RESEARCH/REVIEW ARTICLE

Near-bottom water warming in the Laptev Sea in response to atmospheric and sea-ice conditions in 2007

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Abstract

In this paper we present new data from ship-based measurements and two-year observations from moorings in the Laptev Sea along with Russian historical data. The observations from the Laptev Sea in 2007 indicate that the bottom water temperatures on the mid-shelf increased by more than 3°C compared to the long-term mean as a consequence of the unusually high summertime surface water temperatures. Such a distinct increase in near-bottom temperatures has not been observed before. Remnants of the relatively warm bottom water occupied the mid-shelf from September 2007 until April 2008. Strong polynya activity during March to May 2007 caused more summertime open water and therefore warmer sea surface temperatures in the Laptev Sea. During the ice-free period in August and September 2007, the prevailing cyclonic atmospheric circulation deflected the freshwater plume of the River Lena to the east, which increased the salinity on the mid-shelf north of the Lena Delta. The resulting weaker density stratification allowed more vertical mixing of the water column during storms in late September and early October, leading to the observed warming of the near-bottom layer in the still ice-free Laptev Sea. In summer and autumn 2008, when the density stratification was stronger and sea surface temperatures were close to the long-term mean, no near-bottom water warming was observed. Warmer water temperatures near the seabed may also impact the stability of the shelf's submarine permafrost.

The combined global land and ocean surface temperature in 2007 fell within the 10 highest on record while the average land temperature was the warmest since global records began in 1880 (Levinson & Lawrimore 2008). Almost 40% of the Arctic sea-ice cover that was present in the 1970s was lost by 2007 during the record low in summer sea-ice extent. A comparison of Arctic sea surface temperatures during the summers of 2007 and 2008 provides clear evidence that the temporal and spatial sequence of the sea-ice retreat plays a significant role in determining the distribution of ocean surface temperatures and the magnitude of their increase (Richter-Menge 2009). As the climate warms, the melt season lengthens and intensifies, leading to large areas of open water early during the year and less sea ice at the end of the melt season. Summertime absorption of solar energy in open-water areas increases the ocean thermal energy (Serreze et al. 2009). This is supported by observations showing a +2 to +5°C sea surface temperature anomaly in the Laptev Sea during the summer of 2007 (Steele et al. 2008; Frolov et al. 2009). In this context, an important characteristic of the Laptev Sea appears to be the linear-shaped flaw polynyas that may extend from some 100 km to nearly 2000 km and reach maximal widths of up to 250 km. Flaw polynyas are zones of ice-free water or young ice that are formed between fast ice

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and drift ice by the regional surface wind field. During wintertime, the polynyas produce relatively large amounts of new ice considering their limited areal extent. With the steady increase of solar radiation during spring, flaw polynyas turn to areas of heat gain and strong sea-ice melt (Barreis & Görgen 2005).

A dominant feature of the water column structure in the eastern (east of 125°E) Laptev Sea is a strong year-round stratification that is caused by the high freshwater input by the River Lena and additional sea-ice meltwater (Dmitrenko, Kirillov & Tremblay 2008; Bauch et al. 2009). Because the strong vertical density gradient (pycnocline) separates the fresh surface layers from the more saline bottom waters and impedes the exchange of energy and matter between both water masses, it was assumed that—particularly in the eastern Laptev Sea—the temperature below 20-m water depth is not affected by the distinct seasonal cycle of temperature variations in the surface layer. This assumption was mainly based on the first year-round mooring observations (1998–99) from the mid-shelf of the Laptev Sea at 44-m water depth (Dmitrenko et al. 2002; Wegner et al. 2005) and the analysis of the Russian historical oceanographic record (see below).

From November to July, the water column in the Laptev Sea usually experiences much less exchange with the atmosphere than the shallow shelf seas at low latitudes because the sea-ice cover inhibits the exchange of momentum and energy. During winter, atmospheric forcing influences the hydrography of the Laptev Sea mostly in flaw polynyas, which usually occur at the northern edge of the land-fast ice during periods of southerly winds (Dmitrenko, Tyshko et al. 2005). Based on historical field data and modern observations Dmitrenko, Tyshko et al. (2005) estimated that the probability that density-driven convective mixing erodes the pycnocline in the eastern Laptev Sea completely is less than 20%, supporting the hypothesis that the low temperature (<-1.6°C) and saline (>32) bottom waters on the mid-shelf (20–50-m water depth) and outer shelf (50–200-m water depth) of the Laptev Sea are not affected by seasonal processes. The possibility of turbulent wind or tidally driven mixing was not taken into account by Dmitrenko, Tyshko et al. (2005).

In this paper we present new observations from ship-based summer measurements and oceanographic year-round moorings in the Laptev Sea along with historical data from the Russian Arctic and Antarctic Research Institute (AARI). These observations indicate that in 2007 the bottom water temperatures on the mid-shelf of the Laptev Sea increased by more than 3°C compared to the long-term mean. The temperature increase was accompanied by a distinct freshening of the bottom waters. The analysis of the time series revealed that remnants of this relatively warm and fresh bottom water mass survived the following winter and were traceable until the spring (April) 2008. This phenomenon may have far-reaching consequences. Most of the Laptev Sea and adjacent land remained unglaciated during the last glacial maximum, allowing permafrost to develop to depths as great as 1000 m before the (originally terrestrial) permafrost was flooded during the Holocene transgression. An increase in bottom water temperatures may affect the stability of the upper boundary of the (now submarine) permafrost that extends across large parts of the Laptev Sea Shelf at a shallow sediment depth (Kassens et al. 2007; Overduin et al. 2007).

The major goal of this paper is to demonstrate how the Laptev Sea Shelf will respond to the longer periods of open water and higher water temperatures that Arctic climate change is predicted to entail. Our methods, instrumentation and the AARI data set are described in the following section. We then present the historical data and our observations obtained during two ship-based expeditions in September 2007 and September 2008 and year-round mooring-derived measurements from the central shelf of the Laptev Sea (September 2007 to September 2009). In the subsequent section we discuss the hydrographic conditions and possible mechanisms that led to the observed increase of near-bottom water temperatures on the central shelf of the Laptev Sea that lasted for several months. Finally, we draw conclusions about the probability and consequences of a persistent bottom water warming in the Laptev Sea.

Data and methods

This study discusses water velocity, temperature and salinity measurements from two moorings (KH and AN) that were deployed in the Laptev Sea north of the Lena Delta at 43-m and 32-m water depth from September 2007 to September 2009 (Fig. 1). Both positions are located in the northern part of the recurrent Laptev Sea polynya (Barreis & Görgen 2005). The mooring KH (74° 42.9 N, 125° 17.4 E) was located in a shallow trough that crosses the mid-shelf of the Laptev Sea in a south-east–north-west orientation. The mooring AN (74° 20.0 N, 128° 00.1 E) was deployed in a shallow SSW–NNE-running trough. The general directions of the bottom water flows at the moorings are influenced by the local topography and are in alignment with trough direction. The moorings were deployed, recovered and re-deployed during the ship-based Transdrift expeditions in 2007, 2008 and 2009 (TD XII, XIV and XVI). Ocean current

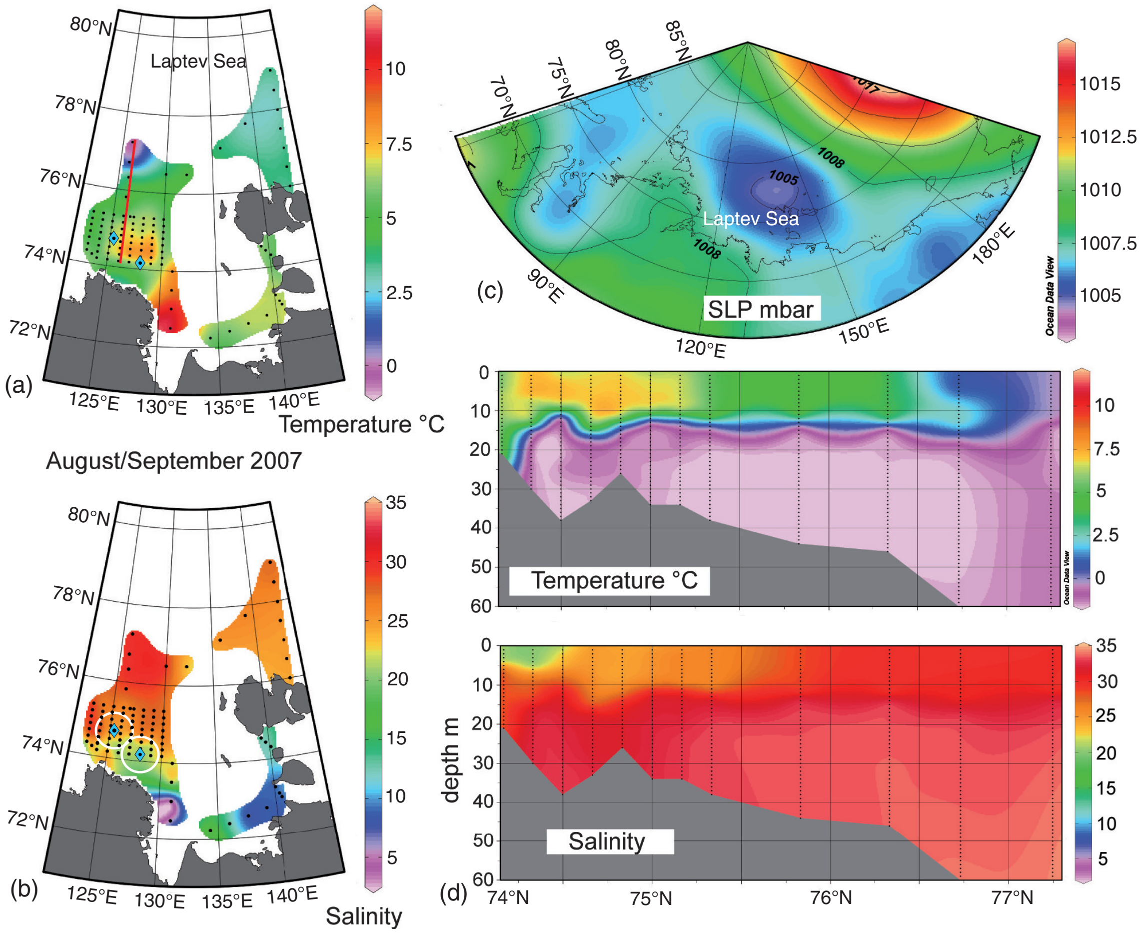

Fig. 1 Spatial distribution of (a) temperature and (b) salinity at 3-m water depth, (c) average sea-level pressure (SLP; US National Centers for Environmental Prediction and National Center for Atmospheric Research reanalysis data for August and September 2007) and (d) cross-shelf transect of temperature and salinity observations during the Transdrift XII expedition in August–September 2007. In (a) and (b), black dots mark the sampling locations and the blue rhombi indicate the positions of the moorings KH (western position) and AN (eastern position). White circles in (b) show the area used for the calculation of the long-term mean of temperature and salinity (1920–2008). The red line in (a) shows the position of the oceanographic transect shown in (d).

profiles were collected using an upward-looking 300 kHz and a downward-looking 1200 kHz acoustic doppler current profiler (ADCP; Workhorse Sentinel, Teledyne RD Instruments, San Diego, CA, USA) set 3 m (300 kHz) and 6 m (1200 kHz) above the sea floor. Continuous profiles were averaged over 30-min ensembles (70/110 pings per ensemble) in 1 m (300 kHz) and 0.2 m (1200 kHz) depth bins with the first bin centred ca. 3.2 m (300 kHz) and ca. 0.7 m (1200 kHz) in front of the ADCP transducer head. Pumped conductivity, temperature and depth (CTD) sensors (SBE 19 SEACATs in 2007–08 and SBE 37-IMP MicroCATs in 2008–09; Sea-Bird Electronics, Bellevue, WA, USA) were installed 4 m (mooring KH in 2007–08) and 5 m (mooring KH and AN in 2008–09) above the sea floor. Additional temperature and salinity sensors (XR-420CTTu Multi Channel–Multi Parameter Logger, RBR, Stadhampton, Oxfordshire, UK) were mounted close to the ADCPs. Battery problems stopped the pumped CTD at mooring KH from taking measurements in April 2008. The unpumped conductivity sensors showed biased measurements due to biofouling in November 2007. Therefore, the conductivity data obtained after October 2007 from the unpumped sensors were not used in this study. The pumped SBE 37-IMP MicroCAT CTDs that were installed on the mooring during the period from September 2008 until September 2009 worked for the whole deployment period. All CTDs recorded data every 15 minutes.

Oceanographic data were collected during two summer cruises with the Russian research vessels *Ivan Petrov* and *Yakov Smirnitsky* in August and September 2007 (TD XII, 29 August–18 September) and 2008 (TD XIV, 5–21

September). CTD profiles in the Laptev Sea were obtained using a pumped SBE19plus system (Sea-Bird Electronics). The SBE19plus was calibrated before the cruises. All CTD data were processed according to standard procedures as recommended by the manufacturer and averaged over 1 m.

The historical data record used in this study is the AARI hydrographic data set, which consists of summer and winter salinity and temperature observations (between 1920 and 1992) complemented with recent summer and winter measurements from 1993 to 2008 (see Dmitrenko, Kirillov & Tremblay [2008] and Dmitrenko, Kirillov & Tremblay et al. [2008] for spatial and temporal coverage before 2006). For the comparison of the newly obtained data from the moorings with the historical AARI data record, only archived observations from stations within a radius of 80 km around the position of the moorings were used. Information about the extent of the ice cover in the Laptev Sea was obtained from Envisat synthetic aperture radar satellite imagery with a resolution of 150 m and from satellite-derived passive microwave data from the Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E) with a grid size of 6.25 km provided by the University of Hamburg (Spreen et al. 2008). Sea-level pressure and wind field information is drawn from the reanalysis data of the US National Centers for Environmental Prediction and the US National Center for Atmospheric Research (NCEP/NCAR), accessed through the website (http://www.esrl.noaa.gov/psd/) of the Earth System Research Laboratory of the US National Oceanic and Research Administration.

Results

We present our results in three parts. The first subsection describes temperature and salinity distributions observed in the Laptev Sea in summer 2007 and 2008. The results are related to the historical data set and the atmospheric forcing. Sea-ice conditions in 2007 and 2008 are described in the second subsection. In the final subsection we present measurement from two moorings deployed in the central Laptev Sea north of the Lena Delta from September 2007 until September 2009.

The summer hydrography of the Laptev Sea (2007 and 2008)

The high variability of summer surface salinity over the Laptev Sea Shelf is mainly attributed to the difference in wind-forced surface currents that are driven by a cyclonic and anticyclonic atmospheric circulation (Špajher et al. 1972; Dmitrenko, Kirillov et al. 2005). The sea-level pressure during the ice-free period in August and September 2007 showed a cyclonic regime with a region of low sea-level pressure north of the Laptev Sea (Fig. 1b) that resulted in persistent westerly winds that, in turn, deflected the freshwater plume of the Lena River to the east. At the same time saline surface water from the north-western Laptev Sea was advected towards the area north of the Lena Delta. Consequently the salinity of the surface layer north and north-east of the Lena Delta showed values above 20 while the surface water salinity in the south-eastern Laptev Sea was characterized by salinities below 15 (Fig. 1b). Highest surface temperatures (>8°C) were observed in the south-eastern Laptev Sea and north of the Lena Delta between 74°N and 75°N (Fig. 1b).

The water column in the whole Laptev Sea is stratified with an approximately 10-m-thick warm surface layer separated by a distinct halocline situated between 10-m and 20-m water depth from the saltier and usually colder water below (Pivovarov et al. 2005). A CTD transect across the Laptev Sea Shelf carried out between 1 and 12 September 2007 (Fig. 1d) revealed that on the mid- and outer-shelf the summertime warming of the surface is restricted to the upper 15 m of the water column. The near-bottom water showed temperatures below –1.5°C. We used the salinity difference between 5-m and 20-m water depth as a proxy for the strength of the stratification. In September 2007 the salinity difference at the stations in the eastern Laptev Sea was about five while the westernmost stations along 123°E showed a difference of about three. The differences in the south-eastern Laptev Sea (south of 74°N) were between 13 and 24.

The comparison of the temperature and salinity distribution (at 2 m) from September 2007 with the historical oceanographic data from 1920 to 2008 (AARI data) showed that the surface salinity north of the Lena Delta was up to 10 higher than the long-term mean for August and September (Fig. 2). This was accompanied by a surface water temperature anomaly that showed 3 to 5°C higher temperatures than the climatic mean for August and September. At the mooring position of KH (Fig. 2) the maximum difference between the long-term mean temperature (within a radius of 80 km around the position of KH) for August and September and the observed temperature in the surface layer on 3 September 2007 was 5.5°C at 10-m water depth. The temperature and salinity of the water column below the pycnocline (>20 m) showed values within one standard deviation of the long-term mean.

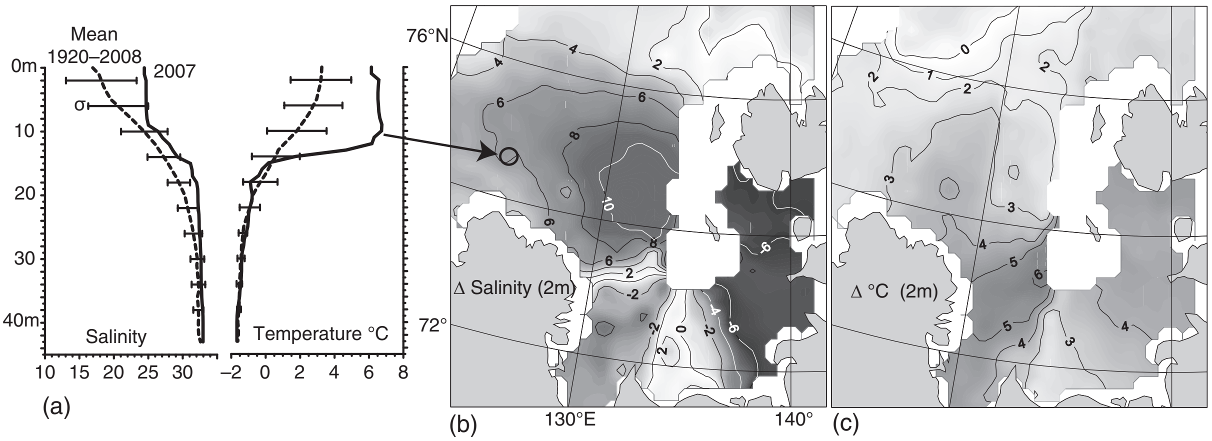

Fig. 2 (a) Temperature and salinity curve at the mooring KH recorded on 3 September 2007 (solid line) and long-term mean for temperature and salinity (broken line) calculated from all observations during August and September (since 1920) within a radius of 80 km around the mooring (see Fig. 1). Horizontal lines indicate one standard deviation. Difference between long-term mean (1920–2008) of (b) salinity and (c) water temperature (°C) at 2-m water depth compared to temperature and salinity measurements from the same level recorded during the Transdrift XII expedition in September 2007.

In contrast to the cyclonic regime of 2007, an anticyclonic atmospheric circulation regime with a region of high sea-level pressure north-east of the Laptev Sea prevailed during August and September 2008 (Fig. 3c). During the anticyclonic regime, winds from the east force the freshwater plume of the Lena to the north-west. This led to surface salinities below 10 in the eastern Laptev Sea north of 74°N (Fig. 3b, d). The salinity difference between 5-m and 20-m water depth in the eastern Laptev Sea and the region north of the Lena Delta was approximately four times higher than the difference observed in September 2007, indicating a much stronger haline stratification of the water column in September 2008.

The CTD profiles from the deeper outer shelf (> 50 m) showed bottom water temperatures between –1.2°C and –1.5°C with salinities between 33.7 and 34 (Figs. 1d, 3d). This water mass is therefore warmer and more saline than the bottom water in the shallower parts of the shelf. The relatively warm and salty bottom water, which was observed during all Transdrift summer expeditions, is most likely advected from the region of the continental slope north of the Laptev Sea. This region is characterized by a relatively warm intermediate water layer (50–125-m depth range) between the mixed surface layer and the inflow of the warm Atlantic water at greater water depth. The intermediate layer shows the same temperature and salinity properties as the warm bottom water on the adjacent northern part of the Laptev Sea Shelf (Walsh et al. 2007; Lenn et al. 2009). As this relatively warm water flows southward on the Laptev Sea Shelf it continuously mixes with colder and fresher shelf water. The CTD profiles obtained during the years 2007 and 2008 indicate that the temperature signal of the relatively warmer outer shelf bottom water did not reach the mid- and inner-shelf south of 75°N.

Sea-ice distribution in 2007 and 2008

The extent of the 2007 and 2008 Arctic summer sea-ice cover was the first and second lowest value of the satellite record that started in 1979 (Richter-Menge 2009). On 1 September 2007, the eastern and central Laptev Sea was ice-free as far north as 80°N. Only in the north-western Laptev Sea, north of 76°N, parts of the Taimyr ice massif persisted throughout the summer. The extent of the sea-ice cover of the Laptev Sea recorded on 1 September 2008 was similar to that of 2007, with the exceptions that the ice margin was closer to the continental shelf break (about 77°N) and the Taimyr ice massif did not last through the summer melt season.

The main difference between the years 2007 and 2008 concerns the timing in the loss of the seasonal sea-ice cover in the Laptev Sea during late winter and spring. The AMSR-E satellite observations of the sea-ice concentration revealed that in April and May 2007 strong polynya activity resulted in unusually large areas of open water and thin ice in the Laptev Sea (Willmes et al. 2011 [this volume]). During the period from March to May 2007 sea-level pressure was low west of the Laptev Sea and higher to the east (Fig. 4). This spatial pattern resulted in predominately southerly winds (according to

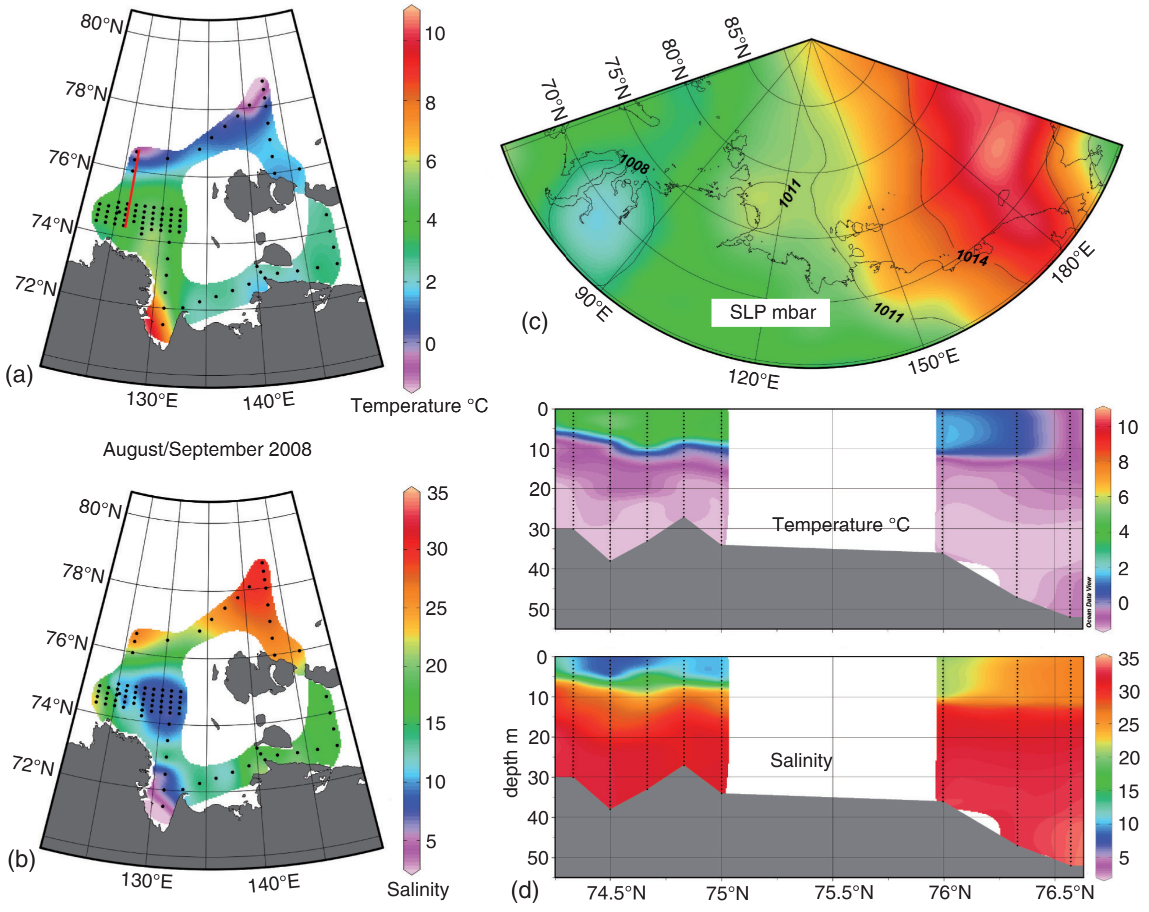

Fig. 3 Spatial distribution of (a) temperature and (b) salinity at 3-m water depth, (c) average sea-level pressure (SLP; US National Centers for Environmental Prediction and National Center for Atmospheric Research reanalysis data for August and September 2008) and (d) cross-shelf transect of temperature and salinity observations during the Transdrift XIV expedition in September 2008. The black dots in (a) and (b) mark the sampling locations. The red line in (a) indicates the position of the oceanographic transect shown in Fig. 2d.

NCEP/NCAR reanalysis data, the average March to May meridional wind speed [v-wind] was ca. 2 m s^{-1} and zonal wind speed [u-wind] was ca. –0.2 m s^{-1}), which forced the drifting sea ice in the Laptev Sea northwards. On 1 June 2007 the western Laptev Sea was already ice-free from the coastal area up to 76°N (Fig. 4). In the eastern Laptev Sea an open-water area stretched out from the northern edge of the land-locked fast-ice belt that still covered the south-eastern Laptev Sea up to 78°N. This ice-free area of more than 150 000 km^2, comprising approximately 30% of the total area that Trešnikov (1985) calculated for the Laptev Sea Shelf, developed in 2007 approximately one month earlier than in 2008 when the open-water area in the eastern and central Laptev Sea on 1 June was less than 25 000 km^2. In contrast to the winter season 2006/07, the polynya activity in 2007/08 was low (Willmes et al. 2011). Although the overall sea-level pressure pattern during March to May 2008 was similar to that of 2007, the average v-wind was only between –0.5 and 0.5 m s^{-1} (NCEP/NCAR reanalysis data).

Evolution of near-bottom water temperature and salinity (September 2007–September 2009)

At both mooring positions (Fig. 1a, b), the records show that low temperatures ($<$–1.6°C) in the near-bottom water lasted until 21 September 2007 (Figs. 5, 6). During the first week of September, bottom water currents to the north-west brought cold bottom water with lower salinities (T $<$–1.6°C, S ca. 32.8–33.0) to the position of KH (Fig. 5). A reversal in bottom water current direction during the second and third weeks of September over a period of north-westerly winds advected a near-bottom water mass with higher salinities ($S > 33.0$) and slightly lower temperatures (ca. –1.7°C) from the

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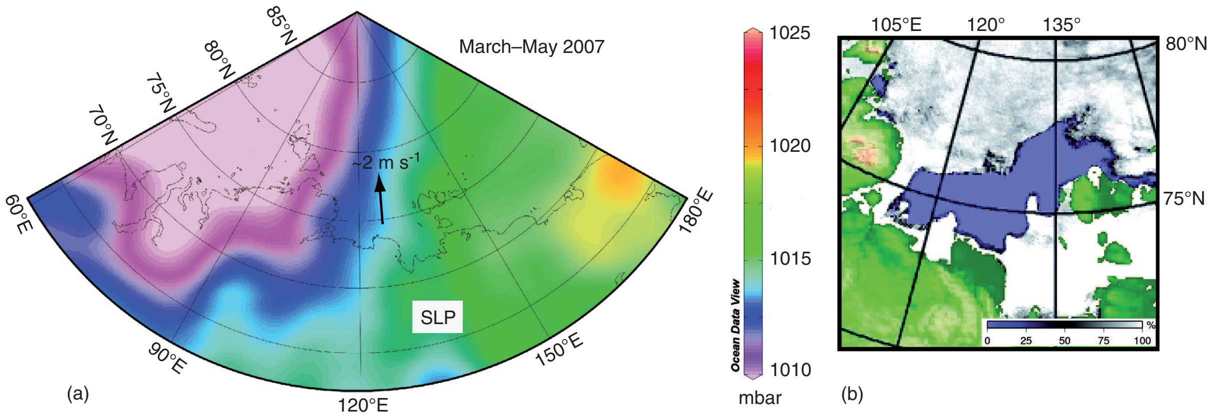

Fig. 4 (a) Average sea-level pressure (SLP) during March to May 2007 (US National Centers for Environmental Prediction and National Center for Atmospheric Research reanalysis data) and (b) sea-ice concentration (Advanced Microwave Scanning Radiometer–Earth Observing System data, calculated using the Artist sea-ice [ASI] concentration algorithm) in the Laptev Sea on 31 May 2007. The black arrow in (a) shows the average wind direction and wind speed during March to May 2007.

north-western Laptev Sea towards the mooring KH (three-day running mean of the meridional [v-] and zonal [u-] wind components is shown in Fig. 6). The recorded temperatures during this period are close to the long-term mean for August to September of –1.55°C (standard deviation [SD] = 0.11°C, number of observations [*n*] = 10) at 38 m water depth.

After 21 September 2007, the NCEP/NCAR reanalysis data show a storm with wind speeds >18 m s^{-1} from the north-west. Current velocities in the upper 10 m of the water column reached 0.7 m s^{-1} towards the south-east on 22 September (Fig. 7, wind speed shown in Fig. 8). Starting on 23 September the water column below a 2- to 3-m-thick wind-driven surface layer with flow directions to the south-east showed a counterflow to the north-west with velocity maxima below 15-m water depth. The ship-based measurements from 29 August to 18 September 2007 demonstrate that the layer with the strongest gradients in velocity and flow direction coincided with the layer of strongest stratification in the Laptev Sea (10–15 m). The observations at KH also indicate that during the storm the level of the layer with strong velocity

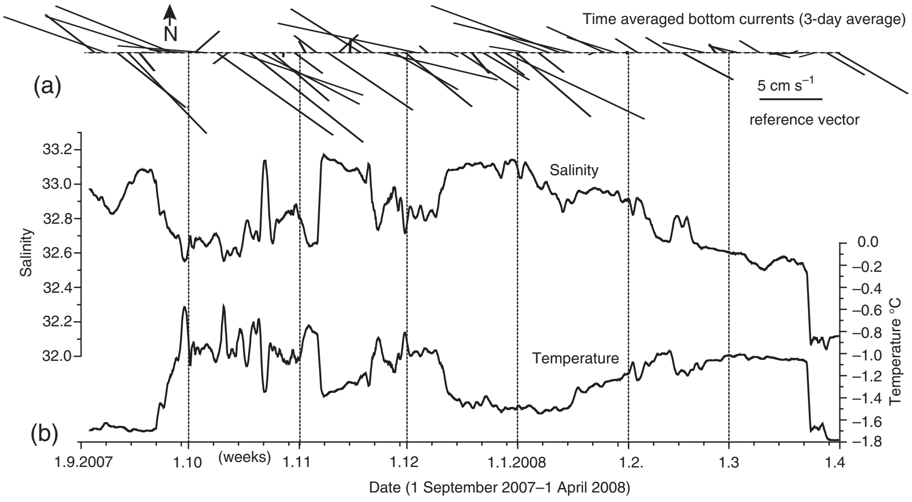

Fig. 5 Seven-month time series of (a) the three-day average of the near-bottom component of velocity (36-m water depth) and (b) low-pass filtered time series (one-day running mean) of salinity and temperature from the KH mooring recorded at 38-m water depth. The observed cooling and salinity increase in the near-bottom water were generally accompanied by an advection of cold and saline bottom water from the western Laptev Sea while warming and freshening resulted from a current from the south-east. The period of alternating warmer/fresher and colder/saltier water masses was abruptly terminated by the simultaneous emergence of a cold and fresh near-bottom water mass and a polynya opening in the last week of March 2008.

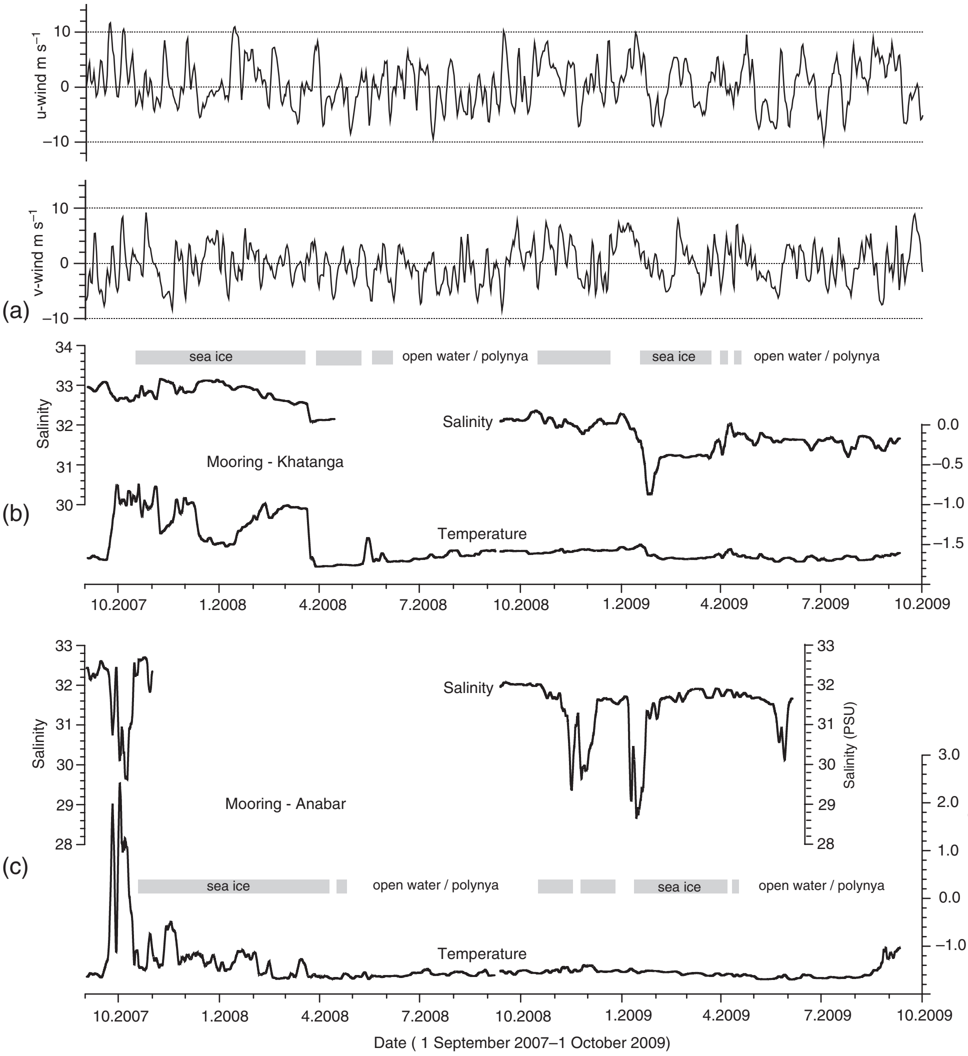

Fig. 6 (a) Zonal (u) and meridional (v) components of the surface wind field at 75°N and 125°E (three-day running mean based on reanalysis data from the US National Centers for Environmental Prediction and National Center for Atmospheric Research) and (b) two-year time series (six-day running mean) of near-bottom salinity and temperature from mooring KH (at 38-m water depth) and (c) mooring AN (29-m water depth until September 2008, afterwards at 27-m water depth). Note the different scales of the temperature axis. Grey bars indicate sea ice above the mooring positions. Only open water/polynya events in the vicinity of the mooring positions (ca. 20 km) that persisted longer than two days were considered. The temperature and salinity data from KH demonstrated that, from the end of March 2008 until the end of the record in September 2009, cold ($<$–1.5°C) and relatively fresh (S $<$32.3) water masses occupied the mid-shelf of the Laptev Sea. Bottom water temperatures and salinities showed only little variability except during periods of large polynya openings in the region of the moorings, which were accompanied by intermittent strong decreases in salinity (November 2008 to February 2009). During spring 2009 (March–May) the bottom water temperature and salinity showed values that are within the range of the historical observations for these months documented in the Russian Arctic and Antarctic Research Institute data set.

gradients shifted down to ca. 22-m water depth. During a second storm from the north-east with wind speeds above 20 m s^{-1} on 4 October 2007, the velocity gradients, and therefore probably also the position of the pycnocline, descended further down to ca. 27 m at KH and reached the near-bottom water (ca. 29 m) at the mooring AN. Because the Laptev Sea becomes unnavigable in the second half of September, no shipboard current, turbulence or CTD observations can be carried out during late September and early October storm events. Since the spatial and temporal resolution of the ADCPs is not adequate to study the vertical current velocity (w) and turbulent processes in detail, we use the standard deviation of the w-current as a proxy for the intensity of vertical current motion of the water column. The comparison between the surface wind speed (NCEP/NCAR reanalysis data) and the standard deviation of w at mooring KH (Fig. 8) shows that the two distinct wind

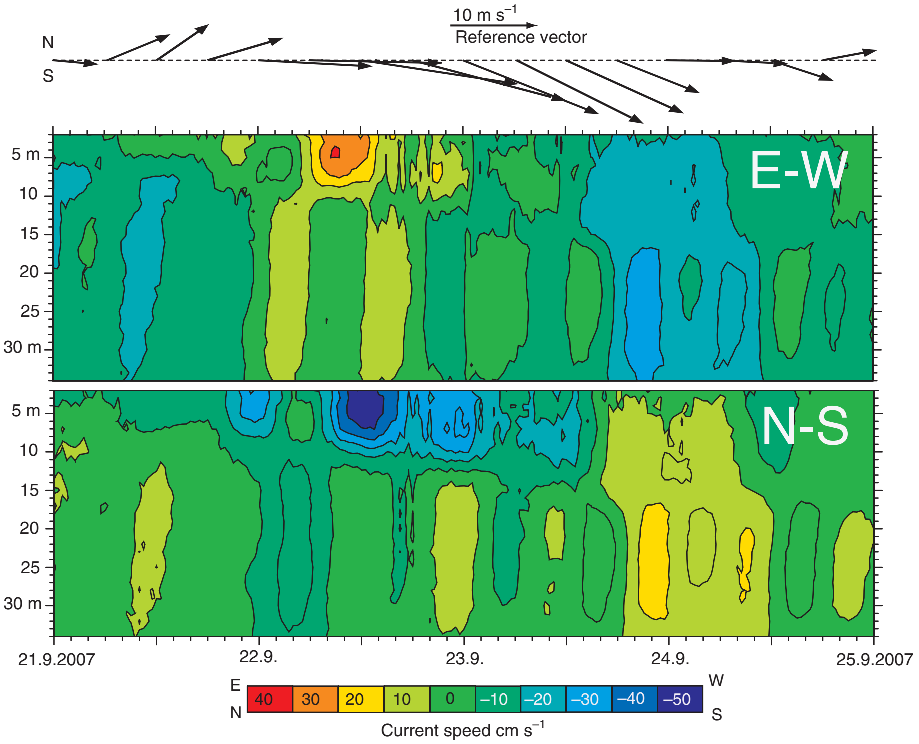

Fig. 7 Surface wind vectors (taken from US National Centers for Environmental Prediction and National Center for Atmospheric Research reanalysis data for 75°N and 125°E) and four-day colour contour profile (2–34-m water depth) of the east–west and north–south component of the currents at mooring KH. Colours indicate the velocity and direction of the current. The strong wind-forcing from north-west (22 September) caused a flow towards the south-east in the surface layer. On 23 September a strong counterflow to the north-west developed in the near-bottom water (15–34-m water depth).

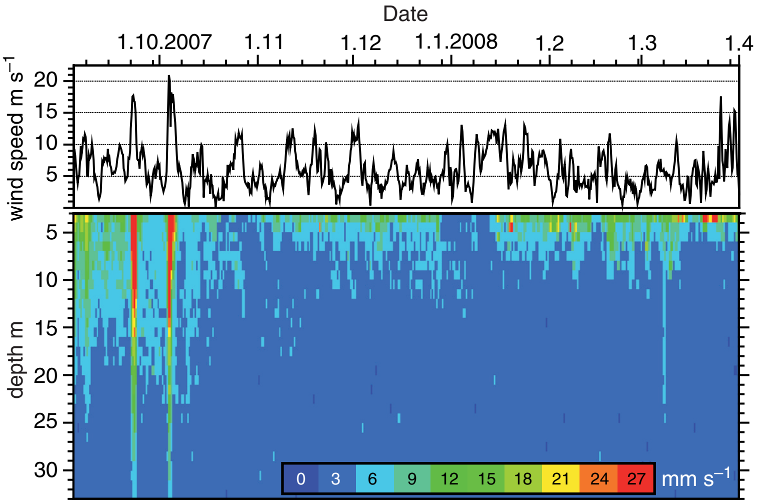

Fig. 8 Surface wind speed (four times daily data from the US National Centers for Environmental Prediction and National Center for Atmospheric Research) and standard deviation of the vertical current velocity (in mm s^{-1}) at mooring KH (upward looking 300 kHz acoustic doppler current profiler) from 3 September 2007 to 1 April 2008. The standard deviation of the vertical current velocity (w) was used as a proxy for the intensity of vertical current motion of the water column.

events in September and October 2007 caused a pronounced increase in the vertical current dynamics down to at least 33-m water depth.

The time evolution of near-bottom water temperature and salinity during the first storm event between 17 September and 27 September 2007 (Fig. 9) suggests that at the position of mooring AN the ca. 15-m-thick water layer below the pycnocline (T = –1.7°C, S = 25.5) was completely mixed with the ca. 14-m-thick surface layer (T = 7.5°C, S = 32.5, shipboard measurements during the first two weeks in September 2007) resulting in a near-bottom temperature of more than 3°C and a salinity below 30. At the mooring KH—deployed in a deeper part of the mid-shelf at 43-m water depth—the storm caused the temperature to increase to a maximum of approximately –1°C and salinities between 32.6 and 32.7 at 39-m water depth. A distinctly higher temperature (about − 0.5°C to 0°C) and lower salinity (ca. 32.5) were recorded at the mooring KH by the unpumped CTD mounted 3 m above the pumped Sea-Bird CTD at 39 m after the storm in October. This indicates that during the storm the depth of the pycnocline at the position of the mooring KH also increased significantly.

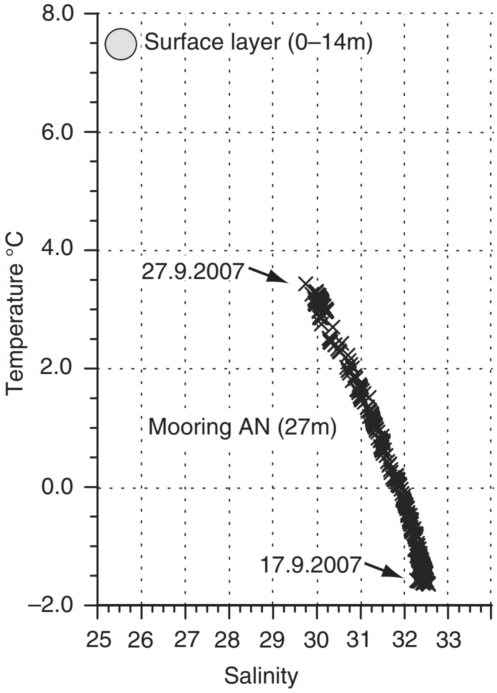

Fig. 9 Time evolution of temperature and salinity of near-bottom water from mooring AN from 17 to 27 September 2007 covering a period of strong winds. The temperature and salinity of the surface layer (shipboard measurement at mooring AN on 31 August 2007) are given as the average of the upper 14 m of the water column. The temperature and salinity properties of the near-bottom water mass on 27 September 2007 indicate a complete mixing of the warm and fresh surface layer (ca. 15 m thick) with the saltier and colder near-bottom layer (ca. 15 m thick) during a storm from 22 to 24 September.

Remnants of the warm near-bottom water mass that formed during September and October 2007 were detectable on the mid-shelf until the end of March 2008 (Fig. 6). At the position of mooring KH warm periods (− 1.2°C < T < –1.0°C) with salinities between 32.5 and 32.9 alternate with periods of lower temperatures (− 1.5°C < T < –1.2°C) and higher salinities (> 32.9). The cooling and salinity increase was caused by advection of cold and saline bottom water from the western Laptev Sea while warming and freshening was a result of a current from the south-east. Similar alteration of warmer and colder bottom water masses was also observed in the bottom water at the mooring AN. Contrary to the mooring KH, warming at AN was usually observed during periods of stronger (> 20 cm s^{-1}) north-easterly current directions in the near-bottom water while cooling was generally associated with weaker (< 15 cm s^{-1}) easterly and south-easterly currents.

A polynya approximately 1000 km in length opened at the fast-ice edge of the Laptev Sea during the last week of March 2008. Above the mooring KH, the polynya reached a width of ca. 50 km on 31 March 2008. The time series at KH (Fig. 7) shows that the period of alternating warmer/fresher and colder/saltier near-bottom water masses was abruptly terminated simultaneously with this polynya opening. During the polynya opening the three-day time-averaged bottom currents showed low velocities, pointing to a more local, polynya-related formation of this near-bottom water mass instead of a long-range advection. Starting with the polynya event until the end of the record on September 2009, cold (< –1.5°C) and relatively fresh (S < 32.3) water masses occupied the mid-shelf of the Laptev Sea with only little variability except during periods of large polynya openings in the region of the moorings, which were accompanied by intermittent strong decreases in salinity (November 2008 and February 2009; Fig. 6). At the beginning of the observational period in September 2007, the near-bottom water salinity was approximately 1 higher than the long-term mean for this region. Two months after the major polynya opening in January 2009 the near-bottom water temperature and salinity was again close to the climatic mean for these months (at KH [*n* = 2] T = –1.62°C, S = 31.6 [SD = 0.34]; at AN [*n* = 7] T = –1.60°C, S = 31.9 [SD = 0.54]).

Discussion

In 2007 southerly winds with an average wind speed of 2 m s^{-1} in March–May advected sea ice northward, creating unusually large areas of open water and thin ice (polynyas) in the Laptev Sea (Willmes et al. 2011). The increase in solar heating of the surface waters due to larger open-water areas at the start of the melt season leads to a further acceleration of sea-ice melt and thus to a feedback mechanism that results in the early appearance of large ice-free areas during summertime. As a result of this sea-ice feedback in 2007, by 1 June the ice-free area had already reached a size (150 000 km^2) that was six times larger than on the same day in 2008 (25 000 km^2), a year with low polynya activity during the preceding winter (Willmes et al. 2011). Because large areas of open water that appear exceptionally early during the year should increase the solar heating of the surface waters (Perovich et al. 2008; Steele et al. 2008), the sea surface temperatures in September 2007 were expected to be higher than in 2008 and also higher than the climatic mean. This assumption was supported by the shipboard oceanographic observations in the eastern Laptev Sea in September 2007, which showed a temperature anomaly of 3–5°C in the upper 10 m of the water column when compared to the climatic mean and the shipboard observations in 2008.

Because most of the Laptev Sea Shelf is ice-free during August and September (Barreis & Görgen 2005), the summer hydrography is mainly influenced by the response of the buoyant river plumes and meltwater to atmospheric forcing (Špajher et al. 1972; Proshutinsky & Johnson 1997; Dmitrenko, Kirillov et al. 2005; Dmitrenko, Kirillov & Tremblay 2008). The summer of 2007 was outstanding in this respect because a pronounced cyclonic atmospheric circulation deflected the freshwater plume of the River Lena to the east, which increased the salinity in the region north of the delta by 10 if compared to the climatic mean. This led to a distinct weakening of the density stratification in this area. In 2008, a summer with a predominantly anticyclonic atmospheric circulation, the buoyant river plume was advected northward. In consequence the surface salinity in the eastern Laptev Sea was close to the climatic mean and the density stratification of the water column was far more pronounced.

Recent observations indicate that although the stratification of the water column in the eastern Laptev Sea is subject to strong seasonal changes a halocline is maintained throughout all seasons (Bauch et al. 2009). Because this density stratification impedes mixing it was speculated that, especially during summer when the halocline is pronounced (Bauch et al. 2009), the strong seasonal variations in temperature in the surface layer would not significantly affect the temperatures near the seabed in the deeper parts (>20 m) of the Laptev Sea Shelf. This assumption was supported by the shipboard observations during the first half of September 2007–08 and by the historical observations that showed no considerable temperature variations on the mid-shelf north of the Lena Delta. The hypothesis that the bottom water temperature on the mid-shelf shows no distinct seasonal variability was also suggested by moored observations of bottom water currents that were recorded in 1998–99 on the mid-shelf north of 75°N at 44-m water depth (Wegner et al. 2005), which showed that the only significant ($>$ 0.1°C) temperature variations during the one-year record were caused by the advection of warmer water from the shelf break.

The analysis of the time-series data of bottom water temperature, salinity and currents on the mid-shelf of the Laptev Sea evidences that during the ice-free period in late September and early October 2007 relatively warm near-bottom water formed at 39-m water depth in consequence of two storms acting on a water column with unusual weak summer stratification. This is in conflict with the hypothesis that the bottom water temperature on the mid-shelf shows no distinct seasonal variability. The time evolution of near-bottom water temperature and salinity during the first storm event between 17 September and 27 September 2007 (Fig. 8) suggests that at the position of mooring AN the ca. 15-m-thick water layer below the pycnocline ($T = -1.7$°C, $S = 25.5$) was completely mixed with the ca. 14-m-thick surface layer ($T = 7.5$°C, $S = 32.5$) resulting in a near-bottom temperature of more than 3°C and a salinity below 30. We assume that this increase is mainly caused by a wind-induced temporary breakdown of the stratification down to 28 m (mooring AN) and an increased turbulent mixing across the pycnocline down to 39 m (mooring KH), which is mainly due to a weaker summer stratification of the water column in 2007. This resulted in a maximum temperature increase of more than 3°C in the shallower parts (28 m) of the mid-shelf and an increase of ca. 0.5°C to a maximum of approximately –1°C at 39 m. The increase in bottom water temperature was accompanied by a distinct decrease in salinity (Figs. 5, 6, 9). The current profiles show that the strong winds to the south-west and south-east in late September and early October 2007 induced a counterflow below the wind-driven surface layer with northerly directions resulting in a distinct velocity gradient and a deviance of current directions in the water column that can probably result in a shear-induced turbulent mixing of the water column that intensifies the mixing of the water column. In fact, the comparison between the surface wind speed (NCEP/NCAR reanalysis data) and the standard deviation of w at mooring KH (Fig. 7) shows that the two distinct wind events in September and October 2007 caused a pronounced increase in the vertical current dynamic down to at least 33-m water depth. This reinforces the suggestion that besides the wind-driven deepening of the surface-mixed layer also distinct velocity gradients in the water column can be a potentially significant source of mid-water mixing, which results in the widening of the pycnocline (Burchard & Rippeth 2009). Observations of mixing processes in the Laptev Sea that were based on mooring records and CTD casts have shown that the breaking of internal waves, particularly at the shelf break and at shoals on the shelf, can also play a significant role in mixing (Zakharchuk 1999; Kirillov 2006).

The time series of the bottom water data did not evidence a seasonal increase of temperature on the mid-shelf of the Laptev Sea during fall 2008, although the wind speeds observed in September and October 2008 were comparable to those observed in autumn 2007 (Fig. 6). This is most probably due to the temperature and salinity structure of the water column north of the Lena Delta, which showed a strong density stratification. This causes a lower probability of mixing on the Laptev Sea Shelf north of the Lena Delta.

Another possible source of warm bottom water on the mid- and outer-shelf is the advection of warm and salty water masses from the continental shelf break of the Laptev Sea (Dmitrenko et al. 2002; Dmitrenko et al. 2009). Nevertheless, the CTD measurements from summer show that only the temperature signal in the cold near-bottom water north of 75°N was influenced by an admixture of the relatively warmer (ca. –1°C) and saltier ($S > 33.8$) water masses from the shelf break.

The relatively warm and fresh bottom water (T ca. -1°C, S ca. 31.6) occupied the deeper part (ca. 40 m) of the shelf north of the Lena Delta until March 2008, interrupted only by episodic advection of cold and saline water from the western Laptev Sea (Fig. 5). Churun & Timokhov (1995) have described that the western Laptev Sea, and particularly the south-western Laptev Sea, is characterized by bottom water masses with low temperatures and high salinities due to intense ice formation from a surface layer initially saltier than in the eastern Laptev Sea. At the mooring AN in shallower water (ca. 30 m), the warm bottom water influenced the region until February 2008. The record at the mooring KH shows that the warm bottom water was replaced by colder and fresher bottom water ($T < -1.7$°C, $S < 31.1$) that appeared abruptly during a polynya opening above the mooring position. The strong decline of near-bottom water temperature and salinity during periods of polynya openings in the eastern Laptev Sea was a common phenomenon during the observational period from September 2007 to September 2009. In particular, the episodic decreases in bottom water salinity (> 2.5) during November 2008 and January 2009 are associated with simultaneous polynya openings above the moorings (Fig. 6). The water column in the eastern Laptev Sea is stratified during winter (Dmitrenko, Kirillov et al. 2005). Even when there are large polynya openings—accompanied by strong ice formation and brine release—the salt flux to the surface water is insufficient to cause a density-driven convective mixing of the whole water column (Dmitrenko, Tyshko et al. 2005; Krumpen et al. in press). In our view, the decrease of near-bottom water salinity that is associated with polynya openings in the Laptev Sea is most probably caused by turbulent mixing of the brine-enriched, but still buoyant, low-salinity surface waters with the more saline near-bottom waters.

Intermittent, short-lived appearances of warmer bottom water are characteristic of the moored record until May 2008. The conductivity sensors at both moorings showed a relative increase of the conductivity during the brief warm episodes, but because biofouling compromised the accuracy of the sensor's conductivity measurements on these occasions we can only speculate about the nature of these events. However, it is plausible to assume that the relatively warm and—after the polynya-induced freshening—relatively saltier water masses are remnants of the warm bottom water mass that formed during autumn 2007.

We cannot draw a conclusion about the frequency of occurrence of warm bottom water events during the last decades. The AARI's historic data set reaches back to the 1920s but oceanographic observations during late autumn and winter are sparse or nonexistent. For the mid-shelf area of the eastern Laptev Sea, the AARI data set includes fewer than 30 observations of bottom water temperatures from January to March. There are no measurements for the important period between November and December. Clearly, the statistical analysis of the historic data set, particularly from late autumn and winter, must be interpreted with caution.

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Conclusions

Our observations demonstrate that in consequence of the unusually high summertime temperatures in the surface layer in the Laptev Sea in 2007, the bottom water temperatures on the mid-shelf increased by more than 3°C compared to the long-term mean and remained warm at least until March 2008. The early retreat of the sea ice in 2007 caused an unusual solar heating of the surface waters in the eastern Laptev Sea. Westerly winds during the ice-free period in August and September 2007 advected the Lena river plume to the east. This reduced the density stratification in the central Laptev Sea so that, during autumn, storms mixed surface and bottom waters. We speculate that further ice reduction in the Laptev Sea will not only cause a persistent change of surface water properties but will also have a lasting effect on the T/S properties of the bottom water. The atmospheric dipole anomaly in 2007 (Wang et al. 2009) with low sea-level pressure north of the Laptev Sea and a high sea-level pressure over the Canadian Archipelago (positive dipole anomaly), which is assumed to be one of the major causes for the record minimum ice cover in September 2007, also caused the westerly winds in the Laptev Sea that led to an increase in surface water salinity and a weakening of the density stratification. A recent study by Simmonds & Keay (2009) demonstrated that the relatively small extent of the sea-ice cover in the Arctic caused the intensity and size of cyclones in the eastern Arctic during September to have increased significantly during the last years, increasing the likelihood of wind-forced mixing of the water column. These findings suggest that the possibility of warming of the bottom water on the Laptev Sea shelf increases during summers with a positive dipole anomaly in the Arctic and a cyclonic atmospheric circulation in the Laptev Sea that follow after a winter with strong polynya activity and an early sea-ice retreat in spring.

The increase of bottom water temperatures may also have an impact on benthic organisms, biogeochemical cycling at the seabed and the stability of the submarine permafrost that covers large areas of the Laptev Sea Shelf (Kassens et al. 2007; Overduin et al. 2007). In contact with relatively warm Arctic saline water (averaging about –1.5°C), the submarine permafrost assimilates heat energy from the seawater. This heat flux leads to a warming of the submarine permafrost close to the thawing temperature of freshwater in the pore space. Results of numerical modelling and temperature measurements from boreholes indicate that the submarine permafrost responds very sensitively to changes applied to the upper boundary condition, in this case seawater (Junker et al. 2008). Since Arctic methane hydrates are permafrost-controlled, they destabilize when submarine permafrost thaws, leading to methane release into the ocean waters and atmosphere. This process has already been described for the East Siberian and Laptev seas (Shakhova & Semiletov 2007; Shakhova et al. 2010).

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