Changes in distribution of brine waters on the Laptev Sea shelf in 2007

D. Bauch,[1] J. Hölemann,[2] S. Willmes,[3] M. Gröger,[4] A. Novikhin,[5] A. Nikulina,[1]
H. Kassens,[1] and L. Timokhov[5]

Received 10 March 2010; revised 8 July 2010; accepted 22 July 2010; published 10 November 2010.

[1] Combined salinity and δ^{18}O data from summer 2007 reveal a significant change in brine production in the Laptev Sea relative to summer 1994. The distribution of river water and brine-enriched waters on the Laptev Sea shelf is derived based on mass balance calculations using salinity and δ^{18}O data. While in 1994 maximal influence of brines is seen within bottom waters, in 2007 the influence of brines is highest within the surface layer and only a moderate influence of brines is observed in the bottom layer. In contrast to 2007, salinity and δ^{18}O data from summer 1994 clearly identify a locally formed brine-enriched bottom water mass as mixing end-member between surface layer and inner shelf waters on one side and with higher salinity water from the outer Laptev Sea on the other side. In 2007, the brine-enriched waters are predominantly part of the surface regime, and the mixing end-member between surface layer and outer shelf waters is replaced by a relatively salty bottom water mass. This relatively salty bottom water probably originates from the western Laptev Sea. The inverted distribution of brines in the water column in 2007 relative to 1994 suggests a less effective winter sea ice formation in winter 2006–2007 combined with advection of more saline waters from the western Laptev Sea or the outer shelf precedent to the climatically extreme summer 2007. The observed changes result in an altered export of waters from the Laptev Sea to the Arctic Ocean halocline.

Citation: Bauch, D., J. Hölemann, S. Willmes, M. Gröger, A. Novikhin, A. Nikulina, H. Kassens, and L. Timokhov (2010), Changes in distribution of brine waters on the Laptev Sea shelf in 2007, *J. Geophys. Res.*, *115*, C11008, doi:10.1029/2010JC006249.

1. Introduction

[2] The dramatic reduction in summer Arctic sea ice extent and thickness in recent years [e.g., *Comiso et al.*, 2008; *Kwok and Rothrock*, 2009; *Kwok et al.*, 2009] has been accompanied by substantial warming of the Arctic Ocean Atlantic intermediate water layer [*Schauer et al.*, 2004; *Polyakov et al.*, 2007; *Dmitrenko et al.*, 2008a]. A main feature of the Arctic Ocean is the cold and fresh halocline, which largely insulates the sea ice cover from the underlying warm Atlantic layer [*Steele and Boyd*, 1998]. The Siberian shelves supply freshwater to the Arctic Ocean halocline and are the main production areas for sea ice. As a result, brine waters are produced and exported to the Arctic Ocean halocline as well as to the Arctic Ocean bottom and deep waters [*Bauch et al.*, 1995, 2009a]. An important question is therefore the feedback of these processes to the ongoing climate change, which may alter the ability of the Arctic Ocean halocline to insulate the atmosphere from the warm Atlantic layer and thereby maintain the perennial sea ice cover.

[3] This study investigates the impact of brine waters on the hydrography of the Laptev Sea for the years 1994 and 2007. The shelf regions are free of sea ice during summer, when large quantities of river water spreads onto the shelves and meltwater is released during this time while sea ice and brine waters are formed during winter. Since the Laptev Sea is one of the main production area for Arctic sea ice and also large quantities of Arctic freshwater are released here by the Lena River, possible changes in the Laptev Sea may potentially influence significantly the Arctic Ocean hydrography. Our study is carried out on the basis of the oxygen isotope composition (δ^{18}O) of the water in conjunction with hydrological data. River water in the Arctic is highly depleted in δ^{18}O relative to marine waters, and the effect of sea ice melting or formation on the water column can be separated from these two sources, since sea ice processes strongly influence salinity whereas the δ^{18}O signal remains nearly unaltered.

[1]Leibniz Institute of Marine Sciences (IFM-GEOMAR), Kiel, Germany.
[2]Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven, Germany.
[3]University of Trier, Trier, Germany.
[4]MPI for Meteorology, Hamburg, Germany.
[5]Arctic and Antarctic Research Institute (AARI), Saint Petersburg, Russia.

0148-0227/10/2010JC006249

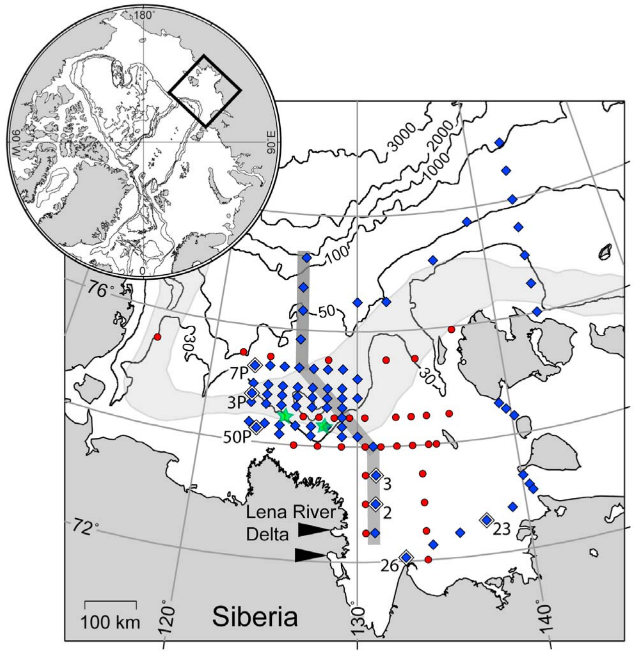

Figure 1. Map of the Laptev Sea with positions of stations occupied in summers 2007 (blue diamonds) and 1994 (red dots). The marked area in the overview map shows the position of the Laptev Sea within the Arctic Ocean. The position of the main discharge channels of the Lena River is indicated by black triangles. The light gray line indicates the position of sections shown in Figures 4 and 7. Labeled are stations 50P and 3P in the western Laptev Sea with vertically mixed temperature and salinity signatures and station 7P, referred to in the text for western Laptev Sea hydrographic signatures. Additionally labeled are stations 3, 2, 26, and 23 in the southern Laptev Sea discussed in Figure 6. The positions of the two moorings, Khatanga (74°42.9′N, 125°17.4′E) and Anabar (74°20.0′N, 128°00.1′E), are indicated (green stars).

On this basis, winter brine production can be quantitatively evaluated based on $\delta^{18}O$ and salinity summer data.

2. Database and Methods

[4] Water samples were collected on board the Russian *RV* "*Ivan Petrov*" during TDXII expeditions in 2007 (see Figure 1) in the frame of the Russian-German cooperation "System Laptev Sea." Oxygen isotopes were analyzed at the Leibniz Laboratory (Kiel, Germany), applying the CO_2-water isotope equilibration technique on at least two subsamples on a Finnigan gas bench II unit coupled to a Finnigan DeltaPlusXL. The overall measurement precision for all $\delta^{18}O$ analysis is ±0.03‰ or smaller. The $^{18}O/^{16}O$ ratio is given versus Vienna standard mean ocean water (VSMOW) in the usual δ notation [*Craig*, 1961]. Additional $\delta^{18}O$ and salinity data were collected in the Laptev Sea in 1994 (see Figure 1) [*Müller-Lupp et al.*, 2003; *Bauch et al.*, 2009a; *Schmidt et al.*, 1999, data available at http://data.giss.nasa.gov/o18data/]. During 1994 at most stations, only single samples were taken within the surface layer and bottom layer. The measurement precision for these data is ±0.05‰ in $\delta^{18}O$.

[5] Salinity data are reported on the psu scale. In addition to the conductivity-temperature-depth (CTD) measurements (SBE19+ calibrated directly before expedition), salinity was determined directly within the water samples taken for $\delta^{18}O$ analysis using an AutoSal 8400A salinometer (Fa. Guildline) with a precision of 0.003 and an accuracy of at least 0.005. The CTD salinity data clearly have a sufficiently high precision, but CTD and bottle data on a shallow shelf are sometimes not well matched when aligned by depth (Figure 2) because of slight differences in spatial and temporal alignment of the instruments during sampling and because of the averaging of the water column at least over the length of each rosette bottle. For a quantitative interpretation of our data, an exact match of salinity and $\delta^{18}O$ value is essential. This fact probably explains the somewhat more scattered data set from 1994 (see below, Figure 5), which is based on a match of $\delta^{18}O$ bottle data and CTD salinities. Since rosette bottle data and CTD data show largest discrepancies in the steep halocline (Figure 2) and sampling in

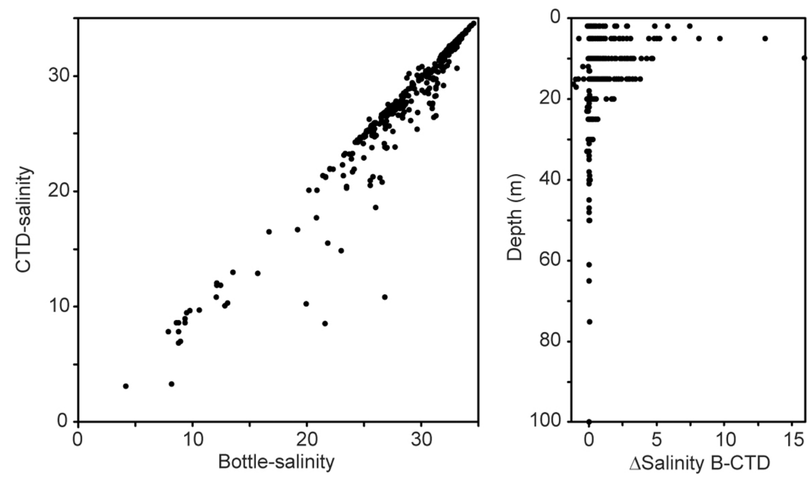

Figure 2. (left) Bottle salinity versus CTD salinity for all samples collected in 2007. (right) The difference between bottle and CTD salinity versus depth.

1994 was mostly restricted to surface and bottom layers only, the problem with a mismatch of salinity and δ^{18}O values is expected to be relatively small.

[6] This study includes also time-averaged water velocity measurements from two moorings, Khatanga (74°42.9′N, 125°17.4′E) and Anabar (74°20.0′N, 128°00.1′E), that were deployed from September 2007 to September 2009 in the Laptev Sea, north of the Lena Delta, in 32 and 43 m water depth, respectively (see Figure 1). Average ocean currents for this study were calculated from an upward looking 300 kHz Acoustic Doppler Current Profiler (ADCP; Teledyne Workhorse Sentinel) set 3 m above the seafloor. For further details on methods and data evaluation, see *Hölemann et al.* [2010].

3. Hydrography of the Laptev Sea

[7] The vast Siberian shelf regions cover more than one third of the total Arctic Ocean area and receive freshwater from several large rivers, primarily the Ob and Yenisey rivers in the Kara Sea and the Lena River in the Laptev Sea (see Figure 1). The Laptev Sea shelf has, over most of its area, a water depth of only 20–50 m (Figure 1). The Lena River, with a runoff of about 541 km^3 yr^{-1}, is one of the largest Siberian rivers, and runoff is released onto the Laptev Sea shelf mainly during summer while it nearly ceases during winter [e.g., *Létolle et al.*, 1993]. This leads to strong vertical and lateral salinity gradients on the Laptev Sea shelf with strong seasonal [*Bauch et al.*, 2009b] and interannual variations [*Bauch et al.*, 2009a, *Dmitrenko et al.*, 2005]. During winter, the Laptev Sea is ice covered, and polynyas and flaw leads are opened repeatedly by offshore winds and freezeup again accordingly [*Bareiss and Görgen*, 2005; *Dethleff et al.*, 1998; *Zakharov*, 1966]. The average position of the Laptev Sea coastal polynya is along the fast ice edge at about 30 m water depth (see shaded area in Figure 1). 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. Oceanographic summer occurs during September with least sea ice cover and warmest surface water temperatures [*Bauch et al.*, 2009b; *Dmitrenko et al.*, 1999]. In addition to these dominant seasonal changes, there is also a considerable interannual variability [*Bauch et al*, 2009a; *Dmitrenko et al.*, 2008b, 2005]. Years with cyclonic atmospheric circulation have predominantly northerly and westerly winds over the Laptev Sea during June to September, which tend to cause a southward-to-eastward alongshore surface water transport, while years with anticyclonic atmospheric circulation have predominantly southerly to southeasterly winds, which tend to cause an offshore transport of surface waters [*Guay et al.*, 2001; *Dmitrenko et al.*, 2005, *Bauch et al.*, 2009a].

3.1. Hydrographic Results From Summer 2007 and 1994

[8] During both summers of 2007 and 1994, atmospheric forcing was favoring a southward 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 in both years (Figure 3) in contrast to years with offshore atmospheric forcing, in which a significantly different north-to-west oriented salinity front prevails within the Laptev Sea [*Bauch et al.*, 2009a]. However, river water spread slightly farther to the north in 1994 and farther toward the east in 2007 (Figure 3).

[9] The vertical salinity and temperature distribution (Figure 4) shows the warm and low-salinity river water within the surface layer. The warm surface layer extends to the shelf break due to warming by solar radiation on the shelf where the sea ice cover has retreated (Figure 4). Surface temperatures are considerably warmer in 2007 (Figures 3 and 4) than in 1994 (Figure 4) in agreement with general results by *Steele et al.* [2008] and *Frolov et al.* [2009]. The bottom layer has relatively high salinities of above 32 in the Lena submarine valley along about 130°E in the southern Laptev Sea (south of about 74.5°N) in summer 2007, while in 1994 bottom salinities are only about 30 and are more typical [*Bauch et al.*, 2009a, 2009b]. In the western Laptev Sea, the bottom layer of both years is above 32 in salinity below about 20–25 m water depth. On the shallow banks of the western Laptev Sea, the salinities are generally lower and the water column is found to be mixed at some stations with nearly constant salinity and temperature, e.g., in 2007 at stations 50P with 12 m water depth (about 25.8 salinity and 5°C) and station 3P with 15 m water depth (about 28.4 salinity and 6°C) (see Figure 1 for locations).

3.2. Current Measurements

[10] These current measurements are the first year-round observations in the Laptev Sea. The mooring Khatanga is located in a shallow NW-SE running trough, and the mooring Anabar was deployed in a shallow SSW-NNE running trough (Figure 1). Consequently, the general directions of the bottom water flow are strongly influenced by the local topography and are dominated by tidal currents along the main axis of the troughs [*Hölemann et al.*, 2010]. For an assessment of the general transport of waters on the Laptev Sea shelf, we calculated an annual average of the currents below the main pycnocline within the bottom layer from about 15 m water depth to about 5 m above the seafloor. The annual average currents are 0.36 cm/s in eastward direction (90°E) and 0.60 cm/s in east-northward direction (60°) from September 2007 to September 2008 at position Khatanga (15–38 m) and Anabar (15–28 m), respectively. From September 2008 to April 2008, average currents at position Khatanga (15–38 m) are 0.76 cm/s in east-southward direction (140°).

4. Stable Isotope Results

[11] The Lena River signal dominates the salinity and δ^{18}O correlation in the Laptev Sea. River water is depleted in its δ^{18}O signal relative to marine water due to fractionation processes during evaporation and precipitation. Siberian River water is additionally depleted in its δ^{18}O signal, mainly because of a transport of moisture from west to east over the Eurasian continent and subsequent partial condensation and precipitation. The general distribution of salinity and δ^{18}O in the water column of the Laptev Sea shelf is quite similar (Figure 4), since a two-component mixing of runoff and seawater dominates the hydrography. Consequently, salinity and δ^{18}O on the Laptev Sea shelf are in first order linearly

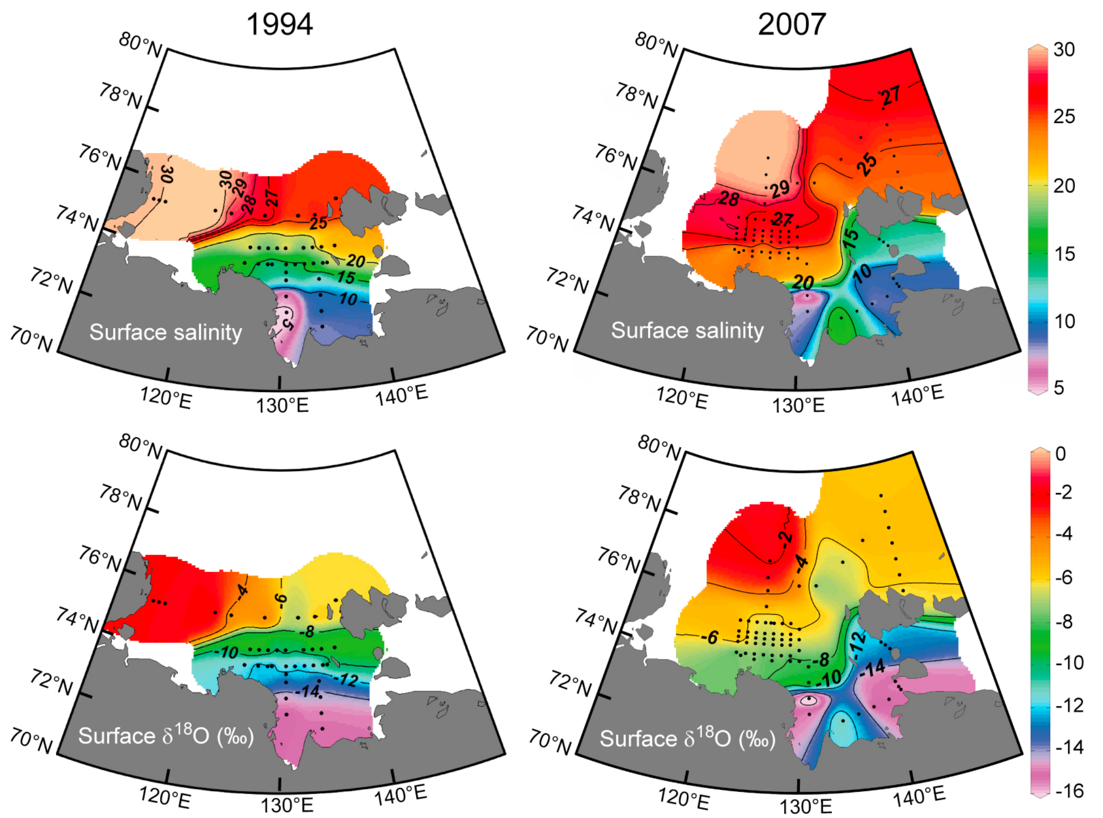

Figure 3. Surface salinity and surface $\delta^{18}O$ (‰) distribution during summer expeditions in (left) September 1994 and (right) September 2007.

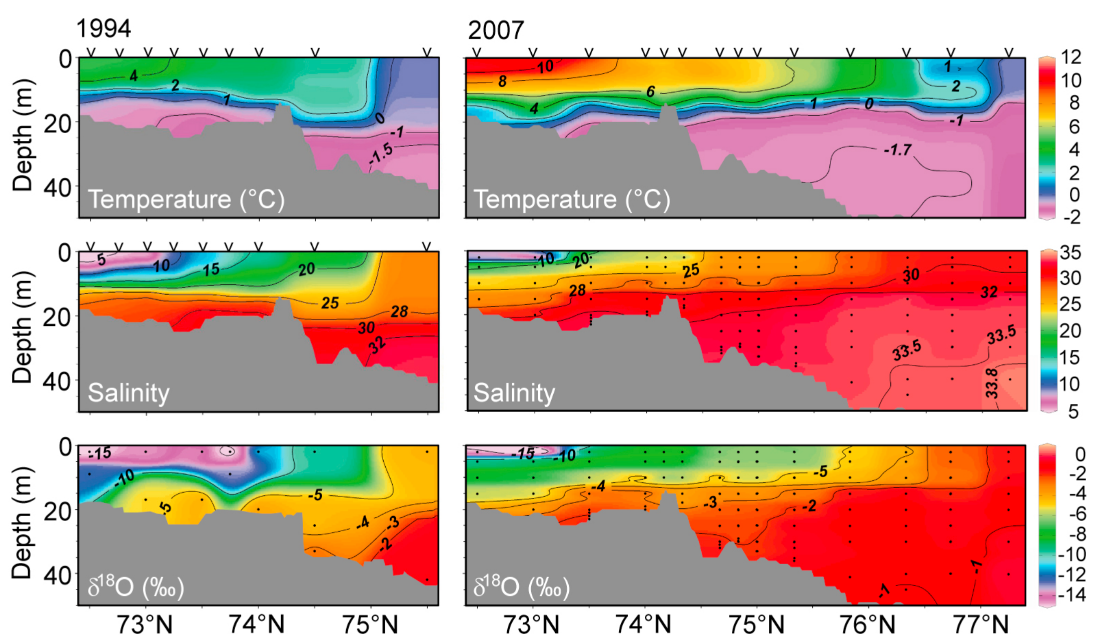

Figure 4. Temperature, salinity, and $\delta^{18}O$ distribution on a south-to-north oriented section along about 130°E–125°E occupied in September (left) 1994 and (right) 2007. For the exact position of the section, see light gray line in Figure 1 (note that northernmost station in 1994 is farther east). The positions for stations are indicated on top of the section for CTD data, and the small dots indicate the distribution of bottle data within the water column.

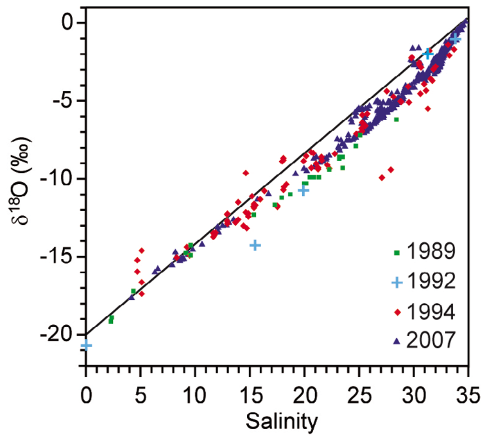

Figure 5. Property plot of δ^{18}O versus salinity in the Laptev Sea during summers 1994 and 2007 as well as data from the southeastern Laptev Sea from summer 1989 [*Létolle et al.*, 1993] and three stations from April 1992 [*Bauch*, 1995]. The light gray line indicates the idealized mixing between river water with −20‰ δ^{18}O and Atlantic source water with 34.92 salinity and 0.3‰ δ^{18}O.

correlated (Figure 5). Sea ice formation adds brines to the water column and its salinity increases concurrent with only a slight decrease in δ^{18}O values, while melting of sea ice on the other hand adds freshwater and the salinity of the water decreases at about constant δ^{18}O. Therefore, any deviations from the direct mixing between river water and marine water can be attributed to sea ice processes.

4.1. Average δ^{18}O Value of Lena River Water

[12] Direct δ^{18}O measurements within the Lena River may reflect local signals within the widespread river delta rather than average Lena River discharge. Therefore, a small database of direct measurements of Lena River δ^{18}O is not necessarily preferable to an interpolation of shelf waters to zero salinity. Shelf waters, on the other hand, are influenced by sea ice processes.

[13] *Létolle et al.* [1993] applied a linear correlation to δ^{18}O/salinity data from the southeastern Laptev Sea collected in summer 1989 and determined a δ^{18}O value of the Lena River of −18.9‰ omitting bottom water samples and surface waters south of the Lena confluence, which indicate a lower δ^{18}O value of −20.3‰. On the basis of the entire 1989 summer data set from the southeastern Laptev Sea, a δ^{18}O value of −19.6‰ is determined for the Lena River (Table 1 and Figure 5). Three stations taken in April 1992 in the southern Laptev Sea and in the direct vicinity of the Lena Delta show a lower river end-member of −20.8‰ [*Bauch*, 1995]. However, this value should be considered with caution because of the small data set and winter sampling with potentially high influence of sea ice formation. From the 1994 summer data set [*Müller-Lupp et al.*, 2003] south of 75°N, a δ^{18}O value of −18.7‰ is determined for the Lena River. In summer 2007, a river water δ^{18}O of −19.8‰ is derived considering all samples taken south of 75°N (Table 1 and Figure 5).

[14] The strict mathematical application of a linear interpolation ignores the fact that not all freshwater originate from the Lena River. Especially close to the Lena confluence at low salinities and relatively high temperatures, strong local melting of sea ice occurs, and at higher salinities, the water column is usually influenced by brines released during sea ice formation. Both physical effects result in a less steep slope of a linear correlation between δ^{18}O and salinity, leading to an overestimation of the δ^{18}O value of the Lena River by this method. Omitting samples with apparently strong brine or melting signal in southern Laptev Sea waters leads to river end-members lower by 0.3‰ and 0.1‰ in 1994 and 2007, respectively. Interannual variations of the Lena River δ^{18}O signature of 1989, 1992, 1994, and 2007 (Table 1) are within 1‰, which is comparable to interannual variation also observed for the Ob and Yenisey rivers [*Bauch et al.*, 2003].

4.2. River Water and Sea Ice Meltwater Fractions Based on δ^{18}O and Salinity Data

[15] Since river water in the Arctic is highly depleted in its stable oxygen isotope composition (δ^{18}O), an admixture of river water can be identified by depleted δ^{18}O values and low salinity relative to marine waters. The additional influence of sea ice melting or formation can be separated from any mixture of marine and river water since it strongly influences salinity, whereas the δ^{18}O signal remains nearly unaltered. The river water and sea ice meltwater contributions can be quantified by applying a mass balance calculation [e.g., *Bauch et al.*, 1995]. It is assumed that each sample is a mixture between marine water (f_{mar}), river runoff (f_r), and sea ice meltwater (f_i). The balance is governed by the following equations,

$$f_{mar} + f_r + f_i = 1,$$
$$f_{mar} {*} S_{mar} + f_r {*} S_r + f_i {*} S_i = S_{meas},$$
$$f_{mar} {*} O_{mar} + f_r {*} O_r + f_i {*} O_i = O_{meas},$$

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.

[16] A special selection of salinity and δ^{18}O end-member values (see Table 2) is required for any individual region [*Bauch et al.*, 2003, 2005]. The marine source for the Laptev

Table 1. Lena River Water δ^{18}O Value Interpolated From Linear Salinity/δ^{18}O Correlations From Laptev Sea Data South of 75°N for Different Years

Year	Lena River δ^{18}O (‰)	
Sep 1989	−19.6	all stations at about 130°E
Apr 1992	−20.8	3 stations only
Sep 1994	−18.7	
Sep 2007	−19.8	

Table 2. End-Member Values Used for Mass Balance Calculations[a]

End-Member	Salinity	δ^{18}O (‰)
Marine (f_{mar})	34.92	0.3
River (f_r)	0	−20
Sea ice (f_i)	4	surface + 2.6 or −7 + 2.6

[a]For further explanation see text.

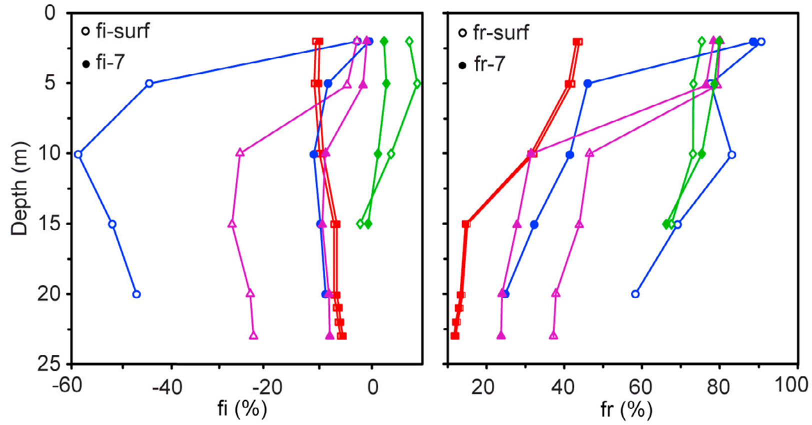

Figure 6. Comparison of (left) sea ice meltwater fractions and (right) river water fractions calculated with different approaches for source water of sea ice meltwater for stations 2 (blue circles), 23 (purple triangles), 3 (red squares), and 26 (green diamonds). Open symbols are fractions calculated with the surface δ^{18}O as source water for sea ice formation, and solid symbols are fractions calculated with a δ^{18}O of −7‰ as measured for surface waters in the polynya region as source water for sea ice formation. For further explanation, see text.

Sea is chosen as the inflowing Atlantic layer in the southern Nansen Basin (34.92 salinity and 0.3‰ in δ^{18}O) [*Bauch et al.*, 1995]. The average δ^{18}O value of river water in the Arctic Ocean is about −20‰ [*Bauch et al.*, 1995; *Frank*, 1996] and is applied as river water end-member in this study. The choice of −20‰ instead of the estimated Lena River δ^{18}O values of about −18.7‰ and −19.6‰, derived for 1994 and 2007, respectively, is used, since, as noted above, linear interpolation from δ^{18}O and salinity values of shelf waters tends to overestimate the Lena River value. This choice also prevents an overestimation of the river water (f_r) and brine components (negative f_i) but might underestimate sea ice melting close to the Lena River confluence. Differences are generally smaller than 1% in both fractions, when −19‰ is used instead of −20‰ for the river water end-member. The end-member value for sea ice meltwater has to reflect the signature of the source water from which the sea ice was formed. In general, 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 measured for multiyear ice [*Pfirman et al.*, 2004]. Since sea ice and underlying water can move independently from each other, this choice is a simplification, but usually a good approximation [*Pfirman et al.*, 2004]. Within the direct vicinity of the Lena River, the summer surface layer is strongly influenced by summer discharge of the Lena River (see Figure 3), so the low δ^{18}O summer surface signature in this area is not a useful end-member for the sea ice formed during winter. Therefore, the average surface value from the winter polynya region (see Figure 1 for average position of the Laptev Sea coastal polynya) of −7‰ in δ^{18}O (compare Figure 3 and Figure 1) was applied as source water for sea ice formation to all stations with a surface δ^{18}O lower than −7‰. The differences in calculated sea ice meltwater and river water fractions in the southern Laptev Sea, when a constant polynya value is used instead of each station's surface signature, are generally small, and calculated fractions remain stable relative to each other (Figure 6, e.g., stations 3 and 26). Only in the direct vicinity of the Lena River conjunction do the calculated values change significantly, and the application of an average surface δ^{18}O value from the polynya region as source water for sea ice formation removes artifacts in the calculated river water and sea ice meltwater fractions (Figure 6, e.g., stations 2 and 23).

[17] A negative sea ice meltwater fraction reflects the amount of water removed by sea ice formation, and the absolute value is proportional to the subsequent addition of brines to the remaining water column. The sea ice meltwater fraction does not include meltwater from ice formed from river water. All fractions are net values reconstructed from the δ^{18}O and salinity signature of each sample and are the result of time-integrated effects on the sample volume over the residence time of the water.

[18] Inventory values of river water and sea ice meltwater are calculated by integration of each fraction over the depth of the water column. Since in 1994 at each station only single δ^{18}O samples were taken within the surface and the bottom layer, the integration for the 1994 data set was made with an interpolation of the δ^{18}O and salinity measurements of each station to the concurrent CTD profile [see *Bauch et al.*, 2009a]. This method clearly cannot capture any variations in the internal freshwater distribution within the water column. For both data sets, the calculated fraction of the deepest sample was extended to the station's bottom depth. The inventory values (Figure 7, numbers on top of sections) represent the thickness of pure river water or sea ice meltwater that needs to be added to a water column of marine waters (Atlantic signature) to recreate the average signatures of the water column at that station. Negative inventory values for sea ice meltwater represent the amount of water removed for sea ice formation.

4.3. Comparison of Brine Water Distributions in 2007 and 1994

[19] The calculated fractions of river water are highest in the surface layer and in the vicinity of the Lena River confluence (see Figure 7). The distribution of river water fractions in the water column is closely related to the salinity distribution (compare Figure 3 and Figure 7), and its distri-

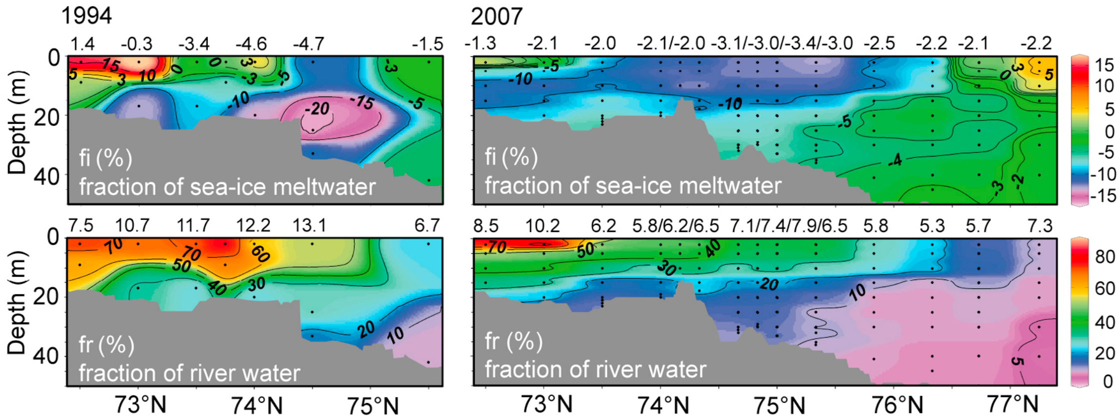

Figure 7. Distribution of calculated fractions of sea ice meltwater (f_i) and river water (f_r) on a south-to-north oriented section along about 125°E–130°E during (left) summer 1994 and (right) summer 2007. See light gray line in Figure 1 for section position in 2007 as well as 1994 (note that northernmost station in 1994 is farther east). During 1994 at most stations, only single samples were taken within the surface layer and bottom layer and the contour lines are mere interpolations between surface and bottom layer values. Inventory values in meters of river water and sea ice meltwater are shown on top of sections. For further explanation, see text.

bution in the water column is rather similar during summers of 2007 and 1994 (Figure 7) as a result of similar atmospheric forcing during both summers [*Bauch et al.*, 2009a; *Dmitrenko et al.*, 2005]. Inventory values for river water contained in the water column confirm the interpretation of stronger river water spread toward the east in 2007 with an earlier northward decrease of river water content for the stations obtained in 2007 (Figure 7, numbers on top of sections).

[20] Positive values of sea ice meltwater of up to 9% are found in the surface layer directly at the Lena River confluence during both summers and at the shelf break with up to 5% in 2007 (Figure 7). The most negative fractions of sea ice meltwater and thereby highest amounts of brines with up to 15% are found in the surface layer of the central Laptev Sea shelf region during 2007 (73.5°N–77°N). In the bottom layer, relatively low brine values of about 5% are detected (Figure 7). Only directly below the Lena River plume, brine fractions of about 9% are highest near the relatively shallow bottom; since these stations are in a restricted area in the extremely shallow southern Laptev Sea shelf only, they are not representative and further on omitted in the discussion. The distribution of brines in summer 2007 contrasts with the distribution in 1994, when maximal values of brines are seen in the bottom layer and relatively low brine values or melting of sea ice is seen in the surface layer (Figure 7). Maximal brine values of up to 30% for bottom water in 1994 are higher compared to maximal brine values of up to 15% for surface water in 2007. Inventories of sea ice meltwater contained in the water column (see Figure 7, numbers on top of sections) show positive values directly in the river plume only. On the middle Laptev Sea shelf at 73.5°N–75°N, shelf negative inventory values are found with about 4 m of net removal of water in 1994 higher than in 2007, when at the same position 2–3 m of water were removed for sea ice formation.

[21] In 1994 when the highest amounts of brines are found in the bottom waters of the Laptev Sea, this brine-enriched bottom water is also the mixing end-member, which can be identified by the discontinuity in the δ^{18}O/S mixing scheme [*Bauch et al.*, 2005, 2009a]. The signature of brine-enriched bottom water found in 1994 is about −5‰ in δ^{18}O at a salinity of about 30 (Figure 8) and a temperature of −1.2°C. In 2007, the bottom waters in the eastern Laptev Sea contain significantly less brines and also less river water compared to 1994 (Figures 7 and 8). The bottom water in 2007 has a δ^{18}O signature of about −2‰, a salinity of 32.7 (Figure 8), and a temperature of about −1.5°C considerably denser than in 1994. Nevertheless, the stratification is not largely different in 2007 relative to 1994, also because surface waters are saltier (see Figure 4; note that at low temperatures density is predominantly determined by salinity and salinity is taken to reflect stratification), probably because of a stronger eastward deflection of the river plume in 2007 compared to 1994.

5. Discussion

[22] In our Laptev Sea data sets, significantly altered hydrographic conditions are apparent in summer 2007 compared to 1994. While the observed salinity and temperature, as well as δ^{18}O distribution, show similar patterns in both years, the influence of winter sea ice production on the water column is inverted. Clearly climatic conditions in the Laptev Sea region were out of the usual range in 2007 with surface air temperatures (September–November 2003–2007) about 3°C–5°C higher [*Serreze et al.*, 2009] and surface water temperatures up to 3°C higher [*Steele et al.*, 2008] than the long-term mean. Hydrographic conditions in summer 1994 were, on the other hand, within the range of usually observed interannual variations [*Dmitrenko et al.*, 2005, 2008b; *Bauch et al.*, 2009a]. Even though in 2007 the surface river plume is shifted farther to the east than in 1994, both summers show a generally onshore atmospheric forcing [*Guay et al.*, 2001; *Dmitrenko et al.*, 2005, *Bauch et al.*, 2009a]. As a result, the patterns of salinity distribution and calculated river water fractions are overall rather similar (Figures 3, 4, and 7), and a predominantly west-to-east oriented surface salinity front developed within the Laptev Sea inner and midshelf in both

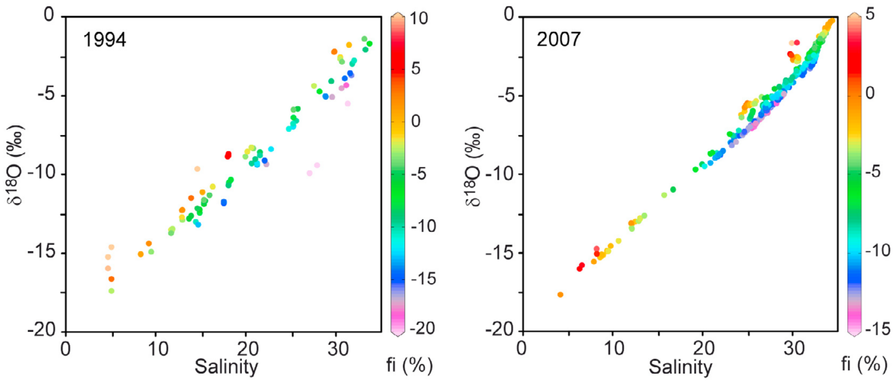

Figure 8. Property plot of $\delta^{18}O$ versus salinity in the Laptev Sea during summers of 1994 and 2007. The color code reflects the sea ice meltwater fraction (f_i) within each sample. While in 1994 the discontinuity in the $\delta^{18}O/S$ correlation is characterized by highest brine imprint (negative f_i), the highest brine values in 2007 are found within the lower salinity mixing scheme of the inner shelf and surface layer.

years (Figure 3) in contrast to years with offshore atmospheric forcing, in which a significantly different north-to-west oriented salinity front prevails within the Laptev Sea [*Bauch et al.*, 2009a]. Also rather typical wind-driven river water and sea ice meltwater distributions are observed in the Eurasian Basin north of the Laptev Sea continental margin for summer 2007 [*Abrahamsen et al.*, 2009]. The differences seen in the distribution of brine waters are therefore not a result of different distribution patterns due to different wind stress during summer [*Guay et al.*, 2001; *Dmitrenko et al.*, 2005, *Bauch et al.*, 2009a] but are a result of other factors such as different sea ice production processes or water mass advection patterns during the preceding sea ice production seasons.

[23] A preconditioning with saltier bottom water may prevent sea ice formation to penetrate a relatively stronger pycnocline and to reach the bottom layer. But it has to be kept in mind that wind-driven polynya openings and subsequent sea ice formation events on a shallow shelf may lead to a freshening of bottom waters. Even though sea ice formation and a subsequent release of brines increase the mean salinity in the water column, the initial bottom salinity decreases when partially wind-driven vertical mixing occurs between the still relatively fresh surface and the more salty bottom waters (Figure 9). This mechanism is confirmed by the relatively high river water fractions in the bottom layer in summer 1994, when brine fractions are also highest in the bottom layer. Therefore, a different preconditioning with saltier bottom water in 2007 compared to 1994 and differences in sea ice formation with weaker sea ice formation in 2006–2007 compared to 1993–1994 may both cause the observed brine and salinity distributions within the water column. Both processes will be discussed separately in the following paragraphs with respect to the effect each mechanism has and in terms of its likelihood in causing the differences in brine water distribution in 1994 versus 2007. First, a different preconditioning is evaluated by assuming advection of relatively freshwaters in 1994 and relatively salty waters in 2007. Then the impact of different polynya activities in 1994 and 2007 is discussed.

[24] The general movement of the upper waters are from west to east along the Eurasian basins continental slope [e.g., *Newton et al.*, 2008], but the average movement of waters on the Laptev Sea shelf is virtually unknown. Direct currents measurements on the shallow shelf are strongly influenced by local factors such as bathymetry and tidal currents and are therefore spacially and temporally highly variable. The

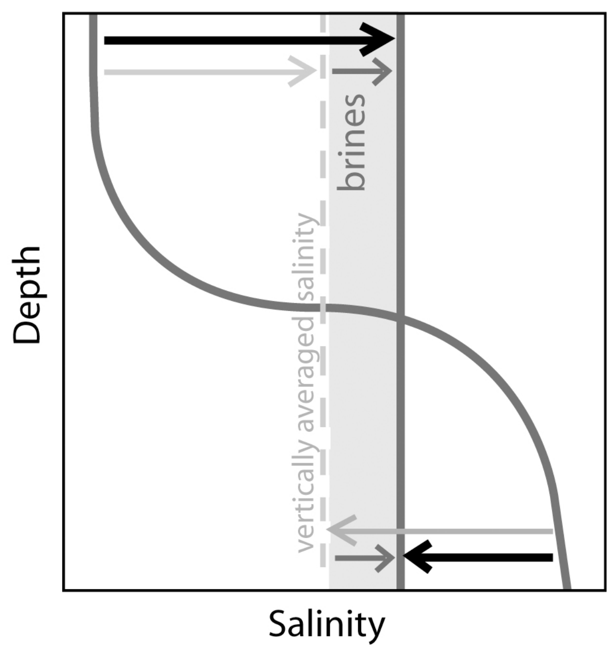

Figure 9. Schematic drawing of a salinity profile changed by a wind-driven polynya event. During certain polynya events, the water column is vertically mixed by the combined effects of wind stress and brine release concurrent to sea ice formation. The typical salinity structure of the Laptev Sea water column with a distinct low-salinity surface layer and a high-salinity bottom layer (gray curve) is transformed into a uniform profile at the average salinity of the initial water column (stippled gray line and light gray arrows) increased by the amount of brines released to the water column by sea ice formation (dark gray arrows and gray line). As a result, salinity increases in the surface layer and decreases in the bottom layer (indicated by black arrows) when the effect of wind stress exceeds the effect of brine release.

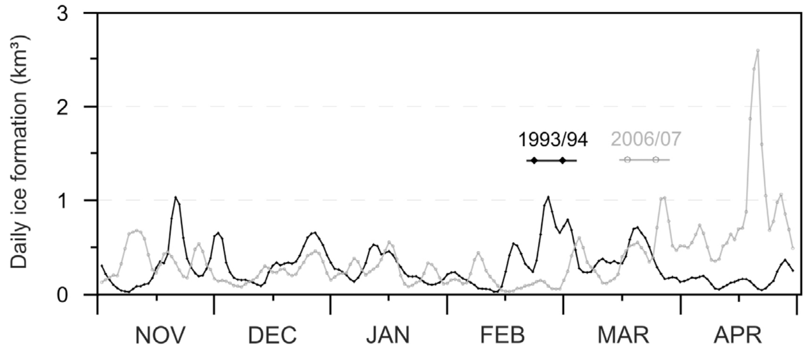

Figure 10. Daily ice production during winter season 2006–2007 and 1993–1994 based on a polynya classification approach (Polynya Signature Simulation Method, PSSM) using passive microwave and thermal infrared satellite data [*Willmes et al.*, 2010].

mooring positions Khatanga and Anabar (Figure 1) are both located in the northern part of the recurrent Laptev Sea polynya [*Bareiss and Görgen*, 2005]. These current measurements are the first year-round observations in the Laptev Sea. The annual time-averaged currents in the bottom layer are 0.36 cm/s eastward (90°E) and 0.60 cm/s east-northward (60°) at position Khatanga (15–38 m) and Anabar (15–28 m), respectively. Data from September 2008 to April 2008 at position Khatanga (15–38 m) show an average current of 0.76 cm/s east-southward (140°). The large differences in average current direction demonstrate the necessity for a process-orientated interpretation of shallow shelf mooring data and highlight the large uncertainty when trying to generalize average currents from these measurements. However, the time-averaged mooring data agree in a roughly eastward current. This is in agreement with an assessment based on direct current measurements from various years [*Ipatov and Yakovlev*, 1999]. A general movement of waters from west to east is supported by general density differences, with saltier and denser waters in the western Laptev Sea and fresher and less dense waters in the eastern Laptev Sea (World Ocean Database (WOD09), accessible at: http://www.nodc.noaa.gov/) [see also *Bauch et al.*, 2009b]. A long-term movement of waters from a generally northwestern direction may act as compensation current in response to an export of fresh surface waters and also relatively fresh brine-enriched bottom waters in the eastern Laptev Sea [*Bauch et al.*, 2009a]. We may therefore speculate that bottom waters from the western Laptev Sea (compare, e.g., station 7P with −1.67°C, 33.05 psu, −1.6‰ δ^{18}O; for position, see Figure 1) may be the source of the advected bottom waters observed in 2007 in the southeastern Laptev Sea. This bottom water from the western Laptev Sea may be composed of saltier waters originating directly from the northwestern Laptev Sea continental margin, where an episodic entrainment of modified Atlantic layer and halocline waters is observed [*Hölemann et al.*, 2010; I. V. Polyakov et al., NOWCAST: Fate of early-2000s Arctic warm water pulse, submitted to *Bulletin of the American Meteorological Society*, 2010].

[25] We can also speculate on an advection of lower-salinity waters as preconditioning for 1994 relative to 2007. Autumn and early winter storm events may significantly impact the structure of the water column by vigorous turbulent mixing, as long as the sea ice cover is not largely preventing this impact. Turbulent mixing of the water column is usually observed also during summers over the shallow western Laptev Sea shoals (down to 15–20m water depth in both 1994 and 2007). The deeper-reaching vertical mixing in autumn storm events would produce lower surface to bottom salinity and density gradients and favor brine intrusions into the bottom layer by weakening the pycnocline. An excess amount of stored heat in the water column may delay the onset in autumn sea ice formation by about 10 days [*Dmitrenko et al.*, 1999; *Kirillov*, 2006]. Because storm events in the Laptev Sea increase toward winter, a delayed onset of winter sea ice formation increases the probability of vertical mixing. When assuming an advection of lower-salinity waters as preconditioning for winter 1993–1994 relative to 2006–2007, we may speculate on deeper-reaching turbulent mixing of the water column during autumn storm events. To further support speculation about a lower-salinity preconditioning in 1994, the freezeup in autumn 1993 must have been relatively late. But freezeup of the Laptev Sea in autumn 1993 did not occur later than in 2006, but rather about 2–4 weeks earlier (National Centers for Environmental Prediction (NCEP) reanalysis data) [*Kalnay et al.*, 1996]. Therefore, autumn mixing and lower-salinity preconditioning in 1994 is less probable than in 2007 and does not likely explain the differences in brine distribution between summers 1994 and 2007.

[26] Now, the impacts of different polynya activities in 1994 and 2007 are discussed. A comparison of polynya dynamics and sea ice production during the winters of 1993–1994 and 2006–2007 reveals very large differences in the seasonal evolution of polynya area and the resulting ice formation (Figure 10). Winter polynya activity was comparable in terms of the total amount of formed sea ice prior to summers of 1994 and 2007 [*Willmes et al.*, 2010]. The temporal distribution of polynya sea ice formation was quite uniform during the winter season of 1993–1994. During winter season of 2006–2007, the distribution of polynya sea ice formation was atypical with almost 30% of the amount in the month of April (Figure 10) [*Willmes et al.*, 2010]. It seems likely that this significantly altered seasonal pattern of sea ice formation and the proportionally stronger influence of late winter polynya activity in April 2007 may be linked to the altered distribution of brines in the water column in 2007. We are lacking supporting hydrographic data or mooring data from winter 2006–2007 to directly deduce possible physical linkages. However, we speculate that the same atmospheric

forcing that led to the unusually high polynya activity in April 2007 also induced an altered advection rate of waters from the western Laptev Sea. The residence time of bottom waters on the Laptev Sea is not well known. The mean residence time of all Arctic shelf waters was estimated to be 3.5 ± 2 years [*Schlosser et al.*, 1994], and detailed studies on the Laptev Sea shelf have confirmed that the residence time shows strong interannual variations [*Bauch et al.*, 2009a]. Depleted dissolved oxygen concentrations and enriched nutrients (SiO_4, PO_4 and NO_3) indicate a relatively stagnant bottom water mass in 1994 relative to 2007. Therefore, hydrochemical data are in agreement with a more rapid replacement of inner shelf bottom waters with relatively high-salinity waters in 2007.

[27] The calculated maximal fractions of brine waters in 2007 are with a sea ice meltwater fraction of up to 15% in the surface layer smaller than in 1994 (up to 30% in the bottom layer and up to 17% in the surface layer). At face value, such a significant difference in negative sea ice meltwater fractions would indicate a less intense brine production in 2007. On the other hand, it has to be taken into account that the calculated fractions represent net values over the residence time of the water and that the surface layer is more rapidly affected by seasonal influences, e.g., early summer sea ice melting. Therefore, the influence of local sea ice melting during the current summer season will reduce a winter remnant more rapidly in the surface layer than in the bottom layer. The inventory values on the middle Laptev Sea shelf between 73.5°N and 75°N indicate 4 m of net removal of water in 1994, which is greater than in 2007 when only 2–3 m were removed (see Figure 7, numbers on top of sections). However, these values are not an indicator of the last season's sea ice formation since they are vertically as well as time-integrated values over the residence time of the water. A quantitative interpretation has to consider the highly variable residence time of Laptev Sea shelf waters [*Bauch et al.*, 2009a, 2009b], which may be longer for 1994 compared to 2007, since depleted dissolved oxygen and enriched nutrient concentrations indicate that in 1994 bottom waters in the eastern Laptev Sea were more stagnant compared to 2007. In general, it can be assumed that in 1994 brines were released into the entire water column prior to summer 1994 and were diluted with freshwater from sea ice melting in the surface, while they remained undiluted in the bottom layer from sea ice melting of the current summer season. Prior to summer 2007, on the other hand, brines had accumulated mostly in the surface layer during winter and the probably constant amount of sea ice meltwater released at the beginning of each summer directly reduced this brine signal.

[28] The winter 1993–1994 sea ice formation and polynya activity is clearly imprinted in Laptev Sea bottom water as documented by maximum brine influence in the bottom layer of the central Laptev Sea in summer 1994 (Figure 7b), This brine-enriched bottom water mass in 1994 dominates the Laptev Sea hydrology as main mixing end-member between high-salinity outer shelf bottom waters on one side and low-salinity surface and inner shelf bottom waters on the other side (Figure 8). Since in 2007 waters with the highest influence of brines are found within the surface layer, the importance of the polynya on the water mass structure and as a mixing end-member as in 1994 is absent in 2007. Bottom waters in 2007 remained significantly saltier compared to 1994, which forced brines to remain in the surface layer (Figure 8). Surface waters in 2007 were also relatively salty, not due to salt additions by brines but mostly due to a reduction of river water by a stronger deflection toward the east in 2007 relative to 1994 (Figure 3). A more frequent or permanent change in distribution of brine waters in the eastern Laptev Sea from the bottom layer to the surface layer would alter the salinity range of waters exported from this region to the Arctic Ocean halocline [*Bauch et al.*, 2009a]. Data from summer 2007 suggest a wider salinity range and suggests overall an export of saltier waters to the Arctic Ocean halocline when freshwater is deflected toward the east.

6. Conclusions

[29] The climatically extreme conditions in 2007 have led to a displacement of brine waters from the bottom layer to the surface layer. Laptev Sea bottom waters in 1994 are enriched in brine, have relatively high river water fractions, and have their origin clearly within the wind-driven coastal polynya (Figure 1). Laptev Sea bottom waters in 2007 have relatively low brine as well as river water fractions, and bottom waters are defined primarily by advection. Depleted dissolved oxygen and enriched nutrient concentrations indicate that in 1994 bottom waters in the eastern Laptev Sea were indeed more stagnant compared to 2007. The bottom water found in summer 2007 in the central Laptev Sea shelf was probably advected from the western Laptev Sea or outer shelf region, originating from the Atlantic layer in the Arctic basin. This advection may have occurred during winter season of 2006–2007 or before.

[30] Since winter polynya activity was comparable in terms of the total amount of formed sea ice prior to summers of 1994 and 2007, we conclude that the lack of brines in bottom waters in 2007 is the result of a different preconditioning by an advection of relatively salty bottom waters resulting in strong stratification. We speculate that the atmospheric forcing, which caused the atypical seasonal polynya pattern and unusually high polynya activity in April 2007, also induced altered advection rates of waters from the western Laptev Sea. Our observations show that the relatively late occurrence of ice production during winter 2006–2007 could not significantly influence the relatively high-salinity bottom water mass. Further studies will have to clarify if and how the phenomenon of relatively strong advection of high-salinity bottom waters is indeed linked to altered polynya openings and sea ice formation patterns.

[31] It is unknown how frequently the displacement of brine waters from the bottom layer to the surface layer, observed during the climatically extreme summer 2007, will occur in the future. A shift in the distribution of brine waters in the eastern Laptev Sea from the bottom layer to the surface layer alters the salinity range of waters exported into the Arctic Ocean [*Bauch et al.*, 2009a]. If this shift becomes more frequent or persists, it will have long-term consequences on the structure of the Arctic Ocean halocline. Future studies will have to address which long-term influence this development has on sea ice production and water mass production of the Laptev Sea shelf area. Our data from summer 2007 indicate that water masses in the Laptev Sea have a wider salinity range and an export of higher-salinity Laptev Sea bottom waters suggests a steeper Arctic Ocean halocline.

[32] **Acknowledgments.** This work was part of the German-Russian cooperations "System Laptev Sea" and the "Otto-Schmidt-Laboratory for Polar and Marine Sciences" funded by the BMBF under grants 03G0639 and 03PL038, respectively, as well as by Roshydromet and the Russian Ministry of Education and Science. We thank all members of these projects for exceptional working conditions and extensive support during expeditions. D.B. was additionally supported by the DFG under grant SP526/3. We would like to thank two anonymous reviewers for constructive review on the manuscript, resulting in a significant improvement of the manuscript.

References

Abrahamsen, E. P., et al. (2009), Tracer-derived freshwater budget of the Siberian Continental Shelf following the extreme Arctic summer of 2007, *Geophys. Res. Lett.*, *36*, L07602, doi:10.1029/2009GL037341.

Bareiss, J. and K. Görgen (2005), Spatial and temporal variability of sea ice in the Laptev Sea: Analyses and review of satellite passive-microwave data and model results, 1979 to 2002. *Global Planet. Change*, *48*, 28–54. doi:10.1016/j.gloplacha.2004.1012.1004.

Bauch, D. (1995), The distribution of $\delta^{18}O$ in the Arctic Ocean: Implications for the freshwater balance of the Halocline and the sources of deep and bottom waters, *Berichte zur Polarforschung*, *159*, 144 pp., AWI, Bremerhaven, Germany.

Bauch, D., P. Schlosser, and R. F. Fairbanks (1995), Freshwater balance and the sources of deep and bottom waters in the Arctic Ocean inferred from the distribution of $H_2^{18}O$, *Prog. Oceanogr.*, *35*, 53–80.

Bauch, D., H. Erlenkeuser, V. Stanovoy, J. Simstich, and R. F. Spielhagen (2003), Freshwater distribution and brine waters in the southern Kara Sea in summer 1999 as depicted by $\delta^{18}O$ results, in *Proceedings in Marine Science, Siberian River Run-off in the Kara Sea: Characterization, Quantification, Variability and Environmental Significance*, edited by R. Stein, D. K. Fütterer, and E. Galimov.

Bauch, D., H. Erlenkeuser, and N. Andersen (2005), Water mass processes on Arctic shelves as revealed from ^{18}O of H_2O, *Global Planet. Change*, *48*, 165–174, doi:110.1016/j.gloplacha.2004.1012.1011.

Bauch, D., I. A. Dmitrenko, C. Wegner, J. Hölemann, S. A. Kirillov, L. A. Timokhov, H. Kassens (2009a), Exchange of Laptev Sea and Arctic Ocean halocline waters in response to atmospheric forcing, *J. Geophys. Res.*, *114*, C05008, doi:10.1029/2008JC005062.

Bauch, D., I. A. Dmitrenko, S. A. Kirillov, C. Wegner, J. Hölemann, S. Pivovarov, L. A. Timokhov, H. Kassens (2009b), Eurasian Arctic shelf hydrography: Exchange and residence time of southern Laptev Sea waters, *Cont. Shelf Res.*, *29*, 1815–1820, doi:1810.1016/j.csr.2009.1806.1009.

Comiso, J. C., C. L. Parkinson, R. Gersten, and L. Stock (2008), Accelerated decline in the Arctic sea ice cover, *Geophys. Res. Lett.*, *35*, L01703, doi:10.1029/2007GL031972.

Craig, H. (1961), Standard for reporting concentrations of deuterium and oxygen-18 in natural waters, *Science*, *133*, 1833–1834.

Dethleff, D., P. Loewe, and E. Kleine (1998), The Laptev Sea flaw lead-detailed investigation on ice formation and export during 1991/1992 winter season, *Cold Reg. Sci. Technol.*, *27*, 225–243.

Dmitrenko, I. A., V. A. Gribanov, D. L. Volkov, H. Kassens, and H. Eicken (1999), Impact of river discharge on the fast ice extension in the Russian Arctic shelf area, in *Proc. of the 15th Int. Conf. on Port and Ocean Eng. under Arctic Cond. (POAC99), Helsinki, 23–27 August, 1999 1*, 311–321.

Dmitrenko, I. A., S. A. Kirillov, H. Eicken, and N. Markova (2005), Wind-driven summer surface hydrography of the eastern Siberian shelf, *Geophys. Res. Lett.*, *32*, L14613, doi:10.1029/2005GL023022.

Dmitrenko, I. A., I. V. Polyakov, S. A. Kirillov, L. A. Timokhov, I. E. Frolov, V. T. Sokolov, H. L. Simmons, V. V. Ivanov, and D. Walsh (2008a), Toward a warmer Arctic Ocean: Spreading of the early 21st century Atlantic water warm anomaly along the Eurasian Basin margins, *J. Geophys. Res.*, *113*, C05023, doi:10.1029/2007JC004158.

Dmitrenko, I. A., S. A. Kirillov, and L. B. Tremblay (2008b), The long-term and interannual variability of summer freshwater storage over the eastern Siberian shelf: Implication for climatic change, *J. Geophys. Res.*, *113*, C03007, doi:10.1029/2007JC004304.

Frank, M. (1996), Spurenstoffuntersuchungen zur Zirkulation im Eurasischen Becken des Nordpolarmeeres, Ph.d. thesis, pp. 100, Univ. of Heidelberg, Germany.

Frolov, I. E., I. M. Ashik, H. Kassens, I. V. Polyakov, A. Yu. Proshutinsky, V. T. Sokolov, and L. A. Timohov (2009), Anomalous variations in the thermohaline structure of the Arctic Ocean, *Doklady Earth Sci.*, *429*(A9), 1567–1569.

Guay, C. K., K. K. Falkner, R. D. Muench, M. Mensch, M. Frank, and R. Bayer (2001), Wind-driven transport pathways for Eurasian Arctic river discharge, *J. Geophys. Res.*, *106*(C6), 11,469–11,480, doi:10.1029/2000JC000261.

Hölemann, J., S. Kirillov, T. Klagge, A. Novikhin, H. Kassens, and L. Timokhov (2010), Near-bottom water warming in the Laptev Sea in response to atmospheric and sea ice conditions in 2007, *Polar Res.*, in press.

Ipatov, A., and A. Yakovlev (1999), Circulation pattern of the Laptev Sea in summer, obtained on a basis of analysis of measurements (in Russian), *Trydy AARI*, *442*, 100–107.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*(3), 437–471.

Kirillov, S. (2006), Spatial variations in sea ice formation-onset in the Laptev Sea as a consequence of the vertical heat fluxes caused by internal waves overturning, *Polarforschung*, *76*(3), 119–123.

Kwok, R., and D. A. Rothrock (2009), Decline in Arctic sea ice thickness from submarine and ICES at records: 1958–2008, *Geophys. Res. Lett.*, *36*, L15501, doi:10.1029/2009GL039035.

Kwok, R., G. F. Cunningham, M. Wensnahan, I. Rigor, H. J. Zwally, and D. Yi (2009), Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008, *J. Geophys. Res.*, *114*, C07005, doi:10.1029/2009JC005312.

Létolle, R., J. Martin, A. Thomas, V. Gordeev, S. Gusarova, and I. Sidorov (1993), ^{18}O abundance and dissolved silicate in the Lena delta and Laptev Sea (Russia), *Mar. Chem.*, *43*, 47–64.

Melling, H., and R. Moore (1995), Modification of halocline source waters during freezing on the Beauford Sea shelf: Evidence from oxygen isotopes and dissolved nutrients, *Cont. Shelf Res.*, *15*, 89–113.

Müller-Lupp, T., H. Erlenkeuser, and H. A. Bauch (2003), Seasonal and interannual variability of Siberian river discharge in the Laptev Sea inferred from stable isotopes in modern bivalves, *Boreas*, doi:10.1080/03009480310001984.

Newton, R., P. Schlosser, D. G. Martinson, and W. Mabove sea levelowski (2008), Freshwater distribution in the Arctic Ocean: Simulation with a high-resolution model and model-data comparison, *J. Geophys. Res.*, *113*, C05024, doi:10.1029/2007JC004111.

Pfirman, S., W. Haxby, H. Eicken, M. Jeffries, and D. Bauch (2004), Drifting Arctic sea ice archives changes in ocean surface conditions, *Geophys. Res. Lett.*, *31*, L19401, doi:10.1029/2004GL020666.

Polyakov, I., et al. (2007), Observational program tracks Arctic Ocean transition to a warmer state, *Eos Trans. AGU*, *88*(40), 398, doi:10.1029/2007EO400002.

Schauer, U., E. Fahrbach, S. Osterhus, and G. Rohardt (2004), Arctic warming through the Fram Strait: Oceanic heat transport from 3 years of measurements, *J. Geophys. Res.*, *109*, C06026, doi:10.1029/2003JC001823.

Schlosser, P., D. Bauch, G. Bönisch, and R. F. Fairbanks (1994), Arctic river-runoff: Mean residence time on the shelves and in the halocline, *Deep Sea Res., Part I*, *41*(7), 1053–1068.

Schmidt, G. A., G. R. Bigg, and E. J. Rohling (1999), Global Seawater Oxygen-18 Database. (http://data.giss.nasa.gov/o18data/)

Serreze, M. C., A. P. Barrett, J. C. Stroeve, D. N. Kindig, and M. M. Holland (2009), The emergence of surface-based Arctic amplification, *The Cryosphere*, *3*, 11–19, doi:10.5194/tc-5193-5111-2009.

Steele, M., and T. Boyd (1998), Retreat of the cold halocline layer in the Arctic Ocean, *J. Geophys. Res.*, *103*(C5), 10,419–10,435, doi:10.1029/98JC00580.

Steele, M., W. Ermold, and J. Zhang (2008), Arctic Ocean surface warming trends over the past 100 years, *Geophys. Res. Lett.*, *35*, L02614, doi:10.1029/2007GL031651.

Willmes, S., S. Adams, D. Schroeder, and G. Heinemann (2010), Spatio-temporal variability of sea ice coverage, polynya dynamics and ice production in the Laptev Sea between 1979 and 2008, *Polar Res.*, in press.

Zakharov, V. F. (1966), The role of flaw leads off the edge of fast ice in the hydrological and ice regime of the Laptev Sea, *Oceanology*, *6*(1), 815–821.

D. Bauch, H. Kassens, and A. Nikulina, Leibniz Institute of Marine Sciences (IFM-GEOMAR), Wischhofstr. 1-3, Kiel, D-24148, Germany. (dbauch@ifm-geomar.de)

M. Gröger, MPI for Meteorology, Hamburg, Germany.

J. Hölemann, Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven, Germany.

A. Novikhin and L. Timokhov, Arctic and Antarctic Research Institute (AARI), Saint Petersburg, Russia.

S. Willmes, University of Trier, Trier, Germany.