Long-Terms Trends for Sea Ice in the Western Arctic Ocean: Implications for Shipping and Offshore Oil and Gas Activities

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ABSTRACT

Over the past decade there have been dramatic reductions in the areal extent of sea ice in late summer over the Arctic Ocean. For sub-regions in the western Beaufort Sea (off Alaska) and the deeper offshore waters of the Canadian sector of the Beaufort Sea, the trend towards reduced total ice concentrations in late summer ranges from -11.4 and -7.3% per decade, respectively, which is comparable to the reduction of -11.1% per decade in overall Arctic Ocean during late summer. In the central Canadian Arctic sub-regions through the Northwest Passage, the trends in total ice reduction are smaller at +1 to - 6 percent per decade. The trends computed for old ice can be quite different from that of total ice concentrations. In the western "chokepoint" area of the Northwest Passage (Viscount Melville Sound), the late summer trend is -6% per decade and +2.5% per decade for total and old ice, respectively. The trends in the long-term sea-ice thickness measurements in the Beaufort Sea over the continental shelf and in the eastern portions of the Canadian Arctic do not show major reductions unlike measurements from the deepwater Arctic Ocean.

KEY WORDS: Arctic Ocean, Northwest Passage, sea ice, meteorology, climate change, oil and gas exploration, shipping.

INTRODUCTION

Over the past decade there have been dramatic reductions in the areal extent of sea ice in late summer over the Arctic Ocean. These changes in the Arctic Ocean ice regime, and related changes in the atmospheric and oceanic climate, have received widespread attention in terms of the implications of these changes for shipping and oil and gas exploration activities which have increased dramatically over the last 5-10 years in the Canadian Arctic.

In this paper, we consider the sea ice and related conditions along the Northwest Passage of the Western Arctic Ocean (Figure 1). The Northwest Passage connects the Bering Strait entrance/exit to the Arctic in the west to Baffin Bay in the east. Potential chokepoints for shipping along the Passage include the entrance to the Arctic Ocean itself off Barrow Alaska and the interior portions of the Canadian Arctic Islands, most notably Viscount Melville Sound along the deeper northern branch, and M'Clintock Channel along the shallower southern branch.

In this paper, we will examine long-term trends in sea-ice conditions along the Northwest Passage. We will first examine the long-term trends in air temperatures, since air temperature influences sea-ice concentrations, and also it is important in its own right for determining operating conditions within the region. A similar analysis was performed for the Canadian Beaufort Sea (Fissel et al., 2009).

We will then examine the long-term trends in sea ice conditions. For engineering purposes, the ice types of importance are (a) old ice, which consists of second year and multi-year ice, which is of particular interest to marine industrial activities because of its unyielding hardness by comparison to first year ice; and (b) thicker and heavily deformed first year ice, in the form of very deep ice keels and hummocky ice (very long and wide ice floes with a high average thickness).

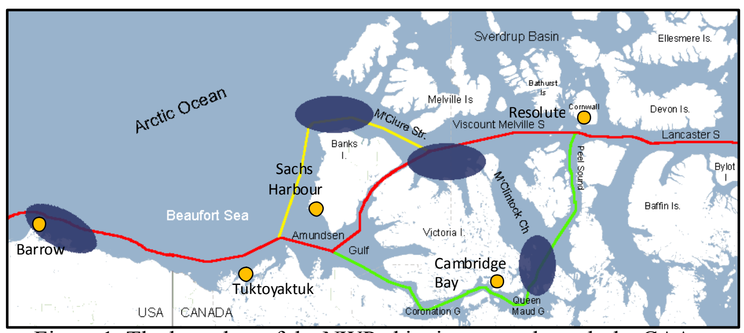

Figure 1: The branches of the NWP shipping route through the CAA: deep route in red, shallow in green, and the least travelled in yellow; navigation choke points (after Wilson *et al.,* 2004) are shown in blue; coastal weather stations in orange.

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).
- Ice thickness measurements made at various locations by the Science branch of the 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 and ENVI v4.8

METEOROLOGICAL CHANGES

Air Temperatures

The annual mean surface air temperature in the Arctic have increased by nearly 2°C from the 1960's to the 2000's and this increase continues into the first decade of the 21st century (Anisimov et al., 2007) at up to twice the global rate of temperature increase. In addition to the trend for increased temperatures, air temperatures also exhibit considerable amounts of interannual variability that arise from complex and numerous nonlinear interactions between and within the atmosphere, cryosphere, ocean, and land processes.

The best available knowledge developed from data analysis and modeling studies of the past and present coupled atmosphere-ocean-ice-terrestrial system for the Arctic region indicates that Arctic region air temperatures will continue to increase, on average, through the 21st century. The largest warming will occur in winter with smaller increases in summer, following the same pattern observed in recent decades. The predictions for the spatially averaged Arctic air temperature increases by 2080-2099, relative to 1980-1999, as computed from an ensemble of 21 climate models (Christensen et al., 2007) are 6.9 °C (minimum to maximum range of 4.3-11.4) in winter and 6.0 °C (2.9-8.9) in autumn versus smaller values for spring (4.4: 2.4-7.3) and summer (2.1: 1.2–5.3).

On a regional basis, the largest warming is projected to occur in winter over northern parts of Canada and Alaska in winter with increases of up to 10 °C over this 100 year period. Overall, it is expected that air temperature increases in the marine areas of the western Arctic along the Northwest Passage will continue to occur at similar seasonal rates to those experienced in the past 50 years (Table 1). The warming is largest in the fall and winter months and smaller in spring and summer.

Table 1: Monthly air temperatures trends from 1960 to 2010 at the five coastal locations shown in Fig.1: computed change in the long-term trend (TC, in °C, computed as 2001-2010 mean less 1960-1969 mean), statistical significance (* $p \leq 0.05$, ** $p \leq 0.01$), and decadal change (DC, in °C/10 years). Med = Median; FW = Fall-Winter; SS=Spring-Summer

	Barrow AK			Tuktoyaktuk			Sachs H.			Cambridge B.			Resolute B.		
Month	TC	p	DC	TC	p	DC	TC	p	DC	TC	p	DC	TC	p	DC
Jan	1.7		0.3	3.9	*	0.8	5.0	**	1.0	4.8	**	0.4	1.5		0.3
Feb	5.8	**	1.1	4.2	*	0.8	4.6	*	0.8	3.0		0.7	1.4		0.3
Mar	3.9	**	0.8	5.2	**	1.0	2.3		0.4	3.0	*	0.7	2.8	*	0.6
Apr	5.5	**	1.1	4.5	**	0.9	4.6	**	0.9	4.1	**	1.2	4.7	**	0.9
May	1.8	*	0.4	1.4		0.3	0.7		0.1	0.4		0.2	1.6		0.3
Jun	1.0	*	0.2	2.6	**	0.5	1.1		0.3	1.3		0.2	2.0	*	0.4
Jul	1.1		0.2	1.0		0.2	1.1		0.2	1.5		0.1	0.9		0.2
Aug	1.8		0.4	0.5		0.1	0.8		0.2	1.1		0.0	0.5		0.1
Sep	3.3	**	0.7	1.9	*	0.4	2.0		0.4	2.3	**	0.7	2.3	**	0.5
Oct	5.9	**	1.2	1.3		0.3	2.3		0.5	2.8		0.4	4.2	**	0.8
Nov	4.6	*	0.9	3.2		0.6	4.0	*	0.8	2.9	*	0.6	4.3	**	0.8
Dec	5.2	**	1.0	2.3		0.5	3.5	*	0.7	2.4		0.6	2.6		0.5
Med yr	***3.6***			***2.5***			***2.3***			***2.6***			***2.2***		
Med FW	5.2			3.9			4.0			3.0			2.8		
Med SS	1.8			1.4			1.1			1.3			1.6		

ICE CHANGES

Ice Concentrations by Ice Type

Arctic sea ice area extent, concentration and ice thickness have been widely studied through analysis of extended multi-decadal data sets and increasingly advanced coupled ice-ocean-atmosphere models.

The Arctic Ocean sea ice extent has been accurately monitored by satellite since 1979. The time series of ice extent for two months (March and September) that define the annual maximum and minimum ice extent are shown in Figure 2. The reductions in minimal Arctic Ocean ice extent since 2002 have been very large. For the past four years (2007 to 2010 inclusive), each year has been reduced by at least 25% below the 1979-2000 mean value up to the remarkable 41% reduction in the year 2007. Reductions in maximal ice extent in March have been smaller but still considerable at -2.7% per decade by comparison to the -11.6% reduction per decade in September.

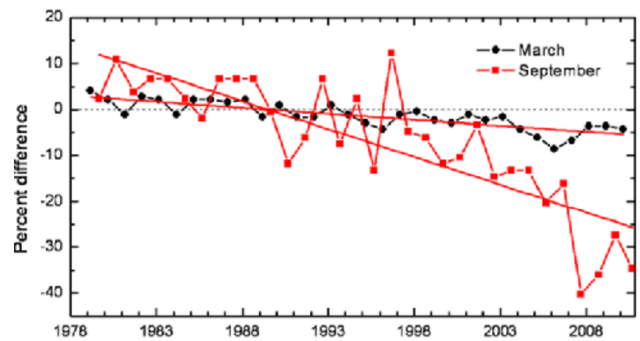

Figure 2: Time series of the percent difference in ice extent in March (the month of ice extent maximum) and September (the month of ice extent minimum) relative to the mean values for the period 1979–2000 (Perovich et al., 2010).

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 3. 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.

The decline in late summer ice extent over the past decade has greatly reduced the age of Arctic sea ice from that of previous decades, as seen in Figure 4 for March of 1988 and 2008. After the summer of 2007, the areal extent of old ice had collapsed to a much smaller area to the north of the Canadian Arctic Islands and in the central portions of the Beaufort Sea than was the case in the latter part of the previous century, when old ice of age 5 years or older covered most of the Arctic Ocean. By March of 2010, the area of old ice had recovered somewhat to a greater spatial extent reaching past the North Pole, but still limited to mostly 2 to 3 year old ice, except for a very narrow strip of 5 plus year old ice off the Canadian Arctic islands, which had contracted in offshore distance between 2008 and 2010.

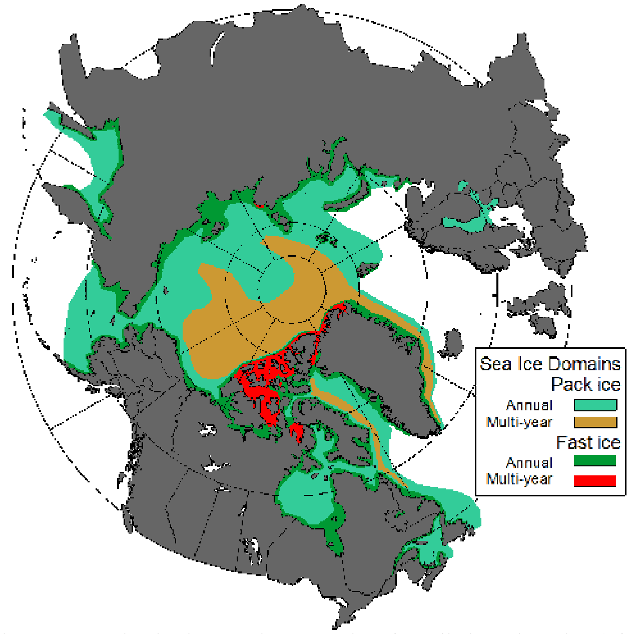

Figure 3: Sea ice in the Arctic Ocean has four distinct domains (after Melling, 2010) made up of two overall ice types (annual or first year ice and old or multi-year ice), and two states of mobility (moving pack ice or non-moving "fast" ice).

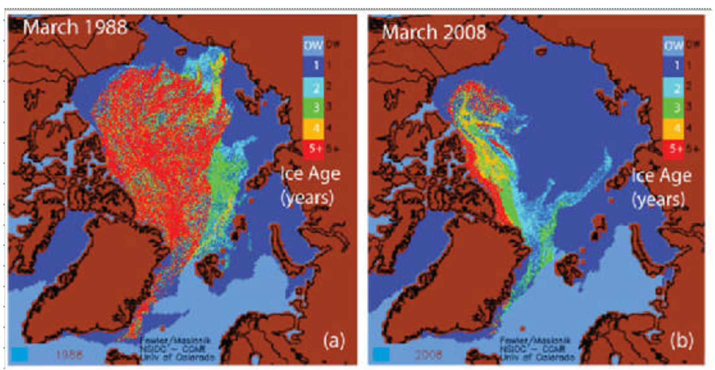

Figure 4: Sea ice age derived from drift tracking of ice floes for the first week of March in a) 1988, and b) 2008. The panels illustrate the substantial loss in the oldest ice types within the Arctic Basin in recent years compared to the late 1980s. (Fig. prepared by the National Snow and Ice Data Center, J. Maslanik and C. Fowler, in Perovich et al., 2010).

Within the Canadian Arctic area, the changes in sea ice concentration vary considerably from one subregion to another (Figure 5). The late summer total ice cover is reduced in all subregions, ranging from -11.3% per decade in the Alaskan Beaufort Sea and -6.9% in the deep waters of the Canada Basin (offshore portion of the Canadian Beaufort Sea) to -2.8% per decade over the Mackenzie Shelf region of the Beaufort Sea, -5.3% in Viscount Melville Sound and -3.7% in the Franklin Strait (from Larsen Sound to Victoria Strait). The reductions in the areal extent of old ice are very large in the Canada Basin subregion and the Alaskan Beaufort Sea, at -9.7 and -8.6% per decade, respectively, *versus* the smaller changes of -2.2%, +0.8% and -1.6% per decade in the Mackenzie Shelf, Viscount Melville Sound and Franklin-Victoria Strait subregions. The small increase in old ice area extent in Viscount Melville Sound, while not statistically significant, indicates a marked difference from the other subregions, especially those in the Beaufort Sea. This change may reflect the increased mobility of ice, for some years, in the areas of the Arctic Islands to the north of this portion of the Northwest Passage, allowing more Arctic Ocean old ice to enter the Passage that may, at times, increase ice hazards for shipping in this subregion (Fissel et al., 2010; Mudge et al., 2010; Howell et al., 2008; Melling, 2002).

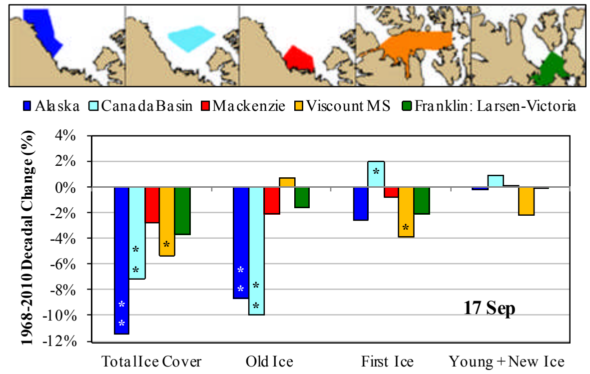

Figure 5: Trends in mid-September sea ice extent for various subregions of the Canadian Arctic, 1968 to 2010 (derived from Canadian Ice Service regional data). Statistical significance shown in the bars (* p≤0.05, ** p≤0.01).

The reductions in sea ice coverage occur earlier in the summer and early fall in the Point Barrow chokepoint subregion, to the west, as compared with the Franklin Strait and Viscount Melville Sound subregions in the Canadian Arctic Islands (Figure 6).

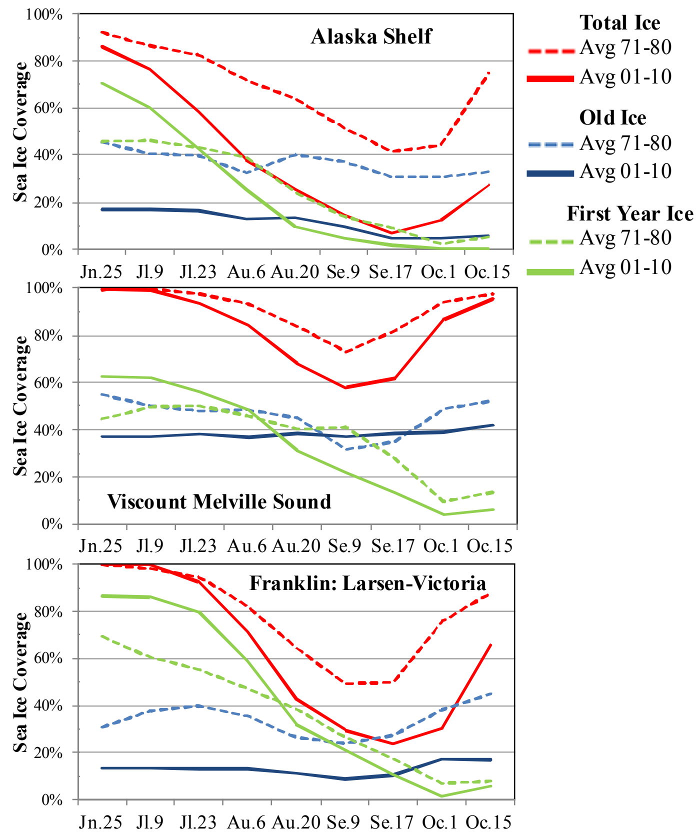

Figure 6. The changes in sea ice concentration from the 1970's to the 2000's, by ice type, for three chokepoint areas of the Northwest Passage.

Total area average ice concentrations (or sea ice coverage) of less than 0.7 (7-tenths) occurred in mid-July in the most recent decade, as compared to early August in the 1970's in the Alaska Shelf region from Pt. Barrow eastward. Over this three decade time span, the concentration of old ice has been reduced from concentrations of > 0.40 to < 0.20 in July. In Franklin Strait on the southern leg of the Northwest Passage, the large reductions in total ice concentrations occur about one month later, in the months of August and September; here, the concentration of old ice is also very large from 0.25-0.40 to 0.10-0.13 from the 1970's to the 2000's. In the Viscount Melville Sound, chokepoint on the northerly leg of the Northwest Passage, the reduction in the total ice concentrations also occur in August and September, with average total ice concentrations decreasing less than in other subregions, from 0.75-0.90 to 0.60-0.80. Moreover, the old ice concentrations remained relatively high in the 2000's (~ 0.40) from 0.3-0.5 in the 1970's. As a result, vessel transit through the Barrow Alaska and Franklin Strait subregions has improved more than for Viscount Melville Sound.

In most sub-regions, where changes in the ice trend are less than 10% per decade, the interannual variability in summer ice conditions is much greater than the long-term trend on a year-to-year basis (Figure 7). For example, in the decade of the 2000's, although the average ice concentrations are reduced from those of earlier decades, there are still years where the ice concentration occur at levels well above the decadal mean. As shown in Figure 7 for August 6, the comparison of the maximum total ice concentration relative to the decadal mean for 2001-2010 is 0.74 vs. 0.38 in the Alaskan Beaufort Sea; 0.90 vs. 0.71 in Franklin Strait; and 0.94 vs. 0.84 in Viscount Melville Sound.

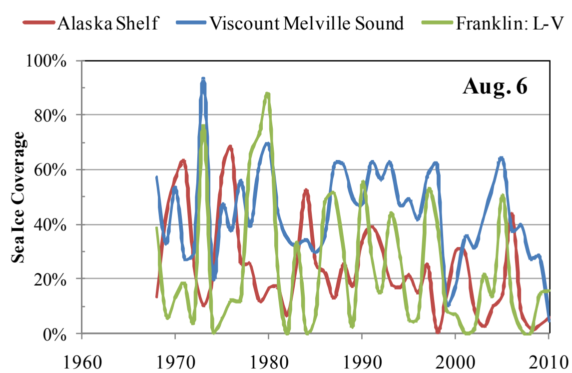

Figure 7. The year-to-year variations in total ice concentrations for Aug. 6 in three subregions: Alaska Shelf, Franklin Strait and Viscount Melville Sound, as derived from the Canadian Ice Service ice charts.

Future Ice Concentrations

Global and regional climate models have been developed and widely used to compute changing Arctic Ocean sea ice conditions in the 21st century. These models are in near universal agreement that Arctic sea ice extent will continue to decline through the present century (Stroeve et al., 2007). On average, the models, as run in the mid-2000s, forecast a 45% reduction in late summer sea ice extent by the year 2050 with reduced levels of sea ice persisting in late summer throughout the 21st century. However, a reduction of nearly this much was realized in the summer of 2007, as discussed above, and the actual sea ice conditions from 2007 to 2010 continue to be lower than the model forecasts leading to the possibility that the Arctic Ocean may be free of sea ice well within this century (Stroeve et al., 2007).

The most recent modeling studies, which are initiated with the actual 2007/2008 Arctic Ocean ice extents, indicate that a nearly ice free Arctic Ocean could be realized by approximately the year 2037, 30 years after the major reduction in summer sea extent experienced in the year 2007 (Wang and Overland, 2009). Another recent climate modeling study (Zhang et al., 2010) indicates that it is not likely that the Arctic Ocean will pass a threshold to become ice free in summer permanently before 2050 even though some individual summers may be ice free prior to that year; however, if Arctic surface air temperature increases 4°C by 2050 and climate variability is similar to the past relatively warm two decade, an summer ice free Arctic Ocean is possible by the mid-2040s or earlier. Because of enhanced winter ice growth, the models forecast that Arctic Ocean winter ice extent remains nearly stable and will continue to be present throughout the 21st century and beyond.

Ice Thickness

Ice thickness, another important sea ice property, has been measured in the Canadian Beaufort Sea for nearly 20 years (Melling et al., 2005) and in through repetitive measurements in the deeper Arctic Ocean from submarines (Rothrock et al., 1999; Wadhams, 2000). In distant offshore areas within the main Arctic Ocean pack ice, sea ice thickness is being reduced in association with the reduced age of the old ice, as discussed above. However, in shelf areas dominated by first year ice that can be highly deformed, the sea ice thickness has yet to exhibit any significant reductions at least through to 2008-2009 (Melling, 2010). As discussed below, for landfast ice, the decrease of first year ice thickness may decrease with increased air temperatures, due to the insulating effects of increased snow cover (Dumas et al., 2005). Thick deformed first year sea ice, in the form of very large ice keels to depths of 20 m or more, or as very highly concentrated ice hummocks or pressure ridges with horizontal scales of hundreds of meters, remains present as formidable potential ice hazards.

Landfast Ice Regime

Landfast ice is a special form of immobile sea ice that is not moving due to proximity to the shoreline and anchoring due to sporadic contact of the sea ice to the sea floor. Landfast formation and development processes in Arctic Canada and northern Alaska have been actively studied over the past two decades by government and university ice scientists. 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 resulted in 24 cm to 39 cm reduction in the mean maximum ice thickness, and a three-week shortening in the duration of landfast ice at coastal locations in the Canadian Beaufort Sea. The duration of the ice-road season would be similarly reduced, along with reducing the load limit on ice roads by roughly 30 tonnes, which could affect the use of these roads for gas exploration. Model results (Dumas et al., 2006) for coastal locations in the Canadian Arctic Islands, driven by projected changes in climate, predict a decrease of 30 and 50 cm in maximum ice thickness, and 1 and 2 months ice duration by the years 2041–60 and 2081–2100, respectively.

There is no obvious spatial pattern to the projected changes in either thickness or duration. The changes in freeze-up dates vary more regionally, ranging from 4-29 days (by 2041-60) with the smallest changes occurring in the western Arctic Islands (Mould Bay and Cambridge Bay) and the largest changes being in the eastern parts of the Arctic Islands (Dumas et al., 2006). The advance in break-up dates is very consistent ranging from 17-21 days. Overall, Arctic oil and gas activities will need to adapt to shorter ice road seasons, yet longer ship-based access time to coastal landing sites, on average, over the next 50 years and beyond. Continuing use of the landfast ice models will be useful for this climate change adaptation.

Glacial ice

Glacial ice can result in large ice islands from tidewater glacier and ice sheets originating in the northern Canadian Arctic Islands, in particular Ellesmere and Axel Heiberg islands, where the large floating ice pieces enter the Arctic Ocean and generally travel westward under the prevailing Beaufort Gyre drift pattern of the western Arctic Ocean. Large glacial ice features of the Greenland glaciers that enter the Arctic Ocean tend to be carried away to the east by the Trans-Polar Drift current. The floating glacial ice entering Baffin Bay is usually in the form of icebergs rather than ice islands. All of the ice sheets in the Canadian Arctic islands have been thinning and receding slowly for at least the last 50 to 60 years (Abdalati et al., 2004). The episodic generation of mobile ice shelf features in the ocean, accompanied by major losses of ice sheets on land and its coastal regions, attract considerable attention due to the ease of monitoring these events with satellite technology, as was seen with the loss of the Ayres ice shelf in 2005 (Copland et al., 2007), and the more recent major losses of ice from the Ward Hunt, Serson and Markham ice shelves in the summer of 2008 (NASA, 2008). By 2010, there has been a greater than 90% decline in the area of ice shelves along northern Ellesmere Island (Copland and Mueller, 2010).

Given their long-term nature over many past decades, such episodes of ice shelves being launched as ice islands may continue, although given the much diminished area off the Northern Canadian Arctic Islands, this process may decrease over the next few decades. The creation of large ice island is routinely monitored and detected by government agencies (e.g. Environment Canada – Canadian Ice Service and the United States' NASA). Large ice islands are marked with satellite tracked beacons to ensure that their location is known as they travel westward in the Beaufort Sea, as was the case with the 2008 ice islands in the Arctic Ocean, and the ice island and iceberg fragments launched in 2010 from the Petermann glacier in Greenland.

The effect of the mobile ice islands on Arctic shipping and industrial activities has seldom been a major issue, because it occurs very infrequently, and the ice islands travel westward at high latitudes well to the north of the major shipping lanes. Occurrences can be managed through modern satellite and ice-beacon monitoring, which are built into offshore operational planning and ice management systems, as well as ship avoidance. For fixed platforms, encounters with ice islands, while very rare, are more difficult to manage through mitigation. In the Eastern Arctic, where icebergs are more prevalent, ship navigators must be vigilant to ensure that icebergs are detected, particularly at times of reduced visibility or when icebergs are located within high concentrations of sea ice.

CONCLUSIONS

In this paper, we have examined trends in summer meteorological and sea-ice conditions on the continental shelf and slope regions of the Canadian Beaufort Sea. The trend analysis was conducted using data collected over the past 30-50 years for selected measurement quantities. The interannual variability for many of these quantities is very large, which leads to uncertainties in the statistical significance on the derived trend results. Air temperatures have clearly risen by 2-4 °C over the past 40 years, according to the measurement location and month of the year. Computed trends in sea-ice concentrations vary considerably with location. Landfast ice durations and thickness are reduced in association with increasing air temperatures and snow cover. In the offshore areas, the regional winds are a major determinant in advection of sea ice, especially from the main Arctic pack ice to the north. Sea-ice concentrations have exhibited enormous variability over the past 40 years in which systematic observations have been compiled in the form of sea ice charts. A trend toward reduced sea-ice concentrations is evident in the summer months, but for most locations and times of the year, the trend is small at -2 to -4 % per decade. Larger trends (- 6 to - 11 %) of reduced ice cover were computed in late summer ice concentrations in the Alaskan Beaufort Sea and the Canada Basin. This is much smaller than the trend towards reduced sea ice in the entire Arctic Ocean of -11% in late summer. In the last decade, there has been a noticeable reduction in the concentration of old ice.

The effect of the general reduction in sea-ice extent, and especially of reduced levels of old sea ice, on commercial shipping and offshore oil and gas activities, will result in generally longer operating seasons, especially in deeper waters. Similarly, ship support operations, including transits through the Northwest Passage, will also benefit from a longer operating season, although the reduction in old ice may not be realized in the Viscount Melville Sound and adjoining areas of the Northwest Passage for some years well into the future due to greater mobility of the old ice into the Passage. Sea-ice forecast modeling to support the extended period of marine operations, along with Canadian expertise in ice engineering, will serve the adaptation of commercial shipping and Arctic oil and gas activities to the changing ice regime. The reduction of the duration of sea-ice coverage in the Canadian Arctic areas will have effects on other ocean environmental parameters, in particular in the form of larger ocean waves and storm surges, and enhanced levels of coastal erosion in the western Canadian Arctic.

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