Gaz Métropolitain

Study of ice conditions at selected sites on the St. Lawrence River for the location of a LNG marine terminal

Final Report – June 2003

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Project 0117

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LIST OF ABBREVIATIONS

CCG	Canadian Coast Guard, Fisheries and Oceans Canada
CIS	Canadian Ice Bureau, Environment Canada, Ottawa
FDD	Freezing degree day (defined in chapter 5)
IML	Institut Maurice-Lamontagne, Fisheries and Oceans Canada, Mont-Joli, Quebec
MANICE	Manual of standard procedures for observing and reporting ice conditions
WMO	World Meteorological Organization
E, W	east, west
N, NE, NW	north, northeast, northwest
S, SE, SW	south, southeast, southwest

1. INTRODUCTION

Definition of the mandate

Ice information presently available for the south Shore of the St. Lawrence River from Quebec City the mouth of the Saguenay River, is neither complete, consolidated, nor disseminated in a form sufficiently detailed or up to date to adequately define the ice forces acting on structures and its potential for obstructing navigation.

The intent of this study is to collect and organize all data on ice conditions at five (5) potential sites. These sites are close to the south shore, in the vicinity of Île Verte, Cacouna, Kamouraska, , Pointe-de-la-Martinière and Pointe-Saint-Vallier. The study is aimed at providing a detailed knowledge of the prevailing ice conditions for design and navigation purposes, including a verification of the ice loads on a proposed structure assumed similar to the Ultramar wharf, a marine terminal servicing large oil carriers located on the south shore at Levis.

The work is carried out for Gaz Métropolitain and Company, Limited Partnership, Montreal, by Paul Croteau et associés inc., in accordance with an agreement dated March 4, 2003 between the parties.

Scope of work

In essence, the work consists in the following:

- examine, assemble and analyze all ice charts maps and aerial reconnaissance surveys of ice conditions in the St. Lawrence River at the sites, available from the Canadian Ice Service and/or the Canadian Coast Guard, from 1953 to present;
- examine other images of ice conditions available from the Coast Guard;
- on the basis of the air temperatures (FDD, or freezing degrees-days) and icebreakers interventions, characterize the last 40 years as mild, normal, and severe and show the typical average ice conditions for below-normal, normal, and above-normal temperatures;
- conduct a detailed study of ice thickness, patterns, and movements of ice features at the sites; and
- compare the ice conditions observed during the 2002-2003 winter months with the average ice conditions observed during a typical year.

Sites under consideration

Figure 1.1 shows a map of Eastern North-America from the Atlantic Ocean to the Great Lakes. The sites of interest, in the estuary of the St. Lawrence River, between Quebec City and the mouth of the Saguenay River are located on Figure 1.2. The conditions at the existing oil terminal at Saint-Romuald are also analysed. This terminal, built by Golden Eagle, now Ultramar, is operated year-round since 1971 and therefore is an excellent benchmark for this investigation.

The location and main characteristics of the sites are presented in Table 1.1.

Site	Latitude	Longitude	Water depth (m)	Width of river (km)	Distance to shore (km)
North group					
Île Verte	N 48° 06′	W 60° 22′	20	17	7[1]
Gros Cacouna	N 47° 58′	W 69° 32′	20	20	1
Kamouraska	N 47° 35′	W 69° 58′	20	17	3.5
South group					
Pointe Saint-Vallier	N 46° 55.5′	W 70° 48′	12	6	1
Pointe de la Martinière	N 46° 50.2′	W 71° 06.5′	20	2	0.5
Ultramar terminal	N 46° 47′	W 71° 12.5′	18	2	0.5

Table 1.1
General location and characteristics of sites under consideration

Note: [1] distance to Île Verte is 4 km

Field reconnaissance was originally planned to take place jointly with ice observers and Coast Guard operations personnel from the Ice Bureau in Quebec City, during regular ice reconnaissance flights. In fact, the 2003 ice season turned out to be very demanding for Escort and De-icing Operations and, as agreed with the Coast Guard Superintendent, operations would have to take priority.

Two field observation missions were conducted in mid-January and mid-February. And a aerial reconnaissance flight was done on March 6, 2003. Sampling of ice, was not deemed to be useful, as thickness could be assessed from visual observations of broken ice near the shore. In addition, the observations were supplemented by a detailed review and analysis of historical ice thickness measurements.

Presentation of the report

After a brief overview of the general ice conditions in the estuary, the report describes in detail the sources and analyses of the various key parameters which enter into the descriptions of ice condition:

- ice charts and maps
- ice thickness surveys
- weather
- tides and currents

and discusses the relative importance of driving forces influencing the movement of the ice cover.

The ranking of ice seasons is then presented, using a variety of methods. Interviews conducted, and observations from the 2003 ice season are then described, followed by an assessment of ice conditions at each site. Ice loading scenarios and forces are discussed, and finally the summary and conclusions are presented.

2. General ice climate for the estuary

From Quebec City where it is about 2 km wide, the St. Lawrence River broadens fairly regularly until it reaches the Gulf of St-Lawrence. At the Saguenay, 200 km downstream it is about 22 km wide, at Matane, 160 km further it reaches 50 km.

The foregoing general description of the ice climate in the estuary of the St. Lawrence River is quoted from an unpublished paper by P.W. Cote, Environment Canada. Although the paper is dated 1985, the description is still very much current, and provides a good initial overview.

> "Ice found in the St. Lawrence River is a mixture of that resulting from local growth and that which began further upstream. Its motion is affected by the general but variable seaward outflow of water, tides, obstructions and prevailing winds. Its growth depends upon local air and water temperature regimes, host water salinity, snow cover and the other factors which influence heat loss or gain. All these factors combined result in a conglomerate of ice floes having different sizes, shapes and histories."
>
> "This area can be divided in two sections; the deep, fairly broad channel east of the Saguenay River and the shallow, confined one from the Saguenay River to Quebec City where islands and shoals are quite common. Ice begins forming first in sheltered shallows, harbours and inlets then spreads seaward. This initial formation normally begins around Quebec City during the first half of December but it is not until late in the month that it spreads east to the Saguenay River. Due to water currents and prevailing winds, this growing ice spreads more rapidly eastward along the south side of the river estuary. Complete ice coverage usually occurs early in January."
>
> "Some ice may remain attached to shore, called fast ice, to be dislodged at a later date or remain in place to deteriorate during spring melt. The remainder generally drifts downstream under the influence of the prevailing winds and local water currents. Fast ice can become well developed in shallow areas and behind islands. When mild weather accompanies spring tides, vast areas of this ice with its accompanying heavy snow can break away to form what is locally known as *batture* floes. These are large obstructions to navigation which cause difficulty because of their size and mass."
>
> "Fast ice normally becomes established during the winter months in the bays and harbours along the North shore from Forestville to Baie-Comeau and also from Rivière-Pentecôte to Sept-Îles. Significant shore-fast ice is also common in sheltered coastal shallows and behind islands of the western portion of the river estuary. During cold winters it significantly affects conditions at Pointe aux Orignaux, surrounds the Kamouraska Islands and extends outward from the shoreline to reach Île du Gros Cacouna and Île Verte, all along the south side. This will normally develop early in January and may persist until the middle of March. Elsewhere, fast ice is confined mostly to the harbours."

“Prevailing northwesterly winds plus the result of the Coriolis force tend to continually steer the ice floes toward the southern shore; thus a higher predominance of larger amounts of ice and thicker ice types. Leads and areas of new and grey ice are prevalent along the north shore. Ice deformation in the form of ridging, rafting and hummocking is also much more frequent along the south side than along the north shore due to the greater frequency of congestion and pressure. The total ice thickness within an ice ridge is in the order of four times the ridge height. Deformed ice also occurs along the north shore but less frequently and generally in the younger and thinner ice types.”

“At the mouth of the Saguenay River, mixing of the waters from the two rivers, plus tidal surges and the broader aspect of the channel all combine to produce a recurring polynya” (*an area of open water*) “which may extend many kilometers east during mild weather or be confined to a very small area during cold periods. It is nevertheless always present to some degree. This feature does expand to influence ice conditions along the south shore mainly by reducing ice concentrations.”

“In general, the easiest ice conditions in the upper river estuary are found with falling tides and southwest winds for then the floes can easily drift seaward. On the other hand, rising tides and northeast winds restrict ice motion and congestion can quickly develop. Traverse du Nord and Passage de l’Île aux Coudres are particularly susceptible to these changes. ”

”Ice cover, which becomes fairly extensive in January, remains more or less constant in February and then diminishes fairly quickly during March. The first signs of break-up in spring is the enlargement of the polynya at the mouth of the Saguenay River about the middle of the month. Much of the St. Lawrence estuary becomes open water by early April except in the extreme western “*(portion)*” and around Quebec City where final ice melt normally occurs about the middle of April. ”

”Wide variations in the beginning of freeze-up and complete ice melt can occur from one year to the next. Ice has been known to commence its seasonal growth around Quebec City as early as the third week of November or be delayed until the end of December. During an early spring season, much of the river estuary has cleared by the second week of March. Conversely ice has been observed around Quebec City in early May.”

The following table summarizes a few descriptive ice parameters for the estuary.

Location	Pointe aux orignaux[1]	Gros Cacouna[1]	Matane[1]
Latitude	N 47° 29′	N 47° 57′	N 48° 51′
Longitude	W 70° 01′	w 69° 31′	w 67° 32′
Date of first ice (early/average)	11 Dec 20 Dec	11 Dec 22 Dec	11 Dec 25 Dec
Date of persistent open water (average/late)	01 April 23 April	27 March 16 April	27 March 16 April
Length of ice season (average/longest)	101 days 120 days	95 days 119 days	91 days 119 days
Highest probability of fast ice and date	31% mid Feb	31% early Feb	15% mid-end March
Normal occurrence of peak ice conditions	mid Feb	mid Feb	early Feb
Median ice concentration	9	9	9+
Average percent ice type, when ice is present : -new ice -grey ice -grey-white ice -first-year ice	13% 22% 36% 29%	19% 21% 31% 29%	14% 25% 29% 32%

Table 2.1
General ice climatology, St. Lawrence estuary

Notes: [1] data for these sites extracted from historical and regional (composite) ice charts from Dec.1959 to April 1985 (from Cote, 1985)

3. ICE DATA ANALYSIS

Sources of ice data

The Canadian Ice Service (CIS) has been producing ice charts since 1959, with evolving scales of coverage, ice data formats and means of data acquisition.

Historical Charts, which designate the early charts prepared between 1959 and 1967, were drawn at a large scale, for several different regions of Canadian waters, including the East Coast. These Historical Charts were generally prepared on a weekly basis throughout the ice season, from direct observations aboard ships, or from reconnaissance flights. From 1967 to 1980, Regional Charts were introduced, which were at a similar scale, but used a different ice code. An example of a Regional Chart, in its original hand-written form, is shown in Figure 3.1. Over the years, Environment Canada systematically compiled the ice chart data on computerized Regional Charts. The data was also incorporated in a geographic information system, where the outline of each ice patch is represented in vector form, and every information contained in the "egg" is coded. The Canadian Ice Service (CIS), in Ottawa, has developed tools capable of searching the database to extract data corresponding to a specified area.

Since 1980, a series of River Ice Charts are prepared at a smaller scale, to cover the St. Lawrence River. These are aimed primarily at providing mariners with crucial information for safely navigating in the St. Lawrence River and Gulf, and support deployment decisions in the course of escort and de-icing operations carried out by the Coast Guard. Thanks to the improvement of technology, the means of data acquisition have considerably evolved and as a result, the precision and reliability of the charts has also increased.

The "egg" code used today, which is described in the following section, has been in use since 1980. The earlier ice codes are presented in Appendix II.

Currently, River Charts are prepared from direct ship- or air–borne observations by ice observers attached to the Laurentian zone fleet of the Coast Guard. Operations on the River are controlled from the Ice Bureau in Quebec City, while operations in the Gulf are jointly managed with the Eastern Center in Halifax. The River Ice Charts are generally prepared twice a week during regular helicopter patrols, but their frequency can vary depending on the support needed for operations, weather, visibility, and the current deployment of the icebreaker fleet. For the present study, River Ice Charts WIS 91 (Saint Nicolas to l'Ile d'Orleans), WIS 92 (Saint Laurent to Cap Brulé), WIS 93 (Saint-Jean-Port-Joli to Cap-au-Saumon) and WIS 94 (Cap-au-Saumon to Pointe-à-Michel) cover the sites of interest. Charts from 1983 to 2002 were purchased from the CIS, and Charts for the current year were downloaded as they became available on the web site of the CIS (http://www.ice-glaces.ec.gc.ca/). Samples of these are shown in Figures 3.2 to 3.5.

At the CIS in Ottawa, electronic Regional Charts are compiled every third day during the ice season, using data from the River Ice Charts, and satellite imagery from Radarsat II.

All River Ice Charts were reviewed and site-specific data was compiled and analysed as described hereafter. Historical and Regional Ice Charts were rapidly reviewed on paper form at the CIS office in Ottawa, for all years prior to 1980. Conditions during cold years were paid special attention. All Regional Charts in cold seasons were also briefly examined from 1980 to present.

It is easily noticeable from an examination of Regional Ice Charts in the months of March, April and May, that navigation in the Gulf is affected by ice conditions much later than in the estuary, at the end of the winter. This 2003 season was a good (although exceptional) illustration of this: all six (6) sites in the estuary were practically free of ice by mid- March; conversely, in the Gulf, the Coast Guard had to rescue a ship completely immobilized by the ice in the last week of April, on the upper North Shore of Quebec, close to the Belle-Isle Strait.

From our overview, it was determined that Regional Charts are suitable to characterize ice conditions in the Gulf but are not drawn at a sufficiently small scale to allow discrimination of conditions between the six (6) sites.

The CIS has published an atlas of ice conditions in the estuary and Gulf of St. Lawrence, based the Historical Regional Charts. A first edition describes average conditions from 1959 to 1974, and the latest edition, from 1971 to 2000. Average ice conditions are presented week by week through the ice season. Although this reference cannot be used for the present study because it reports averages rather than ranges and extremes, the database that was used to develop the Atlas is of great interest to investigate conditions in the Gulf.

Coding of ice data: the "egg" code

The egg code is the standard used by the Canadian Ice Service and the World Meteorological Organization (WMO) to report on ice conditions in the form of an oval shape as shown in Figure 3.6. It is an efficient means of delivering vital information on ice conditions to mariners and other users. The numerical information is arranged in three (3) sections or horizontal strips.

> C: contains the total ice coverage expressed in tenths. For instance, 9 designates an ice cover over 9/10 of the delimited area;
>
> Ca, Sa, Fa: by reading down the three (3) superposed parameters column-wise, the composition of the ice in the cover is described in fractions a,b,c…, providing interrelated information on the concentration, stage and form of each fraction;
>
> Ca is the partial concentration of the faction, expressed in tenths of the total coverage;

Sa is the stage of development, an index related to the thickness;

Fa is the form, an index related to the size of the floes;

Cb Sb Fb, Cc Sc Fc ...describe the other fractions. Normally the fractions are ordered left to right by increasing ice size; if necessary to describe the ice cover, there can be more than 3 columns.

There are various exceptions that are explained in detail in the Manual of Standard Procedures for Observing and Reporting Ice Conditions, or MANICE (Canadian Ice Service, 2002). For agglomerated brash, a very common form in the area of interest, the stage of development (Sa) is designated as a dash (-). When brash is present, 4 partial concentrations, corresponding to brash ice types V,K,M and T, have to be placed below the egg to show its composition :

Very thick	V	> 4 m
Thick	K	> 2 - 4 m
Medium	M	1 - 2 m
Thin	T	< 1 m

Total concentration of brash is equal to V+K+M+T. It is noted that this VKMT code is only used in Canada.

Compilation of River ice data

The sites were separated in two groups, “north” and “south”. It will be seen that this division is quite logical, not only because of geographical proximity, but also because ice conditions are similar among sites in a group, but different between groups.

For each of the three (3) “northern” sites, Kamouraska, Cacouna and Île Verte, each and every River Ice Chart available from Environment Canada between 1983 and 2003 was analysed. . For Kamouraska, Chart WIS 93 is used, while Chart WIS 94 applies to Cacouna and Île Verte.

For the three (3) “southern” sites, there is a much greater number of charts available and a subset had to be selected, for practical reasons. Is was decided to analyse the charts from odd days only. For a given day, there was generally between two to three (3) charts per day. In most of cases, the first chart was made at about 13:00, the second at 18:00 and the last at 20:00 PM. It was decided to select the first observations of the day, unless the data for the specific location was not included, in which case, the second chart was considered. Despite an important reduction in the processing effort, the resulting data is still very representative because there are at least 40 to 50 charts used per season per site. Chart WIS 91 is used for the Ultramar and Pointe-de-la-Martinière sites, while Chart WIS 92 applies to Pointe-Saint-Vallier.

The data extracted from each chart was entered into a spreadsheet. Every element of information included in the "egg" associated with the precise location of the site on each chart was collected for data processing. Table 3.1 shows the total number of charts compiled per winter and per site. It should be noted that each chart corresponds to a specific ice patrol. Ice patrols are not always made at regular intervals over a given season, or between seasons. Therefore, the statistics are representative of the particular sample of observations, and may not be a truly representative of frequencies over time.

	Number of River Ice Charts processed at each site						
	South sites			North sites			
Ice season	Ultramar	Martinière	Saint-Vallier	Kamouraska	Cacouna	Ile Verte	
1982	0	0	0	0	2	2	
1983	32	32	31	5	14	9	
1984	33	12	10	0	11	8	
1985	43	39	34	8	15	14	
1986	52	48	42	8	31	29	
1987	56	52	50	10	31	26	
1988	52	55	48	11	31	25	
1989	65	61	52	32	62	50	
1990	64	61	54	26	36	30	
1991	55	54	53	16	33	27	
1992	109	98	0	18	46	32	
1993	117	109	90	24	48	32	
1994	112	108	87	27	35	20	
1995	105	103	88	32	50	29	
1996	72	67	52	18	45	33	
1997	76	65	49	19	29	18	
1998	43	39	31	17	23	14	
1999	54	50	43	20	30	14	
2000	65	62	52	17	23	9	
2001	96	90	67	20	31	20	
2002	69	63	50	9	17	11	
2003	66	54	39	14	8	4	
Totals	1436	1322	1022	351	651	456	5238

Table 3.1
Number of River Ice Charts processed at each site

Total ice concentration

A set of graphs is presented to show the statistics of total ice concentration for each month and the average for the winter:

- Average frequencies of total ice concentration by month including data from the 6 sites: Figure 3.7
- Average frequencies of total ice concentration by month at Ultramar: Figure 3.8
- Average frequencies of total ice concentration by month at Pointe-de-la-Martinière: Figure 3.9
- Average frequencies of total ice concentration by month at Pointe Saint-Vallier: Figure 3.10
- Average frequencies of total ice concentration by month at Kamouraska: Figure 3.11
- Average frequencies of total ice concentration by month at Cacouna: Figure 3.12
- Average frequencies of total ice concentration by month at Île Verte: Figure 3.13
- Comparison of average of ice coverage between sites: Figure 3.14.

Ice concentration of 8 tenths is the most frequent for each site of the south group and is prevalent about 25% of time (Figure 3.8 to 3.10). Low concentration (1 tenth and less) are rare at those locations. For instance at Ultramar site, there is open water only 13% of the time in March, while at the other two sites, it is less than 10%. The south locations have high ice concentrations from 6 to 10 from December to March and ice-free conditions are rare.

The north group has different conditions (Figures 3.11, 3.12, 3.13). Despite a similar appearance as for the "south" sites, the distribution at Kamouraska indicates open water 33% of time during March, about three (3) times more. In fact, the main difference between the groups is the frequency of ice-free water. As clearly seen in Figure 3.14, low concentration have average frequencies between 19, 27 and 37% of time at Kamouraska, Cacouna and Île Verte respectively, while they vary between 4 and 7% for the south group.

More frequent lower ice concentrations can be easily explained by the enlargement of the St. Lawrence towards the north, from about 2 km wide close to Quebec to 17 to 20 km. For the same reason, one might expect less frequent high concentrations at the north sites, but the reverse is true for concentrations of 9 and 10 tenths. This reflects the fact that most of the ice is concentrated near the south shore.

For each site, higher ice concentrations (9-10) appear during January and February, which is expected in the coldest months of the winter. December and March have more frequent low concentration (1 tenth and less), up to 60% of observations during March at Île Verte.

From Figure 3.14, Kamouraska and Cacouna are the sites where ice coverage is generally the most important. Concentrations superior to 8 tenths are found on 47% of samples for Kamouraska, 49% for Cacouna, and 37% for Île Verte. Concentrations less or equal to 1 tenths are observed on 37% of samples at Île Verte, 27% for Cacouna and only 19% for Kamouraska. The three (3) south sites are about equal, but Pointe-de-la-Martinière has slightly less high concentrations than the other two.

For total ice concentration, we rank the sites as follows, from best to worst: Pointe-de-la-Martinière, Ultramar equal with Pointe Saint-Vallier, Ile Verte, Cacouna, Kamouraska.

Maximum ice thickness

Statistics on ice thickness are estimated from the parameter S, the stage of development. In the following statistics, the maximum thickness of each observed ice cover is taken to provide a conservative evaluation of the heaviest ice that can be met by ships near the sites, regardless of how small or large a fraction of the total cover this heavier ice might represent. As reported during our interviews, even for smaller commercial ships, navigation does not become a problem until the ice thickness reaches about 15 cm. It should be noted that the thickest ice recorded on any of the ice charts analysed for the sites corresponds to Stage of development 1o,medium first-year ice, 70-120 cm.

As before, statistics are extracted from charts prepared between early December and end of March of each year. The following series of graphs show the prevalence at any concentration of ice thickness by site and by month:

- Maximum ice thickness – Ultramar: Figure 3.15
- Maximum ice thickness – Pointe-de-la-Martinière: Figure 3.16
- Maximum ice thickness – Pointe-Saint-Vallier: Figure 3.17
- Maximum ice thickness – Kamouraska: Figure 3.18
- Maximum ice thickness – Cacouna: Figure 3.19
- Maximum ice thickness – Île Verte : Figure 3.20
- Maximum ice thickness – 6 sites: Figure 3.21
- Comparison between average of maximum ice thickness at each site and average at all sites: Figure 3.22

Results of data analysis are shown on Figures 3.15, 3.16 and 3.17 for the south group. The 3 charts have the same trend, ice becomes thicker and thicker during winter and is the thickest in March with a presence of 15-120 cm ice about 80% of the time. For the other ranges of smaller thickness (0-10 cm and 10-15 m), frequencies decrease from January to March. The proximity of the sites can explain the similarity of those statistics. Indeed, maximum ice thickness cannot change much in the short drifting distance between Ultramar and Pointe Saint-Vallier.

The three (3) north sites (Figures 3.18, 3.19 and 3.20) do not have the same trend. Thick ice (>15 cm) is more and more frequent between December and February, but its frequency decreases in March. In addition, thick ice is more frequent at

Kamouraska than at the two other sites. For instance, the frequency of thick ice reaches 75% in March wile it is 62% for Cacouna and 59% for Île Verte. In addition, from statistics on zero thickness, Île Verte has far more open water conditions than Kamouraska.

The comparison between winter average of maximum ice thickness (Figure 3.22) shows that ice of sufficient thickness to influence navigation (15 to 120 cm) is prevalent about 55% of time, for all six locations. The difference between the north and south groups is in the frequency of open water.

The fact that we find the same stage of development to be equally prevalent at every site is, in some measure, due to the grouping of stages 5,6,7 and 1o under one category (15-120 cm). It should be noted that medium first year ice 1o (70-120 cm) appears in 3% of charts and is about equally frequent at north and south sites. Therefore, chart data does not allow to discriminate between sites on the basis of ice development stage.

Maximum floe size

As for the previous statistics on maximum stage of development, maximum floe sizes, from the parameter F, are examined, irrespective of the stage of development or of the partial ice concentration of the fraction representing larger pieces. The following series of graphs show frequencies of ice floe sizes by site and by month:

- Maximum floes size at Ultramar: Figure 3.23
- Maximum floes size at Pointe-de-la-Martinière: Figure 3.24
- Maximum floes size at Pointe Saint-Vallier: Figure 3.25
- Maximum floes size at Kamouraska: Figure 3.26
- Maximum floes size at Cacouna: Figure 3.27
- Maximum floes size at Ile Verte: Figure 3.28
- Maximum floes size at the 6 sites: Figure 3.29
- Comparison of maximum floe size between sites and the average of the 6 sites: Figure 3.30

For the south group (Figures 3.23, 3.24, 3.25), small floes (20-100 m) are highly predominant (50%). Floes larger than 100 m are increasingly present from upstream to downstream, with frequencies of about 9%, 12% and 26% at Ultramar, Pointe-de-la-Martinière and Pointe Saint-Vallier, respectively.

For the north group (Figures 3.26, 3.27, 3.28), the distribution of maximum floe size is different. The presence of floes larger than 100m and pancake ice or strips are more frequent. Moreover small floes, which dominated at the south sites, are less frequent than floes larger than 100 m. The frequency of floes larger than 100m is highest at Kamouraska (44%) and decreases towards Cacouna (41%) and Île Verte (33%). Conversely, pancake ice or strips increases from Kamouraska towards Île Verte. It is noted however, that big floes (500-2 000m) are equally frequent at the three (3) sites (about 7% of the time).

Figure 3.30 confirms that medium and big floes are more frequent at sites from the north group than at sites from the south group. Pancake ice and strips are rare near Quebec because these tend to be associated with low total ice concentrations, and, as seen above, high concentrations are more frequent in this area.

The predominance of small floe at Ultramar, Pointe-de-la-Martinière and Pointe Saint-Vallier can be explained by the narrowness of the river close to the Quebec bridges. Indeed, big floes become fragmented (either naturally of by the action of the icebreakers) when passing under the bridges. As a result, only small floes remain (Figure 3.31 and 3.32). Hence, for the south sites, there is no correlation between thickness and floe size, and the analysis presented later to establish such a correlation considers only the north sites, where the river is much broader and where ice can develop naturally, both in size and thickness.

On the basis of maximum floe size, ranking of the sites, from the best to the worst, would be Ultramar, Pointe-de-la-Martinière, Pointe Saint-Vallier, Île Verte, Cacouna and finally Kamouraska.

Weighted thickness by year and by site

The weighted thickness of ice is calculated in two steps. First, for each chart a weighted thickness (WT) is calculated tacking into account the partial concentrations associated with the stage of development of each fraction :

$$WT = \sum_{i=a \;\; e} \frac{Ci \quad Si}{Ct}$$

where:

Ci: partial ice concentration i
Si: stage of development i
Ct: total ice concentration.

Secondly, an average of all weighted thickness indices is made by year and by site. The result is a number that does not truly convert to a thickness index because it is decimal, but nevertheless provides a reasonable estimate of the prevalence of ice thickness ranges. Only observations from early January to end of March are included in theses statistics, to remove small numbers, therefore providing a more conservative estimate. The resulting graph of Figure 3.33 clearly shows more severe ice conditions in 1992, 1993 and 2003.

Weighted floe size by year and by site

The weighted size of floes in a given year is computed based on the same logic as above for the weighted ice thickness. The weighted size (WS) is calculated as follows:

$$WS = \sum_{i=a \quad e} \frac{Ci \quad Fi}{Ct}$$

where:

Ci: partial ice concentration i
Fi: floe size i
Ct: total ice concentration

The resulting graph is at Figure 3.34. The fact that floe sized appear to be larger at Cacouna, Kamouraska in 2003 is probably due to the excessive weight given to a few large numbers, since the amount of data at the sites is small in 2003 (see Table 3.1).

Correlation between weighted size and weighted thickness

The year-to-year variation of the weighted thickness and size curves, averaged over the 3 north sites, is shown in Figure 3.35. As explained before, the south sites are excluded from this analysis because ice is broken in small pieces near Quebec. The correlation between the two indices is quite apparent, as confirmed by the joint occurrence diagram of Figure 3.36 and the correlation coefficient r equal to 0.87 (r^2=0.76) close to 1.0.

Limitations to the accuracy of the ice data

The ice charts, compiled by and available from Environment Canada, present data obtained from ship-borne or air-borne ice observations by personnel from the Canadian Ice Service. It is important to note that the data contained on these charts is obtained in support of the escort and de-icing operations, which is mandated to keep the navigation channel open up to Montreal throughout the winter. Since the observations are entirely dedicated in support of operations, the Canadian Coast Guard and Environment Canada do not guarantee the completeness or scientific accuracy of the data contained on these charts. There are three (3) reasons for this:

1. as we have noted during the 2003 season, some ice data potentially representing the worst conditions at a any given site may not be available, because of severe local weather or poor visibility preventing over-flights, or because of the deployment of the fleet to address a problem in a particular area. Examples of problems which have occurred in 2003 include an ice jam at Lac St. Pierre, a blockage at the entrance of the Matane harbour due to ice, or having to provide navigation assistance or rescue to vessels in the Gulf; this potentially introduces an unconservative bias, by under-sampling severe conditions;

2. the focus being the navigation channel, which is generally located on the north side of the river in the zone of interest, any data regarding ice conditions near the south side, should be considered as approximate, particularly, when the river is very wide;

3. although this capability is gradually being implemented, none of the historic ice data is systematically geo-referenced; therefore, positions and outlines of the various ice zones, including the extend of fast ice, can vary by up to several kilometers.

Hence, the above ice climatology study is based on a dataset which does not have randomly selected samples in time and space, as seen in the numbers of available charts in Table 3.1. The results of this analysis must therefore be used with caution, in particular with regard to extreme events, which might not have been accurately captured.

Despite its theoretical shortcomings, the dataset from CIS is the most comprehensive set of objective data available for this study. Confidence in the results of the analysis is supported by the fact that the trends interpreted from the analysis are reasonable and entirely consistent with observations and opinions collected from the various sources consulted during this investigation.

4. ICE THICKNESS DATA

Ice thickness measurements were made at 135 locations throughout Canada since 1955, providing useful data for the Arctic, several lakes in most provinces, the Great Lakes, the St. Lawrence Seaway, the St. Lawrence River and the Saguenay River. The sampling usually took place on a weekly basis, but the period and frequency of measurements may vary depending on the location. Minimum, maximum, mean and standard deviation values of the thickness are presented week by week in the Ice Thickness Climatology 1961-1990 Normals (Canadian Environment Canada, 1992).

The database of all measurements collected during this program is directly accessible on Environment Canada's web site. Table 4.1 summarizes the information contained in the database for several sites of interest. The maximums are similar to those in the Ice Thickness Climatology, although several years of additional data (1990 to 2002) have been included in the results presented.

Station	Sta.Q21 Cap Rouge	Sta.Q22 Beauport	Sta.Q35 Cacouna	Sta.Q36 Rimouski	Sta.S06 Baie des Ha!Ha!	Sta.S02 Pointe au Bœuf
Years of data (since 1983)	1983-1990 (8 years)	1983-1994, 1996,1997, 1999-2001 (17 years)	1990-1998,2000, 2001 (11 years)	1990-1992 (3 years)	1983-2002 (20 years)	1983-2001 (19 years)
Max. thickness (cm)	105	95[(2)]	76	50	100	64
Mean thickness (cm)	40	38	30	17	45	24
Std. Dev. (SD) thickness (cm)	35	32	28	22	35	21
Mean + 2 SD (cm)	110	102	86	62	115	66

Table 4.1
Fast Ice thickness at Federal measurement stations

Notes:
(1) Cap Rouge is on north shore, west of the Quebec Bridge; Beauport is west of the Port of Quebec; Rimouski is on the south shore, 70 km east of Île Verte; Baie des Ha!Ha! and Pointe au Boeuf are on the Saguenay River.
(2) actually maximum is 126, but rafting is suspected

It should be noted that the mean and standard deviations are computed from all observations at a given site, so that these represent the distribution throughout the season, as well as throughout the years. It is noted that the standard deviation is quite similar to the mean value, for most stations. We also note that the mean plus two (2) standard deviations figures appear to give a conservative estimate of the maximum values.

Except for one measurement at the Beauport location, where rafting is suspected (the previous measurement a week earlier is half), the above data represents the thickness of a uniform sheet of ice, grown at the given location. Therefore, this does not account for any rafting, ridging or piling of ice which could occur due to interactions of the ice with solid boundaries or within the ice pack. As appropriate, proper allowance for these phenomenon is made later in Chapter 11, when establishing ice conditions scenarios to compute design loads.

The most impressive ice features to be considered, both for its potential to obstruct navigation, and to produce the greatest loading affecting marine structures or vessels, are the thick floes formed on the shoals, or *battures*. Large piece of landfast or *batture* ice, reaching several kilometers in size, can become detached from the shore and begin drifting freely or hitting obstacles, rotating, jamming across the river, or fracturing into smaller floes. This is why ice observers participating in Coast Guard operations actively monitor the development of the land-fast ice in selected areas, and continually report the imminent and actual detachment of large floes on the river. As soon as a giant floe threatens in the narrower parts of the river or in Lac Saint-Pierre, icebreakers are sent to break it up and manage it, to maintain the ice cover in motion. The area of the bridges and harbour near Quebec are also managed closely.

Because of the bathymetry, *batture* floes are most prevalent on the south shore. Depending on its origin, a *batture* floes can be of two (2) types:

- a fairly uniform sheet: thickness data discussed above, corresponding to the natural growth of an ice cover, applies to these floes. The ice is typically sound, so that the strength is high, except late in the season. Failure of the ice against a vertical structure is likely to occur by crushing, which develops high forces.
- an irregular floe, composed of pieces of varying thickness and texture, sometimes coloured by mud, are formed under the influence of tidal heaving, pressure from currents, natural growth and growth by re-freezing agglomerated pieces. The *batture* floe can grow to a thickness several times that of the single sheet of ice. While thickness will tend to stabilize after the ice has become grounded, size may continue to increase with successive tides, mostly from the upstream. With these large dimensions, these features offer a lot of resistance, if the ice is in a confined state, under pressure. Otherwise, it has much less mechanical strength than a solid sheet of ice, because of the in-homogeneity, voids, debris and lack of consolidation due to re-freezing. Upon impact, this type of *batture* floe is likely to fracture along planes of weakness.

Correspondingly, various load cases are considered in chapter 11.

5. WEATHER DATA ANALYSIS

Environment Canada operates a national network of weather stations. In the general area of interest for this study, weather data measurements are available from the stations identified in Table 5.1.

Station location	Station id	Span of data	Remarks
Quebec	7016294	1953-2003	airport
Saint-François, Île d'Orléans	70132G9	1994-2003	island in middle of St. Lawrence near Quebec
Rivière-du-Loup	7056616	1994-2003	airport
Île Rouge	7043BP9	1994-2003	island in middle of the St. Lawrence River, in front of the Saguenay
Mont-Joli	7055120	1953-2003	airport

Table 5.1
Weather stations considered in area of study

Wind data

Before ordering weather data files from Environment Canada, Dr. Yvon Ouellet, Professor of Civil Engineering at Laval University, was consulted regarding the choice of measurement stations for the zone of study. Dr. Ouellet is very familiar with weather data issues in the region, having authored many studies on the wave climate (which is generated from wind statistics) on the estuary and Gulf of St. Lawrence (Ouellet 1994, 2001). The map shown as Figure 5.1 shows the delimitation of wave climate zones in the estuary and Gulf of the St. Lawrence, for future reference. Note that our sites of interest are located in zones V (north sites) and VII (south sites).

From a recent study of wind records between 1988 and 1999, Ouellet compared wind records at Rivière-du-Loup, Île Rouge and Mont-Joli. He concludes that Rivière-du-Loup is the site having the lesser wind velocities, while winds are 1.5 to 3 times faster (depending on direction) at Île Rouge, and 1.25 to 2.5 times faster at Mont-Joli. For wind direction, there are also marked differences. Dominant directions at Rivière-du-Loup and Île Rouge are NW and SW, while SW dominates at Mont-Joli, with NW, NE and SE winds being about equally present. Dr. Ouellet produced the wind roses shown in Figures 5.2 and 5.3, derived from wind data from 1988 to 2002, for Île Rouge and a site representative of zone V.

We have the following remarks :

- the intensity and direction of winds are dependent on the local terrain surrounding the measurement stations; in particular, winds at Île Rouge are influenced by two funnelling effects: the first one is due to the Saguenay Fjord (the co-called Saguenay "cannon"), which amplifies winds from the NW; the other one is due to the Charlevoix passage in the mountains west of the Saguenay, which amplifies winds in the SW direction between Montmagny and Rivière-du-Loup (Philippe Gachon, personal communications, 2003);

- therefore, pending further analysis of the data, it is useful to examine the Climatological Atlas, to evaluate and compare site-specific conditions.

The Climatological Charts applicable to the region of interest for January, February and March (and the legend) are reproduced in Figures 5.4 to 5.7 (Environment Canada, 1994). From the wind roses on these charts, we notice that the location closest to Île Rouge is indeed the windier location, with dominant winds from the NW. These conditions would be representative for Île Verte and somewhat conservative for Cacouna. Further downstream at Mont-Joli, the dominant direction shifts to the W, while further upstream, representative of Kamouraska and west of Kamouraska, the dominant direction is SW, and NE, aligned with the St. Lawrence.

Table 5.2 summarizes key indicators of winter wind conditions, extracted from the Climatological Charts at the proposed sites.

Site	Pointe Saint-Vallier	Kamouraska	Cacouna, Île Verte[1]	Mont-Joli
Station in Weather Atlas	Saint-Jean-Port-Joli	Rivière-Ouelle	Rivière-du-Loup	Mont-Joli
January				
Dominant direction (frequency)	SW(23%)	SW(28%)	NW(35%)	W(32%)
Corresponding avg. velocity	20 km/h	24 km/h	38 km/h	30 km/h
Frequencies				
wind >20 kn (38km/h)	6%	8%	35%	25%
wind >33 kn(61km/h)	0%	3%	3%	2%
February				
Dominant direction (frequency)	SW(19%) / NE(14%)	NE(25%) / SW(20%)	NW(36%)	W(28%)
Corresponding avg. velocity	22 /19 km/h	20 / 30 km/h	39 km/h	31 km/h
Frequencies				
wind >20 kn (38km/h)	6%	35%	36%	24%
wind >33 kn(61km/h)	0%	5%	3%	4%
March				
Dominant direction (frequency)	NE(24%)	NE(30%)	NW(29%)	W(22%)
Corresponding avg. velocity	24 km/h	24 km/h	35 km/h	28 km/h
Frequencies				
wind >20 kn (38km/h)	9%	11%	26%	26%
wind >33 kn(61km/h)	1%	0%	2%	1%

Table 5.2
Wind characteristics at selected sites, during winter

Notes: data from Climatological Charts of the St. Lawrence (Environment Canada, 1994)
1 kn =1 nautical mile per hour = 6080 ft/h = 1.85 km/h = 0.51 m/s

The complete data sets for each of the weather stations identified in Table 5.1 were purchased from Environment Canada on February 23, 2003, including hourly records of temperature, wind velocity and wind direction. The wind data is therefore available for further site-specific studies, to specify final design criteria for the terminal and land-based infrastructure. Wind data was examined to some limited extend in this work, as reported later, in an attempt to establish some correlation with ice conditions.

Temperature data analysis

Temperature data was analysed in some detail to establish a climatic severity index, as presented in section 8. In accordance with usual practice, a representative daily temperature was computed from hourly temperatures as the average of the maximum and minimum value of the day. The "freezing-degree-day" (FDD) figure for the day, is zero if the daily temperature is above 0˚C and the negative of the daily temperature otherwise. The cumulative FDD is therefore a positive number, expressed in ˚C.

To reduce the size of the data set and facilitate presentation of results, only the records between December 1 and March 31 were considered, since the data before and after this period is negligible for the annual FDD statistics.

Figures 5.8 shows the total cumulative FDDs by year computed from temperature data at four (4) different weather stations. Quebec and Mont-Joli have 50 years of data, whereas the more local stations of Rivière-du-Loup, and Île Rouge have only 9. For 2003, weather records were only complete up to February 23; a uniform amount of 300 additional FDDs was added to the totals accumulated at each station as of February 23, 2003, in order to represent the entire ice season. This approximate correction was derived as the average of actual data sets for the missing period, supplied by Fisheries and Oceans. Therefore, actual accumulated FDDs for 2003 may vary slightly from those shown on the graphs.

Comparing Quebec and Mont-Joli in Figure 5.8, there are evident significant differences in the FDD curves. The two stations are separated by about 200 km, and located in very different geographic settings. Île Rouge is warmer (although windier) than the others.

It is apparent that Mont-Joli provides a better approximation of temperatures at stations closer to the sites of the north group under investigation. Quebec and Mont-Joli records will therefore both be analysed when establishing the climatic ranking of winter seasons presented in Chapter 8.

6. CURRENT VELOCITY DATA

The average net discharge of the St. Lawrence River fresh water towards the Gulf is approximately 12 000 m^3/s. In the zone of interest, it will become clear that variations in the discharge have little influence on the current velocity, compared to tides.

Tides

Tides influence water levels in the St. Lawrence River up to Trois-Rivières. Tides are semi-diurnal, which means that there are two complete tidal cycles daily with small inequalities in height and time, as illustrated in Figure 6.1. Tidal ranges at the sites of interest vary from 3 to 6 m, as described in Table 6.1.

Site	Quebec Ultramar terminal	Pte de la Martinière	Pte St. Vallier	Kamouraska	Cacouna	Île Verte
Mean water level	2.3	2.5	2.9	3.3	2.6	2.4
Tidal range						
-mean tide	4.4	4.7	4.5	4.2	3.7	3.4
-large tide	5.8	6.2	6.1	6.2	5.3	5.0
Extreme water levels						
-low	-1.2	-0.8	-0.4	-0.7	-0.9	-0.6
-high	7.4	7.0	7.3	7.5	6.5	6.2

Table 6.1
Tide data for sites of interest

Note: from Canadian tide and current tables 2003 (Canadian Hydrographic Service, 2003)
Elevations are in m above chart datum

The volume of the tidal wedge upstream from the Saguenay River is roughly 15 km^3 for an average tide (21 km^3 for large tides). Therefore the mean flow associated with an average tide is approximately 700 000 m^3/s (15 km^3 divided by 6 hours), more than 50 times the net outflow of the river. It is therefore obvious that tides have a profound effect on hydraulic conditions in the St. Lawrence estuary, and consequently on the ice regime.

On the one hand, these tides cause the ice to move up and down. For zones of shallow water, this can cause land-fast ice to become locally a lot thicker than it would in calm water because of constant breaking, jacking and freezing of entrapped water. At the edges of the fast ice or on vertical surfaces, a thick bulge of compact ice can form, which has to be taken into account when designing docks and marine structures. On the other hand, tides create very dynamic hydraulic conditions due to the huge amounts of water sloshing in and out of the river twice a day. Recurring, predictable tidal currents, having velocities many times greater than the main flow of the river towards the ocean, are produced. Therefore tides tend to keep the ice in motion back and forth, but with an average net progress toward the Gulf at every cycle. Together with the constant navigation on the river, the agitation of the water tends to grind pieces of ice together, which is why brash ice is so common on the river.

Tidal currents

The tidal currents are influenced primarily by the bathymetry, but also by density profiles of the water masses due to changes in temperature and salinity. Figure 6.2 shows a spectacular 3D view of the bathymetry of the St. Lawrence River looking from some point in the estuary towards Quebec City. The underwater wall at the outfall of the Saguenay River and the deeper waters along the north side of the river are clearly visible. It is readily apparent from the irregular topography of the river bed, that tidal currents do not follow simple patterns.

The variations in amplitude and direction of tidal currents are described throughout the tidal cycle for any site located along the St. Lawrence from Trois-Rivières to Les Escoumins in the Atlas of Tidal Currents, (Canadian Hydrographic Service, 1997). Figures 6.3 to 6.7 provide samples of the tidal current patterns at the sites under consideration. Only the surface currents are shown, which represent the instantaneous direction and velocity of a small, independent floating body, for an average tide, in open water conditions. This would also represent the movement of floating ice, in the absence of any cohesion or interaction between floes. The navigation channel, on the north side, is typically an area of high current velocities, which indicates a natural tendency to clear the ice during ebb tide.

Winds and atmospheric pressure, which are responsible for extreme water levels, can cause currents to vary somewhat from the predicted tidal patterns.

Table 6.2 summarizes peak current velocities in the direction parallel to shore at selected sites of interest. The data is a rough estimate, read from the charts of the Atlas. It may be observed that open water tidal currents are equally dynamic, having similar velocity ranges at all sites from Quebec City to the Saguenay River, but somewhat less at Île Verte, where the river widens.

Site	Quebec Ultramar terminal	Pointete-de-la-Martinière	Pointe Saint-Vallier	Kamouraska	Cacouna	Île Verte
Max. current velocity (kn)	2.0	3.0	2.5	3.5	1.5	1.5
Miminum current velocity (kn)	-2.5	-2.5	-1.5	-1.0	-1.0	-0.5
Velocity range (kn)	4.5	5.5	4.0	4.5	2.5	2.0

Table 6.2
Approximate tidal current velocities

Note: approximate data, interpreted from atlas diagrams (Canadian Hydrographic Service, 1997)
1 kn = 1 nautical mile per hour = 6080 ft/h = 1.85 km/h = 0.51 m/s

Early and late in the season, when there is little ice, floes can be assumed to behave as independent, small floating bodies, drifting generally with the surface current. During the ice season, fast ice and zones of high ice concentrations develop. This modifies the distribution of currents to some degree. In addition, ice floes interact with each other.

Therefore, current velocities reported in the Atlas represent a higher bound estimate of the ice drift velocities. Moreover, tidal current patterns provide a reasonable first approximation of drift patterns for the purpose of this study. If deemed useful for the specific site finally selected for the marine terminal, the influence of fast ice on tidal current patterns could be determined using the same hydrodynamic model used to develop the Atlas. Some ice modeling should also be introduced in the same model, to help validate the final layout and design of the marine terminal.

7. DRIVING FORCES AND NUMERICAL MODELING FOR FLOATING ICE

In order to gain some understanding of the relative influences of the external driving forces on the ice, the following rough estimates of driving forces may be computed. The magnitude $\mathbf{s_W}$ (units of N/m^2) of the wind drag may be expressed as

$$\mathbf{s_W = d_A \; C_{DAI} \; u_A^2}$$

where $\mathbf{d_A}$ (units of kg/m^3) is the density of air, $\mathbf{C_{DAI}}$, the drag coefficient between air and ice and $\mathbf{u_A}$, (units of m/s) the air velocity at the surface of the ice. Similarly, the magnitude $\mathbf{s_C}$ of the current drag force may be written as

$$\mathbf{s_C = d_W \, C_{DWI} \, u_W^2}$$

where $\mathbf{d_W}$ is the water density, $\mathbf{C_{DWI}}$, the drag coefficient between the water and the ice and $\mathbf{u_W}$, the water velocity near the surface. Substituting standard values for densities of $\mathbf{d_A}$ = 1.225 kg/m^3 and $\mathbf{d_W}$ = 1000 kg/m^3 and drag coefficients

$$\mathbf{C_{DAI}} = (0.87 + 0.078|\ \mathbf{u_A}\ |) \times 10^{-3} \qquad \mathbf{C_{DWI}} = 4.5 \times 10^{-3}$$

suggested by Saucier and Roy (2003, personal communication), we find the following range of force values, derived for typical wind and current velocities at the sites of interest:

	Wind drag force (kN/km^2)	Current drag force (kN/km^2)
Wind 20 km/h (11 kn)	49	
Wind 40 km/h (21 kn)	270	
Wind 60 km/h (32 kn)	740	
Current 1 m/s (1.9 kn)		4 500
Current 2 m/s (3.8 kn)		18 000
Current 3 m/s (5.8 kn)		40 000

Table 7.3
Typical magnitude of driving forces for floating ice

It is readily apparent that current is by far the dominant driving force for the ice in the St. Lawrence estuary.

When the ice cover becomes sufficiently extensive and ice concentration is high, the ice cover, having gained strength and cohesion, will interact with the shore, the shoals, the islands, and other fixed or floating ice features. These obstacles will modify its trajectory, and internal stresses will develop within the ice cover, under the influences of the external forces, its own inertia and boundary conditions. The ice cover will behave as a deformable solid. Mathematical models are available to simulate this complex behaviour.

At the Maurice-Lamontagne Oceanographic Institute, affiliated with Fisheries and Oceans Canada, a large scale mathematical model of the Gulf of St. Lawrence is operated on a daily basis during the ice season. The two-dimensional equations of motion of the ice, based on Hibler's model (Flato and Hibler, 1992; Hibler 1980; Saucier, Roy, Gilbert et al., 2002), account for gravity effects due to the water surface elevation, inertia of the ice mass, the wind drag force, the water drag force, the Coriolis effect and internal stresses in the ice. The rheologic model for the ice cover uses a viscoplastic material.

Computations are performed on a grid of 5 km by 5 km. Each daily simulation runs 48 hours. Weather input data is updated daily. Ice observations compiled at the Canadian Ice Service in Ottawa, are updated in the model every 3rd day. The results from these simulations, which have been done since 1997, are gradually being integrated as a normal tool to guide de-icing, navigation and escort operations in the Gulf of St. Lawrence. Currently, daily ice motion simulations are systematically being compared to field conditions as they actually develop. It is not unusual that the results from the model stray from actual conditions after several hours into the simulation, mostly because of the inaccuracy of the weather forecast that is used. It is expected that the accuracy of the predictions will improve over time, and that this sophisticated tool will become a truly operational aid.

It should be noted that the initial conditions (atmospheric pressure, winds, ice concentration, ice thickness…) introduced in the model for every simulation run are the actual conditions as they can be best described by Environment Canada daily, including a compilation of all Regional weather and ice data from all pertinent sources.

From data entered into the numerical model, an ice severity index is computed. The severity index represents the relative ease of advance of a small vessel, having 15 000 HP of propulsion power. This corresponds roughly to the power of the larger icebreakers in the fleet of the Canadian Coast Guard, the CCGS Des Groseillers, or the CCGS Pierre Radisson . The parameters for computing the severity index are derived from naval architecture principles and have been calibrated during actual sea trials with an icebreaker (unpublished paper by Roy, F., F.J. Saucier, N. Michaud and R. Corriveau, 2001). Although this index is still under development and is therefore not yet employed routinely in support of escort and de-icing operations, it does provide a useful comparative yardstick to describe ice conditions affecting navigation. Sample conditions in the Gulf are illustrated in Figures 10.1, 10.2 and 10.3.

It was mentioned during our interviews, that the largest vessels, including the huge tankers that visit the Ultramar facility, have little difficulty dealing with ice conditions in the St. Lawrence estuary, due to their enormous mass and power. However, approach and berthing operations are always handled with great care, with the assistance of three (3) tugs in the ice season, two (2) for the rest of the year.

8. RANKING OF WINTER CONDITIONS

Ranking from Coast Guard annual reports

Table 8.1 contains a series of statistics regarding the annual escort and de-icing operations carried out by the Laurentian zone of the Canadian Coast Guard. These statistics, which include a severity index for the climate and a severity index for the ice conditions, are extracted from the Review of Operational Program (CCG, 1990 to 2002) produced at the end of each season. It should be noted that the Climate Severity Index (CSI) is based on the annual FDD count at the Quebec weather station. The Ice Severity Index (ISI) is a subjective assessment of the level of escort and de-icing effort deployed during the season.

It is readily apparent that the CSI and ISI do not agree. Focusing on difficult/cold years, it is apparent from the limited series shown than difficult ice years are necessarily cold, but cold years are not necessarily difficult ice years.

Year	Icebreaker trips		No of Escorts	No of Helicopter patrols	Hours of Helicopter patrols	CCG Climate Severity Index	CCG Ice Severity Index
	zone L03[1]	zone L04[2]					
1990			402	359		Normal	Easy
1991			263	245		Normal	Easy
1992			354	255		Cold	Difficult
1993			317	298		Cold	Difficult
1994			435	356	229	Cold	Easy
1995			499	116	628	Mild	Easy
1996	57	91	310	333	538	Normal	Easy
1997	14	0	211	342	730	Normal	Normal
1998	34	53	145	251	472	Mild	Easy
1999	40	63	160	295	488	Mild	Easy
2000	41	80	173	318	511	Mild	Easy
2001	73	67	202	391	701	Normal	Normal
2002	12	60	143	229	344	Mild	Easy

Table 8.1
Statistics from CCG escort and de-icing program

Note : [1] zone L03 is from Portneuf to Tadoussac;
[2] zone L04 is from Tadoussac to Pointe-à-Boisvet

Figure 8.1 depicts the above data visually, at an arbitrary vertical scale. Keeping in mind that the numbers may vary through the years because of factors unrelated to weather or ice conditions (for example better accuracy in data, improving technology, better decision tools, changes in the seagoing or airborne fleet, budget constraints…), it is nevertheless notable that the objective, countable operational statistics (number of patrols, trips, escorts, hours of operation…) follow the trends of the indices. The fact that difficult ice years are a subset of cold years also shows up well in Figure 8.1.

Ranking from temperature data

Since these two stations have long temperature data sets, total accumulated freezing degree-days (FDDs) at Quebec and at Mont-Joli are considered as indicators of Climate Severity. The key statistics are shown in Table 9.1 and values in degrees ˚C are plotted in Figure 8.2a and 8.b, for Mont-Joli and Quebec respectively.

Station	Mean value FDDs (deg C)	Standard deviation (SD) FDDs (deg C)
Mont-Joli	1155	156
Quebec	1167	165

Table 9.1
Statistics of accumulated annual FDDs at Mont-Joli and Quebec

The corresponding mean values and the band comprised between the mean and plus or minus one standard deviation are also shown on the graphs. For the sake of simplicity, it may be assumed that a normal distribution applies and that these boundaries delimit cold, normal and mild years.

This establishes the ranking of ice seasons from weather data as follows for Mont-Joli:

warm : 1955, 1956, 1958, 1960, 1966, 1969, 1998, 1999, 2000, 2002;
normal: 1957, 1959, 1961 to 1965, 1967, 1968, 1970, 1971, 1975, 1978 to 1991, 1995, 1996, 1997, 2001 and 2003;
cold: 1972, 1973, 1974, 1976, 1977, 1992, 1993, 1994.

Although colder then average, it is noted that 2003 is at approximately 1254 FDDs, and therefore ranked normal.

For Quebec, the cold seasons, established on the criterion of mean plus one standard deviation are as follows:

cold: 1959. 1968, <u>1972</u>, <u>1976</u>, 1990, <u>1992</u>, <u>1994</u>, 2003,

and the common cold years for Mont-Joli and Quebec are underlined. It should be noted that 2003 ranks as a cold year for Quebec.

Expressing the ranking differently, 2003 is the 11th coldest out of 50 years at Mont-Joli, and the 8th coldest in 50 years at Quebec. Therefore, 2003 falls in the 16% to 22% coldest percentile, and is therefore a moderately severe year.

Ranking from site-specific ice data

Several different ice statistical parameters can be used for ranking the ice seasons. Site-specific data developed in Chapter 3, such as the weighted average ice development stage (or thickness), or the weighted average floe size, which were found to be correlated for the sites of the north group, can be used.

Site-specific ice thickness

The distribution of the annual weighted average ice thickness at the three (3) north sites combined is shown in Figure 8.3. Assuming as before boundaries to be defined by the mean plus or minus one (1) standard deviation, the ranking of ice seasons is as follows:

easy:	1984, 1986 and 1999
normal:	1983, 1985, 1987 to 1991, 1994 to 1998 and 2000 to 2002
difficult:	1992, 1993 and 2003

The rating of 1992 and 1993 as difficult ice seasons matches the assessment by the Coast Guard.

Site-specific floe size

The distribution of the annual weighted average ice floe sizes at the three (3) sites combined is illustrated in Figure 8.4. With boundaries based as before on mean plus or minus one (1) standard deviation, the rating is as follows:

easy:	1983, 1998 and 1999
normal:	1984 to 1992, 1994 to 1997, 2000 to 2002
difficult:	1993 and 2003

Ranking from Regional ice data

As described in Chapter 3, the Canadian Ice Service has constituted an extensive geographic information system containing, amongst others, the entire collection of Regional Ice Charts for Eastern Canada. Once a zone has been outlined, the database can be searched to reconstitute weekly records of ice parameters, averaged over the selected region. The data contained in each weekly record is the equivalent to the contents of the "egg code", developed to provide the total area with ice concentration of 1 tenths, 2 tenths, ..., the total area of ice at development stages 1,2,..., the total area of ice floes sizes 1,2,..., etc. Hence, a record of global ice conditions over the zone of interest is produced weekly from 1969 to present.

A search of this type was done for the larger, regional area outlined in Figure 8.5. This corresponds to the East Coast Regional zone, which includes the estuary starting at Quebec and the entire Gulf of St. Lawrence: the total sea area is 487 000 km^2.

Total accumulated ice coverage in the Gulf

From this database of weekly records, CIS has supplied a graph showing the annual variation of the total cumulative ice coverage in the Gulf. This index is computed by adding together the total area covered by ice in the zone (any non zero concentration), week after week. Despite the lack of any true physical meaning, this index provides some measure of the severity of the general ice conditions. The total annual accumulated ice coverage in the Gulf index is plotted in Figure 8.6. Comparing the trend with the curve of Figure 8.2, it is readily apparent from the graphs (and also intuitively logical) that this index is correlated to the total annual FDDs. Therefore it is not an ideal measure of Ice Severity, but rather of Climate Severity.

Maximum volume of ice in the Gulf

From a similar database, the maximum annual volume of ice produced in the St Lawrence River and Gulf, was computed at Institut Maurice Lamontagne (IML), a ocean sciences research center affiliated with Fisheries and Oceans Canada, located in Mont-Joli.

Two different databases are utilised. Before 1997 (the 'Bugden' database), the data is integrated from grid points with a unit cell of 1° longitude by 0.5° latitude (roughly 50 x 50 km) and ice concentration data updated once a week. Since 1997, the computations are based on a much finer mesh, with a unit cell of 5 x 5 km and ice concentrations are updated every third day (CIS database). Moreover, the use of the observation satellite Radasat (1997) has improved reliability of ice concentration data in recent years. Maximum annual ice volumes computed by IML for years 1963 to 1993 and 1997 to 2003 are plotted in Figure 8.7. The average volume of ice production in the estuary and Gulf of St. Lawrence is about 75 km^3, but the relative variation between maximum and minimum annual values is very large (Dr. Francois Saucier and François Roy, interview of March 5 2003).

Based on mean plus or minus one (1) standard deviation boundaries, the ice severity index based on maximum ice volume is as follows:

easy:	1969, 1970, 1980, 1981, 1988, 2000
normal:	1963 to 1968, 1971, 1973 to 1977, 1978, 1979, 1982 to 1991,1997, 1999, 2001, 2002.
difficult:	1972, 1992, 1993, 2003

Composite ice severity ranking

Based on the results reported by these various methods, the following ice seasons are deemed to be the ones with the most difficult ice conditions:

1972, 1992, 1993 and 2003.

It is noted that 2003 had severe ice conditions in the Gulf, not in the estuary.

9. INTERVIEWS AND FIELD OBSERVATIONS DURING 2002-3 ICE SEASON

Interviews

As seen in earlier discussions, there are limitations to the reliability of ice data owing to the fact that such data is typically collected towards a specific operational purpose. Use of the data as if it were compiled from scientific research, is therefore not completely reliable. Therefore, it is essential to complete the "objective" data that can be gathered from various sources with field observations and interviews with people who have experience of ice conditions in the area.

A series of interviews were conducted throughout the winter season of 2003. The persons met, listed here by alphabetical order, offered precious comments, observations and sometimes data, which has been included in this work and forms an essential part of the knowledge base developed during this study. Detailed notes of most of these meetings are included in Appendix I.

- Captain Leopold Anctil (retired), Kamouraska
- Denis Blanchet, Project Manager, Arctic Engineering, BP Petroleum, London, U.K.
- Professor Thomas Brown, University of Calgary
- Richard Chagnon, Archive Manager, Canadian Ice Service, Environment Canada, Ottawa
- Captain Réginald Corriveau, Superintendent, Escort and De-icing, Canadian Coast Guard, Quebec City
- Captain François Gauthier, Société des Traversiers du Québec (STQ), Quebec
- Captain Marc Harvey, commander of the Rivière-du-Loup to Saint-Siméon ferry, Rivière-du-Loup
- Adrien Julien, Meteorologist and Climatologist, Environment Canada, Saint-Laurent
- Maria MacLeod, Claire Piché, Robert Tessier, personnel from Environment Canada, Canadian Ice Service-Client Services
- Captain Guy Marmen, pilot and president of Corporation des Pilotes du Bas Saint-Laurent, Quebec
- Dan Masterson. Engineering Manager, Sandwell, Calgary
- Yvon Morin, Manager, Harbour and Coastal Engineering, Public Works and Governmental Services Canada, Hull
- Professor Brian Morse, Department of Civil Engineering (hydraulic structures, river ice), Laval University
- Professor Yvon Ouellet, Department of Civil Engineering (marine hydraulics, waves), Laval University
- Marcellin Papillon, Manager of the Technical Service Division, Transport Canada, Marine Safety, Quebec
- Roger Provost, Senior Ice Patrol Officer, Environment Canada, Ice Bureau, Quebec
- Patrice St-Amant, VP Operations, Société des Traversiers du Québec (STQ), Quebec

- Dr. François Saucier and François Roy, Institut Maurice Lamontagne (physical oceanography, ice dynamics), Fisheries and Oceans Canada, Mont-Joli
- Dr. Gary W. Timco, National Research Council of Canada, Ottawa
- Captain Germain Tremblay, commander of icebreaker "Desgroseiller", Canadian Coast Guard, Quebec

Description of conditions during 2003 season

A description of climatic and ice conditions encountered on the estuary and Gulf of St. Lawrence during the current ice season is included each year in the Operational Program Review prepared by the Coast Guard. Then 2003 issue of this report is due to be available in the coming Fall. The brief description given hereafter is based on our monitoring of ice conditions by the daily examination of published ice charts, several field trips and comments from various interviews. In general, the 2003 ice season has been normal for these sites, despite temperatures colder than average and heavier than average ice production. However, there have been few winter storms and winds have generally kept the ice moving well all winter in the estuary.

On the other hand, ice conditions in the Gulf have been quite severe and icebreakers have had to lend assistance to ships several times, particularly in March and April. It should be noted that this study has been focused to the specific ice conditions at the six (6) sites under consideration. Conditions in the Gulf should be addressed as required in future work.

Analysis of the temperature data at Mont-Joli indicates that the first day with a non-zero FDD was on October 31, 2002. The progression of cumulative FDDs throughout the season is illustrates in Figure 9.1, together with curves from other ice seasons. For 2003, different phases, distinguished by slope changes, are noticeable. A steep slope indicates a sequence of cold temperatures, while a flat portions represent warmer days. Temperatures become gradually colder after Christmas and a first period of heavy sustained cold can be identified from January 12 to 30; a second cold period is experienced from February 5 to 19.

Average daily wind velocity and direction at Mont-Joli from December 1, 2002 to February 23, 2003 are illustrated in Figures 9.2 and 9.3. The same data for Quebec is also plotted for comparison. For Mont-Joli, the average daily wind velocity is 21 km/h and peaks of 48 km/h occurred. The average and peak are 17 and 45 km/h for Quebec. Wind directions are quite variable but the average direction is from the SW (225°azimut) and therefore aligned with the river. There are two episodes of relatively steady wind from the W-SW from January 7 to 17, 2003 and from January 20 to 20, 2003, which coincides with the first cold period.

The most heavy ice conditions at the south sites occurred in late February 2003, as illustrated in Figure 9.4. The large quantities of ice formed upstream during the earlier cold weather have drifted to this narrow passage of the river and form a high ice concentration cover, predominantly formed of brash and first-year ice (30 to 70 cm thick). There is typically more pressure upstream from the bridges and in the bend in front of Lauzon, and less ice at Ultramar and Pointe-de-la-Martinière. This condition is clearly illustrated in Figure 9.5 dated March 22 2003. This chart is also included to be related with photographs taken during the ice patrol – see Figure 11.2, Photos 31 to 33 in Annex IV).

For the north sites, ice conditions are examined during the first cold period. On January 13, the first chart is produced for Kamouraska (Figure 9.6). Wind is blowing from the SW with an average velocity of 18 km/h. The total ice concentration reads as 9 tenths. At the middle of the period, on January 21 (Figure 9.7), total ice concentration is still 9 tenths, likewise on January 27 (Figure 9.8) at the end of the period. Though total concentration had not evolved, ice development stage has increased from <10 cm to 30-70 cm.

Figures 9.9, 9.10 and 9.11, show conditions at Cacouna on January 17, 30 and February 1: total ice concentration decreases during this period.

After the first cold spell, winds veer from SW to E. Ice conditions are not particularly interesting during the second cold period, and Figure 9.12, a chart dated February 10 2003, shows representative conditions of the latter part of the winter season; there is little ice on the north side, and ice is moving easily along the south side.

This winter has been a cold winter with two long periods of persistent cold to about minus 15°C. Owing to the moderately severe temperatures of 2003, ice was well developed at all sites of interest in the estuary. Fortunately, other conditions kept the ice moving well throughout 2003.

10. ASSESSMENT OF ICE CONDITIONS AT EACH SITE

An assessment of ice conditions is given for each site, starting with the one furthest out in the estuary and ending with the existing terminal at Saint-Romuald, furthest upstream. Some comments are then made regarding navigation in the estuary and in the Gulf.

Île Verte

Of the three (3) northern sites considered in this study, the site located to the east of Île Verte is the least severe in terms of ice conditions, being in the vicinity of the recurring polynya. This is well reflected in the comparative statistics of the combined concentrations 9, 9+ and 10 obtained from the analysis of the river ice charts.

Located just across from the Saguenay River, the site is has dynamic tidal current conditions, though somewhat less intense than at the other sites, because of the great width of the river. Currents in all directions are typically weak, but somewhat stronger (approximately 1.5 kn) during ebb tides, which helps to clear the ice.

According to verbal accounts from many sources, weather and sea states can be very severe in the wide open area at the mouth of the Saguenay river. Funnel effects create local amplifications of winds, both from the NW, the most prevalent direction, which is also aligned with the Saguenay fjord, but also from the SW. Considerable fetch distances over open water, which is frequent here in the winter, can raise a heavy sea and cause a lot of spray and icing. Referring to this, Captain Harvey stated that moderate ice was often easier to deal with in the winter, than no ice at all. Another phenomenon, called «coup de boeuf du Saguenay», is the very sudden transition from calm water to extremely high waves (reported by some as « columns of water ») under a particular combination of NE winds and shifts in the tidal currents. This has caused the loss of several lives and small craft over the years.

Shore ice

Shore ice forms between Île Verte and the mainland and extends over the foreshore in the bay south of the site. As observed here and elsewhere all along the St. Lawrence River, the edge of the stable fast ice extends at least to the limit of the foreshore, or the 0 m isobath (the *batture*). Throughout the season, the fast ice edge grows further offshore, particularly in shallow water, but can be dislodged in warmer periods and large tides. According to our interviews of ice observers and captains, the fast ice typically reaches the 10 m isobath, but is not permanent. Therefore, extension of the fast ice to the deepwater site is believed to be unlikely. However the site is often covered with drifting ice.

Large floes

As can be seen from the bathymetry and from current charts, flow velocities in the south channel is far more restricted than in the north channel due to broad shoals and a successions of shallows and islands extending upstream to Kamouraska (Rocher Percé, Haut-fonds du milieu, Batture and Île Les Pellerins, Îles de Kamouraska). Therefore, the north channel which is often clear of ice, is the preferred route for large floes drifting from upstream, causing the floe to come out past Île aux Lièvres and to float clear of the site. Referring to large *batture* floes, Robitaille (1957), states: "the possibility of a concentration of drifting ice floes off Cacouna Island … appears to be very slight. According to local knowledge this has never happened". This would therefore also be true for Île Verte, according to our interviews.

Pack ice

While the general area north and northwest of the site is often clear of ice, large quantities of ice are carried downstream through the south channel. Ice concentrations of 9-10 are common. The strong ebb currents rushing between Île Verte and Île Rouge, from which the site is partially shielded, in the lee of Île Verte, tend to pack the ice near the site, while flood currents loosen it (Carter, 2002).

Open water

The large areas of open water north and northwest of the site can be expected regularly through the winter. Since winds are strongest in winter months and predominantly from the northwest, the highest waves would occur at the site in the winter, when there is no surrounding ice, creating difficult navigation and docking conditions, and severe freezing spray on the structures and vessels.

Ice conditions would not appear to be problematic at this site. However, sea states, winds and freezing spray have been described as being brutal. Dr. Saucier, who would be asked to express his opinion on behalf of the Department of Fisheries and Oceans regarding the potential occurrence of an accidental spill, made the following comment: Île Verte is a very exposed site with very severe weather, offering the least potential for containment in case of a spill. This would be a major issue for an oil terminal, but perhaps less for a LNG operation. Overall, from all of our discussions, the general comment on this site has been unanimously negative, but for considerations other than ice conditions.

Cacouna

Deep water is found immediately west and northwest of the Gros Cacouna, a rounded ridge of rock, oriented southwest to northeast, situated at the edge of the St. Lawrence.

The existing harbour, located upstream from the Gros Cacouna ridge, has a minimum water depth of 7 m. It is closed by two rock-fill breakwater structures, and has a narrow entrance. Therefore, the port has very calm waters, which is fine for manoeuvring small ships, but covers with ice easily. Despite declining ship traffic over recent years, the harbour is maintained accessible through winter, and ships entering or leaving the harbour are generally escorted by a Coast Guard icebreaker. The area is thus de-iced regularly every winter, with a degree of difficulty which may vary depending on winds, keeping in mind that this is a closed harbour.

The ice conditions are influenced by the Saguenay polynya, despite its upstream location to this feature, but also by favourable hydraulic conditions.

The deep water location considered in this study is directly offshore from the ridge. The location is shielded by Île Verte from the influence of weather or waves from the deeper estuary, but at the same time, swept by a very dynamic tidal current regime, with velocities in the range of 1.5 and 1 kn at ebb and flood tides respectively. A zone of high velocity currents (up to 7 kn in open water) develops at ebb tide between Île Rouge and Cacouna, sweeping towards the northeast, a few kilometres north of the site.

Strong, sustained winds from the NW are present 1/3 of the time during January and February, which pushes the ice towards the south shore. Winds blow from the W and SW for another 30% of the time, which has the opposite tendency of clearing the area.

Shore ice

Stable shore-fast ice develops on the shoals east of the deep water area up to Île Verte. In mid-January, we noticed a group of local residents fishing over the ice in this area. However, shore ice is least extensive along the upstream part of the ridge. The tidal currents are too active to allow locally formed ice to ground itself firmly, particularly where water depth increases rapidly. However, due to the predominant winds pushing the ice towards the south shore, floating ice may accumulate and remain in place for some time.

Large floes

As described above for Île Verte, the likelihood of large *batture* floes impinging upon the Cacouna site is very low, but possible.

Pack ice

Ice is far more prevalent and persistent in the south channel, where progress of the ice is slower, than in the north channel. As the drifting ice emerges from the channel south and east of Île aux Lièvres, currents will tend to steer the ice clear of Île Verte, and therefore clear of the Cacouna Island. Ice incursions from upstream are unlikely because of the limited strength of the driving force from the wind compared to that of the strong ebb currents, and because of the rampart created by Île Verte. However, ice charts and photographs from previous investigations (Carter, 1976) show that a band of concentrated ice can form along the northwest shore, passing in front of the Island. In fact, ice concentrations of 9-10, including significant partial concentrations of first year (30-70 cm) ice are not unusual.

According to Robitaille (1957), only a N wind can cause ice to remain for some time, forming a belt fringing the NW shore of the island, stopping temporarily the net progression of the floating ice. Winds from the NW could also produce the same effect. When this occurs, it is likely that marine operations would have to be delayed, since it would be difficult to remove the ice from the front of the dock.

From the standpoint of ice conditions, the Cacouna deepwater site is therefore not ideal but feasible.

Kamouraska

The Kamouraska site is located 50 km closer to Quebec in deep water, just upstream from the entrance of the south channel described above. After the pronounced curve at Cap-aux-Oies and broadening of the river in front of La Malbaie, the flow becomes slightly more restricted at Kamouraska. The site is a zone of convergence for ice. This is borne out clearly by the statistics from river ice charts presented earlier. Because of the focus to the north side, there is less ice data available at this site, compared to the other two.

Currents are strong (3.5 kn ebb, 1 kn flood) at this site and wind directions are more aligned with the river than at the other sites further north and the predominant direction is from the SW. The site is likely to have wind velocities somewhat stronger than shown in the Atlas, with local acceleration due to the Charlevoix passage.

Shore ice

Stable shore ice forms on the shoals on both sides of the Cap-aux-Orignaux, but there is little extension into the river. In any case, shore ice does not extend to the site, which has to be away from the coast to reach sufficient water depth.

Large floes

With a broad river section upstream, strong currents and dominant SW winds, the site is likely to be impacted by large *batture* floes, although the frequency of such an occurrence cannot be determined from current data.

Pack ice

With the slower flow of ice in the south channel, immediately downstream from the site, drifting ice with 9-10 concentrations is a common occurrence. As for the other sites, there is no indication, from the available data or comments received, that sustained congestion from ice occurs, which would render this site unsuitable. As mentioned earlier, available ice observations are less frequent at this particular site (see Table 3.1), so that prudent design assumptions should be made. From a navigations standpoint, further site specific observations are required. However, the close proximity of an anchorage area, with little ice, is noted, in the bay to the north side, east of Cap-aux-Oies. This provides a safeguard in case there is any delay in accessing the dock.

From the standpoint of ice, the Kamouraska site appears practicable, but there is limited knowledge of ice conditions, little has been learned from local residents or from ice observers, and there is less data on the ice charts in that specific area. Further investigations in the field and systematic review of all the available satellite imagery would be recommended to supplement existing data.

Pointe Saint-Vallier

This site is located across from Île d'Orléans, in a zone where the St. Lawrence is starting to widen very rapidly. The site is about 1 km from shore, in the south channel, one that is not used by commercial ships because of the limited water depth. The water depth at the site, which is greater than 12 m, is sufficient for large vessels but access might be delicate due to the presence of Île Madame between the north channel and the site, and zones of shallower water (about 11 m) close to the site, and a perhaps shallower area north of the site where dredging material is disposed.

Pointe Saint-Vallier offers a pointed headland, with a sharp slope, about 20 m high. The surrounding land is not very much developed, in terms of occupancy.

Shore ice

Land-fast ice forms a narrow band along the south shore that rarely reaches the site due to fairly deep water. However, the presence of a jetty or berth would create a new zone of fast ice, similar to that observed at Ultramar.

Large floes

Approaching Pointe Saint-Vallier, floes are of small to medium size and would not pose any particular problem for the terminal. Big *batture* floes are very rare, since there are few areas where these could form on this side of the Quebec bridges. Big floes from further upstream are managed and broken before reaching the bridges. *Battures* at Beauport, at the mouth of the Saint-Charles river, are also closely monitored by the Ice Bureau and maintained stable by Coast Guard icebreakers so that they do not threaten to interrupt navigation.

Pack ice

High ice concentrations of 8 to 10 tenths occur regularly at the site, but ice flows well in the south channel and congestion is rare.

Open water

Compared to other sites, there is little open water and few occurrences of low ice concentration during the heaviest part of the ice season at Pointe Saint-Vallier. Located just at the end of a very narrow passage in the river, this is to be expected, when comparing to the sites further downstream, where the river becomes much broader and ice rarely covers the entire width, but concentrates on the south side.

Hence, ice conditions are not expected to be problematic at this site, but the limited water depth is a disadvantage.

Pointe-de-la-Martinière

This site is located about 500 m from the south shore, across from of Île d’Orléans, in a passage of the St. Lawrence slightly narrower than at the Ultramar terminal. Deep water is accessible very close to the shore.

The normal navigation channel is near the island, on the north side. However, the limited width of the river imposes prudent planning of vessel movements and leaves little room for error. This is also true of the Ultramar site, which has been operated for 31 years without any serious maritime incident, according to our interviews.

Shore ice

Since water depth increases rapidly, fast ice does not develop much at the headland, but does in the bays on each side. The construction of a terminal would stabilize land-fast ice on the upstream side, but this would not encroach into the river beyond the last protective dolphin. The combination of deep water and very high tides creates a discontinuity at the edge of the ice cover, which breaks off at low water and can remain grounded until the next high tide, or several tidal cycles later. Eventually the broken ice floats away during a subsequent high water interval. Several photographs taken on February 19 2003 (photos 6 to 12 in Annex IV) illustrate this zone of highly deformed ice, with some grounded pieces of imposing dimensions. Subsequent observations during the air reconnaissance of March 6 2003 demonstrate that this ice has been removed by tidal action.

Large floes

As for Pointe Saint-Vallier, which is very close, the likelihood of encountering large ice floes is very remote at Pointe-de-la-Martinière, due to the active management by the Canadian Coast Guard.

Pack ice

The passage at Pointe-de-la-Martinière has a heavy ice load, with typical concentrations from 7 to 10 tenths. The moving pack ice is rarely pushed against the south shore, because the site is protected from northerly winds by the landscape of Île d’Orléans. High tidal currents, typically 2.5 - 3 kn, keep the ice in motion.

Open water

This site is rarely free of ice because of the narrowness of the river. However, during ebb tide, some open water appears at the edge of the fast ice on the south side (as was observed on February 19 2002, see photos 8 and 11 in Annex IV). This indicates a component of the current directed offshore, perhaps due to the deviations of the downstream current by the headlands at Sainte-Pétronille on the north side and Pointe-de-la-Martinière on the south. This effect is favourable for the evacuation of the ice, but it might be somewhat modified by the presence of a terminal.

Ultramar

Ultramar, formerly Golden Eagle, operate a marine terminal handling the import of crude to its refinery located in Saint-Romuald, and the export of finished hydrocarbon products. The design of the terminal, which is being considered for the LNG project under consideration, is described in the next chapter. The study of ice conditions at the site of this terminal provides the opportunity to benchmark all site conditions with conditions at a real working facility, having a successful track record of operations, without a single day missed because of ice conditions, according to our interview with the superintendent of the facility.

Similar to Pointe-de-la-Martinière, the water depth increases very rapidly at the edge of the shoal, a key consideration to have an efficient and economical design if road access to the dock is required.

Shore ice

There is rarely total ice coverage in front of the terminal where the vessels must operate. However, the jetty and protective dolphins create an obstruction to the flow of water and ice which causes the fast ice to become stable out to the inside edge of the dock. Since tankers come and go on a 3 to 4 day cycle, ice maintenance of the dock is done regularly with only a tug boat. Ice breakers are not required.

Large floes

Big floes have never been a problem at the Ultramar terminal, because they are broken by icebreakers before reaching the site. The largest floes at the site are small, 20-100 m.

Pack ice

The area in front of the Ultramar terminal is often loaded with ice, sometimes packed against the shore. However, due to the strength of tidal currents, a tug boat, working with the assistance of the receding waters, suffices to evacuate the ice from the berthing area. Early in the season, pack ice accumulates quite far upstream from the protective dolphins, and eventually stabilizes, creating a protection against direct impacts from upstream. An incoming floe would be deviated towards the centre of the river, most likely avoiding the dock and berthed vessel altogether.

Local navigation at the sites

In recent annual operational reviews published by the Coast Guard, a single instance is reported when the navigation channel has been closed to traffic for four (4) days due to ice. This ice jam occurred in late March of 1984, near Quebec City. According to senior ice observer Roger Provost (see notes from interview, Annex I), this condition developed under sustained winds from the NE. As seen in a previous chapter where years are ranked according to climate or ice severity, 1984 appears to be a normal year.

This particular event should be further investigated so that it's probability of occurrence might be assessed with confidence. For the time being, it is reasonable to assume that navigation can be completely obstructed at a narrow passage such as the one near the Quebec City bridges for several days , once in twenty years. This could also potentially occur at a sharp bend in the river, such as the one in front of Beauport. However, forced delays due to local congestion by ice have not been reported at the Ultramar terminal and are therefore considered unlikely further downstream at the at any of the three (3) sites from the south group.

For the sites from the northern group, since most of the marine traffic takes place close to the north coast, there is not much experience of winter navigation near the south shore of the river. Ships never come close to Kamouraska during the winter. At Cacouna, there is indeed year-round traffic near the south shore, coming and going to the existing harbour with assistance from the Coast Guard. The only problem reported at Cacouna is the maintenance of the closed harbour, because ice has nowhere to go once the ice breaker has opened the way. Matane, located much further downstream often experiences problems, because the narrow entrance to the harbour becomes congested, in sustained W and NW winds. In his opinion, closed harbours should be avoided on the south shore.

The region of the estuary in which the three (3) northern sites are located does not appear to be particularly problematic in terms of accessibility of vessels during the winter. We would expect some delays due to local conditions, but limited to one or two days. All vessels stop for a pilot change at Les Escoumins, which is across the river, a few miles downstream from Île Verte, so there is a large safe anchorage zone available if any waiting time is necessary.

Navigation in the Gulf

In addition to potential delays due to local ice conditions at the marine terminal, vessels might also be delayed due to ice conditions in the Gulf, which have not been included in the scope of this study.

The severity of navigation conditions through ice in the Gulf of St. Lawrence can be assessed using the maps produced by the numerical model developed at Institut Maurice-Lamontagne, which was described previously. For example, ice severity conditions on March 20, 2003, are illustrated in the map of Figure 10.1. Figure 10.2 and 10.3 show the corresponding distribution of total ice concentration and ice thickness. Although plotted by the numerical simulation model, the maps of initial conditions, such as Figures 10.1, 10.2 and 10.3, are real conditions. The conditions shown are for the worst conditions of season 2003. It should be noted that ice is no longer a problem at the sites along the estuary by this date. In fact, ice conditions observed on March 6, the date of our aerial reconnaissance (see photographs in Annex IV), were already very easy. This illustrates that adverse ice conditions typically occur in the Gulf much later in the Spring than in the estuary.

The present study provides little guidance relative to travel time or delays associated with ice conditions in the Gulf. The severity index applies to small ships. Large vessels such as oil tankers or LNG vessels have a lot more power and are therefore not affected to the same degree, if at all. Therefore, a modified severity index, appropriate for large powerful vessels, should be used to evaluate ice navigation. This can be done using the existing database of ice conditions in the Gulf.

11. ICE FORCE ESTIMATES

Figure 11.1 gives a general aerial overview of the marine terminal operated by Ultramar, near its oil refinery in Saint-Romuald, on the south shore of the St. Lawrence River, between Quebec City and the Quebec bridges. The terminal provides water a minimum water depth of 18 m for berthed vessels and it is used regularly by large 150 000 DWT oil tankers. It should be noted that the least water depth (12.5 m) between the Gulf and Quebec is found at the so-called Traverse Nord, a dredged portion connecting the channel south of Île d'Orléans to the channel along the north shore.

Stable land-fast ice is formed upstream from the terminal, right in Figure 11.1, which protects the dock from ice incursions from that direction. This permanent ice affects the velocity and direction of the currents locally, and produces a thrust towards the centre of the river during flood tide. Stable ice would also form between the shore and the berthing dolphins if not for the maintenance on both sides. This maintenance is done with ease using simple tug boats during ebb tide to facilitate clearing. The open design of the dock is therefore an important characteristic which allows the full benefit from the sweeping action of the currents.

Dock design and load scenarios

The dock required for the proposed LNG terminal may be assumed to be very similar to that at Ultramar.

Ultramar's open wharf is formed by a series of large circular dolphins having ample distance between them to allow flow through of water and ice. The berthing dolphins are aligned with the shoreline and two additional dolphins, spaced closer together are placed upstream to protect against drifting ice. This design has proven very successful, since the facility has been able to operate without any interruption due to ice since its inauguration in 1971, according to the superintendent of dock operations. It therefore appears to be an appropriate design for the proposed facility.

Dolphins are connected by steel bridges (some additional photographs are provided in Annex IV), supporting a roadway and necessary piping. A jetty and a short bridge provide access to the berth from the shore. Despite its short distance from the shore, the terminal can accommodate ships both inside and outside of the dock. However, because of vessel size and space required for tug operations, the larger tankers, similar in size to the LNG vessels being considered, only use the outside location.

As a starting assumption, to be refined in future studies, ice forces on the dolphins are established based on a 30 m diameter. The dolphins at the Ultramar terminal have a 23 m diameter.

The following ice loading scenarios are assumed to be applicable at all sites.

Brash. Everyday ice forces are exerted by brash, sometimes quite thick. Although brash may be a significant nuisance to navigation, it does not develop substantial loads against structures, compared to other types of ice.

Sheet ice. On a regular basis, the structure is hit by floes of sheet ice, of a size and thickness described by the statistical data presented earlier. Since occurrence of sheet ice sheet impacts is frequent, this should be considered as a working load, and therefore an appropriate load factor should be applied for limit state design. Typical code values are in the range of 1.5 (CSA S6-00; CAN/CSA-S471-92; API-RP-2A), but higher coefficients are found in recent literature (MacGregor et al., 1997). Less probable impacts from large floes should have a smaller load factor, reflecting the lower probability of occurrence;

Floes and floe sizes. Large or small floes, sometimes quite thick due to piling or rafting and subsequent re-freeze, may create high localized punching forces against the hull of a ship of a fixed structure. If the floe is small, the small mass would be arrested by the structure before it has penetrated sufficiently to transmit pressure on a large area. Therefore only the largest ice features, having sufficient kinetic energy, would produce large forces.

The largest floes or *batture* floes can reach a typical maximum of 1 to 3 kilometers, in the area of interest. We distinguish two types:

- floes of **sheet ice** (**fast ice** of uniform thickness) are strong and competent (except in warm spring temperatures), and their thickness is that measured by the surveys, typically 60 to 80 cm: a typical example is the *batture* at Donnacona which comes loose at the end of February, during high tides and westerly winds; Figure 11.2 shows a similar type of floe observed on March 22, 2003, upstream from the Quebec bridges; such a big floe at this location does not generally pose a threat to the 'south' sites because it becomes fragmented either naturally or as a result of an icebreaker intervention; the Coast Guard actively manage the ice in the narrow passage at the bridges to avoid a jam, which would seriously disrupt navigation and water levels;

- floes formed from **agglomerated, rafted or piled ice** : in some bays, the locally grown sheet ice rafts under pressure, brash and broken ice agglomerates and piles-up into very thick *battures*, which can reach 4 metres. *Battures* of this type form at Cap-Rouge. These *battures* can be difficult to penetrate if confined and thick; however, as soon as the confinement pressure is released, for example in a widening of the river when a bottleneck is passed, then these floes tend to break-up easily, because of the presence of voids and poor cementation of pieces.

Significant **pressure ridges** can form due to sustained winds at the edges of the shorefast ice in the wider part of the River, downstream from the sites of interest. We have observed a consolidated ridge at Sainte-Flavie on March 5 2002 and we have photographs of similar pressure ridges near Matane. As the fetch of the wind over the ice becomes more limited upstream, ridges rarely form in the area of this study, and when they do so, they are generally formed of fairly thin ice and simply disintegrate at the subsequent tide, as confirmed in our interviews. Therefore pressure ridges are not an important consideration for the sites under study.

With a layout of the terminal similar to that of Figure 11.1, a stable sheet of shore-fast ice forms upstream, provided the dock is close enough to shore. This protects most of the facility from direct impacts, except perhaps the leading protective dolphin furthest from the shore. Therefore, direct impacts from large floes of strong, cold ice are not impossible, but would have a low probability of occurrence. Impacts of large floes from downstream would be unlikely because icebreakers would have reduced it to small pieces during the previous ebb tide. The extreme but rare occurrence of an impact by a large *batture* floe, several times the thickness of a single sheet of ice, must also be considered as an exceptional load. A lower load factor would be applied to a rare extreme loading event, to provide a balanced reliability index between loads.

Simulation of impacts

Three ice loading cases are considered, corresponding to a thin, medium and thick ice floe (refer to thickness data of Table 4.1, for Cacouna). The effective compressive strength of sound ice is taken as 1.5 MPa (CSA S6-00; Michel, 1970; Carter and Michel, 1971), but a reduced value of 1.0 MPa is deemed reasonable for the thickest sheet ice in the spring, and 0.75 MPa in warmer batture floe, which is irregular and non-homogeneous. Using the usual expressions for ice forces developed by crushing against vertical structures (Blanchet, 1998; Fenco, 1984; DnV, 1984; Tsinker, 1994; USACE, 2002), and an indentation factor $Ci = (5t/D + 1)^{½}$ (CSA S6-00), ice forces are computed as follows:

Ice load scenario	Representative compressive strength	Unfactored Load	Approximate Load Factor	Factored Load- "Limit state"
Thin first-year ice floe T= mean+1 SD= 0.6 m	1.5 MPa	28 MN	1.5	42 MN
Medium first-year ice floe T= mean+2 SD= 1 m	1.0 MPa	40 MN	1.25	50 MN
Batture ice floe T= avg. thickness 2m	0.75 MPa	52 MN	1.0	52 MN

Table 11.1
Ice loading scenarios- crushing against a vertical structure

Note: assumes driving forces sufficient to develop crushing on the full width of the dolphin; load factors are given nominal values, but should be determined by a rational analysis

Loads in Table 11.1 are computed from usual formulas using the input parameters described above, which are deemed to be most reasonable. Compilations of extensive full scale measurements of ice forces on narrow structures have been published recently (Johnson, M.E., G.W. Timco and R. Frederking, 1999a,b) and these are in fair agreement with the usual formulas. Scale effects due to the nonsimultaneous failure of the ice across a wide structure may cause forces to be smaller. However, there is no full scale data on freshwater ice forces against wide structures, only data from arctic conditions involving very cold sea ice (Blanchet, 1998). Some data from sea ice forces on Confederation bridge piers (conical - 15 m diameter at waterline) is soon to be published, which indicates forces levels lower that the design estimates (Brown, personal communication, 2003). The estimates provided in Table 11.1 are the best available but could be improved by field measurements on wide structures.

The tabulated loads represent the maximum theoretical force applied to the full width of the dolphin. Reaching this force implies that the floe has sufficient kinetic energy to attain complete penetration. It can be shown this will be the case if a big floe (larger than 500 m) is considered, driven at a representative tidal current velocity, say 3.5 kn. However, the low probability of an actual direct hit at high velocity must be properly considered in the load factor which should be developed by simulation of random events.

A quasi-static loading scenario, where a big floe has come in contact with the structure at low velocity, and is then pushed against the structure by the drag force from the wind or current acting on the floe. As seen earlier, current drag will govern over wind drag. Using a velocity of 3.5 kn, the driving forces per unit area of ice floe becomes

$$\mathbf{s_c = d_w\, C_{DWI}\, u_w^2} = 16\ 000 \text{ kN/km}^2.$$

Using a floe size of, say 1 x 1 km, the driving force applied to the ice is therefore is 16 000 x 1.0^2, or 16 MN. Although this scenario does not appear critical, we note that the force is very sensitive to the floe size. A systematic examination of satellite imagery records could provide a more reliable statistical determination of the floe size at the sites of the northern group. However, dynamic impacts would appear to govern the magnitude of the design ice force.

Determination of design loads

The recent update of the Canadian bridge design code CSA S6-00, and recent work for the design of the Northumberland Strait Bridge, have introduced rational probability-based means of establishing the appropriate force magnitudes and load factors, to provide a desired target safety index, typically 3.5 for usual bridges, 4 to 4.25 for the Strait Crossing (Brown, T.G., 1997; MacGregor, J.G., D.J. Laurie Kennedy, F.M. Bartlett et al., 1997; Brown, T.G., I.J. Jordan and K.R. Croasdale, 2001).

In an analysis of this type, estimates of the design event having a 100-year return period are developed based on best estimates (expressed by a probability distribution function) of all parameters affecting the ice force calculations. The 100 year event is also the basis followed in all design codes for offshore structures (DNV, API, ACI, CSA). Hence, the random nature of the impact velocity, which depends on the timing within the tidal cycle, the random variations of thickness, strength, floe size, relative position of the floe and the structure in the river (the floe can actually drift clear of the dock), etc… should be modeled to refine design loads at a later stage of the project.

For now, the forces and load factors shown in Table 11.1 are considered to be reasonable estimates, based on current codes, and various discussions (Brown, Blanchet, Timco): an ultimate load of 40 to 50 MN should be considered at all sites, assuming a cylindrical dolphin 30 m in diameter.

12. SUMMARY AND CONCLUSIONS

Several potential sites are being considered for the construction of a marine terminal on the south shore of the St. Lawrence River. The terminal will be capable of receiving large LNG transport vessels throughout the year. Six (6) sites along the estuary are investigated with respect to ice conditions. The three (3) sites furthest to the north, are Kamouraska, Cacouna and Île Verte. The three (3) other sites furthest to the south and close to Quebec, are the Ultramar terminal in St-Romuald, Pointe-de-le-Martinière and Pointe Saint-Vallier. For each site, ice conditions are investigated to determine if the sites are suitable for access and operation during the ice season, and to verify the ice loads assumed in early studies of the facilities.

Work accomplished

All River Ice Charts available from Environment Canada archives from 1980 to present, were thoroughly examined and ice characterization data at the specific sites was extracted for compilation and analysis. Detailed statistics of the site-specific ice data were generated, including comparisons among the sites, and trends through the years.

All earlier Historical and Regional Ice Charts were rapidly reviewed on paper form at the Canadian Ice Service office in Ottawa, for all years from 1959 to 1980. Conditions during cold years were paid particular attention. Regional Charts from 1980 to 2002 were also briefly reviewed.

Ice thickness data compiled by Environment Canada at selected measurement stations were reviewed and analysed in detail. For the relevant measurement stations, some have datasets starting in 1983, which allows the computation of meaningful statistics.

Site-specific weather and current data at the sites were compiled from existing atlases. Environment Canada records at several weather stations were analysed and compared. From these comparisons, Mont-Joli was designated as the most representative for the sites further north and Quebec for the sites to the south. Hourly temperature records data since 1953 were used to compile total annual cumulative freezing-degree-days (FDDs). Statistical analysis of annual FDDs provided a ranking of ice seasons from which cold, normal and warm winters were identified.

Interviews were conducted with more than 20 knowledgeable persons, and discussion notes were prepared.

A narrative description of the 2003 ice season, including numerical weather and ice data was presented. All sites were inspected from the ground on January 15, February 19 and March 5, 2003, and from the air on March 6, 2003. Photographic records are included.

The report includes a general assessment of ice conditions at each site and preliminary estimates of ice loads for the marine structures.

Key findings

Site-specific ice condition may be assessed from River Ice Charts (1980 to present). Earlier Historical or Regional Charts (1959 to 1979) are suitable to characterize ice conditions in the Gulf but are not sufficiently precise to discriminate conditions between sites in the estuary.

Ice conditions affect navigation in the Gulf much later in the season than in the estuary.

According to the annual FDD figures at Mont-Joli, 1972, 1973, 1974, 1976, 1977, 1992, 1993, 1994 are "cold" years, and 2003 is slightly colder than "normal".

For Quebec, the cold years are 1959. 1968, 1972, 1976, 1990, 1992, 1994, 2003.

Common cold seasons to both weather stations are underlined. 2003 is the 11th coldest out of 50 years at Mont-Joli, and the 8th coldest in 50 years at Quebec. Therefore, 2003 falls in the 16% to 22% coldest percentile, and is therefore a moderately severe year for climate, occurring on average once every 5 years.

Based on a detailed analysis of River Ice Charts from 1980 to present, the most severe ice conditions occurred in years 1992, 1993 and 2003.

Preliminary indices of Regional ice conditions in the Gulf, compiled by the Canadian Ice Service and Institut Maurice-Lamontagne personnel, indicate good correlation between severe ice seasons at the sites and in the Gulf. According to this index, cold years are 1972, 1992, 1993 and 2003.

2003 represents a recurrence of one in 10 years, or the 10th percentile of highest severity, for ice severity.

All severe ice seasons identified in the last 40 years (1963-2003) are colder than normal. Therefore, cold weather is a necessary condition to generate severe ice conditions, but not a sufficient condition. In other words, cold years are not necessarily difficult ice years, but difficult ice years are usually cold.

All six (6) sites have high tides, strong tidal currents, dynamic ice conditions. There appears to be no tendency for any of the sites to become congested with ice for very long periods. A single episode of ice jamming in the narrow channel near Quebec City is reported. This occurred in March of 1984 and navigation was stopped for four (4) days. The probability of such a jam may be assumed to be less than once in twenty years but further study of this event is deemed useful to better understand its causes and estimate its likelihood.

Large *batture* floes are a potential threat at Kamouraska, less likely at Cacouna and Île Verte. Their presence is even less likely near Quebec where any large ice floe is routinely managed and broken by icebreakers.

The ice force to be considered for the design of the most exposed 30 m dolphin, has been estimated. A factored design load between 40 and 50 MN is recommended. It is noted that there are few full scale measurements of freshwater ice forces on wide structures. If the ice force governs the overall stability of the dolphin, then full scale tests on wide structures would be useful. A rational determination of the load factor based on a probabilistic analysis is needed to provide reliable design criteria.

Investigation of ice conditions in the Gulf were not included in this study, but have been examined to some degree, using preliminary indices, supplied by specialists from the Canadian Ice Service and Institut Maurice-Lamontagne. As far as we know, winter navigation with large tankers commuting to the Ultramar terminal has not been a problem, presumably because these ships are very powerful and massive, and timing of arrival and departure time can vary by one or more days without affecting operations. If timing issues are critical, then conditions in the Gulf should be studied in some detail.

Site selection recommendations

The six (6) sites are feasible, from the point of view of ice conditions. Other selection factors, which are believed important, are mentioned.

We first review the sites furthest to the north:

- **Île Verte**, has less ice but is very exposed. Because there is more open water, the wave climate is very severe, and the site is prone to sea-spray. There is little natural means of protection against the downstream propagation of a spill. In addition, the site is far from shore, so a considerable jetty is required if access by road is needed. There are bird sanctuaries near by. Most persons interviewed have rejected this site, for one or more of these reasons.
- **Kamouraska** has less database for ice conditions, is more vulnerable to impact by *batture* floes, far from the shore, and close to an bird refuge located in the neighbouring islands.
- **Gros Cacouna** is already an industrial site for which there is a some marine operating knowledge available, including ice management experience. It is close to shore, better protected to some extent from large floes, severe sea states and winds. The site has successfully passed previous environmental reviews and full public hearings, for a LNG terminal (BAPE, 1981). Episodes of sustained winds from the NW may cause ice to accumulate and remain at the site for hours or days, but the ice cover will soon be cleared away with a suitable combination of winds and tidal currents.

Of these three (3), **Cacouna** is the only one we would retain for further consideration.

Neither of these three (3) sites is close to a local tug boat operator in the winter. The tug operation at La Baie, up the Saguenay River, shuts downs in the winter, so the closest support would presently have to come from Quebec or to be organized locally.

We now examine the three (3) other sites, closer to Quebec:

All three (3) sites are close to the shore, and have very similar ice, hydraulic and weather conditions.

- **Pointe Saint-Vallier** is the least developed, an advantage compared to the two (2) others, a large area of water for marine traffic, slightly less current velocity, but a draft limitation to 11 m in the immediate vicinity of the terminal.
- **Pointe-de-la-Martinière** is located along a narrow passage south of Île d'Orléans with river and ice conditions very similar to those at the Ultramar terminal. Deep water is available very close to shore.
- The existing **Ultramar** site is a useful reference because of the relevant marine operations experience gained in the last thirty years with large oil tankers, similar in size to LNG carriers. It has enjoyed safe operations and no reported delays. The site is close to an urban area having little land available for storage and processing facilities close to the terminal.

Therefore, since all sites are acceptable from the point of view of ice conditions, further work needs to be done to better establish the other feasibility issues at the three (3) sites closest to Quebec.

Recommended future work

- assessment of navigation conditions in the Gulf: if timing of arrivals is critical, probability and duration of delays in travel time through the Gulf, should be assessed using the Canadian Ice Service database, and some numerical modeling;
- advance the conceptual design of the terminal, establish the sizing of a typical dolphin, confirm design loads (including ice, waves, currents, seismic) and stability analysis;
- with respect to ice conditions, resolve current uncertainties common to all sites: analysis of 1984 jam, discuss instrumentation for ice forces on wide structures with National Research Council of Canada and Laval University, sheet ice and *batture* ice resistance;
- as appropriate to the final site, resolve ice-related uncertainties: sheet ice and *batture* dimensions (from satellite imagery or other), *batture* resistance and dimensions, extreme values of ice features, probabilistic treatment of ice forces, influence of terminal on hydraulic and ice regime, influence of fast ice on hydraulic regime, optimization of terminal layout to ensure ice clearing capability, finalize design of terminal.

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Acknowledgements

We gratefully acknowledge the contributions of all persons listed on pages 9-1 and 9-2, who accepted to meet us, to spend time in telephone conversations and to provide precious information.

Olivier Kervella patiently analysed thousands of ice charts, processed the statistics and was a pleasant collaborator during the interviews and field trips.

Special thanks are extended to Professor Brian Morse, who provided stimulating discussions and commented the manuscript.

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