

## Enfotec Technical Service

Final Report. Sea Ice Risk Assessment for the Bakki Aluminium Smelter Iceland.

March 2007

## Útdráttur á íslensku

Í þessari rannsókn er metin áhætta fyrir sjóflutninga fyrir álver á Bakka vegna hafíss.

Í skýrslunni er fjallað um eftirfarandi þætti:

### **Samantekt á sögulegum gögnum um hafís á Húsavíkursvæðinu**

Hafið við Ísland er hafislaust að jafnaði en stöku sinnum gerist það að hafís frá Austur Grænlandshafi komi upp að ströndum landsins og sé þar allt frá nokkrum dögum upp í mánuði eins og gerðist á sjöunda áratug síðustu aldar. Þéttur hafís við land gæti stöðvað umferð skipa sem ekki eru gerð fyrir íssiglingar eins og þau sem flytja munu varning fyrir álver á Bakka.

### **Spá um hafís sem búast á við á Húsavíkursvæðinu næstu 50 árin**

Sterkar vísbendingar eru um að hafís við Íslandsstrendur tengist neikvæðri Norður Atlantshafssveiflu (NAO). El Niño sveiflan (ENSO eða Suður sveiflan) gefur aftur á móti ekki góða vísbendingu um hafísaðstæður við Ísland. Greining á áhrifum hlýnandi loftslags jarðar benda til að búast megi við hafísaðstæðum, eins og voru hér við land á sjöunda áratug síðustu aldar, á næstu 50 árum. Hinsvegar er ólíklegt að reglubundnar hafískomur eins og voru á 20. öld verði hér á næstu 50 árum.

Áhrif væntanlegra verstu ísaðstæðna á hverjum 50 árum fyrir Húsavíkursvæðið myndu verða erfiðar siglingaraðstæður til hafnar einu sinni á því ári.

### **Spá um áhrif mjög sérstakra hafíss aðstæðna (200 ára atburðar) við Húsavík**

Niðurstaða greiningarinnar er að búast megi við að minnsta kosti einu sinni á öld geti báðar siglingaleiðir að Húsavíkurhöfn lokast í allt að 50 daga vegna hafíss, með samfelldri lokun í fjórar vikur. Mjög ólíklegt er að tíðir hafísatburðir, eins og voru á 19. öldinni, endurtaki sig á næstu 200 árum.

**Final Report  
Sea Ice Risk Assessment  
for the  
Bakki Aluminium Smelter Iceland**

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**Enfotec Technical Services  
Report Documentation Page**

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<b>Abstract:</b> This study provides a description of the ice conditions and shipping assessment to the proposed Bakki aluminium smelter near Húsavik Iceland.	
<b>Key Words:</b> Shipping assessment, ice study, Iceland	
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## **Executive Summary**

This study investigates the risk sea ice poses to the marine transportation component of the proposed new Bakki aluminium smelter near Húsavík on the north-eastern coast of Iceland. This project was completed by Enfotec Technical Services for BECHTEL Canada Co.

The findings of the objectives are summarized as follows:

### **Review the historical record of ice conditions in the Húsavík region.**

Icelandic waters are ice free in most years but on rare occasions ice from the East Greenland Sea approaches the coast in periods lasting from a few days to a few months, as was the case in some years of the 1960's. The presence of very close pack ice, although infrequent, essentially halts shipping into Bakki to the low ice class vessels envisaged for this project.

### **Estimation/prediction of expected sea ice trends for the Húsavík region over the next 50 years.**

There is a strong correlation between the presence of sea ice near Iceland and a negative North Atlantic Oscillation (NAO). Conversely, the Southern Oscillation (ENSO) is not a good indicator of ice conditions for Iceland. An analysis of the influence of global warming shows that the ice conditions experienced in the 1960's can be expected again in the next 50 years. However, it is highly unlikely that regular occurrences of sea ice as experienced in the 19th century will return within the next 50 years.

The impact of an expected 50-year worst ice condition for the Húsavík region would be a possible four week period of difficult for navigation conditions to the port for shipping once in the year (and only in the 50-year worst condition).

### **Estimation /prediction of the impact of “extreme” sea ice event (200 year event) for the Húsavík region.**

The conclusion from this analysis is that it can be expected that at least once a century the access to the Húsavík region of Iceland will experience an ice year where the port could be blocked by ice up to 50 days with individual closure periods spanning four weeks. It is highly unlikely that the frequent occurrence of ice in the region as experienced in the 19th century will reoccur in the next 200 years.

**Recommendations on countermeasures available to deal with predicted sea ice events.**

The following countermeasures are proposed:

1. Monitoring of the North Atlantic Oscillation
2. Monitoring of sea ice conditions north of Iceland
3. Inventory control at Bakki
4. Selection of shipping services
5. Use of vessels with ice class
6. Use of icebreakers to clear a path
7. Use of ice navigators on the cargo vessels
8. Use of portable shipboard ice navigation technology

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# Final Report

## Sea Ice Risk Assessment for the Bakki Aluminium Smelter Iceland

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### **2.0 Introduction**

This report presents the results of the risk assessment of sea ice for marine shipping to the proposed Bakki Aluminium Smelter in Iceland, undertaken by Enfotec Technical Services for BECHTEL CANADA.

Alcoa is exploring the feasibility of constructing a 250,000 tpy aluminum smelter at Bakki near Húsavík in northern Iceland. Raw materials for the smelter operation as well as the metal product and other export materials will be transported by sea through the existing Húsavík harbour, which will be expanded for the task. The ship sizes will range from 5,000 DWT container ships to 60,000 DWT alumina ships. Sea ice does occur along the north coast of Iceland across the proposed shipping routes to the Húsavík harbour.

Sea ice is an infrequent visitor to the coasts of Iceland. As such, Enfotec has relied heavily on historical data and analysis provided by the Icelandic Meteorological Office (IMO) and, in particular, analysis provided by Trausti Jónsson, Senior Meteorologist from IMO.

### **1.1 Objectives**

The objectives of this study were:

1. Review the historical record of ice conditions in the Húsavík region.
2. Estimation/prediction of expected sea ice trends for the Húsavík region over the next 50 years.
3. Estimation /prediction of the impact of “extreme” sea ice event (200 year event) for the Húsavík region.
4. Recommendations on countermeasures available to deal with predicted sea ice events.

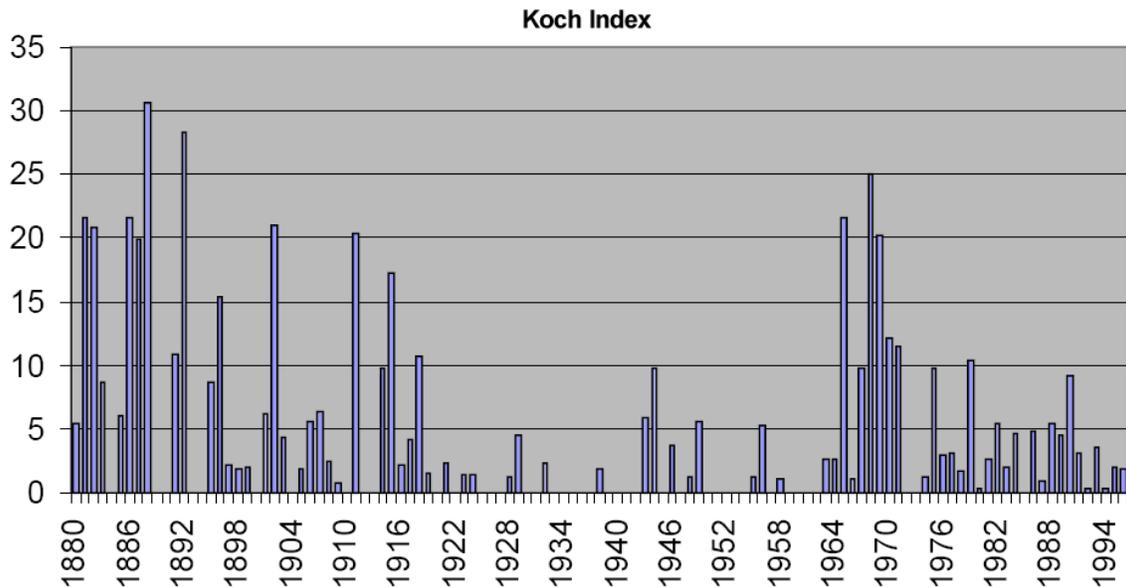
## 2.0 Results

### 2.1 Task # 1 Review of the Historical Record of Ice Conditions in Húsavík

#### 2.1.1 Historical Ice Conditions

While waters around Iceland remain ice free in most years, ice does approach the coast in some years in periods lasting from a few days to a few months. Almost all ice at the coast of Iceland is advected there by ocean currents and winds. The likelihood of a coastal ice incursion is determined by the amount of ice in the East Greenland Sea and by the prevailing wind and ocean currents.

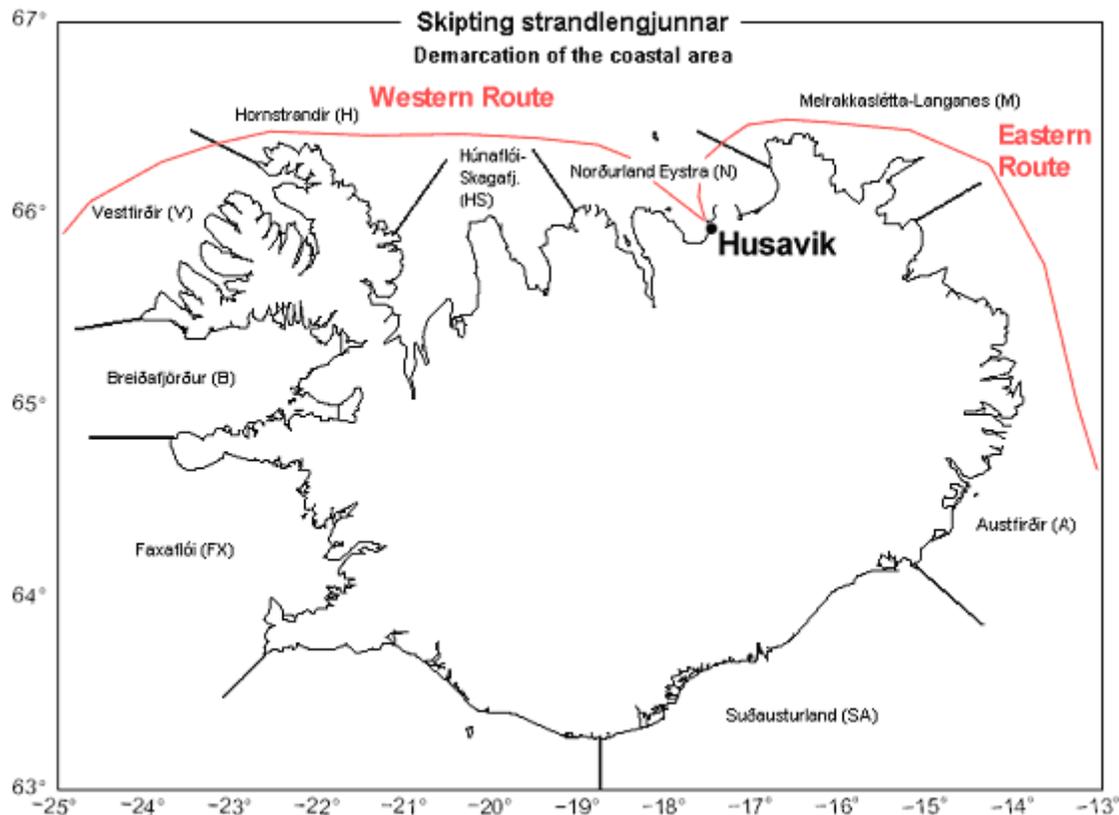
The inter-annual variability of sea ice along the Icelandic Coast has been documented historically through a measure known as the Koch Index presented here as Figure 1 (Jakobsson et al 2002). The heavier the ice conditions the higher the index for a 12 month period running from the beginning October to the end of September. The index is derived by dividing the coast of Iceland into 10 approximately equidistant units as defined in the map of Figure 2. The number of weeks each of the units is filled with ice in a year is summed to form the Koch Index. An index of zero indicates that no ice approached Iceland that year. Iceland is one of the few places in the world that has such a long record of ice observations.



**Figure 1 Koch Index 1880 to 1996 (from Jakobsson et al 2002)**

Looking at the Koch Index from 1880 to 1996 it is clear that the occurrence of sea ice is episodic. The highest values occurred in the 19<sup>th</sup> Century with another major episode in the 1960s. Although the Koch index provides a measure of ice occurrence along the coasts of Iceland, it does not specifically address how difficult this ice would have been for navigation nor, specifically, to the Húsavík region of Iceland.

Observations from Iceland since 1964 have a much better level of documentation in that daily ice observations are available for each of the regions utilized in the Koch Index. These data are reported in Jakobsson et al 2002. These data have been analyzed to determine the potential sea ice incursion to in the access to Húsavík via the eastern approach.



**Figure 2** Regions used to define the Koch Index

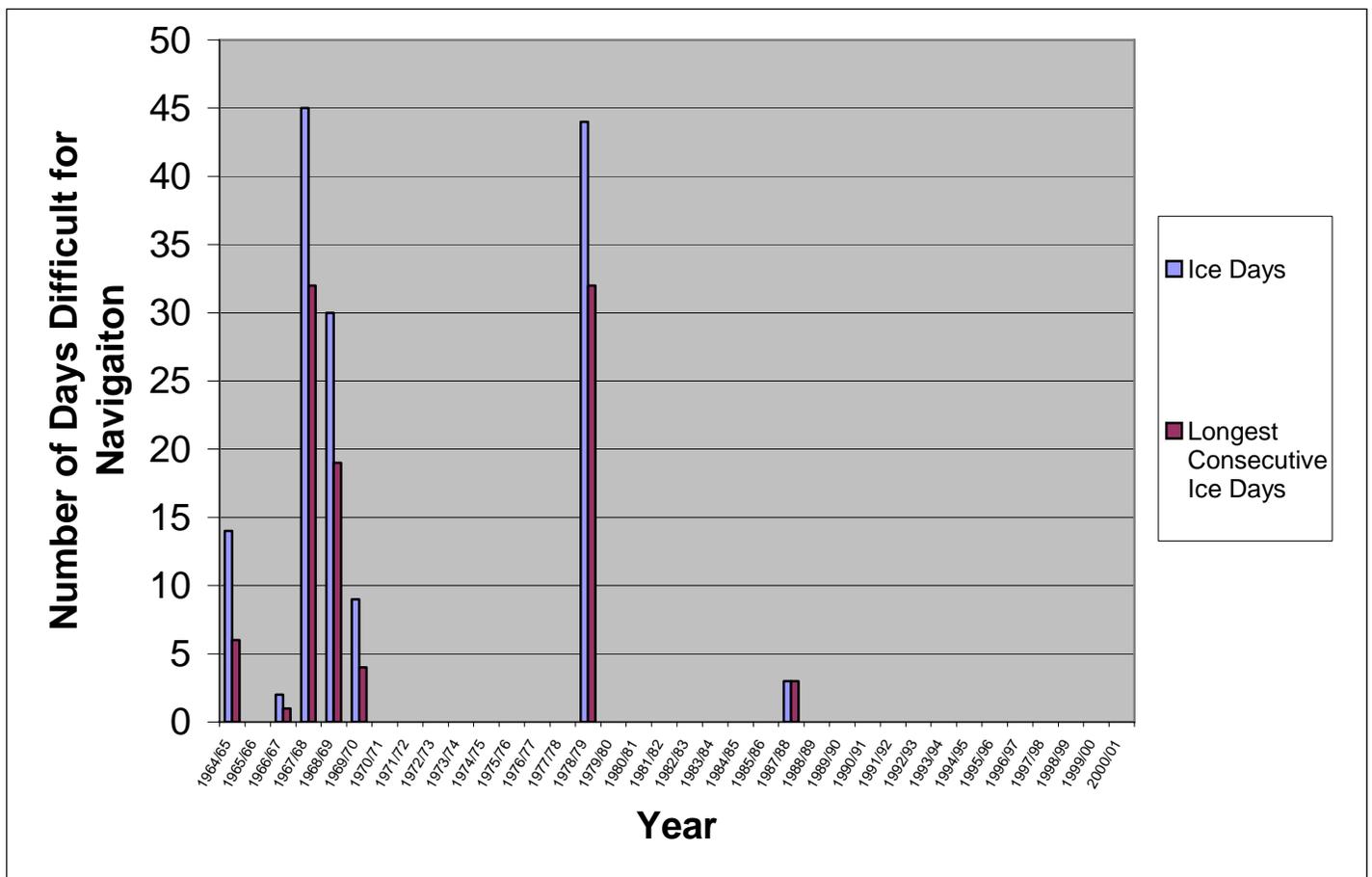
The Jakobsson et al (2002) study contains an overview of sea ice off the coast of Iceland from 1964 - 2001. For each “ice year” (October – September) the number of ice days, i.e. days where sea ice was observed within 12 nautical miles offshore for each of the ten regions shown in Figure 2, is tabulated. These observations also include the severity of the ice cover. The following data were used to construct the tables: sea ice reports from ships, aircraft and meteorological stations to the Icelandic Meteorological Office (IMO), reports and maps from the Icelandic Coast Guard ice reconnaissance, monthly reports from meteorological stations, *Hafís við strendur Íslands* (“Sea Ice off the Icelandic Coasts” published by IMO), sea ice reports in *Veðráttan* (published by IMO), and reports in *Jökull* (published by the Icelandic Glaciological Society).

Only the eastern access to Húsavík is considered here meaning that ice is documented if it occurs in the following four areas: Norðurland Eystra (N), Melrakkaslétta-Langanes (M), Austfirðir (A), and Suðausturland (SA). Also, for the purpose of this analysis, only references to “dense ice when navigation is difficult or closed” are taken into

consideration. This ignores observations of low ice concentrations where there exist “traces of ice, single or very scattered floes” or where “navigation is possible and the ice in question is scattered, mainly floes in groups, strips or both”. Such conditions would not be a hindrance to ship navigation to the Húsavík region (see the description in Section 2.1.2).

Table 1 presents a summary of the number of days in each year where navigation was identified as “difficult or closed for navigation” in the regions that define the eastern access to the Húsavík region. The data of Table 1 is charted in Figure 3.

In the 36 years from 1964 to 2001, ice would have been a concern in the access to Húsavík in seven years (1964/65, 1966/67, 1967/68, 1968/69, 1969/70, 1978/79, 1987/88).



**Figure 3 Chart of number of days of “difficult for navigation” to Húsavík**

**Table 1 Number of days of “Difficult for Navigation” to Húsavík**

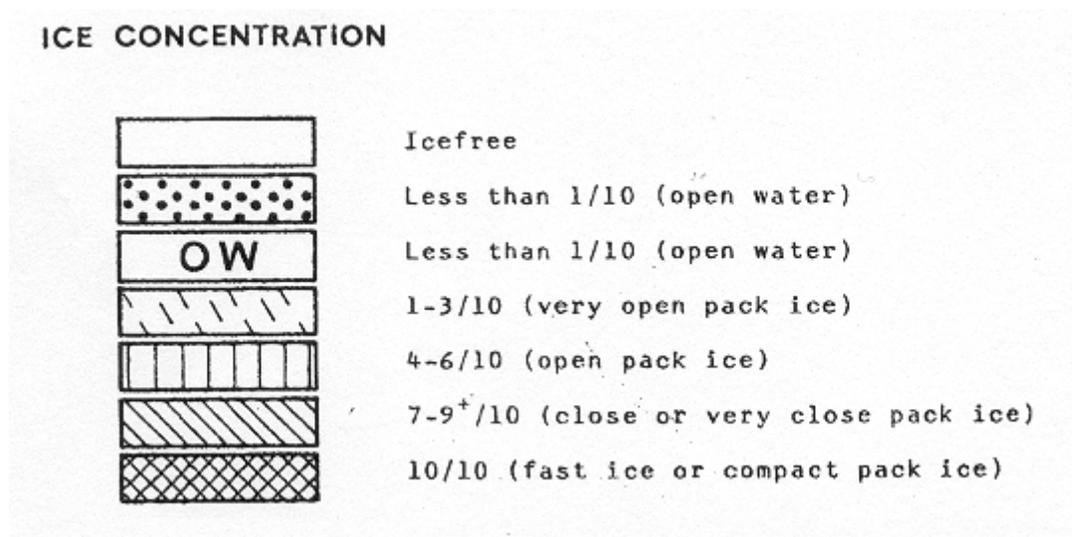
Ice Year	Ice Days	Longest Consecutive Ice	
			Days
1964/65	14		6
1965/66	0		0
1966/67	2		1
1967/68	45		32
1968/69	30		19
1969/70	9		4
1970/71	0		0
1971/72	0		0
1972/73	0		0
1973/74	0		0
1974/75	0		0
1975/76	0		0
1976/77	0		0
1977/78	0		0
1978/79	44		32
1979/80	0		0
1980/81	0		0
1981/82	0		0
1982/83	0		0
1983/84	0		0
1984/85	0		0
1985/86	0		0
1987/88	3		3
1988/89	0		0
1989/90	0		0
1990/91	0		0
1991/92	0		0
1992/93	0		0
1993/94	0		0
1994/95	0		0
1995/96	0		0
1996/97	0		0
1997/98	0		0
1998/99	0		0
1999/00	0		0
2000/01	0		0

The western access is not addressed in Table 1 and Figure 3 since from our analysis it was evident that access to Húsavík is only limited when ice occurs in the eastern approaches. Although ice occurs more often in the west it has no affect on the access to Húsavík as ships coming from the west could simply sail around to the east. It is a matter of efficiency in that it is 315 nautical miles further to come in from the east than the west if the ship is coming from North America. However, a closure from the west does not close access to Húsavík. The eastern access is the critical condition.

The chart and table above show that both the high level of variability in both the extent and severity of heavy ice conditions in the access to Húsavík. Three seasons stand out in particular (1967/68, 1968/69 and 1978/79) where sea ice was present in the access for an extended period of time. In 1967/68 heavy ice conditions were present for 45 days of which 32 days were consecutive. In the 1978/79 season there were 44 ice days of which 32 were consecutive.

For this study we looked at the three heavy ice years in more detail to examine exactly how the ice conditions developed over the course of the season. Enfotec acquired ice charts produced by the Danmarks Meteorologiske Institut (DMI) for the years in question. DMI produces monthly ice charts that include Iceland in their coverage and these charts form the best illustration of the ice in the access to Husavik on those years. The charts classify ice concentration based on the legend shown in Figure 4 below. In addition, sea ice has approached the coast of Iceland in the late winter of 2005 and again in 2007 so these years have been analyzed as well below.

**Figure 4 Legend of the ice shown on DMI Ice Charts**



### Ice Year 1967/68

By all accounts, 1968 was the worst ice year since the late 1800s. Ice started blocking the access into Húsavík around March 24. This first episode lasted until April 18, a period of 26 days. A nine day period of open water and light ice conditions followed before heavier ice conditions once again returned on April 28. These medium and heavy ice concentrations prevailed in the access until May 29, a period of thirty two days. Very light ice conditions returned at the end of May and all ice disappeared from the access by the end of June.

The sequence of monthly ice charts covering the period from the end of February 1968 to the end of June 1968 is presented in Figures 5 to 12 below.

Figure 5 DMI ice chart end of February 1968

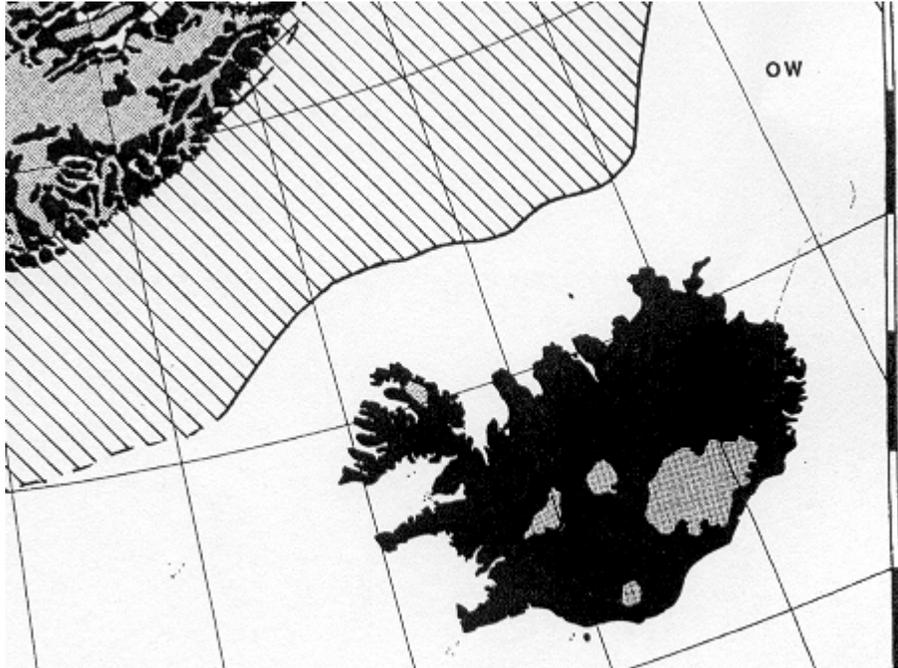
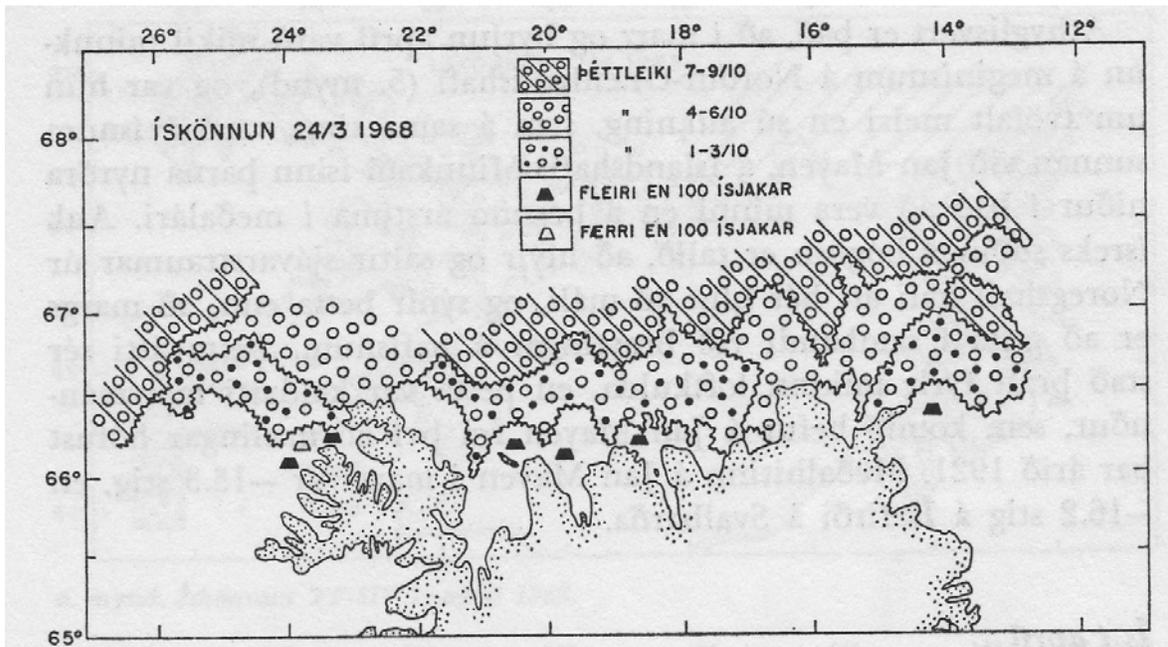


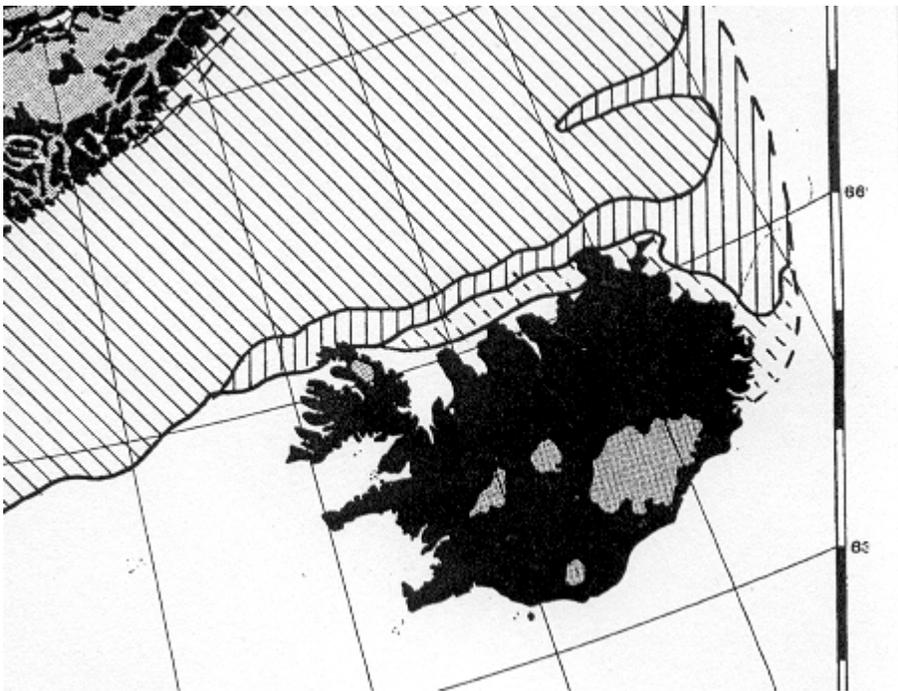
Figure 6 IMO ice chart (March 24, 1968)



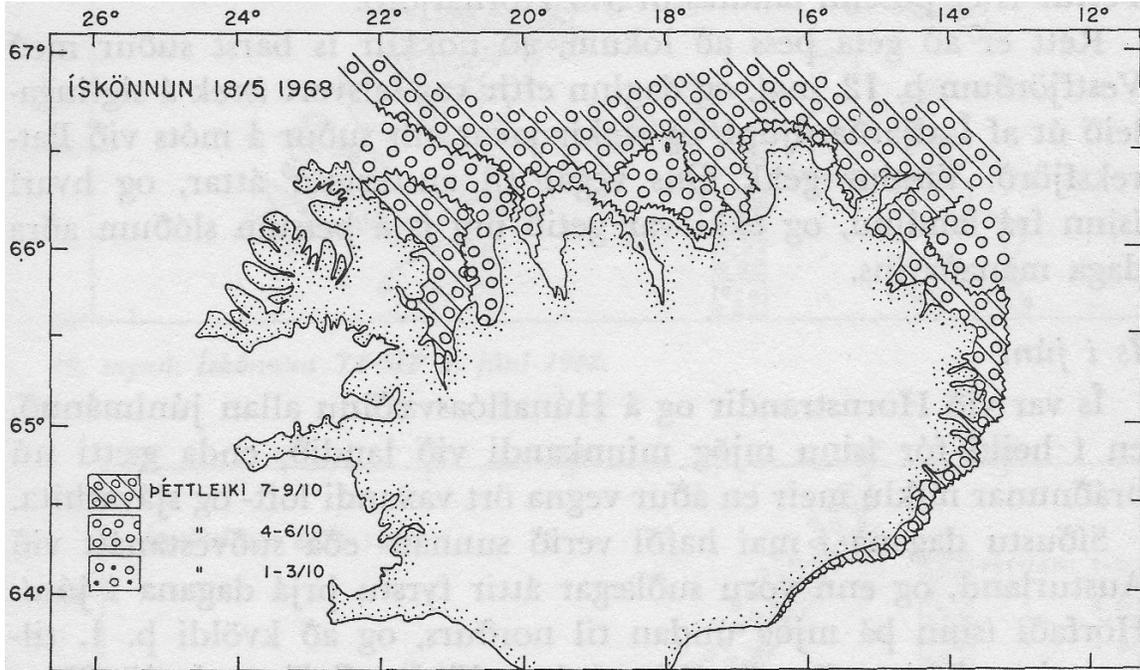
**Figure 7** DMI ice chart end of March 1968



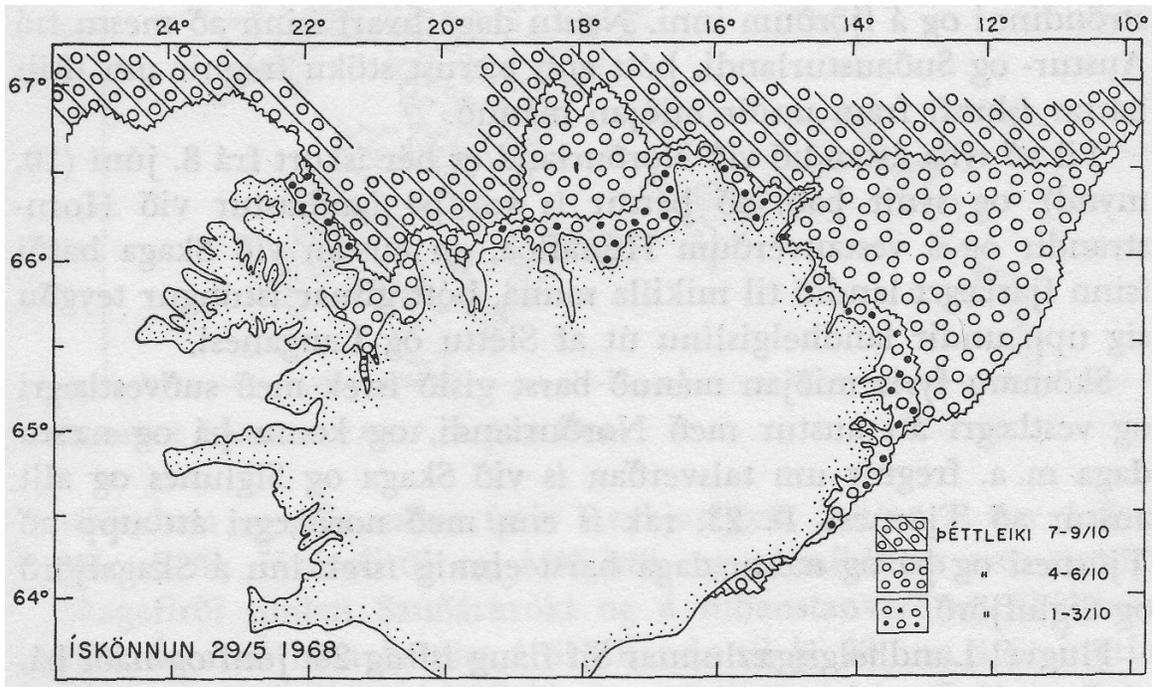
**Figure 8** DMI ice chart end of April 1968



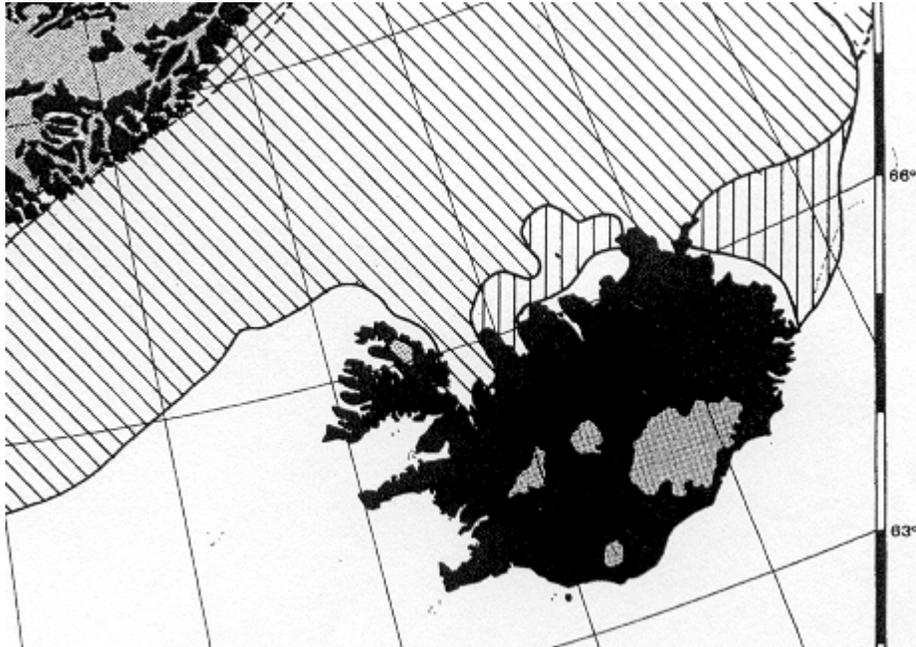
**Figure 9 IMO ice chart (May 18, 1968)**



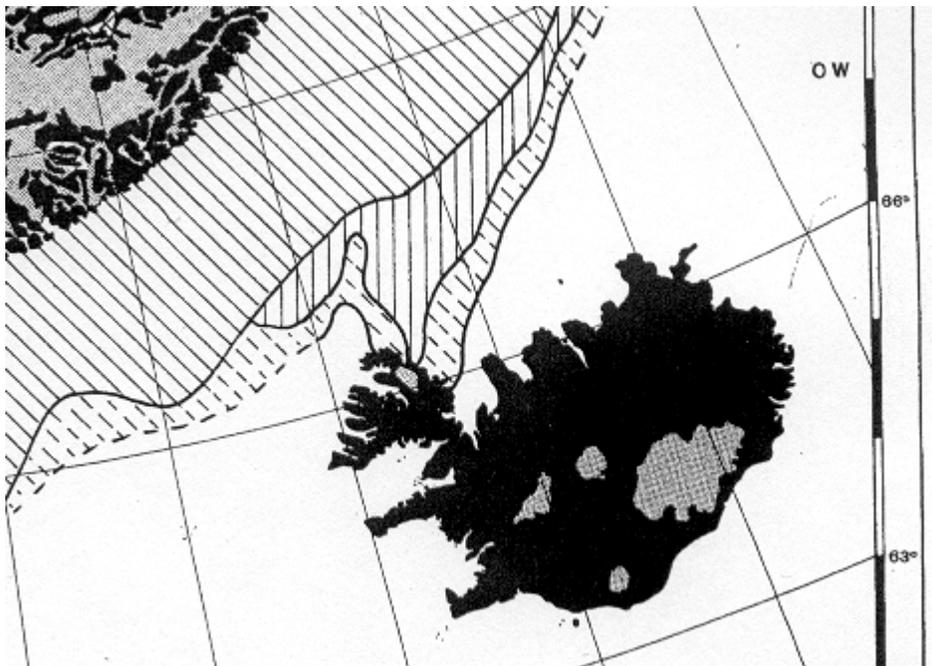
**Figure 10 IMO ice chart (May 29, 1968)**



**Figure 11** DMI ice chart end of May 1968



**Figure 12** DMI ice chart end of June 1968

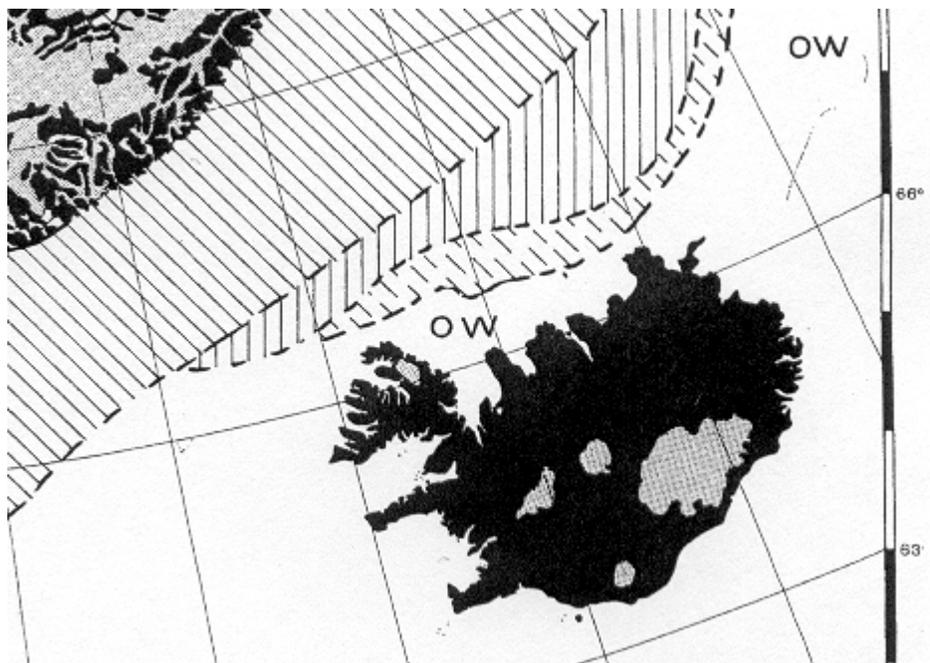


The advance of the ice edge from the East Greenland Sea is apparent during March and April along the north coast of Iceland. It is clearly evident that ice concentrations of 7/10 or greater occurred in the marine access channels in the spring of 1968. These ice charts collaborate the description of “difficult for navigation” as identified in the Jakobsson et al. (2002) study. Unfortunately, the DMI ice charts only report total ice concentration and not the ice by type (i.e. young, first year or old ice). From the source area of the ice from the East Greenland Sea and given the late winter and spring timeframe, we can assume that this ice is composed of both thick first year ice with old ice from the East Greenland Sea.

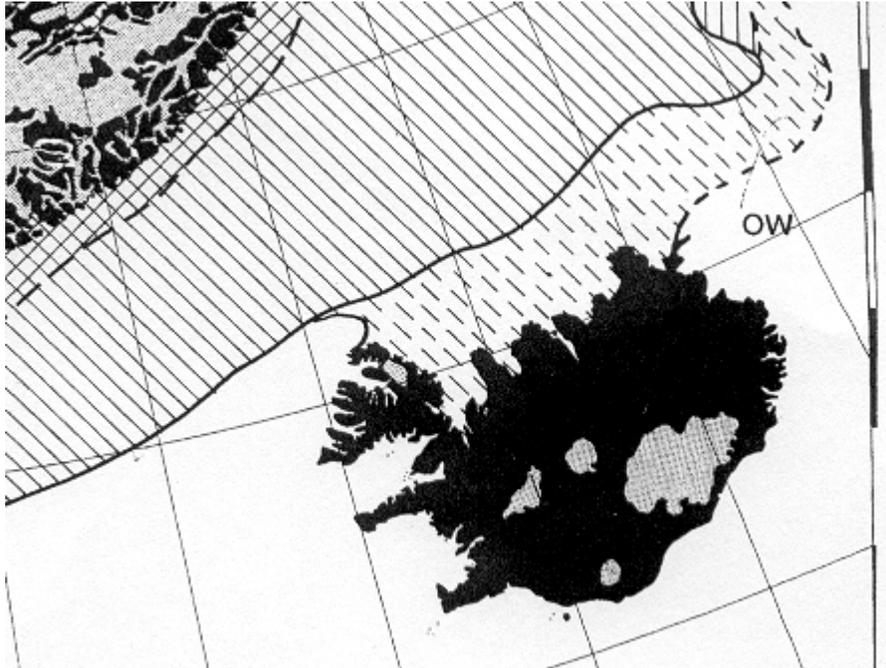
### Ice Year 1968/69

The ice was less extensive in 1969 and lasted for a shorter period of time. The sequence of DMI monthly ice charts spanning from the end of January 1969 to the end of June 1969 are presented in Figures 13 to 18. The first major incursion of sea ice into the access to Húsavík occurred on February 20<sup>th</sup> and lasted for one day. The second incursion lasted for four days from March 9<sup>th</sup> to 12<sup>th</sup> inclusive. The longest period of heavy ice conditions lasted from May 2<sup>nd</sup> to 20<sup>th</sup>, a total of 19 days. Two more days of heavy ice conditions occurred near the end of May – the 24<sup>th</sup> and 30<sup>th</sup>. The last of the heavy ice conditions occurred at the beginning of June, a period of four days lasting from June 2<sup>nd</sup> to June 5<sup>th</sup>.

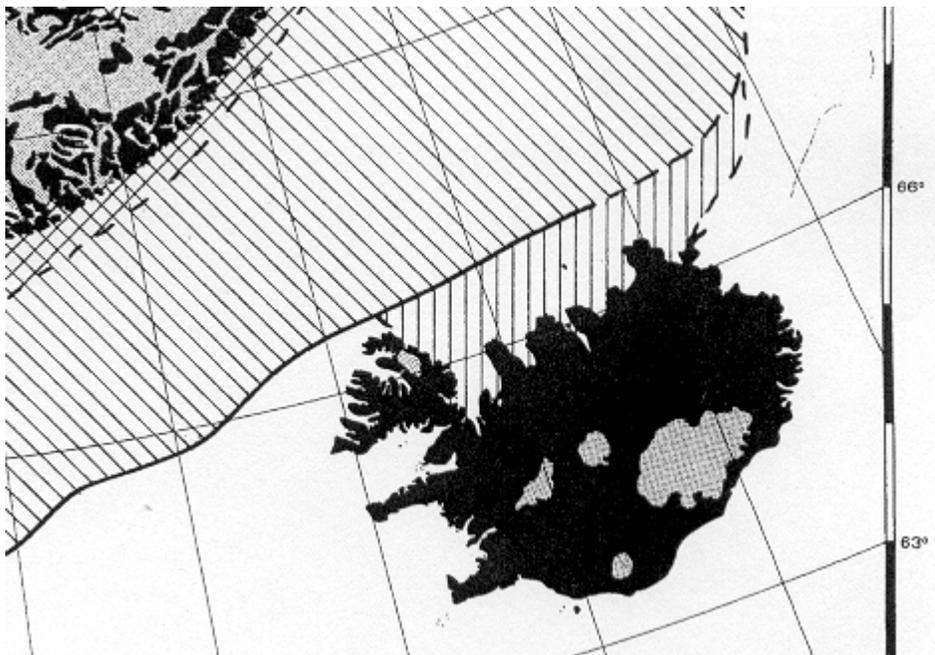
**Figure 13** DMI ice chart end of January 1969



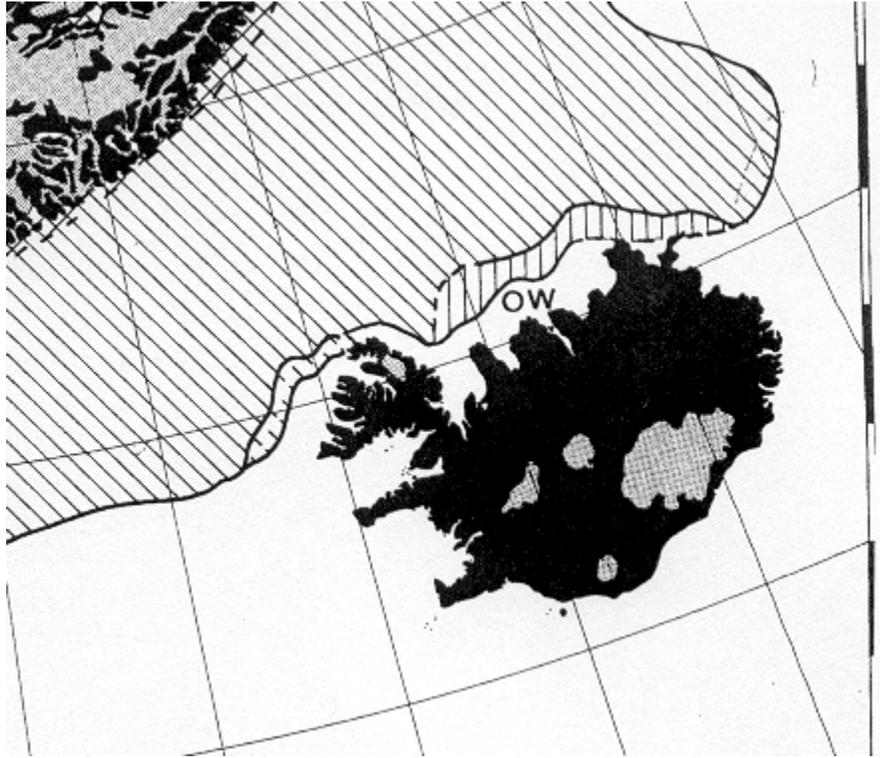
**Figure 14** DMI ice chart end of February 1969



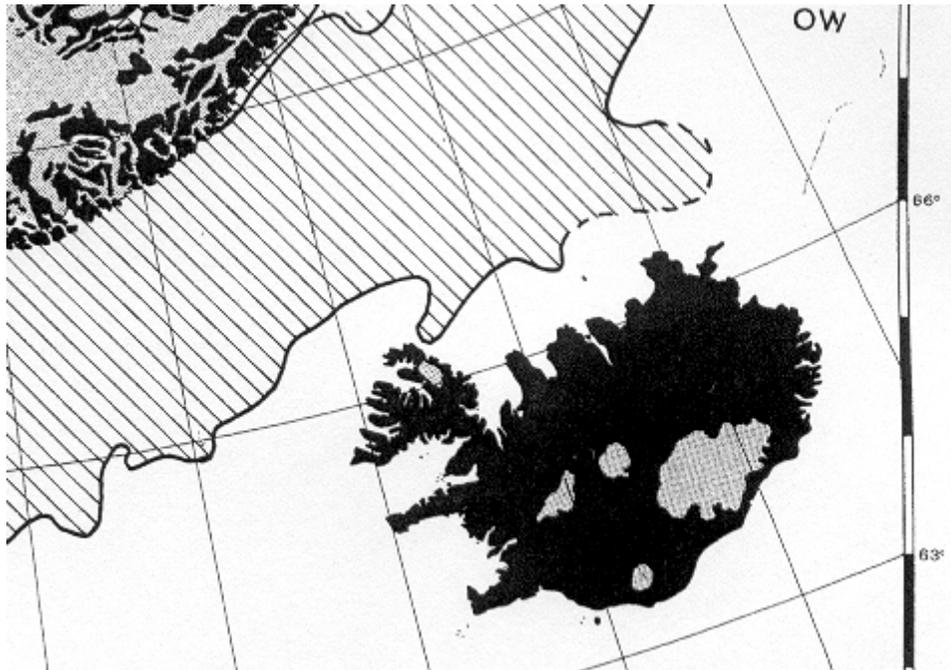
**Figure 15** DMI ice chart end of March 1969



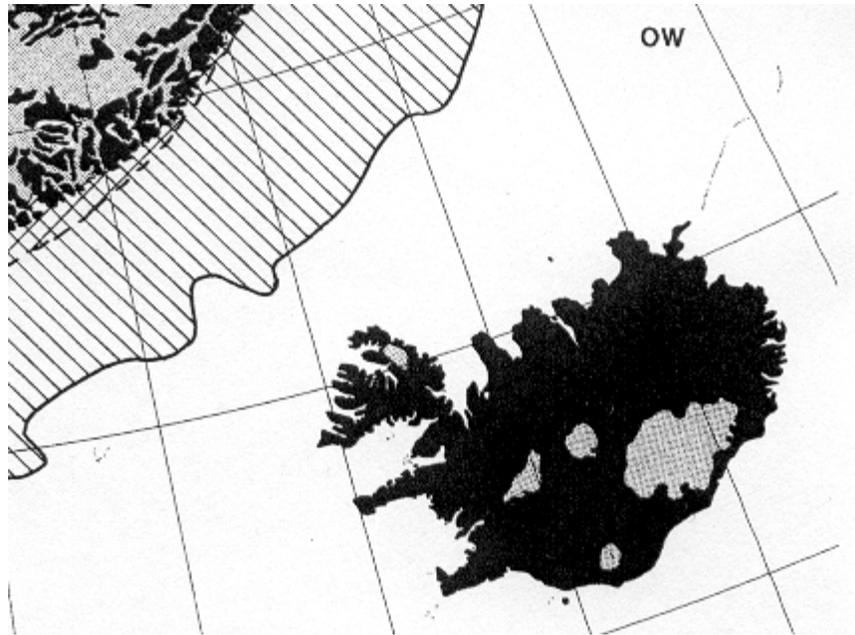
**Figure 16** DMI ice chart end of April 1969



**Figure 17** DMI ice chart end of May 1969



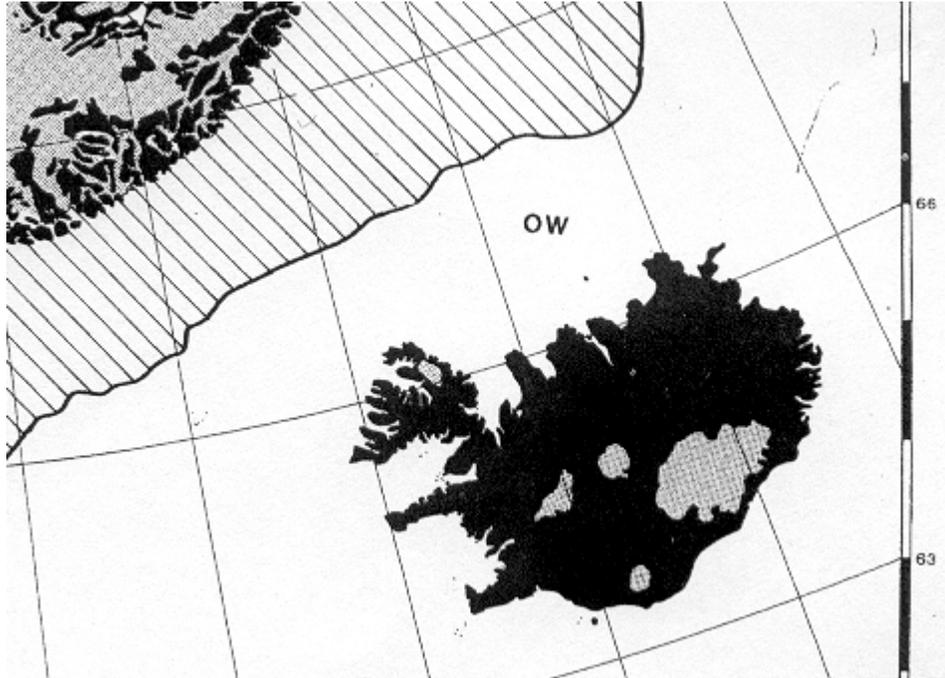
**Figure 18 DMI ice chart end of June 1969**



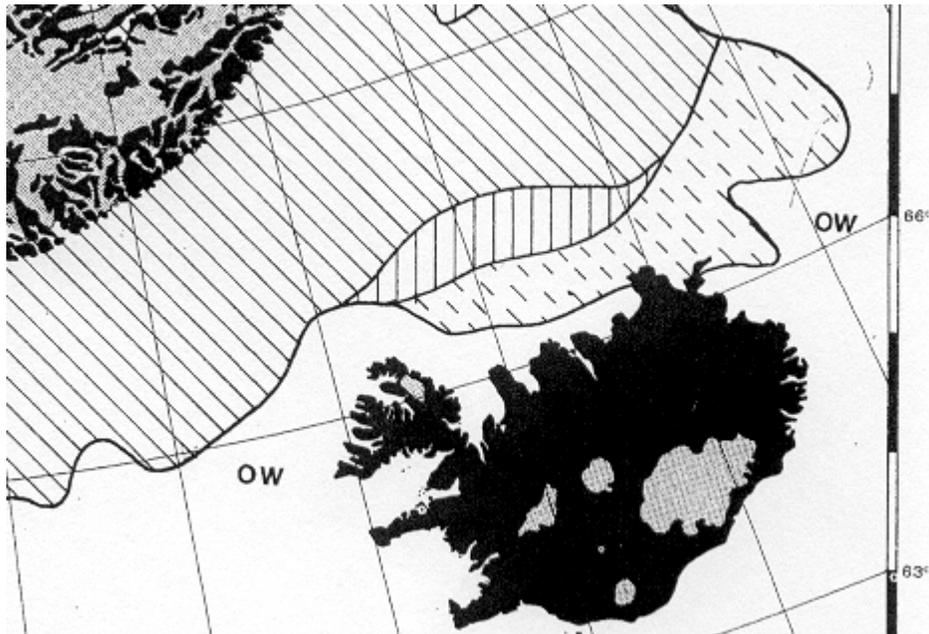
### **Ice Year 1978/79**

In 1979 ice concentrations in the access to Húsavík became heavy in mid-March. Figures 19 to 21 show the advance of the ice to the north coast of Iceland the end of February 1979 to the end of April 1979. Heavy ice conditions occurred on March 14, 17, 21 and 23-24. Heavy ice conditions returned on March 27<sup>th</sup> and lasted right through April 27<sup>th</sup>, a period of 32 days. This makes 1979 a tie with 1968 for consecutive heavy ice days across the access. Open water conditions persisted from the end of April until heavier ice conditions returned on May 13 and once again from May 16 to 23<sup>rd</sup>, an 8 day period.

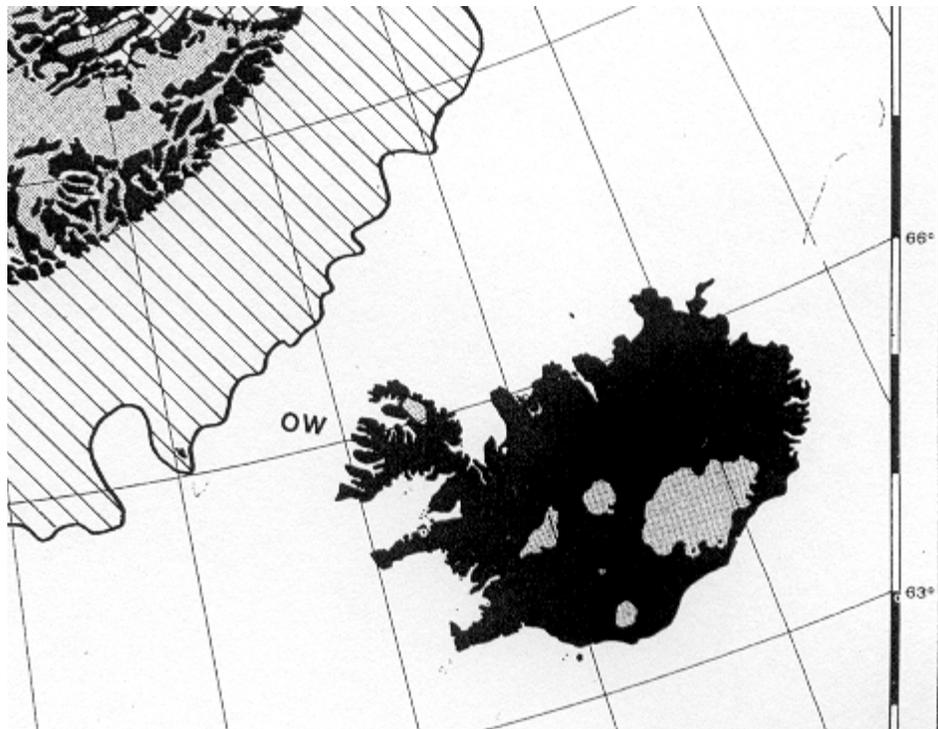
**Figure 19** DMI ice chart end of February 1979



**Figure 20** DMI ice chart end of March 1979



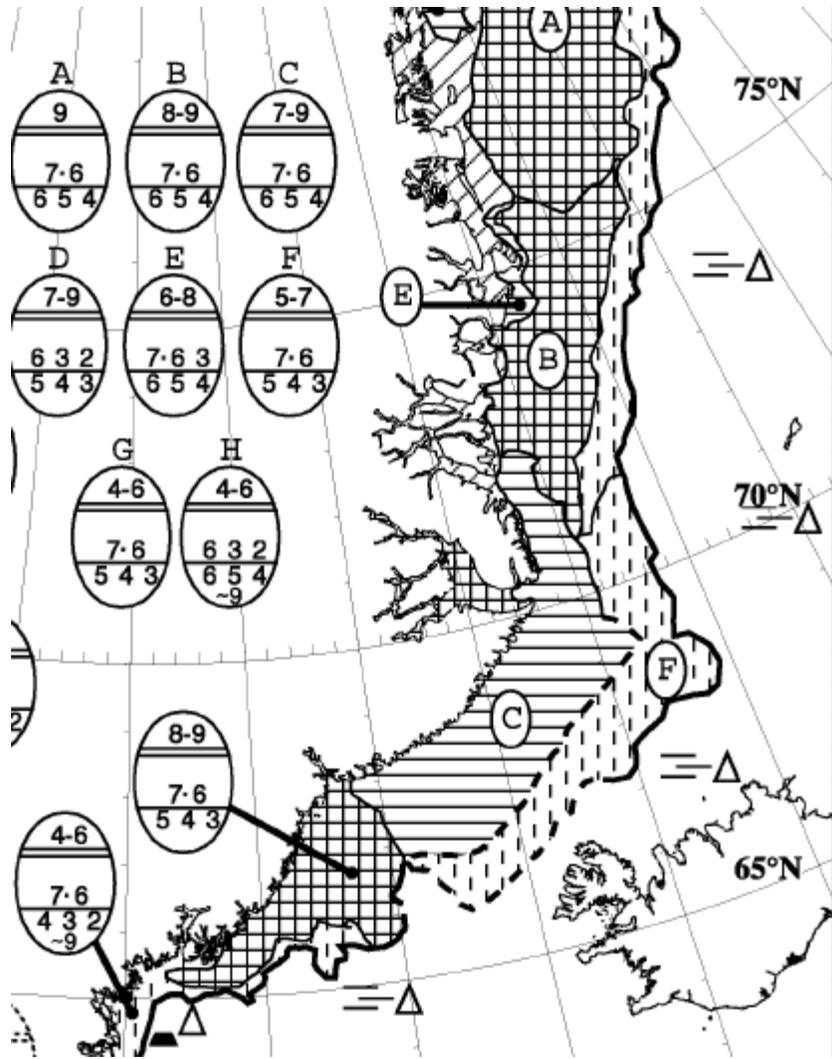
**Figure 21 DMI ice chart end of April 1979**



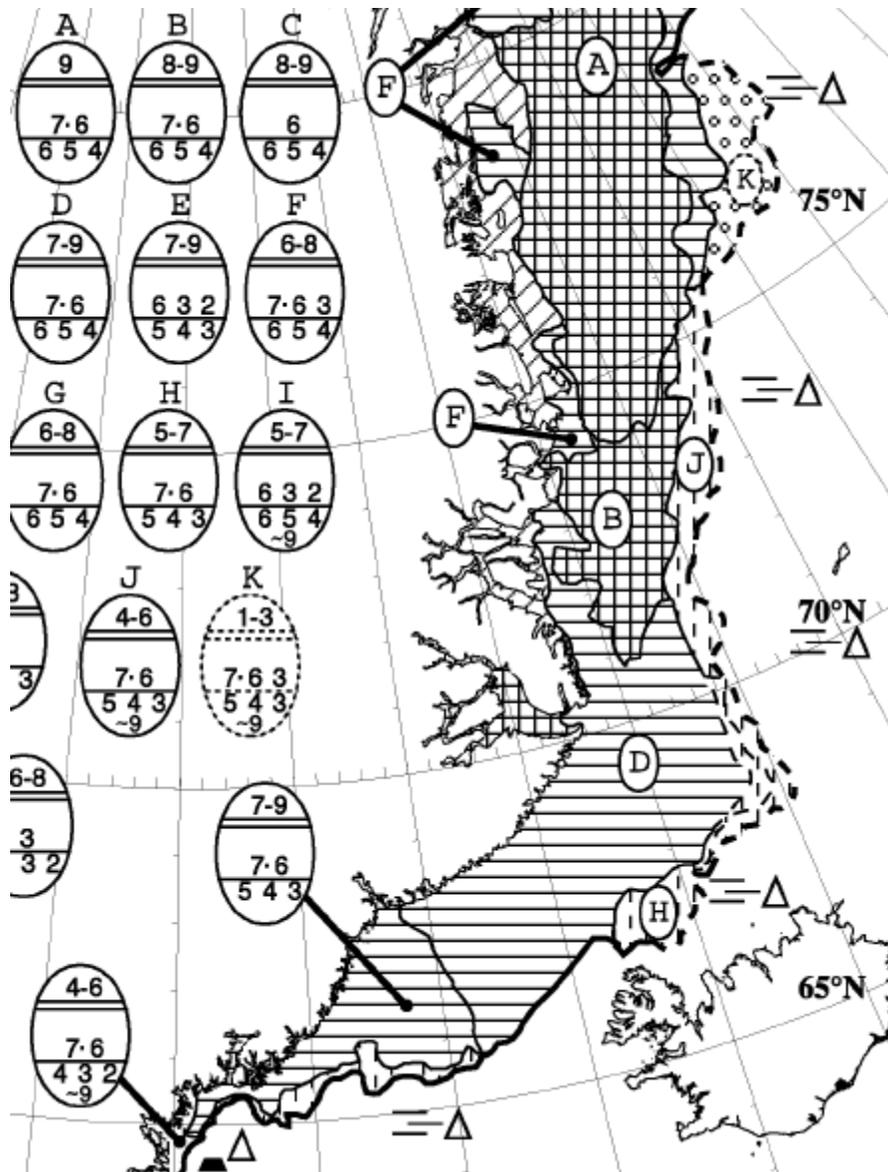
### **Ice Year 2004/05**

The first bulge in the East Greenland Sea pack ice toward Iceland appeared on February 20, 2005, as illustrated in the DMI ice chart of Figure 22. The bulge continued to fill-in with increased concentrations of ice from 5-7/10 to 7-9/10 by the end of February (Figure 23). In early March this ice became entrained in the east-flowing current found north of Iceland (Figure 24). The pack ice remained north of Iceland in concentrations of 4-6/10 through mid- March (Figure 25) before retreating once again toward Greenland by the end of the month (Figure 26).

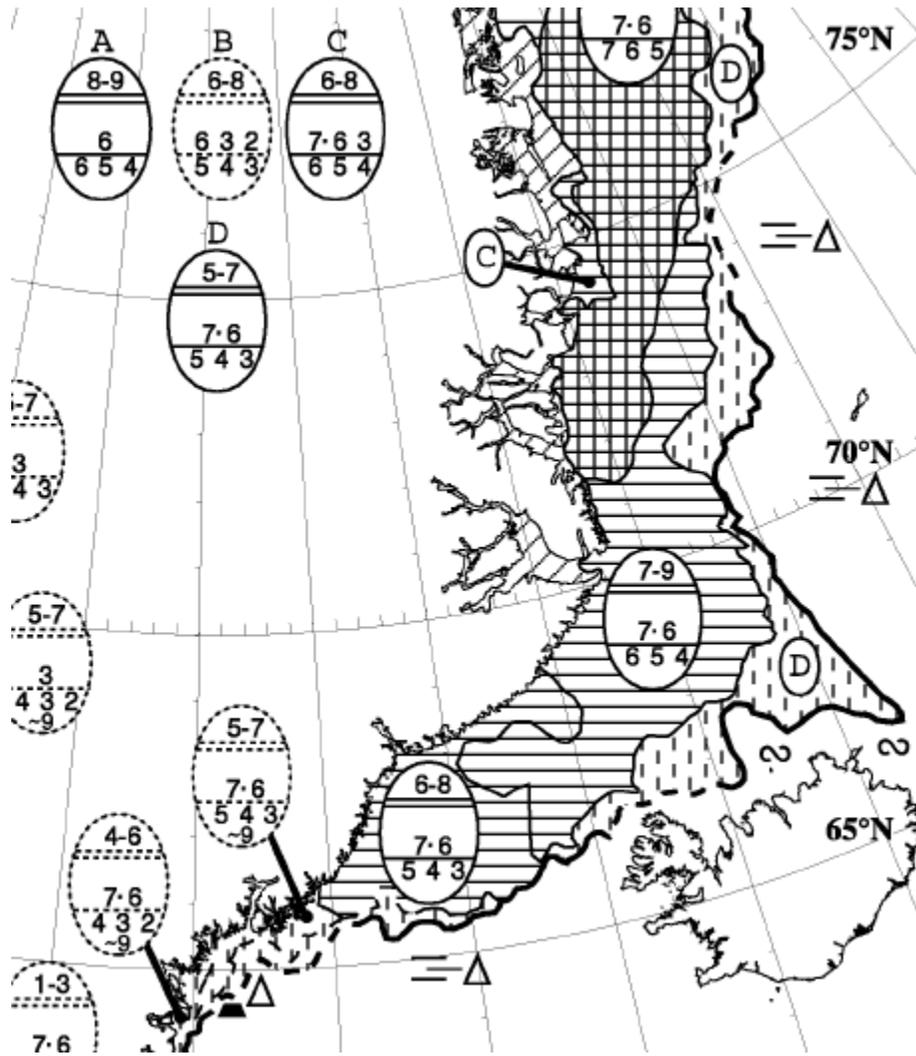
The DMI ice charts from 2005 report that both first year ice (thickness undefined) and old ice in small (20 to 100 metres) to big (500 to 2000 metres) floe sizes.



**Figure 22** DMI Ice chart February 20, 2005, showing the start of the eastward bulge of ice from the East Greenland Sea.



**Figure 23** DMI ice chart February 27, 2005, showing the continued eastward advance of the ice edge north of Iceland.



**Figure 24** DMI ice chart March 6, 2005, showing the continued eastward advance of the ice north of Iceland.

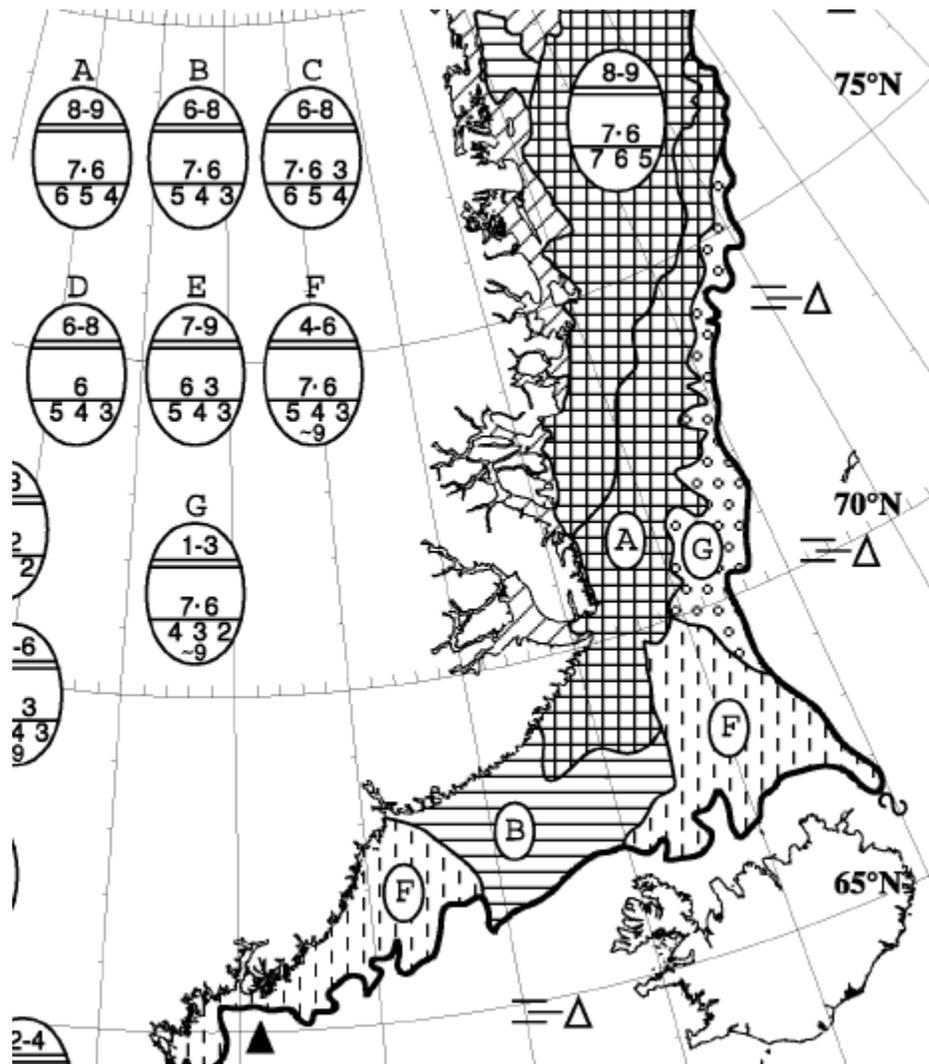
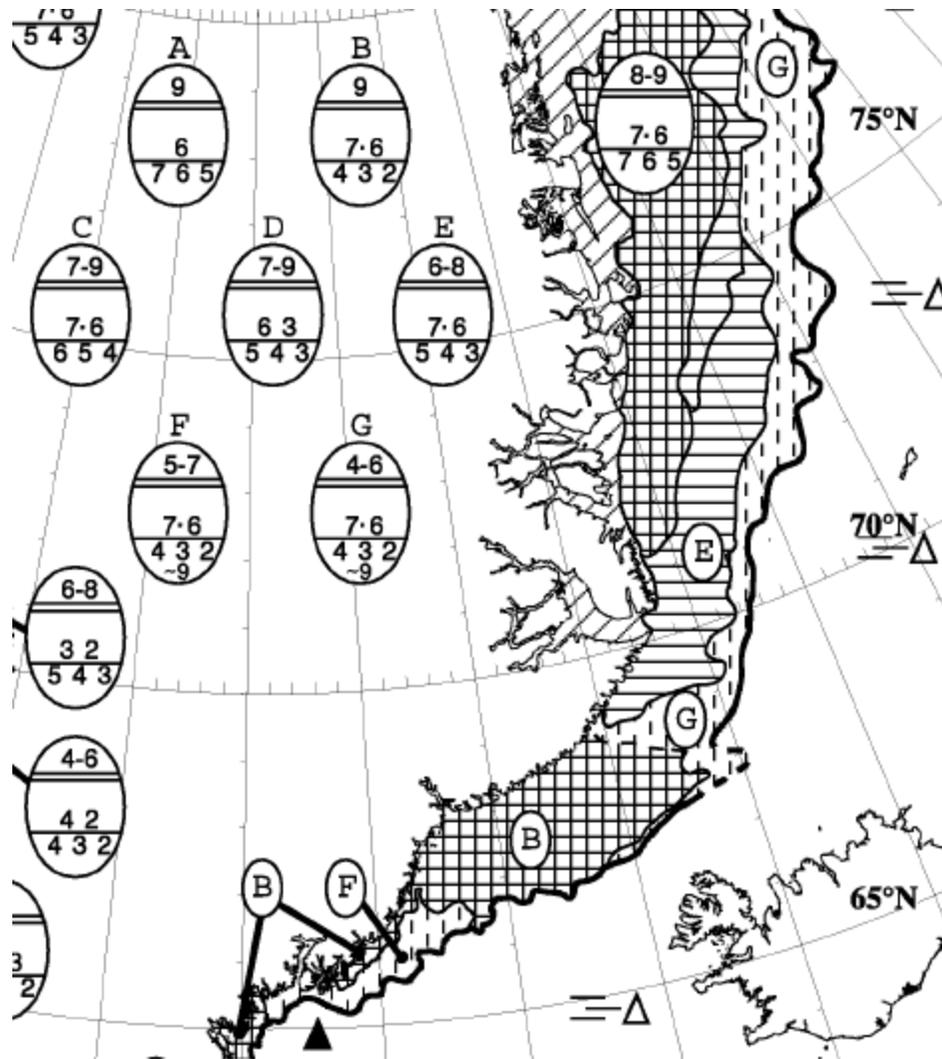


Figure 25 DMI ice chart March 13, 2005, showing the pack ice remaining north of Iceland away from the shipping channels.

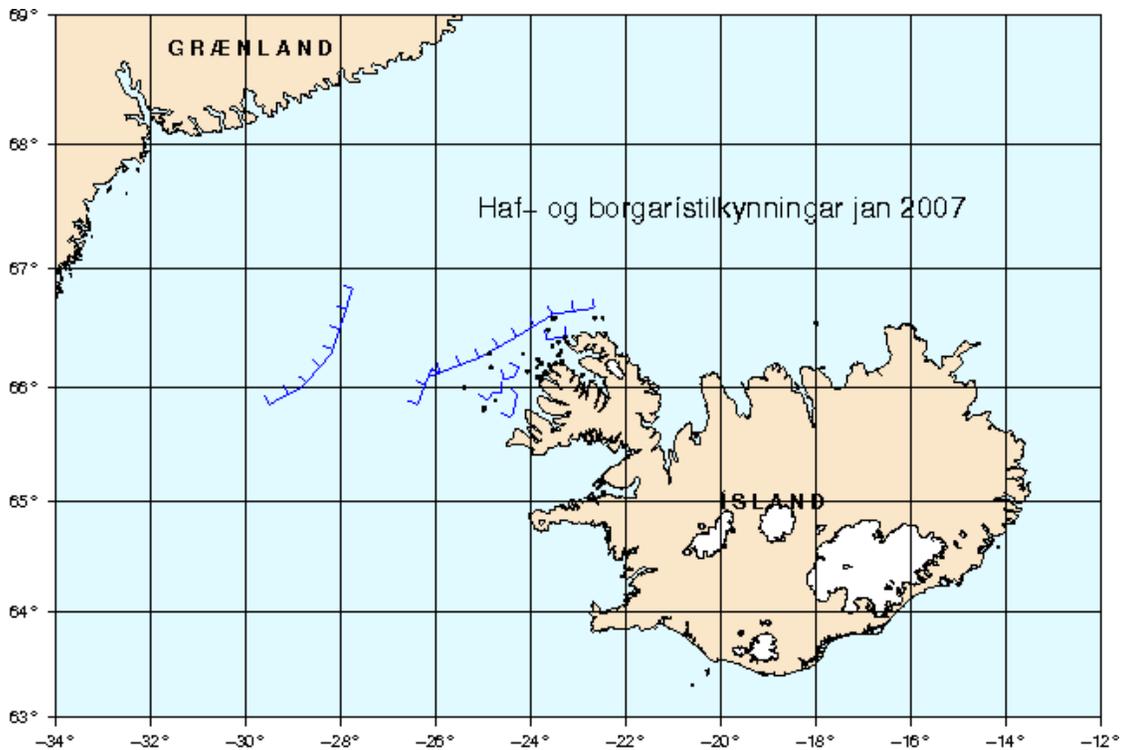


**Figure 26** DMI ice chart March 27, 2005, showing the retreat of the ice edge westward away from Iceland.

At no time during the 2004/05 season did ice actually impede the shipping route to Húsavík during the season.

**Ice Year 2006/07**

Sea ice made a brief advance from the East Greenland Sea to the northwest coast of Iceland in late January of 2007. Figure 27 is an ice chart from the Icelandic Coast Guard of the ice against the northwest coast on January 28, 2007. The ice remained only briefly in the area before moving to the west under easterly winds.

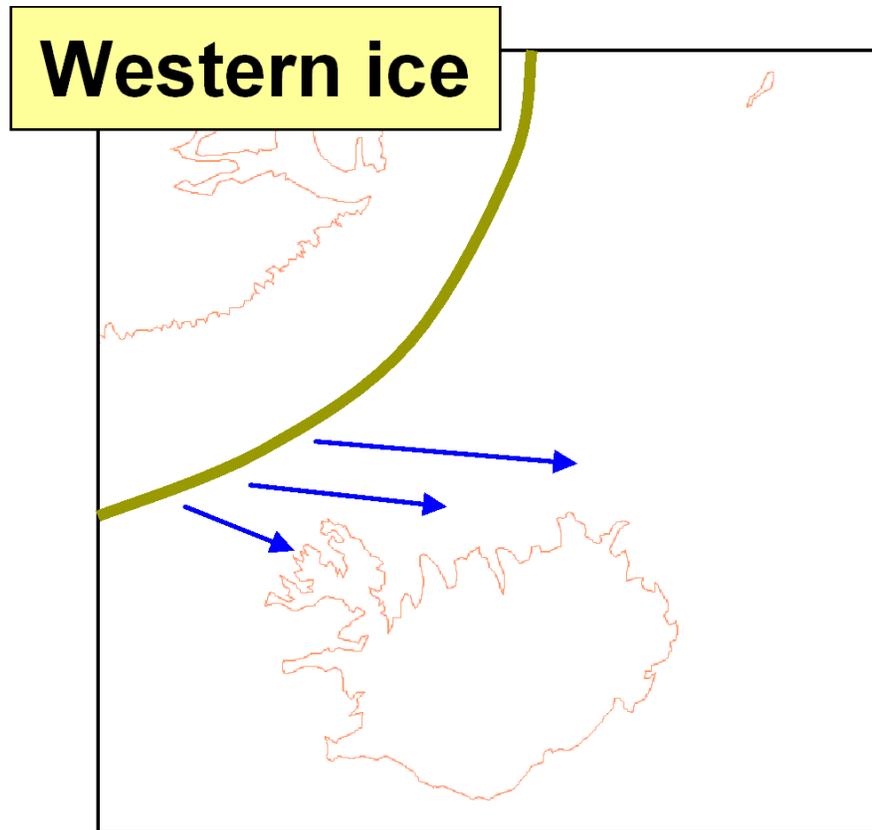


**Figure 27** Icelandic Coast Guard ice chart January 28, 2007.

### Summary

The incursion of sea ice from the East Greenland Sea into the waterways of Iceland has been studied by the meteorologists at IMO. The following material is an extract of the work of Trausti Jónsson, Senior Meteorologist from IMO, on the description of the movement of sea ice into the north coasts of Iceland. Trausti Jónsson has identified three patterns of ice arrival off the north coast of Iceland: western type arrival, northern type arrival and eastern type arrival. Each is described below (note that the material is presented here is copyright of Trausti Jónsson).

## The western type of ice arrival

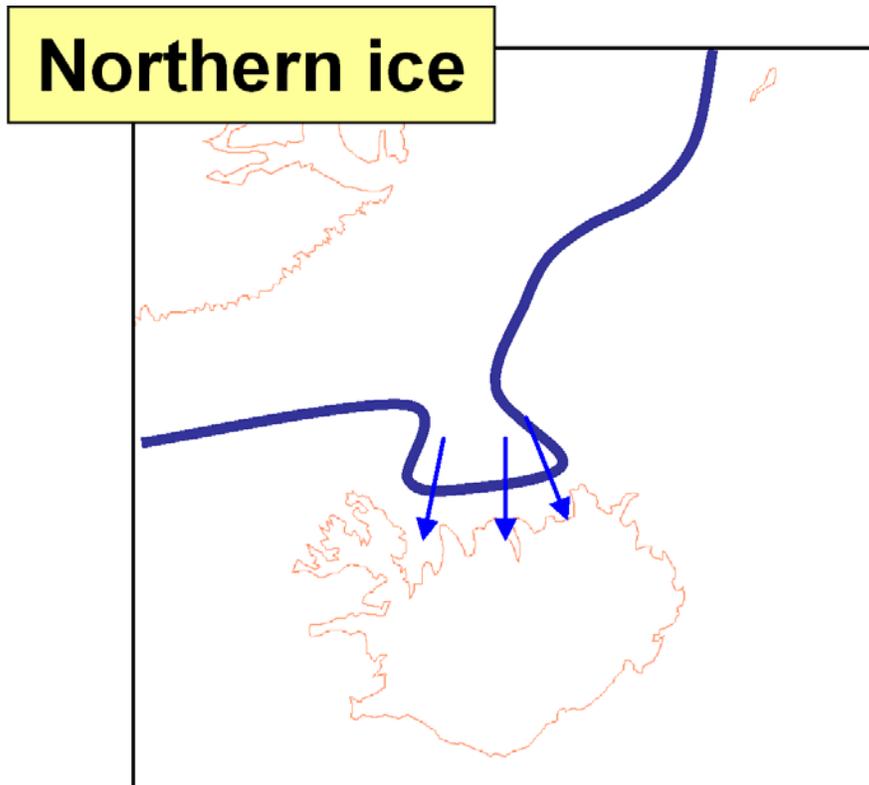


**Figure 28** Western type of ice arrival.

*The western type arrival is illustrated in Figure 28. During most of the year winds from the north and northeast prevail over the sea areas to the north and west of Iceland. As the ice tends to drift at an angle (often about 30°) to the right of the wind direction, the normal situation confines the main ice within the East Greenland current, about half-way between Iceland and Greenland. Occasionally, however, this regular state of affairs is interrupted by periods of variable or even south-westerly or westerly winds both west and north of Iceland. These anomalous winds greatly reduce the ice flow through the Denmark Strait and the ice spreads eastwards in the Strait and in the area to the north of Iceland. Under such circumstances the ice edge tends to become diffuse and in some cases ice drifts to the coasts of Iceland. In most of the anomalously affected areas the ice cover is open with average cover typically only 1-5/10s, but it is usually concentrated in strips or belts with wide open leads in between. As the coast eventually inhibits further drifting towards the east or south, the ice can on occasion accumulate in narrow bands at the coast and disrupt shipping. This type of arrival is informally referred to as “western or westerly ice”, labelled “narrow” by Koch (1945) and is by far the most common type of ice arrival at the coast of Iceland. A western ice episode occurs every few years (e.g. both in 2005 and 2007), but the ice then only very rarely extends all the way to the north-*

eastern and eastern part of the Icelandic coastal waters, and in most cases the ice melts in a few days. Shipping is usually most affected in the Horn/Húnaflói area (western route to Húsavík). A disruption of shipping typically lasts only for one to three days in a row, depending on the wind and the melting rate of the ice. The western ice can occur during periods of persistent westerly winds in almost all seasons, the maximum frequency, however, being in the late winter/spring season when the East Greenland ice cover is at seasonal maximum and to a lesser degree in the summer when the north-easterlies in the area are at the seasonal minimum.

### The northern type of arrival

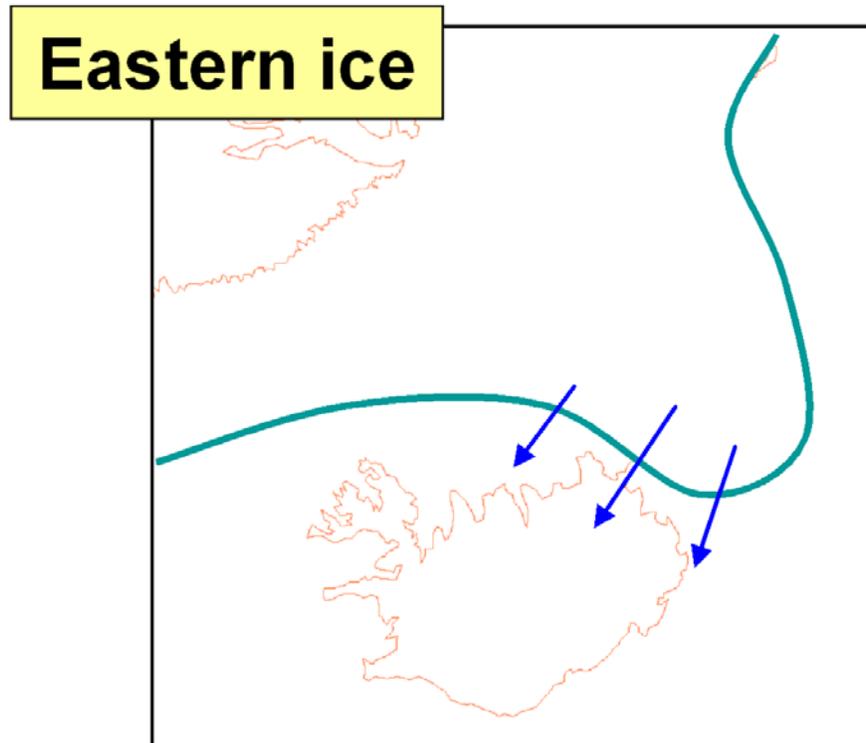


**Figure 29 Northern type of ice arrival.**

Figure 29 describes the northern type of arrival of ice to the coast of Iceland. If there is much ice in the East Greenland current, strong and persistent northerly winds can advect considerable amounts of ice out from the edge directly, to the north of Iceland. This ice then accumulates at the coast where shipping is disrupted. Usually there are more open conditions between the coastal accumulation and the main ice edge to the north. As winds directly from the north tend to drive the ice to the south-southwest, the main ice edge off East Greenland must have reached a relatively easterly position to the north of Iceland at the start of the episode. North-westerly winds would be more effective during more average ice cover periods, but these are rare west of 20°W (see Figure 27). This type of ice arrival is informally referred to as “northern ice” and is considerably less common than the “western” one; it is labelled as “broad” by Koch (1945). One has to

go back to 1979 for a severe episode of this kind. Most of the North coast and partly also the northeast corner can be affected during a northern ice arrival, in contrast to the western ice, that only rarely extends further east than 18°W (Figure 27). As the total ice volume during a northern ice episode is typically larger than in a western one, the ice tends to be more persistent as there is more to melt. The melt water is lighter than the underlying warmer water masses and a cold layer is formed, making the sea surface less hostile for further ice outbreaks. This type of arrival has a seasonal maximum in the late winter/spring.

### The eastern type of arrival



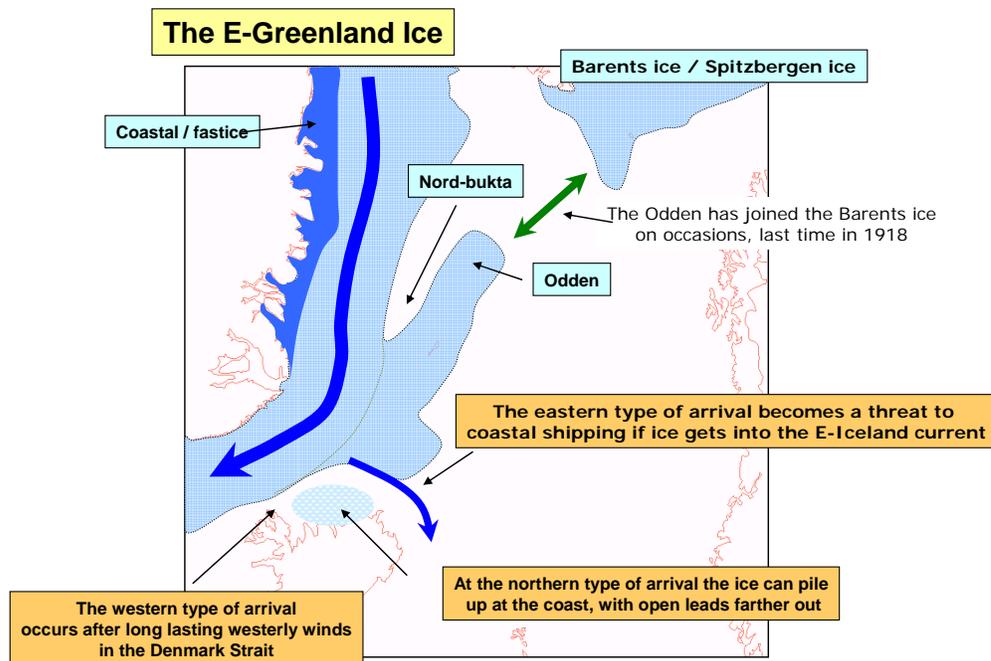
**Figure 30 Eastern type of ice arrival.**

Figure 30 illustrates the eastern type of ice arrival. If the extent of the East Greenland ice is very great, it extends out of the East Greenland current and into the oceanic gyre to the northeast of Iceland, where winds from the northeast will advect it towards the north-eastern and eastern coasts and effectively stopping shipping. This is the most serious ice arrival regarding marine operations and can affect the coast for weeks or even months. It is referred to as “eastern ice”, labelled “very broad” by Koch (1945). However, it is rare, happening the last time in 1968 and 1969 and to a lesser extent in 1965. Prior to that, one has to go back to 1918 for a case. The eastern ice arrives by north- and north-easterly winds, the most common wind direction in the area. This type of arrival only happens when there is exceptionally much ice in the East Greenland area. It is not as dependent on anomalous winds as the western and northern type of arrivals. This is the main threat to shipping in the north-eastern routes as the ice cover is long-lasting and

denser than the other types. On severe occasions the ice also covers the Eastern Fjord area and fills the fjords there. In 1968 a continuous tongue of ice reached almost south to the southern tip of Iceland, narrow at its westernmost reach. During the so-called Little Ice Age (ca. 1600 to 1900) the drift ice reached the Reykjavik area by the way of southern shore on a few extreme occasions. This type of arrival has a seasonal maximum in the late winter/spring, but can last far into the summer if northerly and north-easterly winds persist.

### Summary of Historical Ice Condition

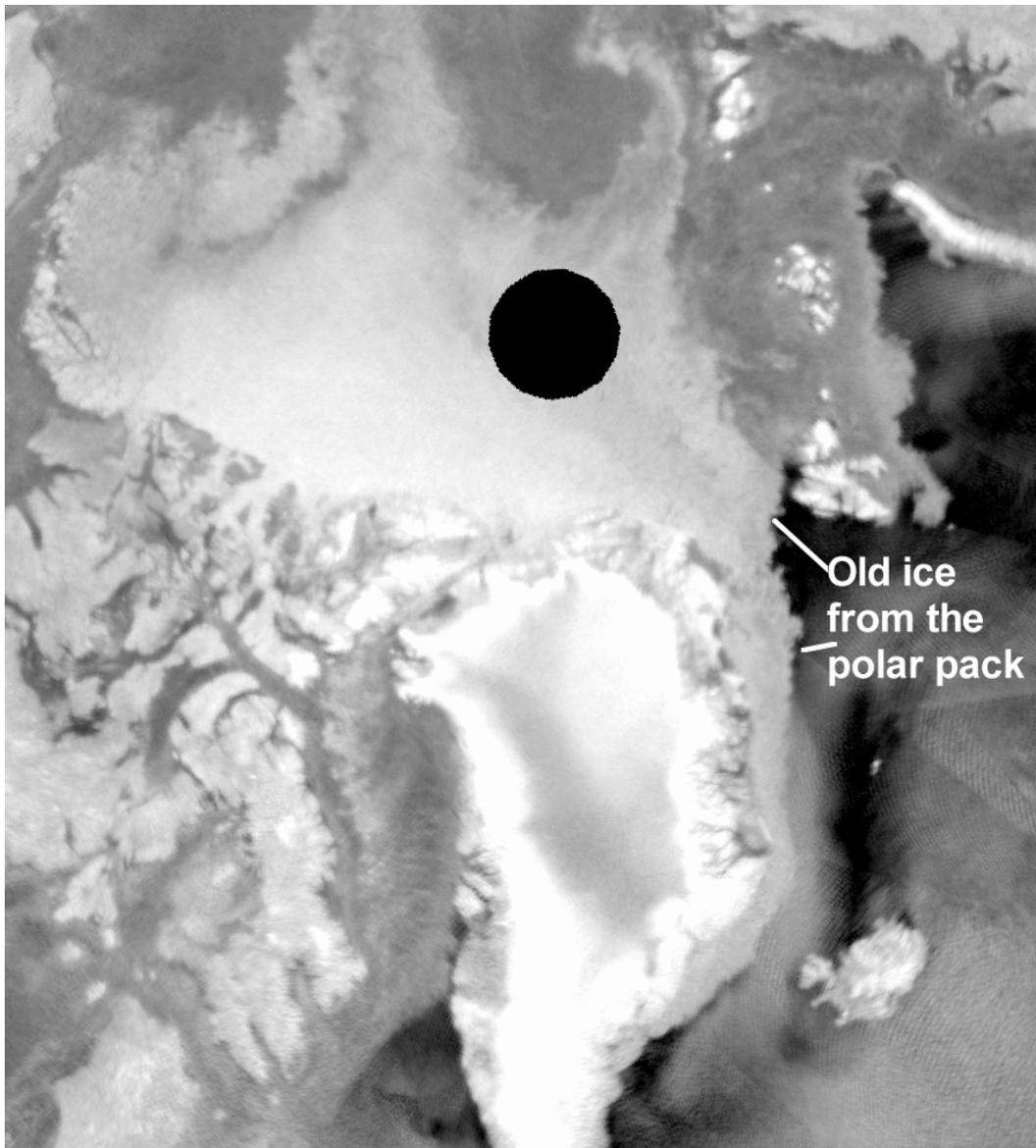
Trausti Jónsson of the IMO has provided a schematic representation of the ice arrival to Iceland in Figure 31.



trj

**Figure 31 Summary of ice incursion into Iceland.**

The controlling feature of the ice of the East Greenland Sea is the East Greenland current shown as the blue arrows in Figure 31. The East Greenland current is the main export current from the Arctic Ocean and is responsible for the main export of the polar old ice pack from the Arctic Ocean. Figure 32 is a QuikSCAT radar image of the Arctic Ocean from March of 2007 illustrating this flow of polar ice out of the Arctic Ocean along the east coast of Greenland following the East Greenland current.



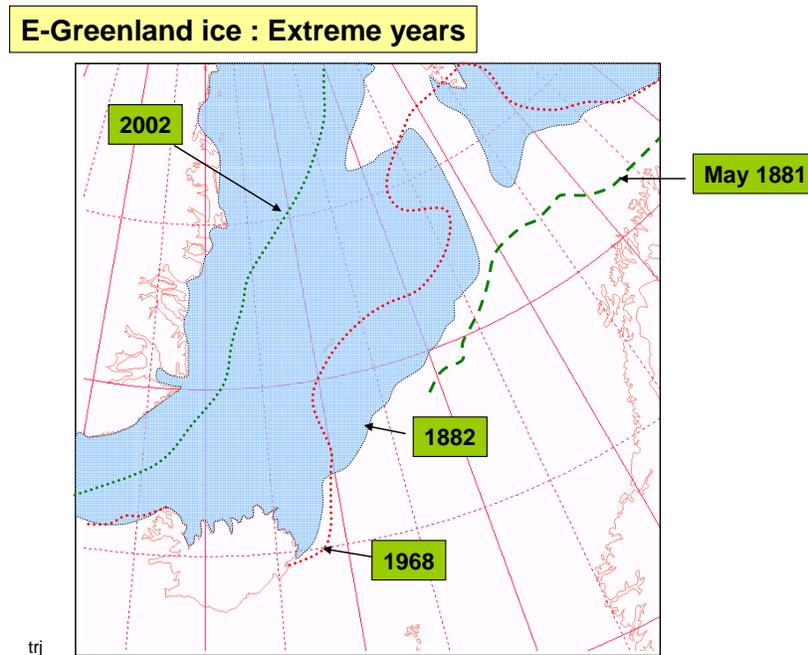
**Figure 32 QuikSCAT image of the Arctic Ocean March 2007 showing export of old ice along the east coast of Greenland.**

The old ice of the polar pack shows up as the bright white ice floes within the Arctic Ocean in Figure 32. The thinner first year ice shows up as a darker grey on the image. The main export of this old ice along the east Greenland coast is evident in the satellite image as the ice floes get carried south in the East Greenland current. In this example the ice is well away from the coast of Iceland.

The old ice of the Arctic Ocean tends to stay close to the Greenland coast with first year ice growth out from the pack ice to the east. This makes the ice of the East Greenland Sea a mix of both old ice and first year ice. Consequently, when sea ice occurs north of Iceland it can be composed of both these ice types. Unfortunately, the historical ice

information for Iceland does not provide a description of the age or thickness of the ice encountered.

A summary of the extremes of ice occurrence to Iceland has been produced by Trausti Jónsson of the IMO and this is provided in Figure 33.



**Figure 33 Summary of historical ice occurrence in Iceland.**

### **2.1.2 Impact of Sea Ice On Shipping**

The ability of any given vessel to navigate in ice covered waters is dictated by the vessel's "ice class". An ice class is a notation that is added to the vessel class certificate by the classification society that classifies the vessel. All ship classification societies belong to an organization call the International Association of Classification Societies (IACS).

Each IACS classification society has its own rules and designations for ice classes but all adopt an equivalent standard that follows the Finnish-Swedish ice rules. These rules are defined to classify ships intending to navigate into the ice covered waters of the Baltic Sea in winter. Both Sweden and Finland control access to their ports in winter by these ice class rules restricting access to only higher ice classes as the ice conditions thicken during the winter.

Table 2.0 below provides a description of Finnish-Swedish ice classes:

<b>Finnish-Swedish Ice-Class Designations</b>	
<i>Ice Class</i>	<i>For navigation in</i>
IA Super	Extremely difficult ice-conditions
IA	Difficult ice-conditions
IB	Moderately difficult ice-conditions
IC	Easy ice-conditions
II	Very easy ice-conditions

**Table 2 Finnish-Swedish Ice Class Designations**

The definition of what constitutes an “easy” or “difficult” ice condition in the Baltic is deliberately kept vague because this is actually a very complex subject. It would not be possible to define exactly what these ice conditions entail due to the many combinations and permutations of ice concentration, thickness, ridging, rubble, pressure etc. that could be encountered. For example, a low ice class vessel can navigate in very thick ice if the concentration is low or very high ice concentration if the thickness is low and this can go on and on. In addition, the assistance of an icebreaker also allows a vessel of lower ice class to deal with heavier ice conditions. These factors are all considered in the application of the Finnish-Swedish designations.

One of the services Enfotec offers is officer training in ice navigation and we use the guide below as the maximum thickness of ice (assuming total ice cover) a master should consider as the limit for each class:

- 1A Super – 120 cm
- 1A- 100 cm
- 1B – 70 cm
- 1C – 50 cm
- II – 30 cm
- No Ice Class – 15 cm

At the maximum ice thickness the ship should only attempt navigation if the floe sizes are very small and well broken-up by an icebreaker. This is only a general guideline as the presence of a channel groomed by an icebreaker can allow these vessels to venture into thicker ice but the risk goes up. A ship should be able to withstand the ice present outside of the icebreaker channel as wind, current and sea swell can close a track leaving the ship surrounded by this ice.

All classification societies closely follow the Finnish-Swedish rules and provide for direct equivalency to their own rules, as described below (the Class society’s notation is

on the left and the Finnish-Swedish equivalency on the right). This guide is presented here as often a ship owner will include this notation when offering a ship for charter.

### **Det Norske Veritas**

Ice-class notation Equivalent Finnish-Swedish Ice-class

<b>ICE-1A*</b>	<b>IA Super</b>
<b>ICE-IA</b>	<b>IA</b>
<b>ICE-IB</b>	<b>IB</b>
<b>ICE-IC</b>	<b>IC</b>

### **Lloyd's Register of Shipping**

Ice-class notation Equivalent Finnish-Swedish Ice-class

<b>1AS</b>	<b>IA Super</b>
<b>1A</b>	<b>IA</b>
<b>1B</b>	<b>IB</b>
<b>1C I</b>	<b>C</b>

### **Russian Maritime Register of Shipping**

Ice-class notation Equivalent Finnish-Swedish Ice-class

<b>ULA</b>	<b>IA Super</b>
<b>UL</b>	<b>IA Super</b>
<b>L1</b>	<b>IA</b>
<b>L2</b>	<b>IB</b>
<b>L3</b>	<b>IC</b>
<b>LU7</b>	<b>IA Super</b>
<b>LU5</b>	<b>IA Super</b>
<b>LU4</b>	<b>IA</b>
<b>LU3</b>	<b>IB</b>

The majority of cargo (bulk and container ship) vessels in the world have little or no ice class, usually the II class or lower. This is particularly true of larger vessel such as the Panamax size where there are virtually no vessels of ice class in this size range on the market. However, this does not mean that these vessels can't navigate through ice covered waters as this is done routinely in winter in both the Baltic and the Gulf of St. Lawrence. The issue becomes one of having the thickness and concentration of the ice as well as the resources of icebreaker escort, ice routing assistance and an experienced Ice Master to guide the vessel through the ice. These issues are dealt with further in Section 3.0 where we discuss countermeasures. In the context of vessel access to the Húsavík region during periods of ice incursion we have the following analysis.

In order to assess the impact sea ice has on vessel access to a region we need to know the concentration, thickness and floe size of the ice as well as whether the ice is under pressure. Although the type of ice has not been identified in the historical ice data for Iceland, we can estimate the likely composition of the ice by the source area in the East Greenland Sea. Since the ice is imported from the East Greenland Sea as drift ice in the latter part of the winter and the spring this would indicate that the ice is of at least

medium to thick first year ice (1.0 to 1.3 metres in thickness), as young ice types are generally not present at this time of year in the East Greenland Sea and would not survive a long drift over open seas to reach Iceland. In addition, old ice from Arctic Ocean is common in the East Greenland Sea, although this ice tends to stay closer in to the Greenland Coast. None-the-less, we can assume that when the East Greenland Sea ice edge advances to Iceland it is carrying the polar old ice with it along with the thick first year ice from the winter's growth, as described in the ice arrival sequences in the previous section. The passage to Iceland would mean that this ice would be exposed to weathering by the sea state which should reduce the floe sizes to 50 to 500 metres in size.

An additional consideration is the presence of icebergs, bergy bits and growlers. Icebergs occur commonly in the east Greenland Sea as well as in the northern Barents Sea and are recorded to drift eastward and southward into the shipping lanes north of Iceland. Icebergs are more prone to drift with current than wind so will follow a different path than the surrounding sea ice so may occur with or in isolation from the surrounding sea ice. Icebergs and their fragments (berg bits and growlers) are "point targets" and in themselves do not limit the access of a port to shipping. However, they do represent a navigational hazard that the navigator needs to be aware. Ships that trade regularly into "berg waters" employ avoidance procedures such as slowing down or stopping in poor visibility and using high powered searchlights during navigation in darkness. In the context of assessing the accessibility of a port such as Húsavík iceberg occurrence is not a factor in terms of port closure.

As for the concentration of sea ice that occurs north of Iceland (i.e. the proportion of the sea surface covered by ice) we know from the analysis of the DMI ice charts with the historical ice data from IMO that when "difficult for navigation" was identified this indicated an ice cover of 7/10 to 9+/10 concentration (i.e. 70% to 99% of the ocean surface covered by ice). Since the ice is drifting toward the north coast of Iceland, pressure would likely be present in the ice when it reaches 9+/10 concentration as Iceland prevents any further southward drift and the ice piles up against the coast.

For vessels with very low or no ice class, it is possible to navigate with caution through thick first year ice floes and old ice when the ice concentration is in the area of 4/10 (40% ice cover). If the floe sizes are very small (i.e. in the range of 100 metres in diameter or less) the concentration could increase to 5/10 if no more than 1/10 of this ice is old ice as the vessel could easily push its way through this ice with an experienced ice navigator. However, for concentrations above this it is very dangerous for vessels of low or no ice class to attempt navigation into these conditions. Consequently, the "difficult for navigation" would mean the closing of the window for shipping to low or no ice class vessels.

Although low ice class vessels navigate in the Gulf of St. Lawrence in winter, they are rarely contending with thick first year ice (i.e. first year sea ice of at least 1.2 metres in thickness) and never with old ice (3.0 metres or more in thickness) both of which are the likely types of sea ice that reaches Iceland during the extreme events.

Looking back on the Baltic ice classes, we can see that even a very high Baltic 1A would have great difficulty in a 9+/10 matrix of thick first year ice and old ice. Even with the use of an icebreaker, it is not recommended to bring a vessel of any of the Baltic ice classes through ice concentrations of thick first year ice and old ice above 7/10 concentration, particularly if there is any pressure on the ice or there is a sea swell present, likely conditions along the north coast of Iceland when the extreme event occurs.

The conclusion here is that very close pack ice conditions are present shipping is essentially halted for that period for the market low ice class vessels envisaged for this project.

## **2.2 Task # 2 Future Sea Ice Trends Over the Next 50 Years**

The work of this task involved the estimation/prediction of expected sea ice trends for the Húsavík region and the proposed shipping routes to the Bakki smelter over the next 50 years, taking into account the possible effect of climate change.

Predicting how often in the future sea ice events will occur along the proposed shipping routes to the Húsavík region depends on whether an underlying climatological trigger for these events that have occurred in the past can be found. Such triggers may include known oscillation events as the North Atlantic Oscillation (NAO), the Southern Oscillation (ENSO) or other similar patterns. Enfotec has studied these phenomena and has found some loose correlations of these events to changes in sea ice occurrences in other regions. In addition, the effects of climate change also have to be considered. In this study, we have analysed three possible trigger factors as follows:

- The North Atlantic Oscillation
- The Southern Oscillation (ENSO)
- Climate Change

### **2.2.1 North Atlantic Oscillation**

There is strong evidence in the scientific record that the inter-annual variability of winter temperatures in northern Europe and eastern North America is the result of variations in a phenomena called the North Atlantic Oscillation (NAO) (Hurrell 1995). The NAO refers to the inter-annual difference in atmospheric pressure between the Icelandic Low and the Azores High, found west of Portugal. When the pressure difference is higher than the historical mean between these systems (i.e. when the gradient between the Azores high is steep compared to the Icelandic Low) then the NAO is considered to be in a “positive” state and when the gradient is below the historical average the NAO is considered to be in a “negative” state (that is, a weak Icelandic Low). Figures 34 and 35 below schematically show the difference between these events.

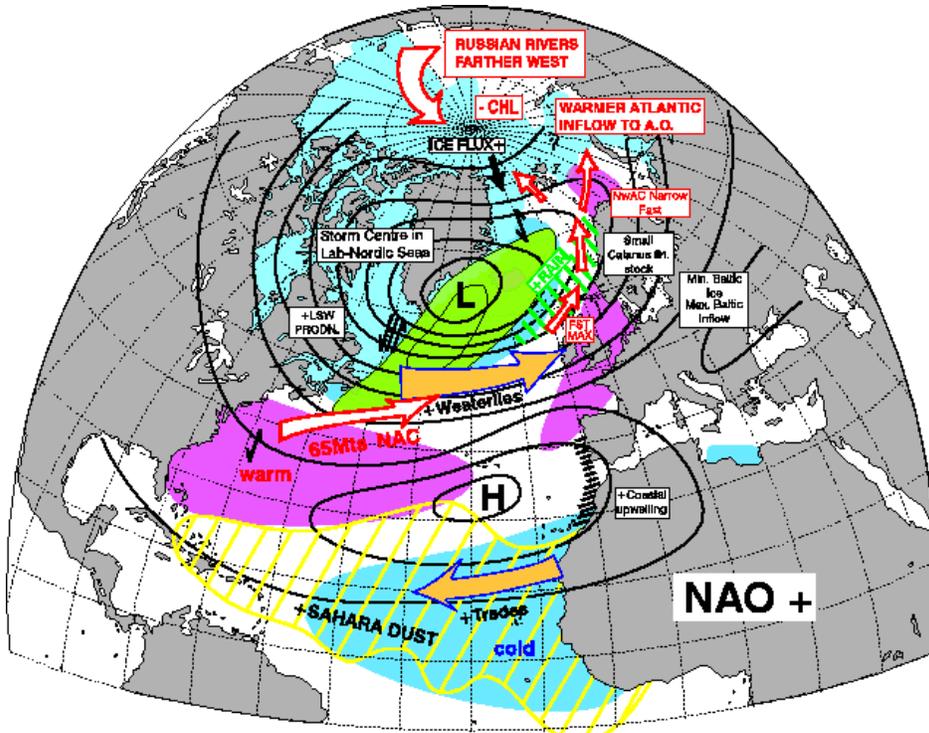


Figure 34 Schematic of a positive NAO Phase (Stephenson 2005)

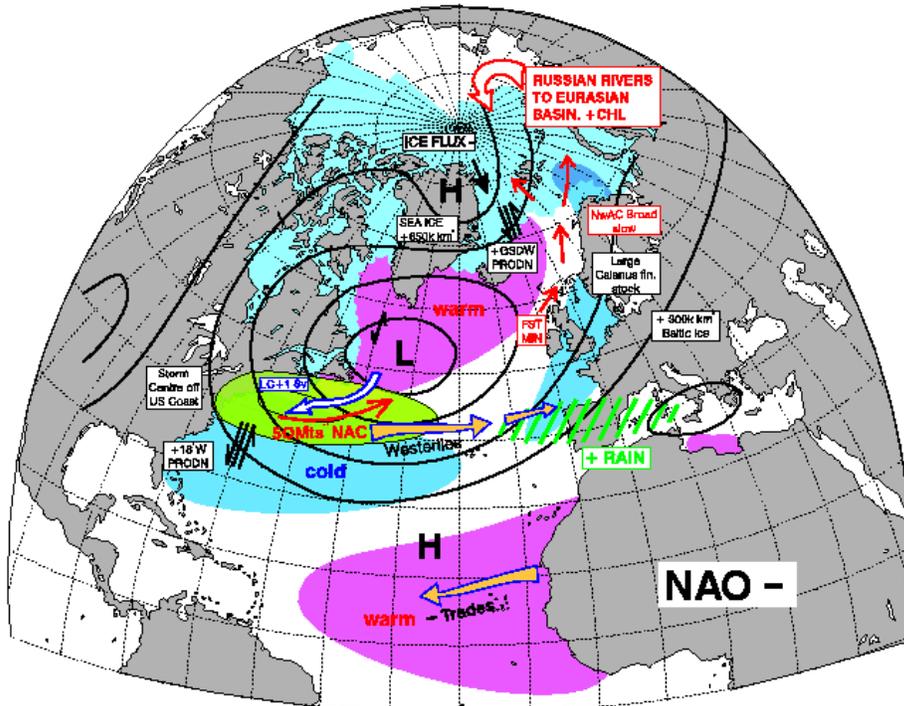


Figure 35 Schematic of a negative NAO Phase (Stephenson 2005)

During a strong positive NAO the Icelandic Low is very strong, drawing down cold Arctic air along the Canadian East Coast and bringing warm moist air into Western Europe. Conversely, when the NAO is negative, the Icelandic Low is weak keeping

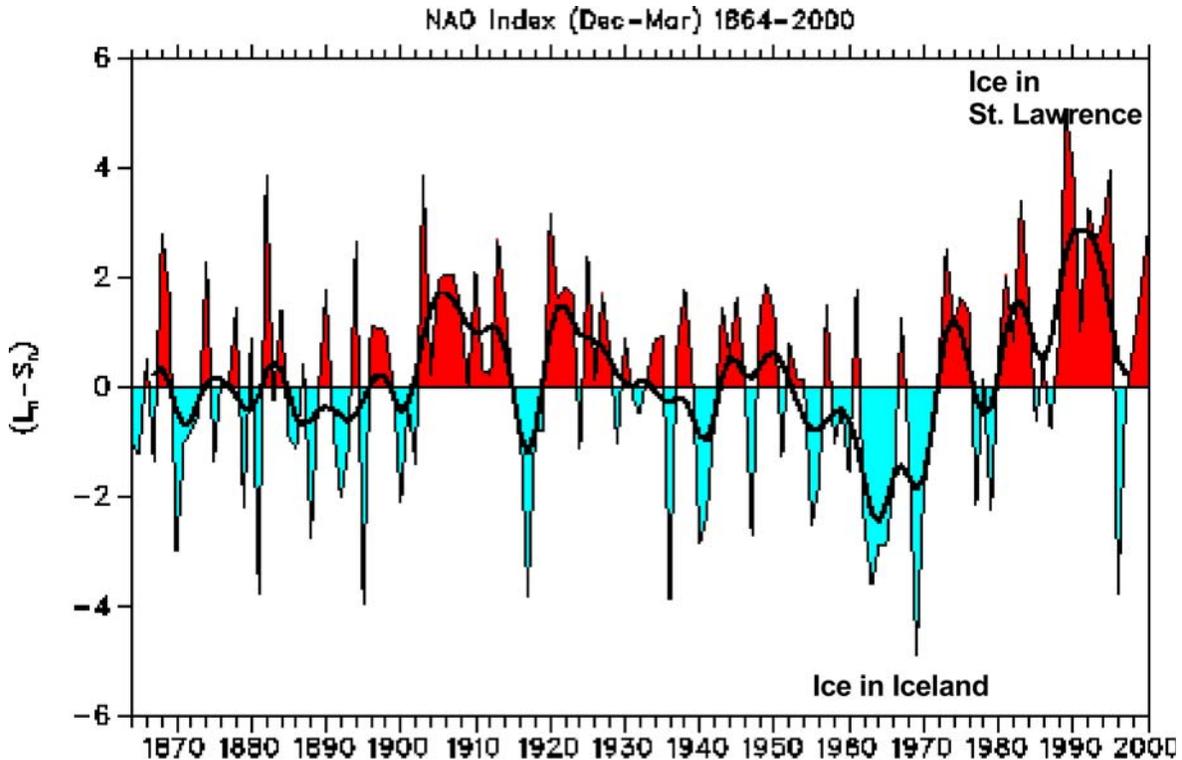
polar air to the north and allowing warm air into eastern North America but cooler and drier air into Western Europe. The NAO has its greatest influence during the winter months when the pressure gradient between the low and high pressure systems at its greatest. A study of ice conditions in the Gulf of St. Lawrence completed by Enfotec has found a close association between positive NAO years and heavy winter ice conditions in the Gulf of St. Lawrence and, conversely, lighter ice conditions during negative NAO conditions (Gorman 2000). This influence on regional weather is so strong that the British Met Office uses the NAO indices as the basis for its long range weather forecast for Britain and northern Europe (Rodwell and Folland 2002).

The IMO has also studied the influence of the NAO and has found convincing correlations to weather and ice conditions that occur in Iceland. This is of course not surprising since the NAO has its northern influence over Iceland! The following paragraph is an extract of the work of Trausti Jónsson, Senior Meteorologist from IMO, followed by additional analysis from Enfotec.

*During negative NAO episodes (high air pressure in Iceland and thus a low gradient difference with the Azores) the winds off east Greenland are more variable than during positive episodes (low pressure in Iceland and a high gradient with the Azores). Variable winds in the east Greenland area favour the spread of the ice edge towards the east and thus increases the likelihood of ice episodes off Iceland. On the time scale of a few years and up to a few decades the correlation of the NAO-index and the extent of the east Greenland ice is quite large (up to -0.6 ; Vinje, 2001) and as the occurrence of ice off Iceland is more likely when the east Greenland ice is extensive, negative NAO-index values favour ice off Iceland. On the century time scale a more complicated picture emerges. The ice was considerably more extensive in the 19th century than later (Vinje, 2001), even though the NAO-index values were often comparable to modern ones. During the early period there was also a substantial correlation between the NAO and the ice area, but the linear regression had a different inception point than later. The correlation between the NAO and ice extent are higher both in the Barents Sea (also negative) and off Labrador (positive correlation), than in east Greenland area (Vinje, 2001). This reflects the more complicated ice budget in the east Greenland area, where there is a substantial component of ice import from the Arctic through the Fram Strait, whereas in both the Barents Sea and off Labrador the ice is produced more locally (see e.g. Vinje et al., 1998; Serreze et al., 2006).*

An analysis of the historical NAO index dating back to 1864 supports the findings from the IMO on the influence of the NAO on ice in Iceland. Figure 36 below charts the NAO index from 1864 to 2000. The Y-Axis index is calculated by the subtraction of the average pressure measured at Lisbon, Portugal ( $L_N$ ) from that of Stykkisholmur, Iceland ( $S_n$ ). A comparison of this graph to the Koch Index of Figure 1 from Section 2.1.1 shows the last major incursion of ice to Iceland in the 1960's corresponded to a strong negative NAO (as well as a negative in 1979). The strong positive NAO in the 1990's that created the long period of minimal ice in Iceland corresponded to the heaviest period of sea ice in the Gulf of St. Lawrence for the same period (Gorman 2000).

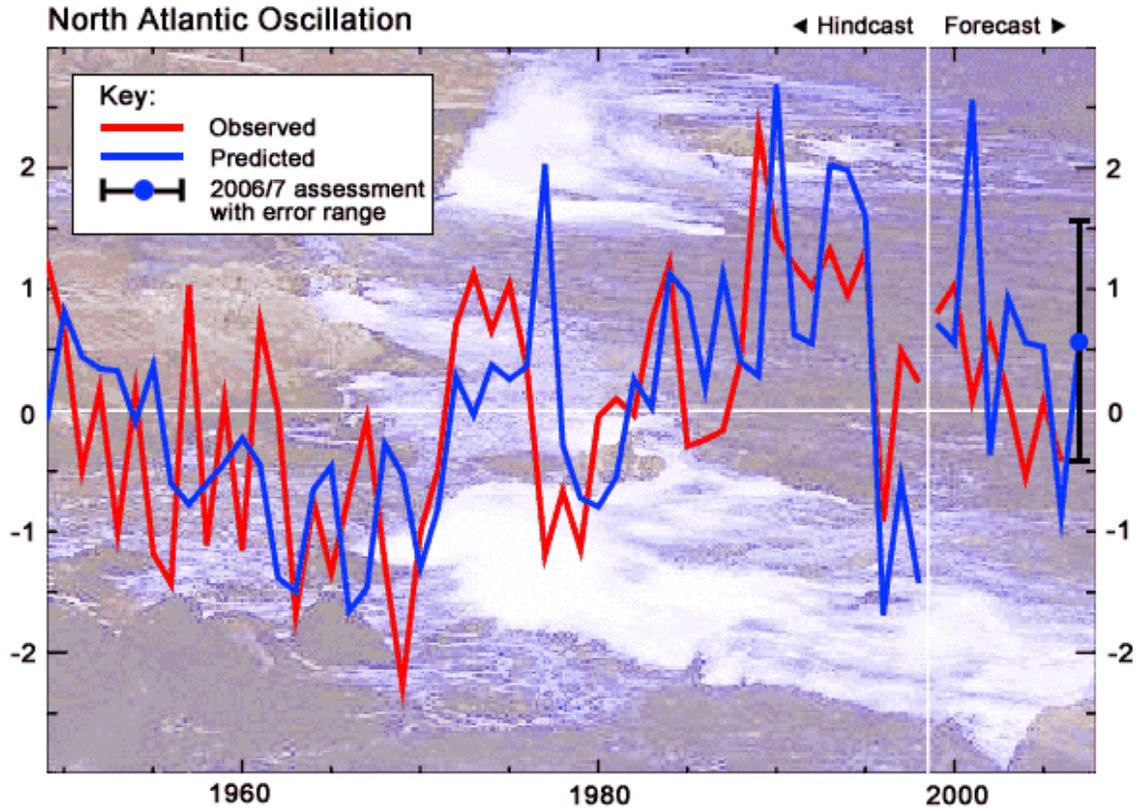
**Figure 36**  
**North Atlantic Oscillation**  
**1864 – 2000 (after Hurrell 1995)**



However, the heavier ice of the late 19<sup>th</sup> century does not correlate as well to the NAO as do the more recent decades, supporting the findings from the IMO in this regard. This indicates that climate change may be a factor in this difference (see Section 2.2.3).

Figure 37 illustrates the recent trend in the NAO as developed by the British Met Office. There has been a trend in the past seven years for the NAO to return to neutral conditions to slightly negative. This may explain the return of more sea ice events off Iceland in recent years (such as in 2005 and a lesser extent 2007). This also correlates to the reduction in sea ice we have seen in the Gulf of St. Lawrence over the same period.

The close association of the NAO index and weather is so compelling that the British Met Office now uses this index as a major factor in the production of their season weather forecasts. This is fortunate for the Bakki development as we will explore in Section 3.0 on countermeasures for this project.



**Figure 37 British Met Office NAO Analysis showing the trend to neutral to slight negative NAO recently.**

A caveat to this analysis is that the earth's climate is very complex and no single index can be expected to provide a statistically significant correlation to observed events. That being said, the association demonstrated in the past 50 years of the NAO to ice in Iceland is worth watching.

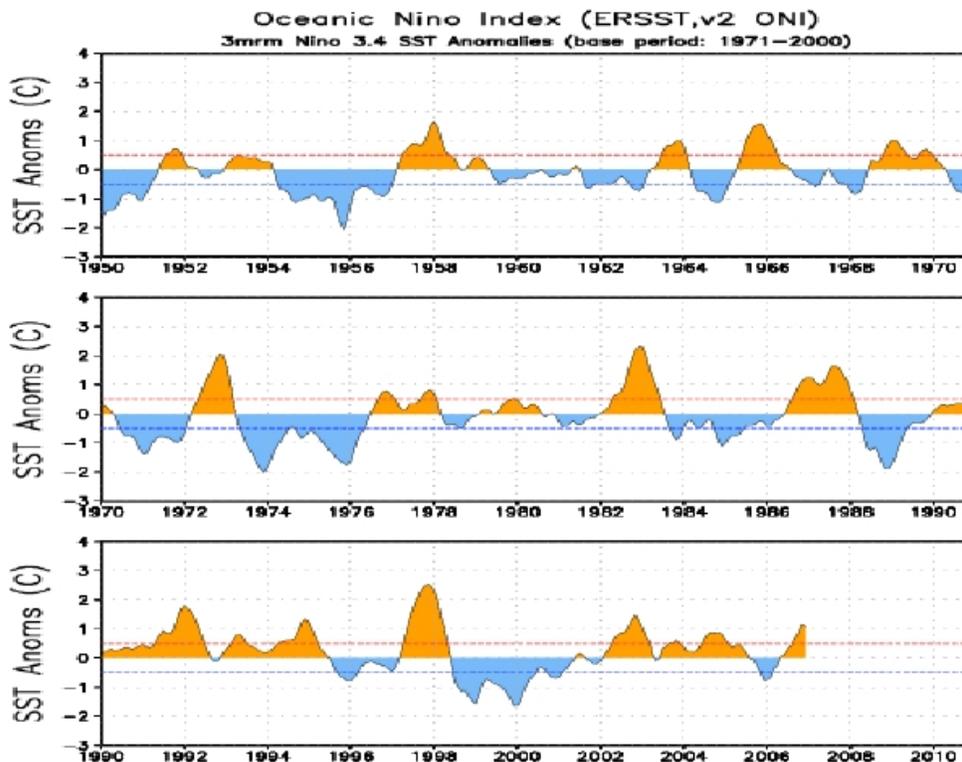
For an analysis of what can be expected for the next 50 years, the close link of ice occurrences to the NAO indicates that the ice conditions experienced during the 1960's can be expected again when strong negative NAO episodes occur in future (tempered with the possible influence of climate change).

### **2.2.2 Southern Oscillation (ENSO)**

The Southern Oscillation is the much more famous cousin of the NAO, more commonly known as the El Niño/La Niña complex. ENSO refers to the cyclic pattern relating to the appearance of warmer than normal equatorial Pacific Ocean surface waters west of South America (the El Niño condition) or cooler than normal waters in the region (the La Niña condition). It is well documented that ENSO cycles have a significant effect on weather conditions experienced over many regions of the planet, particularly in the Pacific Ocean and over North America.

The affect of ENSO on the North Atlantic and Northern Europe is not as clear. Enfotec has studied the ENSO effect on sea ice occurrence in eastern Canada. During El Niño years the Polar Jet Stream that traverses North America splits in two, with a southern branch running across the southern United States and a northern branch running northward along the west coast of North America then plunging southward across the central and eastern portion of the continent. The consequence of this pattern is that western, central and south-eastern North America are placed into the sub-tropical air mass during an El Niño winter, creating much warmer and wetter conditions than usual. This means that Alaska and the Great Lakes should experience favourably warm weather conditions during an El Niño year. The Aleutian Low strengthens to dominate Alaska pushing back the Polar High and bringing warm air into the region. However, north-eastern North America, particularly the Labrador Coast, Hudson Strait and the eastern Arctic should experience colder to much colder than normal conditions. However, during La Niña conditions, the situation is somewhat reversed. During La Niña winters, the intensity of the Polar Jet Stream increases and it moves south to parallel the Canada/U.S. boarder. This brings colder, drier air into central North America providing colder winters over most of the continent except for the Labrador Coast which could see warmer conditions. As stated in the previous sections, these associations are loose and the onset of a particular ENSO will not necessarily mean the condition as described in this paragraph.

Enfotec investigated the possible correlation of ENSO events to the ice conditions in Iceland. Figure 38 below is the pattern of ENSO events from 1950 to 2000.

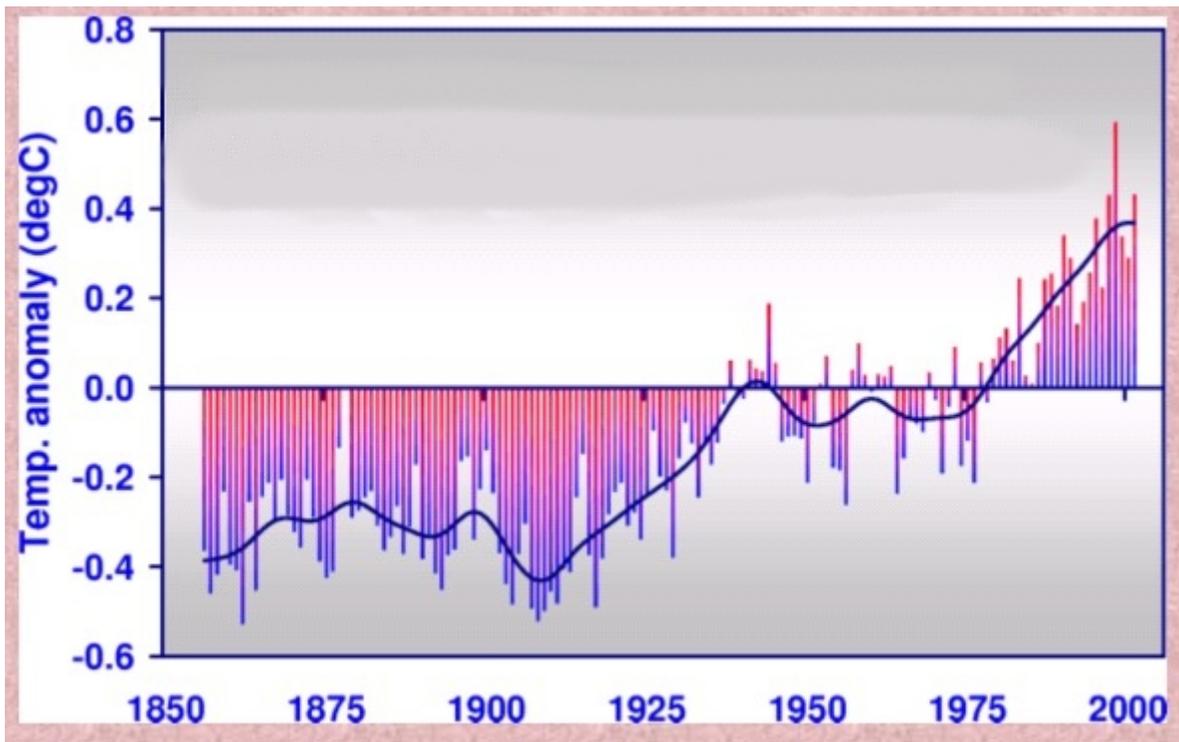


**Figure 38 ENSO Index from 1950 to 2000 (El Niño in orange and La Niña in blue)**

It is difficult to find any indication that there is any correlation between the ENSO and ice occurrence in Iceland. The ENSO follows a very regular cycle over a decade at a frequency much greater than the cycle of many decades of ice occurrence in Iceland. It appears that the ENSO is not a good indicator of ice conditions for Iceland.

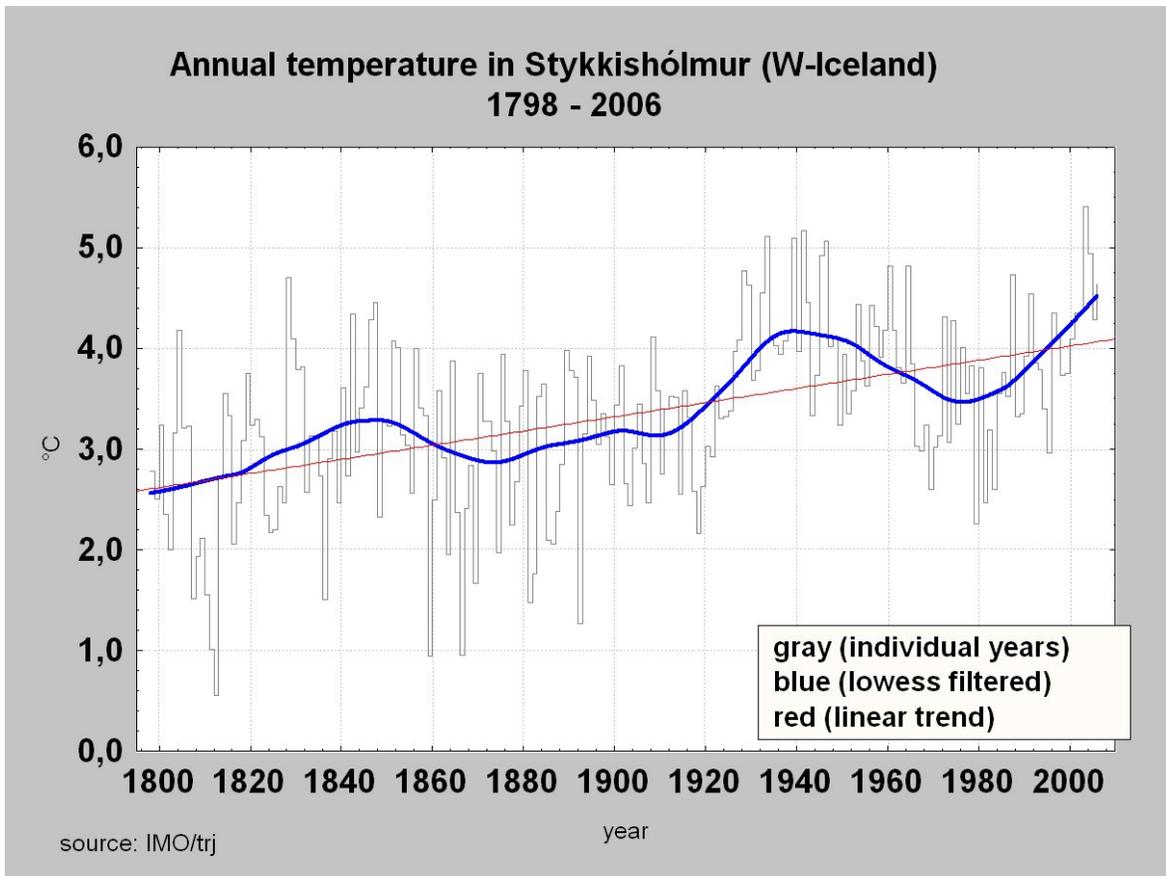
### 2.2.3 Climate Change

It is well reported in the media that the earth's climate has been undergoing a warming over the past century. Figure 39 illustrates the rise in global temperatures since 1850 to the present. The 0.0 line on Figure 39 represents the historical average for the previous 30-years (the 30 year historical average is a running mean used in climate studies).



**Figure 39 Annual rise in global temperatures since 1850 (graph source unknown)**

It wasn't until the mid-19<sup>th</sup> century that global temperatures were measured in such a fashion that accurate global annual temperature averages could be calculated. The measurements made have shown that the earth's average annual temperature has warmed by an average of 0.6C since 1850. However, this temperature rise has not been consistent. The increase in global temperatures over the period can be seen to have occurred during two specific periods between approximately 1915 and 1940 and 1980 to the present. In the case of Iceland, the warming up to 1941 was the most acute, making 1941 the warmest year yet recorded for the country and the flat period to the early 1980's recorded globally was actually recorded as a cooling period in Iceland (Hanna et al. 2004). Figure 40 is a chart of the average annual temperature in Iceland since 1798.



**Figure 40** Average Annual Temperatures for Iceland 1798 to 2006 (from IMO)

The IMO has addressed the issue of climate change as it affects sea ice in Iceland. The following paragraph is an extract of the work of Trausti Jónsson, Senior Meteorologist from IMO, followed by additional analysis from Enfotec.

*It seems that the areal extent of the east Greenland ice has, on the long-term scale, been associated with global temperatures. During the cold 19th century the ice cover was very extensive, but it diminished rapidly during the early 20th century warming. The extent grew again with the colder temperatures of the 1960s and 1970, but it then retreated in concert with the more recent warming. It is generally supposed that the ice extent will diminish as possible warming progresses. This will supposedly influence both components of the ice budget off east Greenland, i.e. the Fram Strait import and the local (i.e. off east Greenland) formation (see e.g. Serreze et al., 2006; Holland et al., 2006 and Bitz et al., 2006). If the climate gets warmer the local formation will probably decrease as a consequence of higher temperatures of advected air masses and higher sea-surface temperatures in the Norwegian Sea. The Fram Strait contribution is more complicated, however. As late-summer ice cover will presumably decrease in the Arctic Ocean the late-summer/autumn flux in the Strait will also decrease and the ratio (multi-year ice cover/total ice cover) will decrease in the Fram Strait flux. This would leave the imported ice more susceptible to melting and less multi-year ice would thus reach the critical area to the north of Iceland.*

*Some models have indicated that a decrease in the meridional overturning circulation of the oceans (MOC) would take place along with the warming and some sensitivity tests have shown that a breakdown of this circulation is possible in the area (see references in e.g. Serreze et al., 2006). A cooling might then follow. It must be emphasised, however, that an extreme increase of freshwater flux to the ocean is essential for a complete breakdown to occur. This is considered implausible. In the case of a small but significant slowdown of the MOC on the multi-decadal or century scale, a general warming is considered to dominate the effects of such a change, so the result would be a muted rather than absent warming signal. So the ice area would decline in the long run. It must be emphasized that the fate of the east Greenland ice is very uncertain. Therefore an ice episode as the one in the 1960s can not be ruled out although it is likely that a new one will barely be quite as severe given the continuation of the present global warming trend.*

This analysis from IMO highlights the fact that the ice conditions experienced in Iceland during the 19<sup>th</sup> century did not return with any regularity due to the climate warming of the 20<sup>th</sup> century. The return of sea ice in the 1960's corresponds to the period when the rise in temperatures flattens out and actually cooled for Iceland. The year's 1968 and 1979 show up as particularly cool years for Iceland as indicated in Figure 36.

This analysis of the influence of global warming allows us to make the assumption that the ice situation experienced in the 1960's can be expected again in the next 50 years. However, the severity of the ice may be at best similar to what was experienced in the 1960's and possibly less. It can also be concluded that it is highly unlikely that regular occurrence of sea ice as experienced in the 19<sup>th</sup> century will return within the next 50 years.

#### **2.2.4 Expected Worst Condition in the Next 50 Years**

The analysis of the previous sections indicates that an ice condition no worse than that which occurred in the past 50 years can be expected in the next 50 years and may likely even be lighter in ice extents. The worst ice condition experienced in the accesses to the Húsavík region over the past 50 years occurred in 1968.

The incursion of ice into the access channels to Húsavík occurred in April of 1968 with the worst ice conditions occurring in May and completely cleared the region by the end of June. Even though this was reported as being the heaviest ice year recorded in Iceland since 1888, sea ice of sufficient concentrations as to be assessed as "difficult for navigation" was reported in only 45 days for access into the Húsavík region in all of 1968. These days all occurred in April and May with the longest duration being 32 days in late April and May.

The impact of such an expected 50-year worst ice condition for the Húsavík region would be a possible four week period of difficult for navigation conditions to the port for shipping once in the year (and only in the 50-year worst condition). Since the 50-year worst condition would likely occur during a period of strong negative North Atlantic Oscillation, it is likely that other several similar years would occur in succession as was

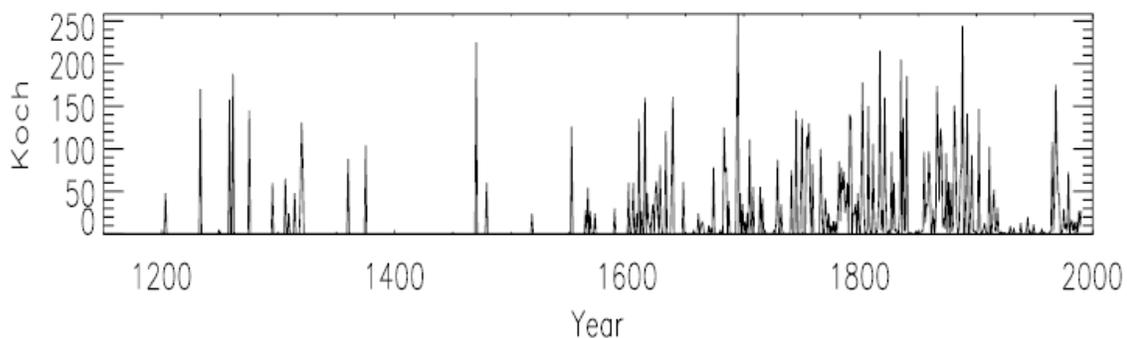
the case in the 1960's. Although the 1968 event occurred in April and May, historical records indicate that sea ice could occur north of Iceland in any month of the year with a greater tendency (when it does occur) in the spring period.

### **2.3 Task # 3 Estimation /Prediction of the 200-Year Extreme Event**

The work in this task involved the estimation/prediction of the expected 200 year re-occurrence maximum ice condition for the Húsavík region of Iceland. This assessment is similar to the 50-year assessment of Section 2.2.3 except that the outlook is further into the future to predict a possible more extreme ice event.

In an assessment of the extreme 200 year event one needs to look back into the historical record to see what, historically, the worst ice conditions were over the preceding 200 years. From a review of the Koch index (Figure 1) extending back to 1880 indicates that the peak year of sea ice occurrence in Iceland occurred in 1888 with an index of 31 compared to the highest recorded value from the 20<sup>th</sup> century of 25 from 1968. Unfortunately, it is difficult to re-construct what the 1888 ice conditions actually represented as all we have to work with is the Koch index itself. As a crude assumption we can make the estimate that 1888 contained 25% more ice than was the case in 1968 where some documentation of the ice conditions exist.

To look back further to beyond 200 years, a study was completed by Wallewik and Sigurjónsson (1998) that applied the Koch methodology to a much longer dataset of Icelandic ice observations. The result of this analysis is shown in Figure 41 below (note that the scale of the index used was different than the Koch index of Figure 1).



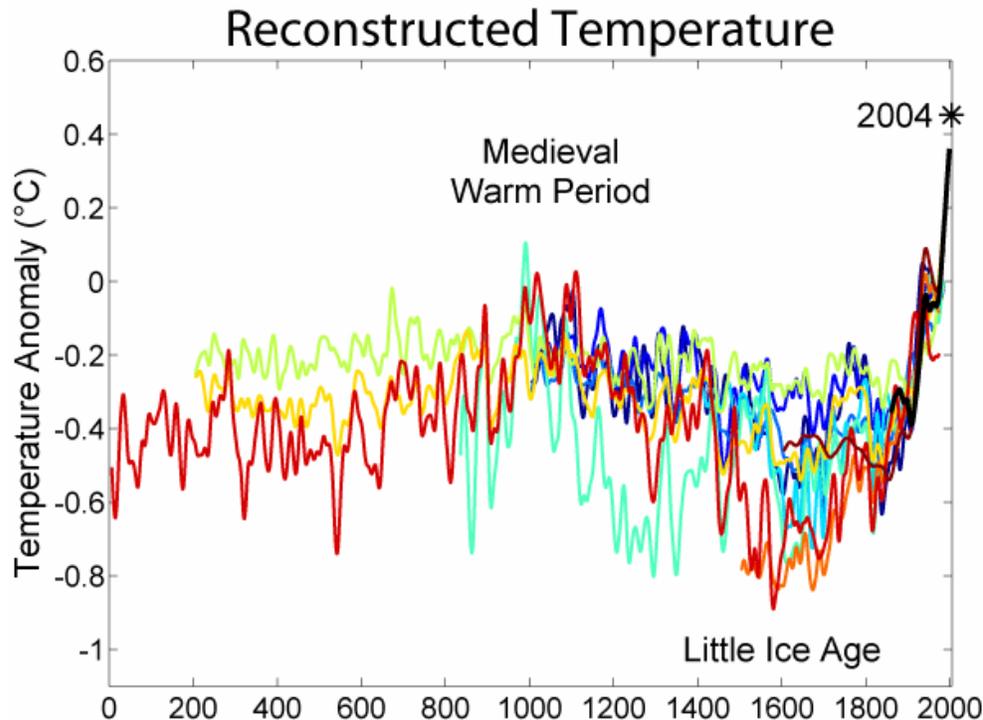
**Figure 41 Annual values of Iceland ice index from Koch (1945) and Wallewik and Sigurjónsson (1998) (Figure from Lassen and Thejll 2004)**

The data from Figure 41 indicates that the heaviest ice year actually occurred in 1695 that was even larger than the 1888 event. Again, a detailed assessment of what the ice conditions actually represented cannot be determined from this data but it does appear to be at least 5% higher in the index than 1888. Therefore, we can make the assumption that the worst year in the 200 year record contained 30% more ice than that recorded in

the 1968 event. If we continue this reasoning we can make the assumption that the worst condition could result in 30% more ice days of “difficult for navigation” than the 1968 event or 59 days in the year with possible individual closures of 42 days. Unfortunately, this is highly speculative as the data we have access to does not provide any details on what the actual ice conditions were like during the extreme years of the 18<sup>th</sup> and 19<sup>th</sup> century. Even the analysis of sea ice conditions in the East Greenland Sea completed by Lassen and Thejll (2004) comment that it is difficult to determine what ice conditions were actually like from the Koch Index alone.

As for the return frequency of the extreme events, a review of Figure 41 above indicates that the similar event to 1968 occurred once in the 20<sup>th</sup> Century (the 1968 event) but up to 10 times in the 19<sup>th</sup> century with fewer in the 17<sup>th</sup> and 16<sup>th</sup> century. There is a noticeable drop-off in total ice events prior to 1600 but events at least as extreme as 1968 still appear at least once a century, even during the minimum conditions of the 15<sup>th</sup> and 14<sup>th</sup> centuries.

To look forward for the next 200 years, an assessment as to why there is the cycle of low and high ice occurrences over the centuries as indicated in Figure 41 is required. Figure 38 is a chart of the measured and approximated world climate trend over the past 2000 years as approximated by a number of different sources (each line on the chart corresponds to a different source) as a measure of the deviation from the historical mean.



**Figure 42 Global climate approximations for the past 2000 years (Rohde 2007)**

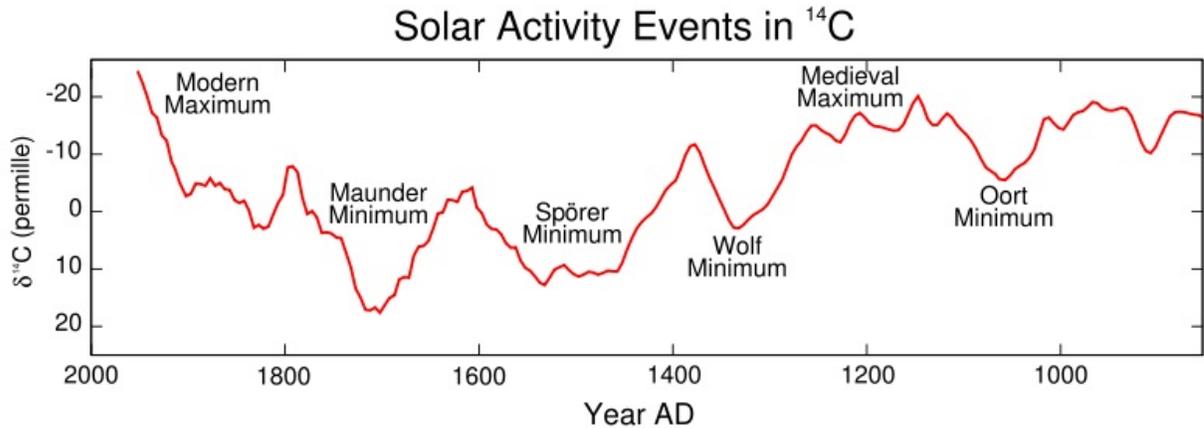
A review of Figure 42 shows a close association of the higher incidences of sea ice off the coast of Iceland as shown in Figure 41. The higher incidences of sea ice in the 17<sup>th</sup> to

19<sup>th</sup> centuries correspond to the climatic temperature minimum known as the “Little Ice Age”. The “Little Ice Age” is a well known period, particularly in the North Atlantic/Northern Europe regions, where very cold winters were experienced that resulted in the freezing solid of many northern European waterways as the Thames River and the Dutch canals. The period preceding the Little Ice Age represented a climatic optimum warm period known as the Medieval Warm Period. The Medieval Warm period represents the time span of the Nordic colonization of Iceland and Greenland and also a period of much reduced sea ice occurrence in Iceland.

We can observe from Figure 42 the modern warming trend that has occurred during the 20<sup>th</sup> Century as the earth’s climate recovered from the Little Ice Age. The modern temperature records indicate that the modern warm period has exceeded the peak of the Medieval Warm Period based on present temperature approximation estimates. This is often presented as the proof of man’s influence on the climate based on greenhouse gas emissions. Consequently, we can assume that the frequent occurrence of ice off Iceland experienced in the 18<sup>th</sup> and 19<sup>th</sup> centuries will not return unless we have a return of “Little Ice Age” conditions, which are not expected given present global warming estimates.

A cautionary note is required in the accuracy of the data in Figure 42. As mentioned in Section 2.2.3 above, accurate measurements of global temperatures have only been made since the 1850’s. These measurements are recorded in Figure 42 as the black line spanning from 1850 to the present. The various coloured lines represent the temperature approximations as determined by a number of climate investigators based on a number of different data sources such as tree ring, ice core, sediment analysis and the like. Consequently, the data sets are based on different source data and the perceived peak of the modern warming above the peak of the Medieval Warm period may or may not be accurate.

Lassen and Thejll (2004) studied the occurrence of ice in the East Greenland Sea (including that which occurred to Iceland) and found a close correlation ( $R=0.67$ ) of the Koch index periodicity to that of the solar cycle length. There is general agreement that the “Little Ice Age” occurred during a period of reduced solar activity known as the Maunder Minimum (McInnes, 07). Fluxes in solar activity causes changes in carbon 14 content in living material (<sup>14</sup>C) and studies of <sup>14</sup>C content has shown a wide variation in solar flux over the past 1000 years as charted in Figure 43.



**Figure 43** Measurement of solar activity by  $^{14}\text{C}$  events (McInnes 07)

Again, we see an approximation of solar activity to the temperature records of Figure 42 with the ice occurrence off Iceland of Figure 41. In looking forward for the next two hundred years, it is unlikely given the present rise to the modern solar maximum that the sun will be reverting to another minimum anytime soon given the history over the past 1000 years. However, the Sun is still a poorly understood body and it is not impossible that another minimum could set in but this is highly unlikely. A cautionary note is required here in that solar activity alone will not dictate the severity of ice off Iceland as the peak years of ice occurrence off Iceland of the 19<sup>th</sup> century due not precisely match the peak of the Maunder Minimum in the 18<sup>th</sup> Century.

The conclusion from this analysis is that it can be expected that at least once a century the access to the Húsavík region of Iceland will experience an ice year where access to the port could be blocked by ice up to 50 days with individual closure periods spanning four weeks. It is highly unlikely that the frequent occurrence of ice in the region as experienced in the 19th century will reoccur in the next 200 years.

### **3.0 Task # 4 Recommendations and Counter Measures**

While waters around Iceland remain ice free in most years, ice does approach the coast in some rare years in periods lasting from a few days to a few months. Almost all ice at the coast of Iceland is advected there by ocean currents and winds. The likelihood of a coastal ice incursion is determined by the amount of ice in the East Greenland Sea and by the prevailing wind and ocean currents. Sea ice can cause conditions difficult for navigation for up to four weeks at a time under extreme conditions which may occur once or twice a century. There is strong evidence that negative episodes of the North Atlantic Oscillation contribute to these severe conditions. The conclusion here is that the very close pack ice conditions present during these extreme ice events essentially halts shipping for the incursion period for the market low ice class vessels envisaged for this project.

The analysis of the ice conditions present in this report indicate that the incursion of sea ice into the marine access channels to the Húsavík region of Iceland although rare, are sufficiently frequent enough that counter measures are required. We can assume for this analysis that under extreme conditions sea ice may limit access to the port site for a period of up to four weeks in one event. The following countermeasures are proposed:

#### **1) Monitoring of the North Atlantic Oscillation**

There is convincing evidence that heavy ice years for Iceland correspond to occurrences of negative episodes of the North Atlantic Oscillation. The British Met Office monitors the NAO and issues a forecast each fall (usually in September) as to the expected NAO for the upcoming winter. This analysis should be used by the project to institute additional counter measures when a negative NAO is forecasted to occur. In addition, further study of the NAO and the influence on Icelandic ice conditions is warranted, particularly with the assistance of the Icelandic Meteorological Office, to help refine this forecasting capability.

#### **2) Monitoring of sea ice conditions north of Iceland**

In every case where we had data (such as ice charts) on the occurrence of sea ice in the navigational channels to Húsavík, the advance of the ice edge from the east Greenland Sea into the region could be seen for a month or more before the ice impeded the navigational channels. With the advent of radar satellites in the past 15 years it is now possible to monitor such events without the need for expensive aerial reconnaissance flights as was required in the past. It is recommended that at the time of start of the project, an ice monitoring centre be established for the northern coast of Iceland. This centre should have a contract to have access to a regular schedule of satellite imagery and the tools to produce an analysis and forecast of ice conditions. This centre could be part of or an extension to the IMO or provided by a private contractor. The monitoring can be done in such a fashion

such that a three-level warning system is applied. Level one would be “no threat anticipated” and would be the normal condition. Level 2 could be “initial threat identified”. Level 2 could be invoked if a negative NAO is forecasted the previous fall. Level 3 could be “sea ice threat is imminent” and would be issued when the ice edge in the East Greenland Sea is noticed to be advancing to the north coast of Iceland. During Level 3 warnings the observations could be augmented with aerial reconnaissance.

### **3) Inventory control**

In the event that a sea ice event is forecasted to be possible (such as the Level 2 noted above) an increase in the inventory of supplies and ore could be planned for the site. Such an inventory would be such as to allow for the continued operation of the plant in the event of a four week disruption in shipping.

### **4) Selection of shipping services**

Not all shipping companies are equal in their ability to handle navigation to ice-bound ports. Many companies avoid navigation in ice covered waters and usually have “ice clauses” in charter parties that prevent such events. It is recommended that shipping services be secured on a long-term contract from a shipping company experienced in navigation in ice covered waters. It should be clear in the shipping tender documents that the Húsavík region is not an ice-free port. In addition, a description of the expected range of ice conditions expected be clearly provided to shipping contractors (including the possibility of icebergs). The use of “spot market” contracts should be avoided as the ice experience of the operator could be much less. In addition, the Húsavík region occurs outside of the IACS (International Association of Classification Societies) warranty limits for hull, machinery and cargo insurance so it is likely charter parties will include ice clauses that will prevent these vessels from navigating in ice covered-waters. The use of shipping contractors with ice experience could also result in the application of additional measures as specified below.

### **5) Use of vessels with ice class**

It is difficult to assess what level of ice strengthen would be required in the vessels to deal with the worst of the ice conditions when they occur. This is because the break-down of how much of the sea ice is polar or “old ice” and how much was annual or “first year” ice from the historical records is not available (see Section 2.1.1 above). From what is known it is likely that even a vessel of Baltic 1A would have great difficulty with the worst of the conditions independently (such as in May of 1968). This would require the use of a vessel built to Polar rules. In any case, such vessels in the general cargo/container class or handymax/panamax class for the ore carriers are extremely rare or non-existent on the market. These would have to be specially constructed for this trade and it is possible they could serve their entire service life without actually encountering

the severe condition! This is particularly acute as the severe conditions would only be for four weeks if it did occur. Having such Polar-class vessels available would decrease delays and increase the utilization of these vessels for routes into the ice cover of the St. Lawrence or the Baltic. Such an arrangement could be discussed with a shipping company as to the possibility of having such vessels available although this would likely be uneconomic for the project.

**6) Use of icebreakers to clear a path**

Icebreakers are not normally available along the north coast of Iceland to assist shipping. However, in the event of a Level 2 ice warning from the ice forecasting service, it may be possible to charter in on short notice icebreaker assistance if a Level 3 warning is declared. Although it is possible for ice to occur at any time of the year the most likely period is in late April and May when icebreaking operations are winding down in the Baltic and St. Lawrence. It would therefore likely be possible to charter the services of a Russian, Finnish, Swedish or Canadian icebreaker during this period should it be required to assist the vessels through the ice conditions. Icebreaker Captains are very experienced in escort operations in ice and this, when combined with an ice experienced shipping company, would be able to handle all but the most severe ice conditions. An arrangement could be made in advance with an icebreaker operator to have the services available on short notice if required. Although this would be expensive (US\$40K to \$50K/day) the cost may be more economical than maintaining large stockpiles or plant temporary shutdown. A check with the Government of Iceland would be required to see if there would be any flag-state issues with the temporary use of a foreign-flagged icebreaker for a short period in such a service.

**7) Use of Ice Navigators on the cargo vessels**

It is routine practice for shipping companies experienced in navigation through ice covered waters to use the services of specially-trained Ice Navigators for the segments of the voyage through ice. Ice Navigators are Master Mariners who have many years of experience guiding low or no ice class vessels through ice covered waters. They are used regularly in the Gulf of St. Lawrence and the Baltic in winter. In the event that a Level 3 ice situation is anticipated arrangements can be made to have ice navigators available to board the vessels prior to ice entry. An arrangement could be made where the ship approaching Iceland could pick-up the Ice Navigator at an ice-free port along the south coast of Iceland before venturing into the ice and drop them off again on the way out to be available to board the next ship. In addition to being experienced in navigation through ice, Ice Navigators are also experienced at vessel docking in ice bound berths. The availability of Ice Navigators would be more secure if the shipping contract is with a company experienced in navigation through ice covered waters as they would have their own Ice Navigator resources available if need be.

**8) Use of portable shipboard ice navigation technology**

In the event that the services of an ice navigator is used on a vessel, then an added measure that could be employed is the use of a lap-top based information system that would connect the vessel with the ice information centre (mentioned in # 2 above). Such a system would allow ice charts and images produced by the ice information centre to be send directly to the vessel (and escorting icebreaker if present) to aid in the passage through ice. Such a system does exist such as Enfotec's IceNav system.

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