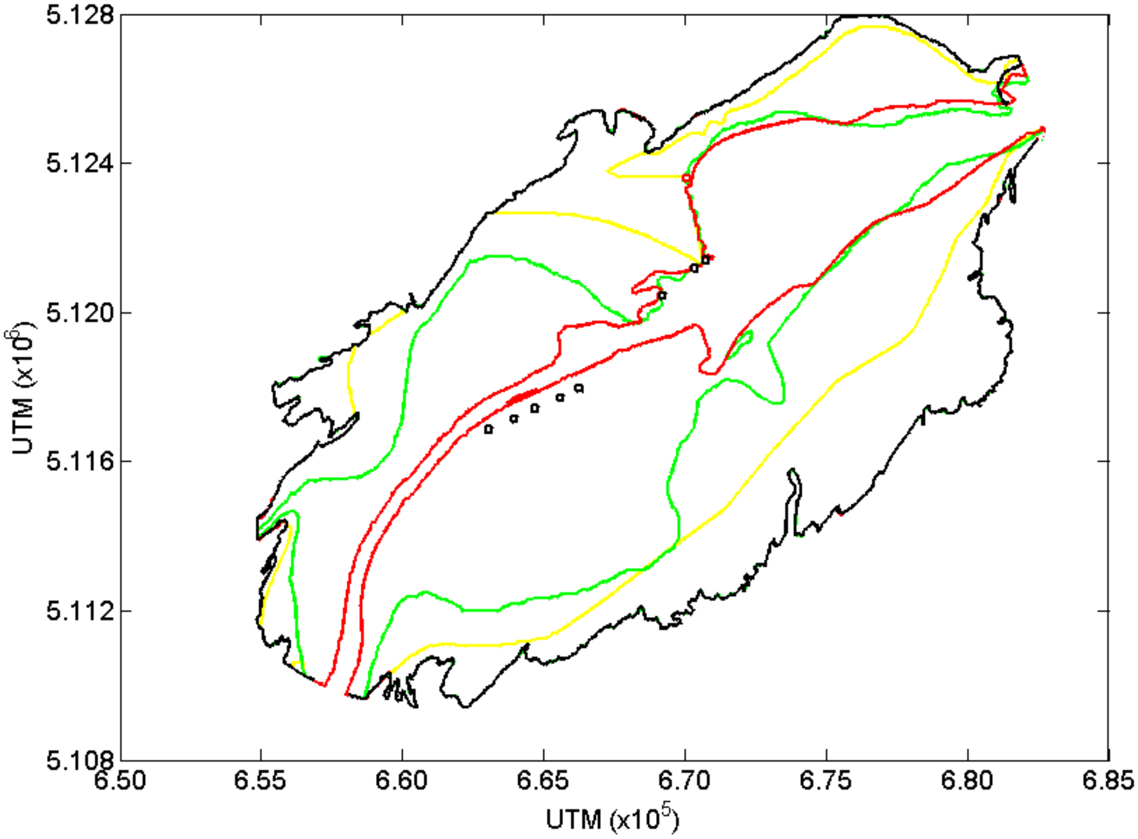

Figure C.3: The edge of the border ice at freeze-up period of 2005-2006

Yellow:	**2005-12-15**	**24.77%**
Green:	**2005-12-20**	**56.65%**
Red:	**2006-02-01**	**91.15%**

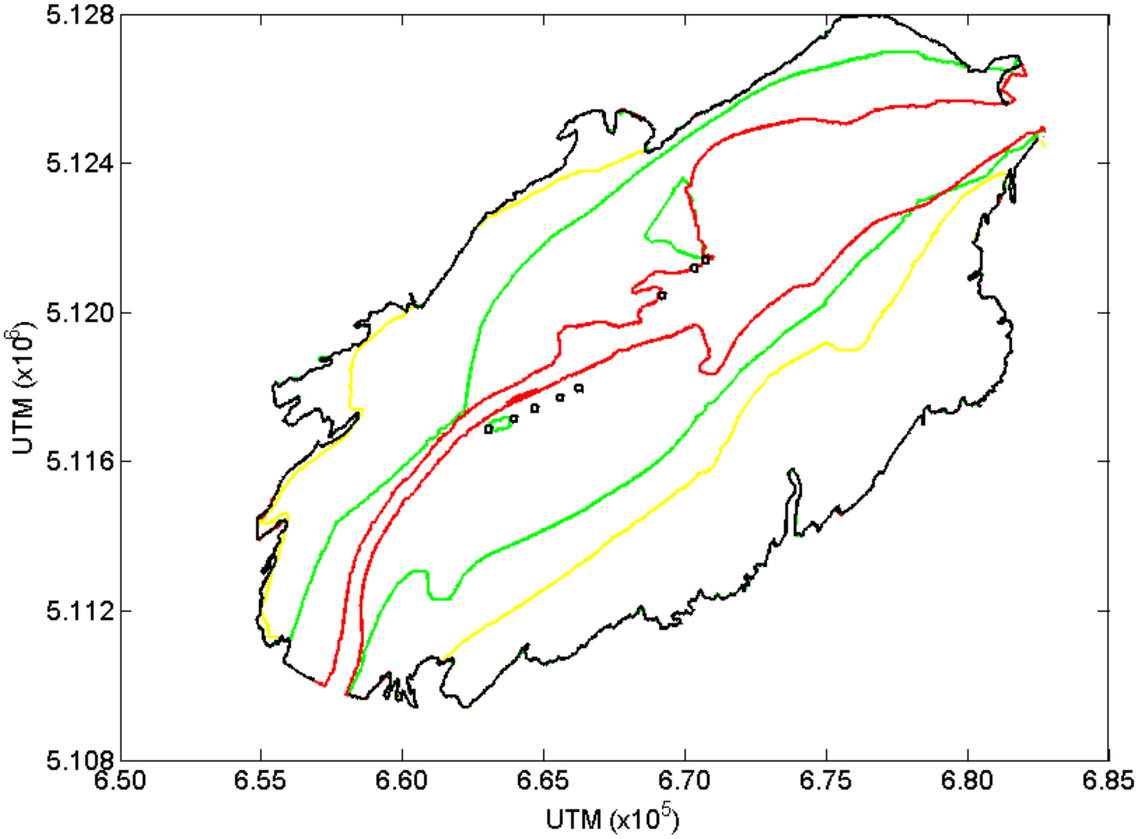

Figure C.4: The edge of the border ice at break-up period of 2005-2006

Yellow:	**2006-03-20**	**28.69%**
Green:	**2006-03-11**	**57.55%**
Red:	**2006-02-01**	**91.15%**

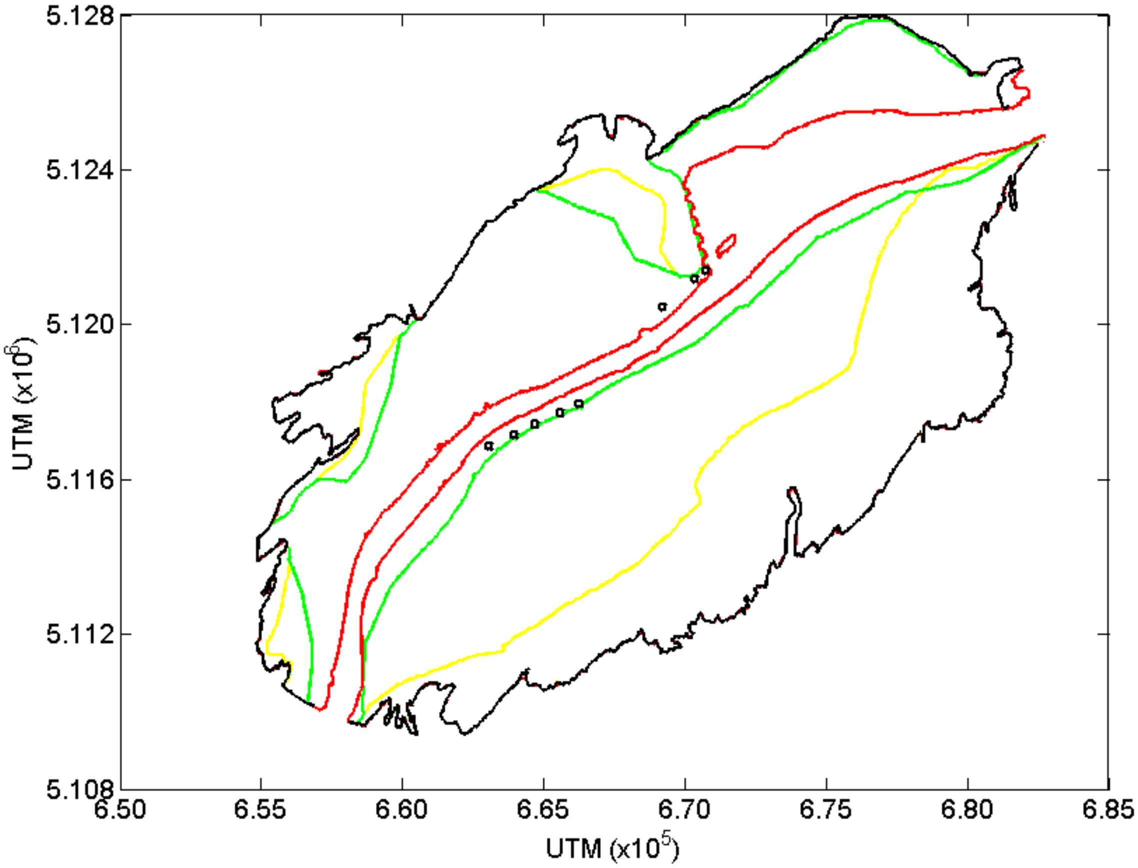

Figure C.5: The edge of the border ice at freeze-up period of 2006-2007

Yellow:	**2007-01-16**	**33.36%**
Green:	**2007-01-17**	**64.54%**
Red:	**2007-02-19**	**97.03%**

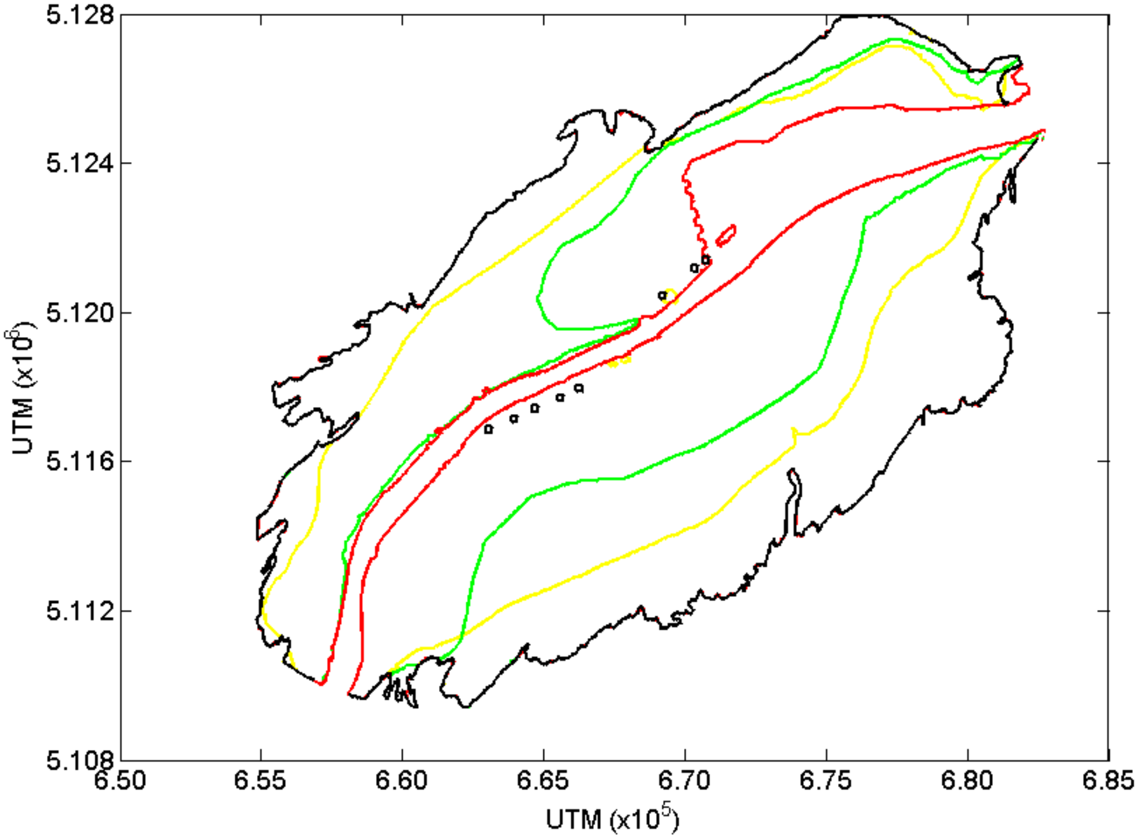

Figure C.6: The edge of the border ice at break-up period of 2006-2007

Yellow:	**2007-03-25**	**32.10%**
Green:	**2007-03-16**	**59.30%**
Red:	**2007-02-19**	**97.03%**

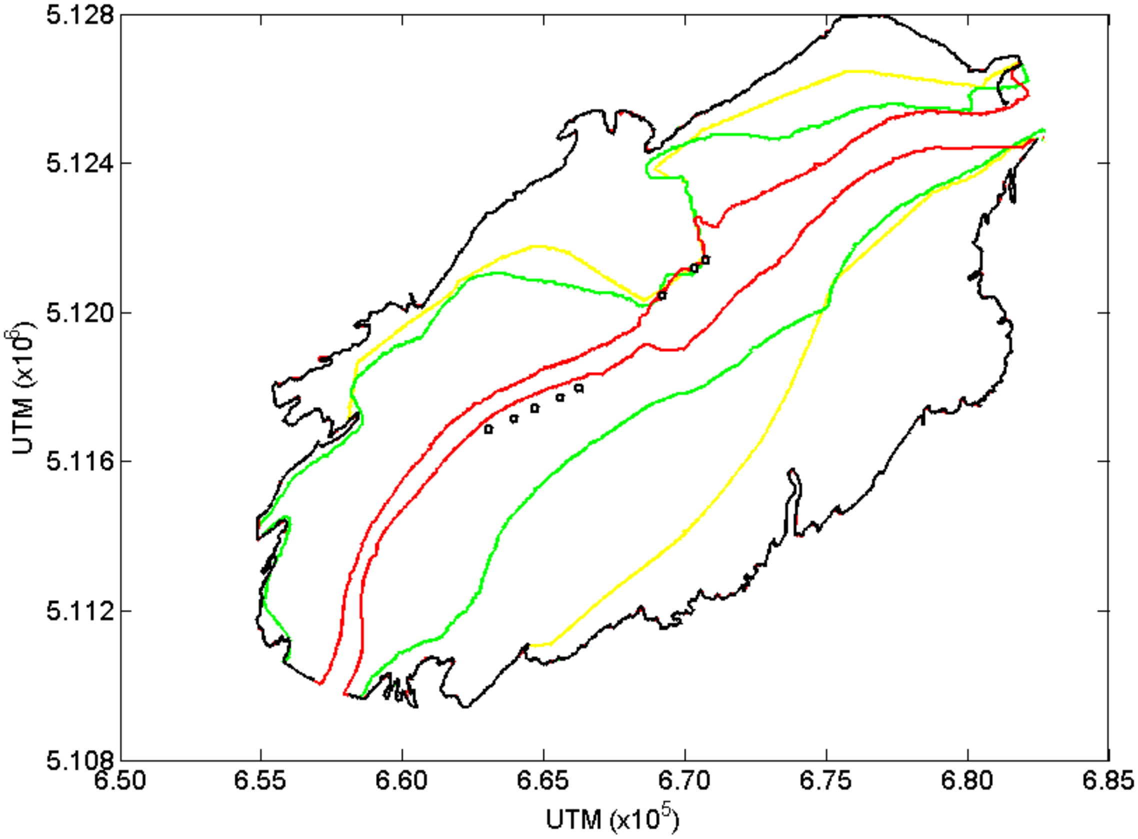

Figure C.7: The edge of the border ice at freeze-up period of 2007-2008

Yellow:	**2007-12-06**	**37.18%**
Green:	**2007-12-13**	**60.81%**
Red:	**2008-01-04**	**100%**

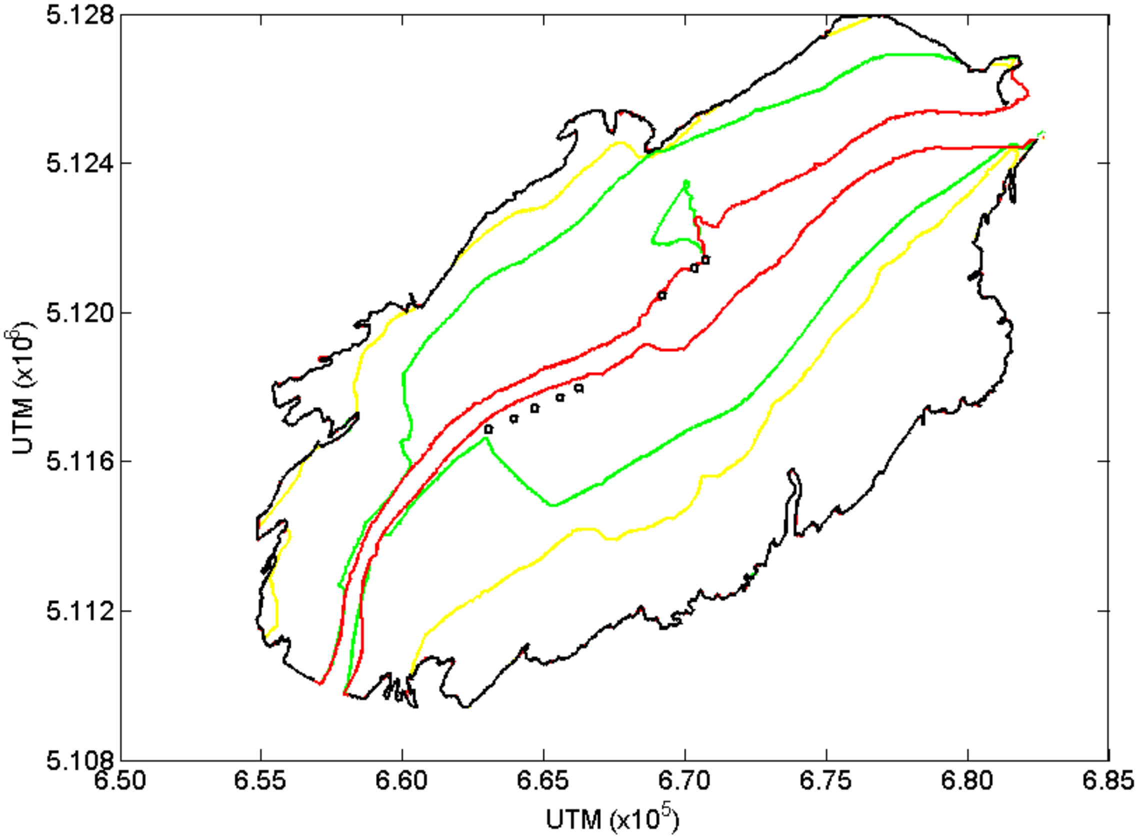

Figure C.8: The edge of the border ice at break-up period of 2007-2008

Yellow:	**2008-04-08**	**31.38%**
Green:	**2008-03-17**	**63.44%**
Red:	**2008-01-04**	**100%**

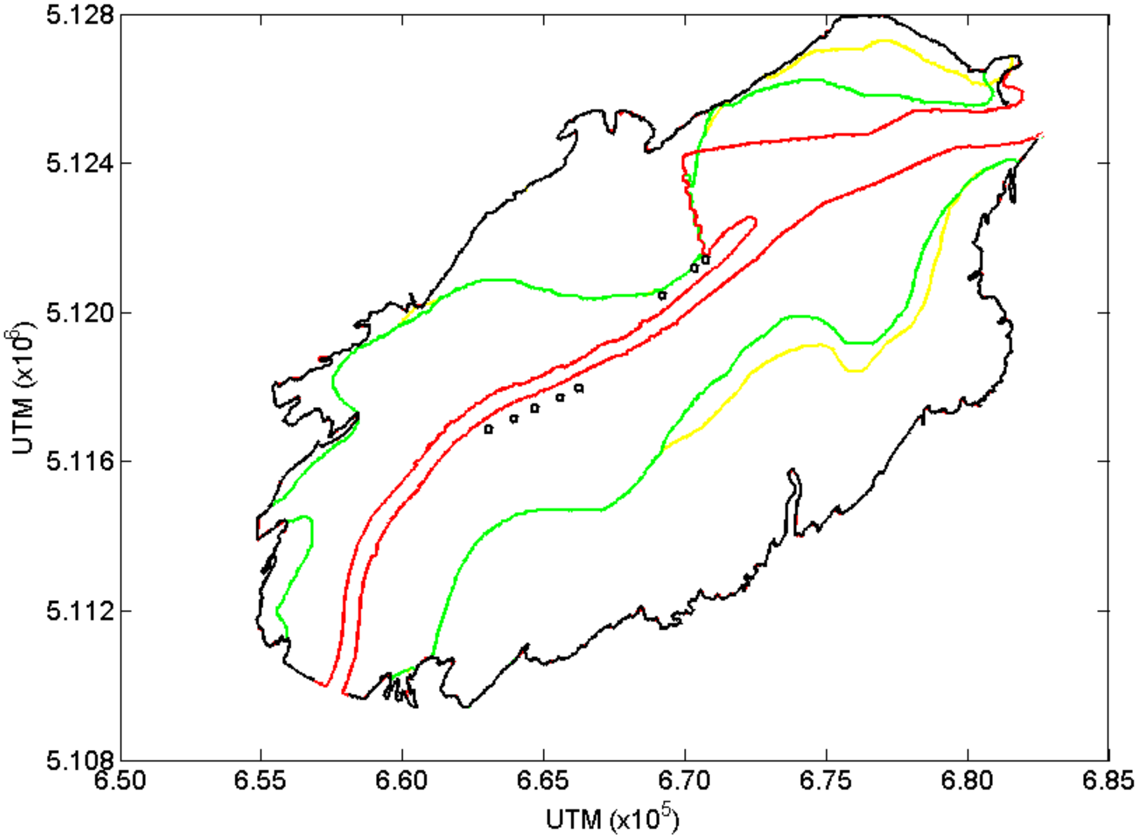

Figure C.9: The edge of the border ice at freeze-up period of 2008-2009

Yellow:	**2008-12-18**	**46.81%**
Green:	**2008-12-19**	**52.39%**
Red:	**2009-02-06**	**99.63%**

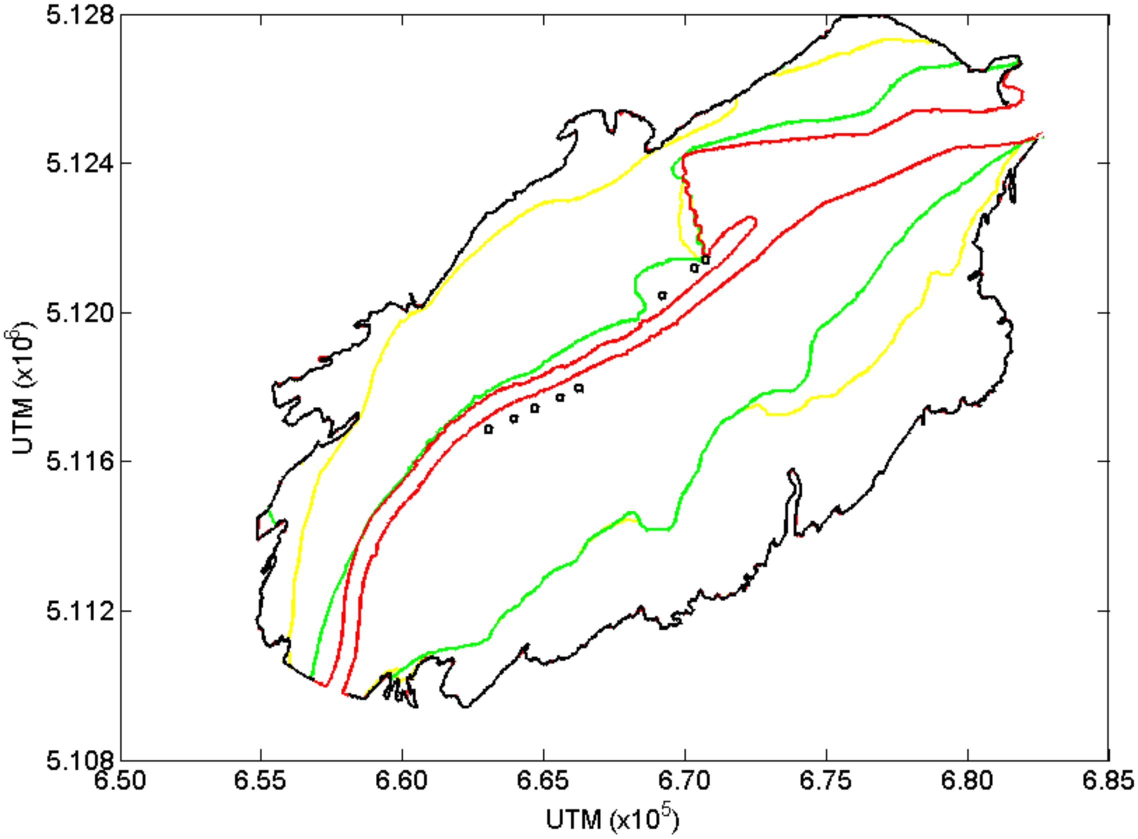

Figure C.10: The edge of the border ice at break-up period of 2008-2009

Yellow:	**2009-03-18**	**31.20%**
Green:	**2009-03-12**	**60.74%**
Red:	**2009-02-06**	**99.63%**

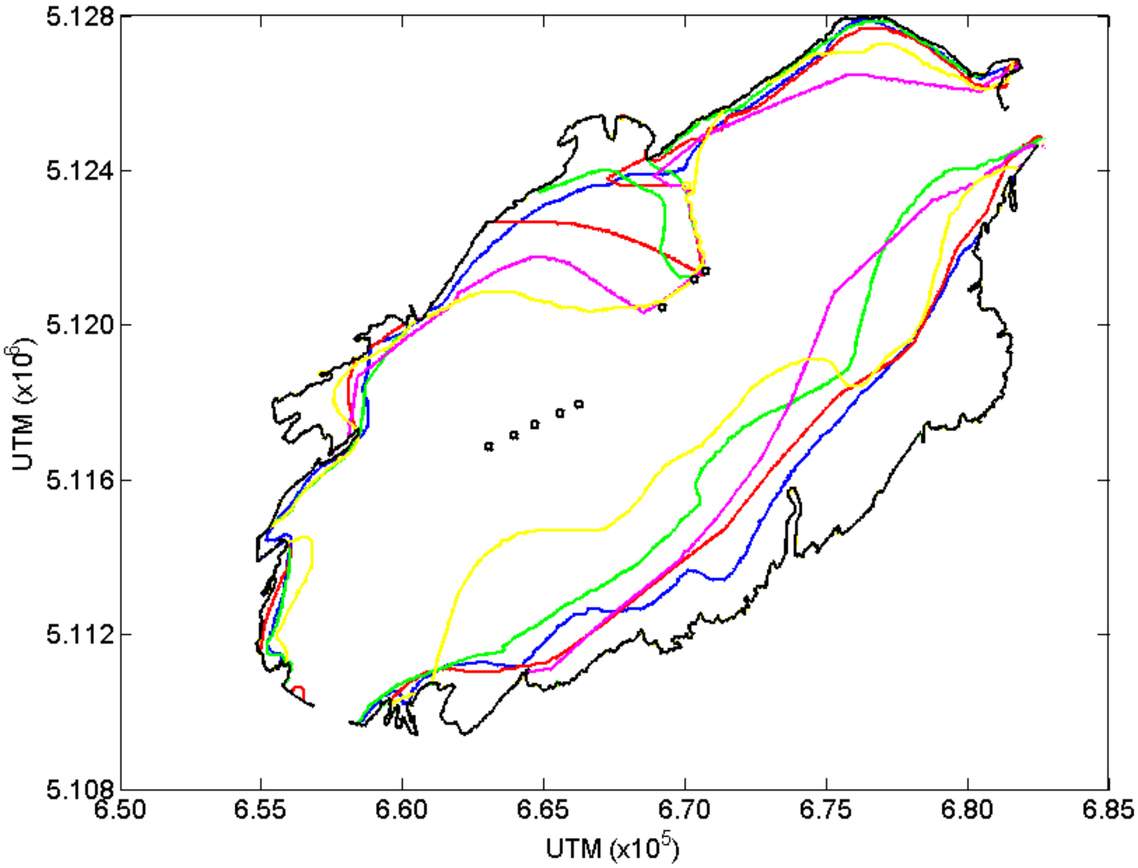

Figure C.11: Border ice coverage of around 30% at freeze-up period of 2004-2009

Blue:	**2004-12-20**	**21.23%**
Red:	**2005-12-15**	**24.77%**
Green:	**2007-01-16**	**33.36%**
Pink:	**2007-12-06**	**37.18%**
Yellow:	**2008-12-18**	**46.81%**

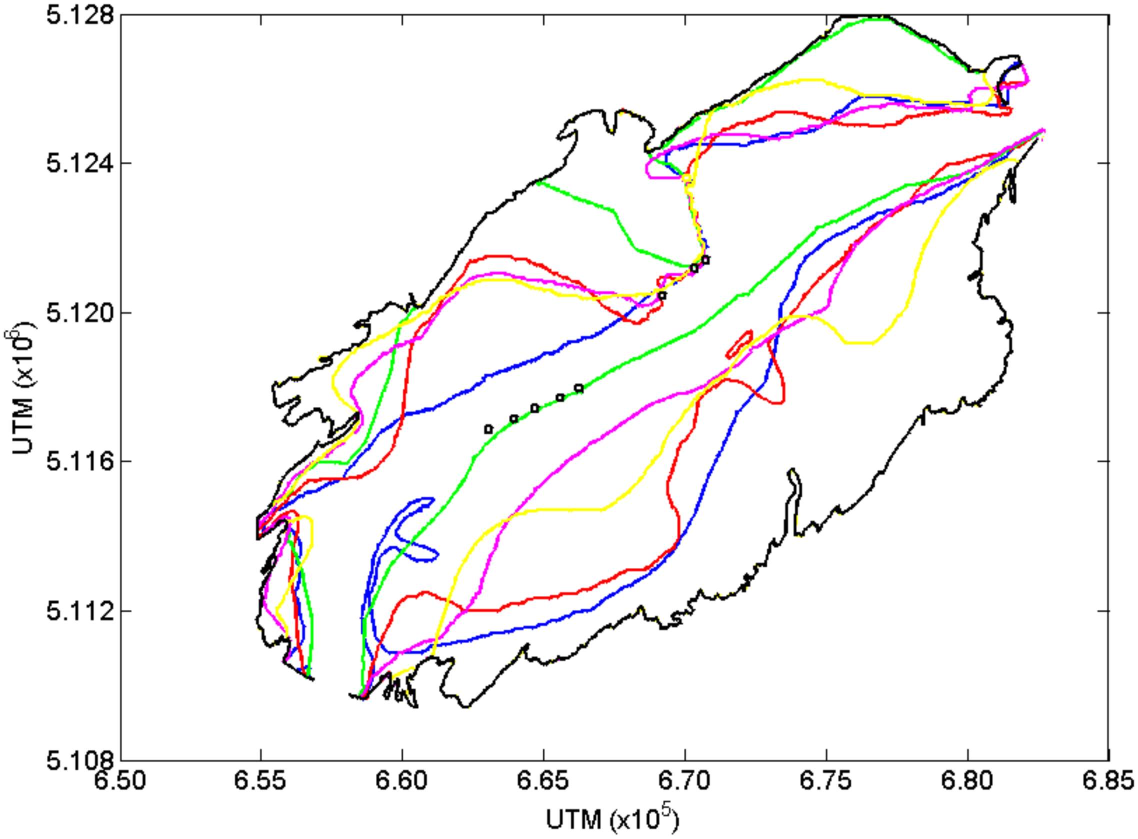

Figure C.12: Border ice coverage of around 60% at freeze-up period of 2004-2009

Blue:	**2004-12-24**	**58.71%**
Red:	**2005-12-20**	**56.65%**
Green:	**2007-01-17**	**64.54%**
Pink:	**2007-12-13**	**60.81%**
Yellow:	**2008-12-19**	**52.39%**

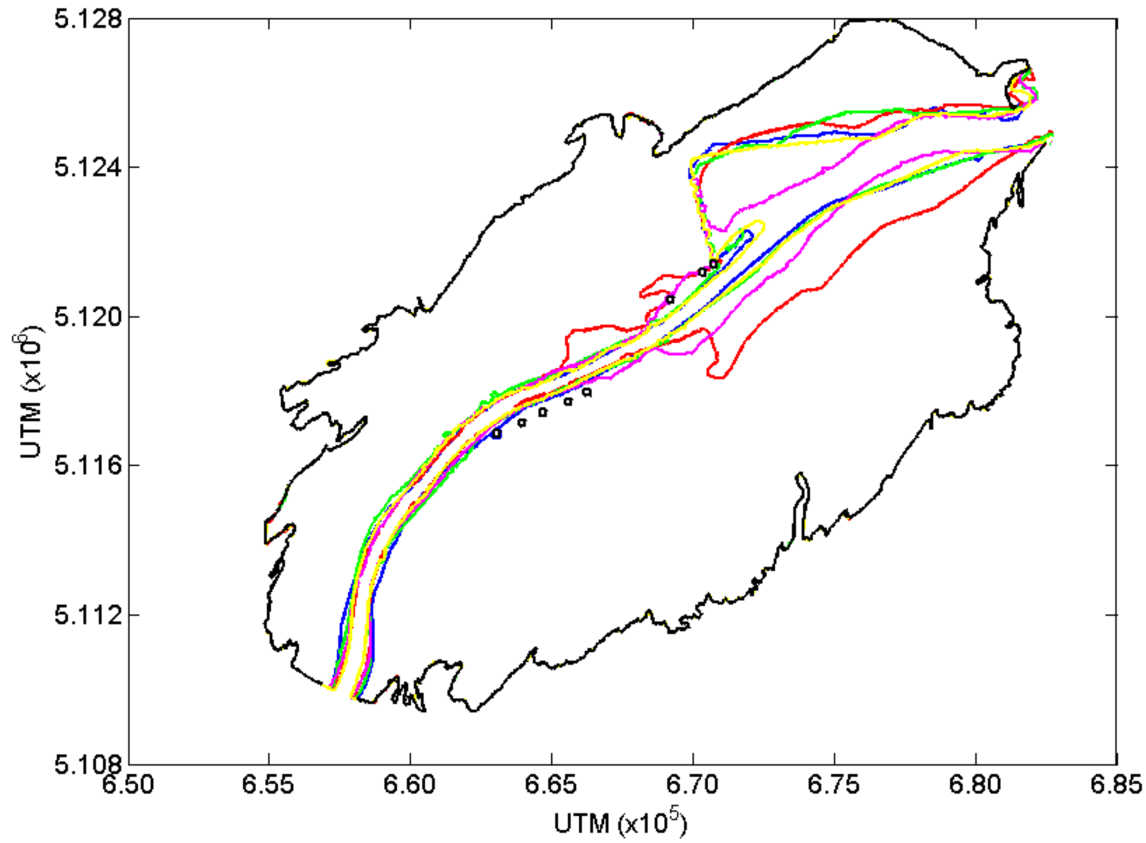

Figure C.13: Maximal border ice coverage at 2004-2009

Blue:	**2005-01-24**	**97.76%**
Red:	**2006-02-01**	**91.15%**
Green:	**2007-02-19**	**97.03%**
Pink:	**2008-01-04**	**100%**
Yellow:	**2009-02-06**	**99.63%**

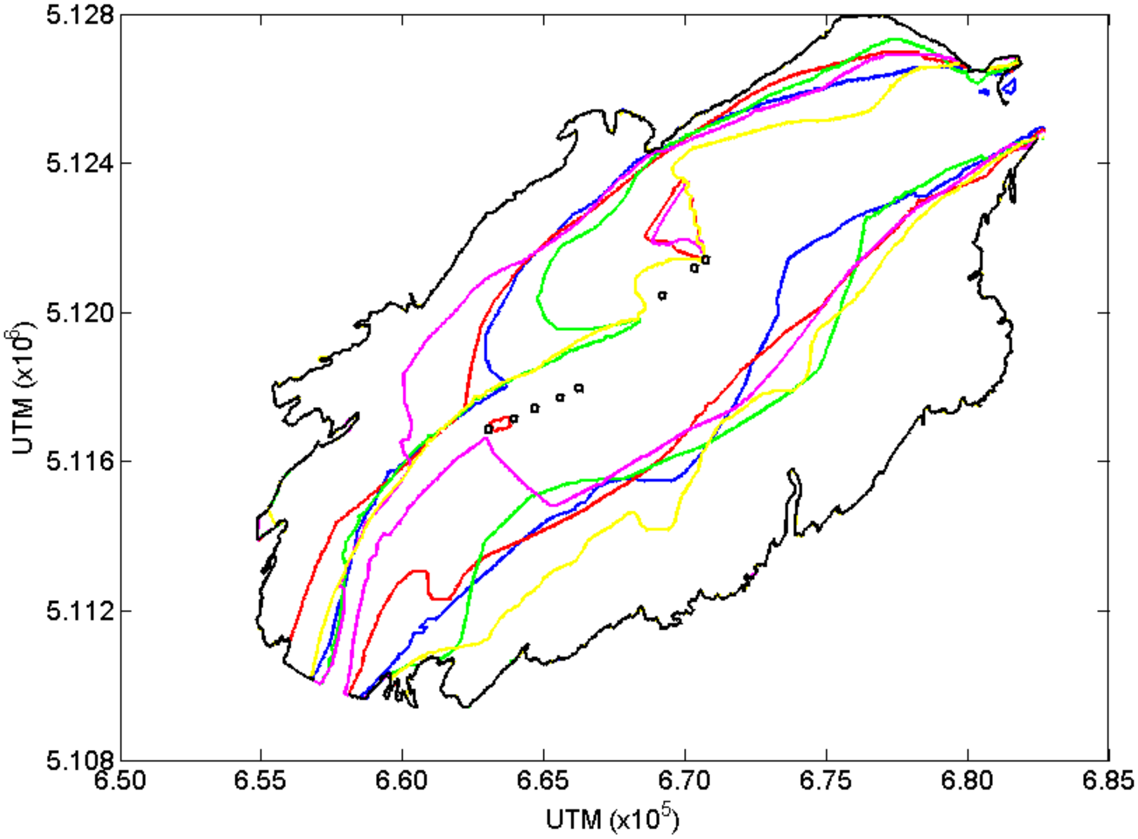

Figure C.14: Border ice coverage of around 60% at break-up period of 2004-2009

Blue:	**2005-03-18**	**60.60%**
Red:	**2006-03-11**	**57.55%**
Green:	**2007-03-16**	**59.30%**
Pink:	**2008-03-17**	**63.44%**
Yellow:	**2009-03-12**	**60.74%**

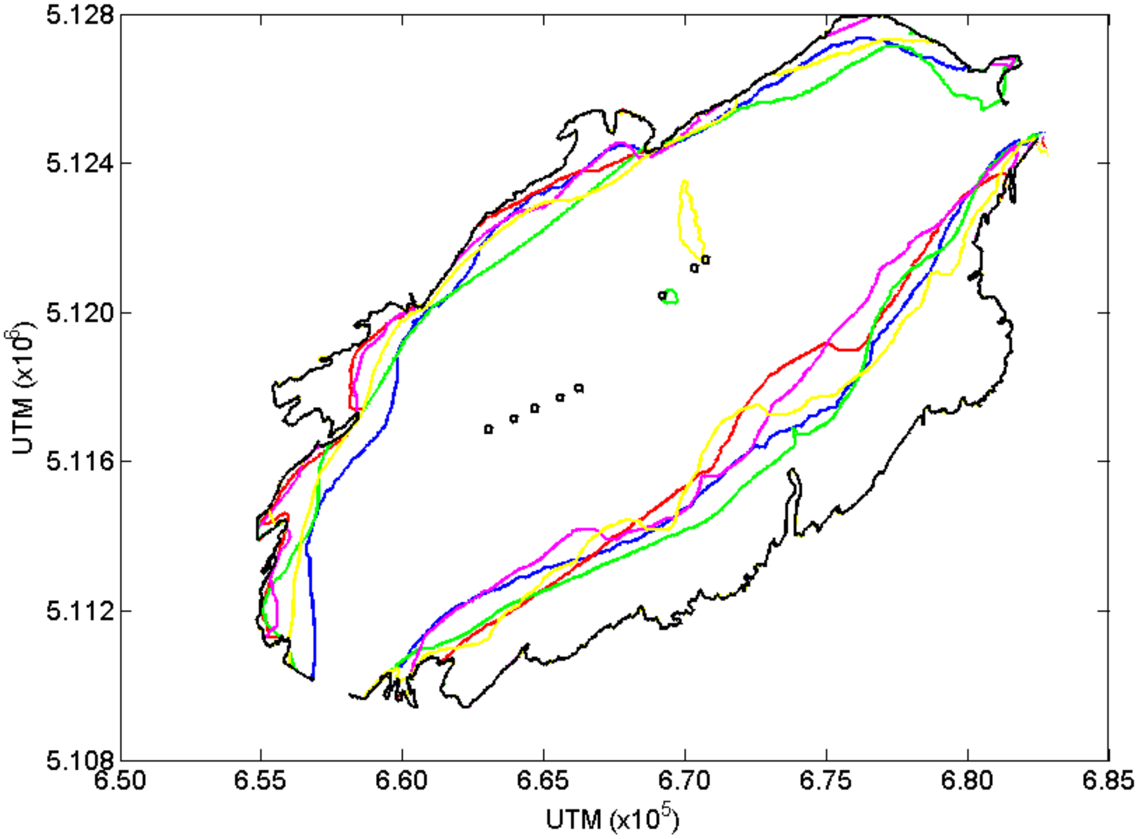

Figure C.15: Border ice coverage of around 30% at freeze-up period of 2004-2009

Blue:	**2005-03-29**	**33.90%**
Red:	**2006-03-20**	**28.69%**
Green:	**2007-03-25**	**32.10%**
Pink:	**2008-04-08**	**31.38%**
Yellow:	**2009-03-18**	**31.20%**

Annex D: Contour line of South side of Lake Saint-Pierre during freeze-up period of from 2004-2005 to 2008-2009

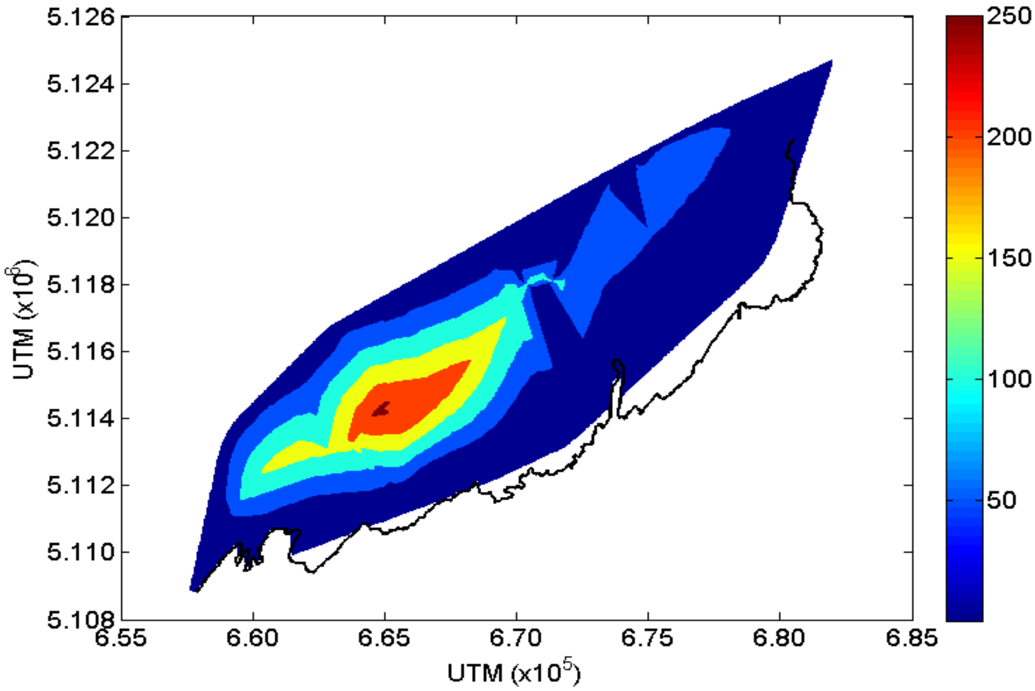

Figure D.1: Contour lines of growth speed (m/h) in 2004-2005

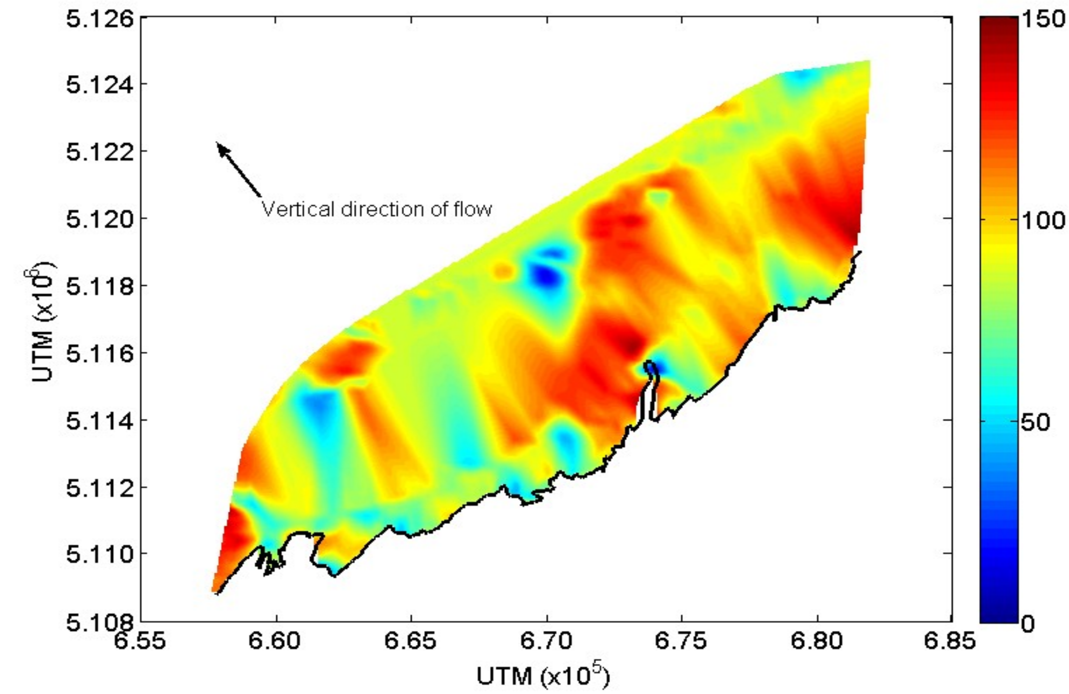

Figure D.2: Contour lines of growth direction (°) in 2004-2005

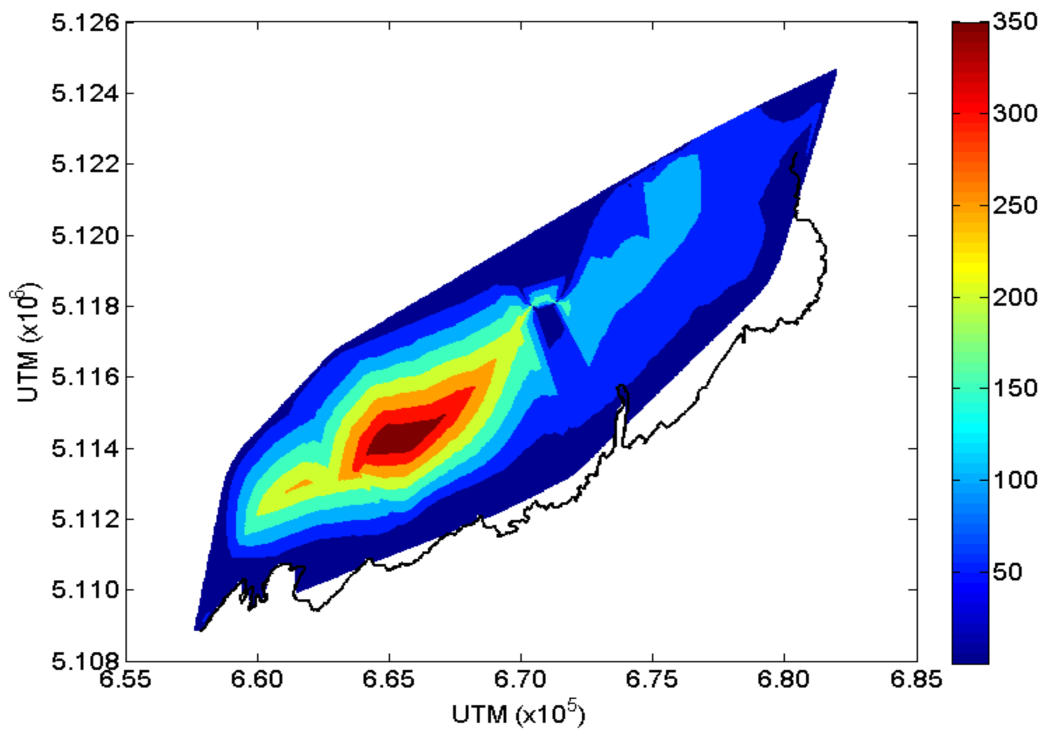

Figure D.3: Contour lines of function f=Δd/ΔAFDD (m/DD) in 2004-2005

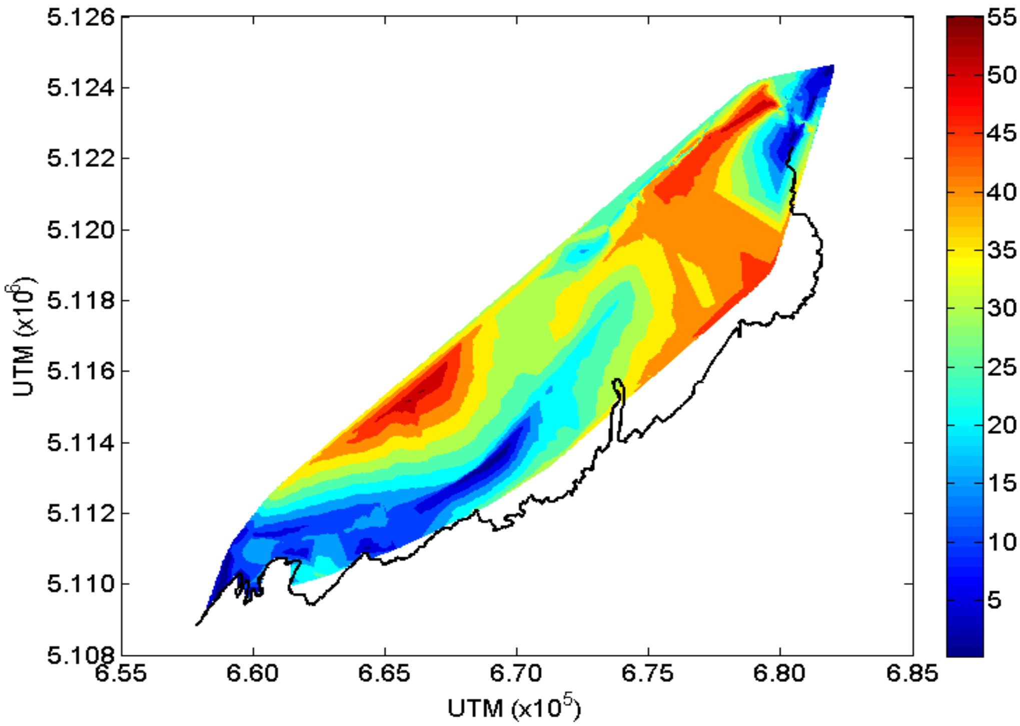

Figure D.4: Contour lines of growth speed (m/h) in 2005-2006

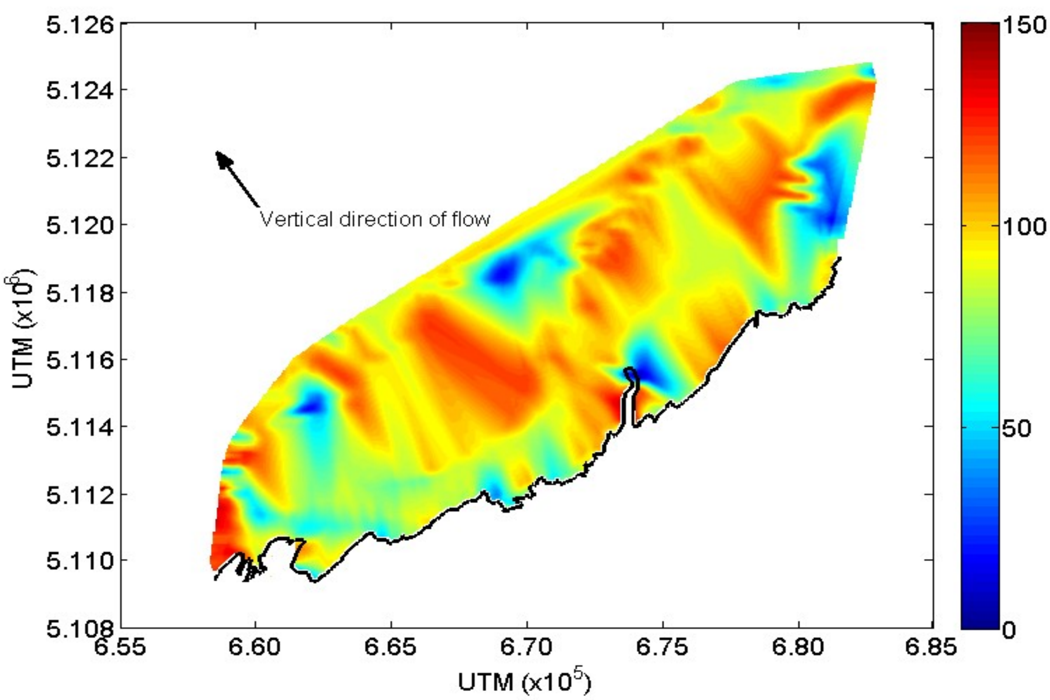

Figure D.5: Contour lines of growth direction (°) in 2005-2006

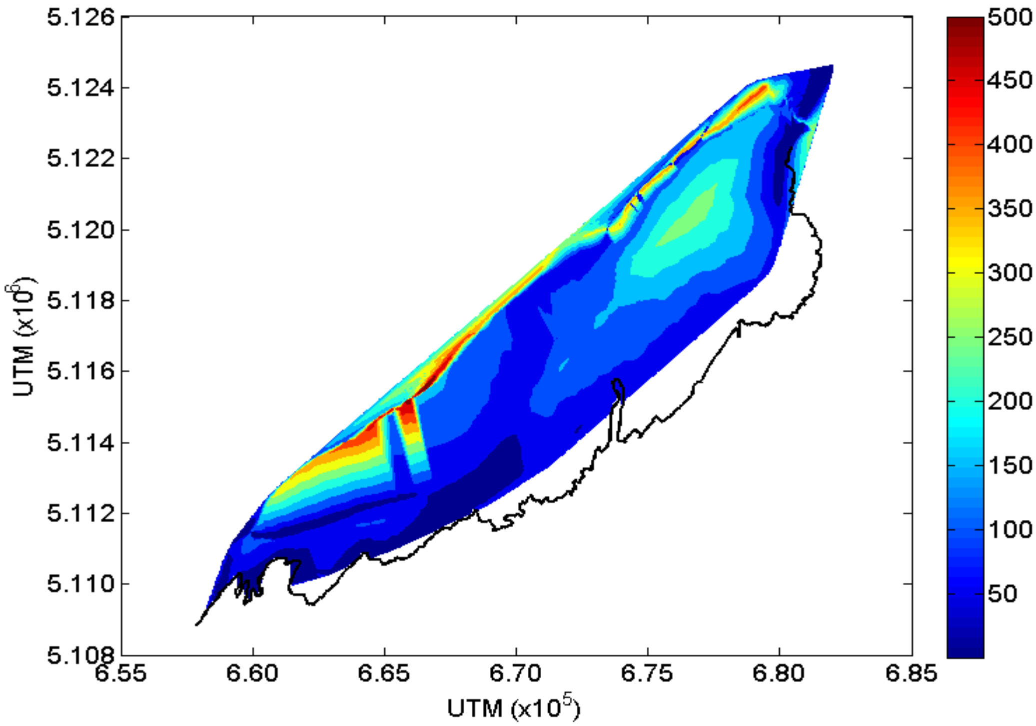

Figure D.6: Contour lines of function f=Δd/ΔAFDD (m/DD) in 2005-2006

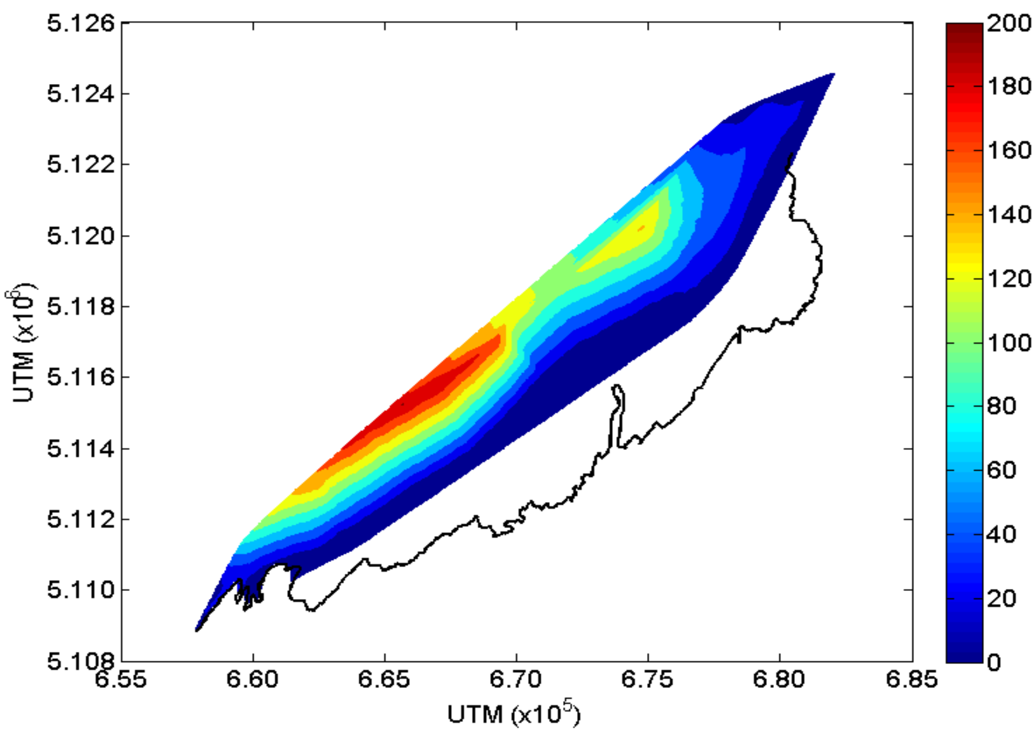

Figure D.7: Contour lines of growth speed (m/h) in 2006-2007

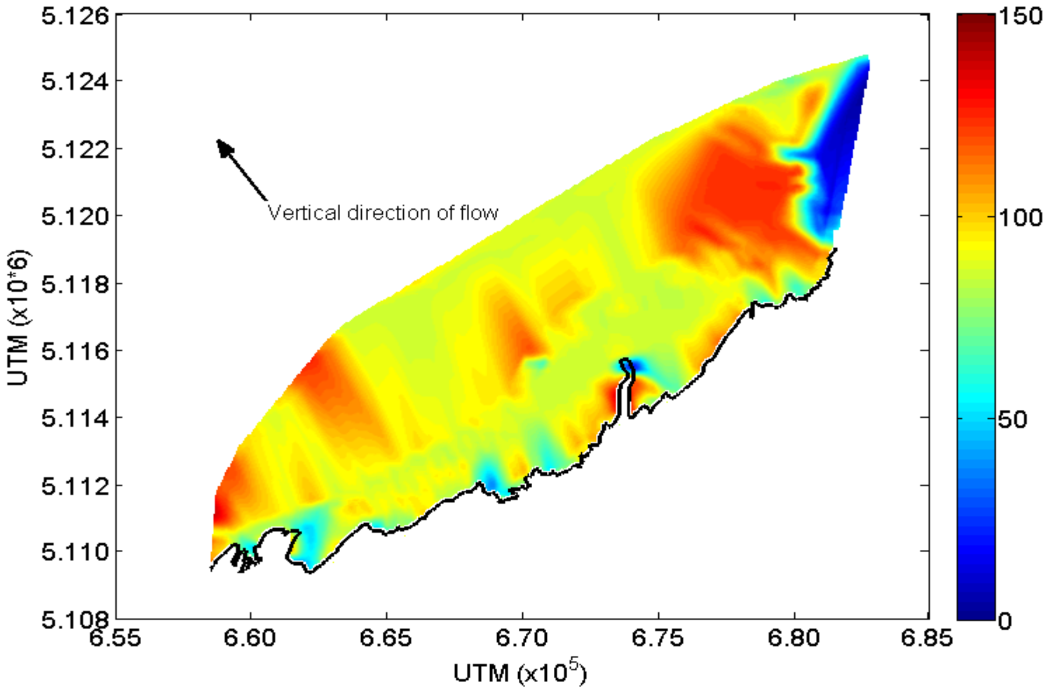

Figure D.8: Contour lines of growth direction (°) in 2006-2007

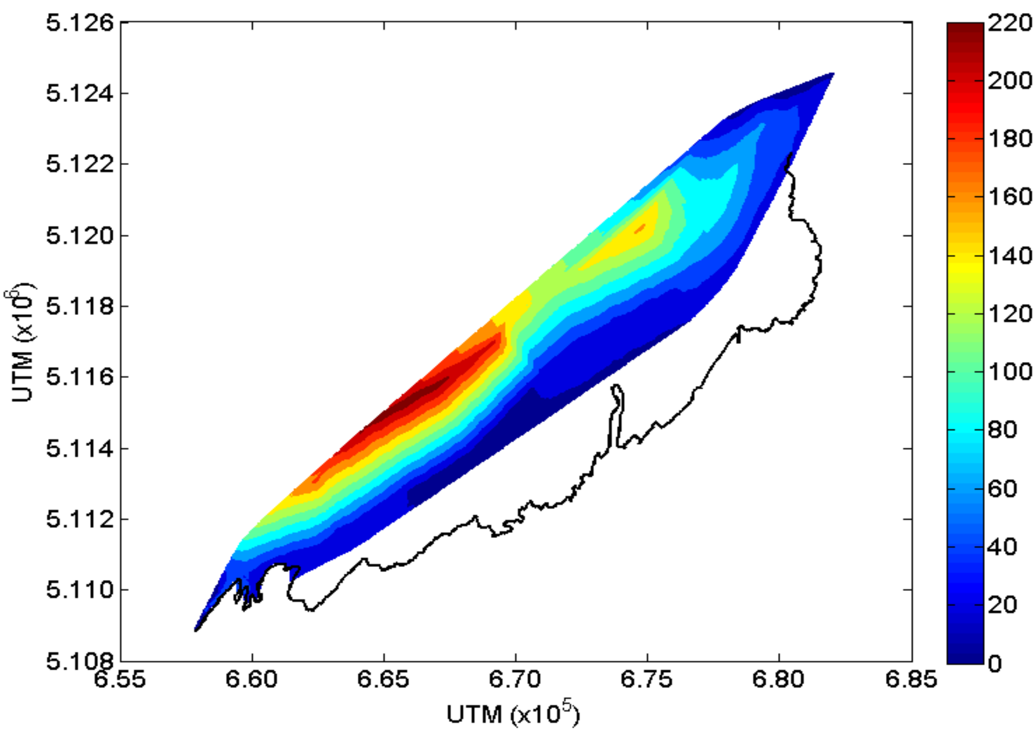

Figure D.9: Contour lines of function f=Δd/ΔAFDD (m/DD) in 2006-2007

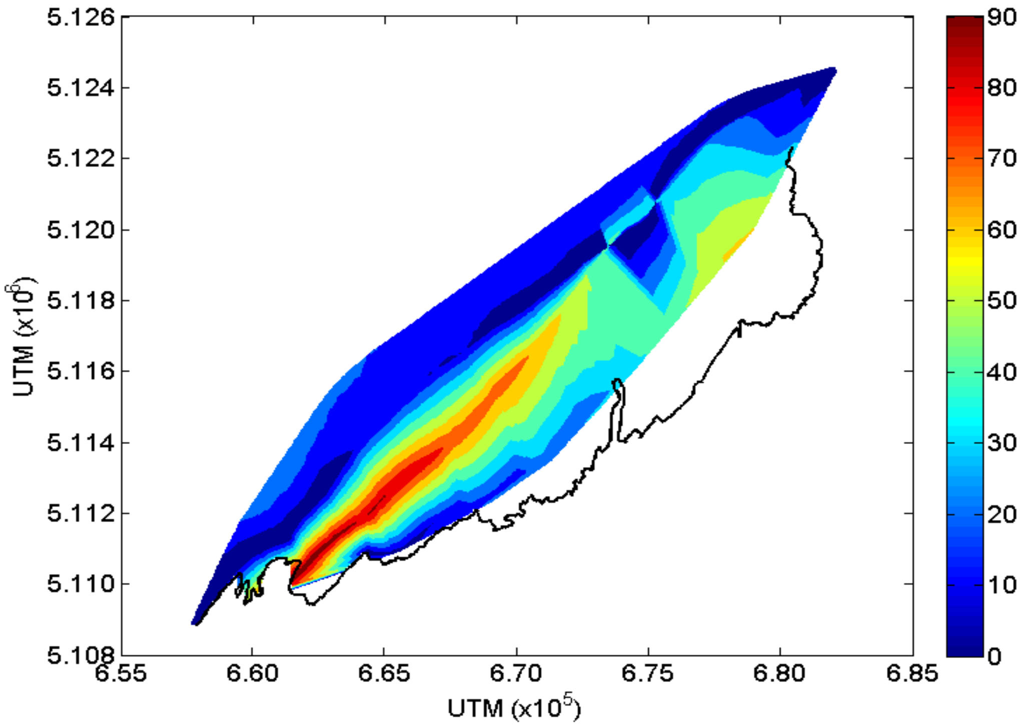

Figure D.10: Contour lines of growth speed (m/h) in 2007-2008

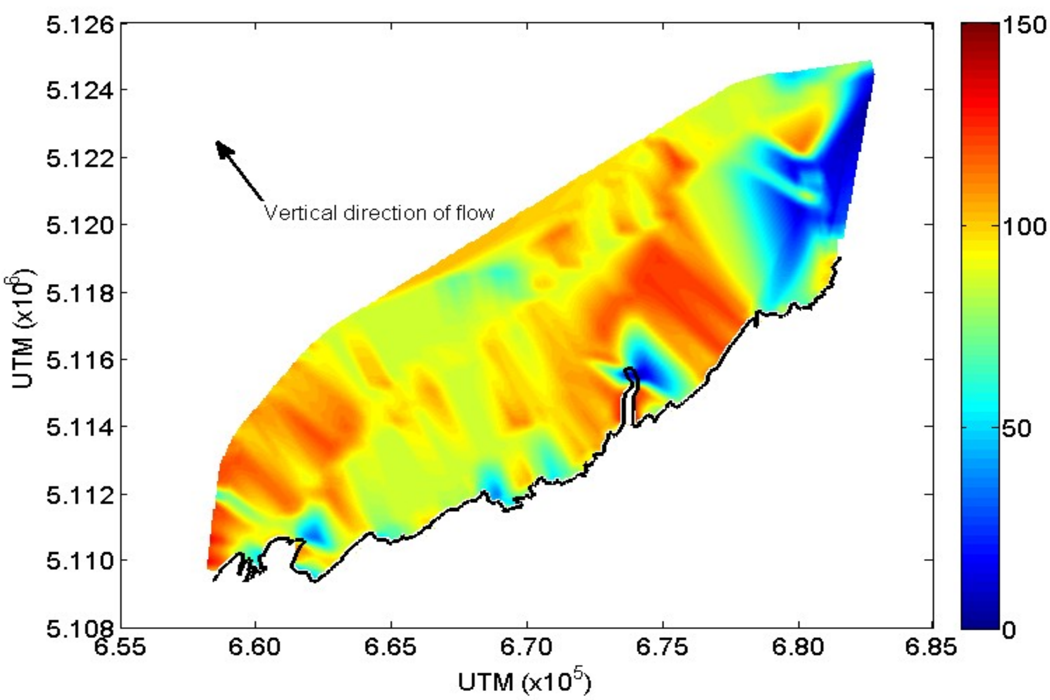

Figure D.11: Contour lines of growth direction (°) in 2007-2008

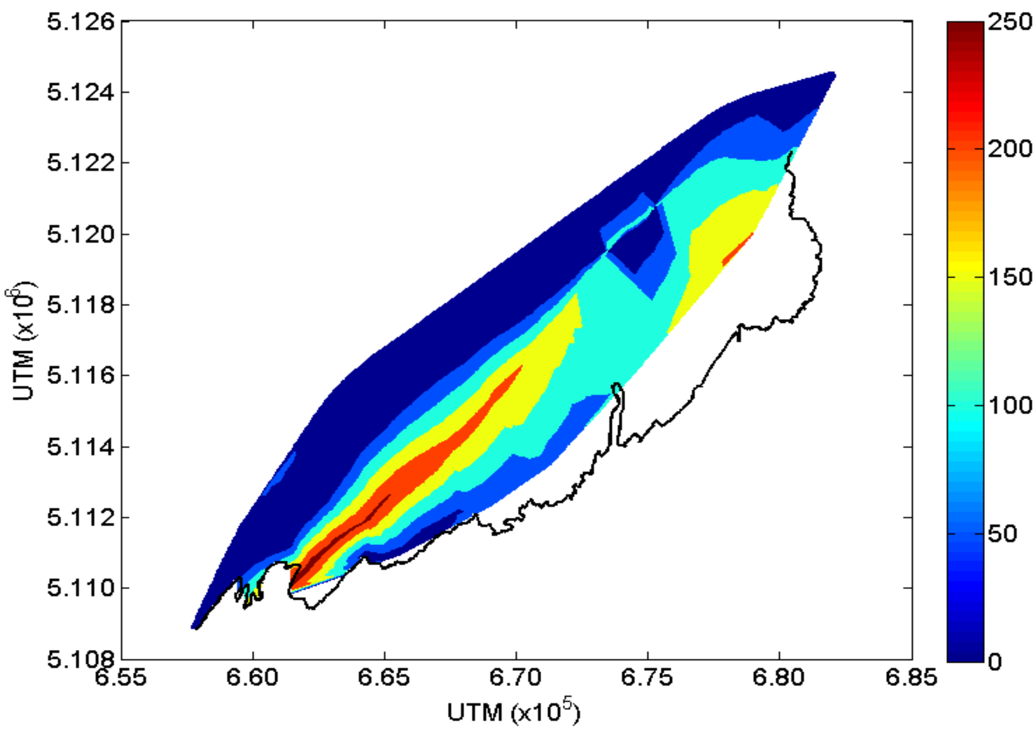

Figure D.12: Contour lines of function f=Δd/ΔAFDD (m/DD) in 2007-2008

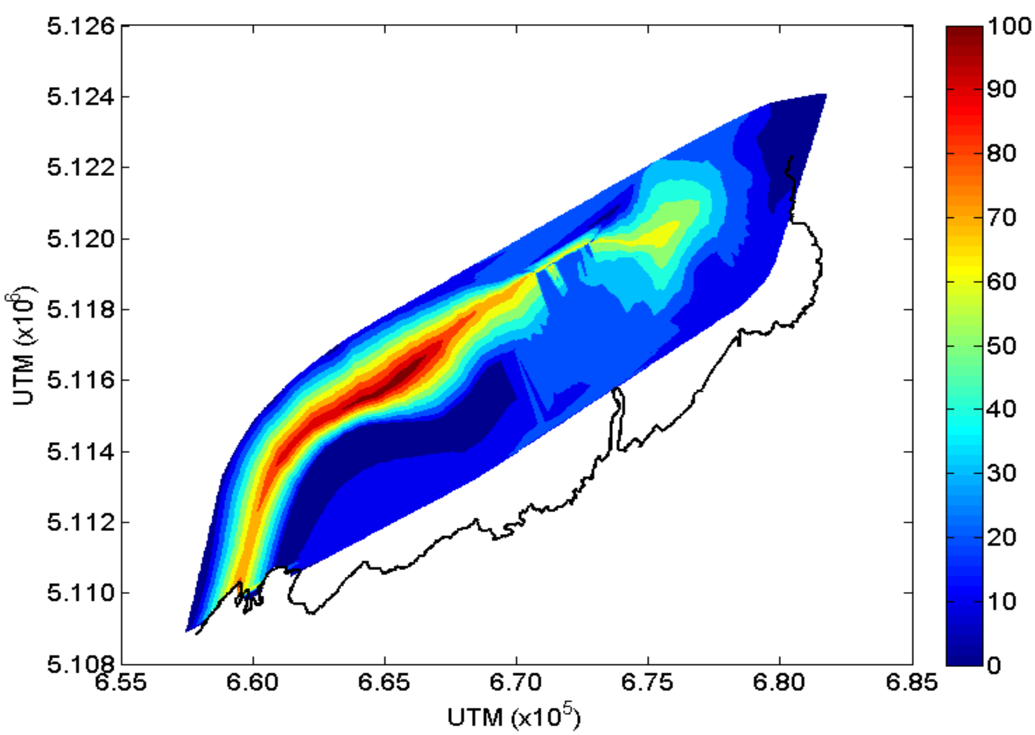

Figure D.13: Contour lines of growth speed (m/h) in 2008-2009

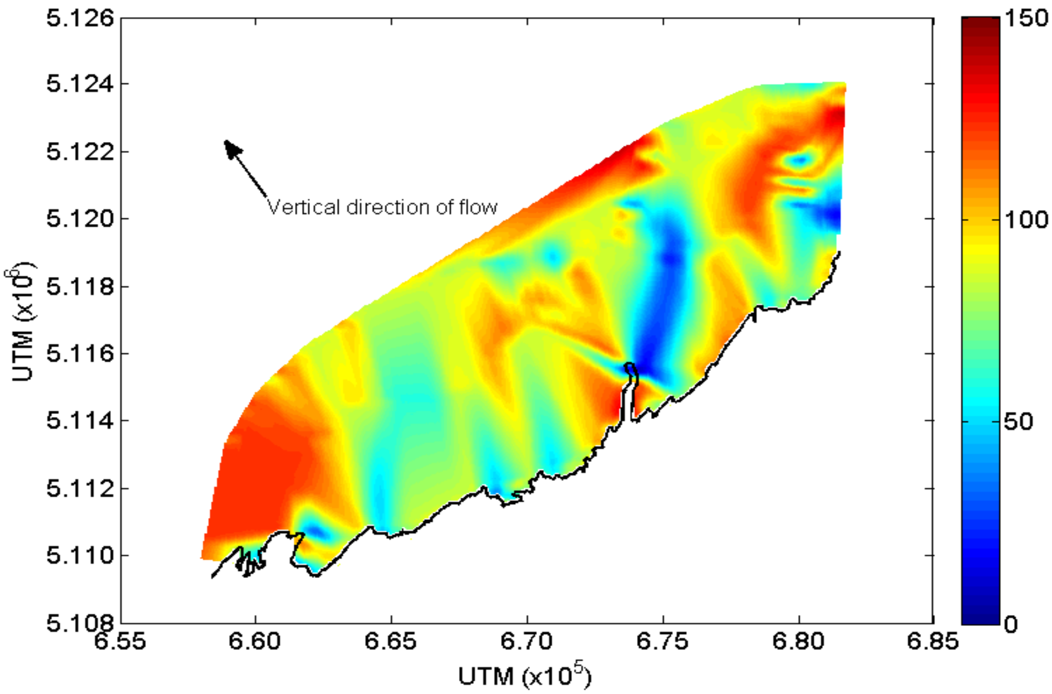

Figure D.14: Contour lines of growth direction (°) in 2008-2009

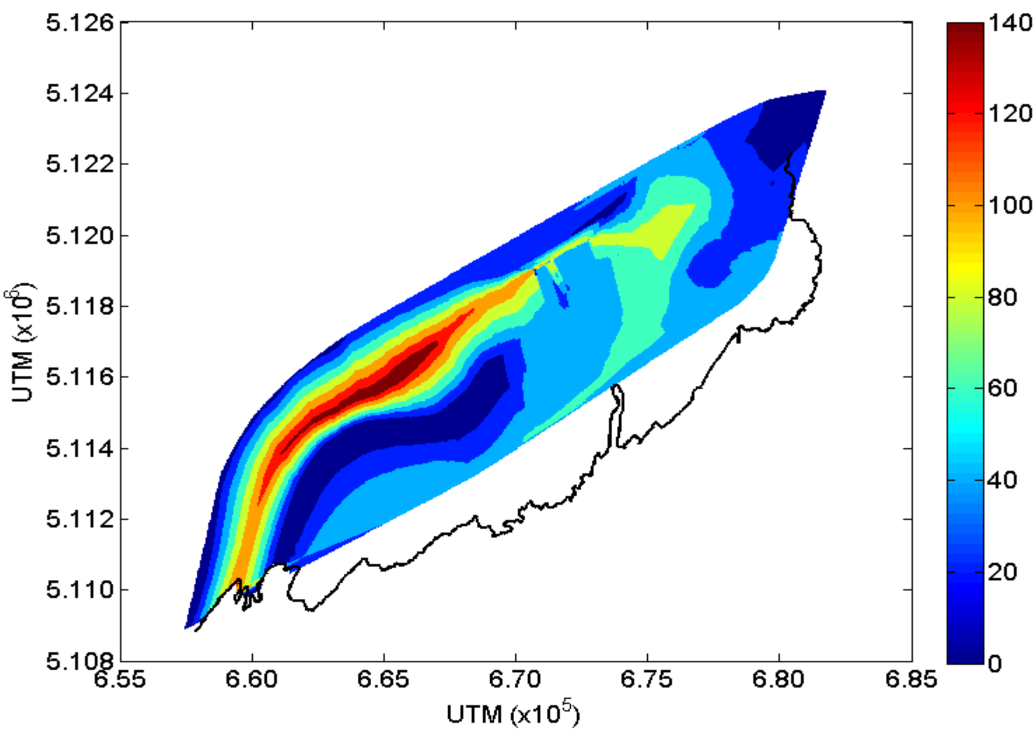

Figure D.15: Contour lines of function f=Δd/ΔAFDD (m/DD) in 2008-2009