The Changing Ice Regime of Northeastern Baffin Bay

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ABSTRACT

The sea ice concentrations and areal extent in Baffin Bay have undergone major reductions over the past 31 years (1981-2011). Of particular interest is the Northeastern Baffin Bay area off West Greenland, which is a promising frontier area for oil and gas exploration. The break-up dates, along with other characteristics of the ice free season, are analyzed using weekly Canadian Ice Service Digital Archive ice chart data on ice concentrations and ice types. The reductions in the early summer ice concentrations occurred quite abruptly in the late 1990's, prior to which, much higher ice concentrations prevailed back to the mid-1980's. The underlying causes of the change in the sea ice conditions are explored in this paper.

KEY WORDS: Baffin Bay; Sea Ice; Climate Change.

INTRODUCTION

Marine Activities in Baffin Bay

In this paper, we examine the long-term reductions in the sea ice conditions of Baffin Bay and in particular, within northeastern Baffin Bay over the past 30 years. In recent years, northeastern Baffin Bay has become an active area for oil and gas exploration. The summer clearing of sea ice in northeastern Baffin Bay is also important for shipping into the northern communities of West Greenland and also as the primary shipping route for vessels that transit to the Canadian Arctic areas in early summer. Icebergs which are ubiquitous to Baffin Bay are also important to marine operations. Although icebergs are not discussed in this paper, sea ice concentrations are important in determining the mobility, range and deterioration of icebergs (Marko et al., 1994).

Changing Sea Ice Conditions in the Full Arctic Region

The reductions in the areal extent and concentrations of Arctic sea ice are very well known in both the scientific literature and in the popular press. Over the entire Arctic Ocean and its adjoining areas, sea ice areal extent has been reduced by 12.0% per decade for September over the period 1979-2011 (Perovich et al., 2011). The largest reductions in sea ice concentrations have occurred since 1996 (Figure 1). There have been related changes in the wind-driven circulation regime that has dominated the Arctic Ocean over the past 14 years (1997-2011) combined with relatively warmer air temperatures over the past decade (Proshutinsky, 2011).

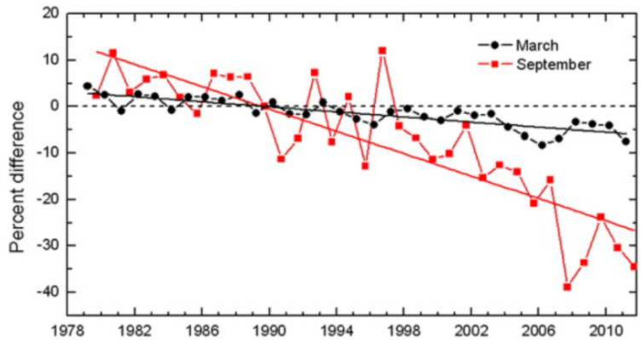


Figure 1: Time series of the percentage difference in Arctic sea ice extent in March (the month of ice extent maximum) and September (the month of ice extent minimum) relative to the mean values for the period 1979-2000. The computed, rate of decrease for the March and September ice extents is -2.7% and -12.0% per decade, respectively (from Perovich et al., 2011).

Baffin Bay Ice Conditions

Baffin Bay is a peripheral sea of the Arctic Ocean connected to the later via Nares Strait in the north and to the Atlantic Ocean via Davis Strait and the Labrador Sea to the south. The pattern of the formation and clearing of sea ice in Baffin Bay (Figure 2) begins in the fall with new ice formation in northern Baffin Bay. By March, nearly all of Baffin Bay is completely ice covered, with the exception of the southeastern area in the vicinity of Disko Island and further south to Cape Farewell. The pattern of sea ice clearing in late winter through spring is a two-pronged reduction in sea ice concentrations (a) in the east as the open water along the west coast of Greenland extends northward and (b) in the northwest, as the Northwater polynya area expands southward from Smith Sound in the spring. Higher ice concentrations and generally thicker ice (the "Middle Ice" pack) persists through spring and early summer in western and central Baffin Bay due to these clearing patterns. As a result, ships entering the Canadian Arctic transit into the area from eastern Baffin Bay waters to avoid the higher ice concentrations to the west.

A previous study of changing ice conditions in Baffin Bay and the Labrador Sea (Parkinson and Cavalieri, 2008) over the years 1979-2006 revealed a large decrease in average sea ice extents of -9.0 ± 2.3%/decade. A significant trend toward reduced ice extents is apparent for each season (Figure 3) with the largest reductions occurring in summer (-16.0 ± 4.8 %/decade), along with a considerable amount of year-to-year variability in ice extents. The reduction in autumn is also larger than the yearly average values at -12.5 ± 2.7 %/decade.

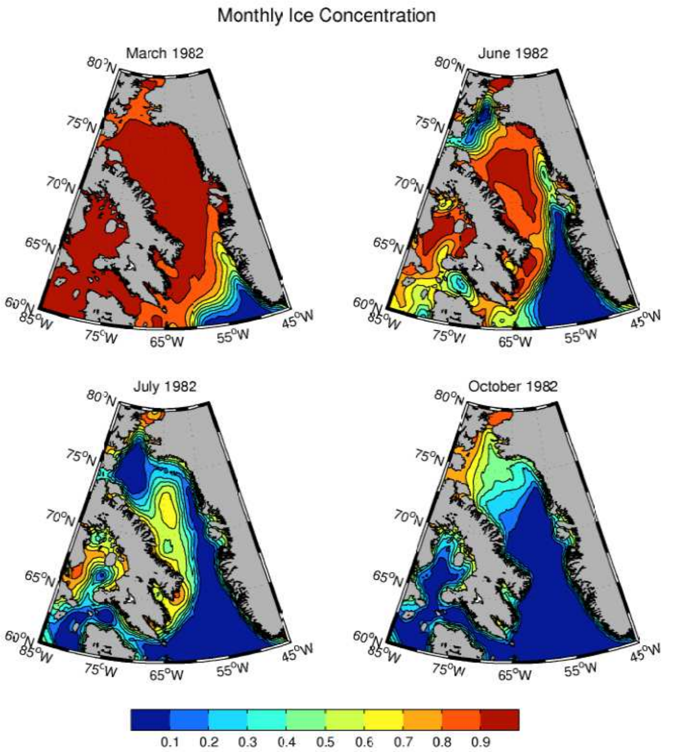


Figure 2: Typical patterns of sea ice areal extent in Baffin Bay in the months of March, June, July and October 1982 (from Tang et al., 2004).

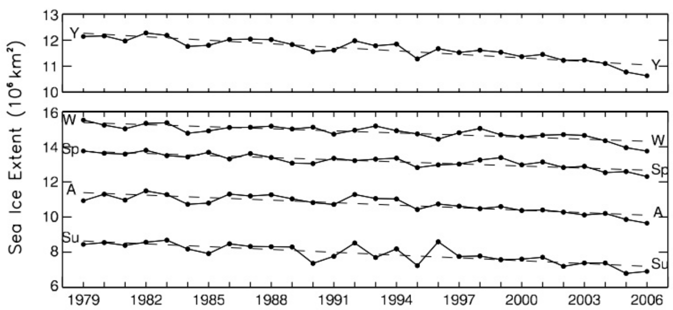


Figure 3: Yearly and seasonally averaged sea ice extents in Baffin Bay and the Labrador Sea for the years 1979–2006. The winter (W), spring (Sp), summer (Su), and autumn (A) values cover the periods January -March, April–June, July–September, and October–December, respectively (Parkinson and Cavaleri, 2008).

The patterns in the Baffin Bay/Labrador Sea ice extent variations are quite different among the seasons. Mysak et al. (1996) relate the heavy ice conditions in 1983–1984 to the strong El Nino episode of that time, which is also tied to a deepened Icelandic Low and negative anomalies in the sea surface temperatures of Baffin Bay/Labrador Sea. There is also a correspondence between the high ice extents of the early 1990's with the lesser 1991-92 El Nino event. However, large ice extents did not occur during the strong El Nino event of 1997-98.

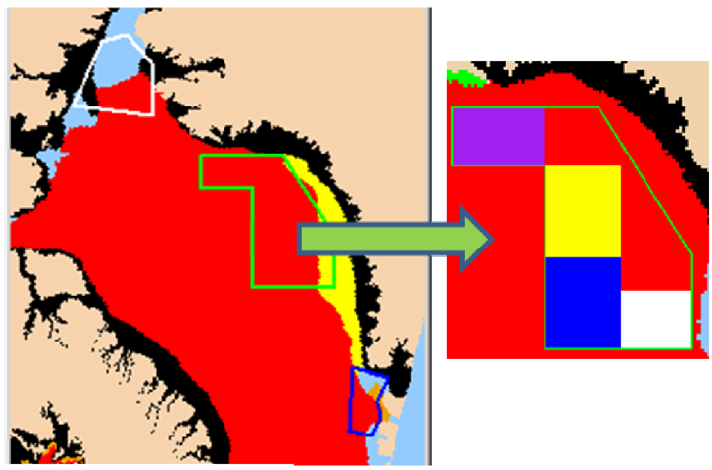
In this paper, we will extend the analysis of long term trends in sea ice extent to the region of northeastern Baffin Bay. Of particular interest, for marine shipping activities and offshore oil and gas exploration, are the changes in the dates of clearing of the sea ice and the duration of the open water season.

ANALYSIS METHODS

Historical Sea Ice Data

The trends in the open water duration and the clearing dates each year are determined from the computer-based analysis of digital Canadian Ice Service (CIS) weekly ice charts. The study used the Eastern Arctic CIS digital ice charts for the 31 year period 1981-2011 (Tivy et al., 2011). The horizontal resolution of the digital ice charts is 4 km.

In the analysis of the ice conditions, three Areas of Interest (AOI) were defined and applied to the analysis as shown in Figure 4. The large AOI in NE Baffin Bay is the key area, since it encompasses the license areas for oil and gas exploration and also the shipping routes between Labrador Sea to northwestern Greenland settlements and to the Canadian Arctic in early summer. The Smith Sound AOI is used as an indicator of the clearing of sea ice in northern Baffin Bay under the influence of the Northwater Polynya (Barber and Massom, 2007) which results in ice clearing immediately to the south including the entrance to the Northwest Passage at the mouth of Lancaster Sound. The third AOI is the area off Disko Island off the central West Greenland coast where the clearing of sea ice begins and expands northward into NE Baffin Bay. The patterns of sea ice clearing in spring and summer are described in more detail below.



rest (AOI's) used in the analysis of the CIS ler) Smith Sound in the Northwater Polynya der) NE Baffin Bay which includes the active ; and (blue border) the area offshore of Disko W. Greenland.

NE BAFFIN BAY ICE CONDITIONS

Average Ice Clearing Dates

Over the past 30 years, the average break-up date (Figure 5) in the deep waters of central portions of northeastern Baffin Bay occurred during the week of July 16 or later. Further to the north and the west, ice broke up earlier, in June, in association with the expansion of the Northwater Polynya in June. To the east, nearer the West Greenland coastline and towards Davis Strait there was an even earlier breakup prior to June. The area of the "Middle Ice Pack" which does not clear on average until August is shown by the purple colours.

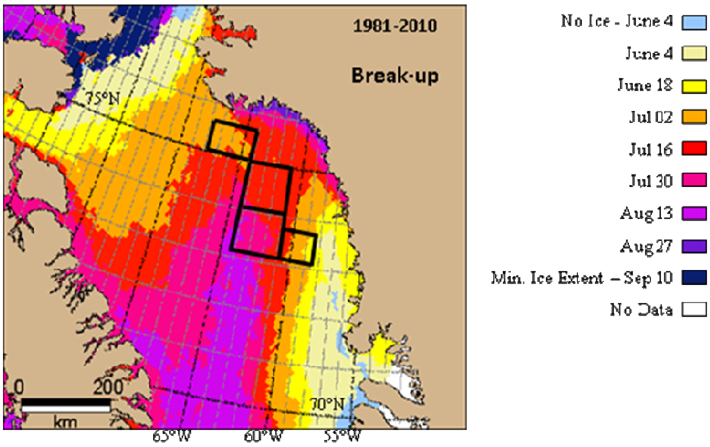


Figure 5: The average clearing or break-up dates for sea ice as derived from the CIS digital ice charts for the period 1981-2010. Also shown are the license areas for oil and gas exploration in the northeast Baffin Bay region.

Long Term Trends and Interannual Variability of Ice Concentrations for Selected Areas of Interest (Spring and Summer

For the NE Baffin Bay AOI, the sea ice concentrations for each year from 1981 to 2011 are shown in Figure 6 for the dates of April 30, June 18, July 2, July 16 and July 30. For the spring and summer period, the ice present is almost completely relatively thick First Year Ice (FYI) which developed during the previous winter, with rare occurrences of very low concentrations of old ice (second year and multi-year ice). On April 30, the nearly complete (> 9-tenths) ice coverage of the winter and early spring remains in place. By June 18, partial clearing occurs in some years to ice concentrations as low as 7-tenths in the 1980's and 1990's and more clearing in the 2000's with ice concentrations as low as 2-tenths (2009). The seasonal progression toward lower sea ice concentrations continue through July, with considerably larger reductions in the most recent 13 year period from 1999-2011. Within this latter period (by comparison to the period from 1981-1998), the median ice concentrations were 2 (vs. 8 in 1981-1998) on July 2; 1 (vs. 6) on July 16; and 0 (vs. 3) on July 30.

The dramatic decrease in ice concentrations, from well over 5-tenths to 2-tenths or less in early and mid-July, occurred abruptly starting in 1999. Since 1999, for July 2, there have been only 3 years (2001, 2005 and 2011) in which ice concentrations exceeded 4-tenths, while ice concentrations exceeded 7 tenths in the previous years from 1981-1998. The reduction of ice concentrations for 1999-2011 vs. 1981-1998 amounts to a shift in ice clearing of approximately 3 to 4 weeks. Starting in 1999, ice clearing over the large area of the NE Baffin Bay AOI has been nearly complete (< 2-tenths) in 10 of 13 years by July 2, in 11 of 13 years by July 16 and in all 13 years by July 30. The changing ice regime allows shipping or oil and gas activities to start up to one month earlier than was the case in the 1980's and 1990's.

The computed linear trend for sea ice concentrations for the NE Baffin Bay AOI is statistically significant (at the 99% confidence level) for the ice charts of June 18, July 2 and July 16 with changes of -14% per decade, -24% per decade and -16% decade, respectively. For all other periods in Figure 6, the trends are not statistically significant at the 95% confidence level.

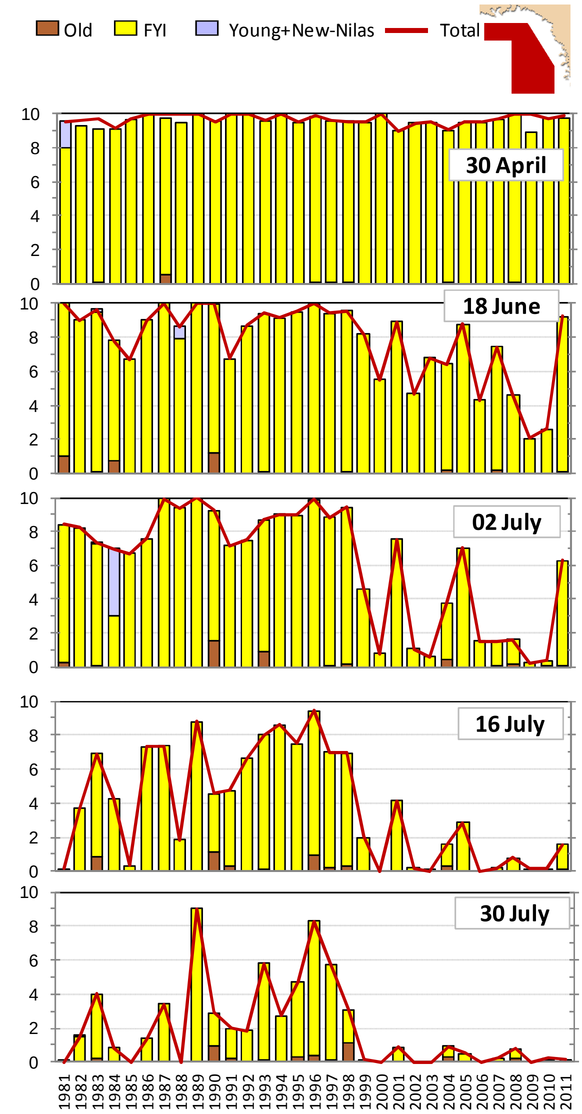


Figure 6: The sea ice concentrations (tenths) for each year from 1981 to 2011 inclusive for the NE Baffin Bay AOI for the weekly ice charts of April 30, June 18, July 2, July 16 and July 30. The total ice concentrations are presented (red line) as well as the partial ice concentration for old, first year ice (FYI), and the combined young/new/nilas ice type categories.

The corresponding results for the Smith Sound AOI (see Figure 7) show that ice clearing starts much earlier, in April, with total ice concentrations of less than 7-tenths in some years. Neglecting the concentrations for thin ice types (young, new and nilas categories), the ice concentrations are usually in the range of 2 to 9 tenths with a median value of about 4 tenths. Old ice is rarely reported in most years and when present is limited to concentrations of less than 2 tenths.

Ice concentrations decrease only slightly by May 14, with much larger reductions occurring by June 6 (not shown). By June 18, ice concentrations in Smith Sound are much reduced to values ranging from 0- to 8-tenths with a median value of only 1-tenth. In July, the Smith Sound ice concentrations decline further but more gradually than the seasonal decline experienced in June. The different rate of decline in June from that of July is associated with the increased presence of old ice in July. By mid- and late-July, old ice represents the majority of sea ice present in most years, albeit at low concentrations of 3-tenths or less with a median value of less than 1-tenths. Although old ice represents a hazard to marine operations, the low concentrations allow operations to proceed throughout June and July as long as precautions are taken to avoid ice floes.

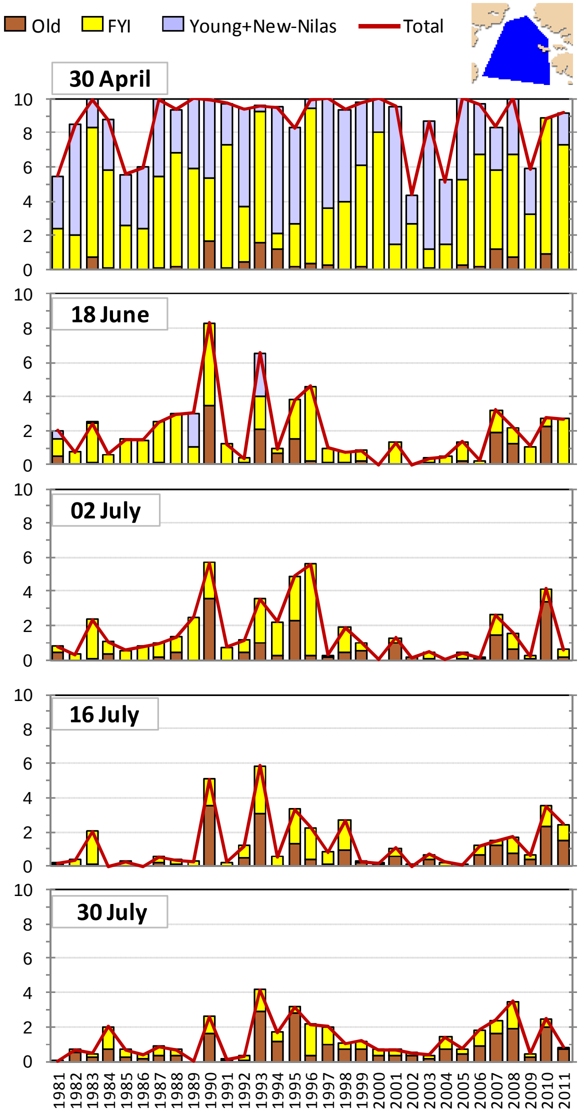


Figure 7: The sea ice concentrations (tenths) for each year from 1981 to 2011 inclusive for the Smith Sound AOI for the weekly ice charts of April 30, June 18, July 2, July 16 and July 30. The total ice concentrations are presented (red line) as well as the partial ice concentration for old, first year ice (FYI), and the combined young/new/nilas ice type categories.

Unlike the NE Baffin Bay AOI, there are no pronounced long term trends computed from 31 year time series record of the sea ice concentrations in the Smith Sound AOI for any of the weeks displayed in Figure 7.

The results for the Disko Island AOI (see Figure 8) show that ice clearing starts by late April with total ice concentrations below 9-tenths in most years with values as low as 4-tenths. The reductions in ice concentrations continue through May 14 and June 6 (not shown) and by June 18, the ice concentrations are greatly reduced to median values of 1-tenth and maximum values of 6-tenths. By July 2, ice concentrations are zero in most years with maximum concentrations of only 2-tenths, and by July 16 and beyond, the ice concentrations are effectively zero.

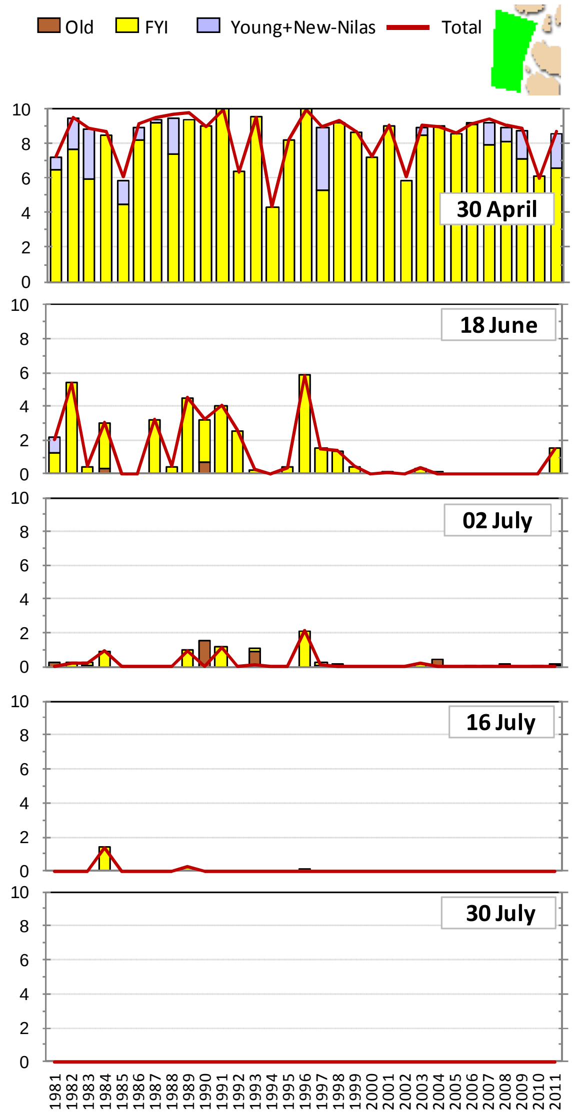


Figure 8: The sea ice concentrations for each year from 1981 to 2011 inclusive for the Disko Island AOI for the weekly ice charts of April 30, June 18, July 2, July 16 and July 30. The total ice concentrations are presented (red line) as well as the partial ice concentration for old, first year ice (FYI), and the combined young/new/nilas ice type categories.

There is a trend towards reduced ice concentrations in recent years in mid-June and early July. The computed trend for June 18 is -9% per decade (statistically significant at the 99 probability level) with a very marked reduction to zero or very low ice concentrations (less than 2-tenths) starting in 1999. The timing of the reductions is similar to that of the NE Baffin Bay AOI, although the magnitude of the reductions are less.

Potential Ship Passage Dates Under Changing Sea Ice Conditions

The potential for Arctic resupply vessels to pass through northeastern Baffin Bay was examined based on the CIS ice chart digital data sets. The potential for ship passages was determined according to the criteria that a passage existed over a width of many kilometers in which total ice concentrations were 2-tenths or less. A manual review of the ice conditions in each AOI was undertaken for the available CIS digital ice charts from 1981 to 2011 for the weeks of April 30, May 14, June 6, June 18, July 2, July 16 and July 30 to determine if a potential ship passage was possible for that particular week and year. Because a full assessment of the dates for a passage of a ship depends on the ship's ice rating characteristics in relation to the prevailing ice conditions (e.g. see Mudge et al., 2010), the results presented in this paper can be associated with the potential for a ship having very limited ice capabilities to pass through the area.

Table 1: The potential for ship passages (N- not possible, O-possible, N/D – no data) for selected weeks from 1981-2011 in the Smith Sound AOI.

	30 Apr	14 May	06 Jun	18 Jun	02 Jul	16 Jul	30 Jul	13 Aug
1981	N	N	N	O	O	O	O	O
1982	N	N	O	O	O	O	O	O
1983	N	N	N/D	O	O	O	O	O
1984	N	N	N/D	O	O	O	O	O
1985	O	O	N/D	O	O	O	O	O
1986	N	N/D	O	O	O	O	O	O
1987	N	N/D	N/D	O	O	O	O	O
1988	N	O	N/D	O	O	O	O	O
1989	N	N/D	N/D	N	O	O	O	O
1990	N	N/D	N/D	N	O	O	O	O
1991	N	N/D	O	O	O	O	O	O
1992	N	N/D	N/D	O	O	O	O	O
1993	N	N/D	N/D	N	O	N	O	N
1994	N	N/D	O	O	O	O	O	O
1995	N	N/D	N/D	O	O	N	O	N
1996	N	N/D	N/D	N	N	O	O	O
1997	N	N	N/D	O	O	O	O	N
1998	N	O	O	O	O	O	O	O
1999	N	N	N	O	O	O	O	O
2000	N	N	N	O	O	O	O	O
2001	N	N	O	O	O	O	O	O
2002	O	O	O	O	O	O	O	O
2003	N	N	O	O	O	O	O	O
2004	O	O	O	O	O	O	O	O
2005	N	N	O	O	O	O	O	O
2006	N	O	O	O	O	O	O	O
2007	N	N	O	O	O	O	O	O
2008	N	N	O	N	O	O	O	O
2009	N	N	O	O	O	O	O	O
2010	N	N	N	O	O	O	O	O
2011	N	O	N	O	O	O	O	O

The results of the determination of potential ship passages are presented in Table 1, Table2 and Table 3 for the Smith Sound, NE Baffin Bay and Disko Island AOI's.

For the Smith Sound AOI (Table 1), potential ship passages are possible in most years by June 6 due to relatively low ice concentrations and presence of thinner ice associated with the Northwater Polynya. Potential ship passages are possible in late April and May in a few years. It should be noted that our analysis did not make a distinction for the presence of ice types that have low ice thicknesses, especially young ice, new ice and nilas. As seen in Figure 7, these thinner ice types are present in large quantities on April 30 and also on May 14 (not shown). As a result, more passages would be potentially possible for Smith Sound in April and May, depending on the ice rating of the ship.

Ship passages of Smith Sound are potentially possible in nearly all years for the weeks of June 18, July 2, July 16, July 30 and Aug. 13. Since 1998, ship passages have been possible in all years for the weeks in July and August 13. Prior to 1998, there were a few years in which ship passages may not have been feasible due to short periods of higher concentrations of sea ice, including a high percentage of old ice types (see Figure 7).

Table 2: The potential for ship passages (N- not possible, O-possible, N/D – no data) for selected weeks from 1981-2011 in the NE Baffin Bay AOI.

	30 Apr	14 May	06 Jun	18 Jun	02 Jul	16 Jul	30 Jul	13 Aug
1981	N	N	N	N	N	O	O	O
1982	N	N	N	N	N	O	O	O
1983	N	N	N/D	N	N	N	N	O
1984	N	N	N/D	N	N	N	O	O
1985	N	N	N/D	N	N	O	O	O
1986	N	N/D	N	N	N	N	O	O
1987	N	N/D	N/D	N	N	N	N	O
1988	N	N	N/D	N	N	O	O	O
1989	N	N/D	N/D	N	N	N	N	N
1990	N	N/D	N/D	N	N	N	N	O
1991	N	N/D	N	N	N	N	O	O
1992	N	N/D	N/D	N	N	N	O	O
1993	N	N/D	N/D	N	N	N	N	O
1994	N	N/D	N	N	N	N	O	O
1995	N	N/D	N/D	N	N	N	N	O
1996	N	N/D	N/D	N	N	N	N	N
1997	N	N	N/D	N	N	N	N	O
1998	N	N	N	N	N	N	N	O
1999	N	N	N	N	O	O	O	O
2000	N	N	N	N	O	O	O	O
2001	N	N	N	N	N	N	O	O
2002	N	N	N	N	O	O	O	O
2003	N	N	N	N	O	O	O	O
2004	N	N	N	N	O	O	O	O
2005	N	N	N	N	N	O	O	O
2006	N	N	N	N	O	O	O	O
2007	N	N	N	N	O	O	O	O
2008	N	N	N	O	O	O	O	O
2009	N	N	N	O	O	O	O	O
2010	N	N	N	N	O	O	O	O
2011	N	N	N	N	N	O	O	O

For the NE Baffin Bay AOI, potential ship passages (Table 2) were only possible starting in mid-July during most of the 1980's and 1990's. However, there is a distinct trend towards earlier potential ship passages starting in 1998. This change in potential ship passages is consistent with the changes in overall sea ice conditions noted in the previous section.

For the Disko Island AOI (Table 3), potential ship passages start much earlier than in the NE Baffin Bay AOI. In nearly all years, potential ship passages are possible by the week of June 18, and in many years, ship passages are possible in early June.

Table 3: The potential for ship passages (N- not possible, O-possible, N/D – no data) for selected weeks from 1981-2011 in the Disko Island AOI.

	30 Apr	14 May	06 Jun	18 Jun	02 Jul	16 Jul	30 Jul	30 Jul
1981	N	N	N	O	O	O	O	O
1982	N	N	N	O	O	O	O	O
1983	N	N	N/D	N	O	O	O	O
1984	N	N	N/D	O	O	O	O	O
1985	N	N	N/D	O	O	O	O	O
1986	N	N/D	O	O	O	O	O	O
1987	N	N/D	N/D	O	O	O	O	O
1988	N	N	N/D	O	O	O	O	O
1989	N	N/D	N/D	O	O	O	O	O
1990	N	N/D	N/D	N	O	O	O	O
1991	N	N/D	N	N	O	O	O	O
1992	O	N/D	N/D	O	O	O	O	O
1993	N	N/D	N/D	O	O	O	O	O
1994	N	N/D	O	O	O	O	O	O
1995	N	N/D	N/D	O	O	O	O	O
1996	N	N/D	N/D	O	O	O	O	O
1997	N	N	N/D	O	O	O	O	O
1998	N	N	N	O	O	O	O	O
1999	N	N	N	O	O	O	O	O
2000	N	O	O	O	O	O	O	O
2001	N	N	N	O	O	O	O	O
2002	N	O	O	O	O	O	O	O
2003	N	N	O	O	O	O	O	O
2004	N	N	O	O	O	O	O	O
2005	N	N	N	O	O	O	O	O
2006	N	N	N	O	O	O	O	O
2007	N	N	O	O	O	O	O	O
2008	N	N	O	O	O	O	O	O
2009	N	N	O	O	O	O	O	O
2010	N	N	O	O	O	O	O	O
2011	N	N	N	O	O	O	O	O

CHANGES OF SEA ICE EXTENT IN RELATION TO ATMOSPHERIC INDICES

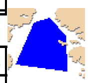
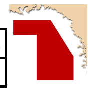
To examine the underlying causes of the changing sea conditions in the three AOIs used in this study, a correlation analysis was undertaken of the bi-weekly total ice concentration with large scale atmospheric climate indices: the North Atlantic Oscillation (NAO) index, the El Niño Southern Oscillation (ENSO) index and the Arctic Oscillation (AO) index.

The NAO index is computed as the normalized difference in sea level pressure between southwest Iceland and Gibraltar. Above (below) normal air temperatures off West Greenland are associated with below (above) normal values of the NAO index (Cappelen, 2008). For the purposes of this study we considered the NAO for the spring months, for the winter (January to April) and for the previous fall and winter (October to April). There were no statistically significant correlations found for sea ice concentrations with the spring NAO. Only very sporadic statistical correlations were computed for sea ice concentrations with the ENSO and AO indices.

The only consistent correlations between sea ice concentrations and climate indices was found for the NE Baffin Bay AOI sea ice concentrations from mid-June to late-July with the winter and fall-winter NAO index (Table 4). For the Smith Sound and the Disko Island AOIs there was no indication of any statistically significant correlations for any of the weeks considered in spring and summer.

Table 4: The computed probability F-statistic for correlations between 1981-2011 sea ice concentrations with the NAO winter and fall-winter index values for the years 1981-2011. Note that the F-statistic represents the probability that the computed relationship between the sea ice concentrations and the NAO index occurs by chance, i.e. 0.05 represents a 5% chance that the relationship occurs by chance. A large value of the F-statistic indicates a greater probability that the computed correlation is due to chance. F-statistic values, which are highly unlikely to arise by chance, are highlighted in yellow for the table entries.

	30 A	14M	06 Jn	18 Jn	02 Jl	16 Jl	30 Jl
Smith Sound AOI							
Jan-Apr avg	0.36	0.12	0.67	0.19	0.64	0.44	0.86
prev Oct-to yr Apr avg	0.61	0.62	0.51	0.50	0.93	0.77	0.77
NE Baffin Bay AOI							
Jan-Apr avg	0.51	0.66	0.08	0.05	0.15	0.05	0.06
prev Oct-to yr Apr avg	0.31	0.47	0.26	0.11	0.16	0.03	0.21
Disko Island AOI							
Jan-Apr avg	0.40	0.35	0.62	0.21	0.89	NI	NI
prev Oct-to yr Apr avg	0.52	0.15	0.64	0.86	0.58	**NI**	**NI**


The apparent coupling between the marked reductions in June and July sea ice concentration in the late 1990's within the NE Baffin Bay AOI with similar changes in the winter NAO index is shown, for example, in Figure 9 for the week of July 16. The higher sea ice concentrations in the 1980's to mid-1990's is tracked by a relatively high and increasing NAO index values, followed by reduced and consistently low NAO index values in the late 1990's and throughout the period 2000-2010 when the sea ice concentrations are greatly reduced. The higher winter NAO values are associated with lower winter air temperatures which may result in more ice growth and higher ice concentrations. Of course, there are many other physical factors that are important as well to the changing sea ice regime of Northeastern Baffin Bay in early summer.

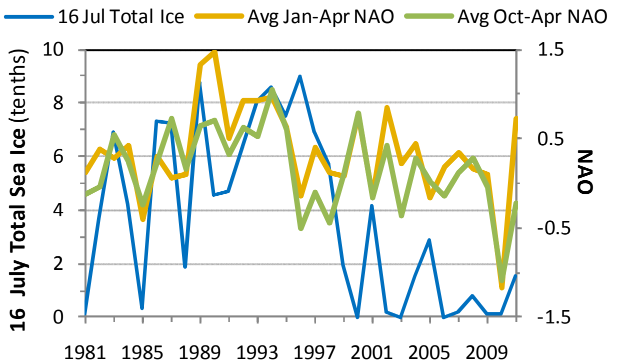


Figure 9: A plot of the July 16 total sea ice concentration in the NE Baffin Bay AOI (blue line) vs. the NAO index for January to April (orange line) and the average NAO index from October (previous year) to April (green line).

SUMMARY AND CONCLUSIONS

Over the last three decades, there has been a trend towards less sea ice coverage of Baffin Bay. The area of the Northwater Polyna historically clears early in the season, in April through to early June, but shows no significant trends towards lower sea ice concentration over the past 31 years. In contrast, the area west of Disko Island, a region that also begins clearing in April, and the area of northeast Baffin Bay, a region that typically clears later in the season, have dramatic shifts towards lower ice concentrations since 1999. This trend is greatest in late June to mid-July for northeast Baffin Bay where ice concentrations have decreased between -14% and -24% per decade. This trend has resulted in ice clearing approximately 3 to 4 weeks earlier than what was observed in the 1980's and 1990's. The starting time of potential ship passages through northeast Baffin Bay has likewise shifted from late/mid-July to late-June. These lower ice concentrations will have a similar impact on earlier starts to yearly offshore oil and gas operations in the area.

The observed changes in the sea ice regime may be driven by many physical parameters, of which, atmospheric forcing is probably the most important. We observed a high correlation between the sea ice concentrations of northeast Baffin Bay in June and July with the North Atlantic Oscillation (NAO) index of the preceding fall, winter and early spring period. The index, which is the difference in sea level air pressure between Gibraltar and Iceland, is also associated with above and below normal winter temperatures off West Greenland.

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