Long-Term Changes in Metocean-Ice Conditions in the Canadian Beaufort Sea

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ABSTRACT

Existing long-term metocean-ice data sets are reviewed and analyzed for estimation of trends and changes relevant to offshore oil and gas and shipping/navigation activities in the Canadian Beaufort Sea (CBS).

An analysis of 45 years (1968-2012) of sea ice properties from Canadian Ice Service sea ice charts indicates that the summer and early fall concentrations of sea ice are decreasing by up to 7.4% per decade (September to mid-October). Old ice concentrations are decreasing at a higher rate along the slope and deeper offshore waters of the Beaufort Sea at rates of 10.5% per decade. There is also evidence of an increasing presence of glacial ice features passing through the Canadian Beaufort Sea. In contrast to the deeper offshore waters, the reductions in ice concentrations over the continental slope are smaller but still statistically significant in some subregions. The mid-outer shelf region also exhibits substantial reductions in mid-October with the loss of old ice and young ice being a large part of the total ice reduction. However, there have been no significant changes observed in ice thickness in continental shelf region. The duration of the landfast ice off the coastline of the CBS is also being reduced with a delay in formation date of 2.8 weeks per decade and an advance in break-up date of 0.65 week per decade.

An analysis of long-term air temperatures reveals that the largest warming occurs in the fall and winter corresponding to a temperature elevation of about 4°C over the past five decades or an equivalent rate of decadal change of, approximately, 0.8°C. The regional wind patterns in the region exhibit little evidence of long-term trends in coastal zones, while cyclonic activity appears to be increasing in offshore areas. The combination of the reduced areal extent of sea ice in summer and especially in the fall, and continuing and perhaps increased cyclonic activity in offshore areas, is leading to increasing occurrences of large ocean waves, as seen through analyses of moored upward looking sonar data obtained over the past decade.

KEY WORDS: Arctic Ocean, Beaufort Sea, sea ice, meteorology, oceanography, ocean waves, climate change, oil and gas exploration, shipping.

INTRODUCTION

Arctic Ocean Basin: Changes and Trends

In recent years, changes in the Arctic Ocean sea ice, weather and ocean regime have received much attention in the scientific literature as well as the popular press. There is evidence of widespread and persistent overall warming and reductions of sea ice within the past 30 years. These changes are due to the impacts of a persistent warming trend that began over 30 years ago (Jeffries et al., 2013).

The trend towards reduced levels of the areal extent of Arctic summer sea ice is particularly dramatic. The most complete (passive microwave) data on the annual areal coverage of all types of ice for the Arctic Ocean and adjoining areas, dating back to 1979, provides the best measure of changes over the intervening decades in, at least, the spatial extent of ice coverage. These changes are most evident in the annual extents as estimated at seasonal extreme points: March when coverage is maximal and September when it reaches minimum extent. The March ice extent (Figure 1) showed comparatively decreases of approximately 3% per decade relative to the indicated 1979–2000 average arising largely from reduced extents of ice moving out of the Arctic Basin to lower latitudes. On the other hand, the much larger decrease in the September ice extents (Figure 1) of approximately 13% per decade is suggestive of underlying major changes in the composition of Arctic sea ice due to accelerated decreases in old ice, especially in the past 10 to 20 years (Maslanik et al., 2011).

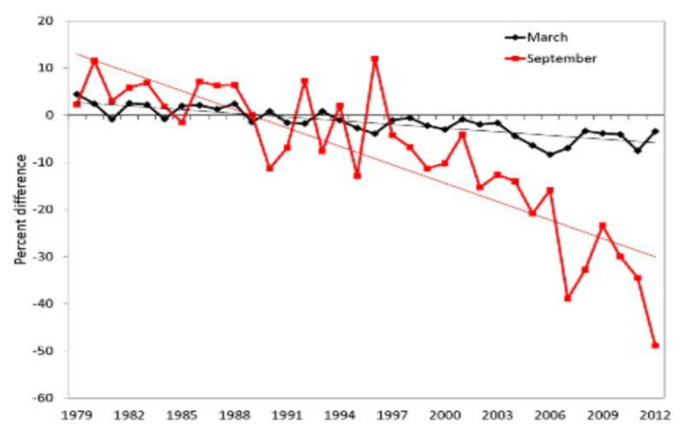

Figure 1: Time series of the percent difference in Arctic ice extent in March (the month of ice extent maximum) and September (the month of ice extent minimum) relative to the mean values for the period 1979–2000 (Perovich et al., 2012).

In this paper, we examine the changes and trends observed over past decades for sea-ice, meteorological and ocean wave conditions of the continental shelf and slope regions of the Canadian Beaufort Sea. The changes in this region are compared to those observed and reported over the full Arctic Ocean system.

The changes and trends are considered and discussed in the context of oil and gas exploration and shipping activities at present and over the next 10-30 years, based on our present understandings and uncertainties in the metocean and ice conditions of this region.

Floating Ice: Types and Hazardous Features

The overall distribution of sea ice in the Arctic Ocean takes the form of two principal sea-ice types (first-year, multi-year ice) and two states of mobility (active pack ice, static fast ice). The distribution of these sea-ice types and mobility vary considerably over the entire Arctic Ocean, as shown in Figure 2. Mobile pack ice dominates the Beaufort Sea portion of the Western Arctic Ocean, including both first year (annual) and multi-year (old) ice. Along the shorelines and in the confined channels of the Canadian Arctic Islands, the sea ice becomes immobile (or fast) through much of the year from mid-autumn through to summer. Old or multi-year ice occupies much of the northern and western channels of the Canadian Arctic Islands, while first year ice is dominant in the more southerly and easterly channels.

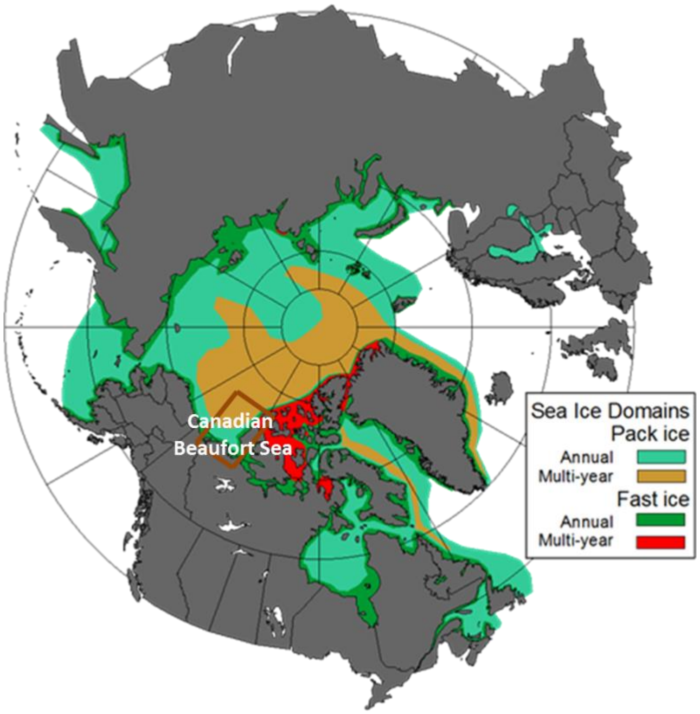

Figure 2: Sea ice in the Arctic Ocean has four distinct domains (after Melling, 2010) made up of two overall ice types (annual or first year ice and old or multi-year ice), and two states of mobility (moving pack ice or non-moving "fast" ice). First year ice that survives September becomes old ice in October and non-moving ice often becomes mobile in mid- to late-summer.

For engineering purposes, floating ice is of particular importance including changes in (a) old ice, which consists of second year and multi-year ice because of its unyielding hardness by comparison to first year ice; (b) thicker and heavily deformed first year ice, in the form of very deep ice keels and hummocky ice features with large ice masses and (c) very rare occurrences of large ice islands of glacial origin (having widths of kilometers and thicknesses of many tens of metres), which break off ice sheets and glaciers on Ellesmere Island and northern Greenland to the east.

DATA SOURCES AND METHODOLOGY

Data Sources

The summaries and trends computed for this study are derived primarily from long-term published measurements made by Canadian Government Departments and Agencies, specifically:

- Meteorological data sets collected since the 1950's at Environment Canada weather stations in the Canadian Beaufort Sea and CAA.
- Weekly ice charts prepared by the Canadian Ice Service of Environment Canada since 1968 based on satellite and airborne remote sensing data as well as ship-based reports (digitized for this study from the Canadian Ice Service website).
- Upward looking sonar measurements of sea ice draft and ocean waves made from long-term sub-surface moorings by the Institute of Ocean Sciences laboratory of the Canadian Department of Fisheries and Oceans.

Methodology

The processing and analysis methods began with a review of the time series data sets to detect any missing or physically incorrect data values. Periods of missing data were replaced by interpolation for intervals of up to one day in duration and otherwise not included in the analyses. The computation of statistical parameters and long-term trends were made using standard algorithms in Excel, ENVI v4.8 and Matlab.

SEA ICE

The major ice features of the Beaufort Sea (Figure 3) consist of landfast ice (quasi-stationary) adjoining the shoreline to water depths of 20 m, a shear zone of highly deformed ice features and a much larger transition zone to the main Arctic Ocean polar pack ice. The large compression ice ridges formed in the shear zone represent potential ice hazards. The offshore pack ice drifts on average to the west as part of the Beaufort Gyre clockwise circulation pattern (Proshutinsky et al., 2011).

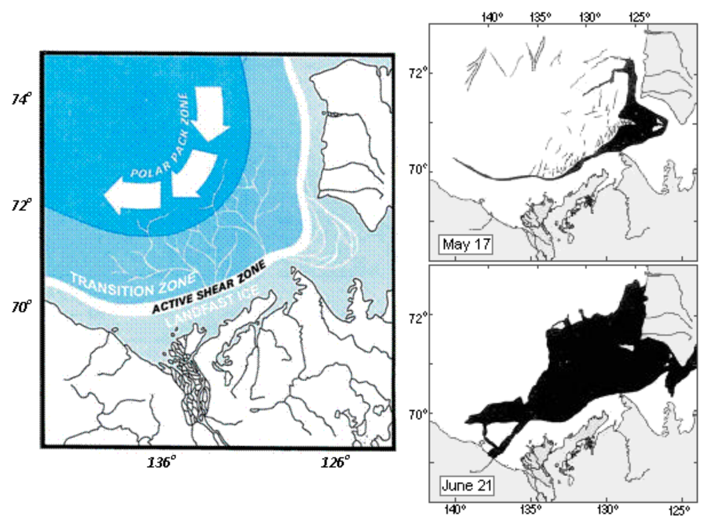

Figure 3. The ice regimes of the Beaufort Sea in winter and spring (left panel), and the typical break-up and dispersal patterns of sea ice in May and June. The inshore landfast ice usually disperses by late June or early July.

Ice Concentrations and Area

Offshore oil and gas activities, and related shipping activities, occur during the summer and early fall months for areas in deep-water over the middle and outer continental, and more recently over the continental slope. Inshore drilling activities in the landfast ice zone take place in winter and early spring.

The overall areas of interest for this study are primarily confined to Environment Canada's Mackenzie Region and the inner portion of the Canada Basin Region. Environment Canada's (2011) Canadian Ice Service historical ice chart sea ice concentration database for these areas spans the time period 1968 to the present. The yearly time series of sea ice areal coverage data, expressed as a percentage of total area, for the middle of the months of June, July, August, September and October are presented in Figure 4 and Figure 5. A striking feature of the sea ice extent is the large amount of inter-annual variability, particularly in the Mackenzie Shelf region. The variability occurs over a wide range of periods, ranging from two years or less to eight years or longer. The downward trend in the ice coverage data (Figure 4) reflects the offshore retreat of the pack ice edge (Figure 3) to the north and west (Galley et al., 2013).

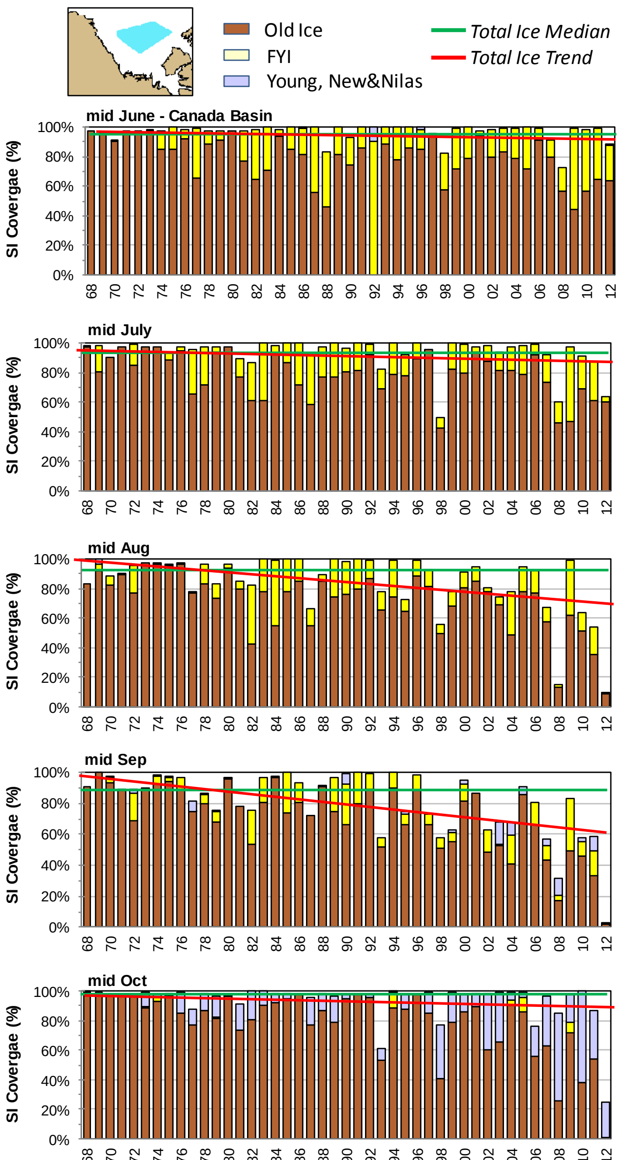

Figure 4. Mid-month historical sea ice (SI) percentage areal coverage for the Canadian Ice Service "Canada Basin" region from mid-June to mid-October, 1968–2011 for total ice and individual ice types. Also shown are the median and the long-term trend of the total ice concentrations

Trend data extracted from the CIS database for the Canada Basin and Mackenzie regions are presented in Figure 6. In both regions the decadal trends in overall ice extents and in the corresponding major ice age/thickness categories ((old = multi-year, first year (FY) and young/ thin ice (thicknesses < 50 cm)) are plotted for mid-month June through October. As expected, the Canada Basin trends are similar to those noted above for the encompassing Arctic Basin area, with changes in total ice caused primarily from the old ice fraction which, in the late summer and fall months, was seen to decrease at rates ranging between 8% and 11% per decade over a period of 44 years. The only statistically significant changes in the Mackenzie region are limited to early season (June) data and correspond to somewhat lower, 6% to 8%, changes in both total and old ice coverage. Since old ice concentrations in this southerly region were usually low these results corresponded to early summer reductions in the amount of both first- and multi-year ice components.

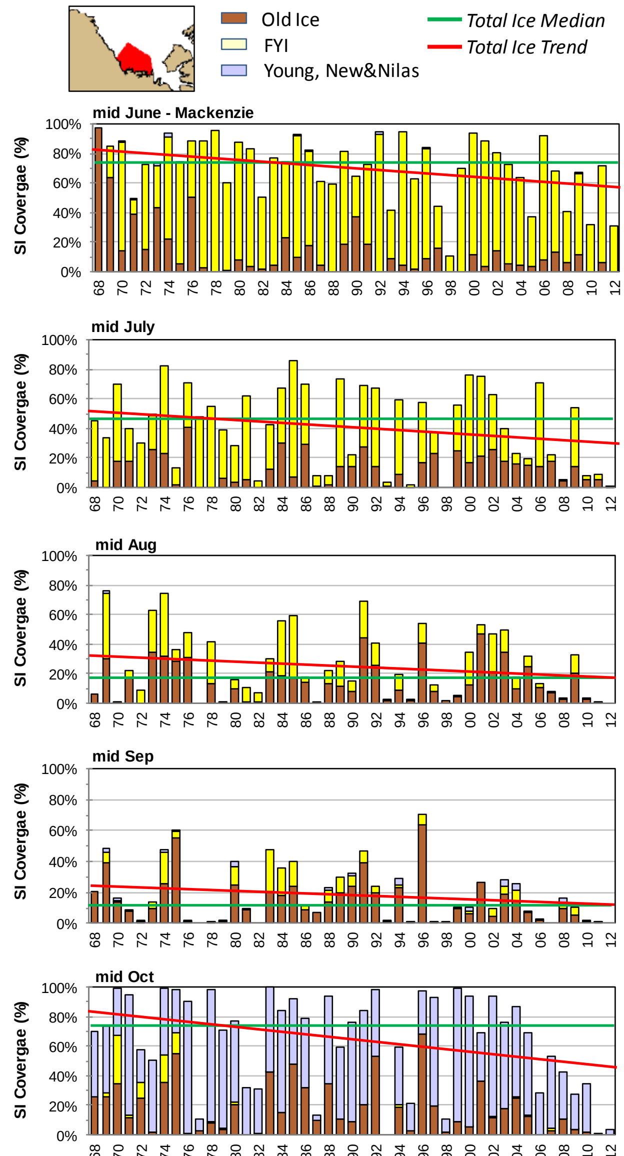

Figure 5. Mid-month historical sea ice (SI) percentage areal coverage for the Canadian Ice Service "Mackenzie" region from mid-June to mid-October, 1968–2011 for total ice and individual ice types. Also shown are the median and the long-term trend of the total ice concentrations

Data were also extracted from this same database on smaller spatial scales corresponding to the four distinct sub-regions of the larger Mackenzie region (the red area shown in Figure 5). The smaller subregions, as shown in Figure 7, include the Inner Shelf and Kugmallit Bay, which is covered by landfast ice in winter and spring, and the Mid-Outer Shelf area, which is the part of the transition zone shown in Figure 3. The changes for each sub-region (Figure 7) are generally largest in the slope region, as would be expected from the Arctic Ocean and Mackenzie Shelf results presented in Figure 6.

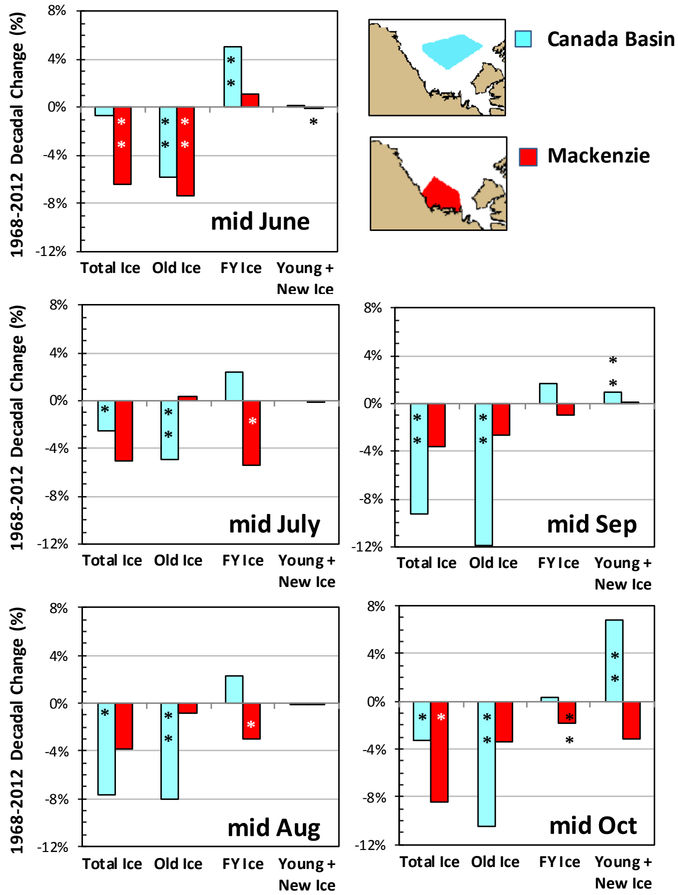

Figure 6. Trends in sea ice coverage from mid-June to mid-October for the Canada Basin and Mackenzie regions in the Canadian Arctic, 1968–2012 (derived from Canadian Ice Service regional data). Statistical significance shown in the bars:* $p<0.05$: ** $p<0.01$.

The largest change for the Canadian Beaufort Sea sub-regions, of nearly a 10% reduction per decade, occurs in mid-October (Figure 7) with much of the sea ice reduction being due to the loss of old ice. Although less than that of the slope, the mid-outer shelf region also exhibits substantial reductions in mid-October with the loss of old ice and young ice being a large part of the total ice reduction. The long-term trends towards reduced sea ice concentration are much smaller in the inner shelf in mid-September because little ice is present in this area in mid- to late-summer. However, consistent reductions do occur in mid-July and mid-October. Because old ice is present in smaller quantities in the inner shelf, these trends are very small. In the inshore area of Kugmallit Bay, the long-term trends in sea ice concentrations are lower during the summer, but a reduction in total ice concentration does occur in mid-October. This is due to the later formation of sea ice resulting in a reduction of the thicker, first-year ice type, which is partially offset by an increase in the thinner young-ice categories.

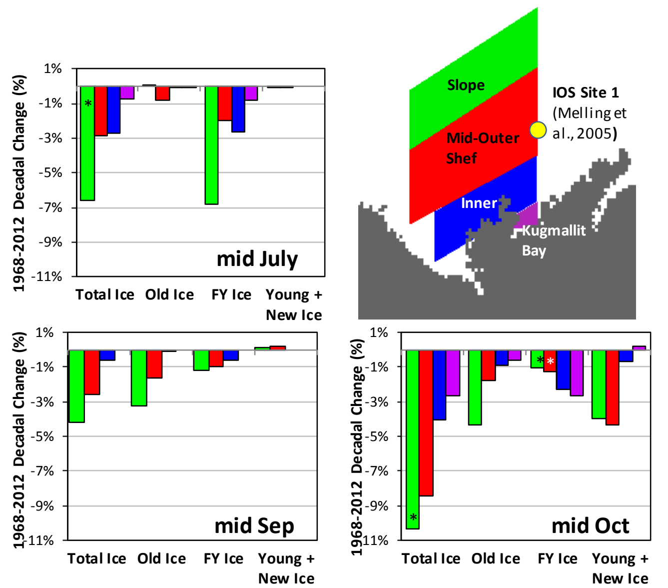

Figure 7. The computed changes in sea ice concentration from 1968 to 2012 for the four subregions (shown on the right) in mid-July, mid-September and mid-October (derived from Canadian Ice Service regional data). Statistical significance shown in the bars:* $p<0.05$: ** $p<0.01$.

Landfast Ice Regime

The landfast ice zone forms in the late fall and grows in place until late spring. The thickness and seasonal duration of landfast ice within the Canadian Arctic depends strongly on air temperature and snow cover (Brown and Cote, 1992). While not without complexity, the underlying physical processes can be modeled on regional scales to provide understandings of the effects of climate change on landfast ice (Flato and Brown, 1996). Dumas et al. (2005) found that an increase of 4 °C in annual average temperature and of 20% to 100% in snow accumulation rate will result in 24 cm to 39 cm reduction in the mean maximum ice thickness and a three week reduction in the duration of landfast ice at coastal locations in the Canadian Beaufort Sea.

The landfast ice zone is important to inshore oil and gas exploration activities as the ice itself provides and operating platform for the movement of heavy equipment by truck and it provides a stable base for winter and early spring drilling platforms.

A recent study by Galley et al. (2012) on landfast sea ice conditions in the Canada Arctic reveals that the formation of landfast ice in the coastal margins of the Mackenzie area of the Beaufort has undergone a delay of 2.8 weeks per decade from 1983 to 2009, which is statistically significant. Over this same 26 year period, the break-up dates of the landfast ice have advanced at 0.65 weeks per decade also at a statistically significant level. Reductions in the duration of the landfast ice season will reduce the duration for use of ice roads, which are used to support inshore oil and gas activities resulting in a curtailment of inshore drilling operations in fast ice during winter and spring. The timing of the onset of the melting of fast ice, which occurs prior to breakup, is very important because after this time, transportation on the ice effectively ends.

Ice Thickness

For the Mackenzie shelf region, more than two decades of ice draft data have been collected by Dr. H. Melling of DFO from upward-looking sonars moored in the southeastern and eastern ends of the Beaufort Sea since 1991. The longest duration record, collected at 70.3^0 N, 133.7^0

W, corresponding to the shoreward half of the mid-outer shelf region NNW of Kugmallit Bay (Figure 7), provides the best basis for detecting change in thickness or draft parameters. This extended data set, derived by Melling for both the corresponding overall and ice-only means, are not indicative of statistically significant trends (Melling et al., 2005; Melling, 2012, pers. communication). Nevertheless, it is of interest to explore the possibility that the apparent post-1998 downward trend in Arctic Ocean Basin ice extents has a counterpart in the draft records. Some insight in this respect could be gathered from the mean thickness data included in Figure 8 for the years 2005–2010. Although still inconclusive these results (Niemi et al. 2012) suggest that recovery from the downward 2005–2008 trend appeared to occur in 2009–2010 leaving intact Melling's conclusion that no trend in thickness or topography has, as yet, been detected on the Mackenzie Shelf and, in any case, any trend present would currently be overshadowed by year to year and shorter term variability.

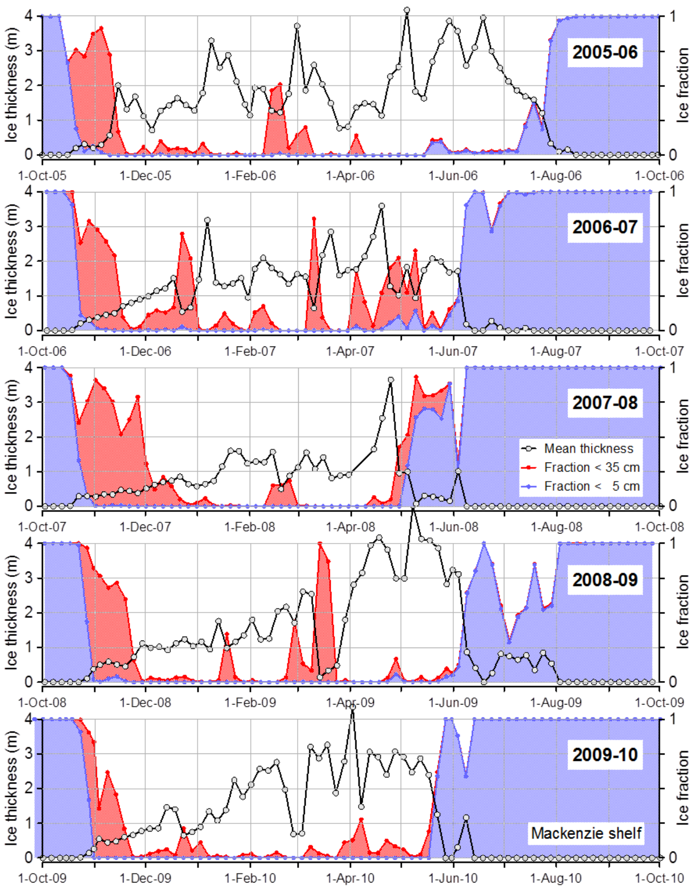

Figure 8. The mean ice thickness, along with ice fractions of thinner ice (< 5 cm and < 35 cm, 5 day intervals) at the mid-shelf location in the Canadian Beaufort Sea for five years: 2005–2006 to 2009–2010.

It should be noted that the ice thickness measurements of Figure 8 are indicative of a combination of local short-term and far field longer term processes due to thermodynamic and dynamic forcing. The absence of a clear trend toward reduced ice thickness at the Beaufort Sea shelf measurement site may reflect a change in far field origin of this ice which is generally to the northwest including the areas offshore of the Canadian Arctic Islands (see Figures 3 and 9). Variability in the far field origin of the sea ice for this measurement site may contribute to the absence of a reduction in ice thickness on the Beaufort Sea shelf in contrast to other areas of the Arctic where larger reductions are observed (Kwok and Rothrock, 2009).

Hazardous Ice Features

Hazardous sea ice features in the Canadian Beaufort Sea and other Arctic regions have recently been summarized in Fissel et al (2012a). These features include large individual ice keels and segments of highly concentrated large hummocky (rubbled) ice. Individual large ice keels have the largest ice thickness of up to 20 m or more while large hummocky ice features have greater horizontal scales of 100 to several hundred meters with lesser ice thickness. Upward looking sonar (ULS) data sets obtained in the Canadian Beaufort Sea over many years have consistently yielded several observations of ice keels exceeding 15 m ice draft for every year at each measurement site. Typical annual maximum ice drafts are in the range of 22 – 30 m and the estimated 100 year sea-ice draft value is 30-34 m (Ross et al., 2012). As these data sets indicate, deformation of first-year ice can create very large sea ice drafts that are likely larger than that of old ice. Under larger ice drifts that have been reported in the Arctic Ocean (Rampal et al., 2009), it is possible that first-year ice is becoming more deformed which may lead to larger maximum ice draft values for first-year sea ice.

For shipping operations, including those associated with station keeping during drillship operations, occasional incursions of sea ice under the influence of onshore winds, especially in a less favorable ice year, are likely to occur. The presence of old ice is important because old ice is harder and less likely to yield to ice clearing and breaking operations. In the deeper waters of the Canada Basin, throughout the year and also on the outer portions of the Mackenzie Shelf in late summer, old ice is the predominant ice type (Figure 4 and Figure 5).

Over the past few decades, considerably less old ice is being reported on the ice charts for the Mackenzie Shelf and Alaskan Beaufort Sea than in previous decades (Figure 6 and Figure 7). The reduction in multi-year sea ice can be quantified through the computation of ice age using satellite observations combined with modeling, as shown in Figure 9, and illustrates how the areal extent of multi-year ice in the Beaufort Sea deep water areas has declined dramatically in the years 2009–2011 as compared to 1988 especially in the four-year and older category. The overall sea ice concentrations in March are little changed, with first-, second-, and third-year ice being present in the area. However, reduced amounts of old ice would lead to reduced ice thicknesses. Nevertheless, the presence of old sea ice is expected to continue in the Canadian Beaufort Sea for the foreseeable future, even as the old ice concentrations decline. The largest source of old sea ice in the Arctic Basin, especially the multi-year ice with an ice age of three years or more is found off the northern shelf of the Canadian Arctic Archipelago (CAA). The CAA is located upstream of the Canadian Beaufort Sea under the prevailing ice drift to the west driven associated with the Beaufort Gyre.

Glacial ice is ice formed on land through long-term processes of freshwater ice accretion in cold climates. For glacial ice shelves in the form of tidewater glacier and ice sheets, very large ice pieces can break off to form icebergs or ice islands. Icebergs are generally very thick with ice drafts of tens of meters to 100 m or more. Ice islands are sheets of level glacial ice that can be several tens of meters thick with very large horizontal dimensions of 1 to 30 plus km. Once launched, these glacial ice features pose formidable hazards to marine operations until they break up and melt. Ice islands can form off northern Greenland and the northernmost Arctic Islands (Ellesmere and Axel Heiberg islands) and drift south-westward through offshore portions of the CAA into the Canadian Beaufort Sea.

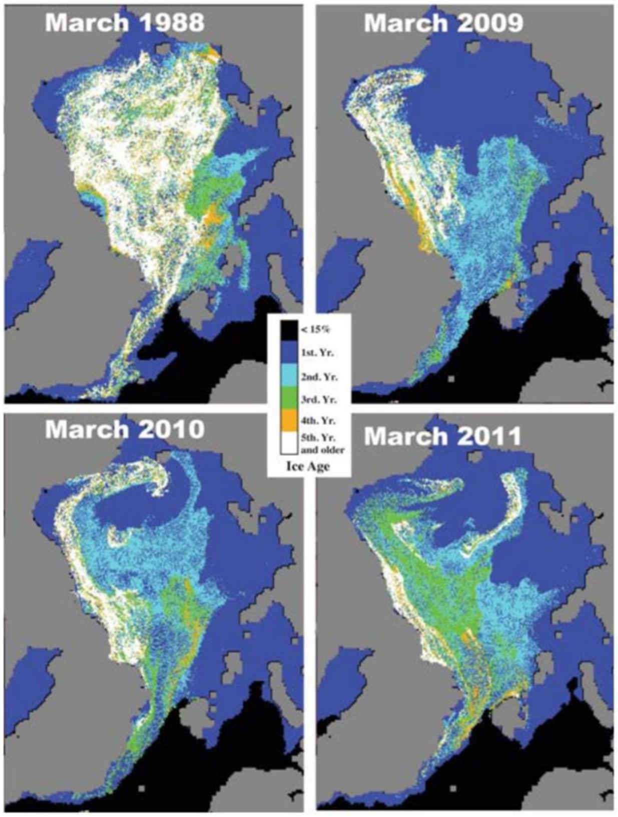

Figure 9. Sea ice age in the first week of March derived from tracking the drift of ice floes in 1988, 2009, 2010 and 2011 (from Perovich et al., 2011).

Recent studies have highlighted the fact that ice shelves along the NW flank of Ellesmere Island have lost significant mass. In the past century, a continuous ice shelf extended for over 450 km of the CAA NW coast, joining many discrete exit glaciers (e.g., Copland et al. 2007). While sporadic losses of ice have occurred from the ice shelves since their discovery in the late 19th century, this large continuous shelf began to break-up at much increased rates early in the last decade with complete loss of the Markham and Ayles Ice shelves and significant mass loss of the Ward Hunt, Milne, Petersen and Serson Ice Shelves. Pieces of these ice shelves have been observed far offshore in the Beaufort Sea Ice Gyre. Recent work onboard the CCGS Amundsen identified and placed GPS position beacons on several (17) of these marine glacial ice features. The features were all very thick (>40m) and extend in area from 100's of meters to kilometers in radius (D.G. Barber, cersonal communication). The detection and management of this marine glacial ice features is a significant hazard to both stationary drill ships and service shipping required by the hydrocarbon industry.

METEOROLOGY

Air Temperatures

Long-term coastal weather station data provides a means of examining changes over many decades. For this study, the Environment Canada weather station data at Tuktoyaktuk and Sachs Harbour were analyzed for long-term trends by individual months (Table 1 and Figure 10). The long-term trend results show an overall increase in monthly mean air temperatures for all months over the past 50 years. The largest amount of warming occurs in the fall and winter with a total warming of nearly 4°C in the past five decades or a median decadal change of 0.8°C for both Tuktoyaktuk and Sachs Harbour. We note that the relationship between warming and sea ice extent can be complex. For example, less ice can create warmer coastal temperatures; warmer coastal temperatures can be due to advection of warmer air masses into the region from the south and may not affect sea ice extent at all. In the spring and summer months, the warming is less and not always statistically significant with increases over 50 years ranging from 1.1°C (August) to 3.1°C (June) at Tuktoyaktuk, with an overall increase of 0.4°C per decade. The warming is less in spring and summer at Sachs Harbour with an overall increase of 0.3°C per decade.

	Tuktoyaktuk			Sachs H.		
Month	TC	p	*DC*	TC	p	*DC*
Jan	4.0	*	*0.8*	5.1	**	*1.0*
Feb	5.5	**	*1.0*	4.8	**	*0.9*
Mar	3.4	*	*0.7*	2.3		*0.4*
Apr	4.2	*	*0.8*	4.3	**	*0.8*
May	2.0		*0.4*	0.8		*0.2*
Jun	3.1	**	*0.5*	1.5		*0.4*
Jul	1.9	*	*0.3*	1.5		*0.3*
Aug	1.1		*0.1*	1.6		*0.3*
Sep	2.4	**	*0.4*	2.5		*0.5*
Oct	2.2		*0.4*	3.1		*0.6*
Nov	3.2	*	*0.6*	4.1	*	*0.8*
Dec	2.0		*0.4*	3.2		*0.6*
Med	***2.7***		***0.5***	***2.8***		***0.6***
Med FW	3.4		*0.7*	4.1		*0.8*
Med SS	2.0		*0.4*	1.5		*0.3*

Table 1: Monthly air temperature trends from 1960 to 2012 at Tuktoyaktuk and Sachs Harbour. The computed change in the long-term trend (TC, computed as 2001–2011 mean less the 1960–1970 mean), statistical significance (* p<0.05, ** p<0.01) and decadal change (DC in °C/10 years) are presented. Med=median, FW=fall-winter, SS=spring-summer).

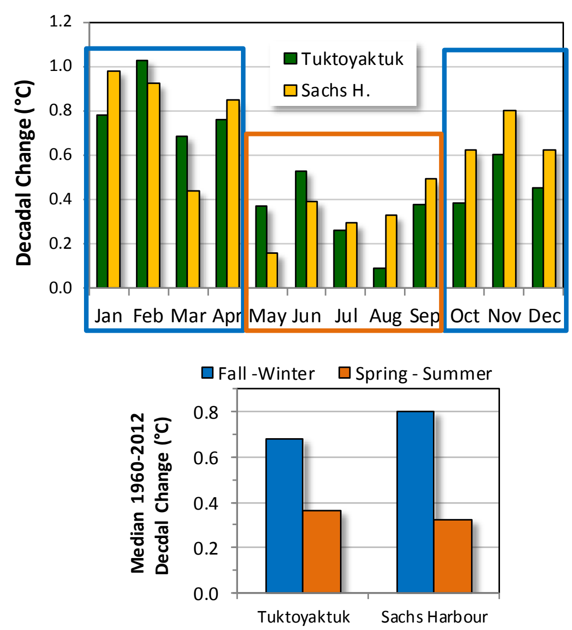

Figure 10: Monthly decadal change in air temperature for Tuktoyaktuk and Sachs Harbour 1960–2012 (upper) and seasonal median decadal changes (bottom).

Winds

Surface wind data from coastal weather stations, available over the past 50 years or more, indicate little or no increase in wind speeds and storm frequencies along the coastline of the Beaufort Sea (Huda and Young, 2002; Atkinson 2005; Manson and Solomon 2007). A recent study of monthly Beaufort Sea winds (measured at Tuktoyaktuk NWT and the marine weather station at Pelly Island NWT) reveal only small trends for most months. The long-term trends in the monthly average coastal wind speeds as computed for the March-April and October-November periods had a net change of approximately –20% over the years 1958 to 2007 (Fissel et al., 2009). The analysis of monthly wind stress from re-analyzed numerical model wind results over the years 1948 to 2006 (Hakkinen et al. 2008) are consistent with negative trends for the inshore shelf waters of the western Arctic Ocean. Overall, the monthly mean wind speeds in coastal areas appear to have decreased over the past five decades. However, wind speeds may be increasing in offshore areas (Hakkinen et al., 2008). There is an increase in the depth of offshore low pressure systems but not an increase in the frequency of cyclones (Lukovich and Barber, 2006). More cyclones tend to follow the sea ice/ocean interface and as such these storms are moving further offshore as the ice edge retreats. The Beaufort Sea high pressure system has become stronger in the years 1996 – 2011 (Moore and Pickart, 2012) leading to enhanced easterly winds in the Beaufort Sea with larger increases at more offshore locations.

OCEAN WAVES

Changes in ocean wave properties are presently occurring, over the past decade as a consequence of reduced ice concentrations and areal extents resulting in a longer duration of ocean wave activity in recent years (Fissel et al., 2012). In recent years there is evidence of, moderate to large wave events starting in early June and extending into November from the previous wave season in the 1980’s of mid-June to late October (Fissel et al., 2012). These trends are expected to continue and increase in the future due to the anticipated future reduction in sea ice cover. Long period swell waves originating from distant storms have only rarely occurred in past decades but may become more frequent in the future (Barber et al. 2010). These long swell waves increase the loss rates of sea ice by breaking up floes into smaller sizes which are more mobile and melt more easily (Asplin et al. 2012).

Large waves and storm surges can affect the marine operations of offshore and nearshore oil and gas industry activities as well as coastal infrastructure required to conduct offshore activities.

SUMMARY: IMPLICATIONS FOR FUTURE OIL AND GAS AND SHIPPING OPERATIONS IN THE CANADIAN BEAUFORT SEA

There is clear evidence that the metocean-ice conditions of the Beaufort Sea have changed significantly in the last few decades, and especially in most recent decade. Ice and water conditions in the Canadian Beaufort Sea are influenced by oceanic and sea ice exchanges with neighboring Arctic Ocean Basin. Sea ice thickness and concentrations of multi-year ice are decreasing especially along the slope and deeper offshore waters of the Beaufort Sea and adjacent regions. These reductions are mainly a result of losses of older multi-year ice. There is also an increasing presence of glacial ice features. In contrast to the deeper offshore waters, there have been no significant changes observed in ice thickness along the Mackenzie shelf and the reductions in ice concentrations are smaller. A later freeze-up and earlier break-up of ice along the inner shelf has resulted in a reduction in duration of days of ice cover for this area.

Mean air temperatures within the assessment area have been increasing over the past 50 years. Storm activity has increased in strength (depth of the low pressure) but not in frequency or in increased wind speed trends. Ocean wave activity is increasing both in the duration of the ocean wave season and the measured maximum significant wave height of the largest wave episodes in the fall.

Looking to the future, the expected reduced sea ice conditions, and their relation to regional and global atmospheric and climate conditions, will coincide with changes in other parameters:

- continuing increase in air temperatures, especially in the fall and winter, at rates similar to those experienced in the past 50 years
- larger ocean waves occurring over longer periods of time in summer and fall, in association with the reduced sea ice coverage.

The effects of the changing metocean-ice conditions are expected to have both positive and negative effects on offshore oil and gas and shipping activities. Positive effects include:

- longer operating seasons for seismic and drilling activities due to reduced ice cover and thickness
- earlier mobilization and later demobilization of vessels both to and from the Beaufort Sea as well as from overwintering anchorages and offshore areas
- reduced icebreaking requirements

Negative effects include:

- increased threats to drilling and production platforms due to increased ice velocities and the increased presence of glacial ice features
- larger wave heights may cause delays in ship support activities and seismic operations
- reduced use of ice roads and ice spray islands in nearshore areas

Climate change effects on oil and gas activities are expected to be greatest for longer term projects such as production activities which can span 30 years or more, and where changes affecting operations may change over the lifespan of the project. Due to the large year to year variations which can occur for weather or ice conditions, operators will be continue to plan for extreme events which could occur at any time through all phases of a project.

There are many information and knowledge gaps that need to be addressed to improve the understanding of the effects of the changing metocean-ice climate on oil and gas and shipping activities. Most of these gaps pertain to atmospheric processes or ice, sea-ice and glacial ice, as well as the upper layer ocean dynamics.

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