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Exchange of Laptev Sea and Arctic Ocean halocline waters in response to atmospheric forcing

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[1] Combined δ^{18}O/salinity data reveal a distinctive water mass generated during winter sea ice formation which is found predominantly in the coastal polynya region of the southern Laptev Sea. Export of the brine-enriched bottom water shows interannual variability in correlation with atmospheric conditions. Summer anticyclonic circulation is favoring an offshore transport of river water at the surface as well as a pronounced signal of brine-enriched waters at about 50 m water depth at the shelf break. Summer cyclonic atmospheric circulation favors onshore or an eastward, alongshore water transport, and at the shelf break the river water fraction is reduced and the pronounced brine signal is missing, while on the middle Laptev Sea shelf, brine-enriched waters are found in high proportions. Residence times of bottom and subsurface waters on the shelf may thereby vary considerably: an export of shelf waters to the Arctic Ocean halocline might be shut down or strongly reduced during "onshore" cyclonic atmospheric circulation, while with "offshore" anticyclonic atmospheric circulation, brine waters are exported and residence times may be as short as 1 year only.

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1. Introduction

[2] Important features of the Arctic hydrography are the inflow of warm and saline waters from the Atlantic Ocean and the cold and low-salinity halocline. The fresh surface layer of Arctic river runoff (10% of global total runoff) and its associated cold halocline layer normally act to isolate the sea ice cover from the warm and saline Atlantic-derived layer below. Within the ongoing discussion on Arctic and global climate change it has now been recognized that the performance of the cold halocline in insulating the Arctic sea ice cover cannot be taken for granted [*Stroeve et al.*, 2008]. In this study a strong variation of waters contributing to the Arctic Ocean halocline from different freshwater sources is observed and investigated at the Laptev Sea continental margin.

[3] The Laptev Sea is considered a main production area of Arctic sea ice since ice is formed at initial freeze up in autumn and throughout the winter within the reoccurring coastal polynya at the edge of the land-fast ice [*Bareiss and Görgen*, 2005; *Dethleff et al.*, 1998; *Martin and Cavalieri*, 1989; *Zakharov*, 1966]. The Laptev Sea also receives large amounts of freshwater from the Lena River as one of the large arctic rivers. The low-salinity surface waters of the Laptev Sea are subject to atmospheric forcing [*Shpaikher et al.*, 1972; *Dmitrenko et al.*, 2005] and may be transported directly northward across the shallow shelf into to the Arctic Ocean interior or may be spreading eastward and subsequently entering the Arctic Ocean interior within the Canadian part of the basin [*Guay et al.*, 2001; *Dmitrenko et al.*, 2005, 2008]. Variations in hydrographic patterns and residence times of Laptev Sea waters may, therefore, significantly influence the structure of the halocline of the Arctic Ocean [*Johnson and Polyakov*, 2001] and may correspond with different prevailing wind-forced circulations within the Arctic Ocean [*Proshutinsky and Johnson*, 1997]. In this study, δ^{18}O data from the Laptev Sea and the continental shelf break are used to infer the contribution and variation of Laptev Sea waters from different freshwater sources to the Arctic Ocean interior. The cross-shelf salinity and δ^{18}O data sets from 2 years are interpreted in terms of freshwater and brine water exchange between the Laptev Sea and the Arctic Ocean halocline in correlation with the prevailing atmospheric forcing.

2. Material and Methods

[4] Hydrographic data were collected by conductivity-temperature-depth (CTD) and Niskin sampling bottles in consecutive casts [*Kassens et al.*, 1994; *Kassens and Dmitrenko*, 1995; *Kassens et al.*, 1997] on the Laptev Sea

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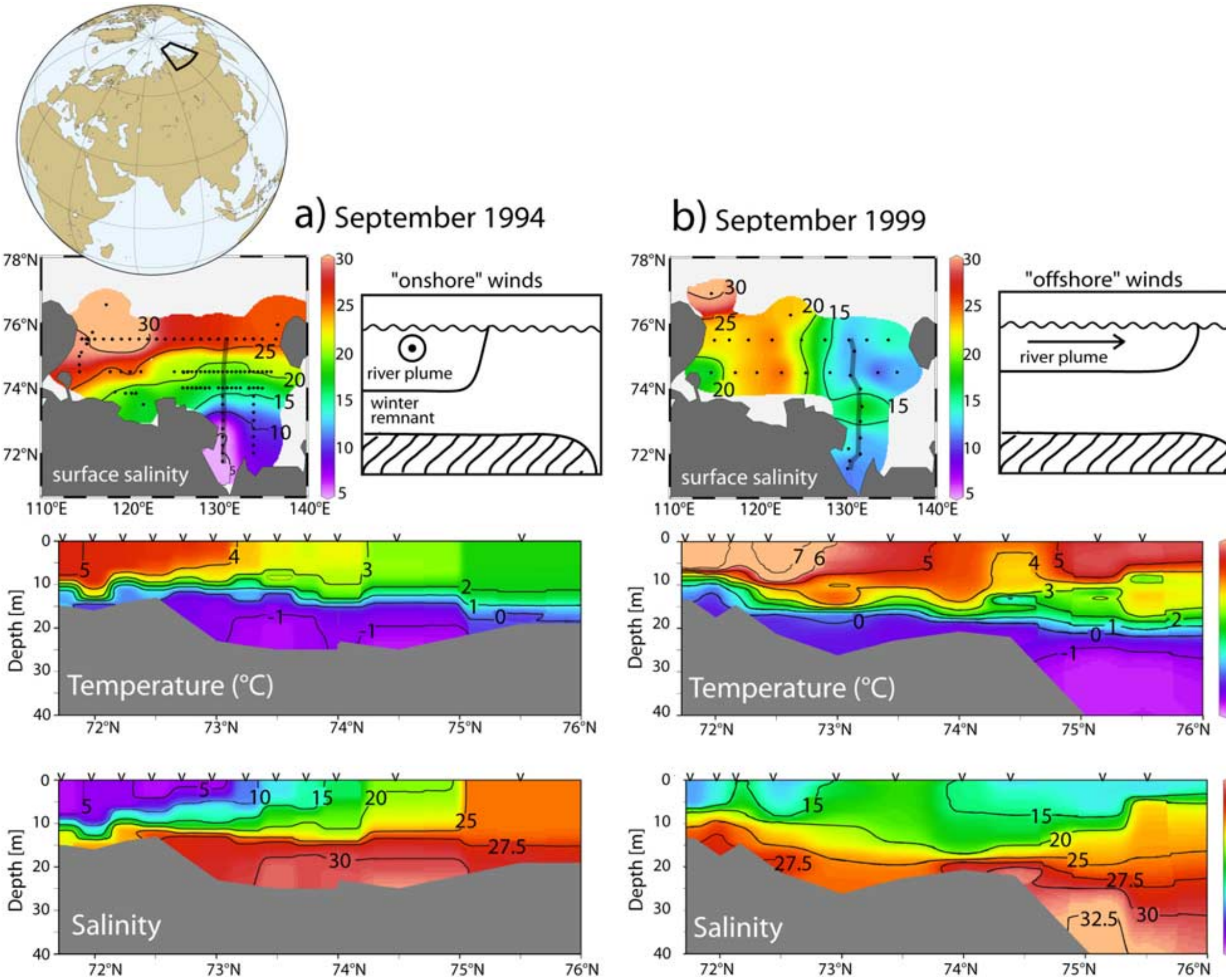

Figure 1. Temperature and salinity data on sections along 130°E for summers (a) 1994 and (b) 1999. Maps indicate surface salinity distributions and section locations (gray line). The marked area on the global view of the Northern Hemisphere shows the position of the maps. Differences in bathymetry of the sections are due to small differences in geographical distribution of stations along about 130°E. Schematic drawings indicate the supposed water circulation during years with "onshore" and "offshore" atmospheric forcing. The flow of the river plume is from west to east in 1994 as indicated by the arrow; for further explanation, see text.

shelf during summers 1994 and 1999 (see maps in Figure 1). All CTD data have an accuracy of at least 0.02°C in temperatures and 0.02 mS cm^{-1} in conductivity [*Kassens and Dmitrenko*, 1995; *Dmitrenko et al.*, 1999].

[5] Stable oxygen isotope data together with salinity data from the Laptev Sea and shelf break are available from G. A. Schmidt et al. (Seawater Oxygen-18 Database, 1999, available at http://data.giss.nasa.gov/o18data/)(for station positions, see map in Figure 3) but have not yet been interpreted in terms of water mass analysis and exchange processes. Salinity and $\delta^{18}O$ data originate from the shelf during the main summer season in September 1994 [*Mueller-Lupp et al.*, 2003] and summer of 1989 [*Létolle et al.*, 1993]. In summers of 1993 and 1995, data were collected from the Laptev Sea shelf break and adjacent basin [*Frank*, 1996]. Measurement precisions and accuracy of $\delta^{18}O$ data are 0.07‰, 0.03‰, and 0.03‰ for 1994, 1993, and 1995, respectively, and 0.2 to 0.1‰ (S. D. Nikolaev, personal communication, 2007) for 1989.

[6] Atmospheric conditions during summer months were classified on the basis of National Centers for Environmental Prediction surface wind data following the approach of *Guay et al.* [2001] in evaluating monthly averaged surface wind from June to September and following the approach of *Dmitrenko et al.* [2005] in using sea level pressure (SLP) data and the vorticity index defined as the finite differenced numerator of the Laplacian of sea level pressure for the area within 550 km of 80°N and 150°E [*Walsh et al.*, 1996].

3. Hydrography of the Laptev Sea

[7] The hydrography of the Laptev Sea is strongly influenced by river water and sea ice processes, which are both highly variable over the seasons. The Laptev Sea receives river water from the Lena River mainly during summer

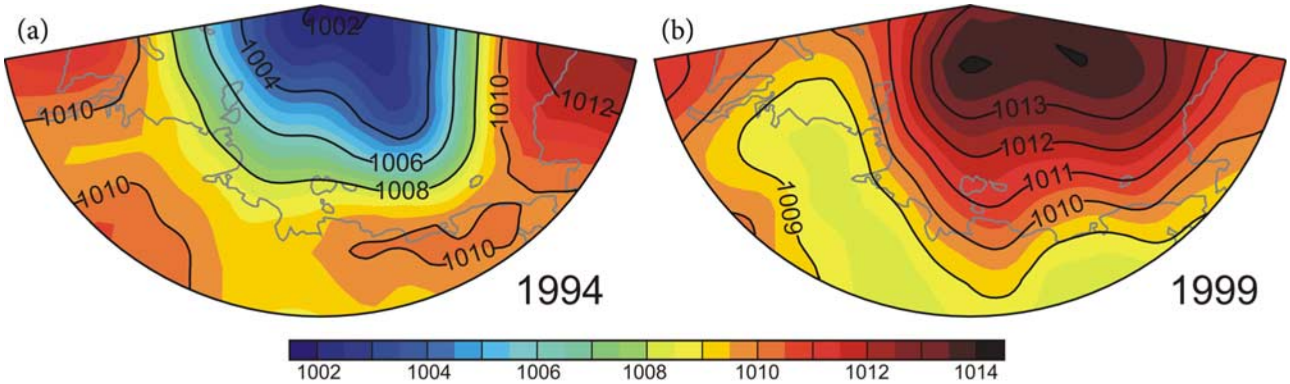

Figure 2. Average sea level pressure (SLP) during July to September for summers (a) 1994 and (b) 1999. The Siberian coastline is indicated by a gray line. SLP is given in hPa.

with an annual averaged discharge of about 541 km^3 a^{-1} (RosHydromet gauge data at Kusur from 1985 to 2007, accessible through the Regional, Hydrometeorological Data Network at http://www.R-ArcticNET.sr.unh.edu), and main outflow during June and July is about 4 to 5 times higher than the annual mean discharge [e.g., *Létolle et al.*, 1993]. During winter the Laptev Sea is ice covered, and polynyas or flaw leads are opened by offshore winds and freeze up repeatedly [*Bareiss and Görgen*, 2005; *Dethleff et al.*, 1998; *Zakharov*, 1966]. The fast ice in the south breaks up in June and July at the time of the main river discharge. Sea ice cover retreats mainly during July and August and recurs in October. Therefore, oceanographic summer occurs during September with least sea ice cover and warmest surface water temperatures (*Dmitrenko et al.*, 1999; D. Bauch et al., Eurasian Arctic shelf hydrography: Exchange and residence time of southern Laptev Sea waters, submitted to *Continental Shelf Research*, 2008). In addition to the dominating seasonal changes there is also a considerable interannual variability as documented by hydrographic data collected in 1994 and 1999 (see Figure 1). Years with predominantly northerly and westerly winds over the Laptev Sea during June to September (cyclonic atmospheric circulation) tend to cause an onshore or eastward alongshore surface water transport, while years with predominantly southerly to southeasterly winds (anticyclonic atmospheric circulation) tend to cause an offshore transport of surface waters [see *Guay et al.*, 2001; *Dmitrenko et al.*, 2005]. Note that at the average shelf depth of about 20–25 m the wind-forced flow is essentially controlled by wind stress and bottom friction and the Coriolis force becomes insignificant. The surface current aligns almost completely with the wind direction.

[8] In 1993 and 1994, summer atmospheric forcing was favoring "onshore"-directed water transport, river water remained mostly within the southern Laptev Sea, and a predominantly west to east oriented surface salinity front developed within the Laptev Sea inner and midshelf (see 1994 CTD data in Figure 1a and 1994 SLP data in Figure 2a). In summers of 1995 and 1999, atmospheric forcing was favoring "offshore"-directed water transport, river runoff was spreading farther northward in the eastern Laptev Sea, and a predominantly south to north oriented salinity front developed (see 1999 CTD data in Figure 1b and 1999 SLP data in Figure 2b). In addition, bottom water properties in the inner shelf remain colder and saltier in 1994 compared to 1999 (see Figure 1).

4. Stable Isotope Results

[9] Salinity and δ^{18}O data are, in first order, linearly correlated and determined by low-salinity Lena River water with a strongly depleted δ^{18}O signal of about −19‰ (see Figure 3) and high-salinity marine water with a δ^{18}O signal close to zero (see solid line in Figure 3). Any deviations from this direct mixing between river water and marine water can be attributed to sea ice processes: Sea ice formation adds brines to the water column, and its salinity increases at nearly constant δ^{18}O values, while melting of sea ice, on the other hand, adds freshwater and the salinity of the water decreases concurrent with a slight increase in δ^{18}O signature only (see schematic arrow in Figure 3).

[10] The contribution of river water and sea ice meltwater can be quantified with a mass balance calculation [e.g., *Bauch et al.*, 1995] (see Figure 5) because the structure of the water column on Arctic shelves is governed by inflowing water from the Arctic Ocean interior, continental runoff, and sea ice processes [*Bauch et al.*, 2005; *Macdonald et al.*, 1995]. Therefore, it can be assumed that each sample is a mixture between marine water, river runoff, and sea ice meltwater. The balance is governed by the following equations:

$$f_{\mathrm{mar}} + f_r + f_i = 1,$$

$$f_{\mathrm{mar}} S_{\mathrm{mar}} + f_r S_r + f_i S_i = S_{\mathrm{meas}},$$

$$f_{\mathrm{mar}} O_{\mathrm{mar}} + f_r O_r + f_i O_i = O_{\mathrm{meas}},$$

where f_{mar}, f_r, and f_i are the fractions of marine water, river runoff, and sea ice meltwater in a water parcel and S_{mar}, S_r, S_i, O_{mar}, O_r, and O_i are the corresponding salinities and δ^{18}O values. S_{meas} and O_{meas} are the measured salinity and δ^{18}O of the water samples.

[11] A special selection of salinity and δ^{18}O end-member values is required for each individual region [*Bauch et al.*, 2003]. The marine source is chosen according to the

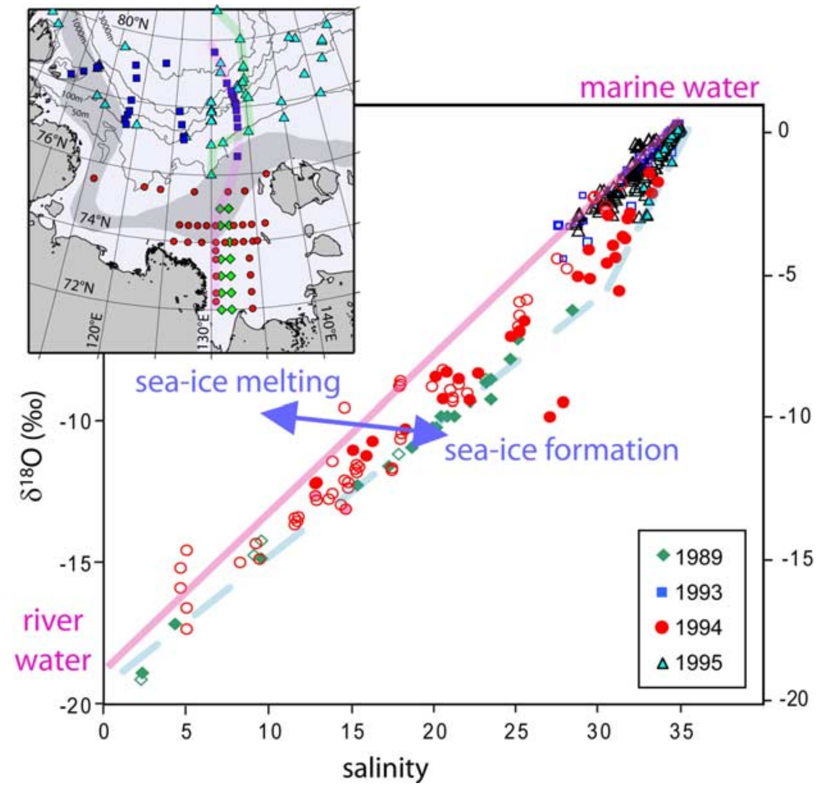

Figure 3. Property plot of δ^{18}O versus salinity and geographical distribution of expedition data collected in summers 1989 (diamonds), 1993 (squares), 1994 (circles), and 1995 (triangles). Bottom, intermediate, and surface samples are indicated with closed, shaded, and open symbols, respectively. A mixing line between river water and Atlantic-derived waters (solid line) is indicated as well as mixing lines including a brine-enriched bottom water mass (dashed lines). The schematic arrow indicates the effects of sea ice melting and sea ice formation; for further explanation, see text. Insert map shows the position of stations. The shaded gray area represents the position of the coastal polynya in the Laptev Sea during winter sea ice coverage according to *Zakharov* [1997]. The main outflow of the Lena River is between about 72–73°N and 128°E. Light red and green lines show position of sections (see Figure 5) for data sets from 1993/1994 and 1995, respectively.

Atlantic Layer in the southern Nansen Basin (34.92 salinity and 0.3‰ in δ^{18}O [*Bauch et al.*, 1995]). The mean value of river runoff within the Arctic Ocean of −20‰ [*Bauch et al.*, 1995; *Frank*, 1996; *Ekwurzel et al.*, 2001] is taken as river water end-member. The choice of −20‰ instead of the slightly higher Lena River δ^{18}O values (−19‰) prevents an overestimation of the brine component (negative f_i) at the shelf break but gives proportionally altered values on the Laptev Sea shelf. River water fractions are higher by up to 5%, and sea ice meltwater fractions are lower by up to 20% when river water δ^{18}O end-member values of −19‰ instead of −20‰ are taken. For sea ice meltwater the δ^{18}O value of surface water at each station together with a fractionation of 2.6‰ [*Melling and Moore*, 1995] is taken, and a salinity of 4 was taken as measured for multiyear ice [*Pfirman et al.*, 1990].

[12] When integrating the calculated fraction over the depth of the water column (down to the bottom, or down to maximal 300 m water depth), inventory values can be derived. River water and sea ice meltwater inventory values (see Figure 5, numbers on top of sections) represent the thickness of the water column containing pure river water or sea ice meltwater, respectively. A negative sea ice meltwater fraction f_i reflects the amount of water removed for sea ice formation and the subsequent addition of brines. Negative inventory values for sea ice meltwater represent the thickness of the water column removed for sea ice formation. All fractions and inventory values are net values reconstructed from the δ^{18}O and salinity signature of each sample over the residence time of the water.

[13] Most stations on the shallow shelf, where the water column is dominated by a strong pycnocline (Figure 1), are covered by single samples within the surface and within the bottom layer only, and a simple integration across these two points is rather rough. In these cases the δ^{18}O and salinity measurements of each station were used for an interpolation of δ^{18}O to the salinity of the station's concurrent CTD profile. Interpolated δ^{18}O values were used for the fraction calculation, and the calculated fractions were integrated for inventories. Internal structures visible at some stations within the CTD profile across the pycnocline cannot be interpreted in terms of freshwater sources with such an interpolation and are, therefore, ignored with this method. Stations were omitted for interpolation and inventory

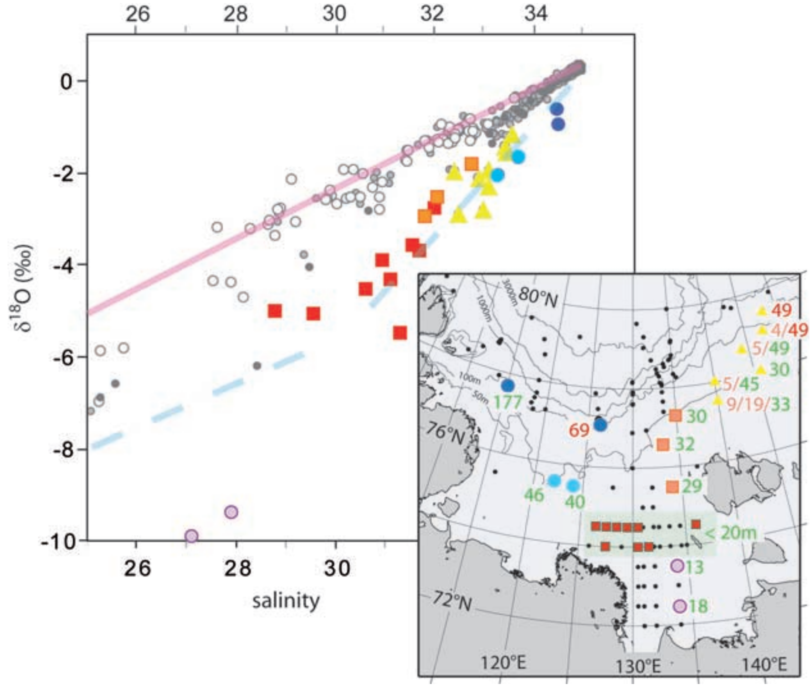

Figure 4. Property plot of $\delta^{18}O$ versus salinity for data with salinities above 25 (see Figure 3 for complete data set). Data points on the light blue mixing line between Atlantic Water and brine-enriched bottom water were labeled according to their geographical distribution as shown on the map. For further explanation, see text. The numbers given on the map next to the color labeled positions give the sampling depth in meters at which the brine-enriched waters are found. Green numbers are brine-enriched waters found at bottom depth. Orange and red numbers are brine-enriched waters found above bottom depth. Stations in the south of the polynya region at which brine-enriched waters are found are all shallower than 20 m and are marked with a shaded green box.

calculation when sampling occurred within the surface layer or bottom layer only.

5. Discussion

[14] The combined $\delta^{18}O$/salinity summer data demonstrate that the influence of sea ice production and sea ice export is predominant within the Laptev Sea even during summer season when sea ice is melting locally (Figure 3). Only three surface values at relatively low salinities show excess melting. For all other values, the influence of sea ice formation balances or exceeds summer melting since all fall on or below the direct mixing line between Lena River water (about −19‰ in $\delta^{18}O$) and Atlantic core water (about 0.2‰ in $\delta^{18}O$ at 34.92 salinity [*Bauch et al.*, 1995]). This net influence of sea ice formation on Laptev Sea waters is in agreement with the concept of the Laptev Sea as major production area of Arctic Ocean sea ice [e.g., *Rigor and Colony*, 1997]. The mean residence of surface and bottom waters is, thus, at least half a seasonal cycle since the winter brine signal is visible within the bottom layer as well as within the surface layer during summer season. Surface waters from the shelf break, on the other hand, have salinity and $\delta^{18}O$ data directly on the mixing line between river water and Arctic Ocean halocline surface waters (see open symbols for 1993 and 1995 data in Figure 3).

[15] The brine-enriched waters on the Laptev Sea shelf fall on two different mixing lines in dependence on their salinities (see dashed mixing lines in Figures 3 and 4) and indicate the existence of a water mass with physical properties of the intercept at about 30 salinity and −4‰ in $\delta^{18}O$ [*Bauch et al.*, 2005]. These waters containing the highest amount of brines (about 20 to 30% and 40 to 50% when adopting a river water $\delta^{18}O$ end-member of −20 and −19‰, respectively) are all bottom waters in the southern Laptev Sea below 20 m water depth (Figure 4, red squares) within the region of the winter polynya (compare Figure 3). Since sea ice is produced within the polynya at high rates and continuously throughout the winter, the polynya region is likely the production area for brine-enriched bottom water (BEBW). But brine-enriched waters may also be formed during initial freeze up beneath the land-fast ice in the southern Laptev Sea during October to December. An extreme enrichment with brine waters is found at two stations at salinities of about 27 and 28 (Figure 4, purple circles) in a depression imbedded around a shallow bank in the southern Laptev Sea. These two bottom samples are off the general mixing scheme (see Figure 3) and are the remnant of brine waters produced below the fast ice at considerable lower salinities of about 17 compared to about 25, which is inferred for the initial salinity of the BEBW. But clearly, BEBW is dominating the hydrography within the Laptev Sea as documented by the mixing lines described by the combined $\delta^{18}O$/salinity data (Figure 3).

[16] Toward the north, BEBW mixes with higher-salinity water and is found either at the bottom (see Figure 4,

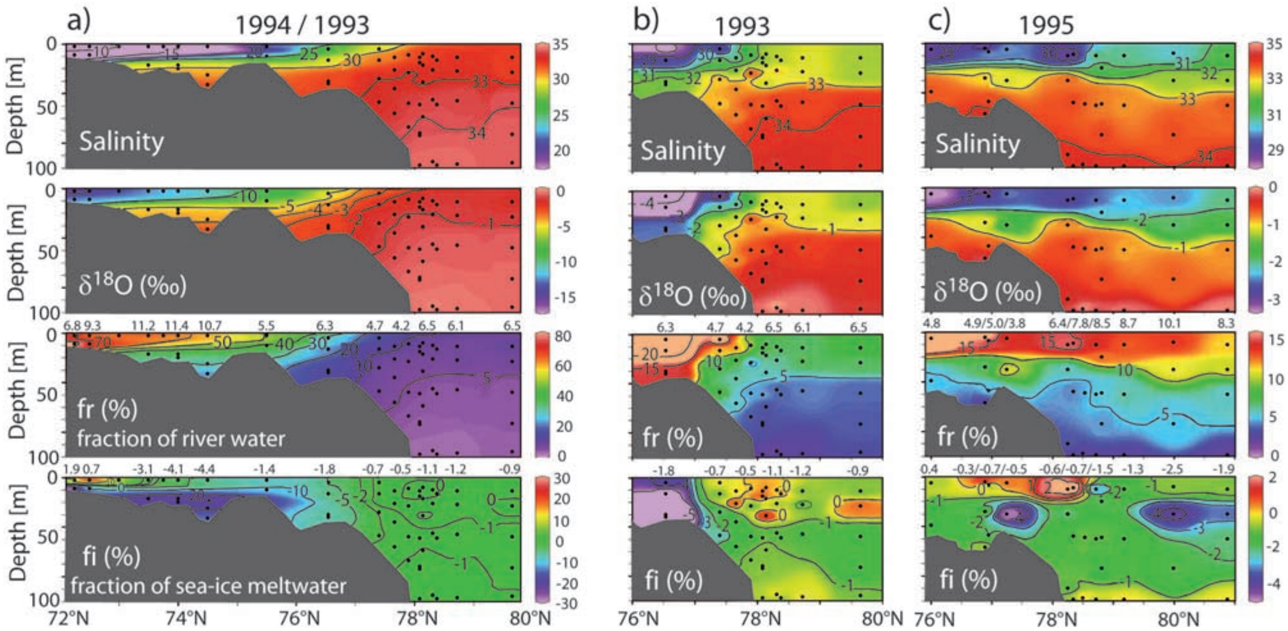

Figure 5. Sections along about 130°E of salinity and $\delta^{18}O$ as well as the calculated fractions of river water (f_r) and sea ice meltwater (f_i). The position of the sections is indicated in Figure 3. Data are from summers of (a) onshore years 1994 and 1993, (b) 1993 data repeated on a finer scale, and (c) offshore year 1995 on same scale as 1993 data from Figure 5b. Inventory values of river water and sea ice meltwater are shown on top of sections. For further explanation, see text.

symbols with green numbers) or at about 50 m water depth at the shelf break of the northeastern Laptev Sea (Figure 4, yellow triangles with orange and red numbers). This indicates the entrainment of BEBW from the southern Laptev Sea into the Arctic Ocean halocline. In the western Laptev Sea, brine-enriched waters are found at the bottom (Figure 4, blue circles) and at the shelf break at higher salinities and correspondingly deeper water depth. At salinities below 30, BEBW is mixing with bottom and surface waters within the Laptev Sea in addition to local effects, e.g., sea ice melting (Figure 3).

[17] The mixing scheme as suggested by the $\delta^{18}O$/salinity data is compatible with an estuarine-like circulation on the Laptev Sea shelf [*Macdonald*, 2000; *Dmitrenko et al.*, 2001] and is also in agreement with the interannual variation (compare schematic drawing in Figure 1). Clear interannual differences in hydrographic conditions are observed in the northerly extent of low-salinity surface waters (see Figure 1) [*Dmitrenko et al.*, 2005; *Guay et al.*, 2001] and are also apparent in lower temperatures of the bottom water within the southeastern Laptev Sea during onshore years compared to offshore years (e.g., 1994 and 1999 data, Figure 1). This interannual difference is also apparent in the $\delta^{18}O$ and salinity data sets from the Laptev Sea and shelf break (Figure 5). Both 1993 and 1994 show an atmospheric forcing favoring onshore water transport, while 1995 atmospheric forcing is favoring offshore surface water transport. While river water fractions decrease below 10% north of the shelf break at 78°N during the 1993 onshore year, the river water fractions are around 15% during the 1995 offshore year (Figure 5). Inventory values also depict clearly the different freshwater distributions between onshore and offshore years with river inventories of about 6 m and about 9 m, respectively (Figure 5). These differences are predicted by model results which have demonstrated a different freshwater spreading in correlation to the atmospheric forcing [*Johnson and Polyakov*, 2001] and have also been pointed out before for these years [*Guay et al.*, 2001]. With the calculated fractions we additionally derive quantitative information on the amount of river water and on the brine components contained in subsurface waters. The amount of brine is directly correlated with the negative sea ice meltwater fraction f_i with values as high as about 30% within the bottom layer of the Laptev Sea shelf (Figure 5a, at about 73 to 74°N). The distribution of river water and brines north of 76°N is quite opposite in the 1995 offshore year compared to the 1994/1993 onshore years at the shelf break: Slightly positive meltwater fractions within the upper 30 m of the water column and brine contributions of about −1% in sea ice meltwater are found at about 50 m water depth in the onshore situation (Figures 5a and 5b), while in the 1995 offshore year the sea ice meltwater fractions remain negative and a brine signal is found centered at about 30 to 40 m water depth with sea ice meltwater fractions as low as about −4% (Figure 5c). Thus, the data sets indicate that during summers with a predominantly onshore wind setting, the brine-enriched bottom water remains largely on the shelf, while it is exported from the Laptev Sea shelf at about 30 to 40 m water depth during summers with a predominantly offshore wind setting. Unfortunately, we are missing data south of 76°N during the 1995 offshore year; therefore, this conclusion is based largely on the different brine distributions north of 76°N, and we cannot support our conclusion that brines on the Laptev Sea are largely missing during offshore years by direct $\delta^{18}O$ evidence from 1995. Nevertheless, observed

differences in colder temperature and lower-salinity signatures in the southern Laptev Sea in 1994 onshore year compared to 1999 offshore year (Figure 1) support our speculation as slightly warmer bottom waters with the observed salinity signature might originate from the western Laptev Sea farther north. The residence time of waters on the Laptev Sea shelf may thereby be as short as one winter-to-summer cycle during offshore years but may be correspondingly longer during onshore years. Particularly wind-driven coastal Ekman circulation may induce vertical mixing that leads to saltier water influx from below [*Sanders and Garvine*, 2001]. The differential response of a buoyant river plume to upwelling and downwelling provides an additional complication to our interpretation.

[18] A simple budget based on river water inventory values was calculated for the eastern Laptev Sea within the area south of 76°N and 125 to 140°E on the basis of δ^{18}O data collected in 1994. Data sets from other years have no or too little data coverage within the Laptev Sea in order to derive a budget. The inventory values were interpolated on a regular grid and multiplied by the area covered; thereby budgets of 2083 and 1845 km^3 were observed when applying river end-member δ^{18}O values of −19 and −20‰, respectively. By comparing the derived river water budget in the eastern Laptev Sea for 1994 with the annual mean discharge of the Lena River of 541 km^3 a^{-1}, rough estimates of the residence times of about 3.8 and 3.4 years are calculated, applying a river water δ^{18}O end-member of −19 and −20‰, respectively. This residence time is a slight overestimation because the discharge of the Lena River is mainly released during early summer and, therefore, a river budget during winter will be considerably lower than the river budget derived from our summer sampling. In order to get a measure of this overestimation we will assume that the winter budget is smaller than our summer budget by 495 km^3, which is the amount of the mean Lena River discharge during summer (May to October data from 1985 to 2007), and represents the maximum value by which the winter budget might be smaller than the summer budget. With these numbers we derive mean annual river budgets of 1833 and 1598 km^3 and residence times of 3.4 and 3.0 years when applying river end-member δ^{18}O values of −19 and −20‰, respectively. In our estimate we use the annual input of the Lena River water, which is mainly stored in the surface layer, and assume that the thereby derived residence time also applies to the bottom layer because our data show that the bottom layer responds in the same qualitative manner to the atmospheric forcing as the surface layer. Since the surface layer responds more directly to the atmospheric forcing, this approach provides a lower limit for the residence time of the bottom layer. Atmospheric forcing was clearly favoring onshore transport during summers of 1994 and 1993, and positive summer and winter vorticity indexes indicate that onshore transport generally prevailed since 1991 [see *Dmitrenko et al.*, 2005]. Our simple estimate of about 3.5 to 3 years residence time of waters in the eastern Laptev Sea in 1994 is, therefore, in agreement with a predominantly onshore atmospheric forcing during the same period. It is also in agreement with the estimate of a mean residence time of about 3.5 years on the basis of transient tracer data and estimated with a standard deviation of ±2 years [*Schlosser et al.*, 1994]. Our data from 1994 supports this mean value, and our data from 1995 indicates that at times the residence time may be much shorter and thereby our data overall demonstrate a strong interannual variation in residence times.

[19] Model results of *Johnson and Polyakov* [2001] yield an enhanced production of sea ice and brines in the Laptev Sea during periods with an anticyclonic wind vorticity during winter. The winter atmospheric forcing is not a subject of this paper. With the interpretation of δ^{18}O/salinity we can reconstruct the influence of winter sea ice formation during summer, but from summer data sets alone we know nothing about winter-to-summer modification, and all conclusions on residence times are made on the basis of the assumption that comparable amounts of brines are produced each winter. If comparable amounts of brines are produced each winter and are only distributed differently during summers as indicated by our data set, brine waters observed in our data set in 1994 on the Laptev Sea shelf might have been released to the Arctic Ocean halocline in 1995 only because of significantly different residence times.

6. Conclusions

[20] Brine-enriched bottom waters are formed during winter as depicted by δ^{18}O and hydrographic summer data. During years with prevalent offshore wind setting, brine-enriched waters are exported to the Arctic Ocean halocline at about 50 m water depth, and the mean residence times of these waters may be as short as 1 year only. Our data suggest that during years with a predominant onshore wind setting, brine-enriched waters remain on the Laptev Sea shelf and mean residence times may be much longer than 1 year, accordingly. The fraction of brines in the bottom layer may be as high as 30%. On the basis of the assumption that comparable amounts of brines are produced each winter, our data indicate that these brines remain mostly on the shelf during onshore years; for example, residence times in the eastern Laptev Sea are about 3 to 3.4 years in 1994 while they are released to the Arctic Ocean halocline during summers with a predominantly offshore atmospheric forcing.

[21] In respect to the ongoing climatic change an important question is to what extent long-term hydrographic changes on the Laptev Sea shelf will influence the hydrology of the Arctic Ocean. Modeling studies have to test how climate change may affect, e.g., the frequency of years with a predominantly offshore or onshore wind situation. A shift either way will affect the stability of the Arctic Ocean halocline [*Johnson and Polyakov*, 2001]. At present, we can derive from existing δ^{18}O data sets where and when bottom waters are exported from the Laptev Sea to the Arctic Ocean halocline. More detailed single year data sets are required to derive further budgets and quantitative export rates.

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