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Surface freshening of the Canada Basin, 2003–2007: River runoff versus sea ice meltwater

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[1] The extent of summer Arctic sea ice has reduced dramatically in recent years and, simultaneously, we have observed surface freshening over the Canada Basin in 2006 and 2007. In order to identify the source of this fresh water, either meteoric or sea ice meltwater, salinity, $\delta^{18}O$, and alkalinity were analyzed. Results show that sea ice meltwater increased in the surface water over the central part of the basin in 2006 and 2007, corresponding to the melting of an additional 2.7 m (1.3 m a^{-1}) of sea ice. Anomalously fresh surface water observed in the southern part in 2007, however, was mostly attributed to Mackenzie River water extending into the basin interior, a source that was mainly absent in the early 2000s. Comparison with previous data shows that the meltwater component of surface water in the southern part of the Canada Basin has progressively increased at a mean rate of 0.27 m a^{-1} since 1987. This can be explained by a reduction of winter sea ice formation rate by 0.45 m or more during the past two decades. The runoff component showed larger variability in the southern basin but no obvious temporal trend. In the central basin, the river runoff component showed an increasing trend of 0.7 m a^{-1}.

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1. Introduction

[2] The retreat and thinning of Arctic sea ice in summer, observed in past decades, accelerated during the 2000s [*Rothrock et al.*, 1999; *Serreze et al.*, 2007; *Stroeve et al.*, 2007; 2008; *Comiso et al.*, 2008]. In 2007, the summer Arctic sea ice extent had declined significantly, setting a new record minimum of 4.28×10^6 km^2 in September, which was 1.28×10^6 km^2 or 23% smaller than the previous record set in 2005 [*Stroeve et al.*, 2008]. There are several factors that influence sea ice extent and thickness: one is the air temperature increase which has contributed to decrease the volume of Arctic sea ice since the 1960s [*Rothrock and Zhang*, 2005]. In addition, an anomalous wind field observed during the 1990s has advected thick old ice from the Arctic Ocean through Fram Strait. Since the late 1990s, a reduced and thinner ice cover, preconditioned during preceding decades, has enhanced the absorption of solar radiation and upper ocean circulation, resulting in an accelerated decline of sea ice in the Arctic Ocean [*Shimada et al.*, 2006; *Zhan et al.*, 2008]. Such changes in sea ice must be accompanied by changes in the salinity of surface seawater. As stratification of Arctic water depends primarily on salinity, changes in salinity influence biological activity, ocean circulation and geochemical cycles, and, in turn, affect both regional and global environments [e.g., *Aagaard and Carmack*, 1989; *Häkkinen*, 1999; *Carmack*, 2007].

[3] In this paper, we investigate changes in surface salinity from 2003 to 2007 in the Canada Basin of the Arctic Ocean. Freshwater tracer data are used to examine the cause of salinity changes, since changes in salinity reflect not only melting/formation of sea ice but also the input of freshwater from other sources. In most parts of the Arctic Ocean, including the Canada Basin, river runoff is the major source of freshwater in the surface layer [*Yamamoto-Kawai et al.*, 2005; 2008] and any fluctuation of its pathway effects salinity distribution [*Macdonald et al.*, 1999; 2002; *Guay et al.*, 2001]. Variabilities in freshwater content of seawater flowing from the Bering Sea [*Woodgate et al.*, 2006] and direct precipitation may also change the salinity of surface water in the Canada Basin. Here we investigate temporal changes in surface waters of the Canada Basin from 2003 to 2007, and examine the freshwater composition and sources. We also compare our results with previous data from the southern Canada Basin.

2. Freshwater Tracers

[4] Two tracers are used in this study to distinguish freshwater sources. The first tracer is the oxygen isotope

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Table 1. End-Member Values Used in This Study

	PW	SIM	MW
Salinity	32.5 (31.9–33)	4 ± 1	0
δ^{18}O (‰)	−0.8 (−1.2 to −0.5)	−2 ± 1.0	−20 ± 2

ratio, expressed as δ^{18}O and referenced to Vienna Standard Mean Ocean Water (VSMOW) as follows:

$$\delta^{18}\mathrm{O} = \left(\left(\mathrm{H_2^{18}O}/\mathrm{H_2^{16}O}\right)_{\mathrm{sample}}/\left(\mathrm{H_2^{18}O}/\mathrm{H_2^{16}O}\right)_{\mathrm{VSMOW}} - 1\right)10^3\,[‰].$$

δ^{18}O has been successfully used as a freshwater tracer in the Arctic Ocean for decades [e.g., *Östlund and Hut*, 1984; *Bauch et al.*, 1995; *Ekwurzel et al.*, 2001; *Macdonald et al.*, 1999, 2002; *Schlosser et al.*, 2002; *Yamamoto-Kawai et al.*, 2008]. Arctic meteoric water (MW; MW = river runoff + precipitation) is largely depleted in ^{18}O and its δ^{18}O value is −20‰ [*Cooper et al.*, 2005] whereas the δ^{18}O value of sea ice is ∼0 to −2‰ in the Arctic Ocean [*Eicken et al.*, 2002; *Pfirman et al.*, 2004]. Thus contributions of these two fresh water sources can be quantitatively distinguished with salinity (S) and δ^{18}O measurements. Assuming that each seawater sample is a mixture of three end-members, sea ice meltwater (SIM), MW and a saline end-member (SE), the fraction of each end-member component (f) is estimated by using the following mass balance equations and observed values of S and δ^{18}O (S_{ob} and $\delta^{18}O_{obs}$):

$$f_{SIM} + f_{MW} + f_{SE} = 1,$$

$$f_{SIM}S_{SIM} + f_{MW}S_{MW} + f_{SE}S_{SE} = S_{obs},$$

$$f_{SIM}\delta^{18}O_{SIM} + f_{MW}\delta^{18}O_{MW} + f_{SE}\delta^{18}O_{SE} = \delta^{18}O_{obs}.$$

S and δ^{18}O values for the three end-members are summarized in Table 1. S_{SIM} is from *Ekwurzel et al.* [2001] and $\delta^{18}O_{SIM}$ is selected to represent the δ^{18}O value of sea ice in the Canada Basin [*Eicken et al.*, 2002; *Pfirman et al.*, 2004]. The value of $\delta^{18}O_{MW}$ is from *Cooper et al.* [2005]. Sea ice formation, which injects salt into seawater, is represented by a decrease in f_{SIM}. When formation of sea ice exceeds melting, f_{SIM} becomes negative [cf., *Östlund and Hut*, 1984]. Pacific Water (PW) from the Bering Sea with S = 32.5 is selected as the saline end-member in surface water of the Canada Basin [*Yamamoto-Kawai et al.*, 2008]. This is the mean near-bottom S in Bering Strait (∼50 m depth) obtained from 14 years moored observations by *Woodgate and Aagaard* [2005]. The δ^{18}O of this water is −0.8‰ from observations by *Cooper et al.* [2006] and *Yamamoto-Kawai et al.* [2008]. The uncertainties of freshwater fractions (f_{SIM} and f_{MW}), due to uncertainties in the range of end-member values (Table 1) and δ^{18}O analysis, are ±0.03. Note that seasonal variabilities in S of Bering Strait throughflow (S is 31.9–33 [*Woodgate and Aagaard*, 2005]), and corresponding variations in δ^{18}O (−1.2 to −0.5‰), derived from S-δ^{18}O relationship of Bering Seawater [Cooper et al. 2006; *Yamamoto-Kawai et al.*, 2008], alter f_{SIM} and f_{MW} calculations by ±0.02 or less.

[5] The second tracer is total alkalinity. Total alkalinity is a quasi-conservative property in the Arctic Ocean [*Anderson et al.*, 2004] because the dominant biological species do not form carbonate shells (which decreases alkalinity in seawater). Changes in alkalinity due to the assimilation of nitrate and ammonia and remineralization of organic matter can be neglected by using potential alkalinity (pAlk = total alkalinity + nitrate − ammonium) [*Brewer and Goldman*, 1976]. Thus, pAlk of surface seawater will change only as a result of mixing with other waters. When seawater is mixed with precipitation (S ≈ 0, pAlk ≈ 0 μmol kg^{-1}), both S and pAlk are diluted equally, and therefore pAlk normalized with S will remain constant. Normalized pAlk (NpAlk) is calculated by

$$\mathrm{NpAlk} = \mathrm{pAlk}/\mathrm{SS_R},$$

where S_R is the reference S. In this study S_R is 32.5, the S of PW.

[6] Likewise the formation and melting of sea ice affect S and pAlk similarly and therefore the change in NpAlk is small. For example, when seawater mixes with SIM (S = 4 ± 1, pAlk = 263 ± 65 μmol kg^{-1} [*Anderson et al.*, 2004; *Yamamoto-Kawai et al.*, 2005]) and S is decreased from 32.5 to 28, the resulting change in NpAlk is ∼20 μmol kg^{-1} or less. However, when seawater mixes with river water, NpAlk changes significantly. The mean pAlk of Russian river runoff entering the Arctic is ∼800 μmol kg^{-1} and is ∼1600 μmol kg^{-1} in North American rivers [*Cooper et al.*, 2008]. When seawater mixes with Russian runoff, decreasing S from 32.5 to 28, NpAlk is increased by ∼130 μmol kg^{-1}. If the same mixing with North American runoff occurs, NpAlk is increased by ∼260 μmol kg^{-1}. Therefore, seawater mixed with river runoff will have a much higher NpAlk than seawater mixed with precipitation or SIM, and therefore NpAlk can be a tracer of river runoff.

[7] In summary, δ^{18}O can be used to divide fresh water into SIM and MW components, and NpAlk can be used to identify between river runoff and precipitation components. Furthermore, a combination of S, δ^{18}O and pAlk can be used to indicate whether river runoff is from North American rivers or Russian rivers [cf., *Yamamoto-Kawai et al.*, 2005].

3. Data and Analytical Method

[8] Hydrographic observations and sampling were carried out in the Canada Basin every summer (mainly in August, Table 2) from 2003 to 2007 on the CCGS *Louis S. St-Laurent* and in the Chukchi Sea in summer of 2004 (mainly in September) on the Japanese R/V *Mirai* (Figure 1 and Table 2). Seawater samples were collected in Niskin bottles mounted on the CTD rosette and then transferred into smaller bottles for analysis of chemical properties. Detailed information about the sampling and measurement on *Mirai* and *St-Laurent* is reported by *Shimada* [2004] and *McLaughlin et al.* [2008], respectively. S of bottled samples were analyzed using a Guildline salinometer and referenced to IAPSO standard seawater. When bottle S data was unavailable, CTD S calibrated against bottle measurements were used. δ^{18}O samples were measured on a mass spectrometer connected with CO_2-H_2O equilibration unit at the International Arctic Research Center of University of Alaska Fairbanks (*St-Laurent* 2003), JAMSTEC (*St-Laurent* 2005 and 2006), Hokkaido University (*St-Laurent* 2007) or Oregon State University (*St-Laurent* 2004, 2005, and 2007

Table 2. Dates of Cruises

Cruise	Date
Louis S St-Laurent 2003	15 July to7 September
Mirai 2004	1 September to 12 October
Louis S St-Laurent 2004	29 July to 2 September
Louis S St-Laurent 2005	29 July to 1 September
Louis S St-Laurent 2006	5 August to 14 September
Louis S St-Laurent 2007	26 July to 31 August

and *Mirai* 2004). The pooled standard deviation (Sp) of $\delta^{18}O$ for duplicate samples collected in 2004 and 2005 was 0.09‰ (n = 117) and 0.03‰ for samples collected in 2006 and 2007 (n = 35). Although duplicates were not collected in 2003, the analytical precision estimated from standards measured with samples was ±0.03‰. Samples for total alkalinity analysis were collected during the *Mirai* 2004 and *St-Laurent* 2005–2007 cruises. Total alkalinity values were determined by a titration method with HCl and were calibrated against a certified reference material provided by Dr. Dickson of Scripps Institute of Oceanography. The Sp for replicate alkalinity measurement was 9.7 (n = 118) in 2005, 2.4 (n = 296) in 2006, and 3.5 (n = 144) in 2007.

4. Results

4.1. Salinity

[9] Figures 2 and 3 show the distributions of surface salinity in middle-late summer from 2003 to 2007. A large change in salinity was observed in 2006 and 2007, over a large area of the Canada Basin (Figure 2). In 2006 a huge polynya (open water area surrounded by sea ice) appeared in the central part of our observation area (Figure 2b). In 2007 (record minimum Arctic summer sea ice extent to date) the western part of the Canada Basin was covered by far less ice than average (Figure 2c). Similarly, surface salinity abruptly decreased from 2003–2005 to 2006, and decreased further in 2007 (Figures 2d–2f), causing stronger stratification of the upper ocean. In Figure 2d, data from 2003 to 2005 are combined to represent the mean conditions in these 3 years because there is no pAlk data from the *St-Laurent* cruises in 2003 and 2004 (data from *Mirai* 2004 and *St-Laurent* 2005 cruises are available) to compare with salinity. The S distribution in each year from 2003 to 2005 is presented in Figure 3 for comparison. From 2003 to 2005, S at 10 m depth ranged mostly between 27 and 30 (Figures 2d and 3). Very low-S water (S < 27) was observed in the regions north of the Mackenzie River and in Amundsen Gulf, whereas high S water (S > 31) from the Bering Sea was found in the Chukchi Sea. In 2006, S was lower than 27 in the region where a polynya was observed (Figures 2b and 2e) and a decrease in S was also observed in the northern part. In contrast, S increased in 2006 in the southeastern part. In 2007, further freshening was observed over the study area (Figure 2f). The area where S < 26 expanded significantly from 2006 to 2007 and the area in the north where S > 28 had disappeared in 2007.

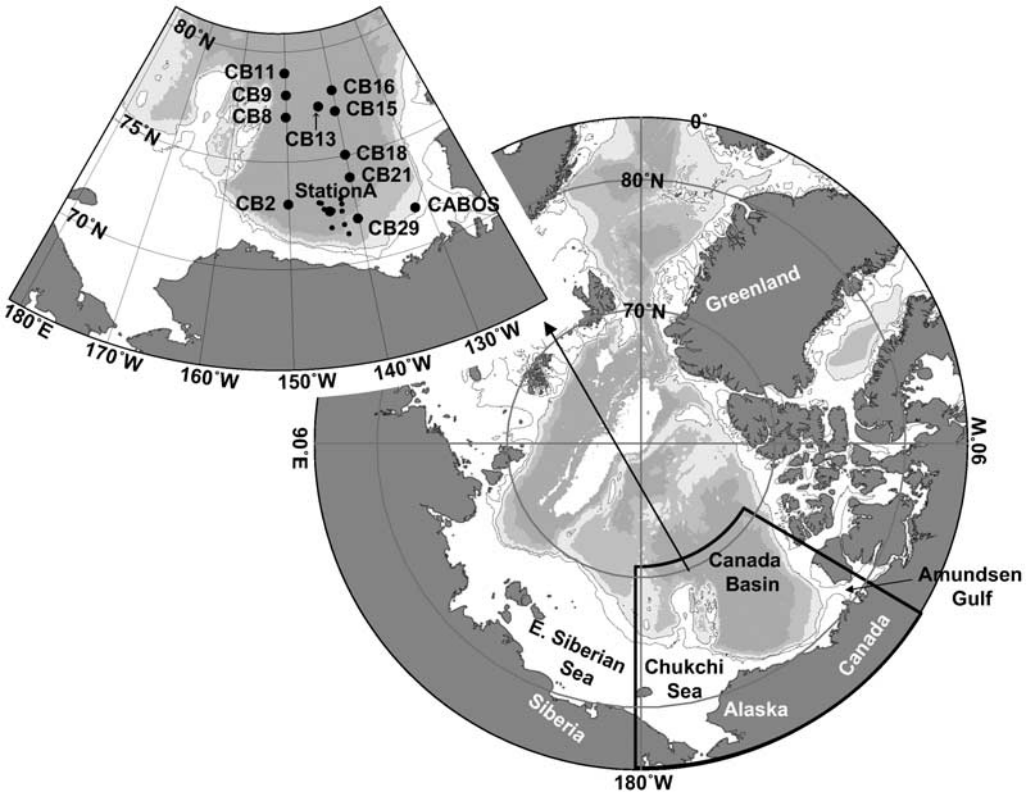

Figure 1. Map of the Arctic Ocean and observation area. Locations of stations used in Figure 6 are shown in the insert map. Smaller dots in the insert map indicate the location of Station A and near by stations used in Figure 8 [cf., *Macdonald et al.*, 1999]. Station locations for each cruise are marked in Figures 2–5.

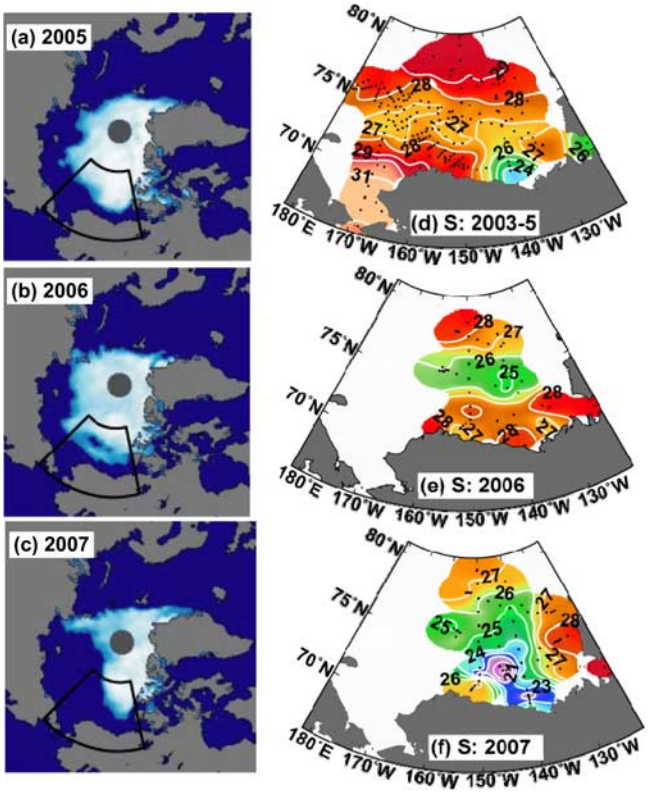

Figure 2. Monthly sea ice concentration (white = 100%, blue = 0%) in September of (a) 2005, (b) 2006, and (c) 2007 [*Fetterer and Fowler*, 2006]. Distribution of summer salinity at 10 m depths in (d) 2003–2005, (e) 2006, and (f) 2007.

4.2. Oxygen Isotope

[10] The method described in Section 2 is applied to estimate fractions of SIM and MW in surface waters of the Canada Basin between 2003 and 2007. Horizontal distributions of freshwater fractions (Figure 4) shows that f_{MW} is higher than f_{SIM} at most stations, indicating MW is the main source of fresh water in the surface layer of the Canada Basin, even in middle-late summer (Table 2) when the contribution of SIM should be at its maximum. *Mathis et al.* [2007] also observed in 2002 that, even though SIM largely increased from spring to summer and exceeded MW in some of shelf/slope regions, MW was two times higher than SIM in the surface water in deep basin.

[11] During 2003–2005, estimated f_{MW} in surface water was ~0.1 (Figure 4a) and f_{SIM} was mostly less than 0.1 (Figure 4d). In the central and eastern part of the basin, f_{SIM} was ~0.05. In the Chukchi Sea, where PW enters via Bering Strait, f_{MW} was lower than 0.05. A high content of MW (>0.15) was observed near the Mackenzie River. In 2006, f_{MW} slightly increased over the Canada Basin (Figure 4b) and increase in f_{SIM} is more apparent (Figure 4e) in the region where the freshest water was found (Figure 2e). Therefore, SIM seems to be the main contributor to the observed surface freshening in 2006. In contrast, water with $f_{SIM} < 0.05$ covered the southern region in 2006. In this region, f_{MW} was also lower in 2006 than in 2003–2005 and f_{MW} higher than 0.15 was not found in 2006, even near the mouth of the Mackenzie River. In 2007, both f_{SIM} and f_{MW} increased markedly and f_{MW} more than 0.15 was found not only near the Mackenzie but also in the southwestern Canada Basin (Figure 4c). This distribution of high f_{MW} coincides with the distribution of low S in the southern part (Figure 2f). The low-S water found in the central basin (Figure 2f), however, does not have high f_{MW} but has a f_{SIM} higher than 0.1. Thus, in 2007, both MW and SIM contributed largely to the surface freshening in southern and central part of the Canada Basin, respectively.

4.3. Alkalinity

[12] Since MW is the major source of fresh water in surface waters in this area, we now examine the source of MW by using NpAlk. The distribution of NpAlk in surface water in 2004–2005 (Figure 5a) shows that waters on the Chukchi shelf had NpAlk of ~2250 μmol kg^{-1}. This is close to the NAlk value of 2200–2250 μmol kg^{-1} observed by *Murata* [2006] and *Nedashkovskii and Sagalaev* [2001] upstream in the western, central and eastern Bering Sea (their observations are recalculated here using S_R = 32.5). *Murata* [2006] and *Nedashkovskii and Sagalaev* [2001] also observed high NAlk (>2300 μmol kg^{-1}) in waters with S ~ 30.5 or less in the coastal region near the mouth of the Yukon River and on the western shelf, and low NAlk (~2100 μmol kg^{-1}) around a coccolithophorid bloom. However, waters we observed on the Chukchi shelf, north of the Bering Strait had S higher than 31 (Figure 2d) and NpAlk was ~2250 μmol kg^{-1}, indicating there was not a significant contribution of river waters. In the Canada Basin, surface water had lower salinity and higher NpAlk

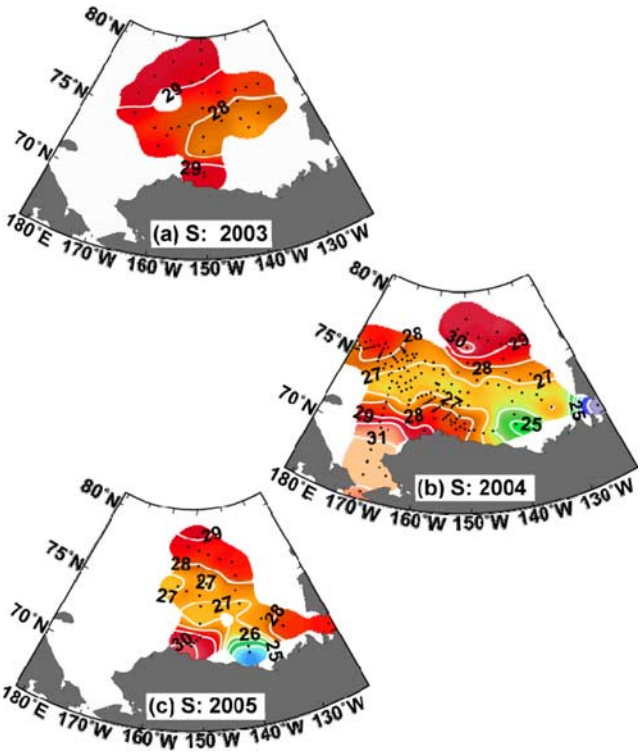

Figure 3. Distribution of salinity at 10 m depth in (a) 2003, (b) 2004, and (c) 2005.

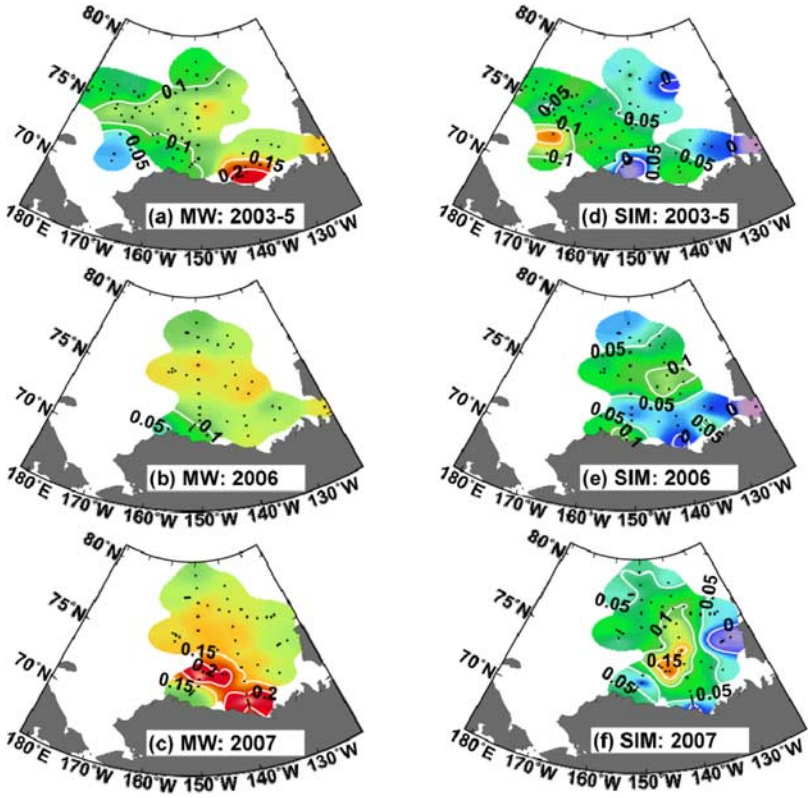

Figure 4. Fraction of MW and SIM in surface seawater (observed between 2 and 8 m depths) in (a and d) 2003–2005, (b and e) 2006, and (c and f) 2007, respectively.

values than observed on the Chukchi shelf. This suggests that surface waters mixed with Arctic river runoff within the basin (Figure 5a). The highest NpAlk was found near the Mackenzie River. The change in NpAlk from 2004–2005 to 2006 is small in the central part of the study area (Figure 5b), but S decreased to less than 26 (Figure 2e). This suggests that freshening observed in 2006 was mainly due to an input of SIM or precipitation and δ^{18}O data (Figures 4b and 4e) show that SIM is the main cause of this freshening. In contrast, freshening in the southwest in 2007 was accompanied by very high NpAlk values where very high f_{MW} was also found (Figures 4c and 5c). This indicates that the source of MW freshening was river runoff. However, further north (>74°N) the low-S water (Figure 2f) does not show a large increase in NpAlk. Thus, the major source of fresh water diluting surface water in the central Canada Basin was not river runoff but SIM. This again agrees with findings from δ^{18}O (Figures 4c and 4f).

[13] Furthermore, δ^{18}O and pAlk can be combined to distinguish between North American and Russian river sources. *Yamamoto-Kawai et al.* [2005] have shown that dilution/concentration effects of sea ice melting/formation on water properties such as S and pAlk can be corrected by using f_{SIM} estimated from δ^{18}O

$$S_0 = (S - S_{SIM} f_{SIM})/(1 - f_{SIM})$$

$$pAlk_0 = (pAlk - pAlk_{SIM} f_{SIM})/(1 - f_{SIM}).$$

Calculated S_0 and $pAlk_0$ represent S and pAlk concentrations in water that has no SIM contribution. The relationship between S_0 and $pAlk_0$ thus indicates a mixing between PW and MW end-members. The S and pAlk of SIM (S_{SIM} and $pAlk_{SIM}$) are set to be 4 and 263, respectively [*Anderson et al.*, 2004; *Yamamoto-Kawai et al.*, 2005]. For waters in the upper Canada Basin with S < 32.5, removing data from stations marked by open diamonds and filled squares in Figure 6, the linear regression of S_0-$pAlk_0$ gives an equation of $pAlk_0 = 44.0\ S_0 + 793$ (r = 0.91). This is close to the mixing line between PW (Alk ~ 2200 μmol kg^{-1} at S = 32.5 [*Murata*, 2006]) and runoff with Alk of ~800 μmol kg^{-1} at S = 0. *Cooper et al.* [2008] reported Alk of Arctic rivers in different years and seasons and, among their 34 observations from North American rivers, only one sample had a value less than 1000 μmol kg^{-1} (617 μmol kg^{-1}). In Russian rivers, Alk was 300–800 μmol kg^{-1} during peak discharge and higher in other periods, with a flow-weighted mean of 816 μmol kg^{-1} [*Cooper et al.*, 2008]. Therefore, the intercept of ~800μmol kg^{-1} in Figure 6 suggests the Russian runoff is the main source of MW in the Canada Basin. Surface waters at stations near the Mackenzie River (open diamonds in Figure 6) have higher $pAlk_0$ values due to mixing with Mackenzie River water with a mean pAlk of 1618 μmol kg^{-1} [*Cooper et al.*, 2008]. In the southwestern region where very high f_{MW} and NpAlk were observed in 2007 (Figures 4c and 5c), the S_0-$pAlk_0$ relationships (filled squares in Figure 6) are similar to waters near the Mackenzie River. This suggests that the source of river

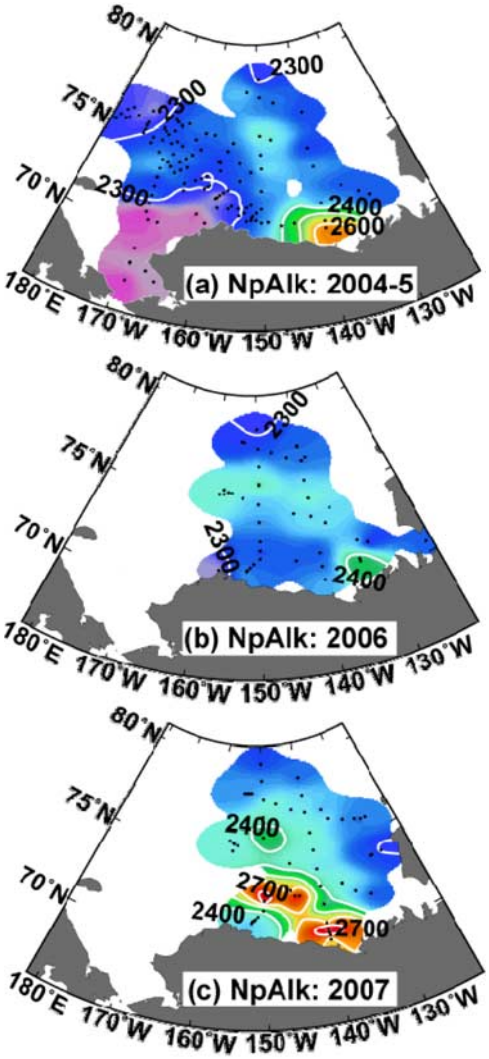

Figure 5. Distribution of NpAlk normalized to S = 32.5 at the surface (2–8 m) in (a) 2004–2005, (b) 2006, and (c) 2007.

runoff in the southwest in 2007 is mainly Mackenzie River water (with minor North American runoff), transported offshore by anomalous westward winds in the summer of 2007 [cf., *Zhan et al.*, 2008].

5. Discussion

5.1. Sea Ice Meltwater

[14] At selected stations where the temporal distribution of data allow comparison from 2003–2005 to 2007, the fractions of fresh water are integrated from the surface to 50 m and these estimated fresh water inventories (I) are shown in Figure 7, together with freshwater fractions at the surface. Both the fraction and inventory of total freshwater, referenced to the salinity of PW according to

$$f_{Total} = (32.5 - S_{obs})/32.5$$

are also shown in Figure 7a. Note that mixing of PW with MW or SIM increases f_{Total} and formation of sea ice decreases f_{Total}, therefore fractions and inventories obtained here, based on middle-late summer observations, represent the net result of seasonal processes. At stations in the central basin (CB8-CB21), especially at eastern stations (CB13–21), surface f_{SIM} increased by ~0.1 but only varied slightly at southern stations (CB2, CB29 and CABOS). The I_{SIM} also increased at stations CB11–21. This is the region that used to be covered by thick and old pack ice [e.g., *Rigor and Wallace*, 2004]. At stations in this region, I_{SIM} turned from negative or zero in 2003–2005 to positive in 2007. A negative I_{SIM} means that formation of sea ice exceeds melting in summer, resulting in either export or accumulation of sea ice. A positive I_{SIM} means the opposite. Although an increase in I_{SIM} could be due to both reduction of ice formation and increase in melting, f_{SIM} values at 50 m depth have not significantly changed (crosses in Figure 7). Assuming that water at 50 m depth is the remnant of the winter mixed layer [*Macdonald et al.*, 1999], in situ formation of sea ice in winter does not seem to have changed significantly. Therefore, the increase in SIM inventory during our observation period is likely largely due to increased melting of sea ice in summer.

[15] The I_{SIM} at stations CB11–21 has increased by 2.5 m, at a mean increase rate of 1.2 m a^{-1}. This corresponds to melting an additional 2.7 m or 1.3 m a^{-1} of sea ice accounting for the density of sea ice (0.91 [*Timco and Frederking*, 1996]). This melting rate of 1.3 m a^{-1} is surprisingly high compared to previous observations of sea ice thinning of ~0.1 m a^{-1} and mean ice thickness of 2–3 m during the 1990s [*Rothrock et al.*, 2003]. Some of the increased SIM may have been advected from the surrounding region. Our results show, at any rate, that a large amount of sea ice has indeed melted and supplied fresh water to the surface water in the Canada Basin, especially in the region that used to be covered by thick pack ice.

[16] In the southern part of the Canada Basin changes in SIM are not obvious during our observation period (Figure 7). However, when these data are compared with data observed

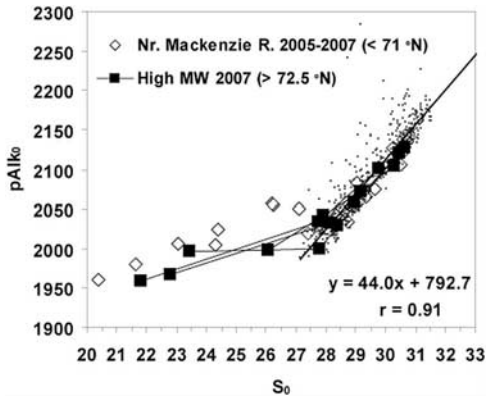

Figure 6. Relationship between S and pAlk after being corrected for SIM effects (see text). Open diamonds show data from stations located near the Mackenzie River (<71°N). Solid squares indicate data from stations within the region of high f_{MW} and high NpAlk observed north of 71°N in the southern Canada Basin in 2007. Small dots are data from all other stations in the Canada Basin and the regression line for these data is shown.

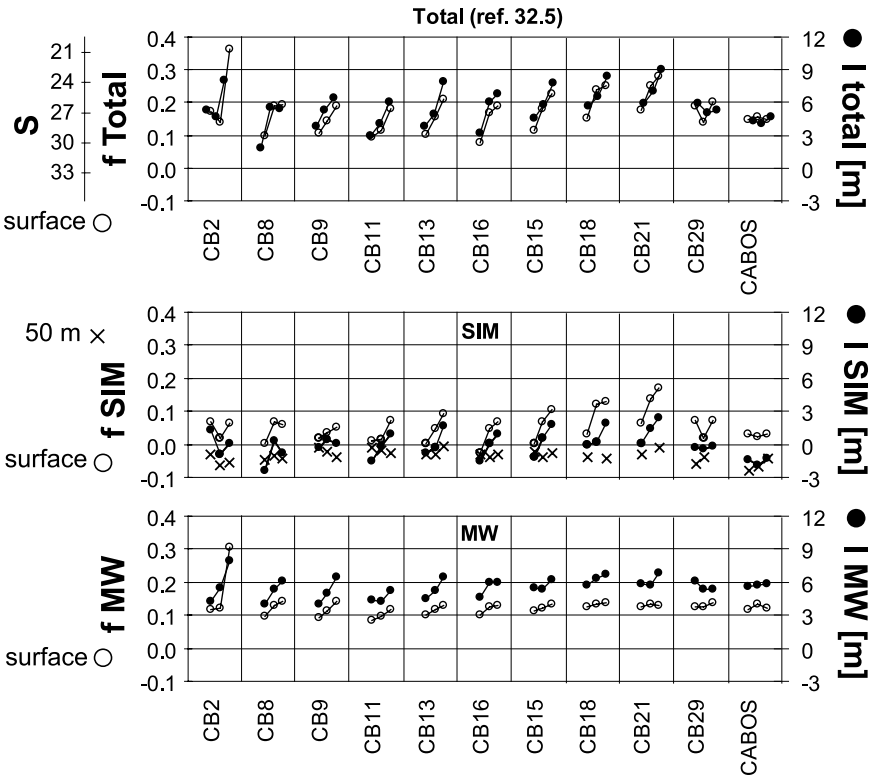

Figure 7. Temporal variation of the fraction (open circle) and inventory (solid circle) in 0–50 m layer at each station indicated on *x* axis (see Figure 1 for locations) of (top) total freshwater, (middle) SIM, and (bottom) MW. For each station the left, center, and right circles indicate the fraction or inventory in 2003–2005, 2006, and 2007, respectively. When there are more than two data points, the average value is shown. Fractions of total freshwater correspond to the salinity scale indicated on the left of Figure 7 (top). In Figure 7 (middle), f_{SIM} at 50 ± 10 m are also shown as crosses.

between 1987 and 1997 (15 August to 27 September) [*Macdonald et al.*, 1999] and in 2002 (16 September) [*Yamamoto-Kawai et al.*, 2005], an increasing trend in SIM is evident (Figure 8a). *Macdonald et al.* [1999] measured S and $\delta^{18}O$ at a time series station (Station A) and nearby stations in the southern Canada Basin and estimated fractions of SIM and MW with different end-member values than we use here. The largest difference is in the choice of saline end-member, as they used water found at ~150 m in the Canada Basin (called Pacific Winter Water). This water has a higher S and a slightly lower $\delta^{18}O$ than our saline end-member because Pacific Winter Water contains brine injected during sea ice formation on Bering and Chukchi shelves in winter and Arctic MW [*Yamamoto-Kawai et al.*, 2008]. Our end-member, PW, represents the mean properties of Pacific water without any influence of sea ice formation/melting or Arctic MW. Because of this and other minor differences in end-member values, their estimates are ~0.045 higher in f_{SIM} and ~0.025 lower in f_{MW} than our estimates. For Figure 8, I_{SIM} and I_{MW} were recalculated using their S and $\delta^{18}O$ data with our end-member values listed in Table 1. As described by *Macdonald et al.* [1999], I_{SIM} increased sharply between 1989 and 1991 and has remained fairly constant since then. Another increase was observed between 2006 and 2007 (Figure 8). However, it should be noted that a trend in SIM was not clear during the 2000s at stations CB2 or CB29 in the west and east of Station A, respectively (Figures 4f and 7).

[17] During the past 20 years, I_{SIM} in the southern portion of the Canada Basin has increased with a mean rate of 0.27 m a^{-1}. Unlike the central basin, f_{SIM} at 50 m showed an increase at Station A [cf., *Macdonald et al.*, 1999], indicating the reduction of sea ice formation during winter. In order to investigate temporal changes in both formation and melting of sea ice, I_{SIM} in winter is estimated by multiplying f_{SIM} at 50 m (taken from samples at 40–60 m depths) by 50 m, assuming that water at 50 m represents the property of winter mixed layer and that the thickness of the water column affected by in situ formation of sea ice is 50 m. Then, differences between the calculated winter I_{SIM} and the observed summer I_{SIM} should represent the amount that SIM increased by summer melting. Results show that increases in summer melt correspond to the observed increases in I_{SIM} between the late 1980s and early 1990s [also see *Macdonald et al.*, 1999, Figure 4] and in 2007 (Figure 8b). *Macdonald et al.* [1999] proposed that the former increase was related to the shift in Arctic Oscillation (AO) to the positive phase and a subsequent shift in the ocean toward the cyclonic regime [*Proshutinsky and Johnson*, 1997]. Under these conditions the ice becomes more divergent and is more mobile and easier to melt in the south [*Rigor and Wallace*, 2004; *Shimada et al.*, 2001]. Figure 8b also shows that there is no significant temporal trend in the summer melting between 1987 and 2007. In contrast, winter I_{SIM} has increased by 4 m during the past 20 years, and this explains most of the observed trend in I_{SIM} at Station A

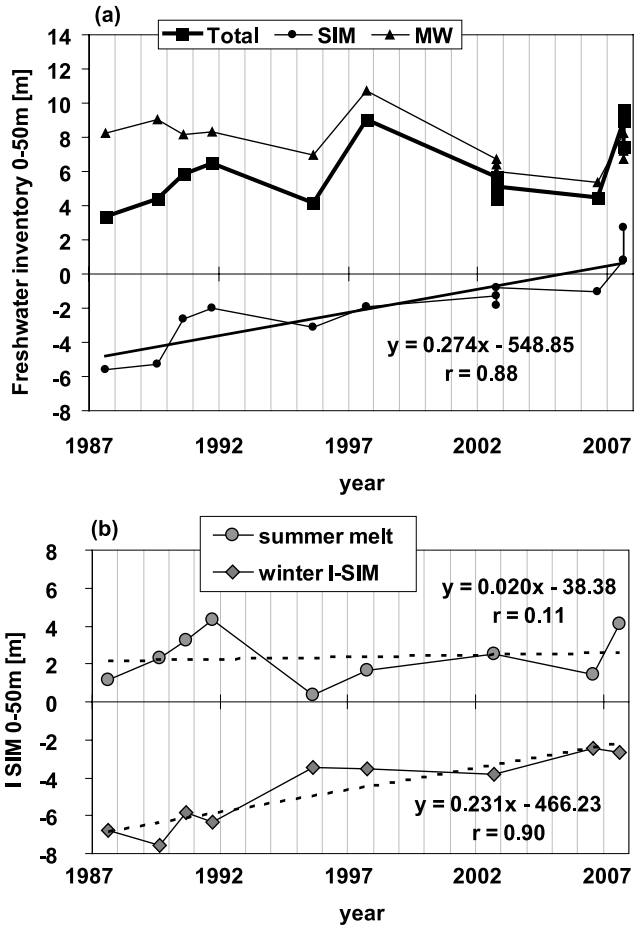

Figure 8. Temporal variation of inventories of (a) total freshwater (squares), MW (triangles), and SIM (circles) and (b) inventory of SIM (I_{SIM}) in winter (circles) and summer input of SIM (diamonds; see text for estimation) in the layer between 0 and 50 m depth at Station A and nearby stations from 1987 to 2007 (see Figure 1 for locations). Regression lines and regression coefficients (r) are also shown.

(Figures 8a and 8b). Converting this 4 m to a change in the annual rate of sea ice formation is not straightforward, because changes in I_{SIM} largely depend on the residence time of SIM in a given region. For example, assuming that the residence time is 10 years and that the system was at a steady state at both end of the 20 year period, the winter formation of sea ice would have decreased by 0.45 m as sea ice. When the residence time is shorter than 10 years and a new steady state has not been achieved, the decrease in sea ice formation would be larger than 0.45 m. *Shimada et al.* [2006] proposed that the large decrease in sea ice observed over the southwestern Canada Basin in the late 1990s triggered a feed back loop in which a reduced ice cover leads to a more mobile upper ocean, more efficient transport of warm Pacific water into the interior Canada Basin and more loss of sea ice. The ice albedo feedback also increases the heat content of surface water to enhance melting and reduce ice formation. These feedback processes may have contributed to the observed increase in SIM in the Canada Basin (Figure 7).

5.2. River Runoff

[18] Results from $\delta^{18}O$ and pAlk showed that there was a large input of North American runoff into the southern Canada Basin in 2007 (Figures 4, 5, and 7). However, the time series data in the southern Canada Basin (Figure 8) reveal that the MW content in 2007 is within the range of fluctuation previously observed. *Macdonald et al.* [2002] mentioned that the offshore plume from the Mackenzie River was constrained to the nearshore and flowed eastward into the archipelago instead of flowing into the Canada Basin in 1974. In 1993 and 1994, *Guay and Falkner* [1997] observed an elevated barium concentration in the surface water of the Canada Basin and suggested it was due to the influence of the Mackenzie runoff in the central Canada Basin, because the Mackenzie has much higher barium concentration than Russian runoff or seawater. *Macdonald et al.* [1999] observed high-f_{MW} water with a very high barium concentration in the southern Canada Basin in 1997. A satellite image also displayed a plume extending from the Mackenzie northward to the basin interior in July 1998 (see cover image of *Geophysical Research Letters*, *26*(15), 1999 from R. W. Macdonald et al.). In the early 2000s, however, the high-alkalinity signal of Mackenzie runoff was absent in the Canada Basin except in the coastal region as shown in Figures 4a and 5a and as observed by *Yamamoto-Kawai et al.* [2005] in 2000 and 2002. Results from $\delta^{18}O$ (Figure 8) also show that the MW inventory in the southern Canada Basin was relatively low in the early 2000s. Therefore, it seems that the flow of Mackenzie runoff is variable and conditions have been favorable to push the Mackenzie water rapidly from the Arctic Ocean via the Archipelago in the early 2000s until 2006. Then in 2007, Mackenzie water remained in the basin interior and contributed the surface freshening of the southern Canada Basin.

[19] In the central part of the Canada Basin, MW content shows a slight positive trend during our observation period (Figure 7). The mean increase rate of MW inventory in the central basin (CB8-CB21) was 0.7 m a^{-1}. A slight increase in NpAlk indicates that precipitation is not likely the source of this increased MW. This increase could be due to input of Russian runoff from the northwest, Mackenzie and other minor North American runoff from the south, or increased transport of runoff from the Bering Sea. Unfortunately, this increase is too small to identify the source of MW using a combination of $\delta^{18}O$ and pAlk. Assuming that this increase rate represents the mean for the region 74–80°N and 130–160°W ($4.8 \cdot 10^5$ km^2), the volume of MW added to the central basin in 2006 and 2007 is estimated to be 670 km^3 or 335 km^3 a^{-1}. This is comparable to the annual input of runoff into the Beaufort Sea from North American rivers (418 km^3 a^{-1} [*Lammers et al.*, 2001]), into the Bering Sea from Russian and American rivers (320 km^3 a^{-1} [*Aagaard et al.*, 2006], or an 0.5 a^{-1} decrease in S of PW. Because there was a large increase in MW in the southern basin and its origin is found to be North American runoff, the MW increase in the central basin could be from Russian rivers or the Bering Sea. Changes in wind field to the anticyclonic mode, together with an increased mobility of surface water caused by a decrease in ice cover [*Proshutinsky et al.*, 2002;

Shimada et al., 2006] may have contributed to the accumulation of MW in the central Canada Basin. The input of runoff into the basin may, in turn, enhance sea ice melt through increased heat input to the surface layer, either directly or indirectly by stabilizing the upper ocean [*Macdonald et al.*, 1999]. Indeed, an increase in SIM was observed north of the runoff plume in 2007, suggesting a linkage between runoff and sea ice melt. River runoff carries not only heat and freshwater but also terrestrial materials such as nutrients, iron, and organic carbon and contaminants [*Dittmar and Kattner*, 2003; *Raymond et al.*, 2007; *Stein and Macdonald*, 2004] and therefore the distribution of river runoff in an ice-free Arctic Ocean will also impact the biological system.

6. Summary

[20] A large surface freshening was observed in the Canada Basin in 2006 and 2007. Resolution of fresh water into constituent sources using S, $\delta^{18}O$ and alkalinity shows that surface freshening in 2006 and 2007 is explained by an increase in SIM over the central Canada Basin, and an episodic input of Mackenzie runoff (with minor North American runoff) into the southern part. River runoff also increased slightly in the central part in 2006 and 2007, which might be due to the strengthened anticyclonic wind forcing and the reduced ice cover during the 2000s [*Proshutinsky et al.*, 2002; *Shimada et al.*, 2006]. The observed increase of SIM in the central basin corresponds to melting an additional 1.3 m a^{-1} of sea ice. However, the SIM content at 50 m depth did not show a temporal trend. Although recent trends in SIM are not obvious in the southern basin, comparison with historical data indicate that SIM has increased in the upper 50 m since 1987, with a mean rate of 0.27 m a^{-1} (0.3 m a^{-1} as sea ice), and mainly due to reduced ice formation in winter. These results indicate that not only sea ice but also the upper ocean is undergoing very rapid changes in the 2000s in the Canada Basin of the Arctic Ocean.

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