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Late winter water column and sea ice conditions in the northern Bering Sea

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[1] Seasonal sea ice concentration and thickness were evaluated on a weekly basis during two years with contrasting ice coverage, 1998–1999 and 2000–2001, using data provided by the U.S. National Ice Center. Ice in the Bering Sea during 1998–1999 was extensive and thick, but by contrast, in 2000–2001, winter sea ice formed late with thin ice, and ice melt proceeded earlier during spring. The presence and timing of a winter polynya (an area of relatively open water or thin ice surrounded by heavier ice) located south of St. Lawrence Island also varied between these two winters. Shipboard measurements south of St. Lawrence Island during two late winter/early spring cruises in 1999 and 2001 showed that some brine injected water was present, resulting in localized areas of bottom water with salinities approaching, or exceeding, 33 psu. The mean salinity of bottom water was significantly higher in 2001 (32.6 psu) than in 1999 (32.3 psu). These varying degrees of brine injection associated with large differences in ice conditions (heavy in 1998–1999, light in 2000–2001) influenced bottom water salinity and density, but there were indications that variation in water mass structure also can explain differences in salinity observed between the two winters. The mean $\delta^{18}O_{H2O}$ values of bottom seawater were significantly higher in 2001 (-0.78 ± 0.16‰ SD) than in 1999 (-0.98 ± 0.20‰ SD) consistent with a more saline, nutrient-rich water being present in 2001. Consistent with these indications, inorganic nutrients (nitrate, phosphate, and silicate) in bottom water were significantly higher in 2001 than in 1999. Although it is seemingly paradoxical that salinities were higher in 2001 (light ice) than in 1999 (heavy ice) when brine injection might have been more prevalent, the sampling period was approximately 1 month earlier in 2001, when ice formation may have been more active. In addition, $\delta^{18}O_{H2O}$ values indicate a higher proportion of Anadyr Water, with higher salinity and nutrients in 2001. Despite these differences in both ice conditions and water mass nutrient chemistry, water column chlorophyll was uniformly low in both years. This indicates that changes in Bering Sea ice regimes during the late winter months, such as may occur under various climate change scenarios, will not necessarily lead to any higher productivity or an earlier onset of seasonal biological production. Despite relatively high inorganic nutrient concentrations in both years, a well-mixed water column was observed with low water column chlorophyll-*a* (chl-*a*) concentrations. These observations suggest that there was little primary production during either cruise in spite of the relatively open water and high water column nutrient concentrations during 2001. Strong southerly winds during winter likely impeded ice formation, vertically mixed the water column, and prevented early spring open water primary production. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 1615 Global Change: Biogeochemical processes (4805); 1050 Geochemistry: Marine geochemistry (4835, 4850); 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; *KEYWORDS:* Bering Sea, sea ice, polynya, sediment chlorophyll, oxygen isotopes, St. Lawrence Island

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1. Introduction

[2] The sea ice regime of the Bering Sea ecosystem has strong seasonal cycles [*Muench and Ahlnäs*, 1976] and a high degree of interannual variability in climate patterns [*Walsh and Johnson*, 1979; *Niebauer*, 1981]. The seasonal cycle of sea ice begins with its formation along the coasts of the northern Bering Sea in October and November [*Overland and Pease*, 1982]. A small percentage of pack ice moves from the Arctic Ocean south through Bering Strait, while the majority freezes within the Bering Sea [*Pease*, 1980; *Overland and Pease*, 1982]. As winter progresses, prevailing northerly winds force the ice southward [*Fay*, 1974; *Muench and Ahlnäs*, 1976; *Overland and Pease*, 1982], setting up what has been described as a conveyor belt of ice movement [*Pease*, 1980]. As ice moves southward it encounters warmer surface water and ultimately melts. This cools the surface water and allows the next southward bound ice movement to advance further. An important feature in this process are polynyas, or relatively open areas of water in ice-covered seas, which form typically to the south of all major peninsulas and islands in the Bering Sea, including St. Lawrence Island [*Overland and Pease*, 1982; *Grebmeier and Cooper*, 1995]. New ice is formed within these polynyas and it is subsequently moved south by northerly winds [*Muench and Ahlnäs*, 1976; *McNutt*, 1981]. In particular, the St. Lawrence Island polynya (SLIP) is an important site for sea ice production [*Muench and Ahlnäs*, 1976; *Stringer and Groves*, 1991].

[3] Maximum Bering Sea ice extent usually occurs about 1,000 km south of Bering Strait at the shelf break near the 200 m isobath [*Muench and Ahlnäs*, 1976; *Alexander*, 1981; *Niebauer*, 1981], however, the location of the ice edge is highly variable. In this study, we defined a heavy ice year as one in which the ice edge reaches St. Paul Island (57.3°N, 170.3°W) or beyond. A light ice year might have a maximum extent only to St. Matthew Island (60.7°N, 172.7°W) or Nunivak Island (60.4°N, 166.5°W) [*Overland and Pease*, 1982]. In the northern Bering Sea, for which we will use the operational definition as being located north of St. Matthew Island, ice melt usually begins in April [*Pease*, 1980] and by late June the sea is ice-free following melt and ice transport northward through Bering Strait [*McRoy and Goering*, 1974; *Overland and Pease*, 1982].

[4] In this study, we took advantage of shipboard opportunities to sample late winter waters in the St. Lawrence Island region, and combined this relatively rare arctic winter deployment of U.S. Coast Guard icebreakers in two separate years with analyses of sea ice thickness and concentrations. The two years of data available, 1998–1999 and 2000–2001, had contrasting sea ice conditions. In 1998–1999 heavy ice was encountered, while in 2000–2001 the Bering Sea was essentially ice-free until March with very light ice concentrations and conditions in April and May. These two contrasting winter conditions may be relevant for understanding the consequences of longer-term variations in the climatology of the Bering Sea. In particular we were interested in how wind forcing and its effects on sea ice variation could impact the timing of biological production. The relationship between sea ice variation, wind forcing, and biological productivity is complex [e.g., *Arrigo et al.*, 1997; *Sakshaug and Slagstad*, 1992; *Constable et al.*, 2003], but the high degree of interannual variation in sea ice coverage of the Bering Sea may provide insights applicable to polar regions in general.

[5] Bering Sea climate conditions during 1999 were similar to the "cold years" prior to 1976, with negative sea surface temperature (SST) and air temperature anomalies and extensive ice coverage [*Radchenko et al.*, 2001]. By contrast, the greatly reduced sea ice conditions and an early warming of SST during spring were characteristic of 2001 and may be similar to scenarios projected with global warming [*Clement*, 2002]. A warming trend has been observed in much of the Arctic throughout the 1980's and 1990's [*Grotefendt et al.*, 1998; *Rothrock et al.*, 1999; *Stabeno and Overland*, 2001]. Whether this warming is due to a natural oscillation or anthropogenic global warming is still unclear. However, there is a general consensus that both Arctic sea ice extent and sea ice thickness have been reduced over the past 20 years [*Grotefendt et al.*, 1998; *Rothrock et al.*, 1999]. It has also been hypothesized that polynyas may be localized areas of increased early season production [*Stirling*, 1980; *Cavalieri and Martin*, 1994; *Gilchrist and Robertson*, 2000]. Our objective in this study was to improve understanding of Bering Sea ecosystem changes by documenting how interannual ice cover variations impact Bering Sea water masses, nutrient concentrations, and biological biomass in the water column concentrations.

2. Materials and Methods

[6] Our retrospective analysis of sea ice conditions in the Bering Sea used data available from the U.S. National Ice Center (http://www.natice.noaa.gov). In addition, physical, hydrochemical, and biological oceanographic data were analyzed from cruises of the USCGC *Polar Sea* (13–27 April 1999) and USCGC *Polar Star* (17 March to 1 April 2001). Some other data from these cruises are already available elsewhere [*Grebmeier and Dunton*, 2000; *Cooper et al.*, 2002; *Lovvorn et al.*, 2003].

2.1. Sea Ice Data

[7] Ice map images were downloaded from the U.S. National Ice Center Web site (www.natice.noaa.gov) in interchange file format (.e00). ArcExplorer 1.1 Import Utility (ESRI®, Inc., Redlands, CA; see http://www.esri.com) was used to convert each map from interchange file format to the ESRI® ArcInfo coverage format. Each ice map was checked against the original "Egg Code" map from which it was digitized. (Egg Code maps are representations of sea ice coverage, condition, and state of development using numerical codes that are placed within oval symbols on National Ice Center sea ice coverage maps.) All discrepancies between the values of the Ice Code field in the digitized maps and the values in the Egg Code maps were changed to match the original Egg Code values, so all explicit and implicit errors present in the original Egg Code values remain in the analyses we accomplished. Each Egg Code map was created from one or more sources of information with various spatial resolutions. The sources include Radarsat (Radar Satellite),

OLS (Operational Linescan System), AVHRR (Advanced Very High Resolution Radiometer), and estimation from a combination of climatology and meteorology. The majority of sea ice data was obtained by the National Ice Center as satellite data.

2.2. Field Data

[8] Physical, hydrochemical, and biological data were collected on both cruises being evaluated in this study and the methods for these collections are outlined below (see *Cooper et al.* [2002] for further description of methodology).

2.2.1. Salinity, Inorganic Nutrients, Sigma-t, Temperature, and Stable Oxygen Isotope Composition

[9] Hydrographic measurements were made using a conductivity-temperature-depth (CTD) profiler with an attached rosette of water collection bottles from which water samples for oxygen isotopes, inorganic nutrients, and chlorophyll were obtained.

[10] Samples for inorganic nutrients (nitrate, phosphate, silicate and ammonium) were frozen shipboard and returned frozen to the Marine Science Institute at the University of California, Santa Barbara, where nutrient concentrations were determined using an autoanalyzer.

[11] The stable oxygen isotope composition of water samples was determined using an automated carbon dioxide equilibration system linked to a Finnigan Delta Plus stable isotope mass spectrometer, with an analytical precision of ±0.04 SD (determined using replicates of an internal water standard, n = 14). These data are expressed in the delta notation, where $\delta^{18}O_{H2O} = [(^{18}O/^{16}O_{sample} \div {}^{18}O/^{16}O_{V\text{-}SMOW}) - 1] \times 1000$ (V-SMOW is Vienna-Standard Mean Ocean Water).

2.2.2. Water Column Chlorophyll-*a*

[12] Seawater samples (250 mL subsamples) were collected from Niskin bottles attached to a CTD/Rosette at up to 12 representative depths over the entire water column. Samples were filtered using Whatman GF/F filters and extracted in 10 mL of 90% acetone. After a 24-hour extraction period, at 4°C, the chl-*a* concentration was measured using a Turner Designs AU-10 fluorometer [*Welschmeyer*, 1994]. At all times, water samples, filters, and acetone extract were kept in the dark as much as possible so as not to affect chl-*a* concentrations. Integrated chl-*a* was calculated by averaging the concentration at adjacent depths and multiplying by the depth difference in each pair of adjacent depths. Finally, all values are summed to give total integrated water column chl-*a* mg m^{-2}.

2.2.3. Sediment Chlorophyll-*a*

[13] Our method followed that of *Cooper et al.* [2002]. Briefly, one cm^3 of surface sediment was collected from the surface of a van Veen grab prior to its opening using a modified syringe. Although the van Veen grab does result in some disturbance of sediments, the sediments in this region are subject to significant macrofaunal bioturbation. Comparison of surface sediments collected at the same stations on the Chukchi shelf (<100 m) indicates that there are no significant differences in sediment chlorophyll in surface sediments collected with a van Veen grab and a HAPS corer that results in less sediment disturbance, although significant differences were present in deeper waters with less bioturbation (L. Cooper, unpublished data, 2002). Following collection, sediments were placed in a centrifuge tube along with 10 mL of 90% acetone. To ensure extraction of all chl-*a*, tubes were refrigerated for 12 hours in the dark and the mass of chl-*a* associated with that 1 cm^3 of surface sediment was measured with the Turner Designs AU-10 fluorometer. Two sediment chlorophyll-*a* samples were taken at each station and the mean of the two is reported here in units of chlorophyll-*a* mg m^{-2} of surface sediments.

3. Results

[14] Ice concentration and ice thickness were evaluated on a weekly basis from December through June 1998–1999 and 2000–2001. Field data collection included 36 stations in April 1999 and 42 stations in March 2001 (Figure 1). Thirty-one stations were reoccupied between the years and were used in paired comparisons, with the Wilcoxon Signed-Rank Test, a nonparametric, paired comparison test. We chose a nonparametric test for data analysis because the data were not normally distributed and sample sizes were low.

3.1. Sea Ice Conditions

[15] Ice extent, concentration, and thickness were very different during 1998–1999 and 2000–2001 over both temporal and spatial scales. During early winter of 1998, ice formed quickly and advanced southward reaching St. Lawrence Island by mid-December. Ice concentration was 90–100% from mid-January to early May 1999 for most of the region south of Bering Strait to St. Matthew Island (Figures 2 and 3). The maximum winter ice extent occurred during late April near the Pribilof Islands, or 920 km south of Bering Strait. Ice breakup began in late May and by mid-June most of the SLIP region was ice-free.

[16] Ice formed much more slowly in the Bering Sea during winter of 2000–2001 (Figures 2b, 2d, and 2f). In addition, a major ice edge retreat occurred during January and February 2001 for the central Bering Sea. In mid-January, the ice edge moved from 181 km south of St. Lawrence Island to 4 km south of the island with a low concentration north of the island to Bering Strait (not shown). These unusual conditions persisted until mid-February (Figure 2b). This retreat was primarily caused by a shift in prevailing winds, rather than surface warming. A southward ice edge progression resumed during early March and reached 200 km south of St. Lawrence Island during mid-March (Figure 2f). Maximum extent reached just south of St. Matthew Island (730 km south of Bering Strait) and occurred during early April. The ice edge quickly retreated after only a few days at this southern limit. Ice breakup began in early May, with most of the central Bering Sea ice-free by mid-May (Figure 3e). The western and eastern portions were ice-free by the first of June (not shown).

3.2. Wind Speed and Direction

[17] Wind data were collected at two different sites for analysis of wind speed and wind direction during February 2001. Data recorded by a buoy at 57.08°N, 177.78°W show that winds were generally out of the north on 1 and

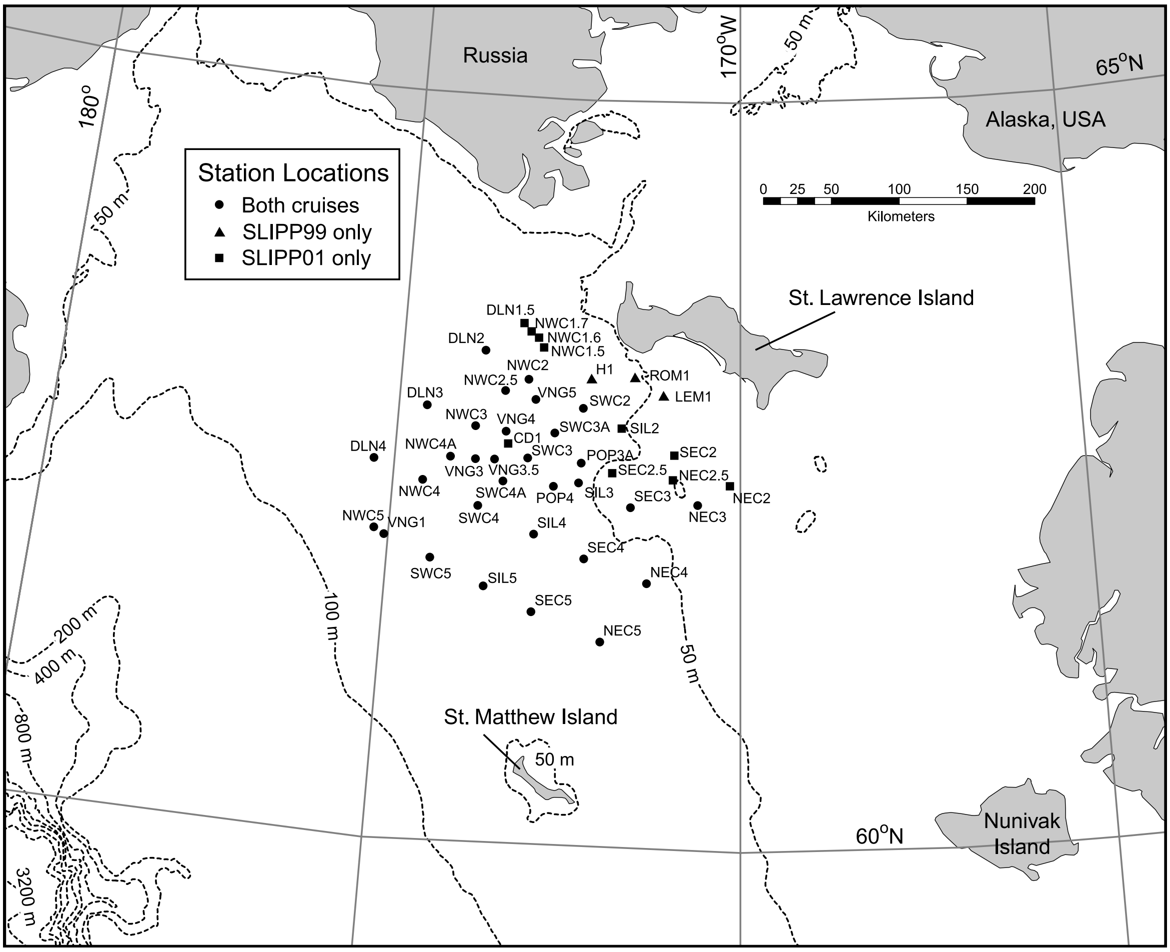

Figure 1. Locations of stations occupied in April 1999 and/or in March 2001.

2 February. On 3 February the wind direction shifted to the east. For the next 5 days, wind was stronger and generally from the south (Figure 4). Data measured at Nome, Alaska show a generally eastern wind direction for the first five days of February. From 6 to 14 February, wind is largely out of the south with stronger speeds up to 25 knots. Around 15 February the wind direction became more variable, but was primarily out of the west and north until the end of February (Figure 5). This wind forcing likely led to reduced ice conditions that occurred in the northern Bering Sea during late winter, 2001 (Figure 2b).

3.3. Ice Thickness

[18] In 1999, the SLIP region was predominately covered in young ice (10–30 cm) from December through February (Figures 6a, 6c, and 6e). In March the ice was mainly thin first year ice (30–70 cm) becoming medium first year ice (70–120 cm) in April, except for a polynya south of St. Lawrence Island, which was characterized by ice <10 cm thick (Figures 7a and 7c). SLIP was predominately covered by young ice (10–30 cm) for the entire ice season (Figures 6 and 7) during 2001. The only exception occurred in April, when the predominant stage of ice was thin, first-year ice (30–70 cm) in the west (Figure 7d). Since sea ice is generally not stable, smooth, or uniform in thickness or concentration [*Fay*, 1974; *Comiso*, 1995], these measures of ice thickness should not be interpreted as absolute, but as estimates of the predominant stage of ice development.

3.4. Polynya South of St. Lawrence Island

[19] A polynya formed south of St. Lawrence Island (SLI) in mid-January 1999 and extended 25 km south from the southern shore of the island. Except for a brief disappearance in early March, the polynya was relatively constant over the winter and grew in size in early April just prior to the beginning of ice melt. The polynya of 2001 also formed in mid-January, however, during February most of the central Bering Sea was ice-free due to ice edge retreat up to the shore of SLI. By mid-March a polynya formed again south of the island and extended about 20 km south. While maps of ice concentration show the polynya to only extend 20–25 km south of SLI, maps of ice thickness give additional information by revealing a larger area of thin ice (Figures 6 and 7). This area is highly variable over time, but thin ice is often found to extend for 20–200 km south of the island with a width of approximately the length of the island (~100 km). It seems reasonable to assume that this area of thin ice is an important ice production zone and associated with the polynya.

3.5. Hydrographics

[20] Depths sampled were from 39 to 82 m in the region south of St. Lawrence Island. Vertical profiles of salinity,

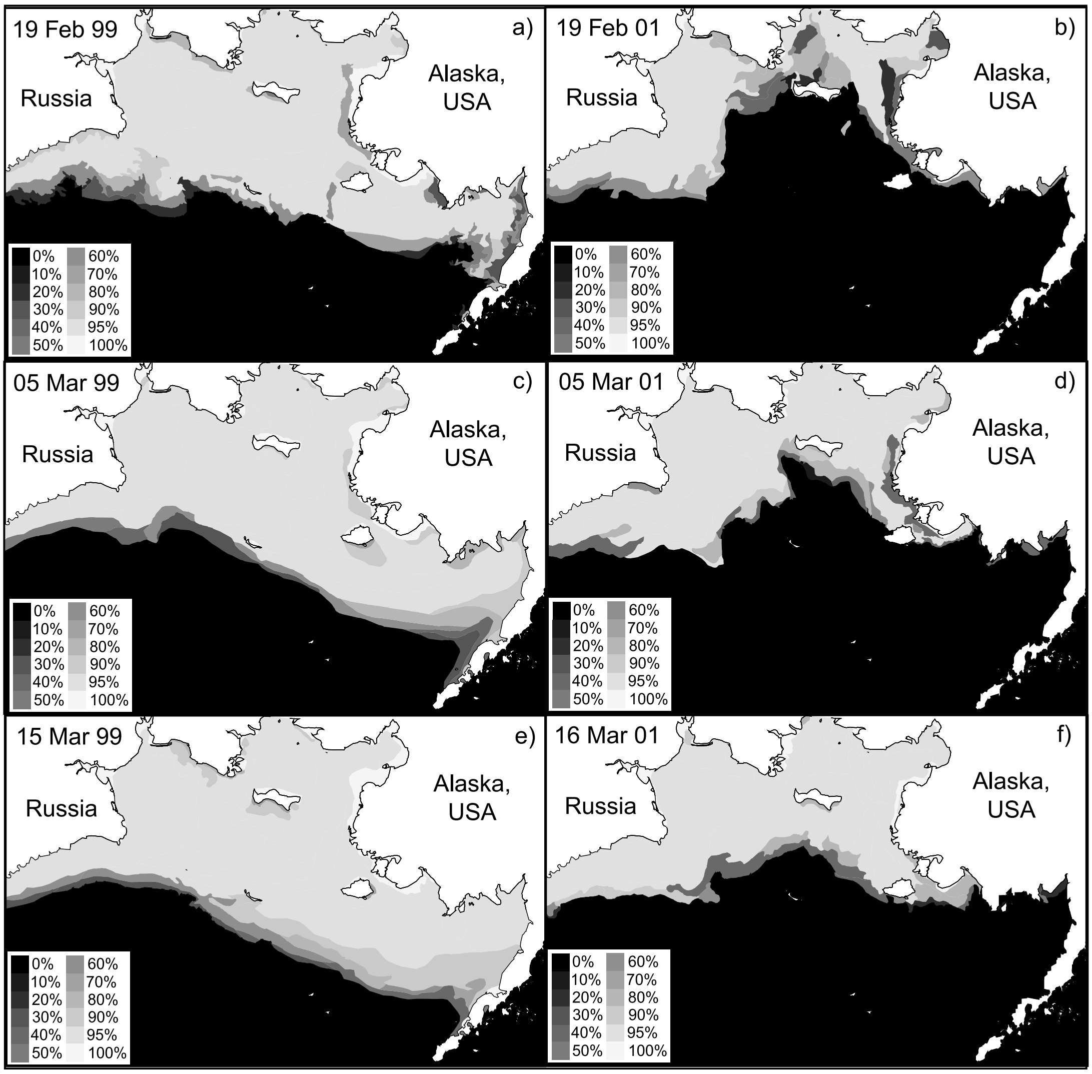

Figure 2. Sea ice concentration during late winter and early spring 1999 and 2001. Data were obtained from the U.S. National Ice Center Web site (www.natice.noaa.gov).

temperature, and sigma-t are representative of a well-mixed water column in both years (Figure 8). Some stations showed a small degree of stratification, but this was based almost solely on salinity, not temperature. Sigma-t was highly dependent on salinity with a correlation coefficient of 0.998 during both cruises combined. Water column chlorophyll profiles also indicated that by and large the water column in both years was well mixed, and relatively low levels of chlorophyll *a* were observed (Figure 9). Comparing between April 1999 and March 2001, chlorophyll concentrations were marginally higher in April 1999 (Figure 9), probably reflecting higher light irradiances in April. In April 1999, at one location (LEM1), the only station occupied that year within the open water of the St. Lawrence Island polynya, chlorophyll concentrations were as high as 2 mg m^{-3}, and photosynthetic active radiation measurements indicated that irradiances were above typical compensation levels for ice associated algae [*Cooper et al.*, 2002; unpublished data].

[21] In 1999, bottom water salinities ranged from 31.6 psu in the east to 33.1 psu in nearshore areas in the west (Figure 10a). In 2001, bottom water salinities varied within a narrower range, from 32.0 to 32.9 psu (Figure 10b). Generally, three water masses are thought to make up the northern Bering Sea shelf: Anadyr Water ($S > 32.5$ psu) is typically found on the western side of the region, Alaska Coastal Water ($S < 31.8$ psu) flows along the coast of Alaska, while Bering Shelf Water ($S = 31.8 - 32.5$ psu) is found in the middle [*Coachman et al.*, 1975; *Grebmeier et al.*, 1988]. Flow is largely northward across the Bering shelf toward Bering Strait, however, flow reversal may occur occasionally [*Schumacher et al.*, 1983; *Overland and Roach*, 1987]. Salinities at or approaching 33 psu are likely to be influenced by brine injection [*Schumacher et al.*, 1983]. This distinction is also based on previous results that show that typical salinities (during summer without the influence of sea ice processes) are approximately 32.5 psu or less [*Grebmeier et al.*, 1990; *Grebmeier*, 1993; *Grebmeier and Cooper*, 1995]. Generally, bottom water salinities were

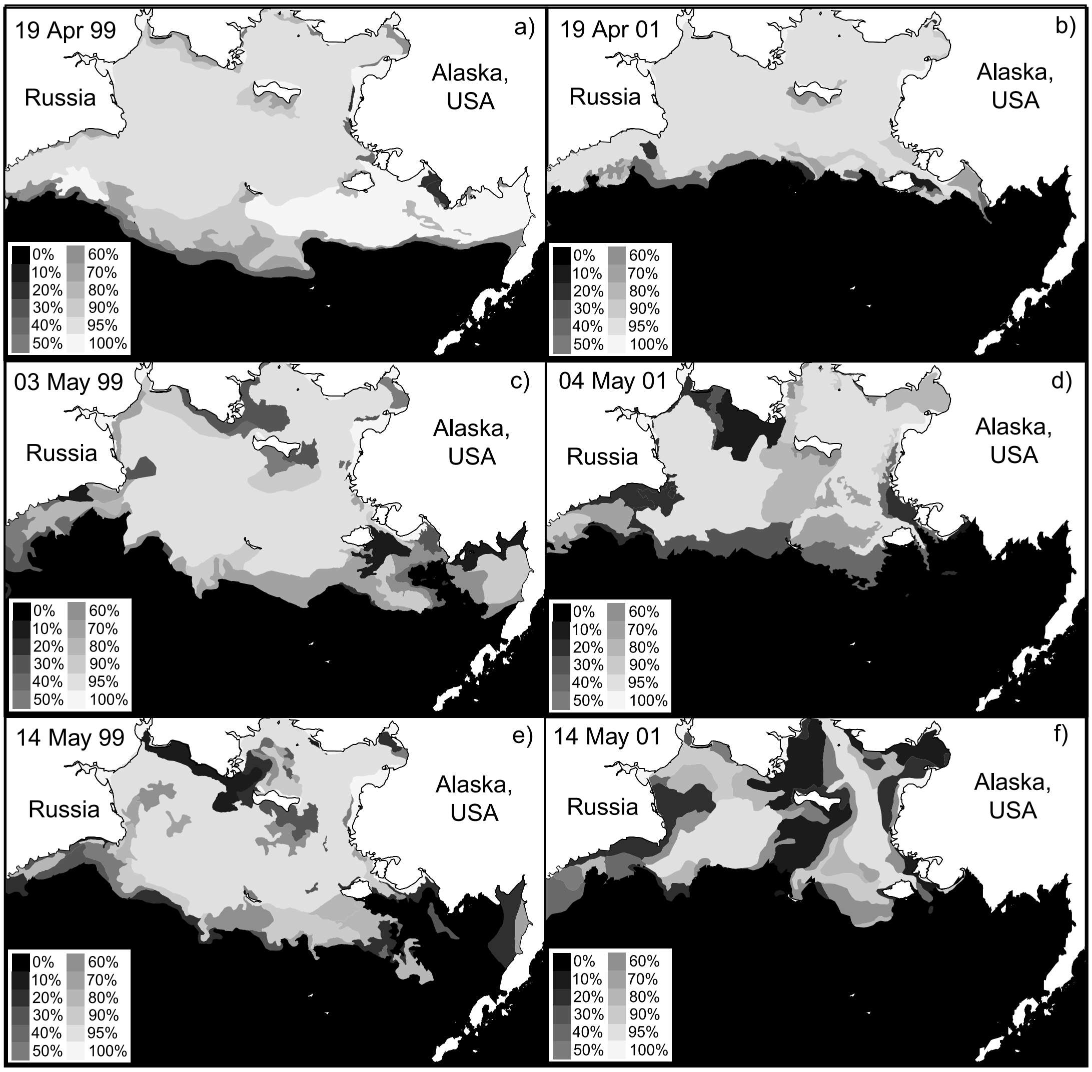

Figure 3. Sea ice concentration during spring and early summer 1999 and 2001. Data were obtained from the U.S. National Ice Center Web site (www.natice.noaa.gov).

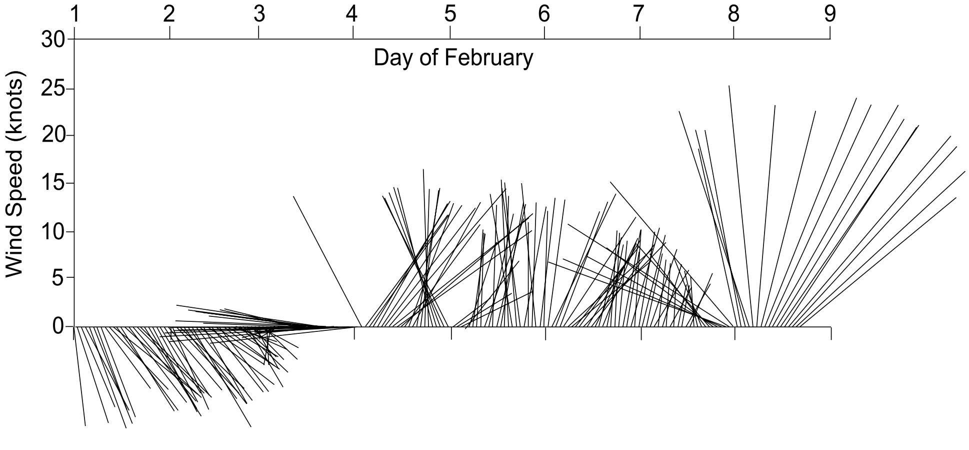

Figure 4. Hourly wind speed and direction during February 2001 as measured at 57.08°N, 177.78°W by a NOAA data collection buoy. Data were obtained from the National Data Buoy Center Web site (www.ndbc.noaa.gov). Wind direction is presented as the direction the wind is coming from in degrees clockwise from south (e.g., south = 0°, 360°; west = 90°; north = 180°; east = 270°).

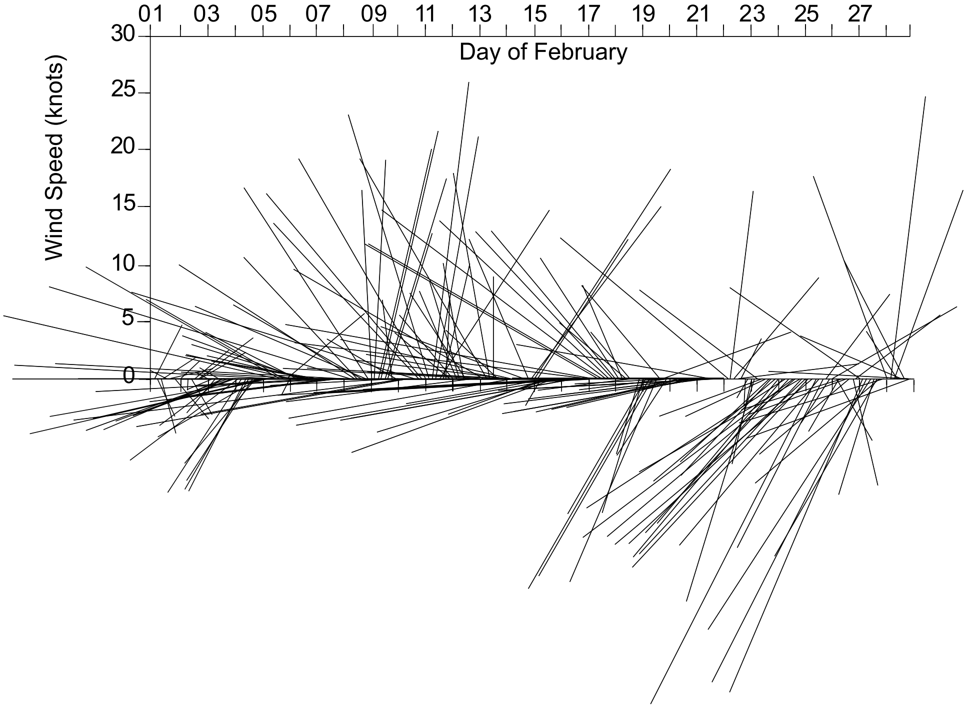

Figure 5. Wind direction and speed during February 2001 presented as 3-hour averages and measured at Nome, Alaska (64.50°N, 165.28°W). Data were obtained from the U.S. National Weather Service Web site (www.nws.noaa.gov). Wind direction is presented as the direction the wind is coming from in degrees clockwise from south (e.g., south = 0°, 360°; west = 90°; north = 180°; east = 270°).

higher in March 2001 (mean = 32.59 ± 0.21 SD) than in April 1999 (mean = 32.32 ± 0.38 SD). For water samples collected on both cruises at the same locations, salinities (and sigma-t densities) in March 2001 were significantly higher (Wilcoxon signed-rank test, $p < 0.0001$; $n = 25$) within a range of 32.1–33.0 psu for the entire study area (Figure 11). The difference in salinity was consistent over the entire study region with higher salinities occurring during March 2001 as illustrated in Figure 11. The greatest differences in salinity between years were in the central and eastern part of SLIP, specifically stations such as POP4, SEC3, SEC4, NEC4, and NEC5 (see Figure 1 for locations). The stable oxygen isotope composition of water was also more depleted in ^{18}O in April 1999 (mean $\delta^{18}O_{H2O}$ = −0.98 ± 0.20; n = 68) than in March 2001 (mean $\delta^{18}O_{H2O}$ = −0.78 ± 0.16, n = 83) (Figure 12). For bottom water samples collected on both cruises at the same locations, $\delta^{18}O_{H2O}$ values in March 2001 were significantly less negative (Wilcoxon signed-rank test, $p < 0.0001$; $n = 30$), although it is worth pointing out that the small mean difference between years for collections at the same locations (−0.97 in 1999 versus −0.80 in 2001) does not greatly exceed analytical precision (±0.04 for these samples). Relative to salinity, most of the $\delta^{18}O_{H2O}$ values fall above a mixing line for $\delta^{18}O_{H2O}$ values versus salinity determined for the bottom waters of the Bering Sea in the summer, salinity = 0.62 $\delta^{18}O_{H2O}$ − 21.1 [*Cooper et al.*, 1997], although at higher salinities (>∼33), samples plotted to the right of this regression line (Figure 13). A plot of temperature versus salinity shows that elevated salinities (∼33 psu) are close to the freezing point of seawater (Figure 14), which would be consistent with brine injection in some of the more saline samples.

[22] Bottom water nitrate was also significantly higher in March 2001 than in April 1999 (Figure 15). Mean values for bottom water in 1999 were 11.4 μM ± 3.7. SD and 15.8 μM ± 0.5 SD in 2001. Due to a well-mixed water column, there was little evidence for any draw-down of nutrients in the surface layers (Figures 8–9). Mean surface nitrate concentrations in April 1999 were 11.3 μM ± 4.4 and 14.7 ± 0.4 in March 2001. For bottom water samples collected on both cruises at the same locations, nitrate concentrations in March 2001 were significantly higher (Wilcoxon signed-rank test, $p < 0.0001$; $n = 29$). These patterns of significantly higher nutrients in 2001 were also reflected in phosphate and silicate values for samples collected at the same locations both years [Wilcoxon signed-rank test; $p < 0.0001$, $n = 29$ (silicate), $n = 28$ (phosphate)]. The mean concentrations in bottom water for phosphate were 1.23 ± 0.29 SD (1999) and 1.62 ± 0.21 SD (2001). The mean concentrations for silicate in bottom water were 29.4 ± 8.1 SD (1999) and 43.6 ± 7.1 SD (2001).

[23] Water temperatures were cold in both years and the water column was almost completely isothermal at most stations. In 1999, the range of bottom water temperature was −1.80 to −1.67°C. A larger range (−1.80 to −1.19°C) was observed in March 2001 due to sampling at six southerly stations not sampled in 1999. Integrated water column chlorophyll-*a* over the whole water column ranged from 9.43 mg m^{-2} to 78.20 mg m^{-2} in 1999 and from 3.11 mg m^{-2} to 54.22 mg m^{-2} in 2001. Previous results for

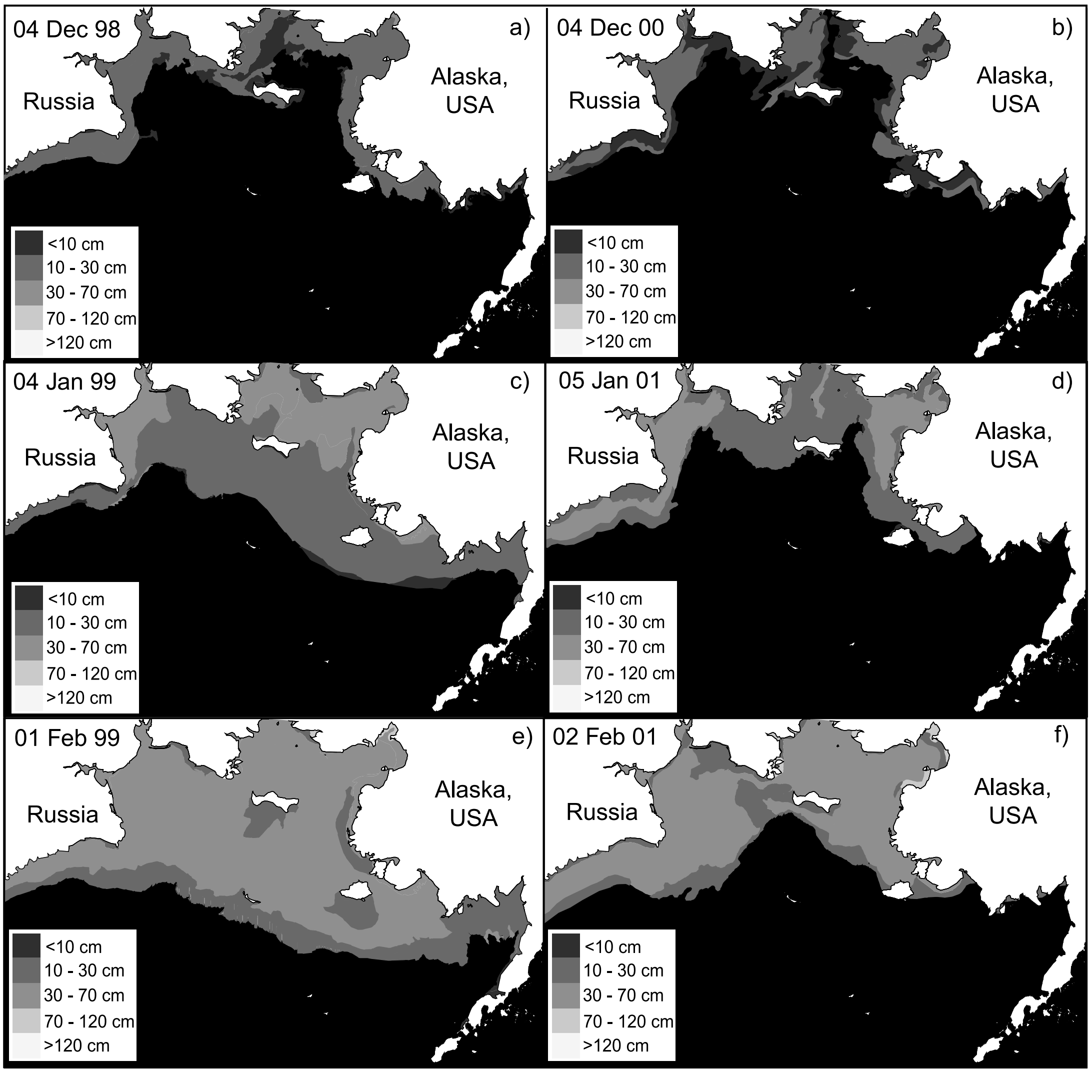

Figure 6. Sea ice thickness during winter 1999 and 2001. Data were obtained from the U.S. National Ice Center Web site (www.natice.noaa.gov).

this region during several different cruises from early spring through autumn [*Cooper et al.*, 2002] indicate that these late winter values are the lowest so far observed in the seasonal cycle. Spring values may exceed 1000 mg m^{-2} while summer and autumn values tend to show a progressive decline to approximately 50–200 mg m^{-2} in September. Sediment chlorophyll-*a* measured in surface sediments (0–1 cm) ranged from 4.15 to 13.41 mg m^{-2} in 1999 and 0.12 to 17.05 mg m^{-2} in 2001, which is also the lowest values so far observed in this region over the seasonal cycle [*Cooper et al.*, 2002].

4. Discussion

[24] The winter of 1998–1999 had early ice formation (most of SLIP covered in 90% ice by early December 1999), extensive spatial coverage (entire northern Bering Sea, south to St. Matthew Island, covered in 90% ice from January to April, except for the polynya south of SLI), and typical melt timing (Figures 2 and 3). By contrast, the winter of 2000–2001 was characterized by late ice formation (SLIP not covered until March), thin ice (the predominant stage of development was young ice), and early ice melt (central Bering Sea was ice-free by mid-May) (Figures 2, 3, 6, and 7). Much of the region south and southwest of St. Lawrence Island typically has large leads, polynya-like features, and open water during the winter due to very high ice shear around the island [*Muench and Ahlnäs*, 1976]. *Muench and Ahlnäs* [1976] also found that in 1974 the ice concentration was generally lower from the coastline of SLI to about 20–25 km offshore from January through April. Satellite images in 2001 indicated a much larger area of reduced ice thickness, with polynya formation apparent throughout the winter (Figures 6 and 7).

[25] Paired comparison tests between data collected during March 2001 and April 1999 indicated that there were significant differences between years in both salinity and sigma-t. We considered whether the higher salinity and sigma-t in March 2001 could be in part due to brine injection within the St. Lawrence Island polynya prior to

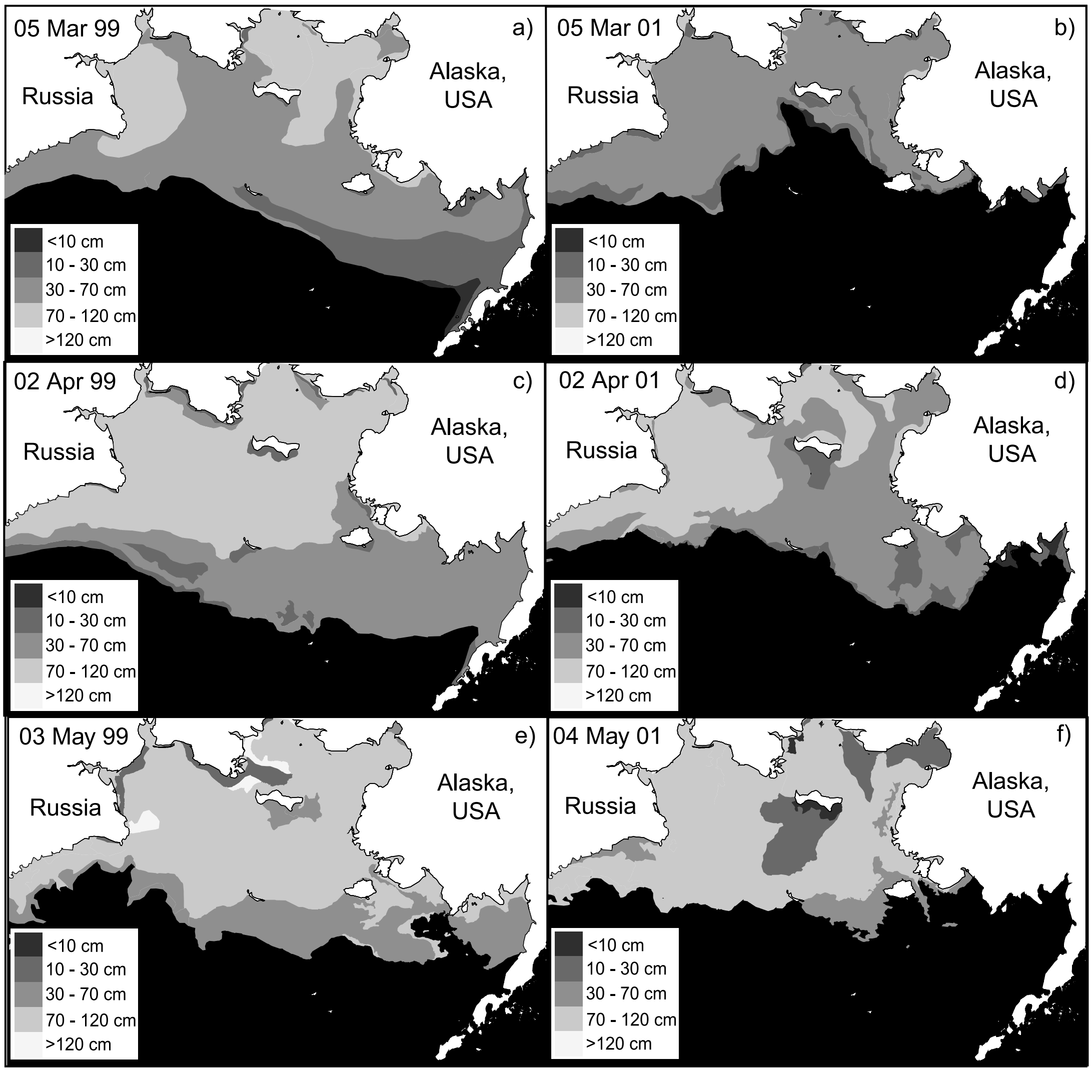

Figure 7. Sea ice thickness during spring and early summer 1999 and 2001. Data were obtained from the U.S. National Ice Center Web site (www.natice.noaa.gov).

our sampling. After the wind direction shifted in early February, this polynya reformed and ice formation resumed in late February. As this new ice was produced, brine was likely rejected and high saline water sank to the seafloor, raising salinity and increasing bottom water density. Previous results [*Muench and Ahlnäs*, 1976; *Schumacher et al.*, 1983; *Stringer and Groves*, 1991] indicate that when open water is present south of St. Lawrence Island, SLIP is likely to be an important ice production and brine injection zone. SLIP was covered in young ice (10–30 cm) during early April, while surrounding areas were characterized by thicker sea ice (Figure 7d). Ice production therefore probably accounts for some of the higher salinities observed in 2001, particularly in those locations where salinities approached 33 psu. However, brine injection was not the sole determinant of the significantly higher mean salinities in 2001, nor was brine injection insignificant in 1999. Our relatively brief shipboard sampling periods also do not necessarily specify the location or timing of any brine formation that might have affected bottom salinities. The maximum salinities (>33 psu) observed during both years were observed in 1999. Based upon salinity variation in the two separate years, both brine injection and water mass variation could have influenced the salinities observed. We use data on stable isotope ratios in order to separate these two potential sources of variation. The mean $\delta^{18}O_{H2O}$ values of bottom seawater were slightly more negative (−0.98‰) in 1999 relative to 2001 (−0.78‰) where samples were collected in both years at the same stations. Since the isotopic fractionation associated with sea ice formation is small in its impact over the whole water column that is affected when the top parcel is frozen, it seems likely that a modest difference in water masses existed between April 1999 and March 2001, with the April 1999 water masses having a slightly higher fraction of a freshwater runoff component. This is also consistent with the significantly higher nitrate concentrations observed in 2001, as higher nutrient water in this portion of the Bering Sea is

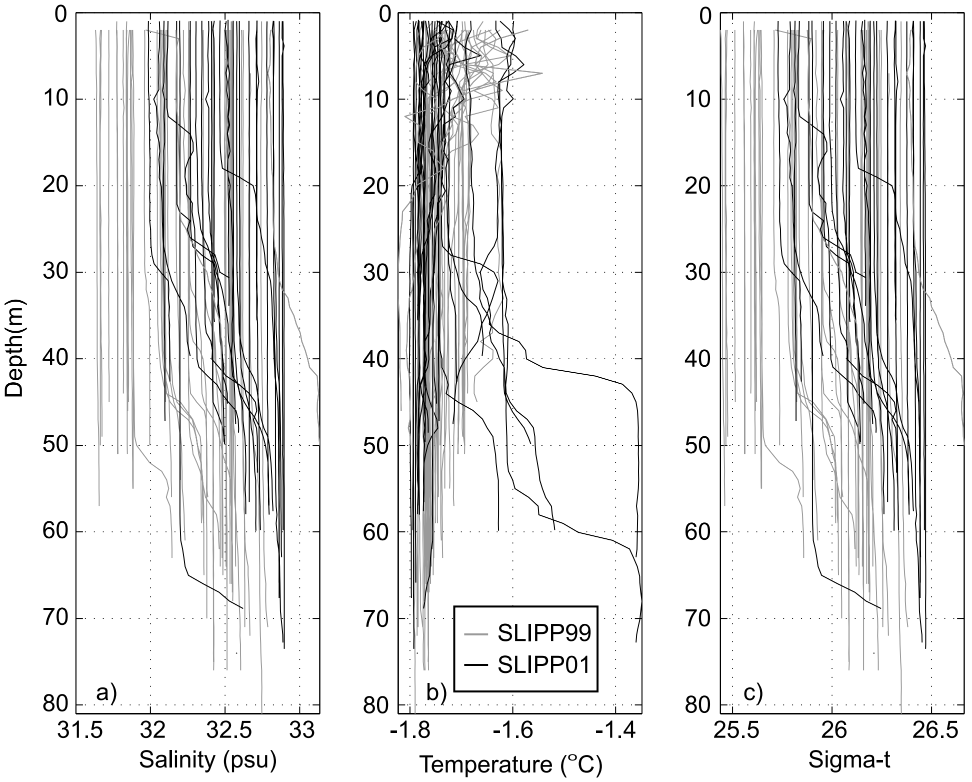

Figure 8. (a) Salinity, (b) temperature, and (c) sigma-t profiles for SLIPP99 and SLIPP01 at all stations.

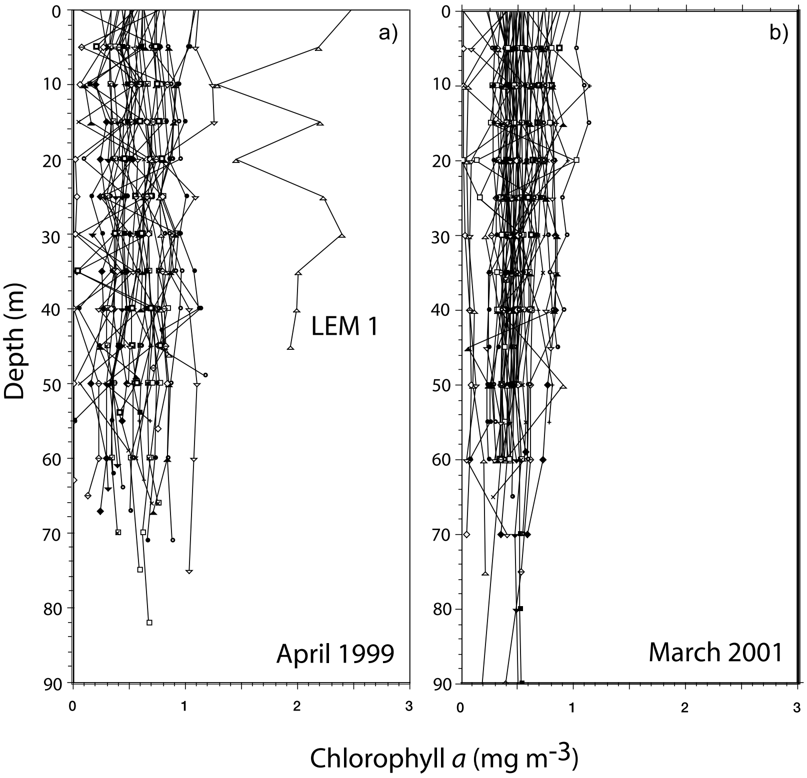

Figure 9. Chlorophyll *a* profiles for (a) SLIP99 and (b) SLIP01 at all stations, showing low homogeneous water column concentrations of chlorophyll. The sole exception with relatively elevated chlorophyll, station LEM 1, was located in the St. Lawrence Island polynya and was the only station on the 1999 cruise in open water (see Figure 1 for location).

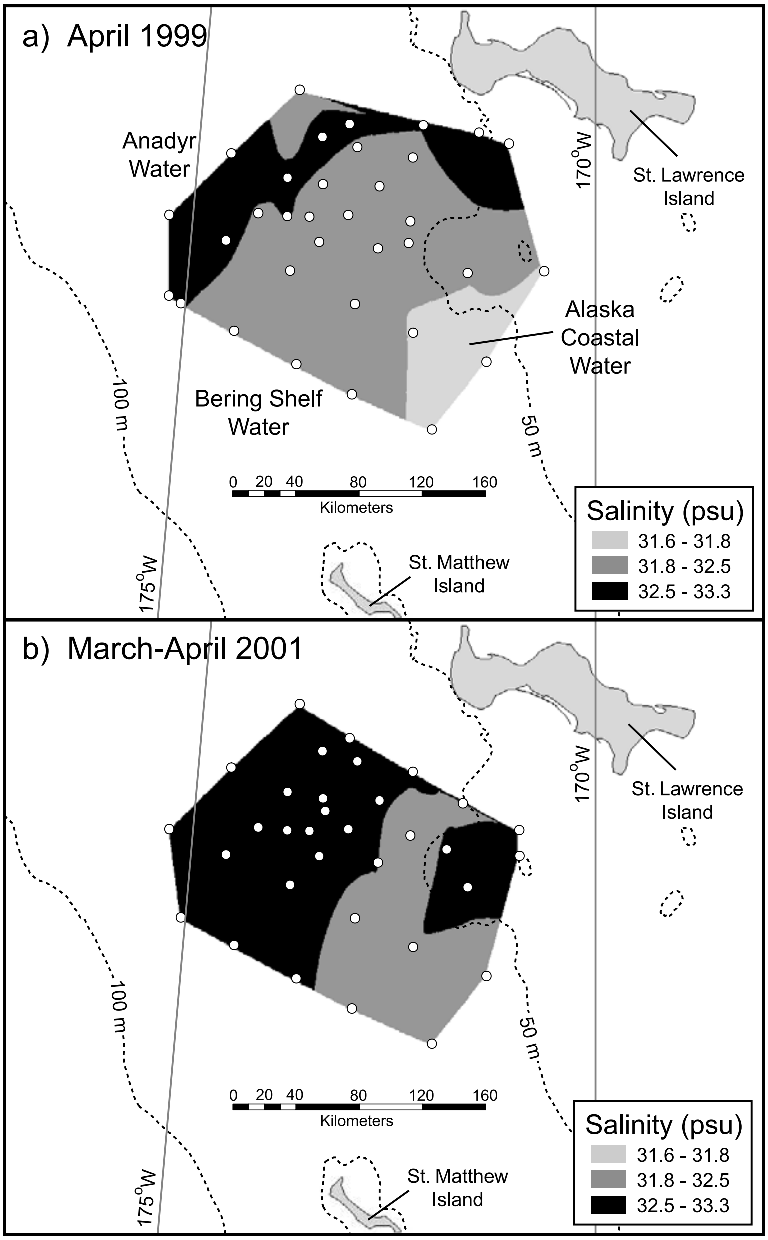

Figure 10. Bottom water salinity during April 1999 and March 2001. Interpolation among station values (open circles) was preformed using ESRI® Spatial Analyst extension to ArcInfo 8.

associated with less negative $\delta^{18}O$ values and higher salinities. According to *Cooper et al.* [1997] the $\delta^{18}O_{H2O}$ values of bottom water in the Bering Sea in summer can be related to salinity by the equation, $\delta^{18}O_{H2O} = 0.62 * \text{salinity} - 21.1‰$. Using the mean bottom water salinity observed in April 1999, 32.32, this equates to a mean bottom water $\delta^{18}O_{H2O}$ value of $-1.06‰$, very close analytically to the mean value that was observed, $-0.97‰$. In 2001, mean bottom water salinity was 32.59 and the predicted mean $\delta^{18}O_{H2O}$ value of bottom water, based upon the *Cooper et al.* [1997] equation, is $-0.89‰$, also very close to the mean value of $-0.78‰$ that was observed. When we plot salinity versus $\delta^{18}O_{H2O}$ values for our samples (Figure 13), most of our late winter data plot above and to the left of the summer mixing line of *Cooper et al.* [1997]. This is consistent in some cases with sea ice melt in surface waters, but even waters with relatively high salinities (>32.5) plot to the left and above this mixing line to an extent greater than analytical precision. This indicates that the $\delta^{18}O_{H2O}$ value of the winter freshwater source (or y-intercept) is less negative than it is during the summer. This is reasonable considering that the large Alaskan rivers such as the Yukon and Kuskokwim have much reduced flows during the winter, so the runoff contribution present in these sampled water masses must originate from more southerly or marine precipitation sources that are diluted with continental runoff in the summer and form the basis for the *Cooper et al.* [1997] relation. On the other hand, the fewer data plotting to the right of the regression equation on

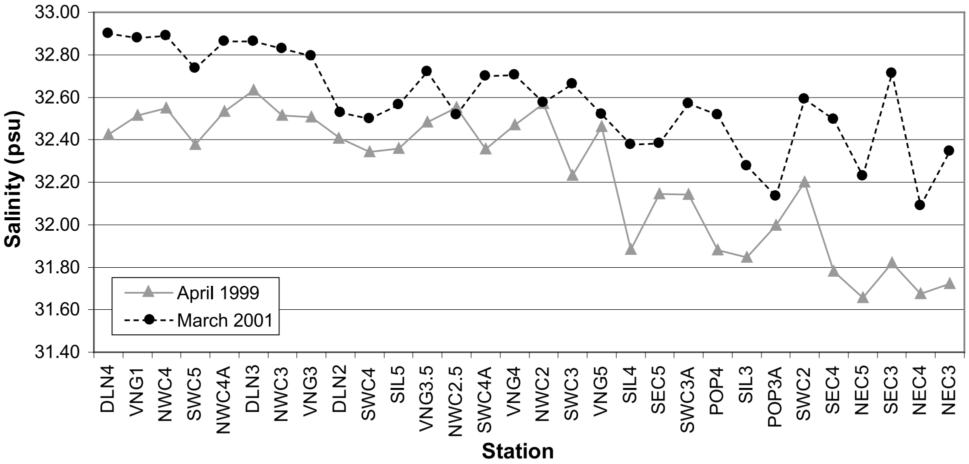

Figure 11. Bottom water salinity comparison between April 1999 and March 2001. Stations are arranged by longitude with western stations on the left and eastern stations on the right. Station locations are presented in Figure 1.

Figure 13 are waters with higher salinities (>~33) which are consistent with brine injection in those instances. It is worth pointing out that the $\delta^{18}O_{H2O}$ values of these seawater samples collected in late winter in both 1999 and 2001 are less negative than observed in the Arctic Ocean upper halocline (~1.1‰). Salinities are also lower than observed in the upper halocline (33.1 psu) where the winter-origin Bering Sea-derived nutrient maximum resides [*Cooper et al.*, 1997]. The necessary increase in salinity and decrease in $\delta^{18}O_{H2O}$ values required to meet the composition of the Arctic Ocean upper halocline indicates that the water we sampled must later mix with both 1) water with a higher runoff component as well as 2) brine injected winter waters before it would meet the physical and isotopic characteristics of the broader Bering Sea inflow into the Arctic.

[26] While bottom water temperature was almost constant across the region in April 1999 (−1.80 to −1.67°C), salinity values were similar in range and distribution to summertime values reported by *Grebmeier and Cooper* [1995]. These typical salinities, representing 4 major water masses in April 1999, are consistent with an end to large-scale ice and brine production and an influx of newly advected water onto the shelf.

[27] Ice data indicates much earlier polynya formation in 1999 relative to 2001. Ice thickness maps show a large polynya in early February 1999, while the polynya was much smaller in February 2001 (Figure 6) due to late ice edge progression (Figure 2). The polynya was likely active during March 2001 just prior to and during our sampling period. These temporal differences may be why higher salinities were detected in 2001, but not in 1999. *Pease* [1980] found little in situ ice formation south of 62°N latitude, indicating that most ice forms in the northern Bering Sea and is pushed south by winds. This prior work also predicted that northern ice production zones would show an increase in salinity from 1.25–7.5 psu over the winter season. Our data show a smaller, but significant difference in salinity of ~0.2 to 0.3 psu between April 1999 and March 2001 in the St. Lawrence Island region. As also indicated by the stable oxygen isotope data, these small salinity differences suggest that there was not as high a degree of ice formation during our sampling as might occur earlier in the winter.

[28] Despite of the extreme differences in ice coverage, measurements of chlorophyll-*a*, both in water and sediment, were low and only marginally higher in the water column during the later season cruise in April 1999 than in March 2001 (Figure 9). Upon finding similar results in the southeast Bering Sea in winter during the late 1960's and early 1970's, *McRoy and Goering* [1974] attributed low chlorophyll-*a* values to low light intensities associated with winter sun, ice cover, and strong vertical mixing. Highly concentrated, thick sea ice was probably responsible for low chlorophyll-*a* values in April 1999, with most chlorophyll-*a* likely associated with sea ice algae and not open water production. Open water production may be possible in the late winter and early spring (March in the northern Bering Sea) as light returns to the system, although determinations of primary production rates were outside the scope of this study. Particularly during the March 2001 cruise, surface photosynthetic active radiation (PAR) fluxes in the polynya were as high as 975 $\mu E\ m^{-2}\ s^{-1}$ [*Cooper et al.*, 2002; unpublished data, 2002], which is significantly higher than typical compensation points for ice algae of 10 $\mu E\ m^{-2}\ s^{-1}$ [*Cota and Smith*, 1991]. However, the same wind events that impeded ice edge migration during February 2001 likely created a mixed water column that was unable to support production during our 2001 sampling period. At only one station in 1999, LEM1, which was the sole station located in open water within the polynya during the 1999 cruise, were chlorophyll concentrations modestly elevated (Figure 9). In the southeastern Bering Sea, *Hunt et al.* [2002] hypothesized that an early ice retreat leads to a later, open water bloom in cold water, while late ice retreat conditions lead to an early, ice-associated bloom in stabilized, surface warmed waters. According to this "Oscillating Control Hypothesis," this leads to conditions in which zooplankton are limited during cold water blooms, with enhanced sedimentation

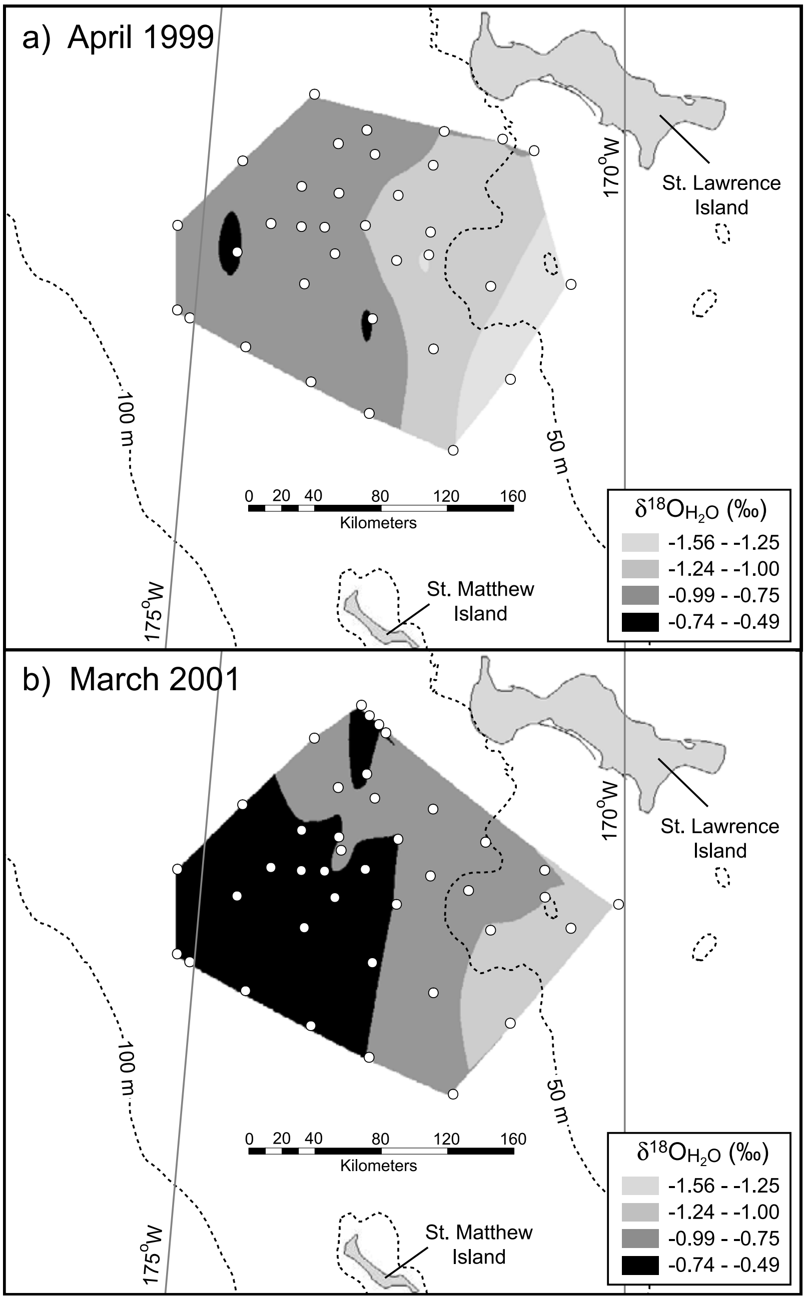

Figure 12. Bottom water $\delta^{18}O_{H2O}$ values during April 1999 and March 2001. Interpolation among station values (open circles) was performed using ESRI® Spatial Analyst extension to ArcInfo 8.

of organic matter. In the present study we find that no significant bloom develops, even in the presence of open water due to significant vertical mixing. However, if vertical mixing was reduced under otherwise similar conditions and stratification developed, significant amounts of primary production could be possible during late winter and early spring.

[29] Anticipated global climate change may lead to reduced sea ice cover in the Bering Sea or even a lack of seasonal ice cover. Although in some polar systems, differences in polynya development can have crucial consequences for deep water formation and other larger scale processes [e.g., *Williams and Bindoff*, 2003] an important consideration in the Bering Sea is whether greater open water will have an effect on biological production. This study provided an opportunity to examine the differences in water mass properties following a winter of heavy ice versus a winter of light ice. Our data indicate that reduced sea ice and higher nutrient levels did not necessarily favor water column production during late winter and early spring 2001 as compared to 1999. This may have been due to high wind intensities that kept the water column well mixed. Therefore, higher or temporally accelerated seasonal biological production may not be a consequence of expected global change in the northern Bering Sea that would reduce ice cover.

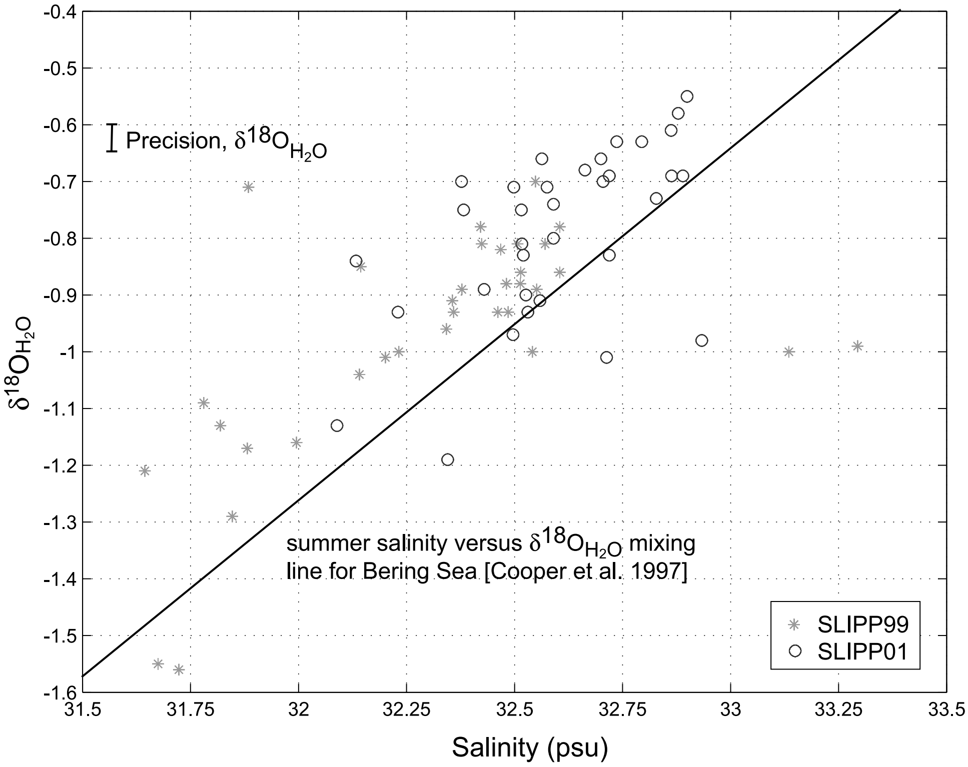

Figure 13. $\delta^{18}O_{H2O}$ versus salinity during April 1999 and March 2001.

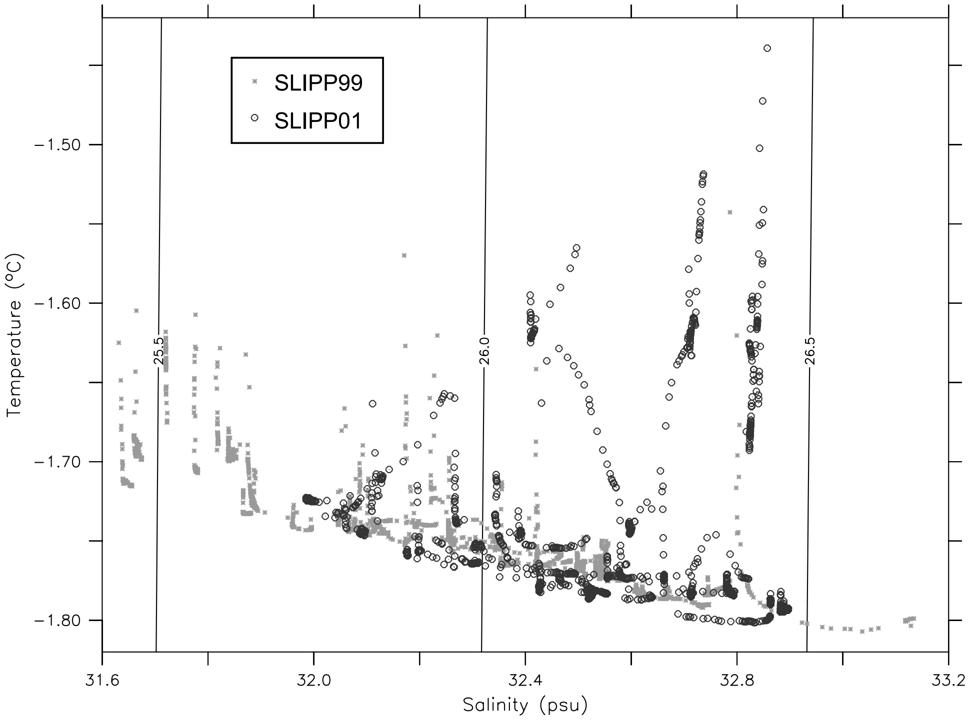

Figure 14. Temperature versus salinity relationships for the two cruises, April 1999 and March 2001.

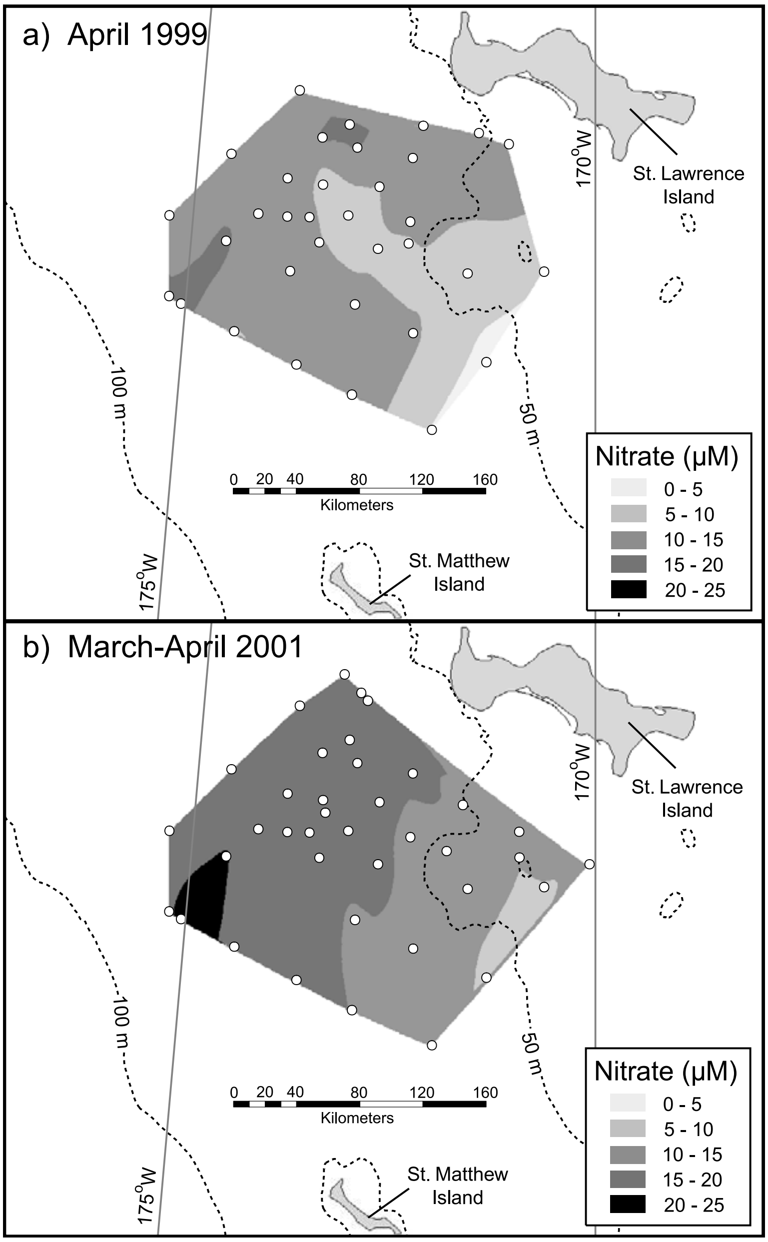

Figure 15. Bottom water nitrate concentration during April 1999 and March 2001. Interpolation among station values (open circles) was preformed using ESRI$^{®}$ Spatial Analyst extension to ArcInfo 8.

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