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# Floating Ice and Ice-Pressure Challenge to Ships

Ivana Kubat, Captain David Fowler, and Mohamed Sayed

## ABSTRACT

The presence of floating ice in northern regions has significant economic, environmental and social implications. Navigation is one of the areas where the influence of floating ice is particularly evident. The history of ice threats to navigation and hardships experienced by early mariners are well known. At present, even with all the new technologies, ice can pose serious challenges. A major threat arises when ice around a ship starts to converge. The compression or ice pressure builds up if wind and water currents drive the ice cover against a land boundary. The ice cover compresses and ice accumulates to form ridges. If a ship is caught in such a situation, pressures on the hull will be high. Additionally, the ridges can introduce serious impediments to ship progress. Consequently ice resistance would dramatically increase, and the ship can become beset. In extreme cases, ships can be damaged, and smaller vessels can be completely lifted onto the ice.

To understand how ice interacts with ships, we must start with ice properties and characteristics of ice covers. Ice ridges, for example, may represent formidable obstacles to ships. The way those ridges form and their properties determine the level of resistance that ships may encounter.

Although the effects of ice pressure are important over all Arctic and northern waters, the focus of this discussion is on the Canadian experience. The particular conditions that lead to ice pressure build-up and the impact on shipping at various specific locations in Canada are

22 surveyed. The discussions conclude with a description of a Captain's experience in dealing with  
23 ice pressure on the Great Lakes.

24

## 25 **1 INTRODUCTION**

26 Seasonal floating ice covers an appreciable part of northern oceans, rivers and lakes. Ice is an  
27 important consideration in many transportation endeavours and can be an obstacle or an aid.  
28 Throughout the north, hunting, fishing and travel by indigenous peoples revolve around the  
29 presence and action of floating ice. There are few road and rail links to the remote communities  
30 of the Canadian Arctic. Most coastal and island communities rely on the northern Sealift, the  
31 annual re-supply by ship of goods and materials. The alternative is costly air transport. While  
32 ice is a major threat to shipping, ice roads provide efficient and relatively safe means of  
33 transport. Arctic regions contain substantial oil, gas and mineral resources. Dealing with ice is  
34 central to the ongoing and accelerating development of these resources. Resource projects not  
35 only have to deal with ice regarding transportation, but also have to consider it in facility design.  
36 For example, offshore drilling platforms and shipping terminals must be built to withstand ice  
37 forces. Ice is also a major consideration in the prevention of and response to any risk of  
38 pollution. In addition, tourism is increasing in the Arctic, particularly voyages by cruise ships.  
39 Floating ice is both an attraction and a danger to these ventures.

40

41 In dealing with ice threats, it is important to consider the progressive change in ice conditions  
42 due to global climate change. The Intergovernmental Panel on Climate Change (IPCC) special  
43 report (IPCC, 2019) states that "Between 1979 and 2018, Arctic sea ice extent has *very likely*

44 decreased for all months of the year”. Whereas the quoted statement refers to sea ice from a pan-  
45 Arctic perspective and is not applicable in many regions of the Arctic year-round as implied,  
46 climate change will nonetheless change ice threat to navigation and offshore resource  
47 developments in most areas for some months of the year.

48 In the more southern waters of the Great Lakes, the formation and movement of ice affects a  
49 multitude of users. Ice conditions are of concern to mariners, industries, municipalities, property  
50 owners, recreational groups, and the general public.

51 There is a large commercial shipping industry in Canada operating year-round, although activity  
52 is much lower between December and March when the St. Lawrence Seaway is closed. Ferries  
53 operate throughout the Great Lakes but they tend to be small vessels for local traffic. Those that  
54 continue to operate in the winter have to suspend operations whenever ice pressure is present.

55 There are some areas of commercial fishing such as in Lake Erie’s Long Point Bay and southern  
56 Lake Huron. Many fishing vessels operate year round and often brave the ice to carry out their  
57 trade (Figure 1). There is also a major fishing industry operating along the East Coast of  
58 Canada, often hampered by severe ice conditions.

59 Insert Figure 1 here

60 **Figure 1 Great Lakes fishing vessels under icebreaker escort near Goderich, Ontario.**

61 The Great Lakes basin is home to a population numbered in the tens of millions. Numerous  
62 water intakes for municipal drinking water and industrial water supply are located throughout the  
63 lakes. Ice conditions, particularly moving ice and ice under pressure, can cause problems with  
64 both the amount and quality of water available at the intakes. Icebreaker activity near intakes  
65 can also cause difficulties. In some areas, hydroelectric facilities set up ice booms to prevent

66 moving ice from flowing into the intakes. High ice pressure has been known to burst the ice  
67 booms resulting in problems for the power utility. When the ice booms are in place on the St.  
68 Lawrence River, shipping traffic is restricted or stopped.

69 Waterfront property and facilities may be damaged by adverse ice conditions. Damage to  
70 riverfront property is particularly prevalent in the spring when moving ice carries away docks,  
71 shoreline protection and occasionally buildings (Figure 2). Severe ice pressure can push ice  
72 ashore onto areas of low elevation and has been known to overwhelm entire buildings. Many  
73 property owners try to protect their docks and facilities with bubbler systems. While these are  
74 effective in land fast ice conditions, they are useless when the ice is under pressure and moving.  
75 In some areas of the Great Lakes, fish farms have extensive exposure to ice. Special  
76 coordination is required with icebreakers when conducting spring ice clearing operations. For  
77 northern communities, ice pile-ups against docks and in harbours during the summer may  
78 severely hinder operations.

79 Insert Figure 2 here

80 **Figure 2 Yukon River Ice Jam near Eagle, AK, 13 May 2009.** *Aerial photo by Matt Nolan.*

81 Snowmobiles, all-terrain vehicles and even road vehicles use the ice for travel when it becomes  
82 sufficiently thick. This generally occurs only on areas of land fast ice, such as the North Channel  
83 of Lake Huron, the channels of Georgian Bay, the Labrador Coast, and in Arctic regions. Some  
84 areas have routes that are marked with small evergreen trees placed in the ice and snow. Ice  
85 movement severely disrupts or destroys these routes and causes safety hazards for users. There  
86 is sometimes conflict between ice route users and marine traffic.

87 Using the ice for recreational activities is a common occurrence in some areas. In addition to the  
88 highly popular pastimes of snowmobiling and ice fishing, people use the ice for sail boarding,  
89 kite boarding, ice boating, Nordic skiing and skating.

90

## 91 **1.1 Ice properties and Behavior**

92 The structure and mechanical properties of floating ice are rather complex. Both saline sea ice  
93 and fresh water river and lake ice have a predominantly columnar structure. Sea ice structure  
94 additionally includes pockets of brine. In general, fresh water ice is stronger and more brittle  
95 than sea ice. The strength of ice increases at colder temperatures, and decreases during the  
96 warming of springtime. Growth of floating ice begins in the cold weather when the surface water  
97 temperatures reaches the freezing point. The balance of heat transfer determines growth rates and  
98 the maximum equilibrium thickness. For example, seasonal ice in the Arctic reaches a maximum  
99 thickness of two metres. The maximum thickness of freshwater ice over Northern lakes and  
100 rivers is much smaller (typically from 0.45 to 0.85 metres for the Great Lakes). Seasonal sea ice  
101 that survives one or more melt seasons is called multi-year ice. Brine drains from such multi-year  
102 ice during the warm season. The ice thus becomes stronger and grows to larger thicknesses than  
103 seasonal ice. There is a rich body of literature dealing with the growth, structure and properties  
104 of ice, comprehensively documented in Michel (1978), and Weeks (2010).

105 Most of the knowledge of ice mechanical properties deals with ice samples that are less than one  
106 meter in diameter. In this small-scale condition, ice structure and deformation are mostly  
107 uniform. At larger scales, ranging from a few meters to a few kilometers, the deformation and  
108 strength of ice are much more complex and not well understood. It is these length scales that

109 affect ships and offshore structures. Over such lengths, the ice cover is non-uniform. It may  
110 contain separate floes, cracks, leads, ridges and accumulations of broken ice blocks (ice rubble).  
111 Such heterogeneous ice covers deform in complex modes when driven by wind and water  
112 currents. As an ice cover deforms in compression or shear, it breaks into blocks that can  
113 accumulate and form ridges and rubble fields. When the environmental forces cause divergence,  
114 tensile stresses create cracks or leads of open water. An ice cover can fail in several ways:  
115 buckling, downward or upward bending, and crushing, as well as cracking or lead opening.  
116 Failure of an ice cover usually encompasses a mixture of those modes. Ships and offshore  
117 structures in the ice can experience such complex interaction processes of ice failure.

118 An important issue on which to focus is what happens when ice around a ship starts to converge  
119 or undergoes compression, as this poses a major threat to navigation. Problems usually arise as  
120 wind or water currents drive the ice cover against a land boundary. The ice cover compresses,  
121 pressures build-up, and ridges form. If a ship is caught in such a situation, pressures on the hull  
122 will be high. Moreover, ridges introduce additional impediments to movement. Consequently ice  
123 resistance would dramatically increase, and the ship can become beset. In extreme cases, ships  
124 can be damaged, and smaller vessels can be completely lifted onto the ice.

125 The following discussion addresses the formation and characteristics of ridges since they form an  
126 important component of the compression processes. The discussion turns next to the build-up  
127 and dissipation of pressure. Examples of besetting events are then surveyed. The chapter  
128 concludes with a section on a Captain's experience in dealing with pressure events over the  
129 Great Lakes.

## 130 **2 ICE RIDGES**

131 Ice ridges form as an ice cover undergoes compressive or shear failure. Ice extending over  
132 hundreds of meters to several kilometres usually deforms over localized zones where ridging  
133 takes place. Once the ice breaks or two areas of ice impinge on each other, ice breaks into  
134 relatively small rectangular blocks typically about five times the ice thickness. Blocks  
135 accumulate to form a sail above water level and a keel below. Pressure or compressive ridges  
136 usually follow narrow paths that may meander (Figure 3). Shear ridges follow distinctive straight  
137 lines (Figure 4). Sometimes, under sufficient environmental forcing, accumulations of ice blocks  
138 or ice rubble coalesce to form wide fields called *hummock fields*.

139 Insert Figure 3 here

140 **Figure 3 Ice Ridge in Gulf of St. Lawrence.** *Courtesy S. Prinsenber.*

141

142 The frequency of occurrence of ice ridges, their geometry and strength have long been the  
143 subjects of considerable interest for a variety of reasons. Early mariners have always been  
144 concerned by the presence of such formidable obstacles. In addition to navigation, the influence  
145 of ice ridging is important for the design of offshore structures and buried pipelines. At larger  
146 geophysical scales of hundreds of kilometres, ridging is of interest to meteorological and climate  
147 studies.

148 The early observations of ice ridges were recorded by mariners. A classic book by Zubov (1945)  
149 includes a description of ridging and methods to evaluate the forces due to such formations on  
150 ships. More recent investigations over the past few decades (many cited by Weeks, 2010) dealt  
151 with characterization of ridge geometry, morphology, and the frequencies of occurrence over  
152 different Northern regions, as well as modeling of the ridging process. Strub-Klein and Sudom

153 (2012) provide a comprehensive analysis of available information on the geometry and  
154 morphology of ice ridges.

155 Insert Figure 4 here

156 **Figure 4 Shear ridge in Beaufort Sea.** *Courtesy R. Frederking*

157

158 Figure 5 sketches a typical cross-section of a first-year ice ridge. A relatively strong *consolidated*  
159 *layer* forms near water level where water freezes within the voids between the blocks of ice that  
160 comprise the ridge. Most of the force that a ship must generate to break through the ridge is  
161 exerted on the consolidated layer. The sail and keel consist of accumulations of relatively loose  
162 ice blocks, and their strength is usually very small compared to the consolidated layer.

163 Insert Figure 5 here

164 **Figure 5 A sketch of a typical cross-section of a first-year ice ridge.** *After Strub-Klein and*  
165 *Sudom (2012).*

166

167 Much research, including manual drilling with ice augers and the use of upward looking sonars  
168 and electromagnetic induction sensors, was directed at measuring the peak sail heights and keel  
169 depths of ridges, as well as the shapes of the ridges. The results of numerous studies giving  
170 statistics of sail heights and keel depths, and correlations of ridge dimensions and shape  
171 parameters, have been compiled by Strub-Klein and Sudom (2012). They cover a wide  
172 geographic area including the Bering and Chuckchi Seas, the Beaufort Sea, Svalbard waters, the  
173 Barents Sea, the Russian Arctic Ocean, the East Coast of Canada, the Baltic Sea, the Sea of  
174 Azov, the Caspian Sea and Offshore Sakhalin.

175 For first-year ice ridges, measurements from various locations over Arctic and sub-Arctic  
176 regions give maximum expected dimensions and typical shapes. The ratio of keel depth to  
177 maximum sail height is approximately 4:1. The mean maximum of ridge sail heights is two  
178 metres and the peak value is eight metres. For the maxima of keel depths, the mean value is eight  
179 metres and the peak value is 28 metres. The mean keel width is 36 metres and the maximum is  
180 202 metres.

181 Efforts to model the ridging process have mainly concerned equating the energy expended by the  
182 converging ice cover to the potential energy required to build the sail and keel of a first-year ice  
183 ridge. The models also consider energy dissipation. The first such model was developed by  
184 Parmeter and Coon (1972). Subsequent computer simulations using a Discrete Element approach  
185 were reported by Hopkins et al. (1991). The latter modeling approach implies that the maximum  
186 sail height and maximum keel depth are limited by the energy that an ice cover can expend,  
187 which is limited by the thickness of floating ice. Thus, one can expect a physical limitation on  
188 extreme ridge dimensions, a conclusion reached by Melling (2002) and Melling and Riedel  
189 (2004). Their analysis was supported by physical arguments, laboratory tests and computer  
190 simulations, and agrees with the data analysis of Strub-Klein and Sudom (2012) that the  
191 maximum possible keel depth of a first-year ridge is 28 m.

### 192 **3 PRESSURE BUILD-UP AND DISSIPATION**

193 Pressured ice forms in all regions where ice is mobile but confined, including those listed above.  
194 Although pressured ice (compressive ice) poses difficulties almost everywhere in Northern  
195 regions, the focus of this chapter is on Canadian waters. At the scales of interest to shipping  
196 operations, local conditions can greatly influence the build-up of ice pressure. This poses a major

197 difficulty in predicting risks to navigation. Pressure build-up depends on environmental driving  
198 forces which arise due the action of wind, water currents and swells. Coastline conditions will  
199 determine the potential for the occurrence and severity of pressure episodes in response to the  
200 environmental conditions. Local geography and idiosyncrasies of the environment must be  
201 considered for each specific region in order to produce reliable forecasts of pressure risks.

202 In the Canadian Arctic, local conditions may vary significantly. Microclimates of local areas can  
203 be drastically different from the forecasts of global models. For example, ship Captains have  
204 observed that wind can change direction at a shoreline, and often follows the shoreline. This  
205 contrasts with what happens in southern climates where onshore winds often occur in the  
206 afternoon due to heating of the land during the day. Over Frobisher Bay, an easterly wind  
207 blowing towards the Incognita Peninsula (the southwest shore of the Bay) may veer to the  
208 southeast at the shoreline. The same phenomenon can be observed in Prince Regent Inlet at the  
209 northwest side of Baffin Island where westerly winds turn to the southwest and follow the Baffin  
210 shore. Another common phenomenon in the Arctic is the katabatic wind, in which air moves  
211 rapidly down slopes, often from an icecap. Captains have observed sudden gale-force winds  
212 near shores even though there are light winds elsewhere in the vicinity. A funnelling effect is  
213 often present in areas, such as long fiords. Concerning water currents, local tidal components are  
214 usually critical to the build-up of ice pressure, in addition to large scale water circulation. This is  
215 particularly evident at the entrance to narrow channels and inlets where the tidal stream is  
216 strongest.

217 Indications of ice pressure, such as ridges and block accumulations, are of obvious interest to  
218 mariners. Ridging is a pronounced indicator of pressure. Although existing ridges could have  
219 formed during past deformation events, if the ice field is immobile, ridged ice indicates presence

220 of pressure. The severity of the pressure increases with ice thickness. Another good visual  
221 indicator of pressure is the state of small broken ice blocks. Block accumulations, with water in  
222 the pores, usually freeze quickly in cold temperatures. The resulting pile-ups of frozen ice pose a  
223 serious impediment to ships. Progress becomes difficult and the risk of damage increases.

224

225 Dissipation of ice pressure is another process that concerns mariners. Relief can happen very  
226 quickly once the driving force has been removed, or can take hours depending on the extent of  
227 the ice field. Wind is not the only factor causing ice pressure to dissipate. Swell also plays a  
228 role, along with tide, current, and type of ice regime under pressure. Wind can die down, but the  
229 pressure can persist. It is therefore difficult to predict dissipation of the pressure.

230

231 Efforts to understand and predict ice-pressure conditions date back to the encounters of early  
232 explorers with ice. A good example is the *Karluq*'s encounter with pressured ice during the  
233 summer of 1913, which is well documented (McKinlay, 1977). Subsequent investigations  
234 include reports of the Manhattan and the Canadian Coast Guard icebreaker Louis S St. Laurent,  
235 and reports describing challenges of navigating in the Arctic, the Gulf of St. Lawrence, the  
236 Northern Sea Route, and the Gulf of Finland (Bradford, 1971, 1972a, 1972b, 1978; Brigham et.  
237 al, 1999; Maillet, 1997; Pärn et. al., 2007; Stolee, 1970; Swithinbank, 1970a; Swithinbank,  
238 1970b; Voelker and Seibold, 1990). Over the past decade, interest in pressured-ice has grown.  
239 Research projects were carried out in Europe and Canada to address various aspects of  
240 forecasting and dealing with pressured ice. Russia also has a long-standing interest and expertise  
241 in dealing with pressured ice. For example Mironov et. al. (2012) provide a summary of

242 numerous studies carried out for several decades at the Arctic and Antarctic Research Institute. It  
243 describes ice phenomena threatening Arctic shipping including a number of examples. Reviews  
244 of research on pressure-ice were also given by Kubat et. al. (2011, 2012, 2013), Kõuts et. al.  
245 (2012), Leisti et. al. (2011), Lensu et. al. (2013a, 2013b), Lilover et. al. (2012), and Browne et  
246 al. (2019).

247

#### 248 4 REGIONAL CONDITIONS AND INCIDENTS OF BESETTING

249 A survey of reports of besetting and events of ice pressure was conducted by Kubat et al. (2012).  
250 The survey included interviews with Captains and documentation of their comments on pressure  
251 ice risks. The reported incidents of besetting obtained through that work are shown in Figure 6.  
252 Most events took place along the St. Lawrence Seaway and on the East Coast of Canada, a  
253 reflection of the busy shipping traffic over those regions. Conditions are much more severe over  
254 the Arctic. The smaller number of reported incidents there is a result of the relatively low ship  
255 traffic. The situation would change if Arctic shipping increased. This section examines the  
256 pressured ice risks over specific regions, and presents some of the reported incidents of besetting.

257 Insert Figure 6 here

258 **Figure 6 Map of reported incidents of ship besetting and damage due to ice pressure, data**  
259 **obtained from Kubat et al., 2012.** 1 – Beaufort Sea, 2 – Peel Sound, 3 – Baffin Bay, 4 – Frobisher Bay,  
260 5 – Labrador Coast, 6 – Newfoundland East Coast, 7 – Great Lakes.

261

262 *The Beaufort Sea:* In the southern Beaufort Sea ice movement against the land boundary is the  
263 main factor associated with ice pressure. The edge of the land fast ice, which consists of level  
264 undeformed ice, also acts as a boundary that makes pressure build-up possible. In addition, local

265 ice convergence caused by the Mackenzie River outflow and differential movements between the  
266 polar and seasonal pack ice areas are recognized as causes of ice pressure. Winter ice zones in  
267 the Southern Beaufort Sea (Kovacs and Mellor, 1974) are illustrated in Figure 7. Pressures can  
268 develop as ice moves southwards against the coastline or the edge of the landfast ice where a  
269 shear wall may develop (Figure 8).

270 Insert Figure 7 here

271 **Figure 7 Winter Ice zones in the Southern Beaufort Sea.** *After Kovacs and Mellor (1974).*

272

273 Insert Figure 8 here

274 **Figure 8 Shear wall at the edge of land fast ice in the Southern Beaufort Sea.** *Courtesy G. Timco.*

275

276 *The Northwest Passage - Peel Sound and Franklin Strait:* The Canadian Archipelago consists of  
277 many narrow channels that are covered with ice most of the year. Peel Sound and Franklin Strait  
278 present challenges since they are susceptible to multi-year ice invasion from the Queen Elizabeth  
279 Islands, and influx of severe ice from the M'Clintock Channel. That area has about 20% of  
280 multi-year ice coverage through the year, and may decrease to 10% in September. Open water is  
281 present from August to October. The limited width of the channel, approximately 35 kilometres,  
282 can contribute to pressured ice build-up and besetting of vessels as they have less room for  
283 manoeuvring to avoid pressure zones than in unrestricted areas. Ice conditions in Southern Peel  
284 Sound during the mobilization of two multipurpose lower-ice-classed vessels are shown in  
285 Figure 9 and Figure 10. The vessels needed assistance from higher-ice-classed icebreaker  
286 Kigoriak during the transit from Southern Peel Sound into Franklin Strait in late July of 2003.

287 Insert Figure 9 here

288 **Figure 9 Ice conditions in Peel Sound, July 2003.** *Courtesy Captain D. Connelly.*

289 Insert figure 10 here

290 **Figure 10 Mobilization of Ice Breaking, Anchor Handling - Tug - Supply Vessels in July 2003 -**  
291 **Southern Peel Sound.** *Courtesy Captain D. Connelly.*

292

293 *Baffin Bay:* In May 1970 a number of pile-up incidents occurred during the Manhattan and Louis  
294 S St. Laurent voyage to Lancaster Sound. Ice pressure forced both ships together and rubble  
295 formed around the hulls up to three meters with some ice blocks up to two meters thick (Figure  
296 11). The ice regime consisted of a combination of first-year and old ice. Neither ship could break  
297 out for 5 days. In addition to pile-ups against the hull, several ridges also formed in the vicinity  
298 of the vessels. During that event, the Louis S St. Laurent was forced towards the Manhattan. The  
299 starboard side was creased for 51 metres fracturing five frames and buckling six frames and the  
300 ice between the ships was pushed under their bows and trimmed them 3.2 metres by the stern  
301 (Stolee, 1970).

302 Insert Figure 11 here

303 **Figure 11 Rubble pile-up (3.3 m) at the Manhattan in 1970.** *From J.D. Bradford.*

304

305 *Frobisher Bay:* Typically, Frobisher Bay would be clear of ice or would have low ice  
306 concentrations during July. However, ice conditions over the bay were relatively severe during  
307 the 2008 and 2012 seasons. During those two years, the prevailing northeast wind caused a delay  
308 of ice clearance in the bay before the beginning of the shipping season. The bay was fully

309 covered by combinations of first-year and multi-year ice. In that region, the ice field is largely  
310 influenced by the surface currents which are driven by the tidal streams in and out of the bay.  
311 This tidal current effectively moves the ice field as long as there is no obstruction such as fast  
312 ice, land, or greater influences, such as high winds or wind-driven current. In areas where there  
313 are geographical obstructions, the flow gets choked and ice pressure therefore increases. This  
314 appears to be the case in the area of the Frobisher Bay west of Cape Osborn where it narrows.  
315 Here a number of vessels became beset during the summers of 2008 and 2012, and had to be  
316 escorted by icebreakers. One of the vessels was severely damaged when her bow was holed.  
317 Photos of ice conditions during those events are shown in FiguresFigure 12-14.

318 Insert Figure 12 here

319 **Figure 12 Ice conditions in Frobisher Bay in 2008. CCG icebreaker escorting a beset vessel.**  
320 *Courtesy Captain J. Vanthiel.*

321 Insert Figure 13 here

322 **Figure 13 Ice conditions in Frobisher Bay in 2012.** *Courtesy D. Lambert.*

323

324 Insert Figure 14 here

325 **Figure 14 Vessels beset in Frobisher Bay – July 2012.** *Courtesy D. Lambert.*

326 *Labrador Coast:* Ocean swells play a major role in ice pressure build-up along the Labrador  
327 Coast, and to some extent over the southern Arctic. An ocean swell not only contributes to  
328 pressured ice conditions, but can dramatically change the strength and make-up of the ice cover.  
329 In such situations, the pressure driven by swells usually persists long after the wind is over. One  
330 example of a pressure build-up took place during the summer of 2007 along the Labrador Coast.  
331 The crew of the Umiak 1, a powerful icebreaking bulk carrier, had a challenge going into

332 Edwards Cove in Voisey's Bay (Figure 15). The ice was much worse than the crew had  
333 experienced in the depths of winter. The shear zone consisted of a rubble field about eight miles  
334 wide that was impenetrable for 10 days. The vessel was in a band of heavily broken, rafted floes,  
335 none of which were particularly thick, but were piled together. The transit felt like digging a  
336 trench through the ice according to T. Keane, FedNav. Similar conditions were also experienced  
337 in April 2012.

338 Insert Figure 15 here

339 **Figure 15 Umiak 1 beset in heavy ice conditions in June 2007; approach to Edwards Cove.**  
340 *Courtesy Tim Keane, Fednav.*

341 *The Northeast Coast of Newfoundland:* Fowler (2019) reported that, in 2007, over 100 fishing  
342 vessels were trapped in severe pressured ice conditions off the northeast coast of Newfoundland  
343 (Figures 16-18). A combination of factors such as coastline irregularities, large number of  
344 shoals, strong winds, ocean current, incursions of multi-year ice and the presence of bergs in the  
345 ice field make this area very hazardous when sea ice is present. In April 2007, the ice pack was  
346 pushed onto the shoreline due to unusually strong and persistent northeasterly winds, trapping  
347 the fishing fleet and requiring extensive Search and Rescue and icebreaking operations. Six  
348 Canadian Coast Guard vessels and three Coast Guard helicopters were involved in the month-  
349 long operation to evacuate non-essential crew from the fishing vessels and then escort the boats  
350 to safety. Descriptions of those events came from several witnesses and were reported through  
351 news media sources; e.g.:

352 <https://www.thetelegram.com/news/local/trapped-in-ice-193574/>

353 <https://www.pressreader.com/canada/national-post-latest-edition/20070419/281719790141479>

354 <https://www.ctvnews.ca/coast-guard-warns-n-l-ice-crisis-far-from-over-1.238160>

355

356 Insert Figure 16 here

357 **Figure 16 CCG icebreaker freeing vessels beset in pressured ice - East Coast of Newfoundland in**  
358 **April 2007.** *Courtesy Captain John Broderick.*

359

360 Insert Figure 17 here

361 **Figure 17 Ice conditions off East Coast of Newfoundland – April 2007.** *Courtesy Captain John*  
362 *Broderick.*

363

364 Insert Figure 18 here

365 **Figure 18 Vessel damaged in pressured ice – East Coast of Newfoundland 2007.** *Courtesy Ron*  
366 *Morrow, CIS.*

367

## 368 **5 PRESSURED ICE ON THE GREAT LAKES**

369 The North American Great Lakes are one of the most interesting areas on the planet. They  
370 consist of five large lakes, containing 20% of the world’s fresh water, connected by navigable  
371 rivers and canals (Figure 19). In the winter, much of this fresh water freezes creating challenges  
372 for those living and working here. The mariner will find that there are major differences  
373 between ice operations on the Great Lakes compared to ice operations in sea and ocean areas.  
374 The navigational challenges that are present year round in the narrow channels and confined  
375 waters of the Great Lake are exacerbated by the ice and cold. The North American continental  
376 climate is only slightly moderated by the lakes, unlike coastal areas where the ocean provides  
377 considerable moderation. Temperatures of -20° to -30°C are not unusual. Strong winds are  
378 common in winter causing freshwater ice accretion on ships, which is much harder to remove  
379 from vessel structures than saltwater ice. Snow, blowing snow and sea smoke reduce visibility.  
380 Commercial shipping is only one of the many groups and organizations in this highly populated  
381 area who have an interest in the ice, and some of these interests conflict. However, there are  
382 many resources available on the Great Lakes to help all concerned, including good ice

383 reconnaissance, expert weather forecasting, excellent port facilities and comprehensive  
384 icebreaking services.

385 Insert Figure 19 here

386 **Figure 19 Map of the Great Lakes.**

387

## 388 **6 FRESHWATER ICE**

389 The freshwater ice found in the Great Lakes is different from the saltwater ice found in coastal  
390 regions. The mariner will notice that it feels harder and “crunchier” than saltwater ice. The  
391 sound of the ice breaking is sharper than saltwater ice and it tends to break with jagged edges  
392 (Figure 20). When under pressure, the pieces of ice tend to hold this jagged shape more so than  
393 saltwater ice, forming ridges with well-defined profiles. In some conditions, pressure causes  
394 large, rectangular pieces, locally called “plate ice”, to slide or raft under other pieces, then freeze  
395 together resulting in floes of ice that appear the same as the surrounding ice, but are actually two  
396 or sometimes three times thicker. During melt, the ice becomes “rotten”, turning black and grey  
397 with many small melt holes. Rotten freshwater ice bends easily and does not shatter as the ship  
398 passes through it, leaving a well-defined vessel track. Rotten ice under pressure tends to  
399 disintegrate into a white slush. In some areas, sediment entrapped in the ice contributes to melt.

400 Insert Figure 20 here

401 **Figure 20 Freshwater ice fracturing.**

402

## 403 **7 CAUSES OF ICE UNDER PRESSURE IN THE GREAT LAKES**

404 The causes of ice pressure in the Great Lakes are the same as in other areas of the world: wind  
405 and current or a combination of these. An additional cause, common in the Great Lakes, is ice  
406 pressure created by vessel movement, which is experienced in narrow channels and restricted  
407 waterways. Wind-induced pressure is mostly short-lived and predominantly occurs on the  
408 eastern shores of the lakes due to the prevailing winds that blow from a direction between  
409 southwest and northwest. The area most affected by wind-induced ice pressure is Lake Erie,  
410 which lies with its long axis in an east-west direction. As the shallowest of the Great Lakes, Erie  
411 is often completely ice-covered in the winter. The relatively milder temperatures of this most  
412 southerly Great Lake keeps the ice relatively soft and fractured, allowing significant ice  
413 movement. A strong southwest wind can blow almost unobstructed along the length of Lake  
414 Erie and cause huge ridges in the area from the Welland Canal to Buffalo and the Niagara River  
415 (Figure 21 and Figure 22). A continuous ridge field extending 10 nautical miles west from the  
416 port of Buffalo is not unusual. Although Lake Ontario is oriented with its long axis east-west,  
417 similar to Erie, the deeper water of this lake results in very little ice development. Other areas of  
418 particular concern for wind generated ice pressure are Whitefish Bay on the southeast corner of  
419 Lake Superior, and the Straits of Mackinac, which is the passage between the northern ends of  
420 Lake Michigan and Lake Huron.

421 Insert Figure 21 here

422 **Figure 21 Ice ridges near Port Colborne, Lake Erie, March 2004.**

423

424 Insert Figure 22 here

425 **Figure 22 Ice ridges near Port Colborne, Lake Erie, March 2004.**

426

427 Ice pressure caused by river current is perhaps the biggest concern on the Great Lakes and nowhere  
428 more so than the connecting waterways between Lake Huron and Lake Erie. Water flows from  
429 Lake Huron, southward down the St. Clair River, into Lake St. Clair and then down the Detroit  
430 River to Lake Erie. A northerly wind in Lake Huron can funnel ice into the southern basin, causing  
431 severe ice pressure. A natural ice bridge often forms above the entrance to the St. Clair River, but,  
432 if it breaks, the 3 to 5 knot current sends ice hurtling down the river, building up on shoals, islands  
433 and bends in the river. The ice can pile up right to the bottom of the river, forming a jam and  
434 creating the risk of flooding in this heavily populated and industrialized area. Ice jams can also  
435 occur in the narrow channels of the Detroit River but they are generally less common and not as  
436 severe as those on the St. Clair River to the north. Ice build-up on the many smaller rivers and  
437 creeks flowing into the Great Lakes often causes jams in the spring, resulting in flooding in low  
438 lying areas. When these ice jams break free, large patches of ice filled with debris such as trees,  
439 docks, small buildings and even small boats flow out into the deeper waters used by ships and can  
440 represent a danger to navigation.

441 Wind-generated currents are found mostly at entrances to harbours. The port of Goderich on  
442 Lake Huron, for instance, usually has a surface current that is perpendicular to the harbour  
443 entrance. Ice movement due to this current creates very difficult conditions for vessels  
444 attempting to transit the immediate entrance to this port. When the current combines with an  
445 adverse wind, an ice transit at this port can be too dangerous to attempt.

446 **8 ENVIRONMENTAL CONCERNS**

447 Ice and ice movement on the Great Lakes is an environmental concern. Ice coverage has an  
448 effect on the regional climatic conditions. When cold wind blows over open water, it picks up  
449 the moisture and causes lake-effect snow squalls in the so called “snow belt” areas in the lee of  
450 the Great Lakes. While these snow squalls are quite localized, the large amount of snow and  
451 poor visibility causes travel chaos. Once an area is completely ice-covered, snow squall activity  
452 ceases. Ice coverage also affects the seasonal water levels of the Great Lakes. During warmer  
453 years with less ice coverage, increased evaporation lowers water levels, causing problems for  
454 shoreline facilities and shipping. Ice movement can cause shoreline erosion, damaging sensitive  
455 wetland areas and waterfront habitat. Water quality can be affected by ice scouring that mixes  
456 sediment into the water column. Wildlife, particularly deer, travel on the ice. Unusual ice  
457 movement and vessel tracks have resulted in deer mortality as they are unable to get back out  
458 onto solid ice once they fall into the water.

## 459 **9 SHIPPING CONCERNS**

460 The opening of the St. Lawrence Seaway in 1959 made Great Lakes ports a destination for ships  
461 from all over the world. The Seaway extends from Montreal to Lake Erie. When the cold  
462 temperatures of winter arrive and ice starts to form, the locks have difficulty operating as ice  
463 plays havoc with lock gates. The ice booms deployed at hydroelectric facilities isolate large  
464 sections of the river, conflicting with the movement of shipping. Ships have difficulty  
465 maneuvering in ice-filled channels. Buoys marking the channel edges are obscured or  
466 sometimes swept away by ice. As the winter season approaches and ice starts to form, ocean-  
467 going vessels rush to leave and domestic vessels prepare to scale back or cease operations for the  
468 winter. The St. Lawrence Seaway, including the Welland Canal, shuts down for the season in

469 late December and remains closed until the third week of March. Traffic continues on the St.  
470 Lawrence River from Montreal downriver to the Atlantic.

471 The “Soo” Locks at Sault Ste. Marie, Michigan, allow vessel transit between Lake Superior and  
472 Lake Huron. They shut down every year between January 15 and March 25. Shipping traffic  
473 continues on Lakes Huron, Michigan and Erie and their connecting waterways throughout the  
474 winter months, but at a comparatively low volume. Domestic bulk petroleum, bulk concentrates  
475 such as salt and iron ore, and occasional manufactured goods such as steel, are shipped in the  
476 winter months.

477 An early freeze-up in the Great Lakes may cause problems for shipping. Numerous vessels  
478 attempting to depart the Seaway combined with limited icebreaker availability and problems  
479 with infrastructure due to freezing and ice build-up can cause delays. Once the locks in the St.  
480 Lawrence River and the Welland Canal are closed, icebreakers are often kept busy with vessels  
481 voyaging between Lakes Erie, Huron, Michigan and Superior. As winter conditions worsen, the  
482 majority of the Great Lakes fleet will lay-up for the winter. Upon closure of the Soo Locks on  
483 January 15, vessel traffic decreases significantly.

484 The shipping industry on the Great Lakes starts to get busy again in mid-March. This is the most  
485 likely time of year for problems with ice. The ice is often at its thickest. Land fast ice starts to  
486 break up and move around. Pack ice may become softer and more fractured and floe size  
487 decreases. Natural ice bridges can break. Melting snow raises water levels and creates stronger  
488 currents. Ice jams are possible. Just as the natural ice cover starts to deteriorate and move  
489 around, shipping traffic increases. Icebreakers can become very busy helping shipping through  
490 the late winter ice. Ridges in areas such as Whitefish Bay, the Straits of Mackinac, and eastern

491 Lake Erie can cause major problems. When strong winds occur, severe ice pressure adds to the  
492 problems.

493 Ice coverage on the Great Lakes varies from year to year. The trend has been towards improved  
494 ice conditions in the last few decades. The winter of 2013/14, however, saw a return to very cold  
495 conditions with extensive ice coverage, causing problems and concerns for the marine industry.

## 496 **10 DEALING WITH PRESSURED ICE: A SHIP MASTER'S PERSPECTIVE**

497 The best way for ship Masters to deal with ice, especially ice under pressure, is to avoid it.

498 Avoidance can be difficult on the Great Lakes because of the more confined waters compared to  
499 coastal and offshore areas. When the connecting waterways, such as the St. Mary's, St. Clair,  
500 and Detroit rivers, are packed with ice, pressure is inevitable and avoidance is impossible (Figure  
501 23). In the more open waters of the lakes, altering course to avoid ice is an option. Good tactical  
502 information can be obtained from the ice charts, which are produced from satellite and visual  
503 observations and are published frequently during ice season. Vessel Traffic Services and  
504 government icebreakers provide information and advice. Most commercial vessels on the Great  
505 Lakes share ice and route information with each other over VHF radio.

506 Large commercial vessels on the Great Lakes tend to follow standard routes that are  
507 recommended by the Lake Carriers Association. These routes are shown on both Canadian and  
508 American nautical charts and usually have separate courses for up-bound and down-bound  
509 vessels. Ice conditions may require a departure from the normal shipping routes. Masters  
510 navigating in ice-covered waters must avoid the temptation to comfortably follow the  
511 accustomed routes and be prepared to go around difficult ice regimes. Mariners must watch the  
512 forecasted wind and avoid ice covered areas with strong onshore winds. Conversely, following

513 shore leads, which are navigable open water areas that have been opened by offshore winds, is a  
514 risky undertaking. A shift in wind can close the shore lead like a steel trap.

515 Insert Figure 23 here

516 **Figure 23 Icebreaker escort in Detroit River.**

517

518 In 1994, the tug Princess was trapped on the north shore of Lake Erie in severe ice pressure. The  
519 pressure was strong enough to completely lift the vessel out of the water and roll it onto its side.  
520 As the crew abandoned ship onto the ice, the Master was injured and was evacuated by  
521 helicopter. A United States Coast Guard Bay Class icebreaker attempting a rescue was beset and  
522 experienced an uplifting of the stern. By the next morning, when the larger and more powerful  
523 Canadian icebreaker Samuel Risley arrived on scene, ice pressure had disappeared and both  
524 vessels were completely back in the water. The crew of the Princess was able to board it and  
525 start its engine. The tug was escorted to a dock in Amherstburg, Ontario but sank the next night  
526 due to damage from the ice.

527 Vessels approaching port or river entrances in ice can expect a significant worsening of ice  
528 conditions. At harbour entrances, local winds and currents often create ice pressure. Navigation  
529 near breakwalls can be very tricky as unusual currents are often encountered near breakwalls,  
530 which can cause unexpected ice movement. Shear lines develop as the moving ice further  
531 offshore encounters stationary ice near the harbour. Vessels can easily swing off course as the  
532 bow passes the shear line and one part of the vessel is in moving ice while the other is not. Night  
533 navigation or poor visibility makes shear lines much harder to see, adding to the danger of these  
534 features. At river entrances, moving ice tends to build up in thickness as the current funnels it

535 into the river. Ships that are proceeding easily through the ice in offshore areas often see a  
536 drastic drop in speed and maneuverability when they approach or enter rivers. A vessel stopped  
537 by the ice in a river is in serious danger as she will continue to move downriver at the mercy of  
538 the ice pack.

539 Ship Masters must use a combination of caution and boldness when entering areas of moving  
540 and pressured ice. If maneuverability becomes a problem when approaching confined waters,  
541 the best action may be to turn or back away from the dangerous area. Caution has to be  
542 exercised when backing in ice due to the vulnerability of rudders and propellers. When  
543 attempting to escape dangerous ice at harbour and river entrances, the best escape direction is  
544 often towards the center of the lake, where ice conditions are usually a lot better. If committed to  
545 an approach, bold engine and rudder movements may be required to keep the ship moving and  
546 under control. Good judgment and lots of experience are vital. If conditions are unknown or  
547 questionable, it is often best to stay well offshore, then approach a harbour perpendicular to the  
548 shore, if water depths and channels allow. Ports on the southern shore of Lake Erie are a good  
549 example of this. Rather than a long approach close to the shore, it is preferable to keep well out  
550 in the lake before swinging directly in to the port. Even a small change of wind direction, from  
551 slightly offshore to slightly onshore, can be enough to create large areas of pressured ice, with  
552 rafting and ridging that will cause even the most capable vessels to become beset.

553 The Canadian Coast Guard (CCG) and the United States Coast Guard (USCG) operate  
554 icebreakers in the Great Lakes. The two Coast Guards work harmoniously to strategically  
555 deploy available icebreakers in the best locations possible, taking into account the capability of  
556 the icebreakers, the ice conditions, and the traffic. It is common to see Canadian icebreakers  
557 working on the American side of the border and vice versa. Icebreaking for flood control takes

558 priority over vessel assistance. Commercial tugs also provide significant icebreaking assistance  
559 to commercial vessels. Tugs operate mainly in ports, breaking ice alongside slips and wharfs,  
560 making tracks through the harbour ice, and breaking out turning basins. In particularly bad ice  
561 years, large commercial vessels occasionally hire tugs as dedicated escorts.

562 A common icebreaking technique in the Great Lakes is to prepare and maintain tracks in the ice  
563 designed to allow commercial vessels to proceed independently (Figure 24). In some areas, such  
564 as the St. Mary's River, only the ice in the navigable channels is broken. The fast ice on the  
565 edge of the channels is left intact. Vessel speed is regulated to minimize collateral damage to the  
566 ice from vessel wake. In other areas, such as the parts of the St. Clair and Detroit rivers with  
567 deep water right up to the shore line, ice is broken from shore to shore. Vessel traffic can keep  
568 ice flowing and help prevent ice jams.

569 Insert Figure 24 here

570 **Figure 24 Rock Cut showing groomed tracks in the ice.** *Photograph source: USCG.*

571

572 The Edgar B. Speer, an American 1,004 foot long bulk carrier became stuck in ice at the Rock  
573 Cut, St. Mary's River on January 18, 2004. The vessel's beam of 105 feet left very little room  
574 between the ship and the edge of the narrow channel. Ice under pressure formed around the ship.  
575 It was thought that the current also forced ice under the vessel, effectively grounding her on ice.  
576 On January 21, the vessel was freed with assistance from USCG icebreakers and four tugs. Ice  
577 problems frequently occur in the Rock Cut with vessels becoming beset in a similar manner to  
578 the Edgar B. Speer.

579 Navigation in the tracks becomes difficult when very cold temperatures are present. As vessels  
580 pass through the ice, they grind it up into a thick brash. As water is exposed to the cold air, the  
581 brash freezes into a thicker layer than it was prior to passage of the vessel. Over time, the ice in  
582 the tracks will become significantly thicker than the fast ice on the sides of the tracks.

583 Icebreakers have the option of creating a new track if there is room, cutting relief tracks on either  
584 side of the original track in an attempt to reduce the pressure, or using a combination of natural  
585 current and their own propeller wash to flush the brash ice out of the channel.

586

587 Any significant ice pressure will move or close the tracks. A combination of warm temperatures  
588 and strong winds may create ice pressure. This can occur throughout the ice season but is more  
589 prevalent in the spring. Icebreakers become very busy when this happens. On the Great Lakes,  
590 when commercial traffic is high, icebreakers will sometimes organize vessels into convoys for  
591 escort through difficult areas of ice. In discussion with the Masters of the commercial ships, the  
592 icebreaker's Master will assign the vessels positions in the convoy based on their capability.

593 When additional icebreakers are available, they will usually start at the end of the convoy so that  
594 they can approach from astern of ships that are having difficulty and get them moving again. If  
595 one particular ship is having problems, the second icebreaker may position itself directly ahead  
596 of that ship. In very difficult ice conditions, particularly when strong ice pressure is present,  
597 keeping a convoy intact may not be possible. Once a commercial ship is stopped by pressured  
598 ice, the friction along the parallel mid-body of the ship may be too great for it to start moving  
599 again. The icebreaker will pass down the side of the beset ship and then move quickly ahead  
600 (Figure 25). The ice along the side of the beset vessel will flow into the track of the icebreaker,  
601 breaking the friction and pressure, and allowing the beset vessel to move ahead again. In a

602 convoy situation, when the next ship ahead stops, all following ships must stop to avoid  
603 collision. In pressured ice, the entire convoy quickly becomes beset. The icebreaker is then  
604 forced to escort ships clear of the ice individually.

605 Insert Figure 25 here

606 **Figure 25 Canadian Coast Guard icebreaker Samuel Risley backing alongside beset vessel.**

607

608 Icebreaker techniques for escorting vessels in pressured ice are many and varied. The icebreaker  
609 must allow the escorted vessel to follow much more closely than would be considered prudent in  
610 easier ice conditions because the track made by the icebreaker closes quickly. This increases the  
611 risk of collision. In severe ice pressure, the escorted vessel may have to be as close as 20 meters,  
612 sometimes less, to the stern of the icebreaker. If the icebreaker gets stopped by heavy ice,  
613 collision is likely. If the escorted vessel becomes stopped, the icebreaker can have considerable  
614 difficulty backing into the pressured ice to free the beset vessel. In the many narrow channels  
615 found in the Great Lakes system, not only does wind and current cause ice pressure but the  
616 channel restrictions add to the problem. The hull of the ship forces ice up against the channel  
617 sides and adds additional ice pressure. Sometimes, the ice pressure is so severe that it is not  
618 possible to move the escorted vessel. Although the best solution may be to wait until conditions  
619 improve, this is not always a safe option. If the entire ice field is moving towards a shoal, then  
620 every effort must be made to get the ship moving in a safe direction. Sometimes, two  
621 icebreakers working together are better able to get a beset vessel moving in pressured ice.  
622 Towing equipment on an icebreaker may be used in extreme situations. One example occurred  
623 in the St. Clair River when the ocean-going vessel Mallard was beset in moving ice with engine  
624 cooling problems and was in danger of running aground. The Canadian Coast Guard icebreaker

625 Samuel Risley was able to successfully tow the beset vessel through the heavy ice to a safe dock.  
626 Another CCG icebreaker, Griffon, provided icebreaking support for the towing operation.

627 Turning a vessel in pressured ice can be very difficult. Vessels underway in ice want to maintain  
628 their heading. A turn must be initiated with bold rudder movements and started well in advance  
629 of a normal open water turn. In fast ice or pressured ice, the vessel may have to make a series of  
630 ahead and astern passes to force their way around a turn. When establishing and grooming  
631 tracks in narrow channels, icebreakers need to pay particular attention to the turns, creating entry  
632 and exit points, and cutting relief areas for ice to flow away from the bow and stern of the  
633 commercial ship. When providing direct icebreaker support to a vessel stuck in a turn, the  
634 icebreaker should break the ice around the stern of the beset vessel on the side opposite the  
635 direction of turn to give the ice somewhere to move, then proceed ahead of the beset vessel to  
636 create a low pressure area on the side of the bow towards the direction of turn. However,  
637 sometimes the conditions are so severe that even an icebreaker can get beset in pressured ice  
638 (Figure 26 and Figure 27).

639 Insert Figure 26 here

640 **Figure 26 Canadian Coast Guard icebreaker Griffon beset with tanker near Long Point, Lake**  
641 **Erie** (*Photo source: United States Coast Guard*)

642

643 Insert Figure 27 here

644 **Figure 27 Canadian Coast Guard icebreaker Griffon beset with tanker near Long Point, Lake**  
645 **Erie**. *Photograph source: United States Coast Guard.*

646

647 **11 CONCLUSION AND PERSPECTIVE FOR THE FUTURE**

648 The build-up of ice pressure at scales of hundreds of meters is a natural phenomenon that has  
649 significant safety, environmental and economic implications. Even powerful icebreakers can  
650 become beset if environmental forces become unfavourable. Mariners often observe that  
651 apparently easy ice conditions can quickly change into impenetrable ice fields if wind, or current  
652 turn towards a coastline. A beset ship becomes very vulnerable to damage. In addition to direct  
653 damage due to ice action, a beset ship can be thrust against hazards or pushed aground. Safety of  
654 crews can then be seriously jeopardized and pollution of the environment can become a serious  
655 possibility. Aside from concerns over safety and environmental pollution, the excessive  
656 resistance of ice and the need for icebreaker escort dramatically increases fuel consumption and  
657 delays transit times. The adverse effect on the efficiency and economy of shipping operations is  
658 considerable.

659 Shipping along Arctic corridors is increasing in both frequency of voyages and tonnage. This  
660 increase in shipping will likely persist regardless of the climatic conditions. In addition to the  
661 shipping of Arctic resources and supply of Northern communities, new routes aimed at reducing  
662 transit times are constantly sought and exploited. Tourism is also growing rapidly. The  
663 escalating shipping in Arctic regions will lead to more encounters with pressured ice conditions.  
664 The potential risks may be further aggravated when the increased traffic includes ships with  
665 limited strength and power, which may venture into dangerous zones. Furthermore, some of the  
666 mariners venturing into such zones might lack the necessary experience with navigation in ice.

667 There are research initiatives underway to enhance the knowledge of the processes of ice  
668 pressure build-up and to develop technologies that can enhance navigation through high risk  
669 zones. One research project, called SAFEWIN, took place in Europe. Another research effort is  
670 underway at the National Research Council of Canada. The research has a number of thrusts:

671 developing accurate forecast models to predict ice pressure and ridging, documentation and  
672 analysis of besetting records, developing guidance to characterize the potential of besetting risks  
673 for specific regions, and fusion of imagery and environmental data into systems which can  
674 support navigation in hazardous ice zones. Training of mariners is also expanding to include  
675 navigation through pressured ice zones. The Marine Institute's Centre of Marine Simulations in  
676 St. John's, Newfoundland, Canada, The Transatlantic Ice Academy in Kalmar, Sweden and  
677 Maritime Training Centre of Admiral Makarov Academy in Saint Petersburg, Russia include  
678 such training in their courses.

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