Correlation of river water and local sea-ice melting on the Laptev Sea shelf (Siberian Arctic)

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[1] Hydrographic and stable isotope ($\delta^{18}O$) data from four summer surveys in the Laptev Sea are used to derive fractions of sea-ice meltwater and river water. Sea-ice meltwater fractions are found to be correlated to river water fractions. While initial heat of river discharge is too small to melt the observed 0–158 km^3 of sea-ice meltwater, arctic rivers contain suspended particles and colored dissolved organic material that preferentially absorb solar radiation. Accordingly, heat content in surface waters is correlated to river water fractions. But in years when river water is largely absent within the surface layer, absolute heat content values increase to considerably higher values with extended exposure time to solar radiation and sensible heat. Nevertheless, no net sea-ice melting is observed on the shelf in years when river water is largely absent within the surface layer. The total freshwater volume of the central-eastern Laptev Sea (72–76°N, 122–140°E) varies between ~1000 and 1500 km^3 (34.92 reference salinity). It is dominated by varying river water volumes (~1300–1800 km^3) reduced by an about constant freshwater deficit (~350–400 km^3) related to sea-ice formation. Net sea-ice melt (~109–158 km^3) is only present in years with high river water budgets. Intermediate to bottom layer (>25 salinities) contain ~60% and 30% of the river budget in years with low and high river budgets, respectively. The average mean residence time of shelf waters was ~2–3 years during 2007–2009.

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1. Introduction

[2] The central Arctic Ocean summer sea-ice extent has declined by ~11% per decade between 1979 and 2007 and was ~37% below the average for this period in summer 2007 [*Comiso et al.*, 2008]. Shelves cover nearly half of the Arctic Ocean's area and are ice-free during summer and ice-covered in winter. The decline in summer sea-ice cover and thickness as well as an increase in mobility in the central basins will likely impact the sea-ice regime and hydrography of the arctic shelves and vice versa. The largest freshwater inventory is found in the upper 300 m of the Canadian Basin [*Yamamoto-Kawai et al.*, 2008; *Rabe et al.*, 2009, 2011] and the relative contribution of river water and sea-ice meltwater to the total freshwater budget has changed in recent years [*Yamamoto-Kawai et al.*, 2009]. A considerable fraction of freshwater in the Canadian Basin is assumed to originate from the Siberian shelves [e.g., *Aagaard and Carmack*, 1989; *Rabe et al.*, 2011], and further investigations are necessary on river water and sea-ice meltwater contributions from the Siberian shelves to understand ongoing changes and to predict future implications.

[3] The Siberian shelves receive large amounts of river runoff mainly during summer, and they are areas of net sea-ice production and sea-ice export [*Rigor and Colony*, 1997]. Sea-ice retreat and export are primarily controlled by atmospheric forcing [*Bareiss et al.*, 1999; *Alexandrov et al.*, 2000]. A net export of sea ice is confirmed by the accumulation of brine-enriched waters due to sea-ice formation [*Bauch et al.*, 2005] and their export, e.g., from the Laptev Sea to the Arctic Ocean halocline [*Bauch et al.*, 2009a, 2011a]. Therefore, past investigations on the Laptev Sea shelf hydrography have focused mainly on freshwater originating from rivers [*Dmitrenko et al.*, 2005; *Guay et al.*, 2001; *Bauch et al.*, 2011b] and on brine-enriched waters related to sea-ice formation [*Bauch et al.*, 2009a, 2010, 2011a]. The purpose of this study is to investigate the freshwater budget of the shelf with the main contributions from river water and sea-ice formation but with an additional focus on the contribution from local summer sea-ice meltwater. With the ongoing changes in the arctic sea-ice regime, an earlier opening of the perennial sea-ice cover and an overall longer exposure time to solar radiation and sensible heat is to be expected. In general, an earlier melt

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onset is considered to be important for the amount of ice that melts basin-wide each summer as early melt onset means an early reduction in surface albedo, allowing for more solar heating [e.g., *Perovich et al*., 2007]. These mechanisms might differ on the shelf compared to the basin [e.g., *Alkire et al*., 2010]. While our study does not aim to resolve all involved aspects, we try to estimate hydrographic implications of the ongoing changes in sea-ice regime in the Arctic by deriving budgets for the different freshwater components and by assessing the controlling factors for the local melting of sea ice on the Siberian shelves.

[4] In this study, the water masses of the Laptev Sea are investigated by a combination of stable oxygen isotope ($\delta^{18}O$) and hydrographic data which allow quantifying the contribution of river water, sea-ice meltwater, or sea-ice formation [*Bauch et al*., 1995]. The thereby derived volume of sea-ice-related freshwater deficit is proportional to the sea-ice export from the shelf. As the shallow shelf hydrography shows strong interannual variations in response to summer atmospheric forcing [*Shpaikher et al*., 1972; *Dmitrenko et al*., 2005; *Bauch et al*., 2011b], our investigations are based on data from four summer campaigns.

2. Database and Methods

[5] Ship-based sampling campaigns with hydrographic investigations and water sampling for $\delta^{18}O$ were conducted during summers 1994 (PM94/TDII from 3 to 24 September 1994) [*Kassens and Dmitrenko*, 1995; *Mueller-Lupp et al*., 2003; *Bauch et al*., 2005, 2009a], 2007 (IP07/TDXII from 22 August to 22 September 2007) [*Bauch et al*., 2010], 2008 (IP08/TDXIV from 5 to 21 September 2008), and 2009 (YS09/TDXVI from 31 August to 19 September 2009) (see Figure 1 for station distributions).

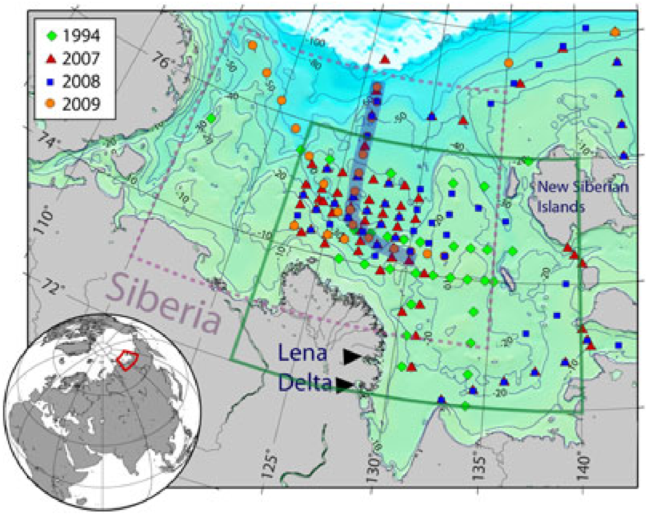

Figure 1. Geographical map of the Laptev Sea and station distribution in summers 1994, 2007, 2008, and 2009. The black triangles indicate the main branches of the Lena River confluence. The position of the section shown in Figure 2 is highlighted. The area evaluated for ice concentration (Figure 8) is outlined by a stippled box. The area included in the budget calculation (Figure 5) is outlined by a solid box.

[6] Water samples were taken with a conductivity-temperature-depth (CTD)-rosette. Individual temperature and conductivity measurements are obtained using Sea-Bird SBE-19+ with accuracy ±0.002 s/m in conductivity and ±0.005°C in 2007, 2008, and 2009 [*Dmitrenko et al*., 2010a; *Kassens and Volkmann-Lark*, 2010] and ±0.02°C in temperature and ± 0.002 S/m in conductivity in 1994 [*Kassens and Dmitrenko*, 1995]. Oxygen isotopes from TDXII, TDXIV, and TDXVI were analyzed at the Leibniz Laboratory (Kiel, Germany) applying the CO_2-water isotope equilibration technique on a Finnigan gas bench II unit coupled to a Finnigan DeltaPlusXL. The overall measurement precision for $\delta^{18}O$ analysis is ±0.04‰. For TDII, $\delta^{18}O$ analyses were performed at the Leibniz Laboratory with a precision of ±0.07‰ [*Mueller-Lupp et al*., 2003]. The $^{18}O/^{16}O$ ratio is given versus V-SMOW in the usual δ-notation [*Craig*, 1961].

[7] Salinity data are reported on the psu scale. For a quantitative interpretation of our data, an exact match of salinity and $\delta^{18}O$ values is essential. While the CTD salinity data have a sufficiently high precision, CTD and bottle data on a shallow shelf are not exactly matched when aligned by depth due to differences in spatial and temporal alignment of the instruments during sampling (for further details, see *Bauch et al*. [2010]). Therefore, in addition to CTD measurements, bottle 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 for TDXII, TDXIV, and TDXVI. Salinity measurements for TDII have a precision of ±0.1 [*Mueller-Lupp et al*., 2003].

[8] Heat content of surface water was calculated using the following equation:

$$Q = C_p \rho \left(t_{\text{meas}} - t_f \right)$$

where C_p is the heat capacity of sea water [J kg^{-1} °C^{-1}], ρ is the density [kg m^{-3}], t_{meas} is the measured water temperature [°C], and t_f is the freezing point [°C] of each sample. The empirical formulas for calculating heat capacity, density, and freezing temperature were taken from *Fofonoff and Millard* [1983]. Heat capacity was calculated based on CTD salinity and temperature data.

3. Hydrography of the Laptev Sea and Hydrographic Results

[9] The Siberian shelves are mostly ice-free during summer, while sea ice is formed during autumn and winter [*Zakharov*, 1966, 1997; *Bareiss and Görgen*, 2005]. Sea-ice meltwater is released on the shelf during spring and early summer; nevertheless, local melting of sea ice does not determine the large-scale decay of the sea-ice cover. The Laptev Sea is an area of sea-ice export [*Rigor and Colony*, 1997], and sea-ice retreat and export are primarily controlled by atmospheric forcing [*Bareiss et al*., 1999; *Alexandrov et al*., 2000]. Arctic rivers show strong seasonality in discharge with maximal values in summer. In the Laptev Sea, the Lena River has an annual mean discharge of ~600–700 km^3 a^{-1} and is the largest Arctic river [*R-ArcticNET*, 2011]. During June and July, the Lena River discharge is 4 to 5 times higher than the annual mean, while runoff nearly ceases during winter [e.g., *Létolle et al*., 1993; *R-ArcticNET*, 2011]. Lena River water may warm up

to 16°C in August, while temperatures during the main discharge period in June are somewhat lower [*Lammers et al.*, 2007].

[10] The low salinity river plume is most pronounced in the surface layer and near the Lena River confluence (Figure 2). Temperatures are highest near the Lena confluence and decrease to the north. Maximal temperatures and minimal salinities are generally found near the surface (Figure 2). Therefore, the temperature and salinity distributions are roughly anticorrelated (Figure 2). Salinity and δ^{18}O are in first order linearly correlated (Figure 3) and therefore generally show a similar vertical distribution (not shown).

4. Stable Isotope-derived Fractions of Sea-ice Meltwater (SIM) and River Water

[11] River water in the Arctic is highly depleted in its δ^{18}O stable oxygen isotope composition [*Cooper et al.*, 2008] relative to marine waters. This depletion in δ^{18}O and the dominance of river water in the Laptev Sea explain the approximately linear salinity/δ^{18}O correlation (Figure 3). Net sea-ice melting and formation can be separated from any mixture between marine and river water since it changes salinity, whereas the δ^{18}O signal remains nearly unaltered [*Melling and Moore*, 1995].

4.1. Calculation of River Water and Sea-ice Meltwater (SIM) Fractions

[12] The river water and sea-ice meltwater (SIM) contributions can be quantified with a mass balance calculation, which was previously applied in the Arctic Ocean basins [e.g., *Östlund and Hut*, 1984; *Bauch et al.*, 1995; *Ekwurzel et al.*, 2001; *Yamamoto-Kawai et al.*, 2008] and shelf regions [*Macdonald et al.*, 1995, *Cooper et al.*, 1997; *Bauch et al.*, 2005]. Thereby it is assumed that each sample is a mixture between marine water (f_{mar}), river runoff (f_r), and sea-ice meltwater (f_{SIM}). The balance is governed by the following equations:

$$f_{\text{mar}} + f_r + f_{\text{SIM}} = 1,$$
$$f_{\text{mar}} * S_{\text{mar}} + f_r * S_r + f_{\text{SIM}} * S_{\text{SIM}} = S_{\text{meas}},$$
$$f_{\text{mar}} * O_{\text{mar}} + f_r * O_r + f_{\text{SIM}} * O_{\text{SIM}} = O_{\text{meas}},$$

where f_{mar}, f_r, and f_{SIM} are the fractions of marine water, river runoff, and sea-ice meltwater in a water parcel, and S_{mar}, S_r, S_{SIM}, O_{mar}, O_r and O_{SIM} are the corresponding salinities and δ^{18}O values (Table 1). S_{meas} and O_{meas} are the measured salinity and δ^{18}O of the water samples. For further details on the selection of end-members applicable for the Laptev Sea region, refer to *Bauch et al.* [2010].

[13] All fractions are net values reconstructed from the δ^{18}O and salinity signature of each sample and reflect the time-integrated effects on the sample volume over the residence time of the water on the shelf. Negative SIM fractions (f_{SIM}) reflect the amount of water removed by sea-ice formation and are proportional to the subsequent addition of brines to the remaining water column. As the mean residence time on the shelf is longer than 1 year [*Schlosser et al.*, 1994; *Bauch et al.*, 2009b], SIM fractions might be negative during summer season sampling when the winter signal exceeds the summer signal. The analytical errors arise from δ^{18}O and

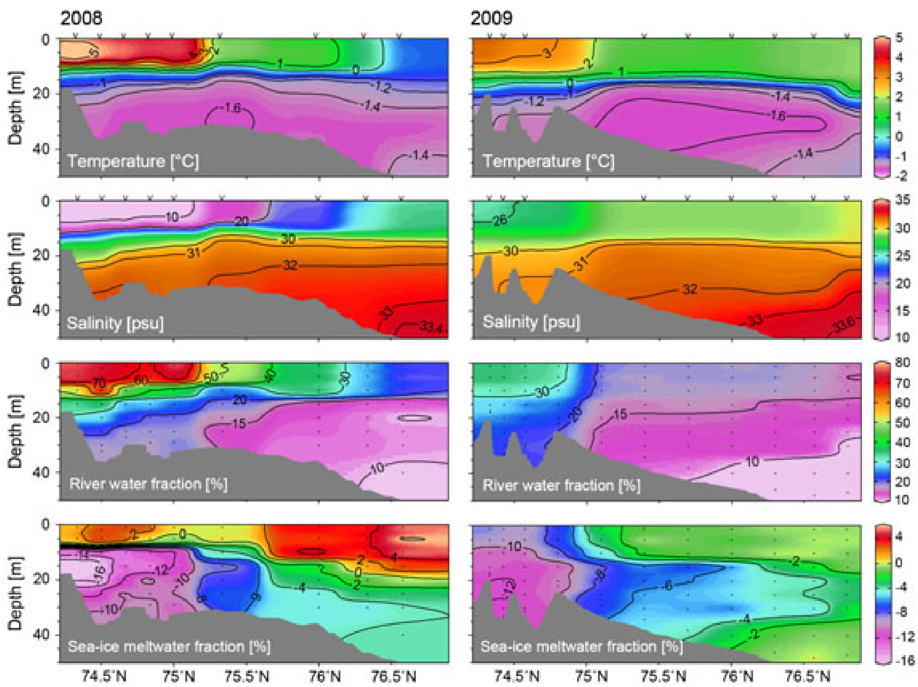

Figure 2. Hydrographic sections of temperature, salinity, and fractions of river water (f_r) and sea-ice meltwater (f_{SIM}) for summers 2008 and 2009 on south-to-north oriented sections (see Figure 1). Note that bathymetry differs due to small differences in station positions. Temperature and salinity sections are based on 1 m averaged CTD data with station positions marked on top of each section. Calculated fractions of sea-ice meltwater (f_{SIM}) and river water (f_r) are based on δ^{18}O and salinity bottle data as indicated by black dots. For sections in 2007 and 1994, refer to *Bauch et al.* [2010].

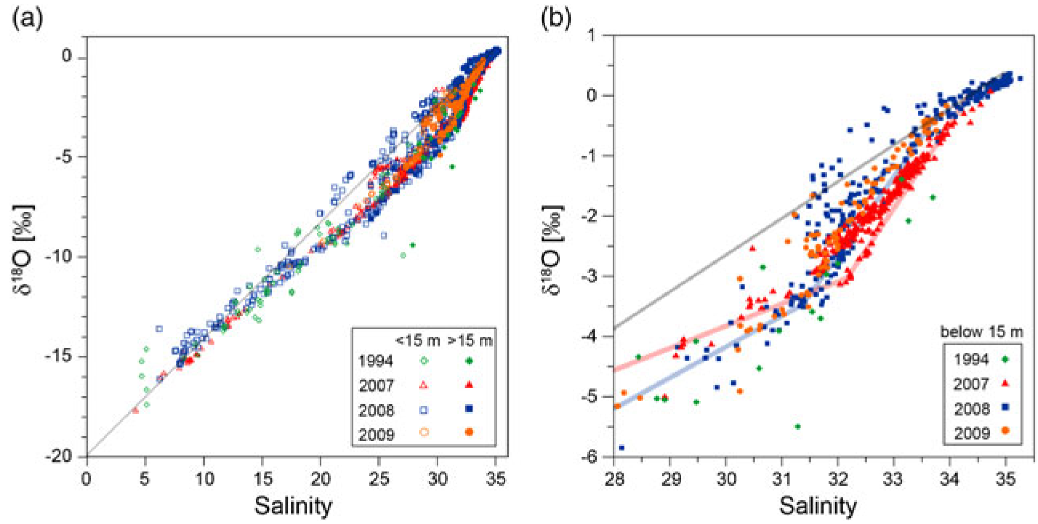

Figure 3. $\delta^{18}O$ versus salinity for summer expeditions 1994, 2007, 2008, and 2009. The direct mixing line between end-member values of marine and river waters is indicated for orientation (gray line). (a) The entire data range shows water from the surface layer (open symbols) and below 15 m water depth (closed symbols). (b) The enlargement shows waters below 15 m water depth, and interannually slightly different mixing lines are highlighted (2007 in red and 2008 in blue).

Table 1. End-member Values Used in Mass Balance Calculations[a]

End-member	Salinity	$\delta^{18}O$ (‰)
Marine (f_{mar})	34.92 (5)	0.3 (1)
River (f_r)	0	−20 (1)
Sea ice (f_{SIM})	4 (1)	surface + 2.6(1) or −7 + 2.6(1)

[a]Numbers in parentheses are the estimated uncertainties within the last digit in our knowledge of each end-member value.

salinity measurements and add up to approximately ±0.3% for each of the fractions, but the additional systematic error depends on the exact choice of end-member values. When end-member values are varied within the estimated uncertainties (Table 1), both fractions are shifted by up to ~1% in absolute values, but results are qualitatively always conserved even when extreme variations in end-member values are tested (refer also to *Bauch et al.* [2011a]).

4.2. Results of $\delta^{18}O$/salinity Mass Balance Analysis

[14] Calculated fractions of river water generally decrease with depth and with distance from the Lena River main outflows (Figure 2; sections for 1994 and 2007 are shown in *Bauch et al.* [2010]). In addition, the distribution of river water shows strong interannual variations (Figure 4). This is in agreement with surface salinities which are known to vary interannually in correlation with atmospheric forcing [*Shpaikher et al.*, 1972; *Dmitrenko et al.*, 2005; *Bauch et al.*, 2009a, 2011b]. In the surface layer, river water fractions are up to 70% and 60% in the central Laptev Sea for 2008 and 1994, respectively (Figure 4). In contrast, river water fractions in 2007 and 2009 are only about 30–40% (Figure 4). While the low salinity river plume spread to the north in 1994 and 2008, it was strongly reduced in the central Laptev Sea in 2007 and 2009 (see Figure 4).

[15] Fractions of SIM are mostly negative throughout the water column of the Laptev Sea and reflect thereby net formation of sea ice, i.e., sea-ice formation exceeding ice melt (Figures 2 and 4). Positive SIM fractions are found near the surface (Figure 2) and in most years only in the direct vicinity of the Lena River delta (Figure 4). SIM fractions close to zero or slightly positive are also found in the north near the shelf break (Figure 4). In summer 2008, net sea-ice melting (positive SIM) is observed also in the central Laptev Sea.

4.3. River and Sea-ice Freshwater Budgets

[16] Budgets of freshwater components were calculated for the entire central-eastern Laptev Sea between 72–76°N and 122–140°E (see Table 2 and Figure 5), where station coverage was considered to be sufficient and similar in all summers (compare Figure 1). River water and SIM station inventory values were calculated by integration of fractions over depth at each station. Station inventories represent the thickness of, e.g., pure river water or SIM contained within the water column. When SIM inventories are negative, they represent the thickness of the layer removed from the water column as sea ice that is proportional to the amount of exported sea ice. Budgets are based on geographical interpolation of river and SIM inventory values between stations and represent the volume of each freshwater component. Negative and positive fractions of SIM were integrated separately in order to get an additional impression of the current summer melting signal. For the spatial interpolation between stations, the nearest neighbor gridding method was applied as the most reliable method since station cover is spatially not regular and varies between years. Other regular interpolation grids were also tested and showed a difference between obtained water volumes of not more than 6%. All freshwater budgets are relative to the 34.92 reference salinity according to the end-member values used in the mass balance calculations (Table 1).

[17] River water budgets for the eastern Laptev Sea show strong interannual variations (Figure 5a). High river water

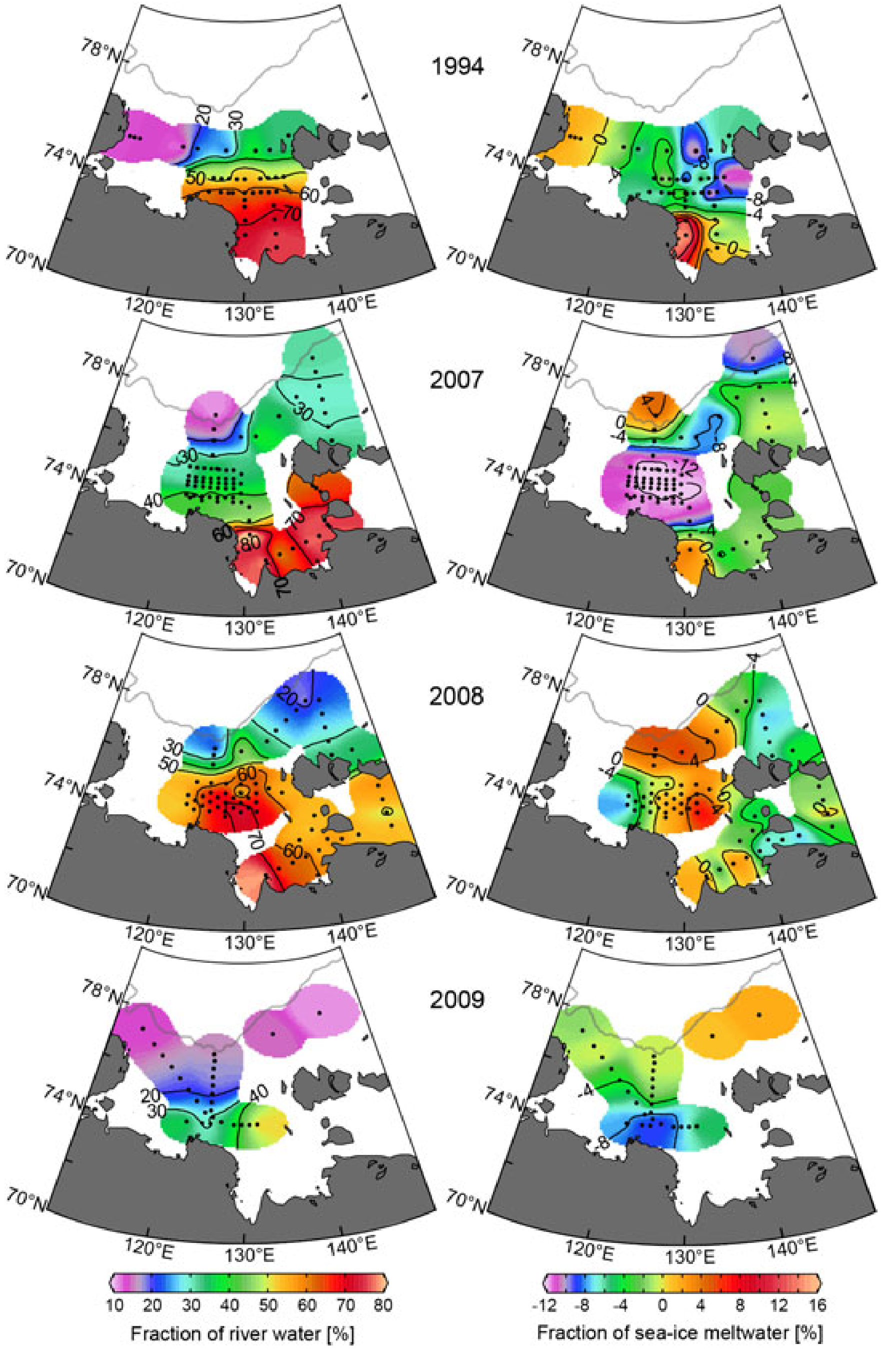

Figure 4. Surface distributions of fractions of river water (f_r) and sea-ice meltwater (f_{SIM}) of expeditions in summers 1994, 2007, 2008, and 2009. Station positions are indicated by small black dots, and the position of the shelf break is indicated at the 500 m isobaths with a gray line.

Table 2. Total Volumes of Freshwater Within the Water Column for the Eastern Laptev Sea (72–76°N and 122–140°E)[a]

Year	Lena River (km^3)	Total Freshwater budget (km^3)	River Budget (km^3)	Sea-ice Meltwater Budget (km^3)	Sea-ice Formation Budget (km^3)	Sea-ice Total Budget (km^3)
1994	678	1495	1733	+158	−396	−238
2007	715	1095	1496	+4	−405	−401
2008	585	1565	1833	+109	−377	−268
2009	637[b]	970	1317	<+1	−348	−347

[a]The sea-ice budget is calculated for positive and negative SIM values separately. For all sea-ice budgets, the water equivalent is given. The Lena River average annual runoff values at Kusur [*R-ArcticNET*, 2011] are listed for comparison.

[b]Runoff data for 2009 are only available till the beginning of September, and the annual average is based on January–August 2009 data and the average September–December discharge for the 2000–2008 period.

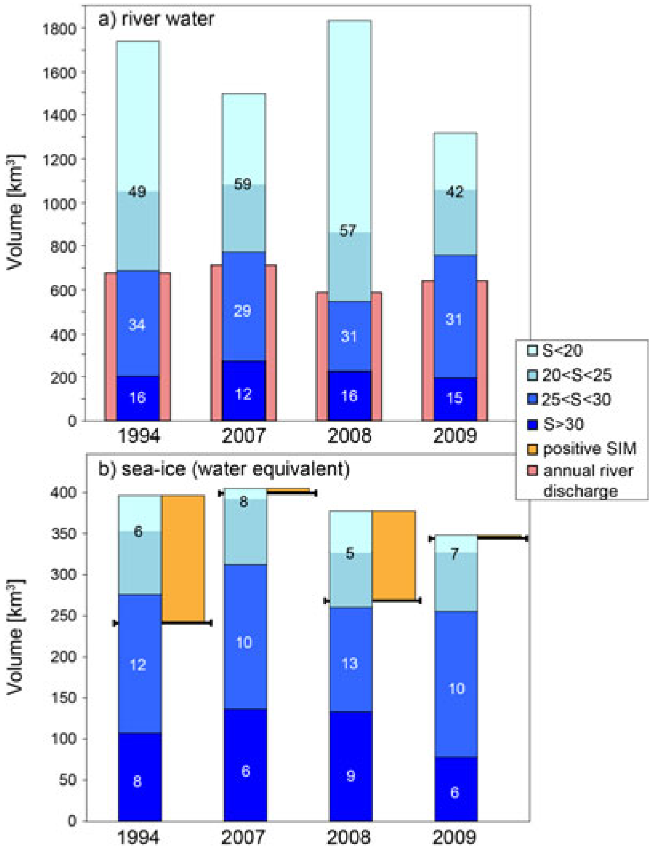

Figure 5. Freshwater budgets of (a) river water and (b) sea ice for the central-eastern Laptev Sea (72–76°N and 122–140°E; see also Table 2) in different salinity ranges for each year. Within Figure 5a, the annual Lena River discharge is indicated for comparison by a red box. Within Figure 5b, volumes of negative SIM (freshwater deficit related to sea-ice formation) are shown in blue. Volumes of positive SIM (sea-ice melting) are found in the surface layer only and are shown as separate orange blocks. The total sea-ice budget is indicated by a black bar. Numbers within section of bars give average fraction of river water (f_r) and sea-ice formation (negative f_{SIM}) in each salinity range (salinity ranges <25 were combined).

budgets of ~1800 km^3 are observed in 1994 and 2008, while lower river water budgets of ~1500–1300 km^3 are seen in 2007 and 2009. Intermediate and bottom layers contain about 60% of the river budget in years when total river budgets are low and about 30% in years when total river budgets are high (Figure 5a).

[18] The budget of negative SIM fractions is proportional to the volume of water removed from the area as sea ice (Figure 5b). Volumes of negative SIM fractions represent a sea-ice-related freshwater deficit and can be directly interpreted in terms of exported sea ice. No significant volumes of net sea-ice melting (positive f_{SIM}) are found in 2007 and 2009 when river budgets are low. Large volumes of net sea-ice melting (positive f_{SIM}) of up to 158 km^3 are observed in 1994 and 2008 (Table 2; and orange blocks in Figure 5b), both years when river water spread to the central Laptev Sea and river budgets are high. Therefore, the total SIM budgets of 1994 and 2008 are much lower as positive and negative f_{SIM} are considered together (~250 km^3 in 1994/2008 compared to 400–350 km^3 in 2007/2009; see Table 2). When evaluating the negative SIM budgets (i.e., sea-ice-related freshwater deficit) separately, volumes are, at ~350–400 km^3, about constant for all years (Figure 5b; Table 2). About 70% to 75% of these negative SIM budgets are contained within the bottom and intermediate layers with salinities above 25 (see Figure 5b).

5. Discussion

[19] Net local melting of sea ice is virtually absent in the water column in some summers, while large areas with net sea-ice melting are observed in the entire Laptev Sea in other summers (see positive SIM signals in Figures 4 and 5). It is the aim of the following discussion to get a general understanding of the observed variations in sea-ice meltwater and the coupling to river water in the Laptev Sea. Thereby we aim to reveal the controlling factors for local sea-ice melting on the Siberian shelves. The overall retreat of the seasonal ice cover in the Laptev Sea is controlled by atmospheric forcing [e.g., *Alexandrov et al.*, 2000]. Also river discharge has been shown to be of minor importance for the large-scale decay of the Laptev Sea ice cover [*Bareiss et al.*, 1999]. However, the coupling between river water and the SIM fractions in the surface layer (Figures 4 and 6) suggests a causal relation between river water and local melting of sea ice.

5.1. Potential Heat Input by River Water for Local Sea-ice Melting

[20] The energy flux of the Lena River can be calculated based on temperature measurements and volume flux data of the Lena River [*Lammers et al.*, 2007]. A water equivalent of 45 km^3 of sea ice could be melted by the annual average energy flux of the Lena River (~15,100 × 10^{15} J) when applied entirely to the heat of fusion for the melting of ice. The energy flux of the Lena River from May to July of ~9,100 × 10^{15} J could melt a water equivalent to 27 km^3 or a 0.5 m thick layer of ice in the southeastern Laptev Sea (~59,000 km^2 within 130–140°E and 71.5–73°N). This is an area where the sea-ice cover generally vanishes early in the summer season (by late July) compared to the central Laptev Sea [*Bareiss et al.*, 1999] (see also National Centers for Environmental Prediction reanalysis data [*Kalnay et al.*, 1996]). This area is south of the recurring coastal polynya and covered by ~1.5–2 m thick fast ice in winter [*Bareiss and Görgen*, 2005; *Dmitrenko et al.*, 2010a; *Bauch et al.*, 2012]. Therefore, the initial heat supplied by the Lena River can account for about one quarter to a third of the energy needed for the melting of the ice cover in the southeastern Laptev Sea. This rough estimate suggests that river water may be an important heat source for the early breakup of sea-ice cover in the proximity to the Lena Delta. Nevertheless, the initial heat contained in the river runoff alone is too small to melt even the area of the fast ice in the southeastern Laptev Sea that is usually free of ice rather early in the summer season. Overall, the calculated volumes of positive SIM fractions of 158 km^3 and 109 km^3 in 1994 and 2008, respectively, are much larger than the volume potentially melted by the initial heat contained in the Lena River water (maximal 45 km^3/a). Therefore, solar radiation and sensible heat must be dominant sources of heat even though the initial heat of the river water might also be locally

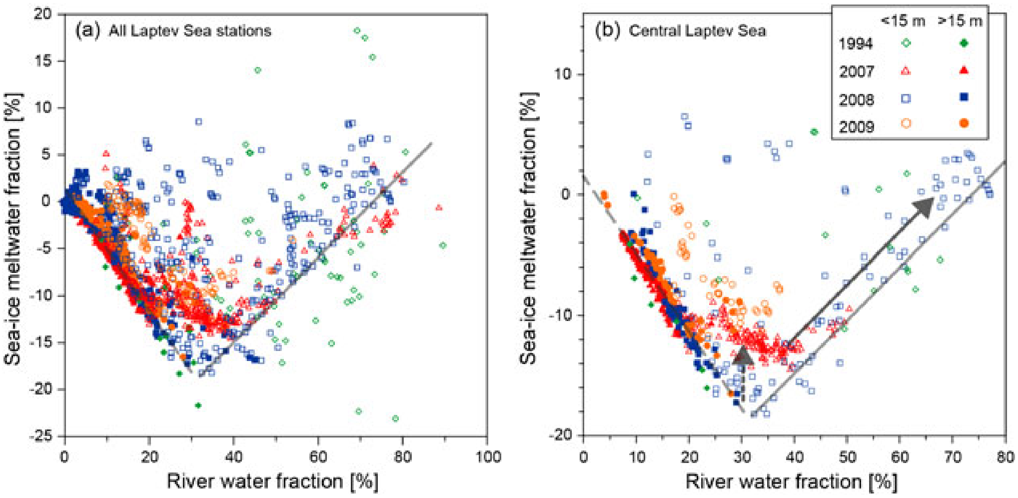

Figure 6. Sea-ice meltwater fractions (f_{SIM}) versus river water fractions (f_r) in the surface layer (0–15 m, open symbols) and in the bottom layer (>15 m, closed symbols) for each summer. Station data is (a) from the entire Laptev Sea (see Figure 1) and (b) from the central Laptev Sea (74–76°N and 120–130°E). Stippled gray line highlights f_{SIM}/f_r ratios of bottom waters, and solid gray line highlights f_{SIM}/f_r ratio in the surface layer. The arrows sketch the modification of f_{SIM} values in the surface layer by melting due to summer river water (solid arrow) and by melting due to solar radiation without river water addition (dotted arrow). For further explanation, see text.

a significant source in the proximity to the Lena Delta during breakup. Variations of bottom water temperatures in the Laptev Sea are of high interest [*Dmitrenko et al.*, 2010b; *Hölemann et al.*, 2011], but the heat in the bottom layer is of no importance for the Laptev Sea surface layer during summer due to its small magnitude and the extreme vertical stratification at that time.

[21] Ocean water containing turbid components strongly absorbs the heat from solar radiation, while clear water reflects a larger proportion of the radiation [*Pegau*, 2002; *Hill*, 2008]. Arctic river discharge contains large quantities of suspended particulate matter (SPM) and colored dissolved organic matter (CDOM) [*Granskog et al.*, 2007; *Stedmon et al.*, 2011]. CDOM absorption rates near the Lena River outflow are up to 10 m^{-1} (at $\lambda = 375$ nm) and show a correlation with salinity on the Laptev Sea shelf [*Loginova*, 2011; Hölemann, unpublished data]. While SPM concentrations are controlled by complex transport mechanisms and bottom resuspension on the shelves [*Wegner et al.*, 2005], SPM concentrations in surface waters on the inner Laptev Sea shelf are clearly related to river water fractions [*Wegner et al.*, 2012]. River water can flood the ice during the initial spring freshet [*Bareiss et al.*, 1999], and the CDOM and SPM components may thus directly facilitate enhanced melting of the still-closed ice cover in the vicinity of the Lena River delta. We may further speculate that river water and SIM may both pool in this region before spreading northward or eastward depending on the prevailing atmospheric wind forcing.

5.2. Sea-ice Meltwater and River Water of the Current Summer Season

[22] In order to further investigate and quantify the role of river water on local sea-ice melting, it is important to identify the melt signal of the current summer season. The calculated SIM fractions are net values and need to be interpreted in relation to the residence time. An average mean residence time of 3.5 ± 2 years was estimated for waters from all Siberian shelf areas [*Schlosser et al.*, 1994]. The mean residence time on the Laptev Sea shelf was found to show large variations [*Bauch et al.*, 2009a, 2011b; *Dmitrenko et al.*, 2008] and estimated to be at least 1 year [*Bauch et al.*, 2009b]. As a result, the $\delta^{18}O$/salinity-derived fractions of SIM are mostly negative also during summer (Figures 2 and 4), indicating that winter sea-ice formation exceeds summer melting due to the export of sea ice from the Laptev Sea [*Bauch et al.*, 2009a]. This implies that sea-ice melting of the current summer season may not be directly reflected in positive SIM fractions but in an offset from the SIM fractions imprinted during the preceding winter.

[23] To identify sea-ice melting of the current summer, the preconditioning from the previous winter has to be known. In winter, sea-ice formation transports river water (f_r) from the surface to intermediate depth and into the bottom layer [*Bauch et al.*, 2012]. Therefore, the whole water column is dominated by a negative f_{SIM}/f_r correlation in winter, and the average winter surface layer has a river water content of ~30 ± 10% [*Bauch et al.*, 2012]. In the consecutive summer, the surface layer is altered by river discharge and sea-ice melting and dominated by a positive f_{SIM}/f_r correlation (see solid line in Figure 6). Nevertheless, the winter preconditioning is still preserved in the bottom layer (see stippled line in Figure 6) and reflects past winter polynya activity [*Bauch et al.*, 2012]. Interannual comparison shows some variations in absolute values and ranges of f_{SIM} and f_r values, but the negative f_{SIM}/f_r ratio in the bottom layer is found constant for all investigated years (see closed symbols in Figure 6). We can therefore rely on this stable f_{SIM}/f_r ratio as the preconditioning from each winter, and any offset from the f_{SIM}/f_r correlation in the bottom layer can be interpreted as SIM signal from the current summer season.

[24] As river water fractions show high interannual variability, similar variations are also seen in the SIM signal of the current summer season. Highest interannual variations in summer surface hydrography are generally observed in the central Laptev Sea [*Dmitrenko et al.*, 2005; *Bauch et al.*, 2009a]. Accordingly, high variations are also observed in our data sets with most apparent interannual differences in the spread of the river plume in the central Laptev Sea (Figure 6b). In summers 1994 and 2008, the river plume spread northwards as reflected in relatively high f_r values as well as a pronounced positive f_{SIM}/f_r correlation in the surface layer of the central Laptev Sea (Figure 6b; see diamonds and squares). In 2007 and 2009 on the other hand, absolute river water fractions f_r remained relatively low in surface waters of the central Laptev Sea, and as a result, sea-ice meltwater values remained also low and no pronounced f_{SIM}/f_r correlation is observed for those years within the surface layer (Figure 6b; see triangles and circles).

[25] In summer 2007, a relatively high sea-ice-related freshwater deficit (negative f_{SIM}) was found in the surface layer and relatively lower values in the bottom layer of the central Laptev [*Bauch et al.*, 2010]. This was a rather surprising situation as it was qualitatively different and inverted relative to other summer observations. Within the view of seasonal successional modification, this "inverted" situation in the central Laptev Sea in summer 2007 can be explained: Due to a southeastward spread of the river plume, the 2007 surface layer in the central Laptev Sea still contained the nearly unaltered f_{SIM} signal from the previous winter. The brine-enriched bottom water component was relatively salty in summer 2007 and therefore had likely experienced less mixing with surface river water in the preceding winter compared to other years (Figure 3b; compare 2007 relative to, e.g., 2008 highlighted by red and blue mixing lines, respectively). The inverted f_{SIM} distribution in summer 2007 [*Bauch et al.*, 2010] was therefore likely the result of a combination of two factors: (i) missing bottom water alteration by polynya activity during the previous winter and (ii) missing surface layer alteration by summer sea-ice melting and river water and therefore preservation of the winter surface layer.

[26] High river water fractions are always associated with elevated SIM fractions (Figure 6b; solid arrow sketches modification of winter SIM values by summer river water). But in summers 2007 and 2009, SIM fractions are also slightly elevated relative to winter preconditioning at low river water fractions of ~20–40% in the central Laptev Sea (Figure 6b; dotted arrow sketches modification of winter f_{SIM} independent of river water). This is evidence of sea-ice melting occurring also independent of river water and shows that solar radiation and sensible heat may also play a role without river water and its heat-adsorbing components.

5.3. Heat Content in Relation to River Water

[27] The heat content of surface waters increases with increasing river water fractions (Figure 7, with linear correlation coefficients of 0.7, 0.4, 0.5, and 0.6 for 1994, 2007, 2008, and 2009, respectively). There are large interannual differences in absolute values and deviations from a rough linear correlation. Much higher heat content values are seen in the central Laptev Sea in 2007 at low river water fractions compared to all other years (1994 and 2008) independent of river water fractions (Figure 7). The high heat content values in 2007 seem to be related to a longer exposure time of the surface waters to solar radiation and sensible heat due to a relatively early opening of the perennial ice cover in 2007 (Figure 8). Daily satellite-based sea-ice concentration

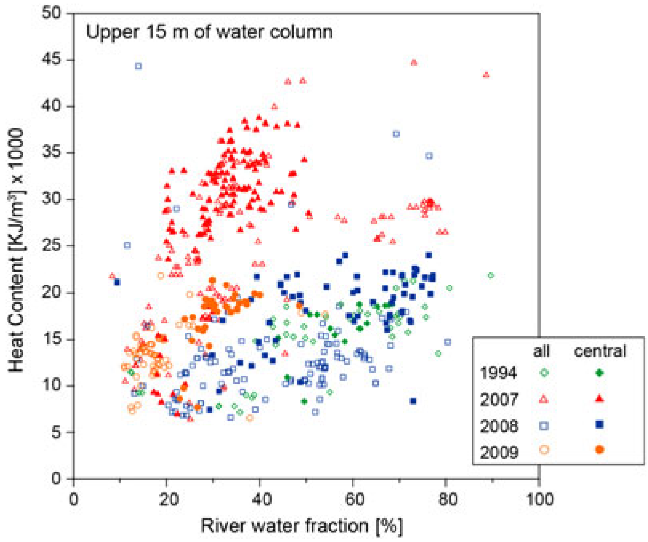

Figure 7. Heat content density versus river water fraction (f_r) for the upper 15 m of the water column for all summer data in the Laptev Sea. Data from the central Laptev Sea (74–76°N and 120–130°E) fall into clusters and are highlighted by closed symbols.

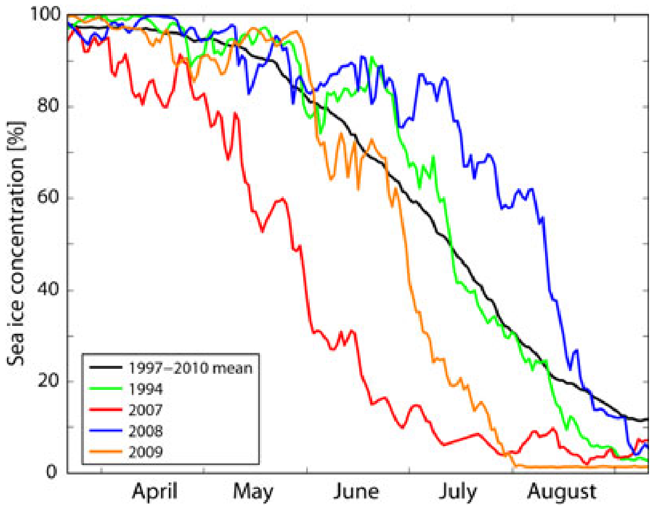

Figure 8. Average ice concentration in the central Laptev Sea (115–135°E, 73–77°N; see Figure 1 stippled box) between May and August derived from daily data provided by the National Snow and Ice Data Center with 25 × 25 km cell size [*Cavalieri et al.*, 2008]. Satellite-based sea-ice concentrations are generated from brightness temperature data derived from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), the Defense Meteorological Satellite Program (DMSP)-F8, -F11, and -F13 Special Sensor Microwave/Imagers (SSM/Is), and the DMSP-F17 Special Sensor Microwave Imager/Sounder (SSMIS). While the seasonal decline in ice concentration between May and August in summers 1994 and 2009 is similar to the average seasonal decline (1980–2011), the ice concentration declines earlier in 2007 and later in 2008.

provided by the National Snow and Ice Data Center with 25×25 km grid resolution [*Cavalieri et al.*, 2008] were averaged for the area 115–135°E, 73–77°N to derive the seasonal decline in ice concentration in the central Laptev Sea. The seasonal decline in ice concentration in the central Laptev Sea relative to the average seasonal decline was taken as a measure for the exposure time to solar radiation and sensible heat (Figure 8). The seasonal decline in ice concentration between May and August in summers 1994 and 2009 was similar to the average seasonal decline (1980–2011). However, compared to the average, ice concentration declined earlier in 2007 and later in 2008 (Figure 8). The river plume was largely absent in the central Laptev Sea in summers 2007 and 2009. While the heat content values appear to be correlated to river water fractions in the central Laptev Sea in 2007 and 2009, the relatively high magnitude in 2007 and relatively low magnitude in 2009 appear to correspond to relatively early and average sea-ice retreat, respectively (Figure 7). The river plume was dominating the surface layer in the central Laptev Sea in 1994 and 2008 when exposure times were average and relatively short, respectively. Nevertheless, heat content values in 1994 and 2008 are similar and appear both only correlated to river water fractions (Figure 7). When the river plume dominates the surface layer, it therefore appears that heat content values are determined by river water fractions and heat content appears to be largely independent from exposure time to solar radiation and sensible heat under these conditions.

[28] With the absence of the river plume and a relatively long exposure time in summer 2007, the heat content far exceeds values observed in years with high river water fractions as in 1994 and 2008. Investigations show CDOM and SPM concentration to raise the heat content by absorption of solar radiation at the surface while at the same time preventing the penetration of solar radiation deeper into the water column and thereby preventing a raise in heat content below the mixed layer [*Hill*, 2008]. Also solar radiation can only warm the surface mixed layer when heating exceeds latent and sensible heat loss governed by air temperatures and wind speed [e.g., *Hill*, 2008]. In agreement with these findings, our data indicate that river water with its turbid components leads to enhanced heating of the surface mixed layer but may also restrict the maximal uptake of heat in the upper 15 m. In years when river water is largely absent, radiation penetrates deeper and increases heat content values below the surface where it may be stored and survive latent and sensible heat loss more easily compared to the surface. In contrast to years with a dominant river plume, heat content values may therefore increase with exposure time in years when river water is largely absent.

5.4. Interannual Variation and Composition of Laptev Sea Freshwater Volumes

[29] The total freshwater volume relative to 34.92 salinity of the central and eastern Laptev Sea varies interannually between ~1000 and 1500 km^3 (Table 2). Our analysis allows a discrimination of the different freshwater components and thereby insight into the coherence of the interannual freshwater changes to changes in river water (f_r), sea-ice melt (positive f_{SIM}), and a sea-ice-related freshwater deficit (negative f_{SIM}).

[30] River water volumes for the eastern Laptev Sea show strong interannual variations (Figure 5a). High river water volumes of ~1800 km^3 are observed in 1994 and 2008, whereas relatively low river water volumes of ~1500 and 1300 km^3 are seen in 2007 and 2009, respectively. While Laptev Sea waters may also be exported to the Arctic Ocean, these variations in river water volume are likely related to interannual differences in the spread of the river plume either into the central Laptev Sea as observed in 1994 and 2008 or into the East Siberian Sea as suggested by the lack of river water in our data sets in 2007 and 2009 (Figure 4). The observed interannual difference in river water volume of about 300–500 km^3 agrees well with the freshwater content anomaly of ~500 km^3 estimated for the export of freshwater from the Laptev Sea to the East Siberian Sea in years with anticyclonic vorticity [*Dmitrenko et al.*, 2008]. The difference in river water volume is on the same order as the annual Lena River discharge (~600 km^3/yr average for 2000–2009). While river water volumes in 1994 and 2008 reflect nearly three times the annual river discharge, budgets in 2007 and 2009 reflect little more than twice the annual average Lena river discharge. This indicates an average mean residence time of Laptev Sea waters between 2 and 3 years during this period. Intermediate and bottom layer (defined as layers with salinities of 25–30 and >30, respectively) contain between 30% and 60% of the total river budget of each year (Figure 5a). While the mean residence time in surface and bottom layer may differ, the relatively high proportion of river water contained in deeper layers indicates that the estimated average mean residence time applies also to the bottom layer. The observed interannual variation in total river budgets and thereby the variation in estimated mean residence time nevertheless primarily depend on variation in the average river water volume within the surface layer (Figure 5; average fractions are indicated within each bar).

[31] The budget of negative SIM fractions represents the sea-ice-related freshwater deficit and is proportional to the volume of water removed from the Laptev Sea area as sea ice (Figure 5b, blue bars). The budgets of positive SIM fractions are the water equivalent of melted sea ice added to the water column (Figure 5b, orange blocks). No significant volumes of net sea-ice melting (positive f_{SIM}) are found in 2007 and 2009 when river budgets are relatively low. Only in 1994 and 2008, when river water spread to the central Laptev Sea, significant volumes of net sea-ice melting (positive f_{SIM}) are observed (Table 2; and orange blocks in Figure 5b). Consequently, the total sea-ice budgets (combining positive and negative f_{SIM}) of these years are much lower (~250 km^3 in 1994/2008 compared to 350–400 km^3 in 2007/2009; see Table 2). About 70% to 75% of the sea-ice budgets are contained within the bottom and intermediate layers (salinities above 25) (see Figure 5b). The volume of sea-ice-related freshwater deficit (negative budget of f_{SIM}) is, at ~350–400 km^3, about constant for all years (Figure 5b; Table 2). This implies that the annual amount of sea ice formed and exported is about constant in each winter. The variation in total sea-ice budgets (melting and formation combined) is correlated to the variation in river water budgets and therefore determined by the spread of the summer river plume as positive sea-ice budgets are related to high river budgets.

[32] With the mean residence time, an annual export of sea-ice-related freshwater deficit (negative budget of f_{SIM})

can be derived. A total volume of ice can be additionally estimated by applying the average salinity of Laptev Sea surface waters as the SIM values are calculated relative to 34.92 salinity. With the density of sea ice of ~0.9, an average salinity of ~20 in the southeastern Laptev Sea and applying a mean residence time of ~2.5 years, a net ice export of ~270 to ~310 km^3 is derived for the central-eastern Laptev Sea. This estimate directly depends on the mean residence time of waters on the Laptev Sea shelf and the average salinity of Laptev Sea surface waters. Satellite-based sea-ice drift and concentration estimates suggest an annual ice export of 3.38×10^5 km^2 from the entire Laptev Sea region up to 81°N (*Krumpen et al.*, 2012). This annual ice export relates to ~350 and 690 km^3 when 1 and 2 m ice thickness are assumed, respectively. Our SIM-based estimate from the smaller central-eastern Laptev Sea region is thereby consistent with the satellite-based estimate from the entire Laptev Sea region.

6. Summary and Conclusions

[33] As a net-export region for sea ice, the large-scale decay of the Laptev Sea ice cover is controlled by atmospheric forcing [e.g., *Alexandrov et al*., 2000], and river water has no significant influence on this large-scale decay [*Bareiss et al*., 1999]. Our study now shows that nevertheless the local melting of sea ice on the shelf is coupled to river water. Salinity/δ^{18}O derived fractions of SIM and river water are correlated within the surface layer (0–15 m). When river water is largely absent, no net sea-ice melting with positive SIM values is observed. The initial heat contained in the Lena River runoff is not sufficient to melt the calculated volume of up to 158 km^3 of SIM. Nevertheless, river water may control sea-ice melting as solar radiation is preferentially absorbed by particles (SPM) and colored dissolved organic matter (CDOM) contained in river discharge [*Pegau*, 2002; *Granskog et al*., 2007; *Hill*, 2008]. As river water may also flood the ice cover during the initial spring freshet [*Bareiss et al*., 1999], river water and the contained CDOM and SPM components may directly facilitate enhanced melting of the still-closed ice cover in the vicinity of the Lena River delta. In agreement with our data, river water and SIM may both pool close to the Lena River outflow in early summer before spreading north or eastward depending on the prevailing atmospheric wind forcing.

[34] In years with a pronounced river plume in the central Laptev Sea, river water fractions and heat content of the surface layer are coupled, and the heat content appears to be largely independent of exposure time to solar radiation and sensible heat. Only in years when the river plume is largely absent in the central Laptev Sea is the heat content in surface waters coupled to exposure time. Compared to all other years, heat content values may be doubled in years with low river fractions and relatively long exposure time. River water and its turbidity preferentially absorb solar radiation, and with a dominant river plume, heat content values are therefore coupled to river fractions. But the turbidity of river water may also be a limiting factor for the maximal heat content by restricting penetration of radiation below the mixed layer and preventing a rise of heat content below [*Hill*, 2008].

[35] The total freshwater budget of the central-eastern Laptev Sea (72–76°N, 122–140°E) varies interannually between ~1000 and 1500 km^3 (relative to 34.92 salinity). Analysis of the freshwater components reveals that the amount and variation of the freshwater budget is dominated by river water volumes of ~1300–1800 km^3. Variation in total freshwater volume is enhanced by sea-ice melt (~109–158 km^3) that is only present in years with high river water budgets. When river budgets are low, net sea-ice melt is absent. Comparison of river water budgets and the annual river discharge indicates a mean residence time of about 2–3 years for Laptev Sea shelf waters during 2007–2009. The budget of sea-ice-related freshwater deficit (negative SIM) is, at ~350–400 km^3, nearly constant for all years, implying an approximately constant annual amount of sea-ice formation. Applying a mean residence time of ~2.5 years and a mean surface salinity of ~20, the sea-ice-related freshwater deficit (negative SIM) in the central-eastern Laptev Sea can be converted to a net ice export of ~270–310 km^3/a.

[36] With the ongoing changes in the arctic sea-ice regime, an earlier opening of the perennial sea-ice cover and an overall longer exposure time to solar radiation and sensible heat is to be expected. Our study indicates that in contrast to the basin, local melting on the shelf is not primarily controlled by surface albedo. Currently, an increase in heat content in surface waters on the Siberian shelves may not directly increase local sea-ice melting. The coupling between SIM and river water in the Laptev Sea suggests that local melting may be restricted to initial breakup of the Lena river and the fast ice, is therefore influenced by processes upstream [*Bareiss et al*., 1999], and is not likely to be influenced locally, e.g., by an earlier local melt onset. Our study also suggests that surface heat content values may be largely independent of exposure time when river water fractions dominate the surface layer. It may be speculated that on the Siberian shelves river water may have a dampening effect on heat content values when exposure times to sensible heat and solar radiation increase. But interannual variations in heat input are only estimated by sea-ice retreat by our study. Further studies are necessary to specifically investigate heat content in relation to river water and incident solar radiation on the Siberian shelves in order to predict future feedbacks and to derive realistic model scenarios.

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