

Extreme Variations of the Arctic Ocean during and after IPY 2007/2008

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Abstract: Large-scale features of Arctic Ocean temperature and salinity distributions observed during 2007-2009 are described and discussed in the context of historical observation in order to document long-term variations. Oceanographic observations carried out in the frame of the International Polar Year (IPY 2007/2008) demonstrated unique conditions in the Arctic Ocean and seas during that period. For example, analyses of upper ocean temperature and salinity patterns 2007-2009 revealed an apparent frontal zone separating the Eurasian and Canadian Basins. We found that after 2007 the temperature and salinity trends of the surface layer of the Arctic Ocean followed the same trajectory as in the past, however their regional distribution and intensity changed. The average salinity in the surface 5-50 m layer of the Eurasian Basin in winter of 2007-2009 was higher than in the 1950s and 1970s, but did not exceed the average salinity in the early 1990s. In the Canadian Basin, the upper ocean salinity in 2007-2009 was much lower than in the 1950s-1960s. Volumetric analysis of water masses demonstrated a general increase of volume of the intermediate (150-900 m depth range) Atlantic Water (AW) temperature, with substantial rise of the upper boundary of the AW. The thermal expansion of AW in the Arctic Basin is unique during the last 20 years. The most distinct variations of the hydrographic conditions were observed in the Canadian Basin. In general, the maximum of the AW temperature decreased in 2009 relative to 2007 and the upper boundary became shallower by 50 to 150 m the Eurasian Basin. The AW salinity in 2007-2009 was not exceptional during the IPY. Observations in the deeper layers indicated that the bottom waters have become slightly warmer and less saline.

Zusammenfassung: Die großskalige Temperatur- und Salinitätsverteilung im Nordpolarmeer zwischen 2007 und 2009 wurde untersucht um im Vergleich mit historischen Daten langfristige Veränderungen aufzuzeigen. Im Verlauf des Internationalen Polarjahres (IPY 2007/2008) und nachfolgend durchgeführte ozeanographische Beobachtungen dokumentieren einzigartige Prozesse im gesamten Arktischen Becken und in den arktischen Randmeeren. So zeigt die Temperatur- und Salinitätsverteilung der Oberflächenschicht in den Jahren 2007-2009 ein deutliches Frontengebiet zwischen dem Eurasischen Becken und dem Kanadischen Becken. Nach 2007 blieben zwar die Temperatur- und Salinitätstrends in der Oberflächenschicht des Nordpolarmeeres dieselben wie zuvor, allerdings änderte sich ihre Intensität und regionale Verteilung. Die mittlere Salinitäten in der oberen Schicht von 5-50 m im Eurasischen Becken waren in den Jahren 2007-2009 im Winter höher als in den 1950er und 1970er Jahren, überschritten jedoch nicht die mittlere Salinität der frühen 1990er Jahre. Im Kanadischen Becken waren die Salinitätswerte der Oberflächenschicht in den Jahren 2007-2009 viel niedriger als in den 1950er und 1960er Jahren.

Eine volumetrische Analyse der Wassermassen zeigt einen allgemeinen Temperaturanstieg des Atlantischen Zwischenwassers im Arktischen Becken (Tiefe 150-900 m), und die obere Grenze der Atlantischen Wassermassen stieg auf äußerst geringe Tiefen an. Die Ausbreitung des warmen Atlantischen Wassers im Arktischen Becken in den vergangenen 20 Jahren ist einzigartig. Besonders ausgeprägte Schwankungen der hydrographischen Bedingungen wurden im Kanadischen Becken beobachtet. Im Jahr 2009 waren die maximalen Temperaturen des Atlantischen Wassers niedriger als 2007 und die obere Grenze des Atlantischen Wassers im Eurasischen Becken lag 50-150 m näher an der Meeresoberfläche. In den Jahren 2007-2009 lag die Salinität des Atlantischen Wassers im Bereich der früher beobachteten Werte und zeigt keine signifikante Veränderung während des IPY. Das Bodenwasser in tieferen Gebieten ist leicht wärmer und weniger salzhaltig geworden.

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INTRODUCTION

The Arctic plays an important role in the global climate system. The Arctic ice cover controls the high-latitude heat balance, reducing the heat exchange between the atmosphere and the ocean and influencing the atmospheric processes through changing albedo (e.g., SERREZE & FRANCIS 2006). Oceanic freshwater transfers across the Arctic reduce the salinity contrast between the Atlantic and Pacific, and thus link large parts of the global ocean system (SERREZE et al. 2006). Export of Arctic ice and freshwater to low latitudes is an efficient regulator for the intensity of large-scale deepwater formation and as such for the global thermohaline circulation (AAGAARD & CARMACK 1994).

Studies from a variety of disciplines document changes in the northern high-latitude environment during the last decades (e.g., LINDSAY et al. 2009, BELCHANSKY et al. 2008, MEIER et al. 2007, POLYAKOV et al. 2005, WALSH & CHAPMAN 2001, STROEVE et al. 2008, COMISO et al. 2008). An intensified warm air inflow from the Atlantic caused an atmospheric pressure decrease, that was not observed earlier and increase of the vorticity of the wind field in the central Arctic in the 1980-1990s (WALSH et al. 1996). The number of the cyclones reaching the Arctic regions from the Northern Atlantic has significantly increased since the end of last century (SERREZE et al. 2000). The frequency of cyclones in the Siberian shelf seas has shown for the period 1983-2004 an average increase of 37 % in summer and 15 % in autumn if compared with the period from 1960 until 1982 (KURAZHOV et al. 2007). The atmospheric circulation regime in the late 1980s changed towards a decrease of the high-latitude zonal index over the circumpolar zone of the northern hemisphere (DMITRIYEV 2007). An analysis of air temperature in the Arctic for the period 1979-1990, that was obtained from drifting buoys, the “North Pole” (NP) stations and coastal monitoring stations has also revealed a warming trend with a rate of up to 1 °C per decade (RIGOR et al. 2000). The warming occurred simultaneously to an increase of the downward ultraviolet radiation (KUANG & YUNG 2000).

The ice cover responded to changes in the atmospheric processes during the 1980s and 1990s by a decrease of the overall volume of polar drifting ice. This was caused by a decrease of the areal extent of the sea ice of about 3 % per decade (PARKINSON et al. 1999), and a reduction of Arctic sea-ice thickness by 1.3 m since the 1960s (ROTHROCK et al. 1999). The sea-ice extent of the Arctic seas, which has increased since the 1960s began to decrease rapidly by the end of the last century (FROLOV et al. 2007).

The sign of the average salinity trend in the surface layer changed: whereas increasing salinity was observed in the Canadian Basin (Fig. 1) from 1950 to 1989 freshening occurred in the following years. In contrast freshening in the transarctic drift zone changed to increasing salinity (GUDKOVICH et al. 2004). STEELE & BOYD (1998) documented the salinity increase in the surface layer of the Eurasian Basin and the thinning of the Arctic cold halocline. There was an increased inflow of intermediate water of Atlantic origin (AW) along the continental slope of the Eurasian Basin deep into the Arctic Ocean and further to the Canadian Basin (QUADFASSEL et al. 1991, CARMACK et al. 1995), causing a displacement of the frontal area between waters of Atlantic and Pacific origin in the central Arctic (CARMACK et al. 1995, McLAUGHLIN et al. 1996).

In the late 1990s, temperatures of the AW layer were back to their climatologic values (e.g., MORISON et al. 2006). The annual surface air temperature anomalies within the 72-85° N zonal belt relative to 1893-2004 began to increase from zero in 1999 to 1.1 °C in 2000. In 2005, the anomaly reached a record maximum of 1.8 °C (3.6 σ) (KURAZHOV et al. 2007, FROLOV 2011). In 2002, a record minimum in the Arctic sea-ice extent and area was documented (SERREZE et al. 2002) and in 2005, a record minimum in sea-ice extent was observed in the Arctic marginal seas (FROLOV et al. 2007). Beginning from 2003-2004, the AW temperature in the Eurasian Basin began again to increase to values never observed before. A large AW temperature increase looked like as if a new step of Arctic warming has been taken (POLYAKOV et al. 2005). 2007 was even more extreme. Starting in spring 2007, meridional winds from the south dominated the wind regime in the region of the coasts of Siberia and Alaska, resulting in high positive anomalies of air temperature in the Arctic reaching in August +8 °C

(FROLOV 2011). Heat fluxes to the ice and wind forcing caused an intense melting of sea ice, the breaking of ice into smaller floes, and a rapid retreat of the ice edge to the north. As a consequence the areal extent of the ice cover in the Arctic Ocean was reduced to an extremely low value (STROEVE et al. 2008, FROLOV 2011). The strongest decrease of the sea-ice extent was observed in the Canadian Basin. In the Pacific part of the Arctic Ocean, a large area, which was previously covered with drifting ice, became ice-free. The seasonal ice retreat broke all historic records since the beginning of instrumental observations (e.g., COMISO et al. 2008, STROEVE et al. 2008).

Although anomalous atmospheric forcing was clearly an important factor in the 2007 sea-ice reduction (ZHANG et al. 2008), the changes might not have been as dramatic if the Arctic ice had not been weakened over the several preceding decades. A sea-ice thinning in the central basin of about 1 m during the period from 1987 to 1997 has been reported by ROTHROCK et al. (2003). In addition to this thinning, the perennial ice fraction observed in March declined from roughly 5.53 10^6 km² in 1970 to 4.03 10^6 km² in 2002 and further to 2.63 10^6 km² in 2007 (NGHIEM et al. 2007) This observed reduction in Arctic sea ice is a result of a complex interaction between the dynamics and thermodynamics of the atmosphere, the sea ice, and the ocean (POLYAKOV et al. 2011).

The causes of the dramatic reduction of the Arctic ice cover in 2007 and during the following years have been examined in many publications (see references in ARCTIC REPORT CARD 2011). But fewer publications are concerned with the hydrography of the Arctic Ocean itself. The present paper reviews observational evidence of the high variability of the Arctic Ocean during the last decade. While acknowledging that sea

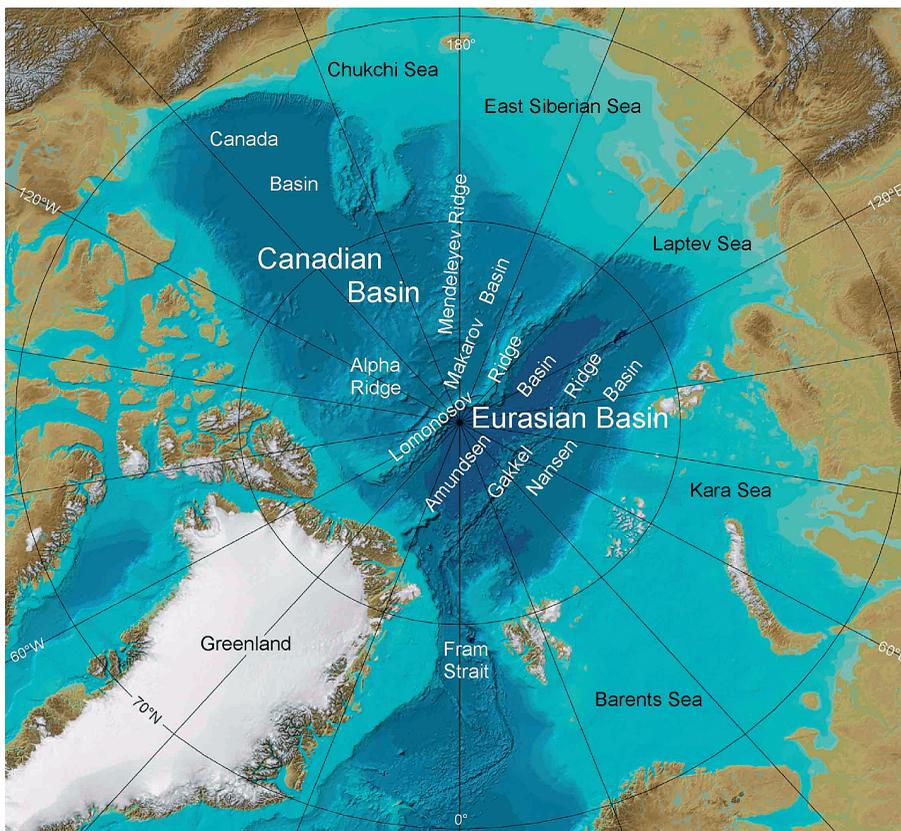


Fig. 1: Outline map of the Arctic Ocean showing major structural units and names referred to in the text. The Arctic Ocean basin is divided into the Eurasian and Canadian basins by the Lomonosov Ridge. The Eurasian Basin includes Nansen and Amundsen basins separated by the Nansen Gakkel Ridge, roughly parallel to the Lomonosov Ridge. The Canadian Basin is divided into the Makarov and Canada basins by the Alpha-Mendeleyev ridges. Map source: <www.ibcao.org>

Abb. 1: Der Arktische Ozean in der Übersicht mit den wesentlichen Struktureinheiten, auf die im Text Bezug genommen wird. Kanadisches Becken und Eurasisches Becken werden durch den Lomonosovrücken getrennt. Das Eurasische Becken umfasst das Nansenbecken und Amundsenbecken, die vom Gakkelrücken getrennt werden. Das Kanadische Becken wird vom Alpha-Mendeleyewrücken in Makarowbecken und Kanadabecken unterteilt. Kartenbasis: <www.ibcao.org>

ice as well as land, ocean and atmosphere processes and feedbacks are important in establishing the current state of the Arctic environment and its future development (ARCTIC IN RAPID TRANSITION 2011) here we focus on extreme changes of the Arctic Ocean in 2007-2010. The first part of the article presents observations of extreme variations of the Arctic Ocean thermohaline structure and discusses their causes. The second part analyzes tendencies of the present thermohaline state of the water masses in the Arctic Ocean. In the third part, current fluctuations of the thermohaline structure are investigated in the context of the changes in 1950-1993. Conclusions are given about the significance of the extreme thermohaline state of 2007 in comparison to past states of the Arctic Ocean. In addition, problems of evolution (development) of the ocean state and extreme changes of 2007-2010 are discussed.

DATA AND METHODS

In this study, we used the AARI hydrography database and products of data objective analysis. Before 1948 only episodic observations exist. 1948 was the first year when the entire Arctic Ocean was covered by observations based on systematic winter (March-May) aircraft expeditions and year-round drifting stations. The aircraft-based program peaked in the 1970s, when seven hydrographical surveys covered practically the entire Arctic Basin and the majority of the Arctic seas (FROLOV et al. 2005). In the 1990s, icebreakers and submarines provided high-quality measurements covering vast areas of the central Arctic Ocean. A significant increase of oceanographic observations was achieved in the 2000s, culminating during the International Polar Year 2007-2008. The temporal distribution of the combined set of hydrographic stations for the years 1948-2011 that cover the Arctic Ocean seaward of continental shelves is given in Figure 2.

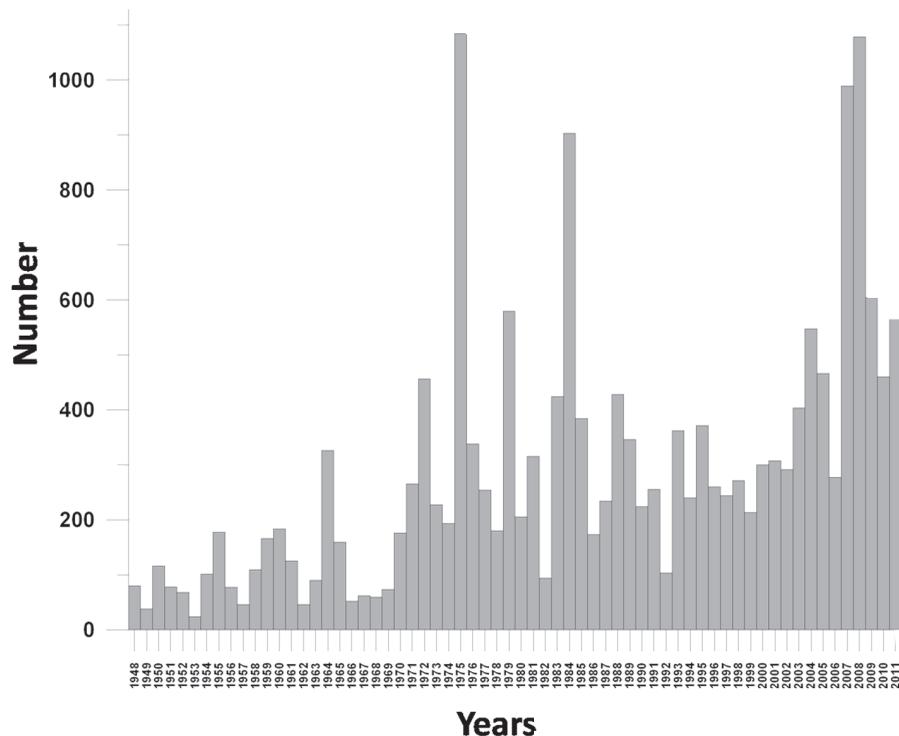


Fig. 2: The temporal distribution by year of the combined set of hydrographic stations for the years 1948-2011 seaward of continental shelves. Observations of ice-tethered profilers (ITP) were used for the middle of each month.

Abb. 2: Anzahl der ozeanographischen Messstationen im Arktischen Ozean jenseits der Schelfkante für den Zeitraum 1948 bis 2011. Positionen der mit dem Meereis verbundenen Driftbojen (ITP) sind jeweils die der Monatsmitte.

The number of oceanographic stations for different months and seasons for the years 1948-2011 shows distinct maxima: March and September (Fig. 3). Based on these statistics of seasonal observations we use the following scale of temporal averaging for the Arctic Ocean. We chose the period March to May as the standard winter analysis period. The period July to September was used as the standard summer analysis period (TANIS & TIMOKHOV 1998).

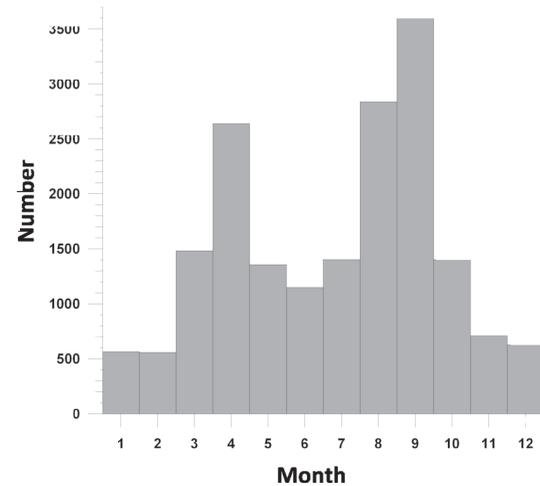


Fig. 3: A histogram of the number of oceanographic stations for different months for the years 1948-2011 in the deep Arctic Ocean.

Abb. 3: Anzahl der ozeanographischen Messstationen im tiefen Arktischen Ozean und zeitliche Verteilung im Jahresgang mit deutlichen Maxima im Winter (März bis Mai) und Sommer (Juli bis September).

To illustrate the spatial distributions of the hydrographic data we plotted maps of station locations in winter and summer for the period 2007-2011 (Fig. 4a,b) and period 1970-1979 (Fig. 4c,d). There is a difference of observational coverage between 2007-2011 and 1970-1979. More observations were carried out the summer period and fewer during winter in the period 2007-2011.

Most temperature and salinity observations prior to the mid-1980s were made at selected depths (levels) in a vertical profile with samples collected using Nansen bottles (bathymetric or bottle series) and with CTD-instruments. Russian (Soviet) expeditions carried out on the drift ice used the lightweight AARI bottles, which were a modification of the classical Nansen bottle. The geographical coordinates of Soviet stations were determined before 1970 using dead reckoning and celestial navigation methods. The effective accuracy of position coordinates was from 1 to 10 minutes of latitude. Measurements of temperature and salinity were carried out at standard depths (in meters below the ocean surface) of 5, 10, 25, 50, 75, 100, 150, 200, 250, 300, 400, 500, 750, 1000, 1500, 2000, 2500, 3000, 3500, ..., bottom. Typical measure-

ment errors are 0.01 °C for temperature and 0.02 for titrated salinity. The comparison of the Russian and western data reveals that mean multi-annual values for both temperature and salinity are in close agreement (TANIS & TIMOKHOV 1998). The best correlation was obtained for the Canada Basin Abyssal Plain largely because the number and period of the Russian and western observations were comparable. The multi-annual mean values for the layer 1000 m to the ocean bottom are in close agreement for all three selected regions. POLYAKOV et al. (2003) found that these data define the Atlantic Water characteristics quite accurately.

After the 1970s, coordinates were determined using radionavigation systems of the "Magnavox" and "GPS" types, allowing the determination of ship location or aircraft landing site with accuracies from 50 to 500 m. More recent oceanographic measurements were made using CTD instruments, which have increased vertical density and accuracy of temperature (0.001 °C) and salinity (0.003) measurements.

For comparison purposes we use in this study "The Joint U.S.-Russian Atlas of the Arctic Ocean" for the winter (1997) and

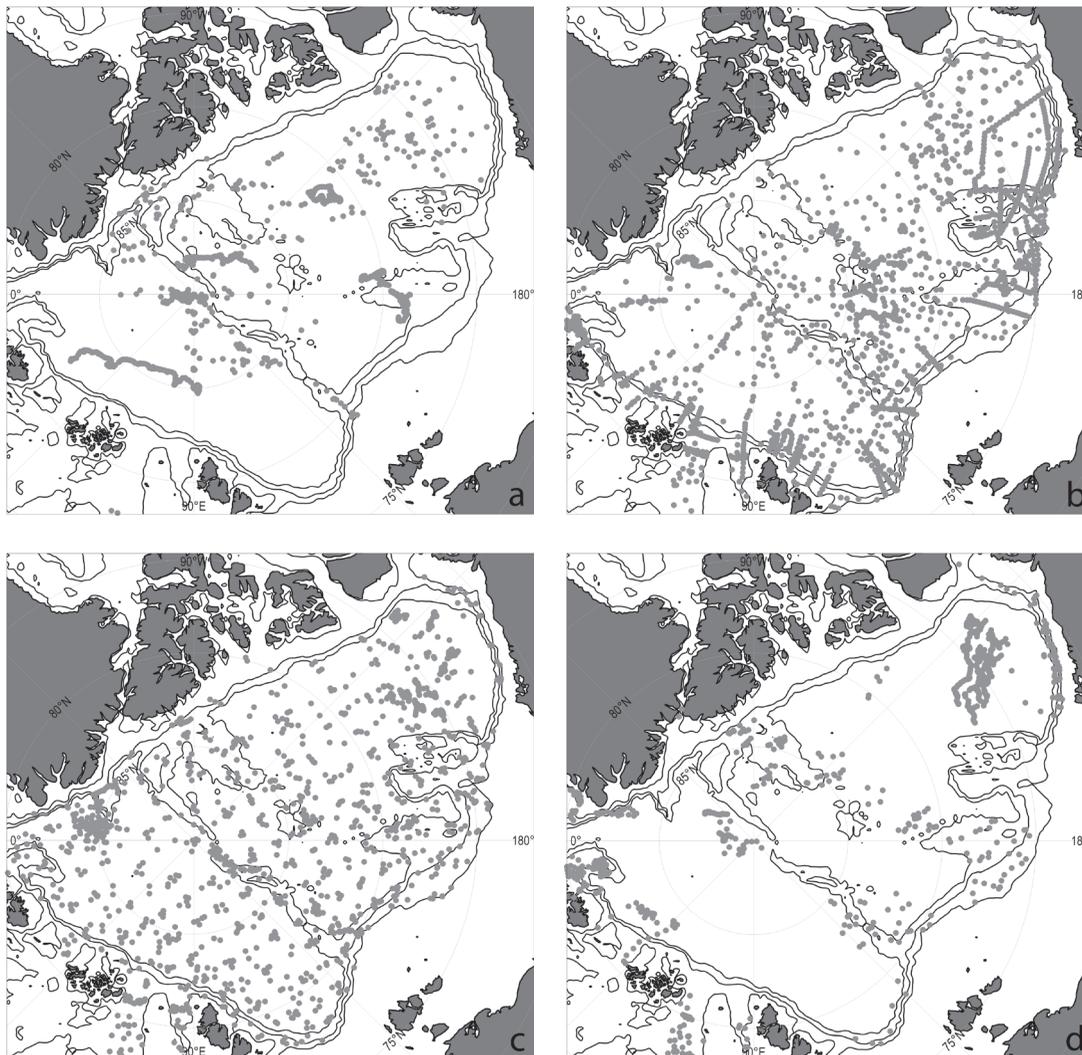


Fig. 4a-d: Location of hydrographic stations in winter and summer for the periods 2007-2011 (a and b) and 1970-1979 (c and d) respectively. Positions of ice-tethered profiler (ITP) drifters in 2007-2011 were shown for a middle of the each month.

Abb. 4a-d: Verteilung der hydrographischen Stationen im Winter und im Sommer für den Zeitraum 2007-2011 = 4a, 4b und 1970-1979 = 4c, 4d. Aus den Positionen der Meereis-Driftstationen (ITP) in den Jahren 2007-2011 wurden monatliche Mittelwerte gebildet.

summer period (1989)” (TANIS & TIMOKHOV 1998) The Arctic Oceanography Atlas contains 50-km gridded data at 23 standard levels, averaged for period 1950-89 and decades 1950-59, 1960-69, 1970-79, 1980-89. Together with mean ocean temperature and salinity fields, the Arctic Oceanography Atlas provides basic statistic such as water temperature and salinity standard deviations.

While preparing the Arctic Oceanography Atlas the spectral method for objective analysis developed by POKROVSKY (1984) was used as the basic method for obtaining the decadal climatic fields of temperature and salinity at the nodes of a regular grid. Among the methods used in the preparation of the Atlas the spectral method for objective analysis provided the best results in comparison with four other Russian and American methods for recovering the temperature and salinity characteristics during test experiments. In addition, this method appears to be the only one able to reconstruct the oceanographic fields from the observations during the summer period, when the data over the essential part of the center of the Arctic basin were absent. Another advantage of the method lies in the provision for the fields of reconstruction errors. This method reconstructs the annual fields within each analysis decade based upon the temporal and spatial empirical orthogonal functions (EOF) (POKROVSKY 1984, TANIS & TIMOKHOV 1998).

The spectral method, the method of principal components, uses the basis of the EOF for the expansion of spatial fields. This method was productively used by SMITH et al. (1986) for the reconstruction of the historical sea surface temperatures, by WEARY et al. (1976) for an analysis of the surface temperature fields in the Pacific Ocean, by SHEN et al. (1994) to analyze the mean fields and by (KOLTYSHEV & TIMOKHOV (1998) for recovering the fields of dynamical heights in the Arctic basin. With the use of the oceanographic database, the Arctic Ocean temperature and salinity fields for the winter period 1950-1993 were reconstructed and we obtained a continuous series of the grid values of characteristics at standard depths (POKROVSKY & TIMOKHOV 2005). This product was used to produce climatic mean winter temperature and salinity fields for the period 1950-1993 at standard depths as well as mean fields for upper layer (5-50 m) and Atlantic water layer.

The temperature and salinity fields of 2007-2010 were constructed from the data using a standard interpolation method. A volumetric TS-analysis was performed following WALSH et al. (2007).

To compare with historical data we used temperature and salinity observations 2007-2010 at standard depths. Mean temperature and salinity of each layer was calculated using records 2007-2010 at the standard levels. This procedure allowed us to minimize an influence of the inhomogeneous modern and historical data sets on the results of the comparative analysis. The temperature and salinity anomalies were calculated as differences of observed values and average climatological values.

UNIQUE FRESHENING AND SALINITY INCREASE AND WARMING OF THE ARCTIC OCEAN IN 2007

The analysis of the observational data revealed the following conditions. At the beginning of spring the temperature measured in the surface layer in the southern part of the Makarov Basin by the “TransArktika-2007” expedition onboard the nuclear icebreaker “Rossiya” on 5 June 2007 was only several hundredths of degree higher than the mean multiyear values (Tab. 1). But already in the second part of June, signs of an anomalous development in the Arctic Ocean (AO) were visible. On 15 June the water temperature measured in 5 m depth at the drifting “Ice camp 2007” station between the Lomonosov Ridge and Chukchi Rise at the position 81° N, 170° E (Canadian Basin) was -1.42 °C. This is close to the summer maximum of the seasonal variations of NP-22, which drifted in this region in 1980. The highest temperature of the entire historical observation period of the Arctic Basin was +4.15 °C recorded at the 5 m depth level where a climatological value of -1.5 °C was determined. It was measured on 31 August 2007 by the expedition onboard the “Akademik Fedorov” in the southern part of the Mendeleyev Ridge (Tab. 1, item 4). This temperature anomaly was accompanied by a significant freshening with a salinity anomaly of -2.25. An even bigger surprise was a TS-record on 21 September onboard the “Viktor Buinitsky” at the continental slope near the Lomonosov Ridge (Tab. 1, item 5) that showed

		Temperature (°C)			Salinity		
		Measured	Average climatic	RMS deviation	Measured	Average climatic	RMS deviation
1	05 June 2007, a/ib “Rossiya“ 168.5 E, 81.3 N	-1.52	-1.6		–	–	
2	15 June 2007, Ice camp-2007 169.8 E, 81.1 N	-1.42	-1.6	+/- 0.25	28.06	30.25	+/- 0.45
3	10 July 2007 Ice camp-2007 170.4 E 82.1 N	-1.38	-1.6	+/- 0.25	27.52	30.25	+/- 0.45
4	31 August 2007 R/V “Akademik Fedorov” 173.4E	4.15	-1.56	+/- 0.35	27.20	29.75	+/- 0.38
5	21 Sept. 2007, R/V “V. Buinitsky” 142.5E 79.8 N	2.32	-1.50	+/- 0.50	27.77	29.40	+/- 0.75
6	05 August 2007 R/V “Akademik Fedorov” 47.3E	-1.69	-1.56	+/- 0.35	33.79	32.40	+/- 0.38

Tab. 1: Water temperature and salinity at the 5 m level measured at six oceanographic stations throughout the spring-summer season of 2007 in the Canadian Basin (items 1-5) and Eurasian Basin (item 6), average climatic values and RMS deviations of characteristics at the station points.

Tab. 1: Wassertemperatur und Salinität in 5m Tiefe auf sechs ozeanographischen Stationen während der Frühlings-/Sommersaison 2007 im Kanadischen Becken (Zeilen 1-5) und im Eurasischen Becken (Zeile 6).

high positive water temperatures up to $+2.32\text{ }^{\circ}\text{C}$ (at a multiyear average of $-1.5\text{ }^{\circ}\text{C}$). A temperature anomaly with a salinity as low as 27.77 (at a multiyear average of 29.40) was never observed before in this region. It is known from past observations that ice melting ends at latitudes near 80° N by about 22 August and after mid September the transition to winter condition starts (GOLOVIN et al. 1993). An analysis of spring to summer conditions in 2007 has shown that the duration of the heat accumulation and freshening phase in the surface layer caused by ice melting in the area of Makarov Basin (at 80° N) lasts longer than three months. The seasonal range of the water temperature in summer of 2007 was $4.0\text{ }^{\circ}\text{C}$, which is 15 to 20 times larger, compared to average values for this region while the seasonal variation of salinity was in the range of 2.0-2.5, which is five times greater than the average variability in the region. So, compared to the climatological means, the development of spring conditions in the Canadian Basin began earlier and the end of the summer conditions was shifted to later dates.

A different situation was observed in the surface layer of the Eurasian Basin. In early August salinity at the 3 m level to the north of the Franz Josef Land at the center of the Nansen Basin (Tab. 1, item 6) was up to 1.39 higher than the mean climatological value or 3.7 times larger than the RMS deviation. During the same time the water temperature was colder than the multiyear average by $0.13\text{ }^{\circ}\text{C}$.

In order to identify the spatial distribution of the differences between the temperature and salinity recorded in the summer of 2007 and the climatological averages, the anomalies for the 5-10 m layer water temperature and salinity were calculated and their distribution patterns were constructed for the entire AO area. We like to point out that for the construction of the charts the observation data for August to October were used, since as mentioned above, the characteristic summer conditions also continued in 2007 into October.

The distribution of summer surface temperature and salinity anomaly in 2007 is presented in Figure 5. Of special interest is

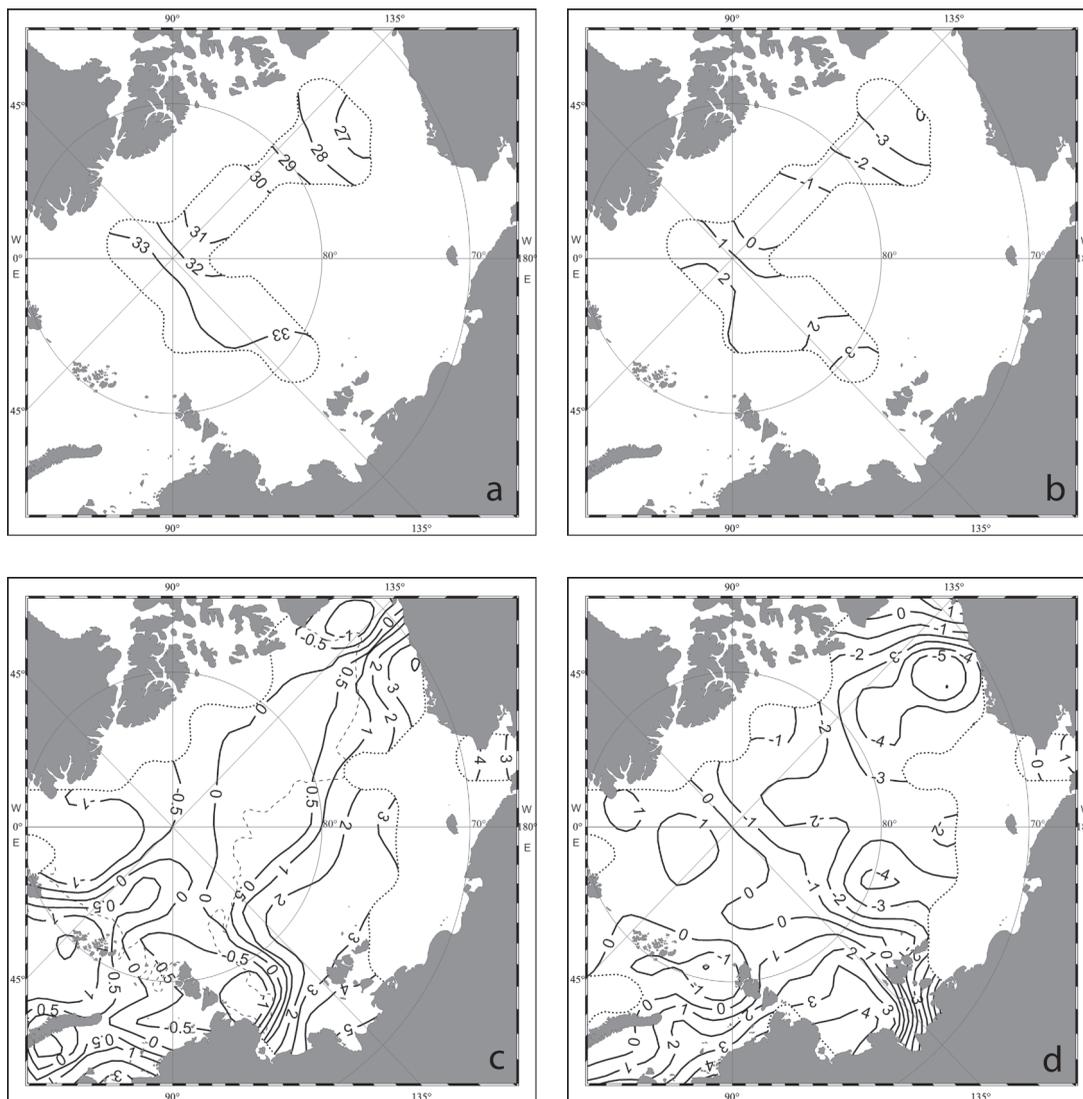


Fig. 5a-d: Distribution of average water salinity in the 5-10 m layer (a) and its anomalies (b) in winter (January-April) 2007, summer water temperature (c) and summer salinity anomalies (d) in 2007 relative to the 1950-1989 series. The dashed line on Fig. 5c denotes the ice edge position.

Abb. 5a-d: Verteilung des mittleren Salzgehalts in der Wasserschicht 5-10 m (5a) und ihrer Anomalien (5b) im Winter (Januar-April) 2007 und der sommerlichen Wassertemperatur (5c) und der sommerlichen Salzgehaltsanomalien (5d) 2007 im Vergleich zur Zeitreihe von 1950-1989. Die gestrichelte Linie in Abb. 5c markiert die Lage des Eisrandes.

a large contrast of the anomalies between the Eurasian and Canadian basins. In the surface layer of the Canadian Basin extremely high water temperatures were observed in summer of 2007 and large positive anomalies of +3 °C occurred. The area occupied by water with a temperature above -1.0 °C, was almost two times larger than the climatological mean. In the central part of the Eurasian Basin, the temperature anomalies ranged from -1.0 °C to +1.0 °C. With anomalies up to +2 °C which were recorded in the northern parts of the Barents and Kara seas the surface layer temperature in this region was much higher if compared to the climatological mean. Also in the eastern part of the Laptev Sea positive anomalies of +2 to +5 °C were observed in the 5-10 m layer.

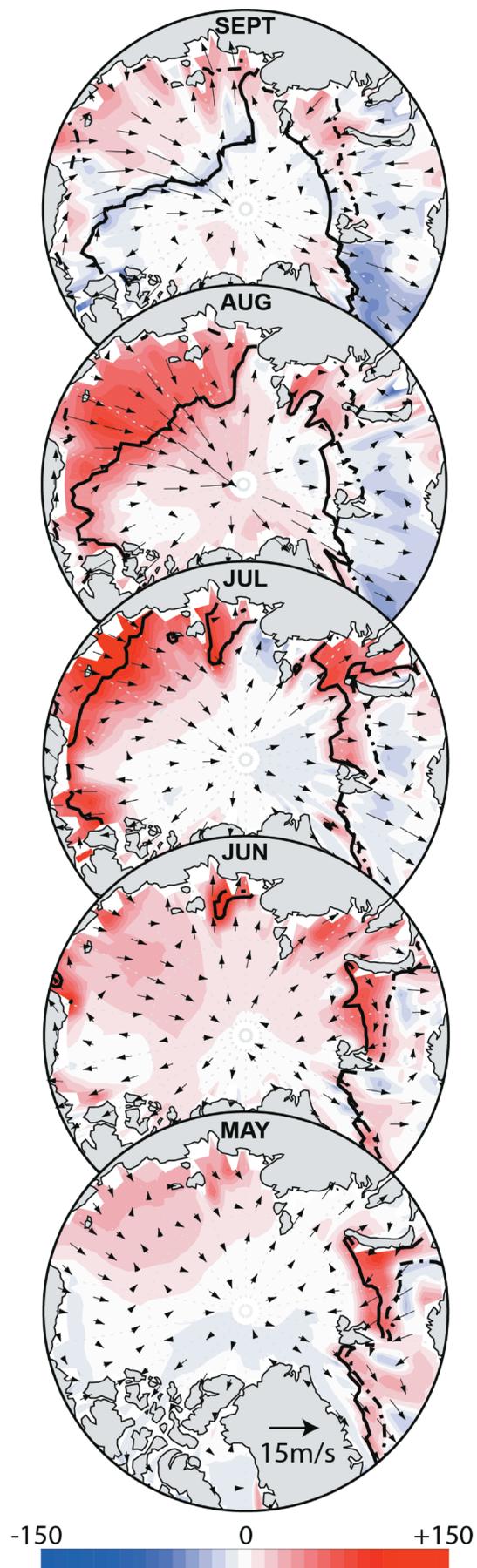
Also extreme salinity values were observed in the surface layer. In the Canadian Basin in summer of 2007, two extensive areas of large negative anomalies (surface layer freshening) from -4 to -6 were identified. The first area was located in the southern part of the Makarov Basin and the adjoining part of the Siberian shelf with a center at 80° N and 160° E. The second area was located in the Canadian Basin. Two small zones display exceptionally positive salinity anomalies. The first zone was located in the southeastern Chukchi Sea. Here the salinity increase was presumably connected with an intensive inflow of relatively high saline water of Pacific origin through the Bering Strait (WOODGATE et al. 2010). The second zone was located in the southeastern Beaufort Sea and the adjoining Amundsen Bay. This zone of positive salinity anomaly was probably formed due to a westward shift of the Mackenzie River freshwater plume.

On the contrary to the Canadian Basin, over much of the Eurasian Basin, a salinity increase of the surface layer was observed with positive anomalies of up to 2 in the central part of the basin, and in the central Laptev Sea up to 6. A zone of positive salinity anomalies was located from Fram Strait to the Laptev Sea, being formed primarily due to the influence of the underlying water of Atlantic origin (the so-called "Atlantic water footprint"). In the southeastern Laptev Sea as a result of eastward shift of river water flow, a small zone of negative salinity anomalies was formed. A zone of freshening in the northwestern Kara Sea was formed as a result of intensive ice melting and outflow from the Kara Sea to the Arctic Basin in September 2007 (FROLOV 2011).

What has triggered such a formation of hydrological anomalies in the Arctic during the summer of 2007? We suggest that one of the main causes of the formation of anomalies in the AO surface layer was an exceptional regime of the atmospheric circulation in agreement to MORISON et al. (2012) for example. Beginning with spring, the southerly winds prevailed

Fig. 6: Monthly mean atmospheric circulation (vectors m s^{-1}) and anomalous net atmospheric heat fluxes (colour, W m^{-2}) in summer 2007. Solid lines show monthly-mean positions of ice edge in 2007; dashed-dotted lines show climatologic mean ice position. Strong summer winds from Siberia pushed the ice edge far northward, pumping atmospheric heat into the upper ocean (BEKRYAEV et al. 2010).

Abb. 6: Monatliche Mittelwerte der atmosphärische Zirkulation (Vektoren m s^{-1}) und Anomalien der atmosphärischen Wärmeflüsse (farbige Schattierung, W m^{-2}) im August 2007. Durchgezogene Linien = monatliche Mittelwerte der Eiskantenlage. Gestrichelt-punktierte Linien = klimatologische Mittelwerte der Lage der Eiskante. Starke sibirische Sommerwinde trieben die Eiskante weit nach Norden und erwärmten die Oberflächenschicht des Ozeans (BEKRYAEV et al. 2010).



in this region and a large positive air temperature anomaly was observed reaching $+8\text{ }^{\circ}\text{C}$ in August. Figure 6 presents a chart of monthly average wind speeds and directions for June-September and the surface heat fluxes values to the ocean. It demonstrates that the areas of the largest heat fluxes from the atmosphere to the ocean surface were located in the Chukchi and East-Siberian seas where the southerly winds were also observed. The heat fluxes and wind forcing caused intense melting, ice decay and a rapid ice edge retreat to the north. In the Pacific part of the AO, a vast area that was usually covered by drifting ice has become ice-free. In late September the ice margin retreated far to the north reaching 87° N in some places. Formation of a vast ice-free water area contributed to significant heating of the surface water layer. Ice mass balance observations demonstrated that there was an extraordinarily large amount of melting on the bottom of the ice in the Beaufort Sea in the summer of 2007 (PEROVICH et al. 2008).

The increase of the open water fraction resulted in an increase of the solar heat input to the upper ocean by a factor of 5, triggering an ice-albedo feedback and contributing to the acceleration of the ice retreat (PEROVICH et al. 2008). Experiments with a model for estimating the role of ice dynamics and heat gain from the atmosphere showed a decisive influence of the second factor in formation of an anomalous reduction of the ice covered area in September 2007 (SHUTILIN et al. 2009).

The atmospheric forcing in summer of 2007 was the dominant, but not the only factor responsible for the unique ice situation. The fact that the ice thickness in the AO in the last years was already much thinner if compared to the mean climatological value also contributed to rapid melting of the ice cover according to e.g. (POLYAKOV et al. 2010). The shift of the anticyclonic ocean gyre in the eastern Arctic Basin influenced the intensification of ice export from the Chukchi, East Siberian and Beaufort seas. In recent years, the anticyclonic gyre moved southward from the center of the Canadian Basin and its intensity has increased. This accelerated the ice export along the periphery of the anticyclonic gyre, which was directed towards the Canadian archipelago (FROLOV 2011).

As a consequence of the abovementioned processes the hydro-meteorological conditions in the Arctic developed during the International Polar Year (IPY) 2007-2008 in a way, which was not observed before. In the surface layer, large contrasts of temperature and salinity were formed. A general increase of Atlantic water temperature in the Arctic Basin was recorded. The upper boundary of the Atlantic Water has risen upward and reached a depth minimum in reference to the available time series. The most distinct changes of the hydrographic conditions were observed in the Canadian Basin.

VARIATIONS OF THE WATER MASS PROPERTIES IN THE ARCTIC OCEAN

In the following, we discuss the modification of the thermohaline structure on the basis of the vertical temperature and salinity profiles from the summer of 2007 recorded at two oceanographic stations in the Eurasian Basin and Canadian Basin (Fig. 1). As a reference the average climatological profiles and ranges of temperature and salinity variations are shown in Figure 7. An analysis of the two stations shows that

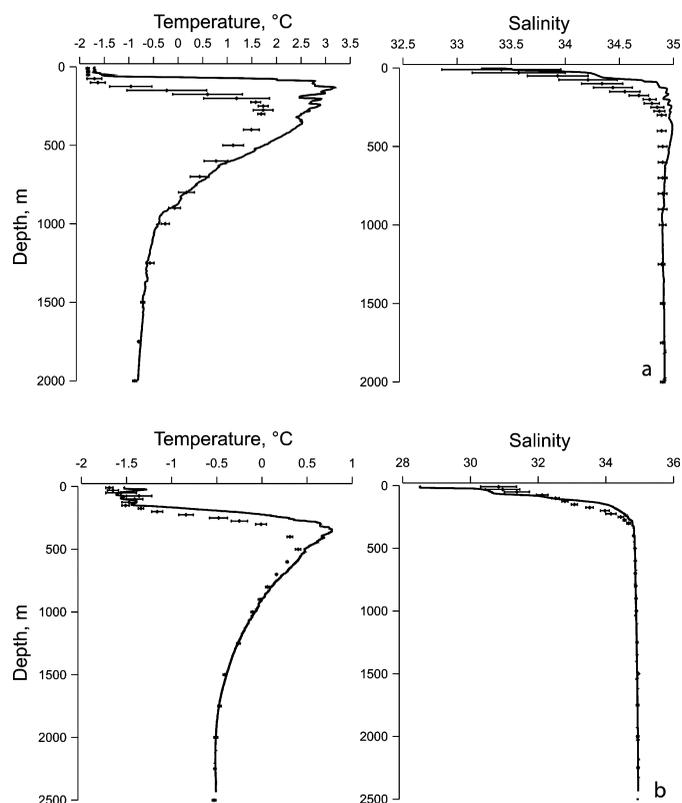


Fig. 7: Temperature and salinity profiles (bold lines) at two oceanographic stations in the Eurasian Basin = (a; $82^{\circ}11.4'\text{ N}$, $97^{\circ}17'\text{ E}$) and the Canadian Basin = (b; $82^{\circ}53'\text{ N}$, $145^{\circ}06'\text{ W}$). Black dots denote average climatological values and lines denote standard deviations of corresponding characteristics from climatological averages. Horizontal dashed lines show upper and lower boundaries of the Atlantic Water (AW) in 2007.

Abb. 7: Temperatur- und Salzgehaltsprofile (fette Linien) der beiden ozeanographischen Stationen im Eurasischen Becken = (a: $82^{\circ}11.4'\text{ N}$, $97^{\circ}17'\text{ E}$) und im Kanadischen Becken = (b: $82^{\circ}53'\text{ N}$, $145^{\circ}06'\text{ W}$). Punkte zeigen klimatologische Mittelwerte, Linien die Standardabweichungen der entsprechenden Parameter der klimatologischen Mittelwerte. Gestrichelte horizontale Linien markieren die obere und die untere Grenze des Atlantischen Wassers (AW) im Jahr 2007.

in the surface layer, negative salinity anomalies occurred in the Canadian Basin, and positive anomalies in the Eurasian Basin. Both anomalies are beyond variations observed throughout the historical observation period.

In the halocline layer in the Canadian Basin, anomalous thermal conditions were observed in the summer Pacific Water (SPW). The positive temperature anomaly for this region had a 5-6-fold higher standard deviation than that of the climatological dataset (Fig. 7b).

In the water layer of Atlantic origin, the following changes were noted in 2007. The highest temperatures were observed in the Eurasian Basin. North of Cape Arktichesky, the expedition onboard the "Akademik Fedorov" on 11 August 2007 measured in the AW core between 126 to 165 m a temperature of $+3.00\text{ }^{\circ}\text{C}$ to $+3.20\text{ }^{\circ}\text{C}$. This is twice as high as the climatological average for this area. The upper boundary of AW has risen in this region by 50-100 m compared with the climatological depth level. Warming in the Canadian Basin relative to the climatological mean was not greater than $0.5\text{ }^{\circ}\text{C}$ (Fig. 7), but positive anomalies were two times higher than the temperature standard deviation in the AW core. This anomalously

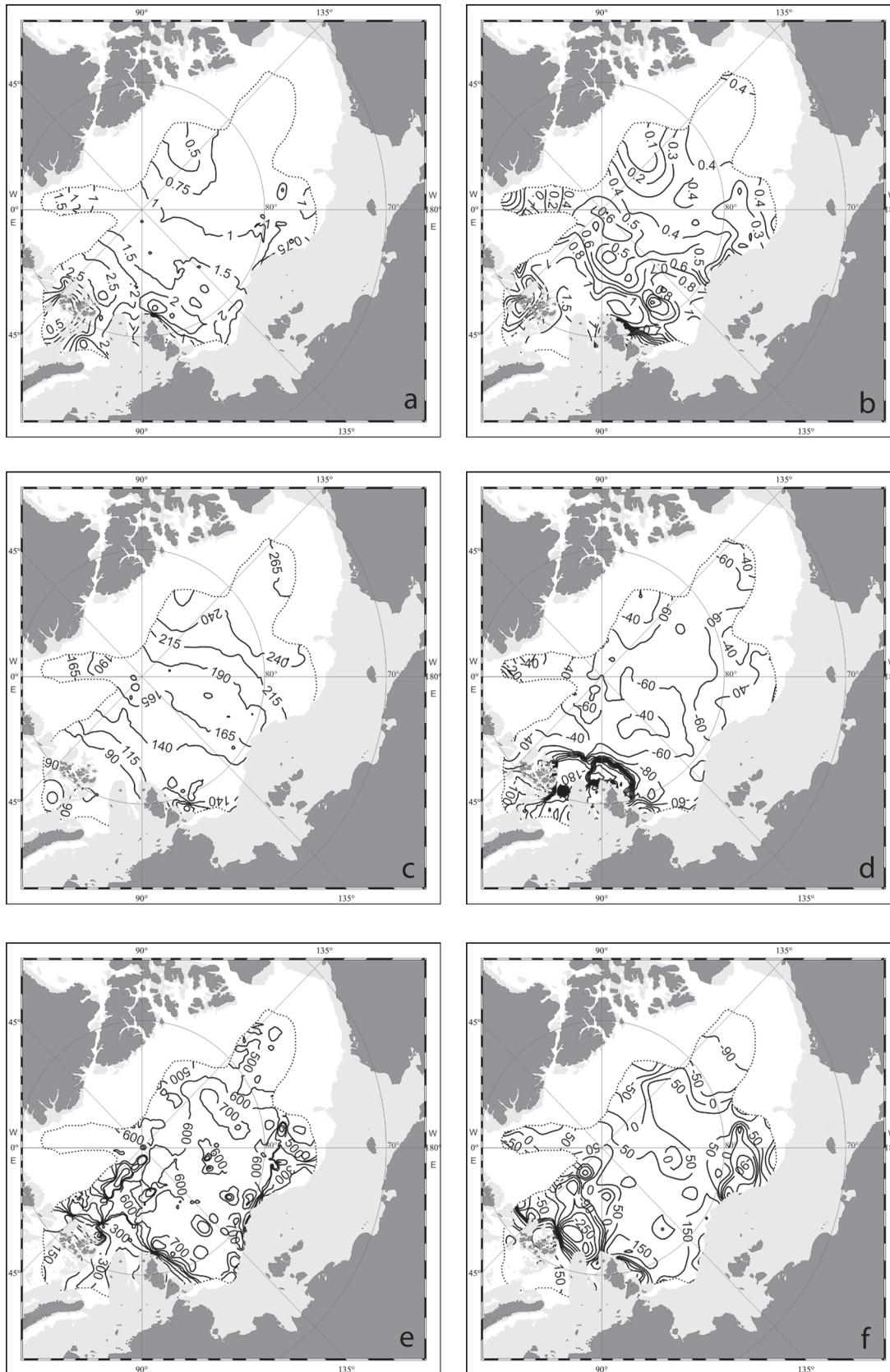


Fig. 8: Distribution of Atlantic Water (AW) characteristics (a,c,e) and their anomalies (b,d,f) in summer of 2007 relative to the 1950-1989 series: maximum temperatures = a,b; depth of the upper boundary = c,d; AW layer thickness = e,f.

Abb. 8: Verteilung der Eigenschaften des Atlantischen Wassers (AW, a,c,e) und ihrer Anomalien (b,d,f) im Sommer 2007 im Vergleich zu den Datenserien von 1950-1989. Maximale Temperaturen = a,b; Tiefe der oberen Grenze = c,d; Schichtdicke des AW = e,f.

warm Atlantic water was observed everywhere in the Arctic Ocean in 2007 together with an anomalous shallow upper boundary of Atlantic water.

In the deeper layers below the AW the changes were not so obvious. Therefore we focus on the AW characteristics and the spatial distribution of the anomalies as there are the temperature maximum and its depth, the depth of the upper and lower AW boundaries, i.e. to the depth of the 0 °C isotherm, the thickness the average salinity and the average potential temperature of the AW layer. In addition the heat content of the AW layer was calculated. Calculations were based on the database, which includes all oceanographic observations that were carried out during the IPY and in 2009. To characterize the state of the AW in 2007, anomalies were calculated as differences of the properties observed in 2007 from the “climatological” mean fields derived for the period 1950-89. Anomalies of maximum temperature of the Atlantic water (Fig. 8b) were positive in the Arctic Basin and in the adjacent Arctic seas. The largest positive anomalies of the maximum AW temperature were observed in a wide belt from Fram Strait to the Gakkel Ridge. The anomalies reached up to 1.5 °C, and in the vicinity of the Eurasian continental slope and within the St. Anna Trough, an all time maximum was observed. In the Canadian Basin, large positive anomalies of the maximum AW temperatures were also observed, and in the Canadian Basin, the maximum potential temperature was higher than the multiyear mean!

Anomalies of AW salinity (no charts are presented) during the IPY were small and negative, i.e., the salinity of the AW was by 0.1 lower than the climatological average.

In summer 2007, the depth of the upper AW boundary was closer to the surface than in the climatological mean. It has

risen almost everywhere in the Arctic Basin and in the adjacent seas by 40-100 m (Fig. 8c,d). The largest rise of up to 120 m was observed to the north of Severnaya Zemlya islands. Simultaneously, an increase of the AW layer thickness was recorded in the main flow from Fram Strait to Severnaya Zemlya islands and in the Canadian Basin (Fig. 8e,f).

To obtain estimates of the changes in the TS-properties of the different layers we have performed a volumetric analysis of the water masses on the basis of all available deepwater oceanographic data obtained during the summer seasons of 2007 and the period of 1970-79. In the 1970-79 period, relatively cold Atlantic water was observed after a warming during the 1940s and before the beginning of warming in the 1990s (POLYAKOV et al. 2004). Therefore we use the decade of 1970-1979 as a reference.

Mean weighted temperature and salinity values were calculated for the entire volume of the Arctic Ocean for 1970-1979 resulting in +0.82 °C and 34.25 for winter and +1.2 °C and 34.06 for summer. According to these estimates, the waters of the Arctic Basin and the adjacent Arctic seas increased in temperature by 0.38 °C and decreased in salinity by 0.19 from the period of the 1970s to the beginning of this century.

The water volumes related to the various temperature and salinity intervals differ significantly for summer of 2007 from the average summer season of 1970-1979 (Fig. 9a,b). The ranges of the thermohaline structure that have occurred in the last 30 years can be clearly seen in Fig. 9c, which presents a difference between the distribution functions of 2007 and 1970-1979. Bars with white caps depict positive anomalies of water volume per temperature or salinity interval, i.e. the volumes are larger in 2007 as in the decade 1970-1979), and bars with black caps indicate the opposite situation.

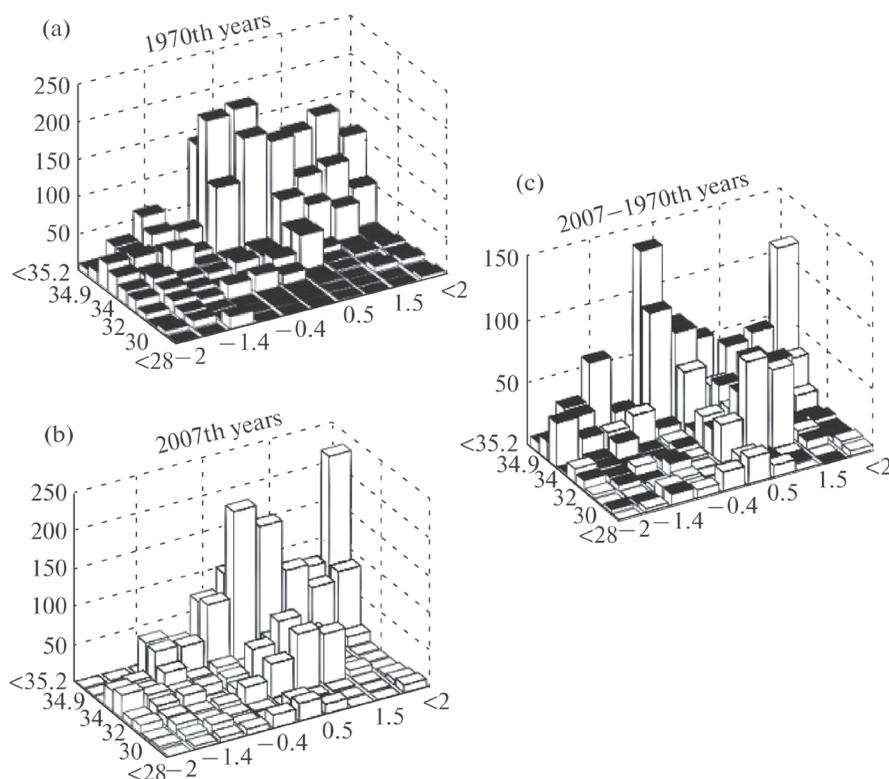


Fig. 9: Histograms of Arctic Ocean water volumes per temperature and salinity interval (vertical axis, water volume in meters per unit area) constructed for the average summer season of 1970-1979 (a) and 2007 (b); (c) = difference of specific water volumes between 2007 and 1970-1979 (FROLOV et al. 2009).

Abb. 9: Wasservolumina des Arktischen Ozeans für bestimmte Temperatur und Salzgehaltssklassen (vertikale Achse: Wasservolumen in m pro Flächeneinheit) für den Mittelwert der Sommermonate von 1970-1979 (a) und 2007 (b); (c) = Differenzen der spezifischen Wasservolumina zwischen 2007 und 1970-1979 (FROLOV et al. 2009).

The anomalous conditions in the surface layer, discussed above, occurred in the temperature range from $-0.4\text{ }^{\circ}\text{C}$ to $+1.0\text{ }^{\circ}\text{C}$ and salinity of less than 30.00. Significant changes occurred in the volumes of the temperature and salinity ranges of $0.0 / +1.50\text{ }^{\circ}\text{C}$; $31.00 / 32.00$ and $0.0 / +1.0\text{ }^{\circ}\text{C}$; $32.00 / 33.00$. The volume of the first range increased by five times to 2007 relative to the decade of 1970-1979. The largest contribution came from the heated surface waters of the Barents Sea and summer Pacific waters. The volume of the second range has decreased in 2007 almost nine times.

The total volume of Atlantic Water with a temperature above $0\text{ }^{\circ}\text{C}$ and salinity of more than 34.6 increased in 2007 by 22 % compared to the 1970-1979 decade. At the same time we recorded changes of volumes of temperature subranges within the AW. For example, the AW volume with a temperature of $0\text{ }^{\circ}\text{C}$ to $2\text{ }^{\circ}\text{C}$ has decreased and the water volume with a temperature of more than $2.0\text{ }^{\circ}\text{C}$ has significantly increased. Such significant modification of the thermohaline structure of the AW layer could be a result of the increased inflow of warmer and less saline AW to the Arctic Basin for the last two decades – especially from 2003-2004 (POLYAKOV et al. 2005).

Changes also occurred in the deeper layers. The volume of lower intermediate water with temperature of $-0.4\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$ and a salinity of more than 34.6 decreased by 30 % in 2007. The bottom waters below have become slightly warmer and less saline. A relation between the increase of bottom water temperature and increasing temperature of Atlantic water in the Arctic Basin was noted earlier (NIKIFOROV & SHPAIKHER 1980). This relation is also confirmed by our analysis. To estimate the bottom water volume in 2007 was not possible due to a restricted amount of measurements deeper than 1500 m.

Consequences of the anomalous oceanographic conditions in 2007 were especially pronounced in the freshwater distribution in the Arctic Basin. For calculations of the fresh water content (FWC), oceanographic observations from the winters 2007 and 2008 were combined. As reference salinity, a value of 34.8 was used. Figure 10 presents charts of average of the climatological distribution of FWC in the winter season for the period 1950-1989 and the distribution of FWC anomalies in winter of 2007-2008 relative to the 1950-1989 series. As can be seen (Fig. 10), the distribution of positive and negative anomalies of fresh water content formed basin scale dipole structure with the zero axis passing from the northern tip of Greenland to the Makarov Basin and further to Wrangel Island. Estimates showed the deficit of freshwater content in the Eurasian basin to be up to 25 % of the average climatological values in this region, and the excess of freshwater content in the Canadian Basin was 30 % of the climatological mean. The difference between the positive and negative anomalies of FWC was several meters of fresh water (Fig. 10). Analysis of long-period FWC changes of the Arctic Basin and the Arctic seas showed that ice production, inflow of fresh water and its transport in connection with the atmospheric circulation are the key factors, that are responsible for the freshening and salinity increase of the upper layer that was observed during the last decades (POLYAKOV et al. 2008). From this it follows that the observed FWC anomalies in 2007-2008 are probably driven by the ice cover and its interaction with the upper ocean layer. In consequence we assume that the Canadian Basin transforms from a region of accumulating ice

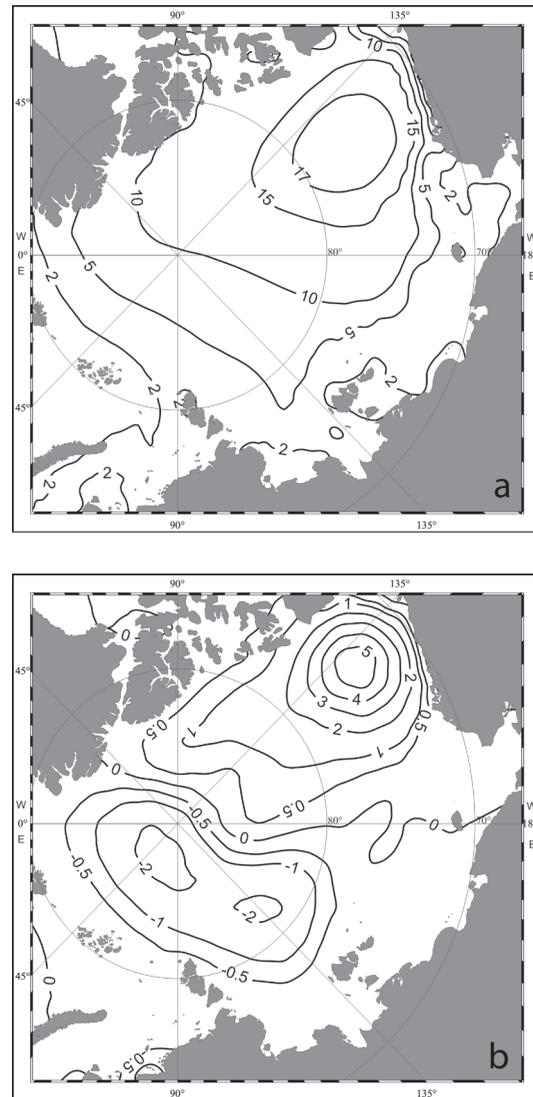


Fig. 10: Distribution of average climatological values of freshwater content (m) in the winter season for the period 1950-1989 (a) and FWC anomalies (meters) in winter of 2007-2008 relative to the 1950-1989 series (b).

Abb. 10: Mittelwerte des Süßwassergehalts (m) im Winter der Jahre 1950-1989 (a) und Anomalien des Süßwassergehalts (m) im Winter 2007-2008 im Vergleich zum Zeitraum 1950-1989 (b).

towards a region, which loses ice due to melting – this is an important change of the basin status in relation to global warming.

TENDENCY OF THERMOHALINE STRUCTURE CHANGES DURING THE IPY 2007/2008 AND LATER

Already in winter (January-April) 2007, which preceded an extreme summer, significant negative and positive anomalies of salinity were observed in the central Arctic Ocean. These formed the initial conditions for subsequent transformations in the spring-summer season. Large changes of thermohaline structure of the surface layer in summer 2007 influenced the formation of the winter 2007-2008 distribution of temperature and salinity. Figure 11 presents charts of the average salinity anomaly in the 5-10 m layer in 2008 and 2009. Maps of temperature distribution are not presented here.

Summer conditions of 2007 (Fig. 5) had a significant influence on the salinity distribution next winter. As shown (Fig. 11a), the negative salinity anomalies increased in the Canadian Basin to extreme values. This underlines the importance of the summer conditions preconditioning the salinity fields next winter. However in the Eurasian Basin, positive (and extreme) salinity anomalies, which were observed in winter of 2007 (Fig. 5b), have decreased by the end of winter of 2008. One of the main causes can be a decrease of the influence of AW, because the AW flows across Fram Strait, after having reached a maximum in August-September 2006, decreased in 2007 and 2008 (POLYAKOV et al. 2011).

In 2008, the summer conditions began with the background of positive temperature anomalies in the Arctic, a dominance of first-year ice in the western and eastern regions of the Siberian shelf and an intensive ice loss, primarily due to ice melting, in the marginal western – Barents and Kara seas – and eastern – Beaufort and Chukchi seas (FROLOV 2011). The combined effect of thermal and dynamic factors, phase transitions and

heat gain of the water in the ice-free areas resulted in summer of 2008 in the formation of a large zone of negative salinity anomaly (Fig. 11b) and a positive temperature anomaly in the surface layer in the Canadian Basin. From Fram Strait along the continental slope to the Laptev Sea, a salinity increase of the surface layer was recorded. The surface water temperature over much of the Eurasian Basin was near the multiyear average. But in the Fram Strait area, a negative anomaly of water temperature was recorded.

The difference of the 2008 summer conditions from the previous year was that the air temperature anomalies in spring, summer and autumn in 2008 were everywhere positive except for the Alaskan region, where weak negative values were observed in summer and autumn. But the air temperature anomalies were by 1-3 °C lower than in 2007. Freshening of the surface layer in the Canadian Basin was also weaker than in 2007, except for the Beaufort Sea and the adjacent area where the negative salinity anomaly in 2008 was slightly higher than in 2007. In the Eurasian Basin no significant

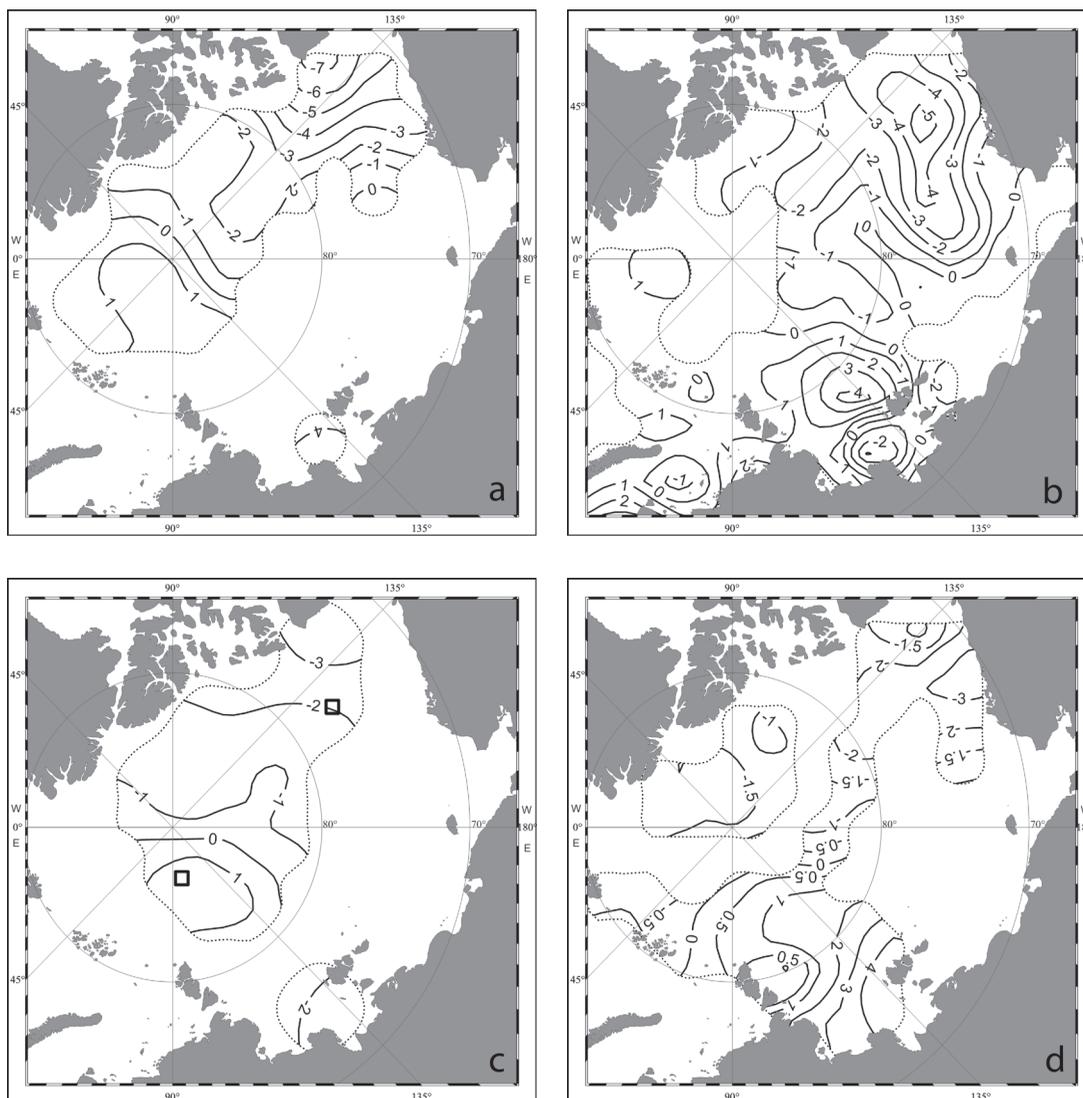


Fig. 11: Anomalies of surface layer salinity in winter (January-May) and summer (August-September) 2008 (a,b) and summer 2009 (c, d). The square denotes the regions for which the curves of seasonal salinity and temperature variability were constructed in Figure 9.

Abb. 11: Salzgehaltsanomalien der Oberflächenschicht im Winter (Januar-Mai) und Sommer (August-September) 2008 (a,b) und Sommer 2009 (c,d). Die Quadrate zeigen die Regionen, für welche die saisonale Salzgehalts- und Temperaturvariabilität in Abbildung 9 abgeleitet ist.

changes occurred in the surface layer. The water temperature of the surface layer in summer of 2008 was close to that of 2007. A small positive anomaly of salinity in the Nansen Basin from Fram Strait to the Laptev Sea was also preserved, and in the Laptev Sea, a positive salinity anomaly has moved northeastward towards the area of the Lomonosov Ridge. The flow of Atlantic Water continued probably to play a dominating role in forming the surface TS fields over much of the Eurasian Basin.

By the beginning of the summer period 2009, similar to the previous two years, positive air temperature anomalies were observed over the Arctic Ocean and its marginal seas. Again a dominance of first-year ice was found in the western and eastern regions of the Russian Arctic seas. However, also differences from previous years were recorded. In August, an extensive cyclonic circulation occurred in the ice drift velocity field with the center to the north of the East-Siberian Sea. In the eastern part of the Beaufort Sea, anticyclonic vorticity was observed determining the motion of both of ice and ice-free water (FROLOV 2011). Under the influence of the latter, in August and September 2009 the ice flow from the Canadian sector to the Beaufort Sea formed a zone of negative water temperature anomaly. In the open water of the Canadian Basin the ice melted intensively, resulting in a freshening of the surface layer and the formation of a negative anomaly of surface salinity in summer 2009 in this region (Fig. 11d), but the value of this anomaly was smaller than in 2007 and 2008.

Under the influence of an atmospheric cyclonic circulation north of the East-Siberian Sea an inflow of drifting ice and an advection of surface water from the Arctic Basin onto the Siberian shelf seas was observed. This has probably led to an increased positive salinity anomaly in the Laptev Sea and the formation of negative salinity anomalies north of the Kara and Barents seas. The surface temperature in the Eurasian Basin changed only little compared to the preceding two years. Some changes were recorded in the salinity field of the surface layer in the Eurasian Basin. In the basin close to Greenland, Spitsbergen and Franz Josef Land, a zone of negative salinity anomaly was formed, i.e., compared to 2007 and 2008, the salinity changed in the surface layer in this region. In the other parts of the basin, a positive anomaly of surface salinity was preserved but with a different spatial structure.

A comparative analysis of the maps of surface salinity distribution and its anomalies in the summertime and the maps of surface salinity anomalies in the winter (Fig. 11) suggests the following conclusions. Extreme freshening of the surface layer in summer of 2007 over most of the Canadian Basin has influenced the increase of the negative salinity anomaly from winter (January-April) 2007 to winter of 2008 (Fig. 11). The salinity of the Beaufort Sea area decreased by 1 to 2. However, in spite of the significant negative salinity anomalies in this region in summer of 2008, the salinity in winter of 2009 has slightly increased but the sign of anomaly was preserved.

The tendencies of temperature and salinity change in the surface layer are illustrated by their seasonal variability (Fig. 12), constructed for the areas to the north of Franz Josef Land (FJL) and in the Canadian Basin (for location see Fig. 11c), because these regions reflect the main features of changes in the surface layer in 2007-2009 clearest. In the Eurasian Basin

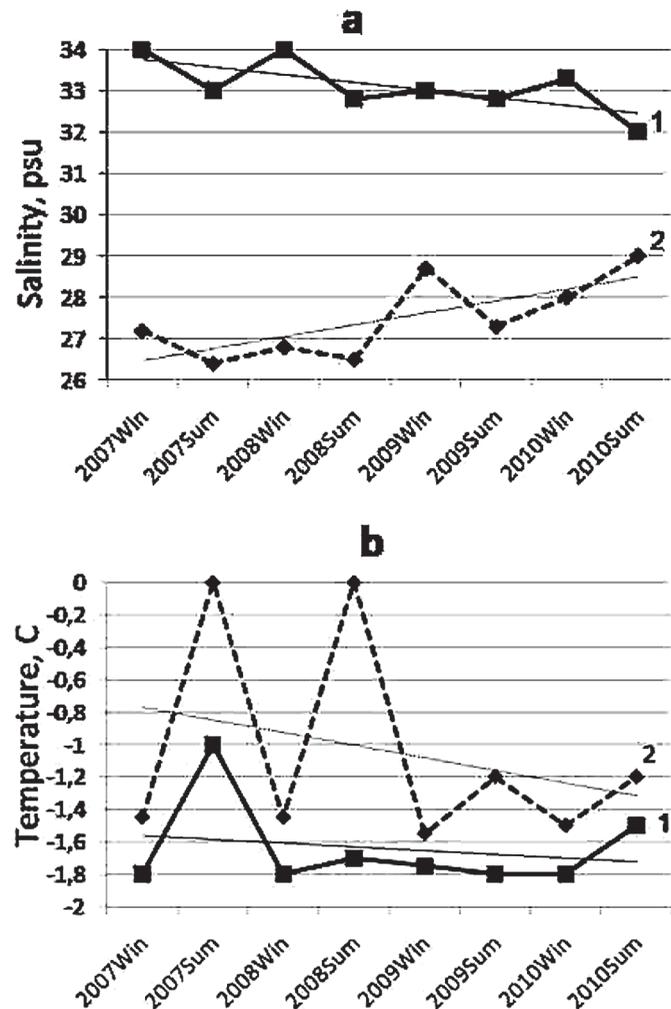


Fig. 12: Diagrams of summer variability from winter 2007 (2007Win) to summer 2010 (2010Sum) salinity = (a) and temperature = (b) of the surface layer and their trends in the Eurasian Basin to the north of Franz Josef Land (1) and in the Canada Basin (2); for location see Figure 11c.

Abb. 12: Variabilität von Salzgehalt (a) und Temperatur (b) der Oberflächenschicht im Sommer für den Zeitraum vom Winter 2007 (2007Win) bis Sommer 2010 (2010Sum) und ihre Trends im Eurasischen Becken nördlich von Franz-Josef-Land (1) und im Kanadischen Becken (2); Lokationen siehe Quadrate in Abbildung 11c.

to the north of FJL, the tendency of salinity is negative, while its increase is observed in the Canadian Basin. The amplitude of seasonal variations of the water temperature in both basins decreases.

The analysis performed allows the conclusion that after 2007, the signs of temperature and salinity anomalies of the surface layer in the Eurasian and Canadian basins were in general preserved, although the areal distribution varied and the intensity of the anomalies also changed. The basin scale differences of the salinity in the surface layer decreased. The above analysis suggests that the thermohaline structure of the surface layer in 2008 and 2009 returned to an average climatological state.

The following changes occurred in deep ocean layers. In 2008, the average of the Atlantic Water layer temperature as its maximum was everywhere higher than the climatological average. The area of inflow and spreading of the main flow of

AW along the continental slope from Fram Strait to the Laptev Sea has significantly changed compared to 2007. The average and maximum temperature of the AW was lower by 0.25-0.50 °C, the total heat content and the AW thickness were reduced. However in 2008 in the Amundsen Basin, we observed a small increase of AW temperature compared to 2007.

Changes in the depth of the upper and lower boundaries of AW were observed. Over much of the Arctic Basin the upper AW boundary was higher by 40-100 m than in the climatological mean. But in 2008 to the north of Spitsbergen, a deepening of the upper boundary of 10-50 m, if compared to the mean position, occurred. In the same part of the Arctic Basin, we observed a shallower lower AW boundary by about 100 m if compared to 2007. In contrast, in the northern Laptev Sea there was an even greater deepening of the lower AW boundary in 2008.

In summer of 2009, the water temperature in the core of the Atlantic water was 0.5-1.25 °C higher than the climatological

mean of the Eurasian Basin (Fig. 13). Compared to 2007, the maximum temperature anomalies in the Nansen Basin decreased by 0.2-0.5 °C, and in the area of the Lomonosov Ridge and the adjacent Siberian shelf, the anomalies increased by 0.25 °C. In the Canadian Basin, positive anomalies of the AW temperature of +0.3 to +0.5 °C were observed. The anomalies were similar to that recorded in 2007. In general in 2009, the maximum AW temperatures have become lower than in 2007. The upper boundary of the AW in the Eurasian Basin ascended by 50-150 m towards the ocean surface.

CHANGES OF WATER MASS CHARACTERISTICS IN THE ARCTIC BASIN FOR THE LAST 60 YEARS

Surface layer

The study of extreme changes of water temperature and salinity in the Arctic surface layer during the IPY 2007/2008 would be incomplete if the state of the surface layer during the

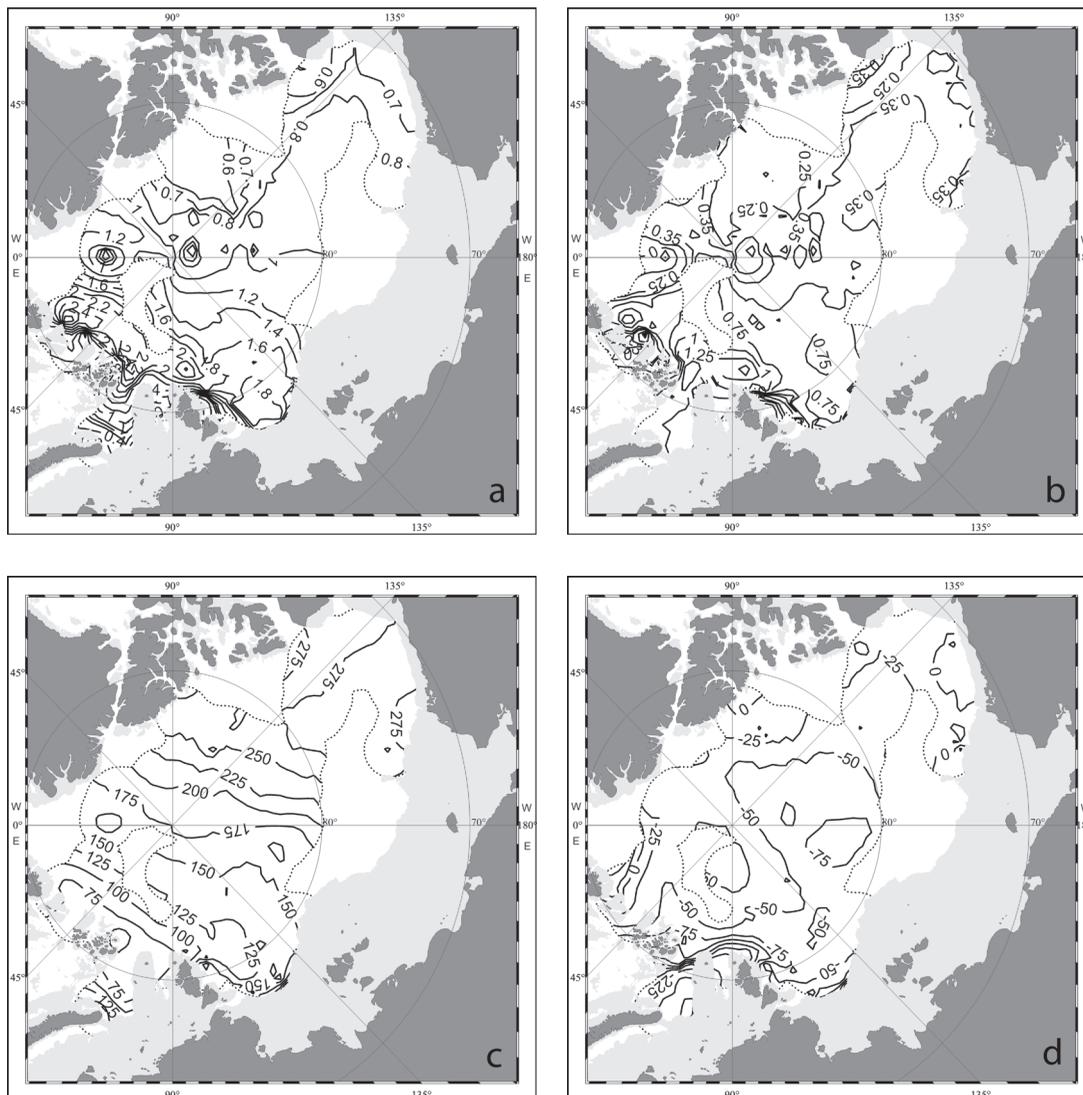


Fig. 13: Distribution of Atlantic Water (AW) characteristics (a,c) and their anomalies (b,d) in summer of 2009 relative to the 1950-1993 series; maximum temperatures = (a,b); depth of the upper boundary = (c,d).

Abb. 13: Eigenschaften des Atlantischen Wassers (AW) (links) und ihrer Anomalien (rechts) im Sommer 2009 im Vergleich zur Zeitreihe von 1950-1993: Maximale Temperaturen = (a,b), Tiefenlage der Obergrenze = (c,d).

IPY would be not compared with the previous years and decades. For this purpose, an analysis of variability of average salinity and thickness of the upper layer (from the bottom of ice cover to the upper boundary of Atlantic Water layer) was performed for the winter separately for the Eurasian and Canadian basins, since the main characteristics of the surface layer conditions in 2007-2009 were water salinity contrasts between these basins.

Using the database, average salinity values in winter were calculated and time series and their linear trends were constructed (Fig. 14). It results that the range of the changes of the average salinity in the Eurasian Basin is 1.5 times greater than the one in the Canadian Basin. But if we consider in contrast to that, the quantity of salt in the layer of 5-50 m, then the variation in the Canadian Basin is more than 1.5 times larger than the Eurasian Basin, and we obtain roughly similar variations of the total salt content in the surface layer of both basins. The linear trends for the periods 1950-1993 are positive in both basins, i.e., there was an overall salinity increase. However, two periods are identified in the Eurasian Basin with a negative trend in 1958-1979 and a positive trend in 1979-1993 and two periods in the Canadian Basin with opposite trends – positive in 1960-1982 and negative in 1982-1993 (Fig. 14).

A statistical analysis of average salinities in the basins allowed us to determine a correlation between the variations in the two basins. The salinity variation in the Eurasian basin is one year delayed in comparison to the one in the Canadian Basin. We assume that this statistical relation with a positive correlation coefficient of 0.31 is the consequence of significant surface water transport from the Canadian Basin to the Eurasian Basin.

A negative correlation coefficient of -0.32 was obtained with an inverse shift of two years, meaning that the salinity increase (decrease) in the Eurasian Basin is coupled in two years with the salinity decrease (increase) in the surface layer in the Canadian Basin. This phenomenon can be attributed to the influence of the following processes. Under the dominance of an anticyclonic regime of atmospheric circulation, the anticyclonic gyre area expands and the surface frontal zone of average salinity moves westward from the Lomonosov Ridge. Freshened water of the Laptev Sea and East-Siberian Sea flows directly to the Amundsen Basin. As a result, the average salinity in the Eurasian Basin decreases and in the Canadian Basin increases. During the cyclonic regime of the atmospheric circulation, the influence of Atlantic Water on the surface layer of the Eurasian Basin is intensified and its average salinity increases. The surface salinity front moves eastward from the Lomonosov Ridge. Freshened water of the Laptev and the East-Siberian seas spreads to the east and together with water of the Chukchi Sea is entrained into the anticyclonic gyre. Salinity in the Canadian Basin and the Beaufort Basin decreased. Thus, we hypothesize that this is the reason for the inverse variations of salinity in the two basins with a delay of two years in Canadian Basin.

It was noted above that in general from 2007 to 2009 a tendency to the return of haline state of the surface layer to the climatological average is observed in the Arctic Basin (see Fig. 11). In this context it is of interest that the average salinity

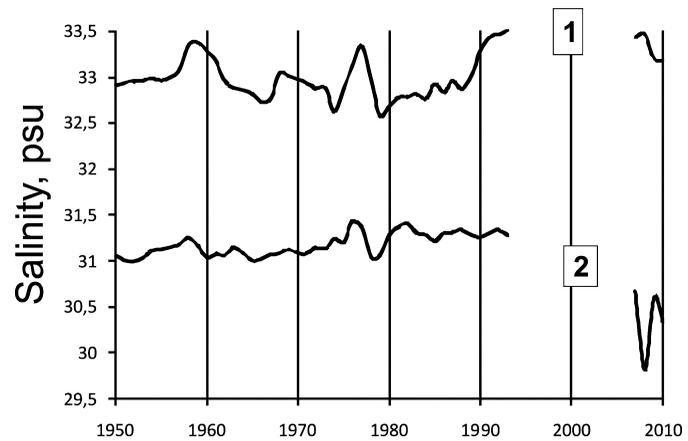


Fig. 14: Inter annual variability (1950 to 2010) of average salinity in the surface 5-50 m layer in winter in the Eurasian (1) and Canadian (2) Basins

Abb. 14: Variabilität des mittleren Salzgehalts in der Oberflächenschicht von 5-50 m im Winter im Eurasischen Becken (1) und Kanadischen Becken (2) für die Jahre 1950 bis 2010.

in the surface 5-50 m layer in the winter of 2007-2009 in the Eurasian Basin were higher than in the 1950s and 1970s (Fig. 14, curve 1), but did not exceed the average salinity in the early 1990s. In the Canadian Basin, the salinity in 2007-2009 was much lower than the minimum values of the 1950s-1960s. A phase of extreme salinity decrease in the Canadian Basin and of the anomalous state of the Eurasian Basin during the IPY and later suggests that in the 1990s or at least in 2007/2008, there was a transition of the “AB surface layer” system to another macro-state stage.

Atlantic Water

Using the hybrid database, we have analyzed the interannual changes of the average potential temperature (we will not further stress the use of potential temperature) and salinity of the Atlantic Water layer for the Eurasian and Canadian basins, which differ significantly in the thermal state, salinity and circulation of AW. Figure 15 presents plots of interannual variability of average temperature and salinity for these two basins. Time series indicate linear trends of the same sign in both basins: positive for temperature and negative for salinity. The longterm decrease of AW salinity, i.e., a negative linear trend is slightly greater in the Eurasian Basin, than in the Canadian Basin. However we do not exclude that the linear trend is caused by an even longer term variation with a typical time scale greater than duration of the series analyzed, which does not allow us to unambiguously interpret the cause of prolonged tendencies in the AW salinity variations in the Arctic Basin, and likewise in average temperatures.

It was shown that the salinity in 2007-2009 was in the range of values observed earlier and did not indicate an exceptional condition of the AW state during the IPY. At the same time the AW average temperature during the IPY in the Eurasian Basin was anomalous and beyond the earlier observed values, while in the Canadian Basin, an extreme situation was registered. As can be seen from Table 2, presenting the climatological average temperature and salinity and anomalies of these characteristics in different time intervals, the average tempera-

	Parameter	Mean	Anomaly								
			1960		1970		1980		1990		2000
Eurasian Basin	Temperature, °C	0.6705	-0.059 1950-1952	+0.039 1953-1963	-0.028 1964-1981		+0.028 1982-1985	-0.039 1986-1988	+0.051 1989-1993	+0.078 2007-2009	
	Salinity	34.877	+0.006 1950-1957	-0.007 1958-1959	+0.008 1960-1978		-0.019 1979-1993				+0.047 2007-2009
Canadian Basin	Temperature, °C	0.284	+0.000 1950-1961		+0.039 1962-1973		-0.010 1974-1993				+0.078 2007-2009
	Salinity	34.842	+0.026 1950-1953	-0.007 1954-1962	+0.003 1963-1969	-0.014 1970-1975	+0.011 1976-1987	-0.014 1988-1993			-0.017 2007-2009

Tab. 2: Multiyear average of potential temperature and salinity of Atlantic Water (AW) for 1953-1993 and anomalies of characteristics relative to a multiyear average for different periods; boxes with positive anomalies are shaded.

Tab. 2: Mehrjähriger Durchschnitt der potentiellen Temperatur und Salinität des Atlantischen Wassers (AW) im Eurasischen und Kanadischen Becken für 1953-1993 und charakteristische Anomalien relativ zu einem mehrjährigen Durchschnitt für verschiedene Zeitabschnitte. Schattierung = Zeiten mit positiven Abweichungen.

ture in 2007-2009 was greater than the climatological multiyear average for this region, and the range of the AW average temperature change from 1993 to 2007 was 10-fold (!) greater than the RMS deviation for the period 1950-1993. Transferring into the thermal expansion it results a unique situation of Atlantic water in the Arctic Basin is unique for the last 20 years in comparison to the entire historical period of instrumental observations. The studies of IPY 2007/2008 describe a unique situation that allows expanding our knowledge on the possible limits of variations of the Arctic marine system. However, one has to keep in mind that during the 2007-2009 period in both basins the temperature decrease and salinity increase of the Atlantic Waters were observed.

From the time series (Fig. 15), the periods were derived during which temperature and salinity were higher or lower than the average for 1950-1993. The duration of these periods is specified. The visual analysis suggests that the AW warming stage of 1952-1960 in the Eurasian Basin was manifested in the Canadian Basin 10 years later and continued in this region three years more. The AW cooling period, which in the Eurasian Basin was observed in 1961-82, began in the Canadian Basin 13 years later. Warming which has begun in the Eurasian Basin in 1989, was noted in the Canadian Basin in the early 2000s (SHIMADA et al. 2004), i.e. for 11-14 years later. The periods of the salinity increase (1950-1957), (1961-1978) and decrease (1958-1959), (1979-1993) in the Eurasian Basin were noted in the Canadian Basin 8-16 years later and the duration of the duration of such periods did not coincide.

Taking into account that the AW changes in the Canadian Basin are first of all a result of the AW flow from the Eurasian Basin, the estimated signal lag given here is quite realistic. We suggest that the causes of the difference in duration of the periods of salinity increase and decrease in the basins, can be found in the difference of the circulation patterns and the AW transformation mechanisms in the Eurasian and Canadian regions, but a safe conclusion requires a further analysis.

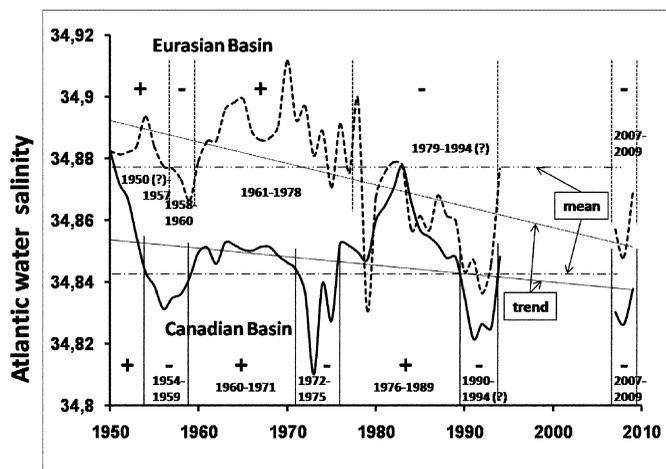
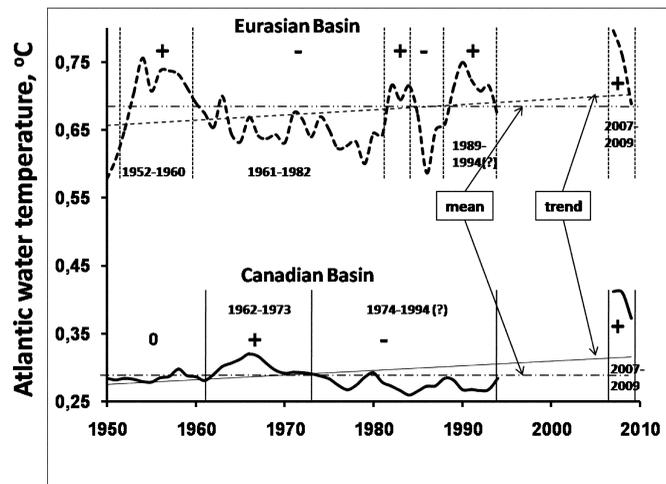


Fig. 15: Interannual variations (1950 to 2010) of average potential temperature (a) and salinity (b) of Atlantic Water (AW) and linear trends in the Eurasian Basin and Canadian Basin.

Abb. 15: Veränderungen der mittleren potentiellen Temperatur (a) und des Salzgehalts (b) des Atlantischen Wassers (AW) und ihre linearen Trends im Eurasischen Becken und Kanadischen Becken in den Jahren 1950 bis 2010.

It is noted that in the Eurasian Basin temperature and salinity anomalies vary frequently in opposite direction. In the Canadian Basin the period of warming of 1962-1973 was accompanied by salinity increase, but in the period 1976-1989 the signs of temperature and salinity anomalies were opposite.

To determine the causes of such relationships between the temperature and salinity changes is not so far possible. This is mainly due to the fact that the average temperature and salinity in the Atlantic Water layer in general for the basins present the generalized indexes of the AW state. In addition to advective transfer, changes of characteristics depend on multiple inner processes of AW transformation in the basins and external factors. That is why this problem requires further careful analysis for its solution.

CONCLUSIONS

Radical changes of surface layer temperature and salinity in the layers of water of Pacific and Atlantic origin, which have occurred in the Eurasian Basin and especially in the Canadian Basin during the IPY 2007/2008 and later raise the following important questions:

(i) Will the modern state of the Arctic Ocean return to the formerly observed state (conditionally equilibrium state) or is the phase of 2007-2009 a pre-collapse state of the former Arctic Ocean conditions?

(ii) What are the limits of the variations of internal parameters of the Arctic oceanic system and is it possible to assess the probability of irreversible changes of the thermohaline structure and water and ice circulation in the Arctic Ocean.

Recognizing the mechanisms and complex nature behind the extreme changes in the Arctic Ocean will be critical to our understanding of the future climate change in the Arctic.

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