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Salinity and Temperature Regimes in Eastern Alaskan Beaufort Sea Lagoons in Relation to Source Water Contributions

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Abstract Shallow estuarine lagoons characterize >70 % of the eastern Alaskan Beaufort Sea coastline and, like temperate and tropical lagoons, support diverse and productive biological communities. These lagoons experience large variations in temperature (−2 to 14 °C) and salinity (0 to >45) throughout the year. Unlike lower latitude coastal systems, transitions between seasons are physically extreme and event-driven. On Arctic coastlines, a brief summer open-water period is followed by a 9-month ice-covered period that concludes with a late-spring sea ice breakup and intense freshwater run-off. From 2011 to 2014, we examined interannual variations in water column physical structure (temperature, salinity, and δ^{18}O) in five lagoons that differ with respect to their degree of exchange with adjacent marine waters and magnitude of freshwater inputs. Temperature, salinity, and source water composition (calculated using a salinity and δ^{18}O mixing model) were variable in space and time. During sea ice break-up in June, water column δ^{18}O and salinity measurements showed that low salinity waters originated from meteoric inputs (50–80 %; which include river inputs and direct precipitation) and sea ice melt (18–51 %). Following breakup, polar marine waters became prevalent within a mixed water column over the summer open-water period within all five lagoons (26–63 %). At the peak of ice-cover extent and thickness in April, marine water sources dominated (75–87 %) and hypersaline conditions developed in some lagoons. Seasonal runoff dynamics and differences in lagoon geomorphology (i.e., connectivity to the Beaufort Sea) are considered key potential drivers of observed salinity and source water variations.

Keywords Beaufort Sea · Coastal lagoons · Temperature · Salinity · Oxygen isotopes

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Introduction

The many shallow lagoons of the eastern Alaskan Beaufort Sea coast support productive biological communities (Dunton et al. 2006, 2012), including diverse benthic assemblages that are food sources for larger higher trophic level consumers such as marine mammals, water fowl, and fish (Brown 2006; von Biela et al. 2011). These consumers, in turn, are important resources to the subsistence lifestyle of local Inupiat villages. The lagoons are estuarine and can experience large temporal variations in temperature and salinity, from almost fresh to hypersaline (McCart 1977) that resident animals must withstand to survive. Much attention has been given to the impacts of climate change on the thermal conditions of Arctic environments (Hinzman et al. 2005) and to hydrologic change (McClelland et al. 2006; Peterson et al. 2006), but how these changes manifest themselves in Arctic lagoons has not been well studied.

While seasonal temperature and salinity patterns in Arctic lagoons are known for the open-water period (McCart 1977; Matthews and Stringer 1984; Hale 1990), seasonal transitions vary from year to year and there is virtually no information for the 9-month ice-covered period. The timing and magnitude of

peak river discharge can also change annually, but over 50 % of annual discharge from rivers on the North Slope occurs during a 2-week period each spring (Carmack and Wassmann 2006; McClelland et al. 2012, 2014). The extent that river water overflows landfast ice also varies and can affect the timing of ice breakup (Lissauer et al. 1984). The summer open-water zone on the Beaufort Sea shelf can extend from 1 to 200 km (Hale 1990), which can in part modulate the amount of ocean water that mixes into lagoons (Lissauer et al. 1984). These lagoons are also affected by wind-generated tidal fluctuations, which can result in marine water intrusions (McCart 1977).

Typically, winter on the Beaufort Sea coast begins with ice formation in lagoons in late September (Sellman et al. 1992). For the next 9 months, lagoons are ice-covered and may freeze completely to the bottom when water column depths are <2 m. During sea ice formation, the remaining water becomes increasingly saline (35 to >60) from ion exclusion, resulting in hypersaline conditions (i.e., salinities greater than adjacent marine water) in shallow areas (<3 m) of the nearshore region and in lagoons (McCart 1977; Hale 1990). In contrast, the deeper adjacent waters of the Beaufort Sea rarely exceed 35 just above the seabed (Sellman et al. 1992).

The spring freshet (associated with rapid snowmelt) typically occurs between late May and early June on Alaska's North Slope (McClelland et al. 2014). Freshwater runoff over this period inundates coastal lagoons and the nearshore environment, accelerating sea ice melt (Pollard and Segar 1994) and flushing highly saline brine water into the Beaufort Sea (Hale 1990). Lagoons are generally ice-free by early July. Freshwater inputs decrease during the summer open-water period (becoming insignificant by early fall) and wind-driven mixing increases. These changes may destabilize the water column and allow complete vertical mixing (Schell et al. 1984). Winds and tides also advect marine water into lagoons further contributing to water column mixing (Hale 1990).

The relative importance of these freshwater sources is not well described for much of the Arctic coast but can be accurately evaluated using both salinity and water column oxygen isotopic ratios (H_2O-$\delta^{18}O$) as tracers of freshwater sources (Ostlund and Hut 1984; Macdonald et al. 1989; Cooper et al. 1997, 2005). The accuracy of the H_2O-$\delta^{18}O$ approach to identify source waters continues to improve as oxygen isotope end-member values become more refined (Cooper et al. 2005, 2008; Yi et al. 2012). Arctic sea ice is typically −2.4 ‰, which is ~1 ‰ more enriched than seawater (~−3.5 ‰; Macdonald et al. 2002; Cooper et al. 2005; Alkire and Trefry 2006). Arctic rivers integrate meteoric precipitation from the preceding winter and are characterized by highly depleted H_2O-$\delta^{18}O$ values (−15 to −22 ‰ depending on region) relative to seawater (Cooper 1998; Cooper et al. 2008). Determining the main source of low-salinity water in lagoons (i.e., sea ice melt vs. runoff) may help researchers predict how

lagoon salinity regimes will be affected by changes in sea ice dynamics as well as hydrological processes occurring on land.

Several lagoons along the eastern Alaskan Beaufort Sea coast were the subject of research led by the US Fish and Wildlife Service investigators in the 1970s and 1980s (Schell et al. 1984; Hale 1990, 1991; Pollard and Segar 1994) that focused on spring and summer dynamics. There is nearly a complete lack of information, however, on the hydrography of these lagoons over the ice-covered period. The purpose of this study was to provide baseline hydrographic information for characteristic coastal lagoon ecosystems in the eastern Alaskan Beaufort to enable better understanding of a system that is projected to change significantly with respect to precipitation, land runoff, sea ice melt, and storms surges (Chapin 2005; Hinzman et al. 2005; Peterson et al. 2006).

Our main objectives were to (1) determine seasonal patterns in the physical structure of the water column in lagoons, (2) to characterize interannual variability in temperature and salinity and identify the timing of key hydrologic events, and (3) to quantify the proportion of low salinity water present in lagoons during spring and summer that originates from sea ice melt and meteoric water. We then considered how differences in lagoon geomorphology, exchange properties, and freshwater inputs might potentially modulate seasonal patterns and interannual variability in temperature, salinity, and source water composition.

Methods

Regional Setting

The Alaskan Beaufort Sea shelf is ~80 km wide and is characterized by a discontinuous chain of barrier islands enclosing a network of coastal lagoons (Fig. 1). Roughly 75 % of Beaufort lagoons have several openings in barrier islands allowing limited exchange with nearshore waters; others have only one opening, and exchange with nearshore waters occurs mainly via tidal pumping and wind-driven upwelling (Lissauer et al. 1984). Because of the large volume of freshwater inflow to lagoons and the inner shelf, the southern Beaufort Sea is characterized as an estuarine system over the summer open-water season (Dunton et al. 2006; McClelland et al. 2012). Lagoon waters begin to freeze by late September and are covered by 1.5–2 m of ice by April, with ice reaching up to 2 m thick by April (Barry et al. 1979) and daily accretions of 0.8 to 1 cm (Matthews 1981).

We measured salinity and temperature regimes within five representative lagoons and embayments along the eastern Alaskan Beaufort Sea coast (Fig. 2) by continuously recording in situ sensors deployed from 2011 to 2014. Discrete measurements of salinity, temperature, and $\delta^{18}O$ were also made on field campaigns in three distinct seasons: winter ice cover (April), spring sea ice breakup (June), and summer open-water period (August) from August 2011 through August 2013.

Fig. 1 Site locations within each lagoon along the coast of the Alaskan Beaufort Sea sampled in April, June, and August of 2011–2013 (see Table 1 for station code definitions). In each lagoon, temperature and salinity loggers were deployed in August 2011 (*black circles*). Temperature and salinity profile data were obtained using a YSI data sonde, and water samples were collected for H_2O-$\delta^{18}O$ analysis (*red circles*) (see Table 3 for list of stations)
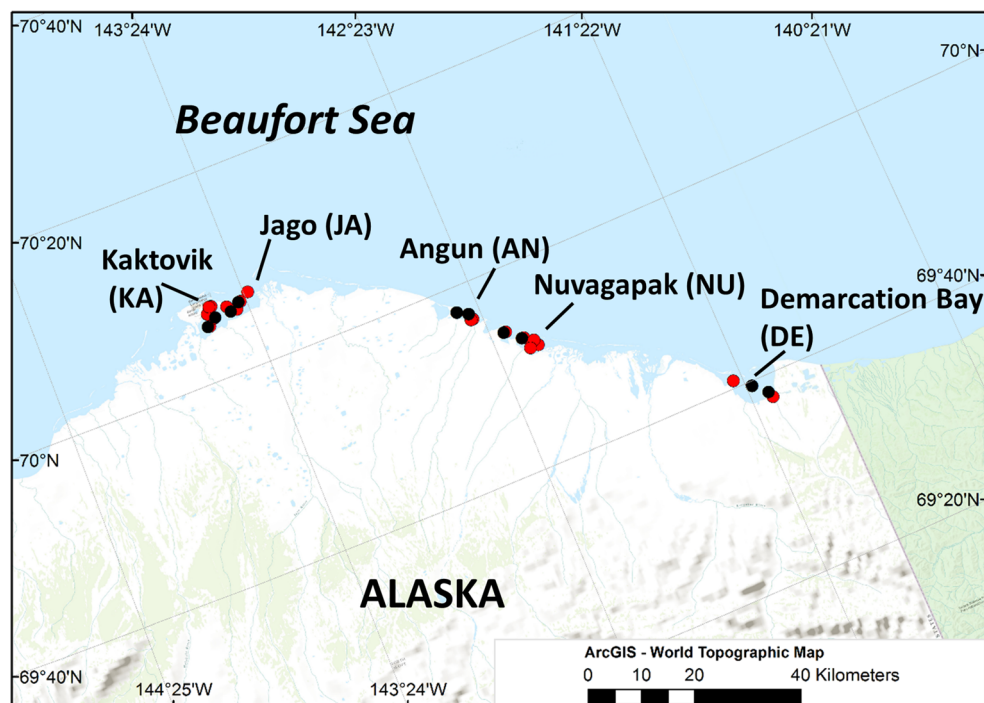
Field Sites

This study focuses on five representative lagoons along the eastern Alaska Beaufort Sea coast—Kaktovik (KA), Jago (JA), Angun (AN), Nuvagapak (NU), and Demarcation (DE) (Figs. 1 and 2). Although these systems are located within 100 km of each other, each lagoon is unique in its physiography, magnitude of freshwater inputs (primarily related to differences in surrounding catchment area), and connections to nearshore waters (Table 1). The lagoons represent the typical range of size, shape, and depth on the Beaufort coast. All lagoons are fully ice-covered in the winter months, although none freeze to the bottom except along their perimeters to depths of 1.8 m.

KA (Fig. 2a), the westernmost lagoon, is almost fully enclosed by Barter Island to the west, a peninsula from the mainland to the east and barrier islands to the north. The nearest named rivers are 9 km to the east (Jago River) and 13 km to the west (Hula Hula River) (McCart 1977). KA is not directly connected to the Beaufort Sea but is connected to other lagoon systems via two channels. JA (Fig. 2a) is northeast of KA; a peninsula that connects to the mainland separates the two lagoons (Hale 1990). In addition to the small channel connection to KA, JA is connected to the Beaufort Sea by two wide (1 km) channels. JA receives direct freshwater inputs from the Jago River in the east, as well as a few small tundra streams in the west. JA connects with Tapkauruk Lagoon east of the Jago River. AN (Fig. 2b), the smallest study lagoon, is located 30 km east of JA. AN is long and

narrow and is mostly separated from the open ocean by sand spits.

NU (Fig. 2b) is 5 km east of AN and is approximately twice the size of AN but is also long and narrow in shape. DE (Fig. 2c) is located within 13 km of the Canadian border, about 40 km east of NU. DE is the largest and deepest study system. DE is shaped like a typical embayment as opposed to the longer, narrower shape of the other lagoons.

Field Methods

In August 2011, HOBO U24 Conductivity Loggers (U24–002-C) were deployed at two stations within each lagoon (KA-A, KA-B, JA-A, JA-B, AN-A, AN-B, NU-A, NU-B, DE-A and DE-B) approximately 30 cm above the seafloor (Fig. 2). Each logger was placed in a PVC housing and secured to a line that was anchored and connected to a buoy approximately 25 cm above the sea floor to maintain correct orientation. The loggers recorded conductivity and temperature (with a resolution of ±2 μS cm^{-1} and 0.01 °C, respectively) at 2-h intervals. They were retrieved and downloaded several times between August 2012 and August 2014 (Table 2). We could not retrieve the AN and NU loggers at the end of the study period due to dangerous weather and sea conditions, thus we have records from August 2011 to 2013 for AN and from August 2011 to 2012 for NU.

We also collected hydrographic measurements and sampled water at discrete depths in April, June, and August over a 3-year period (Table 3). Two stations were sampled in April
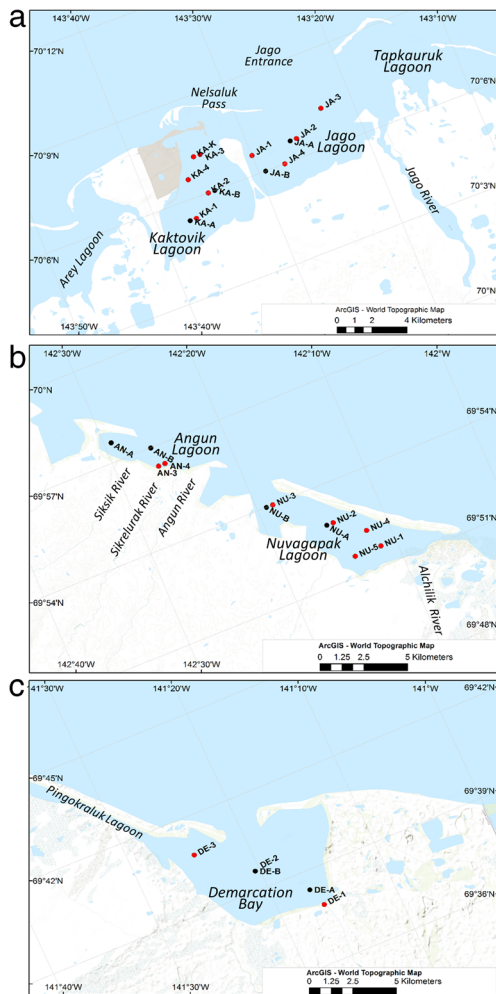
Fig. 2 Station locations within each lagoon site showing the location of HOBO logger deployment (lettered stations, *black circles*), data sonde profiles, and water collection (numbered stations, *red circles*)

and June, while two or three stations were sampled in August when lagoons were more accessible by boat. Preselected stations were located using a GPS with an accuracy of 4 m or

better. Each station was designated as the area within a 10-m radius of the GPS location.

On each sampling trip, hydrographic measurements, including water depth, conductivity/salinity, and temperature, were measured at each station with a YSI 600XL data sonde. Measurements were recorded from the surface, bottom, and mid-water column at 1-m intervals. In April, sonde measurements were recorded at 2 and 3 m to account for an ice thickness that averaged about 1.7 m.

Water samples were also collected for H_2O-$\delta^{18}O$ analysis in 30-mL HDPE sample bottles. These samples were collected using a peristaltic pump from 1 (August only), 2, and 3 m below the water or ice surface. Sample bottles were filled completely and stored unfrozen until analysis. These samples were analyzed at the Stable Isotope Laboratory at the Marine Biological Laboratory in Woods Hole, MA.

Logger Data

Upon retrieval, HOBOware Pro (v.3.7) software was used to download the data and HOBOware Conductivity Assistant (v.2.4) was used to convert conductivity measurements to salinity based on the practical salinity scale of 1978 (PSS-78). Salinity sensors failed on the DE-B and KA-A loggers in the final year, and these data are excluded from our analysis. The remaining loggers exhibited some drift in measurements following exposure to low salinity water. To correct for this drift, the data were calibrated using YSI sonde measurements. A two-point calibration was determined for each lagoon. For KA, JA, and AN loggers, sonde conductivity and temperature measurements collected from 3 m at stations A and B in April 2012 and 2013 were used as the two calibration endpoints. For NU loggers, 3-m sonde measurements were applied from data collected in August 2011 and April 2012. For DE loggers, we applied 3-m sonde measurements from August 2011 and August 2012.

Table 1 Description of study lagoons including their mean depth and description of inlets and outlets

Site	Mean depth	Inlets	Channels and channel depth
Kaktovik (KA)	3–4 m	Small tundra streams	Nelsaluk Pass (3 m) to Jago, minor SW channel (<1 m) to Arey Lagoon; no direct connections with Beaufort
Jago (JA)	3–4 m	Jago River, small tundra streams	Two large wide (1 km) channels to Beaufort (3 m), one narrow channel to Kaktovik lagoon
Angun (AN)	2.5–3.5 m	Three small rivers (Angun and Siktelurak in the east and Siksik in the west)	Three small channels to Beaufort (2 m) in the NE
Nuvagapak (NU)	3 m	Small rivers and streams (including the Alchilik in the east)	Large channel (1.3 m) in the NW, small channel (<1 m) in the NE, both connect to the Beaufort
Demarcation (DE)	3.5–4.5 m	Two small tundra streams on the SE and SW corners	Large wide (2 km) channel (5–7 m) to the Beaufort, small channel (0.5 m) to Pingokraluk Lagoon in the NW

Table 2 Record of HOBO logger (temperature and salinity) deployment, mid-study downloads, and final retrieval

Logger	Deployment	August download(s)	Retrieval
KA-A, KA-B	Aug 2011	2012, 2013, 2014	August 2014
JA-A, JA-B	Aug 2011	2012, 2013, 2014	August 2014
AN-A, AN-B	Aug 2011	2012, 2013	N/A
NU-A, NU-B	Aug 2011	2012	N/A
DE-A, DE-B	Aug 2011	2012, 2014	August 2014

Loggers in Angun (AN) and Nuvagapak (NU) were never retrieved due to dangerous weather and sea conditions. All loggers retrieved in August 2014 had ceased logging in April 2014

The resulting salinity record closely matched (±3) sonde salinity records from each station.

Source Water Partitioning

We quantified the proportion of lagoon water that originated from sea ice melt (SIM) and runoff/meteoric water (MW) using a model that assumes these sources mix with marine waters derived from the polar mixed layer (PML; Alkire and Trefry 2006). We estimated the percent contribution from each of these three sources (SIM, MW, PML) by simultaneously solving the following three equations for all water samples:

$$SIM + MW + PML = 100 \tag{1}$$

where SIM, MW, and PML are the percent of water originating from each source.

$$S = (SIM \times 5) + (MW \times 0) + (PML \times 31.6) \tag{2}$$

where S is salinity of the water sample and each fraction is multiplied by its assumed salinity.

$$\delta^{18}O = (-2.4‰ \times SIM) + (-22.0‰ \times MW) + (-3.5‰ \times PML) \tag{3}$$

where $\delta^{18}O$ is the stable oxygen isotope value of the water sample and each fraction is multiplied by its assumed $\delta^{18}O$ value.

Table 3 Location, maximum depth, and years sampled for five lagoons along the Alaskan eastern Beaufort Sea

Station	Latitude (°N)	Longitude (°W)	Max depth (m)	Years sampled
KA-1	70.086	−143.614	3.5	2011, 2012, 2013
KA-2	70.101	−143.578	3.7	2011, 2012, 2013
KA-3	70.118	−143.570	3.2	2011, 2012, 2013
KA-4	70.109	−143.599	3.7	2012, 2013
KA-A	70.089	−143.623	3.0	2012, 2013
KA-B	70.101	−143.571	3.0	2012, 2013
KA-K	70.124	−143.583	3.5	2012, 2013
JA-1	70.106	−143.503	3.5	2011, 2012, 2013
JA-2	70.110	−143.427	3.5	2011, 2012, 2013
JA-3	70.116	−143.379	2.0	2011, 2012, 2013
JA-4	70.105	−143.463	3.5	2012, 2013
JA-A	70.107	−143.443	3.0	2012, 2013
JA-B	70.104	−143.489	3.0	2012, 2013
AN-1/ AN-A	69.959	−142.494	3.5	2011, 2012, 2013
AN-2/ AN-B	69.948	−142.440	3.2	2011, 2012, 2013
AN-3	69.943	−142.434	3.2	2012, 2013
AN-4	69.942	−142.445	2.5	2012, 2013
NU-1	69.86	−142.19	3.0	2011, 2012
NU-2	69.88	−142.24	3.0	2011, 2012
NU-3	69.90	−142.31	3.0	2011, 2012
NU-4	69.87	−142.20	3.0	2011, 2012
NU-A	69.88	−142.25	3.0	2011, 2012
NU-B	69.90	−142.32	3.0	2011, 2012
DE-1/ DE-A	69.634	−141.267	2.5	2011, 2012
DE-2/DE-B	69.660	−141.340	4.0	2011, 2012
DE-3	69.683	−141.413	3.0	2011, 2012

Station key: '-A' or '-B′ (HOBO data loggers); numbered stations (sonde casts and water samples)

This model relies on assumptions about the $\delta^{18}O$ values of the three endmembers. We assigned a $\delta^{18}O$ value of −22.0 ‰ for meteoric water because small Arctic rivers that drain in the Brooks Range on Alaska's North Slope tend to be more depleted than larger Arctic rivers, whose values range from −15 to −20 ‰ (Cooper et al. 2005). This is supported by runoff values of −23.0 ± 0.3 ‰ and −21.7 ± 0.4 ‰ in the Kuparak and Sagavanirktok drainage basins, respectively (Alkire and Trefry 2006). We assigned a value of −2.4 ‰ for sea ice melt based on measurements from the Mackenzie shelf (Macdonald et al. 1989), which is similar to −1.9 ± 0.5 ‰ (SD) reported for the coastal Chukchi Sea (Eicken et al. 2002). We assign −3.5 ‰ for the PML (Macdonald et al. 1989). These endmembers are similar to those used by Cooper et al. (2005) and Alkire and Trefry (2006) in their mixing model. These equations produced negative values for sea ice melt and PML in a small number of cases, which is probably an artifact of the variability in true endmember values.

Results

Water Column Structure

The April ice-cover water column structure did not vary within lagoons or between years, though there were slight differences in maximum salinities among lagoon systems. Water temperatures ranged from −1.6 to −2.1 °C (Fig. 3). KA and NU had surface (≤2 m) salinities over 40, whereas JA and AN were less saline at 31–35. Salinities at or below 3 m were consistently greater (by 2–5) than salinities measured at ≤2 m, as well as greater than salinities in the PML.

In late June (ice break-up period), results were more variable among years and lagoons (Fig. 3). All lagoons were ~5 °C warmer in June than in April, and all lagoons except for AN had haloclines at one or more sampling locations. Waters ≤2 m generally had salinities between 2 and 4, with the exception of NU, where saltier water was occasionally encountered near the surface. Salinities of deeper waters (≥ 3 m), on the other hand, differed widely among lagoons, with KA consistently experiencing hypersaline conditions, AN consistently experiencing near fresh (~3) conditions, and JA and NU showing a mixture of near fresh to brackish conditions. The salinity regimes of individual lagoons were variable both in time (e.g., NU bottom salinity between years) and spatially (e.g., JA in June).

Stratified conditions were maintained at some locations in August, but differences between surface and bottom water samples were less consistent among lagoons and between years than observed during June (Fig. 3). All lagoons had substantially warmer (>8 °C) and more saline surface waters in August than in June. In 2012, KA and NU still contained highly saline bottom water and were thus stratified with surface and bottom salinities of ~20 and ~38 (KA) and ~4 and ~30 (NU), respectively. In 2012, JA and AN were well mixed with respect to salinity. Water column structure in 2013 was substantially different than in 2012—KA, JA, and AN surface waters were 2 to 6 °C warmer in 2013 than in 2012 and were stratified with respect to temperature. Salinity was relatively constant in upper and bottom layers in KA and only increased by 4 in the bottom layer in JA and AN.

Sonde data were only collected from DE in August. Three stations were sampled; temperature was uniformly 9–11 °C in surface and bottom waters, and salinity varied from 12–15 in surface waters to 23 in bottom waters.

Seasonal and Interannual Variation in Bottom Water Temperature and Salinity from Moorings

Moorings in all lagoons showed the expected (relative to sonde data) seasonal patterns in temperature and salinity, though there were differences among lagoons and between years (Fig. 4). Minimum temperatures (~−2.0 °C) were reached by mid-October in KA, JA, and AN; by early November in NU; and in late November in DE, a pattern which held true in all sampling years. After minimum temperatures were reached over each ice-cover season, hypersaline conditions (>32; PML salinity) developed in most lagoons. KA and NU stations were the most saline (>40), followed by JA, AN, and DE, none of which exceeded 40 (except JA-B, which reached 43 in winter 2014). Maximum salinities during the ice-cover months were somewhat lower in 2013/2014 relative to the two earlier ice-covered seasons. This decrease was observed in all lagoons for which 3 years of data was available but variable (salinity decreased by 5 at JA-A, but increased by 2 at JA-B; decreased by 6 at KA-B; no change at DE-A, but decreased by 6 at DE-B).

Salinity patterns in the winter ice-covered period differed among lagoons and years. KA and NU sites continued to increase in salinity over the entire ice-covered period in every year for which data was available (Fig. 4a, b, g, h). Conversely, salinity at DE-A plateaued around December each year and remained ~36 until the spring freshet (Fig. 4i). JA and AN, however, showed different patterns each year. In 2011/2012 salinity at both JA and AN stations plateaued similar to DE-A, but in 2012/2013, their salinity continued to increase throughout the ice-covered period, similar to KA and NU stations (Fig. 4c–f).

Low salinities and fluctuating water temperatures characterized July and August in all lagoons. Some stations (KA-A, JA-B, AN-B) experienced larger variation in

Fig. 3 Temperature (left column) and salinity (right column) of surface waters (≤2 m; *blue bars*) and bottom waters (≥3 m; *black bars*) from YSI data sonde casts at each lagoon in April, June, and August 2012 (*first bar* of each depth pair) and 2013 (*second bar* of each depth pair). *Horizontal bar* shows the median, *boxes* encompass the interquartile range (i.e., 25–75 %), and *whiskers* display the maximum and minimum values. Data from all years and all stations are included. Demarcation Bay (DE) was visited in August only (data is not shown); NU was sampled only in August in 2012
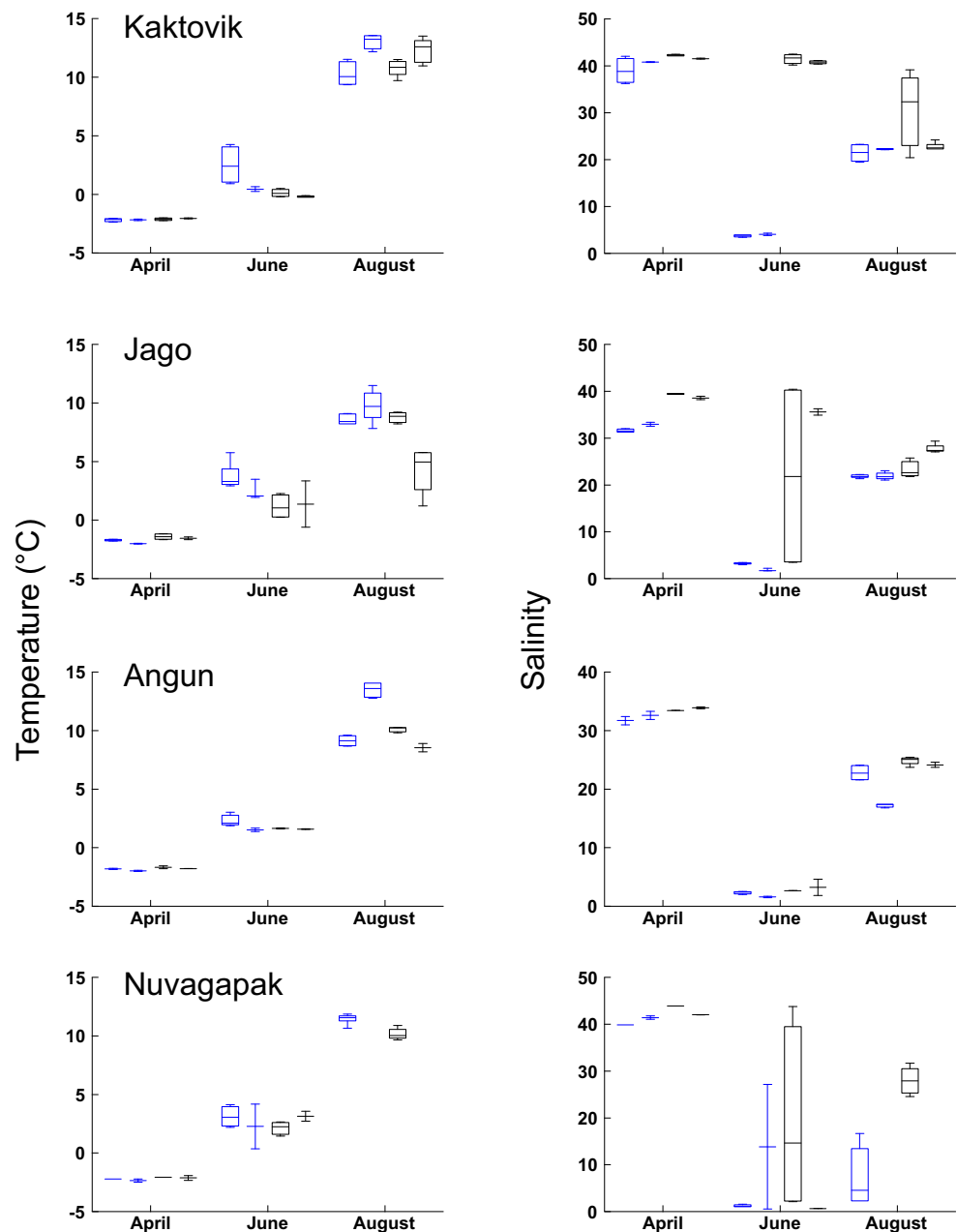
hydrographic parameters in summer (Fig. 4a, d, f). Minimum salinities varied between stations within a lagoon, and among lagoons, with only two stations (KA-A and DE-A) ever becoming entirely fresh (0) in bottom waters (Fig. 4a, i). In late August, temperatures at all lagoons began to decrease and salinities began to increase.

The annual ranges in temperature and salinity varied among lagoons and years. In general, low salinities are associated with high temperatures and vice versa (Fig. 5). Most of the observed ice-covered values fall on the freezing point curve of the T-S scatterplot, which provides one indication that the HOBO loggers

maintained their calibrations through the ice-covered period. JA and AN also experienced several days of extreme freshening (<10) in some years in July and August.

Source Water Partitioning

Seasonal patterns in H$_2$O-δ^{18}O and salinity were consistent across all lagoon systems and provided information on the contribution of marine water and two sources of low-salinity water to each lagoon (Table 4; Figs. 6 and 7). In April, lagoon waters were consistently hypersaline and enriched in ^{18}O,

Fig. 4 Salinity (*black line*) and temperature (*gray line*) of bottom waters for two stations (A and B) within each lagoon from HOBO loggers. Salinity was calculated based on conductivity and temperature data using PSS-78 conversions and calibrated with YSI sonde measurements (see "Methods" section). Months are numbered on the x-axis
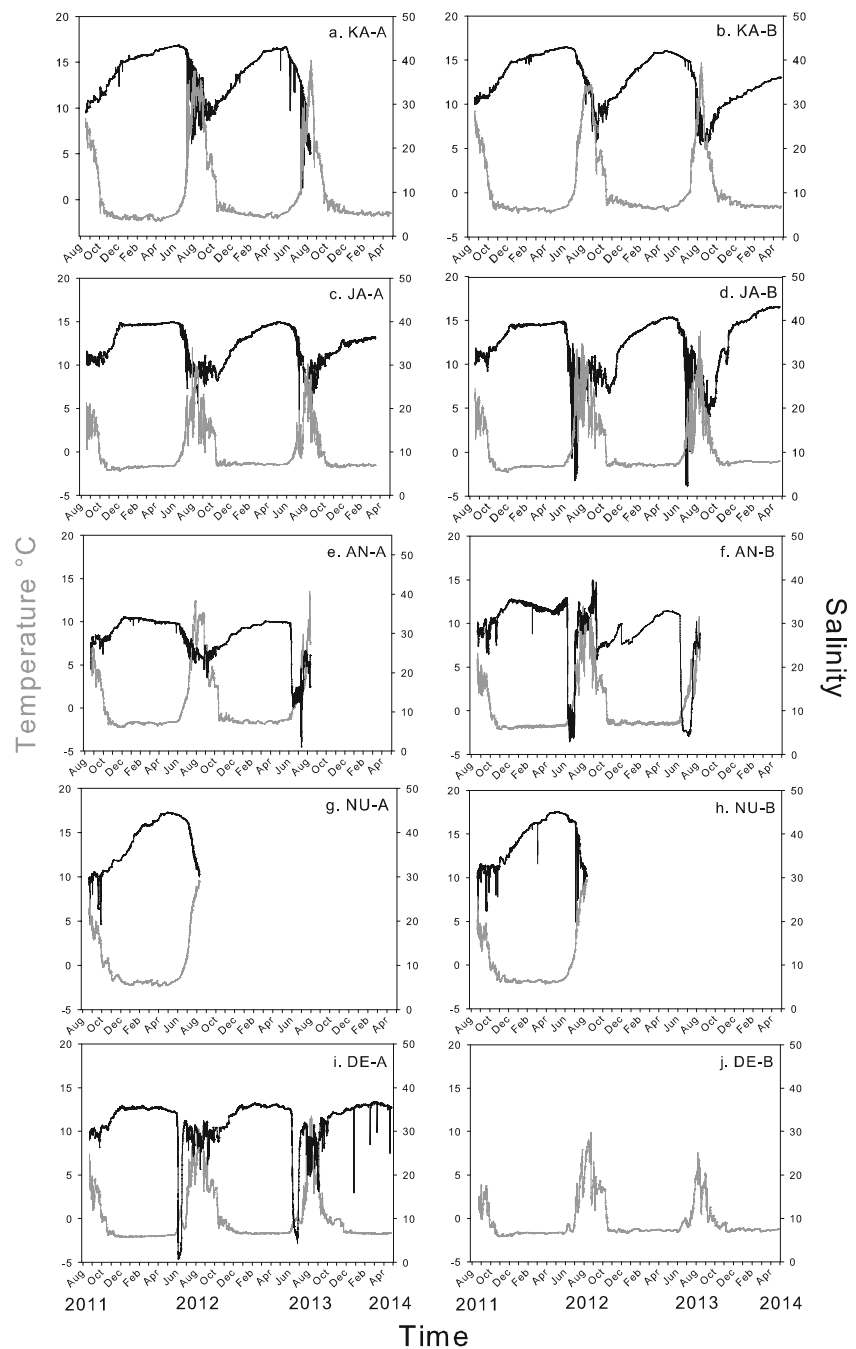

corresponding to large contributions of PML from the Beaufort Sea (>80 %) and minor MW contributions (<20 %). Little to no SIM water was present in lagoons in April. No differences were observed among sampling depths in April.

In June, most lagoons contained low salinity water (<6) that was depleted in ^{18}O (<−10 ‰), with small and variable contributions of PML water (Figs. 6a and 7). When data is averaged across stations, MW was the main source of freshwater input in surface waters at all

lagoons, accounting for at least 50 %. SIM also contributed significant amounts of water to all lagoons in June. PML water was only present in bottom waters of KA, JA, and NU.

August samples spanned a wide range in salinity (5–30) and δ^{18}O values (−20 to −5 ‰), which corresponded to greater contributions of marine water to at least one depth in all lagoons (from about 30 to 65 %) than in June (Figs. 6b and 7). Deeper samples (≥3 m) were generally more saline and more enriched in ^{18}O than were 2-m samples, though 1-m samples

Fig. 5 Temperature-salinity (T-S) scatterplots of daily average values from HOBO loggers located furthest from channels in each lagoon. The *solid line* is the freezing point curve as a function of salinity. *Symbols* denote year (*circles* denote winter 2011 through summer 2012, *crosses* denote winter 2012 through summer 2013), *colors* denote season (*green* = spring break-up, *red* = summer open water, *blue* = winter ice cover). Spring breakup is defined as the first 2 weeks in June, summer open water as mid-June to August, and winter ice-covered as September to May
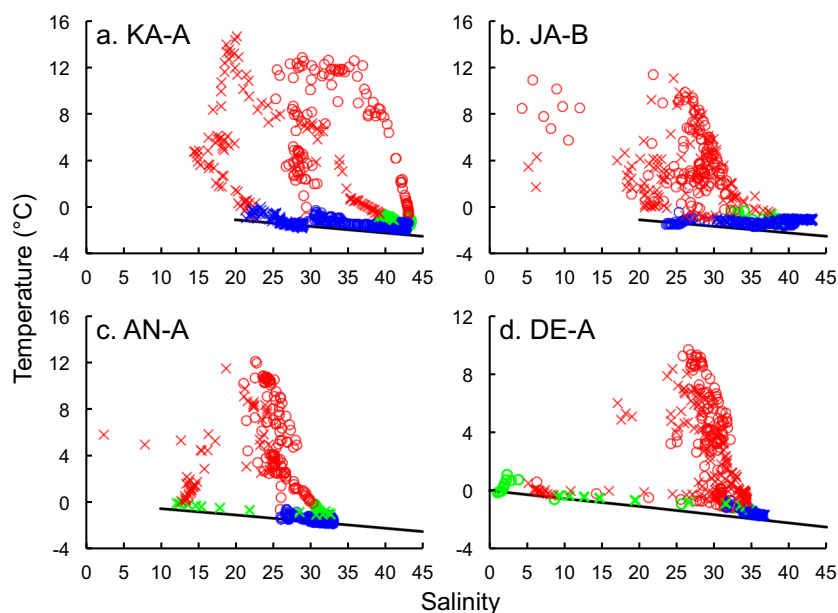
spanned the entire range. MW was the dominant source (30–50 %) of low salinity water in all lagoons, though some SIM water (5–30 %) was also present. NU contained more low salinity water than did all other lagoons.

Table 4 H$_2$O-δ^{18}O (mean ± SE (*n*)) values from water samples collected at 1-, 2-, or 3-m depths by site and season

Site	δ^{18}O (‰)		
	April (28)	June (34)	August (61)
Kaktovik	**−4.2 ± 0.2 (6)**	**−10.0 ± 1.9 (8)**	**−6.8 ± 0.2 (19)**
1 m	–	–	−5.7 ± 0.1 (3)
2 m	−4.1 ± 0.2 (4)	−13.4 ± 0.8 (4)	−7.2 ± 0.3 (8)
3 m	−4.5 ± 0.1 (2)	−6.6 ± 2.8 (4)	−6.9 ± 0.4 (8)
Jago	**−3.6 ± 0.2 (8)**	**−13.5 ± 1.6 (10)**	**−6.0 ± 0.3 (13)**
1 m	–	–	−5.5 ± 0.6 (3)
2 m	−3.4 ± 0.1 (4)	−16.3 ± 0.7 (6)	−6.5 ± 0.5 (6)
3 m	−3.8 ± 0.3 (4)	−9.3 ± 2.9 (4)	−5.7 ± 0.7 (4)
Angun	**−3.4 ± 0.1 (8)**	**−16.8 ± 0.6 (7)**	**−6.5 ± 0.7 (10)**
1 m	–	–	−4.6 ± 0.1 (2)
2 m	−3.3 ± 0.1 (4)	−16.7 ± 0.9 (4)	−7.2 ± 1.2 (4)
3 m	−3.5 ± 0.1 (4)	−16.8 ± 0.8 (3)	−6.9 ± 1.3 (4)
Nuvagapak	**−4.3 ± 0.2 (6)**	**−16.8 ± 1.2 (9)**	**−11.4 ± 1.7 (11)**
1 m	−4.2 ± 0.4 (3)	−19.5 ± 0.9 (4)	−13.8 ± 2.0 (5)
2 m	−4.4 ± 0.3 (3)	−14.6 ± 2.0 (4)	−13.3 ± 3.6 (3)
3 m	–	–	−5.5 ± 0.1 (3)
Demarcation	–	–	**−6.7 ± 1.0 (8)**
1 m	–	–	−4.1 ± 0.4 (3)
2 m	–	–	−9.6 ± 1.5 (3)
3 m	–	–	−6.1 ± 0.6 (2)

Values are averages across all sampling years and stations. Values in boldface type are means across all depths

– no data

Discussion

Winter Ice-Covered Period (April)

We noted some interesting differences in salinity patterns in bottom waters among the lagoons during the ice-covered period that probably reflect exchange with adjacent nearshore waters. For example, the moderate (<40) salinities in Demarcation Bay are coincident with its 2 km wide and deep (5–7 m) connection to marine source waters (PML) of the Beaufort Sea. In contrast, Kaktovik Lagoon, which has no direct connection to Beaufort Sea waters and has only shallow (<3 m) and narrow (12 m) passes with adjacent lagoons, developed hypersaline conditions each winter, with salinities increasing steadily until spring break-up. Jago and Angun lagoons showed different salinity patterns in April depending on the year, which may indicate that its shallow exchange channels froze completely over the winter of 2012/2013, preventing marine intrusion, but did not freeze in 2011/2012. Schell et al. (1984) speculated that currents running through the lagoon channels of AN are sufficiently strong to prevent brine water from accumulating to the extent observed in more closed lagoons. Previous work at Simpson Lagoon, to the west of our study sites, show deeper pockets in the lagoon had salinities >150 in winter (Matthews and Stringer 1984). It is evident that the PML is a major source of water in all lagoons by April, largely due to mixing over the previous open-water period and, in some cases, under ice exchange (Lissauer et al. 1984).
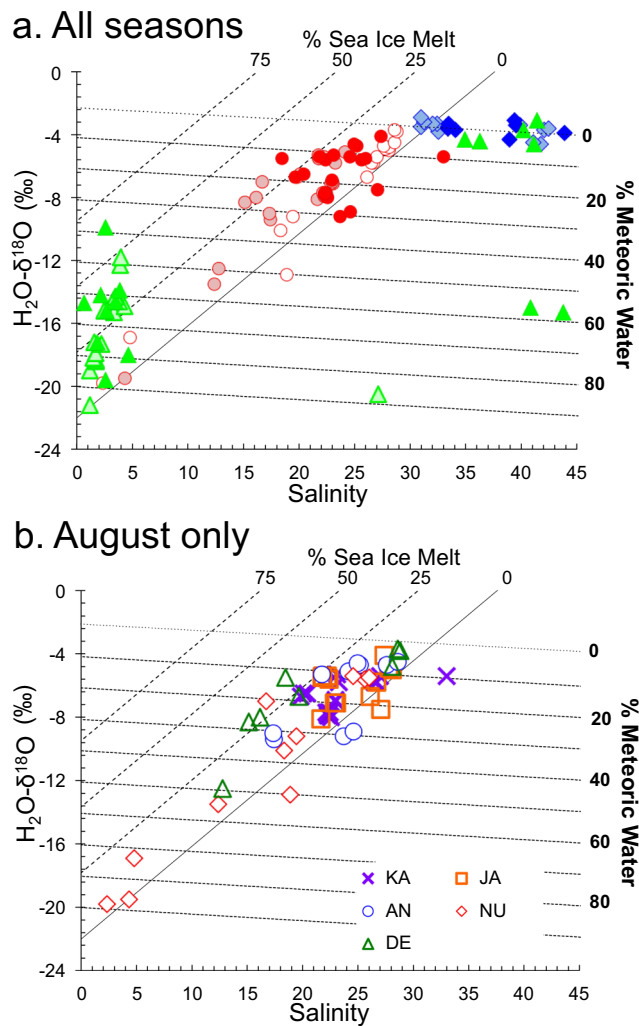
a. All seasons

b. August only

Fig. 6 **a** Relationship between H_2O-$\delta^{18}O$ and salinity for water samples collected from 1 m (*open symbols*), 2 m (*shaded symbols*), or ≥3 m (*filled symbols*) at each lagoon over three sampling months (April = *blue diamonds*, June = *green triangles*, August = *red circles*) from all sampling years. The *solid line* shows the expected mixing line between the Polar Mixed Layer and meteoric water (see "Methods" section). *Dashed lines* show the estimated fractions of low salinity water derived from sea ice melt (*long dash*) and meteoric water (*small dash*, text in bold). **b** Relationship between H_2O-$\delta^{18}O$ and salinity for samples collected in August from all depths

Spring Breakup Period (June)

In general, Beaufort Sea shelf and nearshore waters tend to be more stratified in June when warmer, less saline rivers water float on top of cooler, more saline waters (Dunton et al. 2006). This process is reflected in the vertical pattern of source water contributions (i.e., PML water was only present in bottom waters). Saline bottom layers were cooler than overlying waters in KA, JA, and NU; these bottom waters also had higher salinities than the nearshore Beaufort Sea, which we attribute to brine buildup from the previous winter and not the result of marine intrusion (Schell et al. 1984; Hale 1990). Kaktovik Lagoon, which has only two shallow and narrow channels that

connect it to adjacent lagoons (Hale 1990), is the most isolated of the five lagoons (with respect to its connectivity to the Beaufort Sea) and the most strongly stratified. The stratification established during the spring freshet likely persists until local sea ice melts in place, as tidal mixing is negligible and ice cover prevents wind-mixing.

At the time of our sampling in Angun Lagoon in both June 2012 and June 2013, low salinity water was present throughout the water column, likely a consequence of inputs from several tundra streams that flushed more saline waters from this small and shallow lagoon. The smaller area and volume of this lagoon may contribute to a shorter residence time of its waters (Schell et al. 1984) and may explain why it was completely flushed earlier than the other lagoons each year. In 2013, NU was also brine free in June, though it still contained a deep brine layer in 2012. These interannual differences may be caused by differences in channel ice-depth (if the channel froze completely in 2012, it would prevent marine intrusion) and/or runoff dynamics (more runoff in 2013 would promote flushing). A 1982 study similarly observed that AN did not contain a deep brine layer in late July (in contrast to NU) and that AN's water column became well-mixed several weeks after ice breakup (Schell et al. 1984). Hale (1990) found similar temporal patterns in freshening but with different timing (KA becoming brackish (~13) by early June 1988).

Freshwater from runoff and river inputs eventually mix to the bottom in all lagoon waters, as observed in the HOBO logger data, which were moored near the seafloor (Fig. 4d, f, i; e.g., near 0 salinities for at least 1 week before increasing to ~30). The rate of this freshwater mixing varied among lagoons, however. By late June, most lagoons contained only water from low-salinity sources in response to the large volume of freshwater that inundates these shallow lagoons each spring. This inundation can hasten sea ice melt (Lissauer et al. 1984) and SIM was an important freshwater source (18–51 %) to all lagoons. KA contained the least MW and the most SIM (this is the only lagoon without direct river inputs). Marine water from the PML was only present in the bottom layer of KA, JA, and NU, which represents a small fraction of total lagoon volume. Our results differ from previous work in KA and JA, which concluded these lagoons contain significant amounts of coastal water in early June (Hale 1990, 1991). This may indicate that spring breakup and lagoon flushing is occurring earlier now than in the early 1990s.

Some water samples collected in June did not display the patterns described above. Several bottom water (3 m) samples from KA and JA were more saline (>30) and more ^{18}O enriched than the other June samples (Fig. 6). This water is probably the remnants of winter water that was not fully mixed or flushed from these lagoons in June. One sample from KA and two from NU were more saline (25–45) but had similar $\delta^{18}O$ values to the majority of June samples. These samples may represent low salinity water present in

Fig. 7 The modeled percent of source waters (polar mixed layer (PML), sea ice melt (SIM), and meteoric origin (MW)) present in lagoons at different depths over the three sampling months. Data from all stations and all sampling years are means ± SE
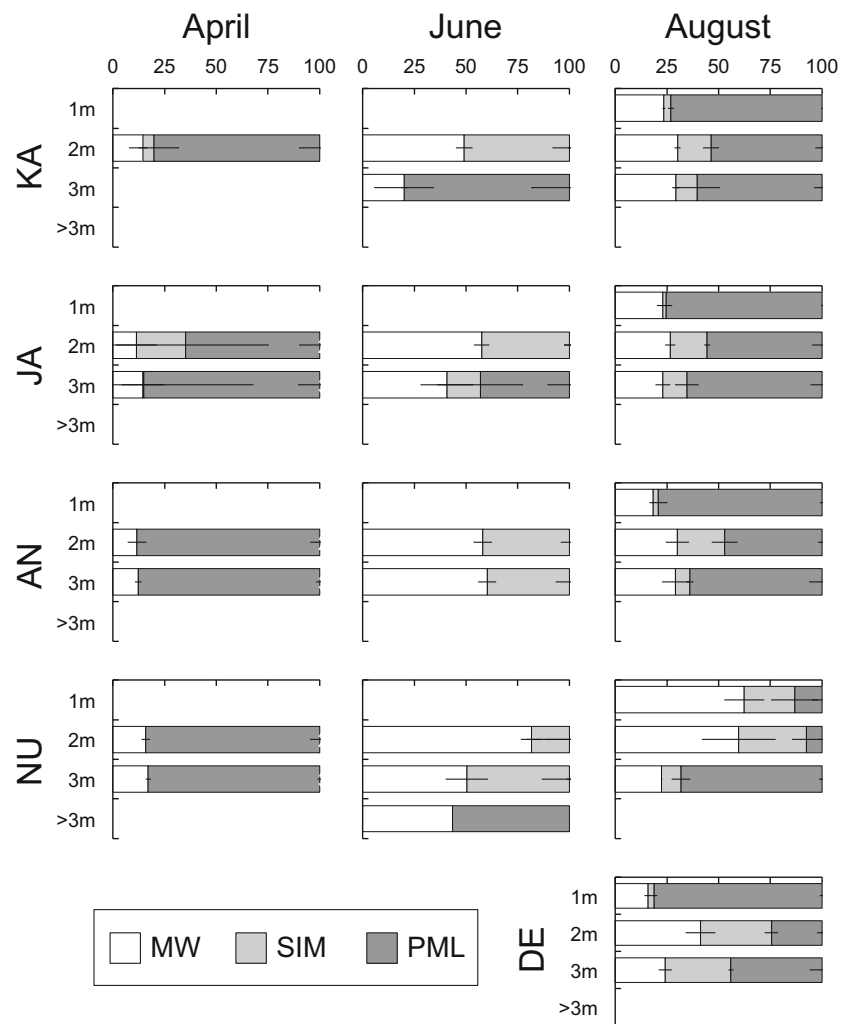
Summer Open-Water Period (August)

Greater proportions of PML water were noted in August than in June in all lagoons as exchange with Beaufort Sea coastal waters increased with ice retreat (Fig. 7). Storm surges and wind-driven upwelling are thought to both enhance lagoon-nearshore water exchange, causing cooler and more saline water from the Beaufort Undercurrent to intrude into lagoons (McCart 1977; Schell et al. 1984; Macdonald et al. 1987). Winds can also increase vertical mixing, but the impact depends on the strength of the stratification. In weakly stratified lagoons, strong winds will mix waters to depth for the water mass, whereas in highly stratified lagoons, only the surface layer experiences increases in horizontal velocity (Hale 1990).

In July and August of 2011–2014, wind speeds on Barter Island (in KA) averaged 9–11 knots and generally blew from the north or north/northeast on the Beaufort coast (AK ASOS Network), which contributed to the vertical mixing of coastal

lagoons. In August, the warm, well-mixed water columns of all lagoons (Fig. 3) indicated that the deep brine layer observed in KA (and at JA and NU in some years) in June was flushed or diluted before August sampling occurred. Our 2012 results for KA and JA differed from previous observations at these lagoons. Hale (1990) reported a halocline in KA and a thermocline in JA over the open-water period. In this study, both lagoons were characterized by similar temperatures and salinities at all depths.

Once lagoons are ice free, water exchange rates with the adjacent marine waters increase (Hale 1990) and water from the PML mixes with lower-salinity water. On average, 30 % of water in lagoons was comprised of MW. Surprisingly, SIM contributed 12–23 % of water in lagoons, even though most lagoons are ice-free by mid-July. Some of this SIM may have originated in the coastal Beaufort Sea and have been advected into lagoons with marine water in August.

The proportion of PML in August varied slightly among lagoons. JA contained the highest proportions of PML and NU contained the least PML and the most MW, with surface layers consisting of >90 % low-salinity sources. There are

several possible explanations for this variation: (1) JA has a much larger entrance than NU, which may allow more marine water to enter, (2) more mixing between upper and bottom layers is typically observed in "bay"-shaped lagoons, like JA, than narrow lagoons (Lissauer et al. 1984), and (3) MW inputs were more important in NU because it did not have another lagoon on its eastern side to dilute river inputs, as did JA (Tapkaurak Lagoon).

Groundwater inflows, which are not quantified in our mixing model, also contribute fresh water to lagoons along the Beaufort Sea coast (Dimova et al. 2015; Lecher et al. 2015). These inputs may be particularly relevant in late summer, when soil thaw depths (active layer depths) are at a maximum and river inflows are at a minimum. Recent studies at Elson Lagoon (near Barrow, AK) suggest that groundwater inputs during the summer are small (Dimova et al. 2015; Lecher et al. 2015), but these inputs undoubtedly vary as a function of topography and precipitation patterns. Thus, groundwater flows need to be investigated at a variety of locations to gain a better understanding of how much they contribute to the freshwater budget of Arctic coastal waters.

Bottom water in all lagoons became increasingly saline in late summer, and within-lagoon salinity and temperature variation decreased after August. This pattern was likely caused by a combination mixing and decreasing air temperatures (Hale 1990, 1991). Decreasing bottom water temperatures in late September and October indicate the beginning of freeze-up, which occurred during the same time period in the 1970s (McCart 1977).

Implications for a Changing Arctic

Although the five eastern Alaskan Beaufort Sea lagoons were subjected to similar climatological conditions over the 3-year period of our study, we observed differences in seasonal salinity patterns and physical structure of the water column among lagoons. We also observed that the source water composition of the five lagoon systems varied greatly among seasons, though there was little variation among lagoons. It is likely that these differences are related to variations in amount of freshwater inputs and the degree of connectivity to the Beaufort Sea. Factors controlling exchange characteristics between the lagoons and open coastal waters may be particularly important. Increasing salinities throughout the winter in lagoons such as KA and NU suggest that exchange was limited at these locations, whereas the attainment of salinity plateau in some lagoons (e.g. Demarcation Bay) likely reflects continual mixing between lagoon and coastal waters.

Climate change may cause significant changes to the hydrology and terrestrial-marine linkages within Arctic lagoons. Rising atmospheric temperatures in the Arctic are predicted to increase precipitation, runoff, and stream flow on Alaska's North Slope (Hinzman et al. 2005; Peterson et al. 2006), which will increase low-salinity water inputs to coastal lagoons. Because riverine inputs contain nutrients and both dissolved and particulate organic carbon (McClelland et al. 2014), higher stream flows may increase benthic production in lagoons and supplement terrestrially derived sources of carbon (Dunton et al. 2012). Projected increases in storm frequency and intensity, along with the duration of the open-water period (Hinzman et al. 2005), is likely to facilitate marine intrusion into lagoons. Changes in the timing and magnitude of freshwater and marine inputs are likely to impact both the hydrological and biological functioning of these lagoons, and as such, our understanding of these highly dynamic and ecologically important systems has become increasingly more imperative.

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