The Changing Met-Ocean and Ice Conditions in the Beaufort Sea: Implications for Offshore Oil and Gas

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ABSTRACT

In recent years, changes in the Arctic Ocean weather and ice regime have received widespread attention in terms of the possible link to Green House Gas (GHG) induced effects on the polar climate, and the implications of these changes on Arctic regional and oceanographic conditions. In this paper, we examine 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 statistical uncertainties in the statistical significance on the derived trend results. Air temperatures have clearly risen by 2-4 °C according to the measurement location and month of the year. The trends in the monthly surface winds are relatively small in relation to the large degree of interannual variability. Computed trends in sea ice concentrations vary considerably with location. The trends in the fast ice concentrations (early summer and fall) are larger than those in the outer shelf and slope regions. In the latter areas, the regional winds are a major determinant in advection of sea ice, especially from the main Arctic pack ice to the north. The implications of the long-term trends on the regional oceanography are discussed.

KEY WORDS: Metocean; sea ice; meteorology; Beaufort Sea; Arctic Ocean; climate change; oceanography.

INTRODUCTION

In recent years, changes in the Arctic Ocean weather and ice regime have received much attention in the scientific literature as well as the popular press. There is widespread, and in some cases dramatic, evidence of overall warming of the full Arctic system (Richter-Menge *et al.*, 2008) occurring in this first decade of the twenty-first century. In this paper, we examine the changes and trends observed over the past several years for meteorological and sea-ice conditions on the continental shelf and slope regions of the Canadian Beaufort Sea and compare the changes in this region 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 activities at present and over the next decade, based on our present understandings and uncertainties in the metocean and ice conditions of this region.

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
- 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, ocean current and ocean wave 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 Matlab software libraries.

METEOROLOGY

Air Temperatures

Over the full Arctic (60° to 90° N), annual surface air temperatures had increased by 2 °C by 2007, the warmest year on record, from the 1961-1990 mean value (Richter-Menge *et al.*, 2008). An even more dramatic increase occurred in the autumn (Oct. – Nov.) air temperatures, with 2005-2007 warming of temperatures of up to 6 °C (Overland *et al.*, 2008) as shown in Figure 1. The largest amount of warming occurred in the central portions of the Beaufort and Chukchi Seas, where record levels of clearing of sea ice occurred allowing extra heat to be absorbed by the ocean from solar radiation. Freeze-up occurred later than usual in these years.

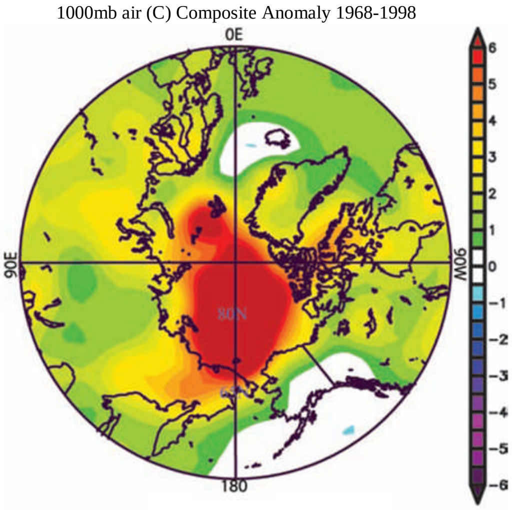

Figure 1. October-November near surface air temperature anomalies averaged for 2005-2007 (from Richter-Menger *et al.*, 2008).

In the Canadian Beaufort Sea, the Environment Canada's Pelly Island weather station, located on a small island in the inshore portion of the Mackenzie Shelf (Figure 2), provides the best long-term measurements of the marine air temperatures over the duration of its operation from 1994 to the present. The average air temperatures at Pelly Island are below 0 ºC for most of the year from October through to May, inclusive. In December, January, February and March, the maximum air temperatures are never above zero and the minimum observed air temperatures plunge to values around – 40 ºC. In July, air temperatures attain their seasonal maximum values with average temperatures near 10 ºC and maximum values as high as 29 ºC.

A second Environment Canada weather station has been operated for nearly 60 years at Tukoyaktuk, located on the Beaufort Sea coastline (Figure 2). The air temperatures at this station in October-November 2005-2007 were not at record high levels as seen in the central part of the Arctic Ocean (Figure 3).

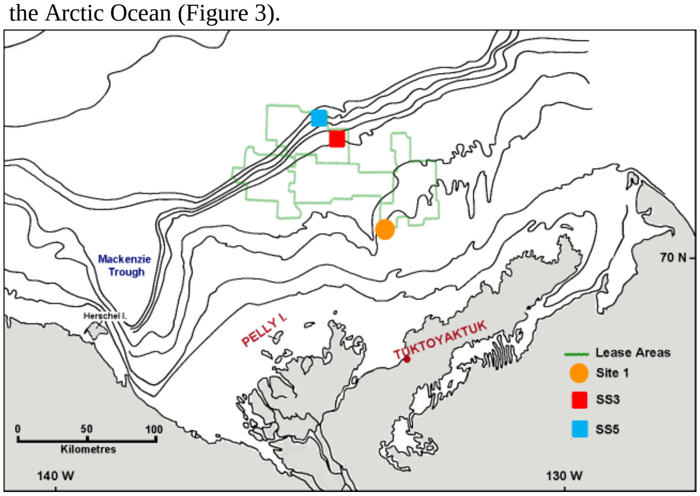

Figure 2. A map of the Canadian Beaufort Sea showing the locations of weather stations at Pelly Island and Tuktoyaktuk, current meter measurement sites and oil and gas exploration license areas.

However, an analysis of air temperature trends at this station, as given in Table 1, does indicate an average increase in air temperatures of 1.8 °C for the last decade (1998-2007) relative to the decade of forty years earlier (1958 to 1968). On a monthly basis, increases exceeding 2.0 °C occurred in January, February, April, June, November and December. A linear trend analysis of the average monthly temperatures for March-April and for October-November (Figure 3) from 1958 to 2007 indicates a net increase of 2.7 °C for the spring and 1.7 °C for the two autumn months, with the spring trend being statistically significant and the autumn trend not at a statistically significant level

Overall, air temperatures in the Canadian Beaufort Sea are increasing over time scales of decades for nearly monthly parameters, but not at the extraordinary levels reported for the years 2005-2007 over the full Arctic Ocean (Figure 1).

Table 1.Air temperature trends at Tuktoyaktuk, NWT, calculated as the difference of the averaged temperature of the first (1958-1968) and the last 10 years (1998-2007) of the record (Environ. Canada)

		Min	Diff	Max	Diff	Mean	Diff
January	*Avg58-68*	-41.32	3.01	-12.07	3.6	-28.89	2.65
	Avg98-08	-38.31		-8.47		-26.24	
February	*Avg58-68*	-41.37	2.69	-12.99	0.43	-29.13	2.95
	Avg98-08	-38.68		-12.56		-26.18	
March	*Avg58-68*	-37.43	-0.21	-9.96	-0.45	-25.95	0.65
	Avg98-08	-37.64		-10.41		-25.3	
April	*Avg58-68*	-32.32	3.29	0.13	0.24	-17.42	3.29
	Avg98-08	-29.03		0.36		-14.13	
May	*Avg58-68*	-18.88	1.75	11.2	0.19	-4.56	1.1
	Avg98-08	-17.14		11.39	0	-3.46	
June	*Avg58-68*	-3.74	1.51	18.16	4.94	4.51	2.26
	Avg98-08	-2.23		23.1		6.77	
July	*Avg58-68*	1.93	0.23	23.68	1.9	10.26	0.92
	Avg98-08	2.15		25.58		11.18	
August	*Avg58-68*	1.05	0.37	22.02	-0.88	8.64	0.28
	Avg98-08	1.43		21.14		8.92	
September	*Avg58-68*	-4.17	0.96	11.47	3.73	2.16	1.73
	Avg98-08	-3.21		15.2		3.88	
October	*Avg58-68*	-20.81	2.9	2.14	0.41	-7.45	1.39
	Avg98-08	-17.91		2.55		-6.07	
November	*Avg58-68*	-33.38	3.41	-5.85	0.38	-20.26	2.33
	Avg98-08	-29.97		-5.47		-17.93	
December	*Avg58-68*	-36.21	2.29	-10.35	1.56	-24.49	2.21
	Avg98-08	-33.92		-8.79		-22.28	

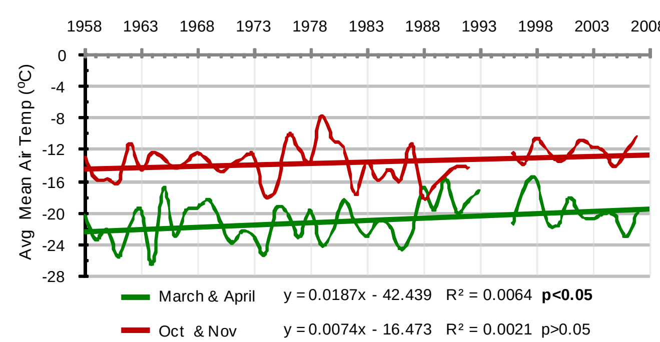

Figure 3. Air temperature (ºC) trends at Tuktoyaktuk NWT calculated as the average of the mean air temperature for March-April, and October-November.

Winds

Winds are very important as a metocean parameter in their own right and also as a major forcing mechanism for ice drift and ocean currents.

Previous studies of storm frequencies in the Canadian Beaufort Sea (Hudak and Young, 2002; Manson and Solomon, 2007) revealed little or no trend for the years 1973-1995 and 1959-2000, respectively. Hudak and Young (2002) identified October as the month with the highest storm frequency, and showed that most storms were of Arctic origin (58%) with a considerable number of Pacific storms (27%) as well. Pacific storms seemed to be less frequent in the 1990's.

A linear trend analysis of the past 50 years of monthly wind speeds at Tuktoyaktuk reveal an overall reduction (Figure 4) for both the March-April and the October-November periods amounting to net change of –1.1 and – 1.2 m/s. Both trends are statistically significant.

The wind measurements available for Pelly Island, while shorter in duration, are considered to be more representative of Beaufort Sea marine winds given their higher speeds and greater variability (Manson and Salomon, 2007). Summary statistics of Pelly Island winds for each month of the year are presented in Table 2, while the Joint Frequency Table of wind speed and direction for September is given in Table 3. There are two clearly dominant directions for winds at Pelly Island: winds blowing from the east to east-southeasterly (ESE) directions and winds blowing from the west to northwest directions. The ESE winds occur most frequently accounting for typically 30% of all observations. For these wind directions, typical wind speeds are 4-6 m/s although peak monthly wind speeds exceed 14 m/s and can reach values of nearly 20 m/s in some months. While larger in magnitude, the west-northwest winds (WNW) occur somewhat less frequently than the ESE winds, typically accounting for 20-25% of all observations in most months. However, the WNW winds represent the largest wind speeds for all months with typical wind speeds of 6-8 m/s, and peak wind speeds of up to 26 m/s.

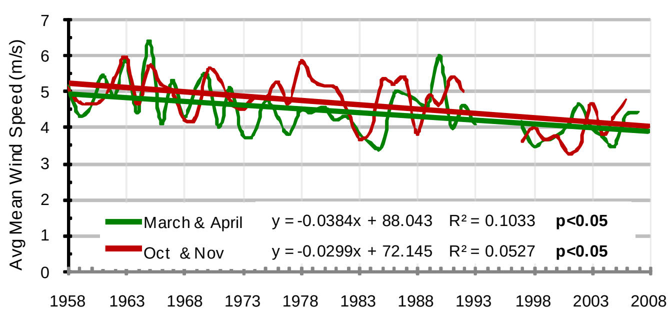

Figure 4. Wind speed (m/s) trends at Tuktoyaktuk NWT calculated as the average of the mean wind speed for March-April, and October-November.

Easterly winds are associated with more favourable sea ice conditions on the Mackenzie shelf and slope areas of the Beaufort Sea because of the tendency of ice drift to move at about 2% of the wind speed at a direction of 20 to 30 ° to the right of the direction that the wind is blowing towards (Nansen, 1902). Conversely, westerly-northwesterly winds are associated with incursions of pack ice onto the shelf and slope areas. The colours used in Table 3 indicate the wind speeds and directions associated with favourable (orange) and unfavourable (blue) ice conditions.

Table 2.Summary of Pelly Island wind statistics (1994-2008).

Month	Dominant		Vector Average		Mean	Max	
	Speed (m/s)	Direction	Speed (m/s)	Direction (deg)	Speed (m/s)	Speed (m/s)	Direction (deg)
January	4-6	ESE E	1.1	180.3	5.6	26.4	290
February	4-6	ESE E	1.0	158.1	6.5	24.7	270
March	4-6	E W	0.3	35.7	5.6	22.2	300
April	4-6	E	1.1	80.7	5.6	18.1	320
May	4-6	E	2.5	64.6	5.6	18.6	280
June	4-6	E	2.2	62.4	5.4	16.9	290
July	4-6 6-8	E	1.9	37.6	6.0	19.4	250
August	4-6 6-8	E	0.9	5.5	6.3	24.2	230
September	6-8 4-6	E	1.4	75.6	6.7	21.1	310
October	4-6 6-8	E E-S-E	1.4	88.0	6.7	19.2	120
November	4-6	E-S-E	0.7	131.4	6.6	20.6	300
December	4-6	E-S-E E	0.3	28.8	6.3	25.3	300

Table 3. Joint Frequency Table of Wind Speed and Direction – Pelly Island. September 1994-2008. Total number of samples = 9786.

Wind Direction	Wind Speed (m/s)														Total Occur. (%)
	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26	26-28	
N	0.62	1.20	1.35	0.82	0.51	0.12	0.15	0.01							4.78
NNE	0.43	0.62	1.14	0.66	0.37	0.15	0.11								3.48
NE	0.65	1.04	1.32	0.98	0.92	0.35	0.02								5.28
ENE	0.37	0.97	2.01	2.08	1.11	0.42	0.06	0.02							7.04
E	0.92	1.86	3.92	5.58	4.86	1.88	0.40	0.17	0.01						19.60
ESE	0.44	1.08	2.36	3.09	2.34	1.06	0.17	0.01							10.55
SE	0.27	0.61	1.91	2.29	1.43	0.66	0.14	0.01							7.32
SSE	0.24	0.31	1.25	1.53	0.63	0.14	0.05								4.15
S	0.37	0.38	1.57	1.93	0.84	0.17	0.13								5.39
SSW	0.06	0.21	0.47	0.55	0.18	0.01									1.48
SW	0.30	0.39	0.69	0.47	0.32	0.17	0.07								2.41
WSW	0.28	0.41	0.79	0.71	0.32	0.12	0.06								2.69
W	0.21	0.65	1.42	1.45	0.98	0.40	0.24	0.16	0.10	0.05					5.66
WNW	0.37	0.59	1.09	1.74	1.39	1.38	0.56	0.20	0.15	0.16					7.63
NW	0.38	0.49	1.23	1.47	1.37	1.53	0.47	0.15	0.07	0.02	0.01				7.19
NNW	0.39	0.80	1.39	1.11	0.97	0.35	0.12	0.05	0.06	0.02					5.26
Total Occur. (%)	6.30	11.61	23.91	26.46	18.54	8.91	2.75	0.78	0.39	0.25	0.01	0.00	0.00	0.00	100.00

white	Ice movement is small or along shore, or no data.
light blue	Favourable Winds - Ice moving **offshore** at moderate speeds
darker blue	Best Winds – Ice drifting **offshore** at high speeds
light orange	Unfavourable Winds - Ice drifting **onshore** at moderate speeds
darker orange	Worst Winds – Ice drifting **onshore** at high speeds

SEA ICE

The major ice features of the Beaufort Sea (Figure 5) 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 pack ice.

Landfast Ice Regime

The landfast ice zone forms in the late fall and grows in place until early summer. This 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.

As shown previously, air temperatures are exhibiting significant increases especially in later winter and spring which will tend to reduce the thickness and the duration of landfast ice cover. Flato and Brown (1996) have shown that landfast ice cover is very sensitive to snow cover as well as air temperature. An increase of 4 °C in air temperature and an increase of 20-100% in snow thickness will result in a decrease of landfast ice thickness of 24 to 40 cm, or equivalently, a decrease in the duration of landfast ice of three weeks (Dumas *et al.*, 2005). Such changes (warmer air temperatures are usually associated with increased snowfall) will impact on winter and spring operations for oil and gas exploration in shallow inshore water areas.

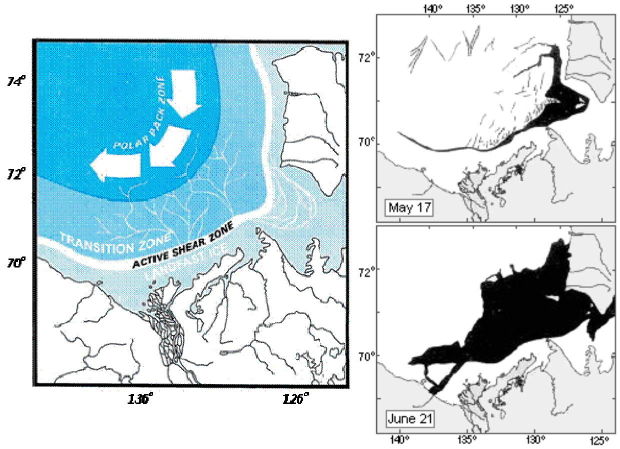

Figure 5. The ice regimes of the Beaufort Sea in winter and spring (left panel), and the typical break-up and dispersal patterns of sea ice in May and June. The inshore landfast ice usually disperses by late June or early July.

Ice Concentrations and Area

Over the full Arctic Ocean, a dramatic reduction in the amount of summer sea ice cover has occurred in recent years. Since the 1970's, the reduction in late summer Arctic ocean sea ice cover has been occurring at an average rate of -11.1% per decade (Richter-Menge *et al.*, 2008). Since 2005 the reductions of sea ice have been occurring at a larger rate. Late summer sea ice coverage reached a record low in 2007, being reduced by 25% from the previous observed minimal extent over the past 30 years (Stroeve *et al.*, 2008). In 2008, the late summer sea ice coverage over the Arctic Ocean was the second lowest year on record.

For areas in deepwater over the middle and outer continental, and more recently over the continental slope, offshore oil and gas activities occur during the summer and early fall months. The seasonal pattern of ice clearing (Figure 6) occurs starting in June on the Mackenzie Shelf of the Canadian Beaufort Sea, followed by partial clearing of sea ice in the Alaskan Beaufort Sea, typically in July. Clearing of the sea ice of the Alaskan Beaufort Sea is very important, as the entry of most commercial shipping in the Canadian Beaufort Sea depends on favourable ice conditions off Point Barrow Alaska and the route eastward into the Canadian Beaufort Sea. Minimum sea-ice concentration in both areas occur in mid-September, as they do over the deeper waters of the Canada Basin, although here the degree of ice clearing is much smaller than that of the shelf areas in most years.

In 2008, the pattern of ice clearing in the Canadian Beaufort Sea occurred considerably earlier and to much larger extent in the Alaskan Beaufort Sea, the Mackenzie Shelf and the Canada Basin (Figure 6).

However, a full understanding of the Beaufort Sea ice regime requires consideration of the very large interannual variability of ice conditions with the region. In the Seasonal Sea Ice Zone (SSIZ) along the shelf edge and continental slope of the Beaufort Sea, the degree of interannual variability by month is shown in Figure 7. While the ice concentrations are at or near 100% in June, the degree of interannual variability increases in the months of July, August, and September, as the ice clearing becomes larger.

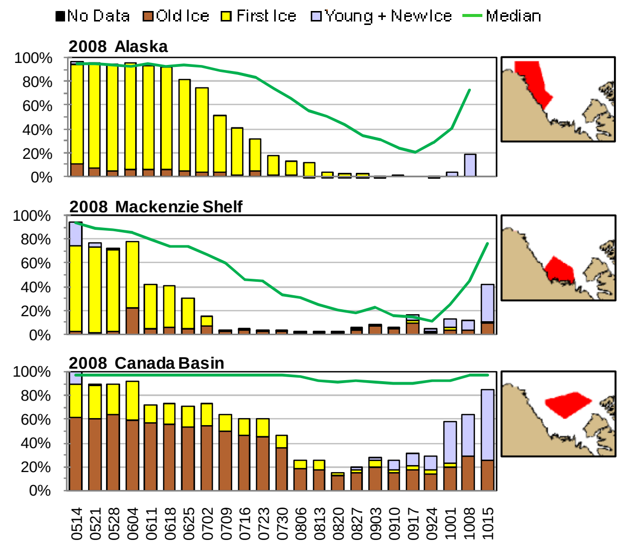

Figure 6. Weekly ice coverage by type for May 14 to October 15 2008 in the Alaska coast, Mackenzie Shelf, and Canada Basin, and 1968-2008 median (data from Canadian Ice Service).

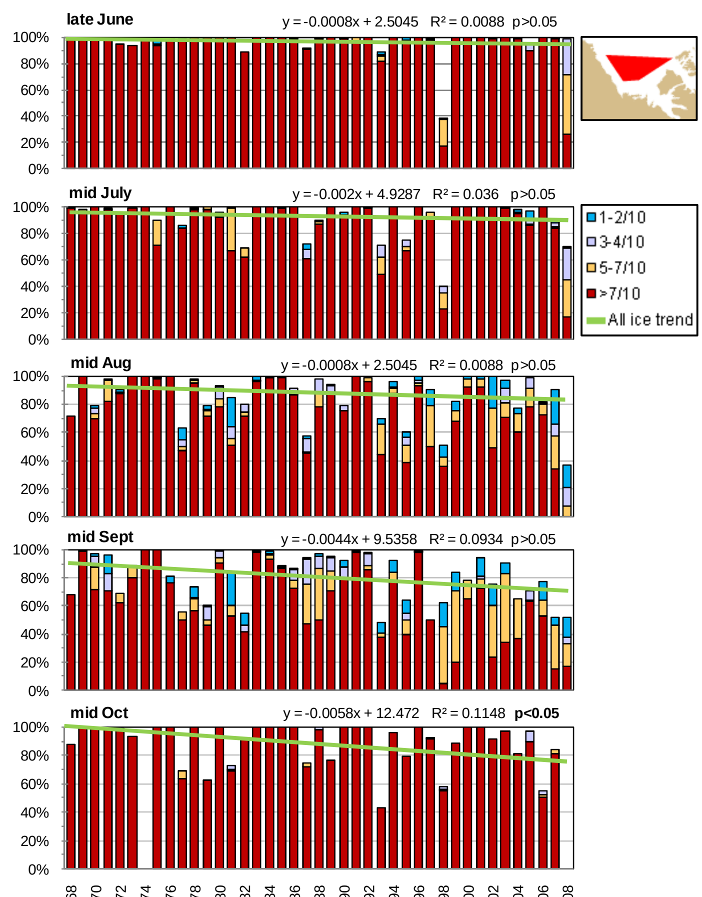

Figure 7. Historical ice coverage (1968-2008) by ice concentration at the shelf edge of the Canadian Beaufort Sea. 1974 charts not available after October 4 (data from Canadian Ice Service).

In mid-August and mid-September, ice concentrations exhibit considerable variability from year-to-year by a factor of 2 or 3. A quasi-periodic variability of a few to several years is evident with relatively high ice concentrations in the mid-1970's, early 1980's, early 1990's, and early 2000's. The magnitude of the interannual variations is much larger than any trend towards lower sea-ice concentrations over the nearly fifty years of observations. In late summer, there is a marginally significant trend of -6% per decade toward reduced ice concentration. Also it is noteworthy that the lowest ice concentration for mid-August occurred in the year 2008 and the second and third lowest ice concentrations for mid-September occurred in 2008 and 2007.

The year-to-year variations for mid-July and mid-September in the Alaskan Beaufort Sea, Mackenzie Shelf and the Canada Basin (Figure 8) are also very large, particularly on the Mackenzie Shelf. As with the SSIZ results, the year to year variability is generally much larger than the computed trend in sea-ice concentration, typically amounting to about -2% to -3% per decade. There are two notable exceptions with much greater trends, of – 11% and -7% per decade for the mid-September ice concentrations in the Alaskan Beaufort Sea and the Canada Basin.

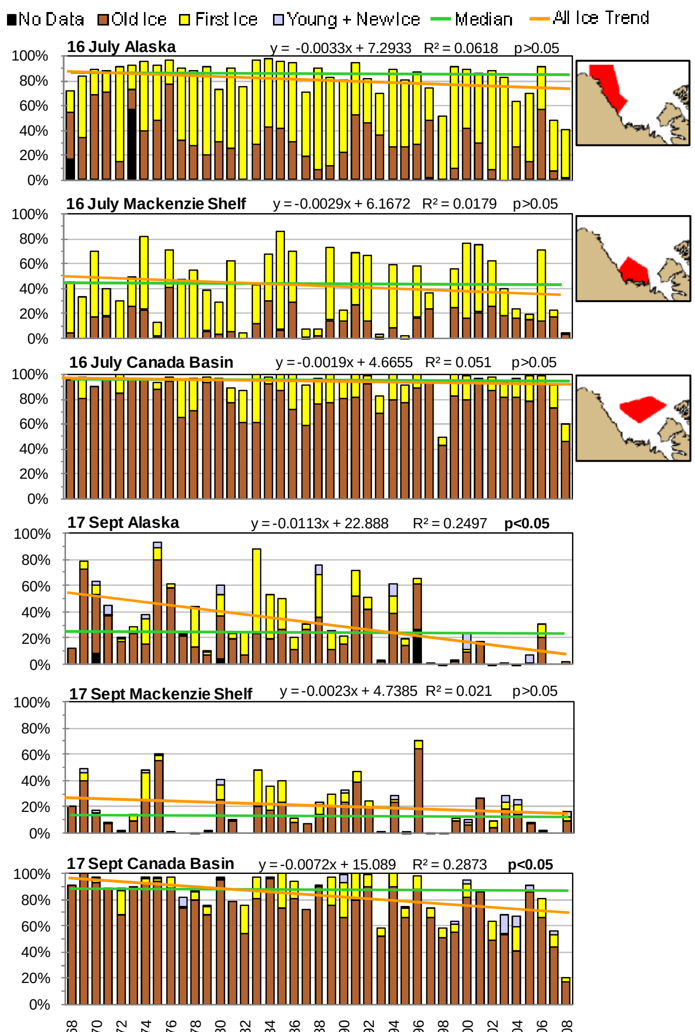

Figure 8. Historical ice coverage by type for 16 July and 17 September 1968-2008 in the Alaska coast, Mackenzie Shelf, and Canada Basin (data from Canadian Ice Service).

Again the very low concentrations of sea-ice in 2007 and 2008 are noteworthy, especially at the time of maximum sea-ice clearing in mid-September. In the summer of 2007, easterly winds were highly prevalent, with only three westerly wind events occurring.

Old Ice

For shipping operations, including those associated with station keeping during drillship operations, occasional incursions of sea ice under the influence of westerly winds, especially in a less favourable ice year, are likely to occur. The presence of old ice, i.e. sea-ice which has survived one or more summers, 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, and also on the Mackenzie Shelf, old ice is the predominant ice type in mid- and late-summer (Figure 8).

In the past few years, considerably less old ice is being reported on the ice charts for the Mackenzie Shelf and Alaskan Beaufort Sea than in previous decades. In the spring to early autumn of 2008, a very large reduction in old ice from normal values was evident in all three major areas of the Beaufort Sea (Figures 7 and 8), with perhaps the most dramatic reduction being the record low amount of old ice in the Canada Basin by mid-September. This marked reduction of old ice may reflect the record low ice concentrations of ice within the Arctic Ocean in the summer of 2007 and therefore a reduction in the amount of old ice in subsequent years.

Ice in Shipping Corridors

As previously discussed, the entry of vessels into the Beaufort Sea is determined by the ice conditions off the western Alaskan Beaufort Sea, in the vicinity of Point Barrow, Alaska. An index derived from sea ice conditions has been developed for the opening and closing dates of shipping from Pt. Barrow to Prudhoe Bay off the western portion of the Alaskan Beaufort Sea (Drobot *et al.*, 2008). As shown in Figure 9, this index has exhibited a very large degree of interannual variability over the past 40 years.

Along with the large degree of variation from year-to-year, there is a tendency towards earlier openings and late closings of the shipping route, although the year to year variations remain considerably larger than the exhibited trend.

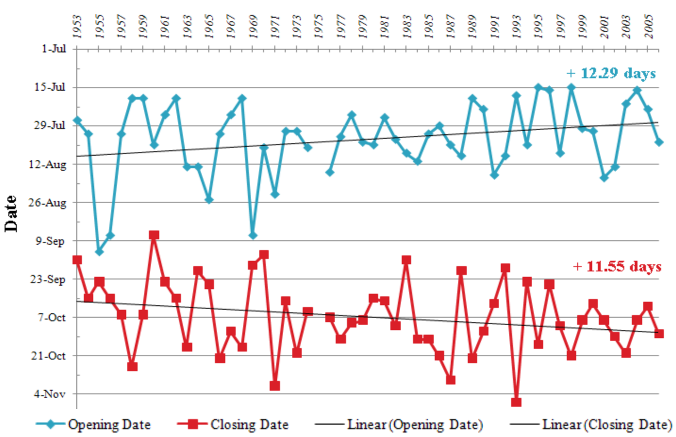

Figure 9: Barrow-Prudhoe Bay Shipping Opening and Closing Dates - Observed Trends 1953-2006 (after Arbetter, 2008).

Ice Thickness

Ice thickness measurements in the Canadian Beaufort Sea are very sporadic in coverage. However, long-term measurements of ice drafts using upward looking sonar devices operated from the sea floor on the Mackenzie Shelf indicate that the year-to-year variability is very large, and much greater than a small and statistically insignificant downward trend (Figure 10).

The large variations in ice drafts may reflect the highly dynamic and variable processes that result in the deformation of sea ice in the Beaufort Sea and adjoining regions, especially the highly concentrated ice conditions off the Canadian Arctic Archipelago to the east of the Beaufort Sea. Under large winds and strong currents acting on ice in the shear zone, first-year sea ice can undergo massive amounts of deformation. Maximum ice drafts of up to 28 m have been measured at the long-term measurements sites on the Mackenzie Shelf.

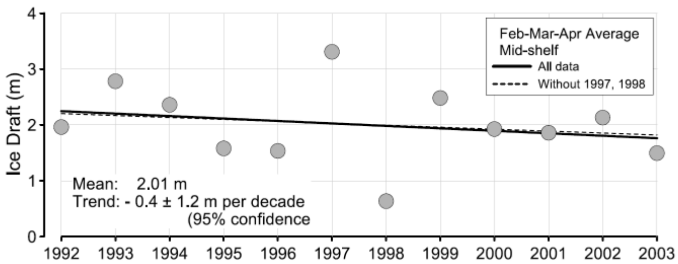

Figure 10. Measured average winter ice draft on the Mackenzie Shelf from 1992 to 2003 (Melling and Reidel, 2005).

OCEANOGRAPHY

Circulation

Based on the limited duration ocean current data sets of just 1.5 years at the locations shown in Figure 1, the maximum current speeds at these sites on outer-continental shelf and the continental slope are determined to be 46 cm/s. During the period of extensive ice clearing in the area from late June to October, the local winds will generate additional currents at the near-surface levels. Based on simple computations for the wind-driven currents at and near the surface, it is estimated that the surface currents could be as much 1.45 times greater than those measured at 35 m depth at site SS-3 for a maximum surface-current speed of 60.3 cm/s.

For currents in the shallow waters of the mid- and inner-shelf, the 5-year long data set at Site 1 (16 m measurement depth in 50 m total water depth) yield a maximum measured current speed of 43.8 cm/s. Stronger currents will be present at the surface during periods of open water clearing. Simple modeling of the wind-driven currents as a function of depth based on Ekman layer dynamics indicates that the surface current speeds could be 1.2 to 1.3 greater than those measured at 16 m depth for an estimated maximum 5-year surface current speed of 55 cm/s. Reviews of historical ocean current data sets in the Beaufort Sea (e.g. Fissel and Birch, 1984; Hill *et al.*, 1991) suggest that the surface currents in the waters that are shallower and inshore of the Site 1 can be larger with observed speeds of up to 75 cm/s. The effect of the Mackenzie River plume becomes increasingly important in these shallow inshore waters.

Table 4. Compilation of near-surface currents (35-50 m depths) on the outer shelf and slope areas of the Canadian Beaufort Sea

	Dominant		Vector Average		Mean	Max	
Month	Speed (cm/s)	Direction	Speed (cm/s)	Direction (deg)	Speed (cm/s)	Speed (cm/s)	Direction (deg)
Site 1	2000-2005						
Jan-Dec	*3-6*	*SW*	*2.3*	*191.5*	*7.9*	*43.8*	*37*
March	3-6	SW	1.8	230.7	4.8	36.5	262
July	6-9	SE	2.0	133.6	8.7	43.8	37
August	6-9	E	4.0	94.4	9.5	34.6	109
September	6-9	E	3.8	118.5	9.8	34.2	92
October	6-9	SSW	2.7	160.9	10.1	37.8	41
SS3	1987-1988						
Jan-Dec	*6-9*	*W*	*3.9*	*206.6*	*10.4*	*41.6*	*73*
March	6-9	W	3.5	250.0	6.9	15.1	207
July	9-12	W	7.5	268.1	13.0	29.5	263
August	6-9	ENE	13.3	66.4	14.1	41.6	73
September	12-15	E	5.8	81.4	15.6	40.7	71
October	6-9	WSW	5.8	274.2	17.5	40.5	257
SS5	1991-1992						
Jan-Dec	*6-9*	*ESE*	*1.9*	*97.7*	*9.1*	*46.0*	*73*
March	6-9	WNW	1.7	248.3	7.0	19.6	134
July	6-9	SE	3.6	149.0	10.4	31.5	37
August	3-6	ENE	9.5	63.7	12.9	46.0	73
September	9-12	NE	5.8	51.4	10.7	36.1	26
October	18-21	W	2.7	273.2	15.0	29.2	272

Waves

All data presented in this section are based on the Meteorological Service of Canada Beaufort (MSCB) project's multi-decade hindcast model, a collaboration between Environment Canada and Oceanweather Inc. (Swail *et al.* 2007). The hindcast was run from Jan 1, 1985 to Dec 31, 2005. It nested a 28 km coarse-resolution Oceanweather 3rd generation wave model that covered all the ocean waters of the Arctic with a 5-km fine-resolution model of the Canadian Beaufort (Figure 11). The MSCB model results can be used for both operational and extreme metocean statistics.

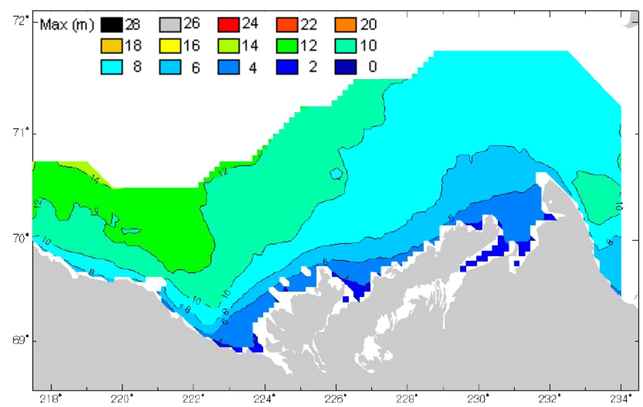

Figure 11. MSC50 Hindcast: combined 25-year (1985-2005) return period of maximum individual wave height (m) for Gumbel ½ Max.

Ice coverage information was based on Canadian Ice Services charts. Where ice concentrations were greater than 50%, the model grid points were treated as land with no wave generation or propagation allowed. Thus, for most winter months (November to May), the MSCB model effectively had 100% ice coverage and no generation of waves. Consistent open water conditions for the generation of waves were present in the months of July through October.

During the MCSB project, extensive efforts were made to get accurate estimates of extrema. This included reanalysis of major storm events, and validation of wave results against historical records that were made in depths of 11 to 87 m. Even with these and other efforts, the authors recognized the difficulties of the project. *In situ* meteorological data from the Canadian Beaufort is limited, and sea ice variability makes the

Canadian Beaufort more complex than more temperate regions. In particular, the offshore areas have limited numbers of observations, which may tend to result in underestimated wind speeds and wave heights. The modeling of wave generation in areas where the wind is blowing over partial ice concentrations is not well understood, and the reduced availability of wind and wave data limits the capability to calibrate and validate the model for this wind-fetch variable under mixed ice and open water conditions. Finally, should ice coverage be reduced in summer in future years due to climate changes, the wave hindcast results will need to be re-examined.

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. The trends in the wind events are relatively small in relation to the large degree of interannual variability. At the coastal weather station of Tuktoyaktuk, wind speeds have exhibited a trend toward lower values both in early spring and in autumn. 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 -3 % per decade. Larger trends (- 6 to -11 %) of reduced ice cover were computed in late summer ice concentrations in the Alaskan Beaufort Sea, the Canada Basin and the Seasonable Sea Ice Zone beyond the continental shelf edge. This is much smaller than the trend towards reduced sea ice in the entire Arctic Ocean of -11% in late summer. In the last few years, there has been a noticeable reduction in the concentration of old ice, although it remains to be seen if this trend will continue.

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