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Trends in the draft and extent of seasonal pack ice, Canadian Beaufort Sea

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[1] Continuous observations by sub-sea sonar form a 12-year draft record for seasonal pack ice in the Beaufort Sea. There has been a small trend (0.07 m/decade) to thinner ice, but this has low statistical significance; net change is comparable to the uncertainty of measurement. Although ice concentration at the monitoring site has increased by 0.14 since 1991, there is little evidence for trend in ice-covered area over the continental shelf in the longer (36-year) ice-chart record. However, local air temperature has increased by 1.6 ± 0.6°C during the last three decades. Clearly longer time series are needed to detect and understand change. Changing snow cover, ice circulation and ice deformation may obscure the direct effects of warming climate on seasonal pack ice.

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1. Introduction

[2] Knowledge of pack-ice thickness lags far behind that of its extent and concentration. Data come chiefly from upward-looking sonar operated from submarines in the Arctic since 1958 [*Lyon*, 1984]. Ice-profiling sonar provides the local draft of the pack as the difference between the echo range and the depth of submergence derived from pressure. Ice thickness is draft multiplied by the ratio of seawater density to the local bulk density of the pack [*Wadhams et al.*, 1992; *Bourke and Paquette*, 1989]. The latter differs for floes and ridges.

[3] A map derived from these data by *Bourke and Garrett* [1987] remains the standard reference on Arctic ice thickness. However, it is clear from cruise tracks [*Lyon*, 1984] that the map is based largely on observations from the deep basins of the Arctic. Two thirds of the northern marine cryosphere lies outside this domain. The excluded fraction is predominately seasonal ice and its thickness is virtually unknown.

[4] We have evidence of thinning Arctic ice only from the old ice zone [*Wadhams*, 1990, 1994; *McLaren et al.*, 1992, 1994; *Shy and Walsh*, 1996; *Rothrock et al.*, 1999; *Wadhams and Davis*, 2000]. The two most recent papers reported that draft averages over 50 km of survey in 1990s were less than values from 1958–1977 at every re-visited location; the decrease averaged 42%, varying regionally over 0.9–1.7 m. Subsequent analysis has revealed that the thinning of ice occurred quite abruptly before 1991 [*Winsor*, 2001; *Tucker et al.*, 2001] and was correlated with a decrease in the fraction of the pack occupied by thick (draft more than 3.5 m) ice [*Tucker et al.*, 2001; *Yu et al.*, 2004].

[5] The thickness of seasonal (undeformed fast) ice has been measured weekly at sheltered coastal locations in Siberia since the 1930s and in Canada since the 1940s. There have been trends in end-of-winter thickness at individual sites during the last half century, but no spatially coherent pattern of change [*Brown and Coté*, 1992; *Polyakov et al.*, 2003]. *Brown and Coté* [1992] show that the primary influences on inter-annual variation in ice thickness have been the amount and timing of snow accumulation, not air temperature.

[6] Monitoring the draft of seasonal pack ice became practical in the late 1980s with the development of ice-profiling sonar (IPS) operating from sub-surface moorings. We now have a record of observations from the southern Beaufort Sea that is continuous since 1990 [*Melling and Riedel*, 2004]. Here we examine the sonar data from a single site for evidence of climate-warming impact on ice draft.

2. Observations

[7] Ice profiling and Doppler sonar have been operated for at least a year at almost a dozen locations in the Beaufort Sea. The data used in this discussion were acquired over the continental shelf at Site 1 (Figure 1) between 1991 and 2003. This site is dominated by seasonal pack ice in winter and ice free for up to four months in summer. The IPS recorded data every 1–10 s and typically surveyed a 2000-km transect each year. Methods for processing and calibration of data to yield ice draft have been described by *Melling et al.* [1995]; values are typically accurate within ±0.1 m (95% confidence limits).

[8] The results presented here have been derived from the time series of ice draft, sub-sampled at intervals of 4 minutes. Time-based statistics may have variable bias relative to values computed after mapping data to regular spatial increments [*Melling et al.*, 1995]. We use time-based statistics here for compatibility with other studies that utilized ice-profiling sonar on moorings without measuring ice velocity.

[9] Figure 2 displays seasonal cycles in pack ice at Site 1 as the average of monthly values over twelve years. The top

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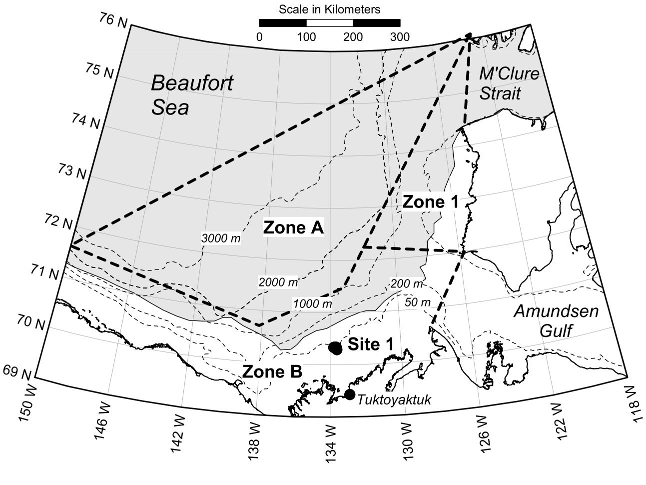

Figure 1. Location of Site 1 for seasonal ice monitoring, 1991 to present. Shading: typical mid-summer ice extent. Thick dashed lines mark zone boundaries for ice-chart analysis.

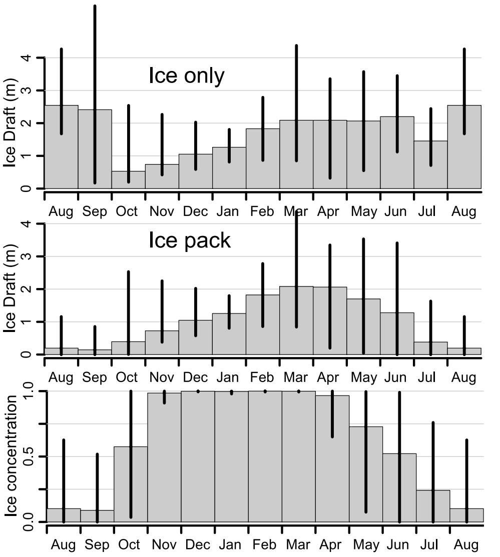

Figure 2. Annual cycles in the pack ice at Site 1, 1991–2003, based on monthly averages: draft of ice only (top), ice-pack draft (middle), ice concentration (bottom). Vertical lines span the observed range in monthly means.

frame shows the draft of ice present, here termed "ice-only draft"; data less than 5 cm have been ignored. Paradoxically, this average is greatest in summer when most thin ice has melted (compare maps of *Bourke and Garrett* [1987]). Averages in the middle frame include areas of open water as ice of zero draft, referred to here as "ice-pack draft". The dramatic drop in draft in summer reflects loss of snow cover, ablation of ice and reduction in ice concentration (Figure 2, bottom). A typical 15-cm of wind-packed snow in late winter contributes about 4.5 cm to ice draft.

[10] The wintertime extreme in monthly average draft occurs in March by either definition. The February–April average is taken here as the pack-ice analogue for the end-of-winter thickness of coastal fast ice [e.g., *Brown and Coté*, 1992].

[11] Figure 3 shows the inter-annual variation of pack-ice draft averaged over these three months. The long-term mean value is 2.01 m with 0.2-m standard uncertainty and 2.7-m range of variation. An apparent trend to lower draft at 0.4 ± 1.2 m/decade has low significance because year-to-year variation is so large. Fortuitously, extreme values associated with an old-ice incursion (a few tenths) in 1997 and anomalous weather in 1998 [*Maslanik et al.*, 1999] offset each other near the mid-point of the sequence, with little impact on trend. Clearly, the time series is too short to make definitive statements about progressive change.

[12] Time series of the anomalies in monthly mean ice draft and concentration are displayed in Figure 4; note unusually thin ice during 1997–98. Overall average values are 1.61 m and 1.09 m for ice-only and ice-pack draft and 0.685 for concentration. The corresponding trends in the anomalies are −0.27 and −0.07 m/decade for draft and +0.12 per decade for concentration. With approximately 70 degrees-of-freedom (2-month de-correlation time), the likelihood that the calculated trend is significantly different from zero is 93% for concentration, 66% for ice-only draft and only 25% for ice-pack draft (95% confidence limits: ±0.13, ±0.55 m and ±0.48 m per decade). Trend in ice-only draft should be viewed with scepticism, since means may be based on few measurements.

[13] A longer perspective is provided by charts prepared weekly by the Canadian Ice Service since 1968 (Ballicater Consulting, documentation for the Canadian Ice Service digital sea ice database, unpublished contract report, 2000, available at http://ice-glaces.ec.gc.ca/). Ice concentration in mid September, the typical date of minimum extent, is displayed in Figure 5 for three zones; zone A is the domain of old ice in the Canada Basin and zones B and 1 are the southern and eastern continental shelves where seasonal ice is much more common (see Figure 1). The ice-covered area of zone A has decreased at an average 0.06 per decade and that of old ice by 0.08 per decade. These trends reflect the unprecedented northward retreat of the old pack from the Alaskan shelf edge since 1997 [*Maslanik et al.*, 1999]. Over the continental shelf (zone B), which is typically almost free of ice in September, there has been no trend in ice-covered area and only a small decrease in old ice. In the east (zone 1) a 0.02 per decade increase in old ice has been offset by a decrease in first-year ice, for no net change. Evidently, trends in ice-covered area over the shelves of the

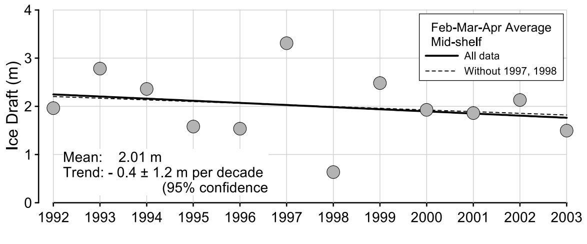

Figure 3. Late-winter draft of pack ice at Site 1. Lines show trend for all data (solid) and excluding two extremes (dashed).

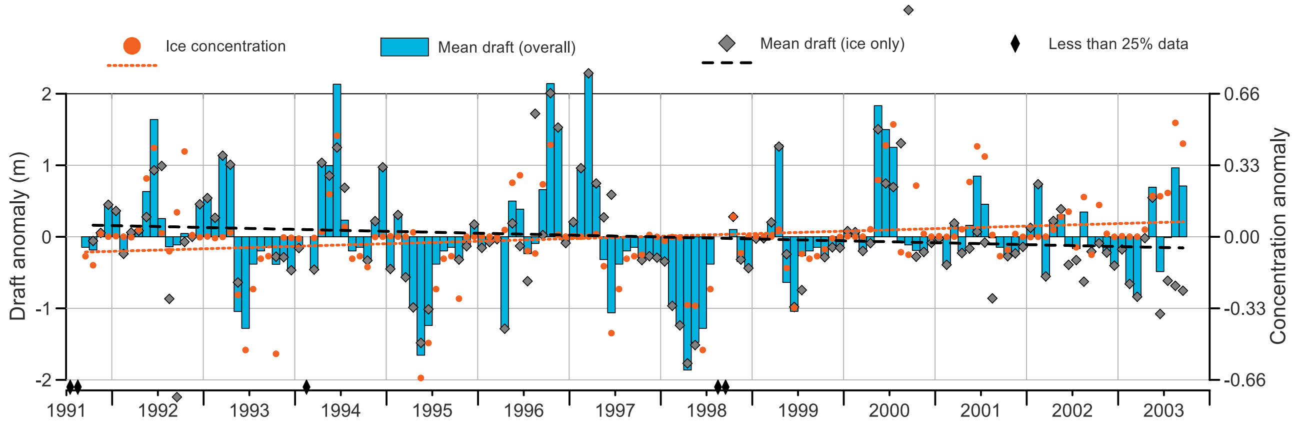

Figure 4. Anomalies in the monthly mean concentration and draft of pack ice at Site 1 on the Beaufort Sea shelf, 1991–2003. Trend lines are shown for concentration and ice-only draft.

eastern Beaufort have been small for much longer than the duration of ice-draft monitoring.

3. Discussion

[14] Surface air temperature increased by about 2.5°C over a wide continental area south of Site 1 during the last quarter of the 20th century [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Since decline in sea ice is a common supposition in warming climate, the lack of unequivocal change in Beaufort seasonal ice over the same period is counter-intuitive.

[15] Observations of air temperature at Tuktoyaktuk, on the coast 100 km south of Site 1, provide the best available approximation to local marine conditions. Although climate cooled here during 1948–62, by about 1°C, it has warmed at an average 0.53°C/decade over the last 30 years. Total warming since 1974 has been 1.6 ± 0.4°C at 95% confidence.

[16] In cold climates, the cryospheric impact of increased temperature during winter differs from that during summer. Figure 6 depicts cumulative potential for freezing and thawing during cold and warm seasons, respectively. Over the last 30 years, annual freezing and thawing degree-days have changed at about the same rate, 3.3 ± 3.5% per decade (95% confidence), the former decreasing and the latter increasing. During the 12 years that ice draft has been monitored, the trend in FDDs remained unchanged but that in TDDs reversed sign to −12% per decade.

[17] Since seasonal ice thickens roughly in proportion to the square root of cumulative FDDs, the warming of winters during 1991–2003 could explain a 2% decrease in thickness of level ice at winter's end (3.6 cm in draft), much less than the apparent trend in Figure 3. The cooling of summers might be implicated in reduced ablation, but linkages with air temperature are obscured by the impacts of sea temperature and insolation on ice deterioration. Or, cooler summers in the 1990s may simply reflect higher ice concentration (Figure 4).

[18] The low thermal conductivity of snow slows ice growth, and its high albedo slows ablation [*Maykut and Untersteiner*, 1971]. Inter-annual variations in snow thickness on seasonal pack ice may have had significant impact on thickness [cf. *Dumas et al.*, 2003]. No assessment is possible in the absence of long-term observations of snow cover on pack ice.

[19] Site 1 is flanked by three zones of strong gradient in ice properties: the fast-ice edge to the south, the edge of polar pack to the north and the ice edge in summer. Conditions can change abruptly with change in the direction of drift. Indeed, the occurrence of bad (from a navigational viewpoint) and good ice seasons is strongly linked to ice-drift anomalies. As example from this series, the pack-ice draft in July at Site 1 was very different in 1998 (0.00 m) than in 2001 (0.84 m). In 1998, the net displacement of the pack from 1 April to 16 May, when Site 1 cleared, was 366 km along 256°T. During the same period in 2001, the net displacement was only 42 km, parallel to the coast (210°T); ice did not clear from Site 1 until early August. Clearly change in ice circulation is a potential source of trend that again is not directly related to warming climate. Others have noted that ice drift is an intrinsic element of thickness variation even deep in the pack [*Shy and Walsh*, 1996; *Rigor and Wallace*, 2004].

[20] Inter-annual variation in ice-cover deformation may also drive variability in pack-ice thickness. Histograms of draft for seasonal pack normally have one or more modes under 2 m and a roll-off associated with ridge keels as deep as 30 m [*Melling and Riedel*, 1996]. *Melling and Riedel* [1995] used such histograms to show that two-thirds of the

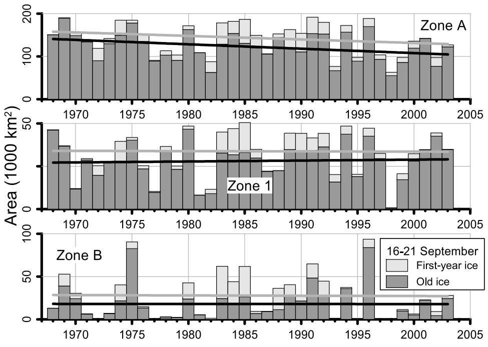

Figure 5. Area covered by seasonal and old pack ice in the Beaufort Sea in mid-September, 1968–2003, derived from the weekly chart of the Canadian Ice Service.

volume (viz. mean draft) of seasonal pack ice in the Beaufort in April 1992 was contained in ridges. Figure 7 illustrates the long-term correlation between mean ice draft and the severity of ridging, expressed as the 80th percentile of the monthly histogram; 97% of the variation in mean draft over seasonal and inter-annual cycles is related to ridging.

[21] The fracturing and deformation of pack ice is driven by variation in the forces applied by wind and current. Variation in the fractional volume of deformed ice will be influenced by variations in ice strength and dynamical forcing. Ice strength depends on its thickness and temperature, both of which may be linked to warming climate. The link to forcing is indirect, via changes in atmospheric circulation: storm winds create weak new ice by opening leads and new ridges by closing them [*Melling and Riedel*, 1996]. Our data indicate that the low mean and 80th percentile drafts at Site 1 in the spring of 1998 (0.86 & 1.2 m) were associated with an anomalously consistent drift of the pack during the preceding five months–1667 km travelled for 951 km of net displacement. In contrast, high values in the spring of 1993 (3.22 & 5.45 m) were associated with repeated reversals of drift – 1319 km travelled for 86 km of net displacement.

4. Conclusions

[22] Moored sub-sea sonar has revealed a small thinning trend (0.07 m/decade) in seasonal pack ice in the eastern Beaufort Sea, 1991–2003, and a larger trend (0.12 per decade) to greater ice-covered area, meaning more ice in summer.

[23] The net change in draft does not exceed the accuracy of measurement (±0.1 m). The trend has low significance since seasonal and inter-annual variability are large.

[24] Data from conventional ice reconnaissance over the last 36 years suggest little net change in ice conditions over the Beaufort shelves, despite dramatic decrease in summertime ice over the south-western Canada Basin.

[25] Measurements of surface air temperature at a nearby coastal site reveal warming by 1.6 ± 0.4°C since 1974. The estimated impact of warming since 1991 is reduced ice growth by 0.04 m. Impact on ablation is difficult to quantify.

[26] Definitive evidence for climate-change impact on seasonal ice will require time series much longer than those presently available.

[27] Mechanisms other than air temperature – snow cover, ice circulation and ridging – are plausible contributors to variability and trend in the thickness and extent of seasonal ice.

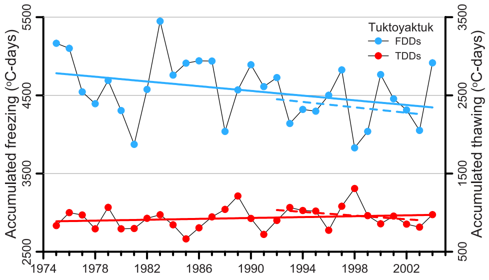

Figure 6. Cumulative freezing and thawing degree-days derived from air temperature at Tuktoyaktuk. Lines show trend over 30 years (solid) and during the 12-year ice-draft record (dashed). Data from Meteorological Service of Canada.

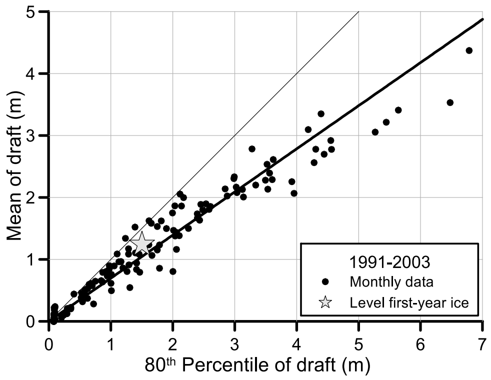

Figure 7. Correlation between mean and 80th percentile draft values at Site 1. The level-ice point is based on 500 drill holes.

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