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Evolution of Landfast Ice Coverage in James Bay

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James Bay is a large mixing area of salt water from the Hudson Bay marine environment and fresh water from runoff discharged mainly through 11 large rivers where winter ice processes are influenced to a certain extent by salt and fresh water mixing. Landfast ice (i.e., fixed shore ice) is often used by coastal communities in the James Bay area for transportation during winter months using snowmobiles. Therefore, the extent of landfast ice along the James Bay coastline is important for land use and any changes to this extent may have significant impacts on the lifestyle of local communities. The eastern coastline has experienced changes in recent decades that might have affected ice processes, namely hydrologic modifications due to hydroelectric development by Hydro-Québec and climatic changes that have been observed worldwide. A statistical analysis in the form of summarized ice charts of the ice extents in the heart of winter have been compiled for the past four decades to highlight any recent changes in ice coverage using data from satellite imagery and ice charts produced by the Canadian Ice Service. A statistical analysis has also been carried out on the freeze-up and breakup dates. Moreover, statistical analysis of hydrological and climatic data have been carried out to determine long term and short term trends of the parameters which influence ice processes. The trends detected in the overall ice regime related to the extents of landfast ice, as well as freeze-up and breakup conditions, have been correlated to the hydrologic and climatic parameters to try to explain the observed changes, and this paper presents the results obtained.

1. Introduction

James Bay is a large mixing area of salt water from the Hudson Bay marine environment and fresh water from runoff discharged mainly through 11 large rivers. Winter ice processes in the area are influenced to a certain extent by salt and fresh water mixing. Landfast ice is often used by coastal communities in the James Bay area for transportation during winter months using snowmobiles. Therefore, the extent of landfast ice along the James Bay coastline is important for land use and any changes to this extent may have significant impacts on the lifestyle of local communities.

The eastern coastline has experienced hydrologic changes in recent decades due to hydroelectric development by Hydro-Québec. In addition, the climatic changes that have been observed worldwide have also had an effect on the winter environment of James Bay.

The objective of this study was, first and foremost, to highlight any changes to the extents of landfast ice along the James Bay coast. Secondly, the analysis aimed at understanding ice processes in James Bay and their long term evolution over the period from 1970 to 2016 in order to determine whether changes to the extents of landfast ice are caused by climatic changes or manmade hydrologic impacts caused by hydroelectric production.

The study area includes the entirety of James Bay (Figure 1) and is bounded to the south by Hannah Bay and Rupert Bay and to the north by Cap Jones on the eastern coast (Québec) and Polar Bear Provincial Park on the western coast (Ontario). The estuaries of the La Grande and Eastmain rivers, as well as Rupert Bay are of particular interest within the study area since they have been subject to hydrologic changes due to Hydro-Québec's hydroelectric developments.

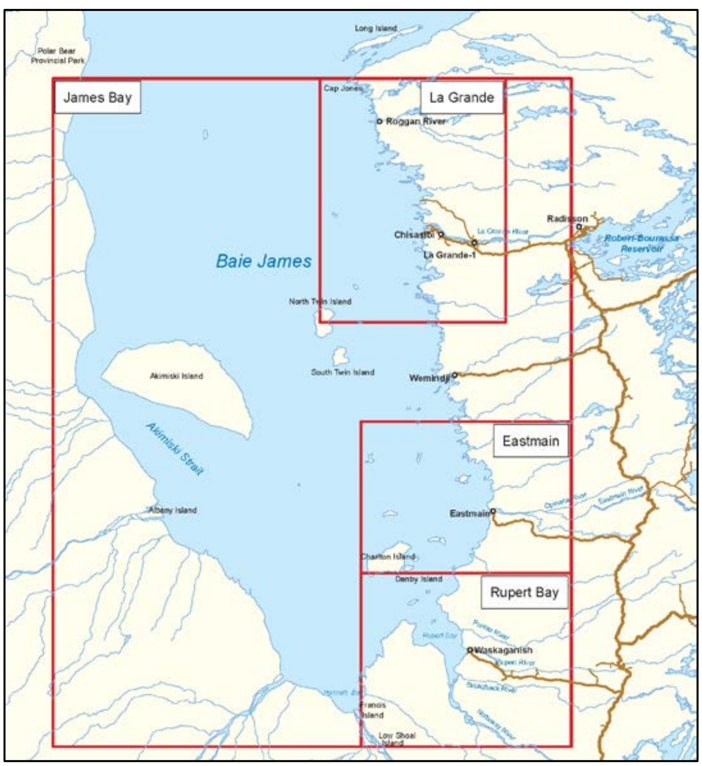


Figure 1: James Bay study area.

2. Methodology

First and foremost, the present study consisted of integrating all available information related to landfast ice coverage in James Bay since 1970, both within Hydro-Québec and publicly available. This step included a thorough literature review and the collection of geographic data portraying landfast ice coverage during the period from 1979 to 2016. The geographic data used includes regional ice concentration maps from the Canadian Ice Service, Landsat satellite images obtained through the *Earth Explorer* interface from the U.S. Geological Survey and MODIS satellite images obtained through the *Worldview* interface from NASA. No geographic data was found for the period from 1970 to 1978, which precedes Hydro-Québec's hydroelectric development in the region and therefore corresponds to the natural conditions of the rivers on the eastern coast of James Bay.

The various parameters which influence ice dynamics were analysed within the scope of the study. Such parameters include flows of the main eastern coast rivers, air temperatures characterizing local freezing seasons, solar radiation and maritime storms. Statistical analyses of aforementioned parameters were performed for the 1979-1997 and 1998-2016 periods in order to draw clear trends.

Moreover, the evolution of landfast ice cover in James Bay was documented through a long term statistical analysis of freeze-up and breakup dates, as well as yearly mapping of the maximum landfast ice cover extent observed during the heart of winter from January to April. The review of nearly four decades of geographic data illustrating the yearly cycle of landfast ice cover evolution has enabled a better understanding of observed ice processes. Finally, the analysis of meteorological and hydrological parameters affecting ice dynamics has allowed the correlation of changes in these parameters to the evolution of ice dynamics.

3. Literature Review

The literature review that was performed allowed for a better understanding of ice dynamics in Rupert Bay, as well as the identification of certain elements related to ice dynamics in James Bay and the estuary of the La Grande River. However, no specific information was found on the ice dynamics surrounding the estuary of the Eastmain River.

Ice processes in James Bay have been studied as early as the 1970s by El Sabh and Koutitonsky (El Sabh and Koutitonsky, 1974). However, most of the work has been focused on overall ice concentrations without much distinction between the extents of ice floes and landfast ice. Michel (Michel, 1973) has also described the oceanographic and hydrologic characteristics of James Bay. The Coriolis force drives a circular oceanic current that brings salt water from the northwestern tip down to the southern part along the western shoreline and then back up along the eastern shoreline exiting the bay from the northeastern tip. The current gets supplied with fresh water passing through the river estuaries and exits the bay with water at a slightly lower salinity. Mixing between salt and fresh water is driven by the turbulence produced by the wind and waves which implies that fresh water plumes are more concentrated near the surface under the ice cover in winter. The tidal currents are also an important parameter, although tidal movements are damped by up to 65% during winter in the southern part of James Bay due to the presence of the coastal ice shelf.

Michel also describes the ice regime in James Bay. James Bay freezes up in early December. The initial ice cover forms in coves and in river estuaries over fresh water where ice formation requires less heat loss. The coastal ice shelf then forms by tiling of ice floes that are drifting under the action of wind and currents. Landfast ice is generally smooth with thicknesses that can reach metric values at the end of winter, but rough ice ridges reaching up to several meters high can also form when the floes are pushed against the leading edge by winds and currents. In the middle of the bay, high concentrations of ice floes with a submetric thickness keep drifting with the wind and currents from January to May. In spring, the coastal ice shelf is dislocated from south to north by the action of wind and currents under warm conditions. It is not clear, however, which heat source contributing to those warm conditions (air temperature, warm fresh water, solar radiation) is predominant during breakup.

The La Grande River estuary has been studied from the 1970s because of hydroelectric development. The La Grande River is the largest river on the east coast of James Bay and has experienced an increase in winter flows throughout the decades. The Société d'Énergie de la Baie James (Société d'énergie de la Baie James, 1994) presents a small description of the ice conditions at the La Grande estuary in natural conditions and compares them to the conditions after construction of the LG2 and then LG1 hydroelectric projects. Before 1979, the estuary had a stable ice cover 6 months per year that the local communities used for snowmobiling. After construction of LG2, warm water from the LG2 reservoir reduced that period to 3 months with frequent openings during warm spells. The ice cover over the river mouth was deemed unsafe and a bridge was built over the river to replace snowmobiling trails. After construction of LG1 in 1991, the ice cover at the river mouth became less stable with an increase in flow rates and water temperatures. Messier & al. (Hydro-Québec and GENIVAR Groupe Conseil inc., 2005) describes the extent of the ice shelf and its relation to the fresh water plume and specifies that during breakup an opening of 5-8 km in radius forms at the river mouth while the ice shelf remains intact. The ice conditions were predicted after partial diversion of the Rupert River towards the La Grande River and showed that the winter flows were likely to increase and the leading edge in the river would be pushed further downstream towards the estuary.

In the southern limit of James Bay, the Rupert Bay is a perfect example of ice formation within a fresh and salt water mixing environment. Michel gives a thorough description of the natural ice dynamics in Rupert Bay. Freeze-up occurs from south to north over a period stretching typically from 40 to 950 freezing-degree-days. The first ice patches are formed in tidal flats and low depth areas and then the fresh water sector to the south of Stag Rock freezes over. The mixing middle area between Stag Rock and Stag Island freezes next and finally three open water channels remain open in the maritime northern part of the bay and freeze latter with high concentrations of ice floes that are transported by tidal currents and jam into the channels. Rupert Bay remains completely covered in ice throughout winter with a predominance of smooth ice in the southern part and hummocked ice in the northern part. During spring time, the creek and river mouths lose their ice covers first due to the supply of high flows of warm fresh water. Open water also appears in tidal flats and low depth areas while the northern channels in the maritime part open up. The southern part of the bay then opens up completely due to the high supply of warm fresh water. The remaining ice in the bay thaws completely by early June. The springtime processes seem to be less influenced by air temperatures as opposed to freeze-up but are more closely correlated to total heat budget ranging from 4 to 294 MJ/m^2.

4. Hydrological and Meteorological Analysis

Daily flows of the La Grande River were collected for the 1979-1997 and 1998-2016 winters. By comparing these two periods, average flow has shown a 16% increase at the beginning of winter and an approximately 32% increase during the heart of winter as well as the beginning of spring. The flow of the Eastmain River has not been subject to any specific changes since 1979 and today represents only 10% of its natural conditions flow, which is why this area is of particular interest, as it serves as a control case. As for Rupert Bay, fresh water flow into the bay has only been reduced by 18% in comparison to natural conditions following the diversion of the Rupert River towards the north in 2010. It should be noted that flow reductions for those two cases are being examined for the winter season, which is already a period of relatively low flow for natural rivers.

Solar radiation levels at the mouth of the La Grande River during the last four decades were compared in order to determine their effect on the evolution of landfast ice coverage in James Bay (Figure 2) (Bird and Hulstrom, 1981). Results show a constant winter evolution in solar radiation from one decade to another and therefore this parameter cannot be a change factor. On a yearly basis, solar radiation reaches its minimum intensity during the winter solstice on December 21st and increases rapidly starting in mid-January. During the month of May, solar radiation intensity is more than five times its December value.

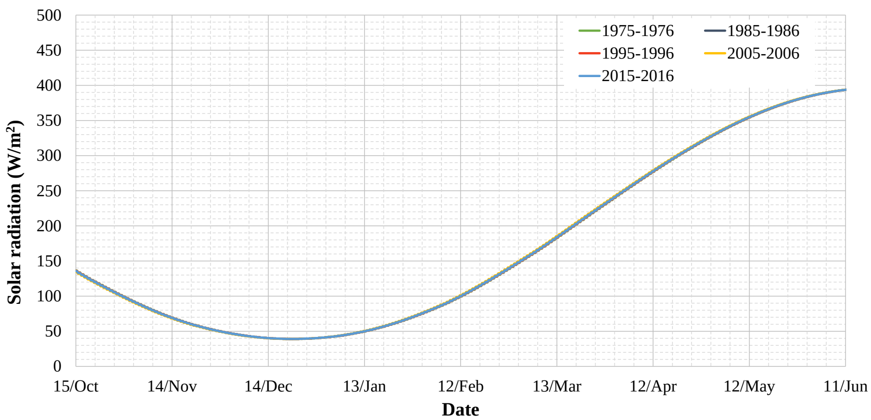


Figure 2: Daily solar radiation average at the mouth of the La Grande River.

Average daily temperatures measured at La Grande on the eastern coast of James Bay and at Moosonee south of James Bay were analysed for the 1979-1997 and 1998-2016 periods (Environment Canada, 2017). As illustrated in Figures 3 to 5, results indicate shorter and less harsh winters in recent years for both meteorological stations. Moreover, on average 1998-2016 freezing seasons began seven days later at Moosonee and nine days later at La Grande and ended a few days earlier for both stations in comparison to 1979-1997 winters. It must be noted that the variations observed in terms of end dates of the freezing season are not as significant as those observed for the start dates of the freezing season because the former also depend, to some extent, on the intensity of solar radiation in spring which remained constant throughout the decades. As for average winter temperatures during winter, it has increased by about 1°C for both sites.

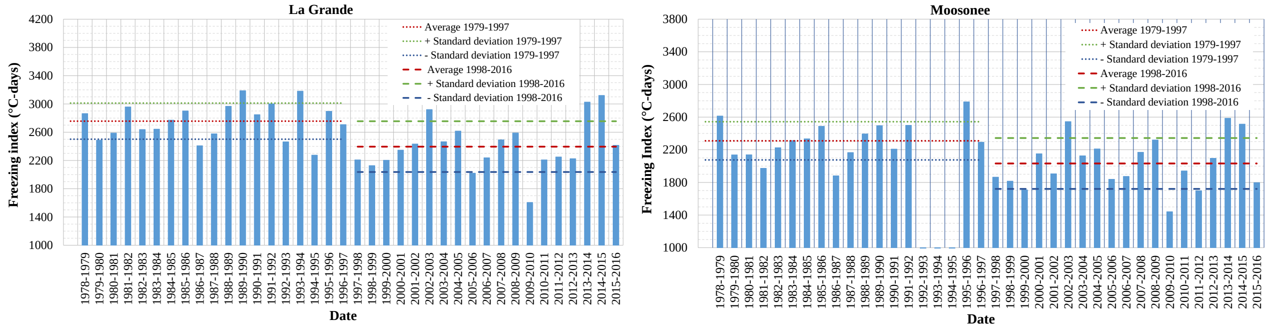


Figure 3: Freezing Index at La Grande and Moosonee from 1979 to 2016.

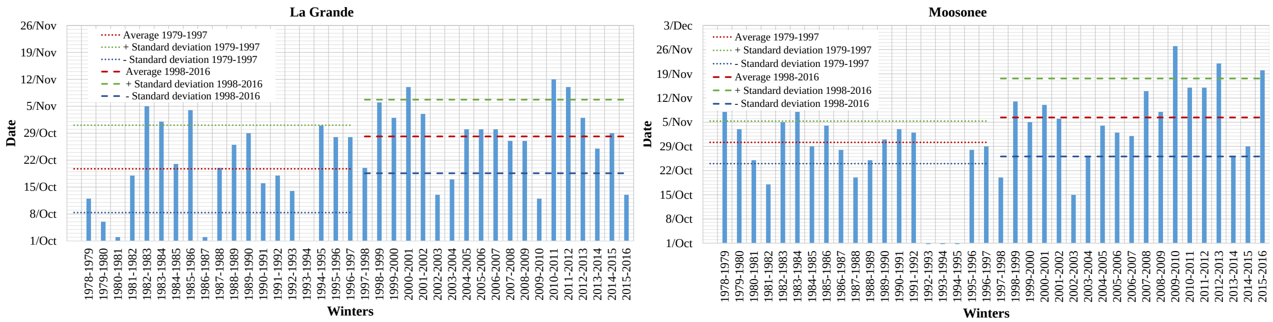


Figure 4: Beginning of winter dates at La Grande and Moosonee from 1979 to 2016.

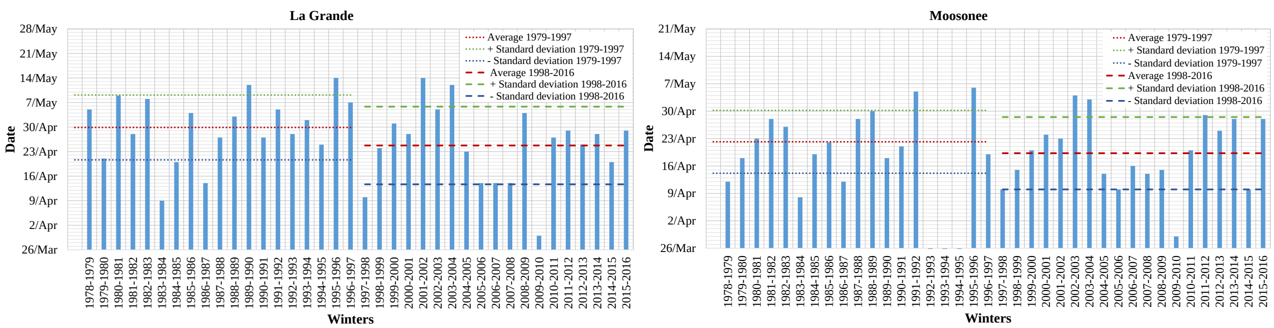


Figure 5: End of winter dates at La Grande and Moosonee from 1979 to 2016.

The analysis of available wind measurements from 2002 to 2016 measured at Rupert Bay (Hydro-Québec, 2017) has shown that dominant winds come mainly from the north-north-west and the north-west, as well as the south-south-east and south-east. High winds result in a positive storm surge when approaching from the north-north-west and north-west and in a negative storm surge when approaching from the south-south-east and south-east. Water levels modelled from 1980 to 2013 in Rupert Bay (Lasalle | NHC, 2016) have resulted in a longer and more intense storm season for the 1998-2013 period in comparison to the 1980-1997 period as illustrated by the exceedance probability of both positive and negative storm surges illustrated in Figure 6. A storm season expanding beyond the month of October could cause a later freeze-up in James Bay. Moreover, the intensification of such storms, especially those coming from the north-north-west and north-west, would have a similar effect on freeze-up dates in James Bay. During spring time, no significant changes have been identified in terms of storm intensity between the 1980-1997 period and the 1998-2013 period.

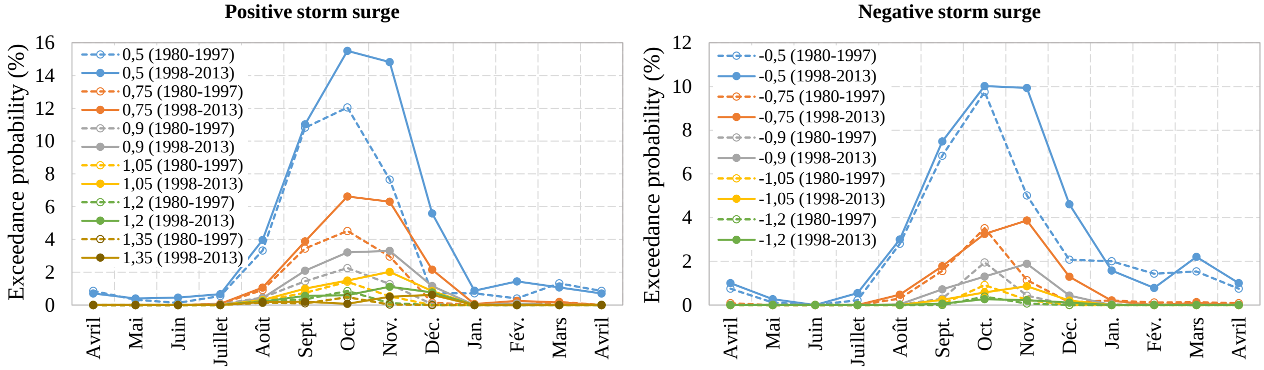


Figure 6: Comparison of exceedance probability of positive and negative storm surge in Rupert Bay for 1980-1997 and 1998-2013 periods.

5. Ice Regime in James Bay

<u>Freeze-up</u>

Freeze-up in James Bay typically lasts around 50 days from late November till early January. It starts with the formation of an initial ice cover between the western coast and Akimiski Island and then the formation of an ice shelf along the southern and western coastlines. Following this initial phase, ice begins to form in the coves along the eastern coast and then develops into a continuous coastal ice shelf. The last phase is the outward push of the southeastern ice shelf towards the islands located north of Charlton Island. Figure 7 illustrates the formation of the southeastern ice shelf by tiling of drifting ice floes being pushed against the leading edge by the currents.

Figure 7: Modis image from December 3rd 2013 showing the formation of the southeastern ice shelf.

Freeze-up dates corresponding to 50% progress of ice coverage are presented in Figure 8 for the 1980-1997 and 1998-2016 periods. For both periods, the freeze-up dates occur on average around early January and don't seem to be affected by the recent delay of the beginning of the freezing season (Figure 4). This observation may be explained by the fact that freeze-up occurs long after the beginning of the freezing season, namely 73 days on average after the former. In addition, freeze-up dates seem to be closer to the winter solstice, which indicates that the middle part of freeze-up may be synched with the minimum intensity of solar radiation. Since the intensity of solar radiation hasn't changed over the decades, it may explain why no change in freeze-up dates is noticeable.

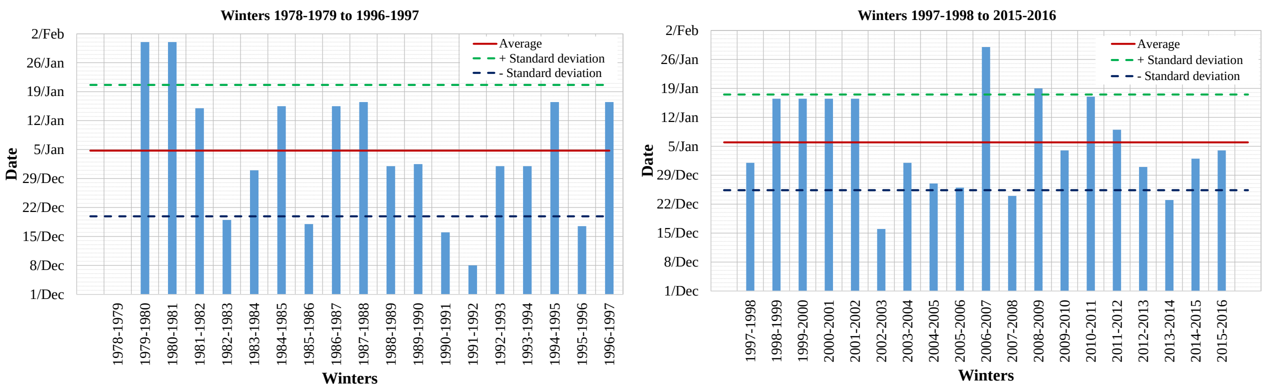
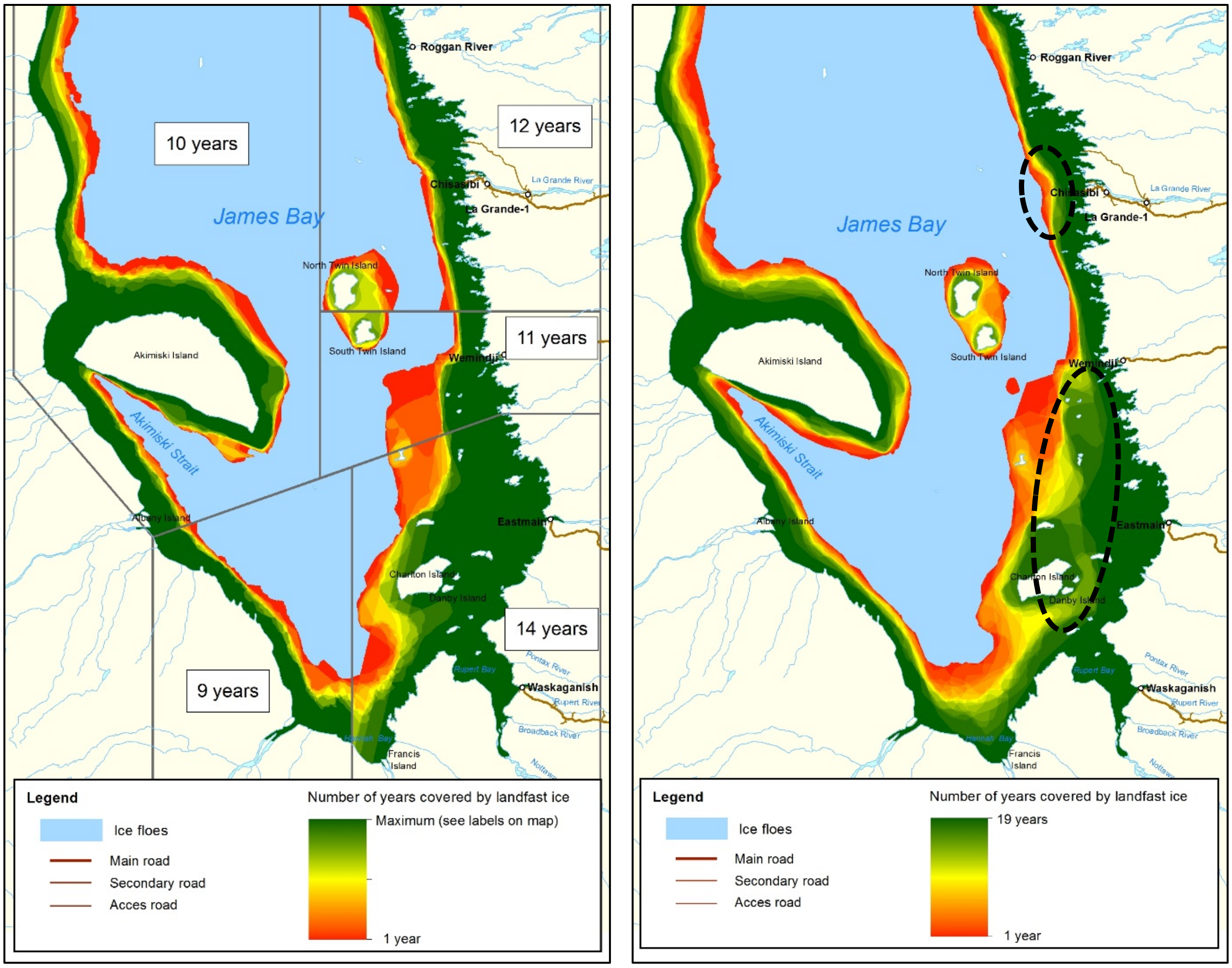


Figure 8: Comparison of freeze-up dates in James Bay for 1980-1997 and 1998-2016 periods.

A similar analysis was carried out for the river mouths of the Eastmain and La Grande rivers, as well as Rupert Bay. The little available data for the 1980-1997 period resulted in an inconclusive comparison with the 1998-2016 period. However, a trend for later freeze-up dates in recent years in comparison to former years was noticed for all three sectors indicating a possible effect of both late and mild freezing seasons and late and harsher storms on these estuarine environments which freeze-up earlier than James Bay as a whole.

<u>Heart of winter</u>

Figure 9a and 9b presents a comparison of fixed ice coverage in the heart of winter (January to March) for the 1980-1997 and 1998-2016 periods. The color code indicates the probability of an ice cover over the evaluated period. Based on Figure 9a and 9b, for the two studied periods, landfast ice coverage extends further out on the eastern coast in comparison to the western coast. This difference can be explained by the predominant north-north-west and north-west winds that keep pushing ice floes against the leading edge along the eastern ice shelf. In addition, landfast ice engulfs Akimiski Island on the west coast and the islands in the eastern part of the bay, which confirms that the landfast ice formation mechanism is highly dependent on the presence of leading edges for the ice floes to attach themselves to. Therefore, the areas with a higher concentration of islands, such as the southeastern corner of the bay, tend to develop a larger fixed ice coverage.



(a) *(b)*

Figure 9: Comparison of the occurrence of landfast ice extent in James Bay for 1980-1997 (a) and 1998-2016 (b) periods.

Comparing both periods shows that there are differences in color tones between both periods. Of particular interest, it can be noticed that, in recent years, the ice coverage along the southeastern corner and locally at the La Grande river mouth has been reduced over the years (see encircled areas in 9b). Locations with a receding ice shelf are the areas where fixed ice tends to form last and at relatively high salinity. Since consolidation of sea ice requires more heat loss than fresh water ice, the most likely cause for the loss in ice coverage in the southeastern corner is the milder winter air temperatures as shown by the lower freezing indices at La Grande and Moosonee (Figure 3). As for the La Grande river mouth, a more focused inspection of the ice dynamics in that area has shown that the coastal ice shelf for both periods tends to form later than the shelf just to the north and to the south of the La Grande river mouth because of the warm water coming out of the river. Once the water coming out of the river is cooled to freezing point, the ice shelf starts to form. However, the delay at this specific location is carried over in the heart of winter when the entire leading edge progresses at the same rate.

For the period of 1998-2016, the small notch in the ice shelf in front of the La Grande river mouth is more significant than the one for the period of 1980-1997. This observation can be explained by the late beginning of winter at La Grande (Figure 4) and the milder winter temperatures that follow (Figure 3). These two meteorological effects can only delay cooling of fresh warm water and result in a later ice shelf formation, which is responsible for a deeper notch at the river mouth.

It should be mentioned that the increase in winter flow rates coming out of the river do contribute to the delay in coastal ice formation at the La Grande river mouth since heat flux, which resists ice formation, is the direct product of flow rate and water temperature. However, it is a secondary effect in comparison to air temperatures because the increased flow rates would not delay ice formation significantly if the water was cooled down to freezing point at the same rate as the period of 1980-1997. This statement can be demonstrated by examining the area immediately at the exit of the river mouth in Figure 9a and 9b. This area is always closed in the heart of winter for both periods and for all years, in spite of the high flows in the heart of winter. It should also be reminded that fresh water remains concentrated in the top layers at river mouths and the coastal ice shelf at those locations are mostly composed of fresh water ice once the water temperature reaches 0°C. Therefore, fresh water coming out of the river seems to be only problematic at freeze-up while the warm river discharge is still being cooled, but not in the heart of winter once the water temperature remains at freezing point.

It should be reminded that the flow rate at the Eastmain river mouth remained unchanged through both periods, yet changes to the ice extent were clearly noticeable in that area. On another account, Rupert Bay has experienced a reduction in flow rate due to the Rupert River diversion but the northern part of the Bay has experienced the same type of changes as the ones reported at the Eastmain river mouth. Therefore, there seems to be no clear correlation between the supply of fresh water and the observed recession in the extents of landfast ice in spite of the fact that changes to fresh water supply certainly affect plume extents and depths.

Breakup

Breakup takes about one month from early May till early June. It starts with the thawing of the southwestern river estuaries, first Moose River and Albany River, followed by Attawapiskat River. Those three rivers during freshet release warm water in a shallow area of James Bay that can easily warm up from solar radiation once the first open leads are formed, thus rapidly thawing the ice shelf in the entire area. Around the second week of May, the La Grande river mouth opens up due to warm water being discharged into James Bay. At that same time, the southeastern part of James Bay including Rupert Bay opens up and the breakup momentum steadily moves up north along the eastern coast. Finally, the western coast north of Akimiski Island opens up last.

Breakup dates corresponding to 50% thaw are presented in Figure 11 for 1980-1997 and 1998-2016 periods. On average, breakup occurs around May 21st for the 1980-1997 period and occurs about 5 days earlier for the 1998-2016 period similarly to the recent 3-5 day shift in the end of the freezing season (Figure 5). Unlike freeze-up, this dependency to air temperatures may be explained by the fact that breakup occurs shortly after the end of winter, namely 22 days on the average after the former.

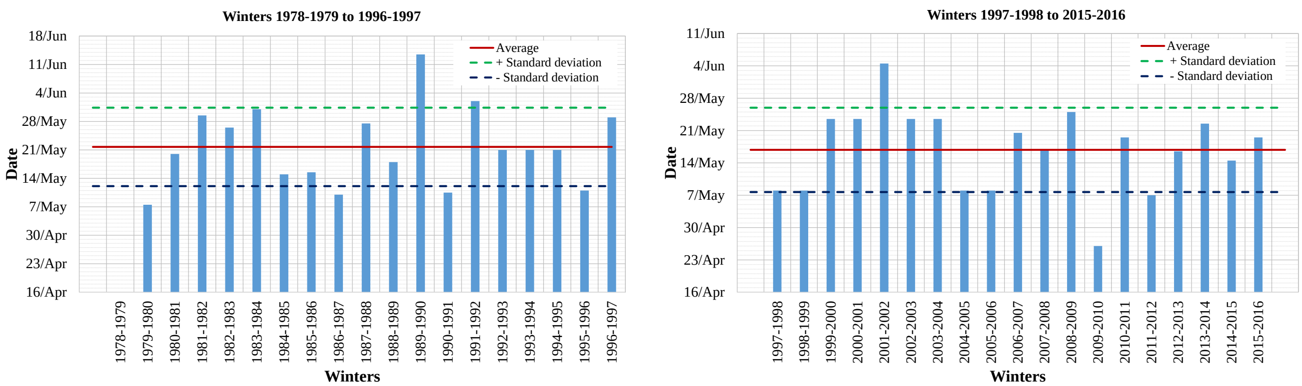


Figure 10: Comparison of breakup dates in James Bay for 1980-1997 and 1998-2016 periods.

This dependency also suggests that breakup in James Bay is synched to spring freshet which is triggered by the end of the freezing season for natural rivers, unlike highly regulated rivers which tend to store runoff in reservoirs during spring. A similar analysis of breakup dates at the Eastmain river mouth and at the La Grande river mouth was carried out and showed that the breakup dates remained unchanged for those two areas that include highly regulated rivers. It seems solar radiation, which remained steady throughout the decades is the driving parameter for such areas.

6. Conclusion

Ice processes in James Bay seem to be mainly driven by meteorological parameters, namely solar radiation and air temperatures. Maritime storms may have also impacted the freeze-up dynamics in estuarine environments. The global trend towards warmer winter air temperatures have been confirmed in the James Bay area and have impacted the extents of landfast ice in certain areas along the coast. Ice maps integrating data from the past four decades allowed to identify receding coastal ice shelves on the southeastern coastline where the ice shelf forms late and forms in a completely saline environment that requires relatively high heat loss, which becomes difficult to achieve with warmer air temperatures. A more subtle impact was also noticed at the La Grande river mouth due to, primarily, a delay in freeze-up at the river mouth because of delayed and milder freezing seasons. As a result, hydrological changes due to hydroelectric development, unlike meteorological changes, don’t seem to have had a noticeable effect on the extents of landfast ice.

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