An Analysis of Sea Ice Condition to Determine Ship Transits through the Northwest Passage

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ABSTRACT

An analysis was carried out to determine the duration of the summer shipping season for deepwater vessels transiting through the Northwest Passage Route. The most likely route segment to obstruct shipping is in Viscount Melville Sound, which is typically characterized by the presence of high concentration mixtures of deformed, thick first year and multiyear ice. The period for ship transits through the Passage is determined from the computer-based analysis of digital Canadian Ice Service weekly ice charts which are available from the late 1960's to the present. Automated computer-based algorithms were developed to estimate the number of, if any, weeks with ice conditions that would successfully allow transit. The results show a very large year to year variability in the duration of the summer shipping season with the trend towards slightly improving ice conditions. The possibility of future increases in old ice concentrations in western and central portions of Parry Channel due to an apparent trend towards more rapid passage of this old ice through the Queen Elizabeth Islands to the north may impede ship passages in the next decade by comparison with the last decade or two.

KEY WORDS: Northwest Passage; Shipping; Sea Ice; Climate Change.

INTRODUCTION

An analysis was carried out to determine the duration of the summer shipping season for deepwater vessels transiting through the Northwest Passage Route. The Northwest Passage (Figure 1) is the shipping route between the Atlantic Ocean (Baffin Bay) to the Pacific Ocean (Bering Sea).

The most likely route segments in which ice conditions may obstruct deep-water shipping occur in the western portions of Parry Channel, specifically in M'Clure Strait (MS) and Viscount Melville Sound (VMS) and northern Prince of Wales Strait (POWS). These so-called "chokepoint" regions (Figure 2; Falkingham et al., 2003) are typically characterized by the presence of high concentration mixtures of deformed, thick first year and multiyear ice from the middle of summer to early autumn when sea-ice concentrations reach their seasonal minimum levels. A third chokepoint region, on the route through Peel Sound is due to the shallower water depths in sparsely charted waterways.

Figure 1. Northwest Passage with the path analyzed through Viscount Melville Sound and Prince of Wales Strait.

Based upon historical ice data, the blockage and delay problems in VMS and POWS are sufficiently serious as to preclude extended duration shipping seasons except for the occasional exceptional year. The ice conditions in MS are even more severe resulting in POWS/VMS being the preferred deepwater shipping route.

ICE CONDITIONS

The well-know trend towards reductions in Arctic Ocean sea-ice during the late summer also occur in the adjoining waterways in the Canadian Arctic Islands. The long-term trends in sea-ice extent within the VMS/POWS along with western Barrow Strait exhibit a clear trend towards reduced total sea ice concentrations (Figure 3). It should be noted that the trend is generally smaller than the degree of inter-annual variability in the summer ice conditions, but nevertheless, the trend towards reduced total ice concentrations is significant.

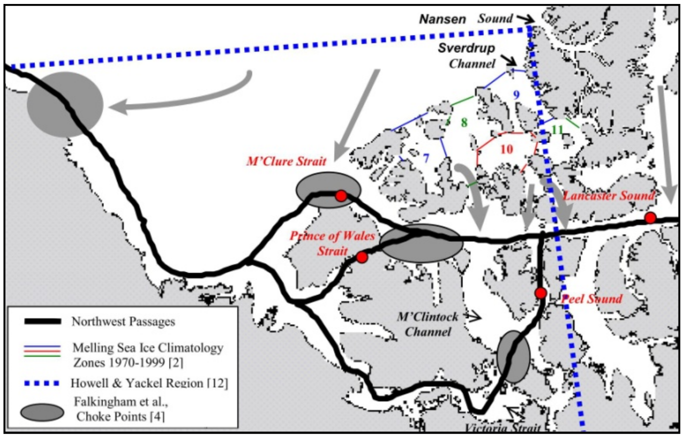

Figure 2. Northwest Passage with zone locations used by Melling (2002) for the Sverdrup Basin (Wilson et al., 2004).

However, the long-term trends in the more hazardous (to shipping) multi-year or old ice (OI) type are quite different from that of total ice. In early September, there is a trend towards increasing levels of OI. The decrease in total ice is consistent with the production of less first year ice each year as air temperatures warm within the Arctic region, as anticipated from global climate models. The lesser amounts of total ice in mid- to late-summer can actually lead to increased mobility of OI within the northern Canadian Arctic Islands and in areas to the north of the islands where most of the Arctic Ocean's remaining OI is found.

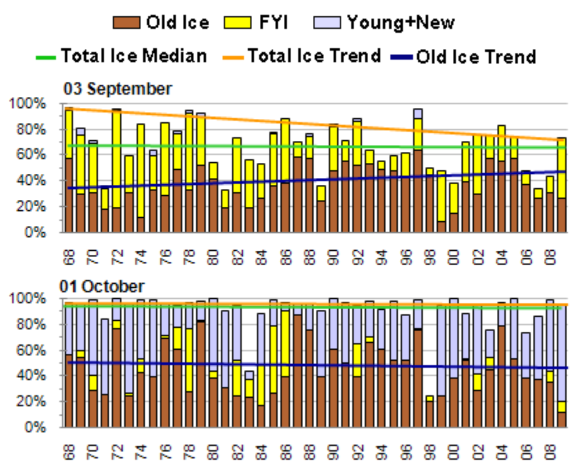

Figure 3. Sea ice trends for September 3 and Oct 1, 1968-2009, derived from CIS historical sea ice coverage for Viscount Melville Sound

Intra- and inter-annual variations in ice conditions of MS and VMS are closely tied to ice conditions in the adjacent marine areas of, the Beaufort Sea and the Queen Elizabeth Islands and. Influxes of OI-rich ice in the MS case are largely driven by westerly winds acting on the adjacent southerly gyral flow in the Beaufort Sea. The VMS influx, on the other hand, is tied to ice discharges from the Islands which are linked to both the melt and weakening of the first year ice in the enclosed Sverdrup Basin (allowing the OI to become mobile) and influxes of, heavily deformed, thick OI from the immediately adjacent portions of the Arctic Ocean which contain a disproportionate fraction of the Arctic Ocean's total volume of such ice.

The effects of such ice on conditions in the central portion of the Northwest Passage are dependent upon the extent of blockage in both the Queen Elizabeth Island's northern channels to the Arctic Ocean and in southern channels (Byam, Austin, Crozier, and Wellington Channels). This dependence upon blockage greatly complicates anticipation of annual ice inputs to the Northwest Passage and the sensitivity of such inputs to long term changes such as regional/global warming and increased clearing of the Arctic Ocean.

Reviews of 30 years (1970-1999) of digitized ice chart and thickness data (Melling, 2002) found significant decreases during the annual growth-melt cycles in the amounts of both old and first year ice (5-12% and 19-40% respectively) in the northernmost zones (7, 8 and 9) of the Queen Elizabeth Islands region (Figure 2) with the greater losses in the first year ice reflecting the expected greater in situ melting in the thinner ice form. Annual replenishment of the OI fraction was effective through Arctic Ocean imports, particularly through the very wide Gustaf Adolph Sea opening (the northern boundary of zone 8 in Figure 2. Likewise, summer collapses of ice bridges in the southern Queen Elizabeth Islands allowed further movement of this OI into VMS and, late in the clearing season, into Lancaster Sound. Similar analyses of 7 years of digitized chart data from the Sverdrup/Peary Channel regions (roughly, zone 9 of Figure 2) showed large year to year variability in net changes in OI content with even northward ice exports noted during one year. A more recent analysis by Howell et al. (2008) provides further analytical evidence that these mechanisms could facilitate the presence of OI for many years into the future.

These results all highlight the complexity involved in forecasting future changes in navigational conditions in the Northwest Passage. The complex interplay of melting and channel blockages could actually mean that progress toward a seasonally ice free Arctic Ocean would actually increase the content of OI in, at least, the VMS and Peel Sound choke point regions. Specifically, the greater mobility of ice in an increasingly first year ice-dominated Arctic region could counteract much of the improvement anticipated in Passage navigation until the Arctic's old ice content is largely dissipated.

ANALYSIS METHODS

Historical Sea Ice Data

The times of ship transits through the passage is determined from the computer-based analysis of digital Canadian Ice Service weekly ice charts which are available from the late 1960's to the present.

Ship Transit Computations

The criteria for successful ship transits is based on specified maximum partial ice concentrations by ice type with high concentrations of old ice combined with thick first year ice representing the limiting conditions to ship transits. Automated computer-based algorithms were developed to estimate the number of, if any, ship routes that would successfully allow transit of selected segments of the Northwest Passage Route using CIS digital egg code ice data available at 4 km resolution.

Transport Canada has traditionally used a Zone/Date System to regulate shipping in Canadian Arctic waters (Timco et.al. 2009). The waters are divided into 16 zones, where the lowest number zone generally has the most severe ice conditions. Opening and closing times for the zones are provided for nine Arctic Classes and five Baltic Type Ships. This system is based on climatological means and does not reflect inter-annual variability or long-term trends.

In 1996, the more adaptable Arctic Ice Regime System (AIRSS 1996) was put in place. This system allows for access decisions outside of the traditional Zone/Date System.

The Arctic Ice Regime System of Transport Canada is a 4-part process:

1. Characterize the Ice Regime
2. Determine the Class-dependent Ice Multipliers (IM) relating to ship capability
3. Calculate the Ice Numeral (IN) using the ice Multiplier and ice concentrations/thickness
4. Decide whether to proceed based on IN. If IN ≥ 0 then passage is allowed while for IN < 0 an alternative route must be found.

The Ice Numeral is defined as;

$$IN = (C_a IM_a) + (C_b IM_b) + \ldots + (C_n IM_n) \quad (1)$$

where C_a is the concentration in tenths of ice type a and IM_a is the ice multiplier (IM) for ice type a.

For decayed ice, the ice multiplier may be modified by increasing it by 1 and for ridged ice it should be decreased by 1. As the CIS digital egg code does not contain any information about decay or ridging, our analysis does not modify the ice multiplier for either case.

An earlier version of the use of Ice Numerals derived from CIS digital ice charts for computations of ship transits is presented in Howell et al. (2004).

Ship Ice Regimes and Ice Navigability

Two vessel types that are in common usage were chosen to investigate, Polar Class 4 and Baltic Type B. Under Transport Canada's Zone/Date System, Type B vessels are not allowed entry into the Zone 1, which includes M'Clure Strait, or Zone 2, which includes VMS and the northern half of POWS, at any time. Only under AIRSS could a Type B vessel operate in these regions of the Northwest Passage. Polar Class 4 vessels have greater access, but are still restricted in areas of high OI concentration.

There is an active community working on standardization of ice classification for vessels and ice multiplier tables. For the present analysis, a modified IM Table (Table 1) was developed based on Transport Canada's IM tables and A. Kendrick (personal communication)

Table 1. Modified Ice Multipliers for Type B and Polar Class 4 vessels.

Thickness (m)		*0-0.1*	*0.1-0.3*	*0.3-0.7*	*0.7-1.2*	*>1.2*	*>2*
	Ice Type	**Brash Ice** (New, Nilas)	**Young Ice** (Grey Ice & Grey White)	**Thin FYI** (1st & 2nd Stage)	**Med. FYI**	**Thick FYI**	**Old** (SY, MY)
Ship Type	*Egg Code*	1 or 2	3-5	7-9	1	6 or 4.	7. 8, 9
			ICE MULTIPLIERS				
Type B		2	1.5	1	-1	-2	-4
Polar 4		2	2	2	2	2	-2

Maps of IN were calculated for both vessel types for the expected entrance and exit weeks based on CIS digital egg codes (Figure 4). The IN was divided into 5 bands

1. $IN \leq 20 \equiv$ No Go – Difficult (Red)
2. $20 < IN \leq 10 \equiv$ No Go – Less Severe (Orange)
3. $10 < IN \leq 0 \equiv$ Transitional (Yellow)
4. $0 < IN \leq 20 \equiv$ Go (Light Green)
5. $IN = 24 \equiv$ Open Water Conditions (Dark Green)

This banding is used in the all the following IN charts.

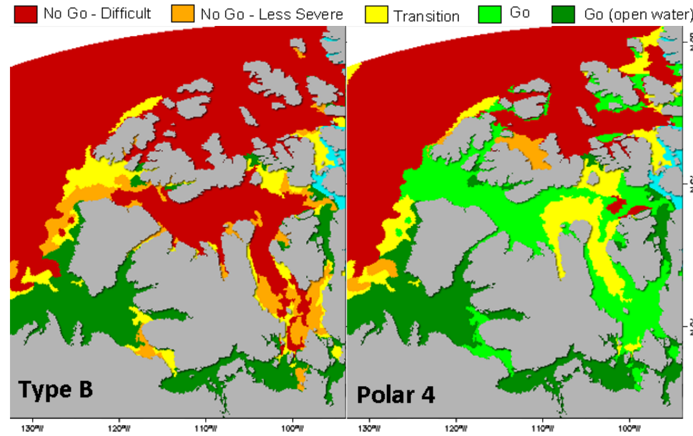

Figure 4. Example of ice numeral maps for Type B and Polar Class 4 vessels, based on the August 17, 2009 CIS digital ice chart.

Automated Path-finding

Computer algorithms have been developed to automatically evaluate safe passage routes through POWS and VMS. The algorithm uses the derived Ice Numeral charts as defined above. Successful routes through these charts were determined using a path-finding algorithm.

Path-finding algorithms have been developed for various applications; including network route optimization, robotic control and computer gaming. Graph search algorithms that determine the shortest path, such as the one developed by Edsger Dijkstra, date back to the 1950's (Dijkstra, 2001). The A* algorithm, a best-first search variant of Dijkstra's method, provides a compromise between determining the optimal path and computational time. By adding a heuristic, an estimate of the travel cost from the present position to the end position, A* computational times are reduced as less paths are searched to find a solution.

RESULTS

Ice Navigability

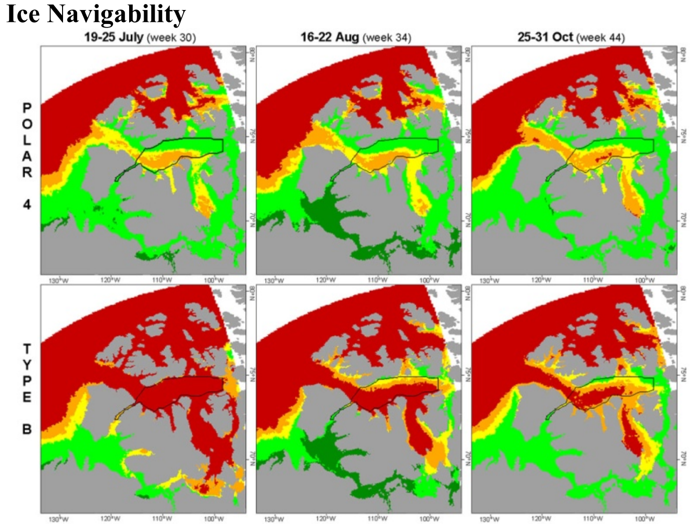

Figure 5. Average IN maps for 1982-2009 for Polar 4 and Type B vessel. Black line defines the Area of Interest (AOI) within POWS and VMS.

As would be expected based on Transport Canada's Zone/Date System, Type B vessels have climatological averaged IN < 0 within VMS for weeks 30 (late July), 34 (mid-August) and 44 (late October; Figure 5), making the Northwest Passage unnavigable, on average, for this ship type. Results were not significantly different for weeks 36, 37, 38 and 40 spanning the month of September. The IN for Polar Class 4, on the other hand, showed climatological averaged high-levels of accessibility into POWS and the northern and eastern areas of VMS. Southern portions of VMS proved less navigable due to the influx of OI from the Beaufort Sea and Sverdrup Basin.

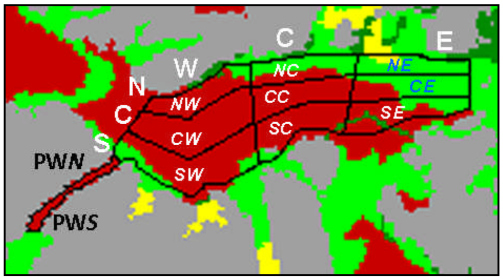

Figure 6. Division of Viscount Melville Sound into 9 sections and Prince William Strait into 2 sections.

The variability of IN both spatially and temporally was quite extensive. VMS was divided into 9 sections as outlined in Figure 6 and POWS was divided into 2 sections. Focusing on just weeks 34 (mid-August) and 44 (late October) for Polar Class 4 vessels, it is clear that the southern sections (SW and SC) of VMS are the least accessible (Figure 7). There is also a trend that the western sections are less accessible than the eastern sections.

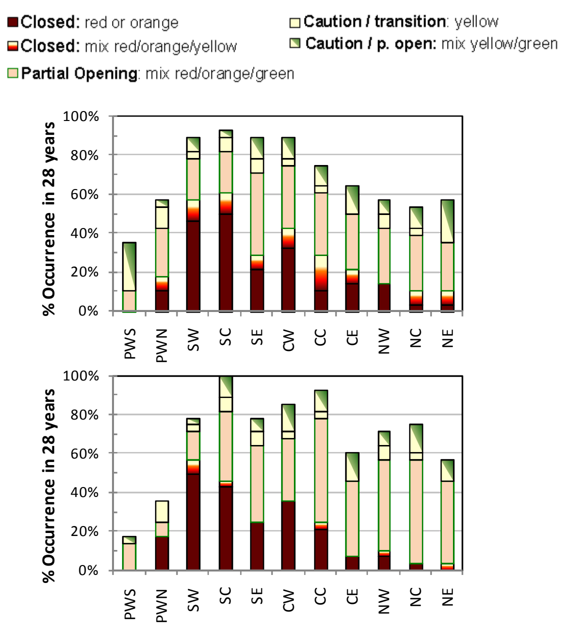

Figure 7. Climatological averages of percentage occurrences for the shipping conditions of Polar 4 vessels during weeks 34 (top) and 44 (bottom) in the 11 sections of POWS and VMS.

Year-over-year variability may prove to be a more important determining factor on accessibility. As might be expected from the inter-annual variability of ice conditions and the increasing trend of OI (Figure 3), there is little discernable trend in the percentage occurrence of IN (Figure 8) for either week 34 or 44 towards greater accessibility.

The recent years of 2007-2009, which had historically low total sea-ice coverage for the Arctic, had only slightly better accessibility than conditions in the early 1990's. However, the years 1982 and 1983, but particularly 1999 and 2000 were significantly better.

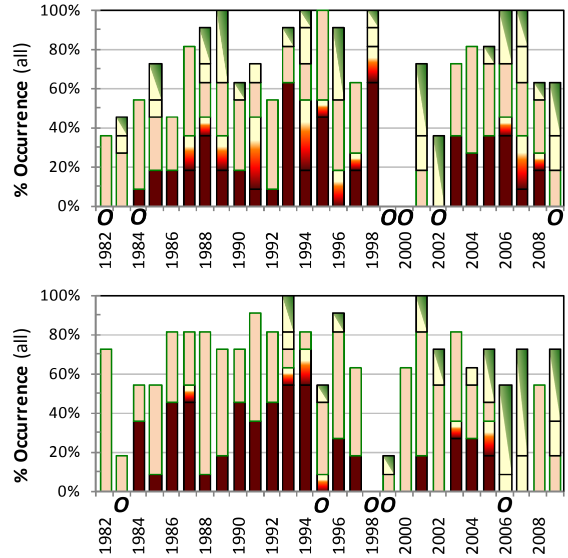

Figure 8. Percentage occurrences of closed or open conditions for Polar 4 vessels for the entire VMS/POWS area from 1982 to 2009 for weeks 34 (top) and 44 (bottom).

Automated Path-finding

We have successfully tested the A* payht-finding algorithm with Ice Numeral charts derived for both Polar 4 and Type B vessels. The center of POWS was taken as the start position for the searches and the end position was placed in the eastern end of VMS near Barrow Strait. Examples were tried where POWS and VMS were completely navigable, partially navigable (Figure 9) and completely blocked.

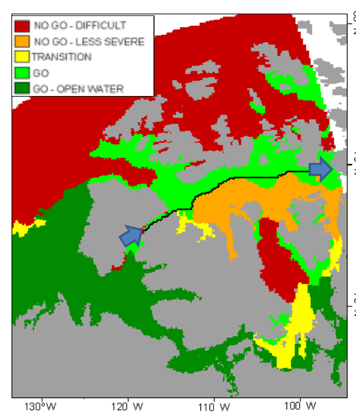

Figure 9. Example of path finding for the VMS/POWS route of the Northwest Passage for a Type B vessel. The black line, which starts at POWS and ending at the eastern end of VMS, is the navigable route overlaid on the Ice Numeral chart.

We will build on these successful tests by automatically searching for navigable routes in a series of weekly IN maps derived from CIS ice charts. Yearly and seasonal statistics of successful routes will be derived, including the first and last weeks with navigable paths. The paths will also be investigated to determine the propensity for multi-year ice to block the southern part of VMS and leave only the northern part of the Sound open for shipping.

CONCLUSIONS

The results show a historically high degree of spatial and temporal variability for shipping conditions within the Northwest Passage. Southwestern Viscount Melville Sound is typically less accessible due to the presence of old ice. While total summer ice coverage in Viscount Melville Sound and Prince of Wales Strait has trended towards a slight reduction, the old ice coverage has been increasing. This trend towards increased old ice coverage may continue for the next several years, with an associated degradation of shipping through the Passage, as melting in the southern channels of the Sverdrup Basin allows for rapid passage of old ice through the Queen Elizabeth Islands. However, large year-to-year variations are also likely to continue as well, so that shipping seasons will continue to be highly variable from one year to another.

ACKNOWLEDGEMENTS

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