УДК 551.465(268.9)

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ИЗМЕНЕНИЯ СОДЕРЖАНИЯ ПРЕСНОЙ ВОДЫ В ВЕРХНЕМ СЛОЕ АРКТИЧЕСКОГО БАССЕЙНА С 1950-Х ПО 2010-Е ГОДЫ

Статья поступила в редакцию 10.04.2021, после доработки 05.08.2021

В начале 1990-х гг. в климатической системе Арктики произошел сдвиг в сторону потепления, которое сопровождалось изменениями температуры и солености водных масс Арктического бассейна под влиянием возросших притоков атлантической воды, поступления со стоком рек, осадками и от таяния льда. Мы оцениваем изменения в содержании и притоках пресной воды в верхний слой Арктического бассейна от десятилетия к десятилетию с 1950-е по 2010-е гг. и связь между изменениями в Арктическом бассейне и в тропической Северной Атлантике. Полученные результаты показывают, что содержание пресной воды в верхнем слое Арктического бассейна в 1990–2000-е гг. понижалось в Евразийской и росло в Амеразийской его частях. В среднем во всём бассейне преобладал рост из-за большего вклада Амеразийской части, занимающей 61 % площади бассейна. Наибольшее содержание пресной воды во всём бассейне получено в 1960-е гг., предшествующие отрицательной солёностной аномалии в Северной Атлантике в 1960–1970-х гг. Сокращение содержания пресной воды в Евразийском бассейне произошло в результате увеличенного с 1990-х гг. притока атлантической воды и осолонения верхнего 100-метрового слоя вопреки росту осадков и речного стока в Арктический бассейн. Накопление пресной воды происходит в круговороте Бофорта и во всей Амеразийской части бассейна. В круговороте Бофорта содержание пресной воды в слое 0–100 м увеличилось в 2000–2010-х гг. на 36 % по сравнению с 1970-ми гг. Более всего (на 46 %) содержание пресной воды увеличилось в этот период в верхнем 50 м слое.

Ключевые слова: Арктический бассейн, пресноводный баланс, атлантическая вода, низкие широты.

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CHANGES OF FRESH WATER CONTENT IN THE UPPER LAYER OF THE ARCTIC BASIN IN THE 1950s-2010s

Received 10.04.2021, in final form 05.08.2021

In the early 1990s, there was a shift in the Arctic climate system towards warming. This shift was accompanied by water temperature and salinity changes in the Arctic Basin due to increased Atlantic water inflow, river runoff, precipitation, and ice melting. We estimated changes in the freshwater content (FWC) and freshwater inflows into the upper layer of the Arctic Basin decade by decade from the 1950s through the 2010s and showed the connection between changes in the Arctic Basin and the tropical North Atlantic. Our results show that the FWC in the upper layer of the Arctic Basin in the 1990–2000s decreased in the Eurasian Basin and increased in the Amerasian Basin. On average, the FWC increase prevailed for the whole basin due to the larger contribution of FWC changes in the Amerasian Basin that occupies 61 % of the Arctic Basin. The largest FWC for the entire Arctic Basin was observed in the 1960s and preceded the negative salinity anomaly that occurred in the North Atlantic in 1960–1970s. The reduction of the FWC in the Eurasian Basin happened due to the increased Atlantic water inflow since the 1990s that caus-

Ссылка для цитирования: *Алексеев Г.В.*, *Смирнов А.В.*, *Пнюшков А.В.*, *Вязилова А.Е.*, *Кулаков М.Ю.*, *Глок Н.И.* Изменения содержания пресной воды в верхнем слое Арктического бассейна с 1950-х по 2010-е годы // Фундаментальная и прикладная гидрофизика. 2021. Т. 14, № 4. С. 25–38. doi: 10.7868/S2073667321040031

For citation: *Alekseev G.V.*, *Smirnov A.V.*, *Pnyushkov A.V.*, *Vyazilova A.E.*, *Kulakov M.Y.*, *Glok N.I.* Changes of Fresh Water Content in the Upper Layer of the Arctic Basin in the 1950s-2010s. *Fundamentalnaya i Prikladnaya Gidrofizika*. 2021, 14, 4, 25–38. doi: 10.7868/S2073667321040031

es salinification of the upper 100 m layer despite the increased precipitation and river runoff into the Arctic Basin. A freshwater accumulation occurs in the Beaufort Gyre and the entire Amerasian part of the Arctic Basin. The FWC in the upper 0–100 m layer of the Beaufort Gyre increased in the 2000–2010s by 36% compared to that in the 1970s. The largest FWC increase (46%) occurred in the upper 50 m layer during this period.

Key words: Arctic Basin, freshwater balance, Atlantic water, low latitudes.

1. Introduction

One of the causes of Arctic warming is an increase in the heat and water vapor supply from low latitudes in winter [1, 2] associated with large-scale atmospheric circulation, which is affected by anomalies of the sea surface temperature (SST) [3–6]. The influence of SST is especially significant at low latitudes, where a significant part of the heat from solar radiation and anthropogenic forcing is stored [7, 8]. SST here also affects the heat and salt transfer to the Atlantic Arctic seas and the Arctic Basin.

Atlantic waters enter the Arctic Basin through the Norwegian, Greenland, and Barents Seas, and then occupy an intermediate layer from 150 to 800 meters, indicated by higher temperature and salinity relative to the waters above and beneath [9, 10]. The Atlantic water (AW) flow and temperature increase affect the structure of water masses in the Arctic Basin and the heat transfer to the overlying layer and the lower boundary of the sea ice above the main AW [11, 12].

Polyakov et al. [13] found that long-term changes in the Arctic Basin freshwater content (FWC) between the beginning of the 20th century and the 2000s correspond to increases and decreases in the temperature of the AW in the Arctic region. Modeling results in [14] showed that the inflow of AW explains most of the variability of the FWC in the upper 1000 m in the model without the freshwater inflows. Findings in [15] also confirm the connection between changes in the Arctic Basin and the tropical North Atlantic. In the early 1990s, a warming shift occurred in the Arctic climate system [16, 17], manifested, in particular, as a temperature increase of the water entering the Arctic Basin from the North Atlantic through Fram Strait [18]. The atmospheric heat and moisture fluxes from the adjacent areas over the North Atlantic and the Pacific Ocean have also increased [19, 20]. These processes were accompanied by changes in the temperature and salinity of the Arctic Basin waters driven by the increases in the inflow of AW, river runoff, precipitation, and ice melting [21].

The warming observed in the early 1990s to the north of the Kara Sea in the waters of Atlantic origin was later registered throughout the entire Arctic Basin [22]. The distributions of the maximum temperature of the AW layer, constructed with the oceanographic stations data throughout the 1990s and 2000s [23–25], show a widespread increase in temperature relative to the 1970s, reaching 1.0 °C in the AW flow near the continental slope. The upper boundary of the AW layer, identified by the zero-isotherm position, shoaled several tens of meters (up to 60 m and more) relative to its position before the warming. The AW layer's maximum temperature depth decreased, as well. The AW lower boundary, also determined by the zero-isotherm depth, sinked, which, combined with the rise of the upper boundary, indicates an increase in the volume of AW in the Arctic Basin. Such large-scale changes in one of the layers affected the vertical structure of the entire water column of the Arctic Basin.

The study [26] established changes in the Atlantic origin water layer and the freshwater content in the Arctic upper layer from the 1970s to the mid-2010s. These changes were traced from the 1950s to the end of the 2010s with subsequent research. The research employs additional sets of oceanographic data, new field observations, improved methods of interpolation, and grid construction, as well as estimates of freshwater flow to the Arctic seas and the basin.

The article presents the results of studies of interdecadal changes in the freshwater content in the upper layer of the Arctic Basin based on observational data from the 1950s to the 2010s, and also considers the relationship of the AW inflow into the Arctic Basin with changes in SST in the tropical North Atlantic and inflow estimates affecting the freshwater content.

2. Materials and methods

In this study, we used oceanographic observations in the Arctic Basin from the 1950s to 2018, obtained during the Severny Polyus (North Pole) expeditions in the 1950s–1980s and 2000s, in High-latitude Air Expeditions in the 1950s and 1970s, ship expeditions in the 1990–2010s, and with the help of autonomous drifting ITP (Ice Tethered Profile) buoys in the 2000–2010s. For decades 1950–1980, gridded data of temperature and salinity at standard vertical levels from the Environmental Working Group (EWG) atlas [27] were additionally used. Figure 1 shows the maps of the oceanographic stations over the Arctic Basin by decades of the 1950s–2010s.

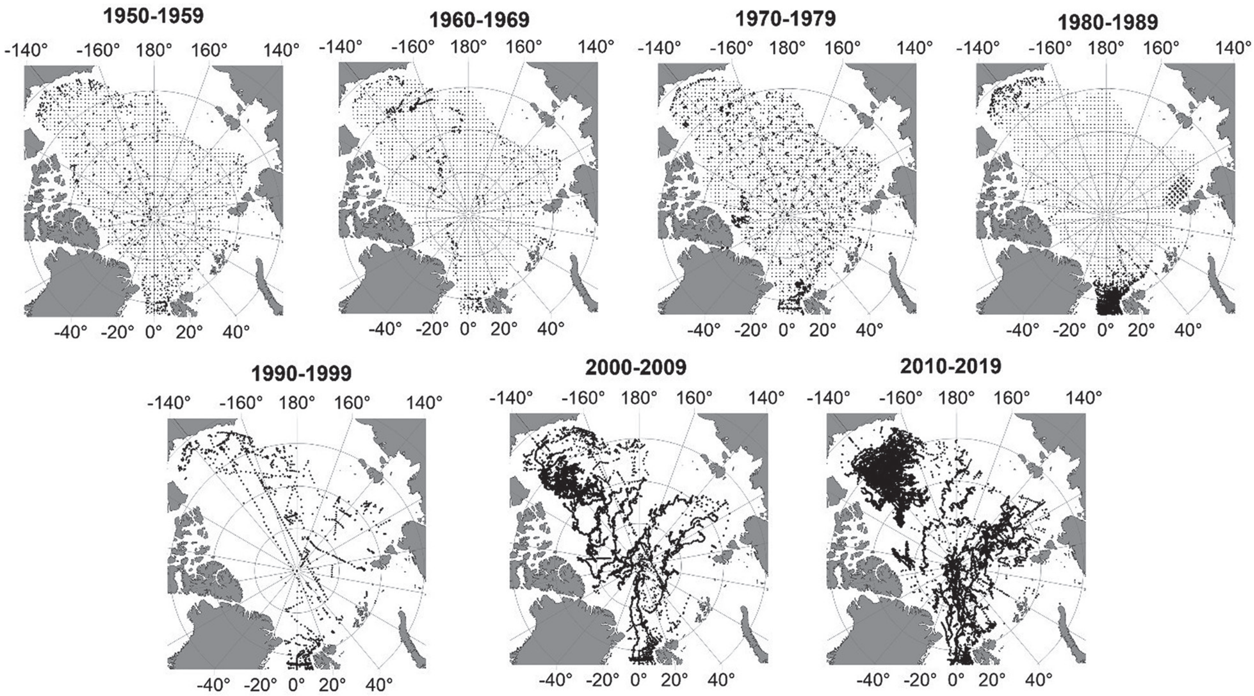

Fig. 1. Spatial distribution of oceanographic data in the Arctic Ocean by decade. Gridded data from the EWG atlas [27] is shown in gray. Points indicate oceanographic stations.

Gridded mean fields were constructed with the DIVAnd algorithm [28], which allows a multivariate variational analysis of observations randomly distributed in space. The DIVAnd interpolation method produces smooth fields of oceanographic parameters while maintaining the necessary level of details. The ability to take into account the bathymetry is the advantage of the method, which prevents interpolation across physical boundaries (capes, islands, etc.). The features of the DIVAnd algorithm are described in detail in the article [28]. The initial data was presented as a set of oceanographic stations grouped by decade. For each decade, text files were generated containing the date of the station, its coordinates, the depth of the measurement, and the salinity value. The data were sorted by year and depth. Preliminary interpolation to standard levels was not performed because DIVAnd allows processing 3-dimensional arrays. To improve the quality of spatial interpolation for decades 1950–1980s, where coverage of the region with observational data was insufficient, we used data from the EWG atlas [27]. All observational data went through standard IODE qulity control procedures and were interpolated to grid nodes with the 0.5 degree spatial resolution. The study area included the entire Arctic Basin with depths greater than 500 m (Fig. 2).

FWC was calculated for the upper layer 0–100 m relative to the salinity of 34.80 ‰. The AW layer boundary positions (depth) were determined by the depth of the zero isotherm.

Precipitation data were obtained from data sets of the GPCC project (Global Precipitation Climatology Center) [29], data on river discharges — from datasets R-ArcticNet [30], ArcticGRO [31].

The HadISST reanalysis (http://hadobs.metoffice.com.hadsst/) provided SST data in the Arctic with a spatial resolution of 1 × 1° for the period from 1951 to 2019, and the mean monthly SST in low latitude areas of the World Ocean was provided by the NCEP project (http://www.cpc.ncep.noaa.gov/data/indices).

Changes in the temperature of water flowing from the Atlantic to the Barents Sea were characterized by temperature changes in the 50–200 m layer in the section along the Kola meridian according to PINRO data [32] (http://www.pinro.vniro.ru). The water temperature in the Kola section is used as an effective indicator of warming signal propagation along the AW flow path to the Arctic Basin through the Barents Sea.

The article assesses FWC in the entire Arctic Basin and in its individual parts in accordance with the division into regions (Fig. 2).

To assess the contribution of freezing-melting processes to changes in FWC, we used the calculation of the ice cover parameters with the coupled ocean-ice model AARI–IOCM [33]. The model was used to calculate the concentration, thickness, ice hummocking, and ice volume. According to the conservation of the volume of ice, the increase and decrease in the volume are calculated for each annual cycle “freeze-melt” for subsequent use in accordance with the formulas

$$V^{g}_{melt} = V^{g}_{\max} - V^{g}_{\min} - V^{melt}_{out}, \quad (1)$$

$$V^{g}_{freez} = V^{g}_{\max} - V^{g-1}_{\min} + V^{freez}_{out}, \quad (2)$$

$$\Delta V^{g}_{freez} = V^{g}_{freez} - V^{g}_{melt} = \left(V^{freez}_{out} + V^{melt}_{out}\right) - \left(V^{g-1}_{\min} - V^{g}_{\min}\right), \quad (3)$$

where V is ice volume, g is year, *melt* and *freez* are melting and freezing phases, max is maximum and min is minimum of the ice volume, *out* is removal from the basin.

3. Results

3.1. Tropical Atlantic SST influence on the temperature of Atlantic water in the Arctic Basin

The analysis of the warming signal propagation from the tropical North Atlantic to the North European Basin and further to the Arctic Basin leads to the construction of the scheme shown in Fig. 3. Field observations between 1963 and 2015 were used to form AW temperature time-series for squares smaller than 200 × 200 km in the Arctic Basin. The center coordinates of the squares are indicated in Fig. 3. The AW maximum temperature of a given profile within a square was attributed to the center of that square. The obtained time-series of AW annual temperature values contained gaps, therefore to calculate the correlations, pairs of time-series were formed, taking the gaps into account.

The SST anomaly in the Fram Strait has a four-year lag compared to the tropical Atlantic during which some interactions between the circulation in the ocean and the atmosphere take place. Further, the anomaly spreads to the Arctic Basin in the AW layer, manifesting itself sequentially at the Arctic Cape (Severnaya Zemlya archipelago), at 80°N, 120°E., and reaches the North Pole area in 5 years. The time lag between Atl and Km (Fig. 3) is 3 years, and between Atl and Fram is 4 years despite the equal or slightly greater distance from Atl to Km, which is explained by the faster signal propagation through the Norwegian and Barents Seas due to the peculiarities of atmospheric circulation. Fronts of the cyclones passing through the Barents Sea generate SW and W winds that accelerate water transfer, while at the back of the cyclones, the NE and N winds over the Norwegian and Greenland Seas slow down the Wes-Spitsbergen Current (WSC) transfer. Correlations and lags between anomalies in Fram Strait, the North Pole (NP) region and the point at 80°N, 120°E do not contradict the condition of transitivity with delays (2+1+2) and (2+1) and correlations (0.63 × × 0.84 × 0.89 ≤ 0.56) and (0.63 × 0.84 ≤ 0.60).

The correlation coefficients 0.60 and 0.56 are given to check the transitivity of correlations and lag times between points on the diagram. AW between Fram and NP does not propagate directly but follows a trajectory along the continental slope and the Lomonosov Ridge (as in the Fig. 3).

The average AW temperatures in Fram Strait in different decades (Table 1) show a rapid increase in the 1990s following an increase in inflow and AW temperature. The same trend is seen in the observations in the WSC off the coast of Spitsbergen, taken from the site http://www.mosj.no/.

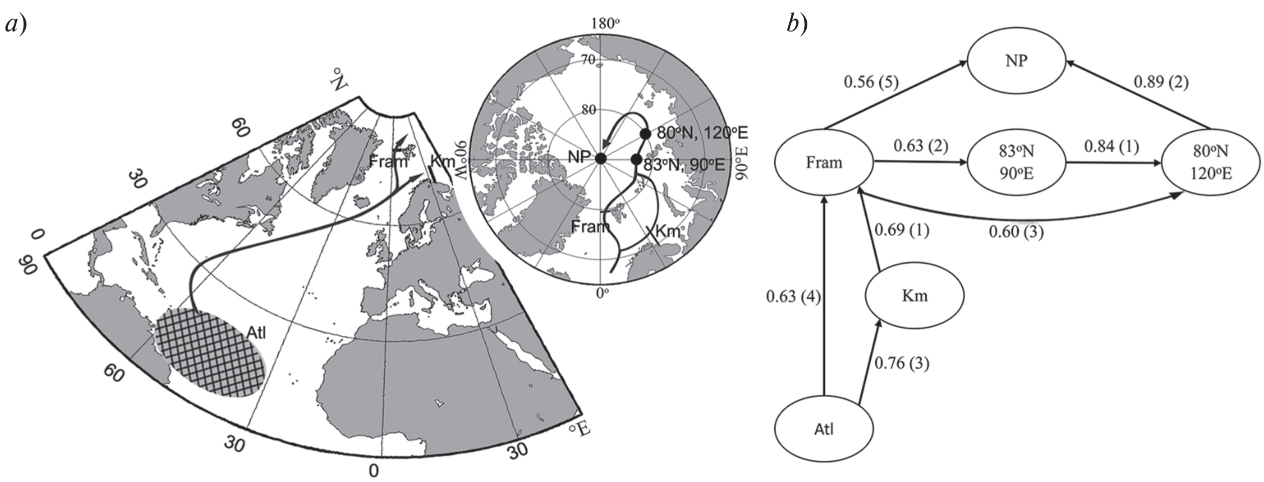

Fig. 3. Propagation of warming signal from the tropical North Atlantic into the Arctic Basin: *a* — the warming signal propagation scheme (Atl — area in the tropical North Atlantic, Km — section at the Kola meridian in the Barents Sea, Fram — the Fram Strait, 93°N 90°E — region with the center at 83°N, 90°E, 80°N 120°E — region at 80°N, 120°E, NP — the North Pole), *b* — correlation graph between changes of water temperature in the regions with relevant delays (years in brackets).

Table 1

Water temperature in the Fram Strait and the West-Spitsbergen Current in the decades 1920–2010s based on the expedition data

	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
T_{Fr}, °C	5.30	5.67	–	4.66	4.12	4.26	4.37	5.70	5.94	5.96
T_{WSC}, °C	–	–	–	–	4.15	4.26	4.53	5.45*	5.62	5.44

*The value of 2.24 for 1998 excluded when calculating the average over the decade.

3.2. Influence of Atlantic water inflow changes on fresh-water content in the upper layer of the Arctic Basin

The AW contribution to the Arctic Basin water column increased with the inflow, while the volume remained unchanged, presumably due to a reduction in the thickness of the upper-most dynamic layer. Accordingly, the FWC of this layer should have decreased. Our calculations of the decadal average FWC in the 0–100 m layer from the 1950–2010s have confirmed this assumption (Fig. 4).

Figure 4 shows a transition to a new distribution of FWC in the 1990s, manifested in a drop in the Eurasian and an increase in the Amerasian region of the Arctic Basin. During the following two decades, the distribution persists with a slight FWC increase in the Eurasian and more noticeable growth in the Amerasian Basin. In the 1960s, the FWC distribution was similar to the 2010s, especially the increased FWC in the Amerasian Basin, which corresponded to the negative salinity anomaly in the North Atlantic in 1960–1970s [34].

The decrease in FWC in the 1990s in the Eurasian part of the basin occurred under the influence of the AW inflow, which is confirmed by a salinity increase at a 100 m depth, also registered at 25 m (Fig. 5). In the Amerasian sector, salinity decreased most of all in the 2000s and 2010s. In the 1960s, a decrease in salinity was most noticeable in the Eurasian part of the Arctic Basin (Table 2).

Quantitative estimates of the mean over a decade of FWC in the Arctic Basin and its two parts (Fig. 6, Table 3) confirm the changes found in the spatial distribution of FWC. Figure 6 shows a decrease in FWC in the Eurasian and an increase in the Amerasian part of the basin in the 1990–2010s with a gradual increase in the average FWC in the entire basin. More detailed estimates of FWC changes are in Table 3.

Table 2

Mean salinity (‰) at different depths (m) in the upper 100 m layer in two parts of the Arctic Basin

Region	Amerasian part				Eurasian part			
Years	25	50	75	100	25	50	75	100
1950s	29.90	30.65	31.63	32.32	32.31	32.72	33.42	33.97
1960s	30.00	30.56	31.46	32.22	31.36	32.10	33.07	33.79
1970s	30.46	30.93	31.68	32.30	31.82	32.40	33.18	33.79
1980s	30.72	31.01	31.65	32.28	32.07	32.60	33.34	33.85
1990s	29.76	30.33	31.43	32.47	32.83	33.14	33.71	34.22
2000s	28.88	29.73	31.08	32.25	32.72	32.99	33.66	34.34
2010s	28.41	29.43	30.94	32.17	32.78	33.04	33.69	34.38

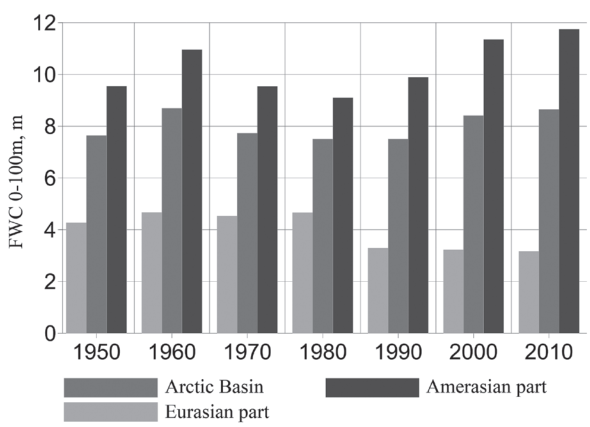

Fig. 6. Diagram of mean decadal fresh water content in the Arctic Basin, Eurasian and Amerasian parts of the Arctic Basin.

Table 3

Mean decadal fresh water content in the upper layers of the Arctic Basin (FWC — equivalent layer of fresh water, m)

Region	Total Basin			Eurasian*			Amerasian part*			Amerasian/Eurasian		
Layer, m Years	0–100	0–50	50–100	0–100	0–50	50–100	0–100	0–50	50–100	0–100	0–50	50–100
1950s	7.64	4.84	2.80	4.27	3.00	1.27	9.55	5.88	3.67	2.24	1.96	2.89
1960s	8.69	5.41	3.28	4.67	3.09	1.58	10.96	6.72	4.24	2.35	2.17	2.68
1970s	7.73	4.67	3.06	4.53	2.87	1.66	9.54	5.69	3.85	2.11	1.98	2.32
1980s	7.50	4.59	2.91	4.66	3.20	1.46	9.10	5.37	3.73	1.95	1.68	2.55
1990s	7.50	4.91	2.59	3.29	2.36	0.92	9.89	6.36	3.53	3.01	2.69	3.84
2000s	8.41	5.60	2.81	3.22	2.45	0.77	11.35	7.39	3.96	3.52	3.02	5.14
2010s	8.65	5.84	2.81	3.16	2.44	0.73	11.75	7.76	3.99	3.72	3.18	5.47
	Changes compared to 1970s,%											
1990s	−3	5.1	−15	−27	−18	−45	4	12	−8	–	–	–
2000s	9	20	−8	−29	−15	−54	19	30	3	–	–	–
2010s	12	25	−8	−30	−15	−56	23	36	4	–	–	–

*The border between the Eurasian and Amerasian parts of the Arctic Basin runs along the Lomonosov Ridge.

Table 3 shows the difference in FWC between the Eurasian and Amerasian parts of the Arctic Basin in every decade. In 1950–1980, the FWC in the Amerasian part was more than two times higher in the 0–100 m layer, almost two times in the 0–50 m layer, and about three times in the 50–100 m layer. In the 1990–2010s, the excess increased, and by the 2010s, it reached almost four times in the 0–100 m layer, more than three times in the 0–50 m layer, and five times in the 50–100 m layer.

A comparison of FWC in different decades with the 1970s reveals that the most changes happened in the 1990–2010s. FWC in the Eurasian basin decreased during this period in all three layers, especially in the 50–100 m layer (56% in the 2010s). In the Amerasian part, the FWC increased, especially in the 0–50 m layer (36% in the 2010s). In this region, FWC expanded significantly in the 1960s (15% higher than in the 1970s).

The influence of the AW flow on the FWC is especially noticeable in the Nansen and Fram Basins, where the main AW flow spreads, and in the area of the Beaufort gyre, in which freshwater inflows accumulate [35]. The diagram in figure 7 shows significant changes in FWC in these areas. The decrease in the FWC in the 1990s is more pronounced in the Fram Basin compared to the Nansen Basin, where the FWC was initially lower, but after the 1990s, the FWC in the basins leveled. On the contrary, in the Beaufort Gyre, there was an increase in FWC, specifically in the 2000s and 2010s. A noticeable increase in FWC in the area of circulation was noted before, in the 1960s.

Table 4 shows quantitative estimates of the content and changes in FWC from the 1950s to the 2010s.

There was an anomalous FWC decrease of more than 60% in the 50–100 m layer in the Nansen and a 50% decrease in the Fram Basins in the 2000–2010s. At the same time, there was also a decrease in FWC in the upper

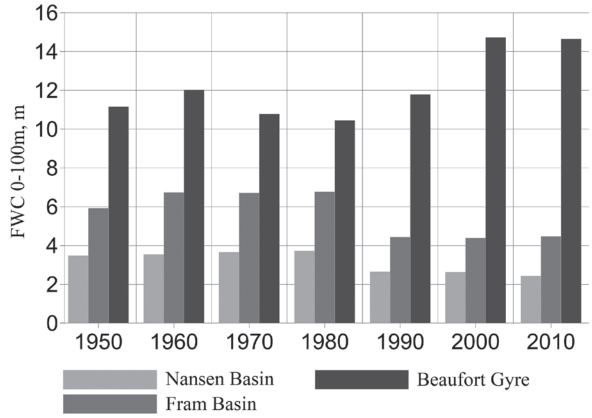

Fig. 7. Diagram of mean decadal fresh water content in the areas of the greatest changes.

Table 4

Mean values of fresh water content in the Arctic Basin areas with the greatest changes (FWC — equivalent layer of fresh water, m)

Region	Nansen Basin (NB)			Fram Basin (FB)			Beaufort Gyre (BG)			BG/NB			FB/NB		
Layer, m years	0—100	0—50	50—100	0—100	0—50	50—100	0—100	0—50	50—100	0—100	0—50	50—100	0—100	0—50	50—100
1950s	3.48	2.57	0.91	5.92	3.90	2.02	11.16	7.08	4.07	3.20	2.75	4.47	1.70	1.52	2.22
1960s	3.54	2.41	1.12	6.73	4.26	2.47	12.02	7.26	4.76	3.40	3.01	4.24	1.90	1.76	2.20
1970s	3.65	2.34	1.32	6.71	4.14	2.58	10.78	6.52	4.26	2.95	2.79	3.23	1.84	1.77	1.96
1980s	3.72	2.70	1.03	6.77	4.43	2.34	10.45	6.23	4.22	2.81	2.31	4.12	1.82	1.64	2.28
1990s	2.65	1.95	0.70	4.44	3.07	1.37	11.78	7.37	4.41	4.44	3.77	6.32	1.68	1.57	1.97
2000s	2.62	2.10	0.52	4.39	3.07	1.31	14.73	9.65	5.08	5.61	4.59	9.73	1.67	1.46	2.51
2010s	2.43	1.96	0.47	4.47	3.20	1.27	14.65	9.43	5.21	6.04	4.81	11.17	1.84	1.63	2.72
	Change relative to the 1970s,%														
1990s	–27	–17	–47	–34	–26	–47	9	13	3	–	–	–	–	–	–
2000s	–28	–10	–61	–35	–26	–50	37	48	19	–	–	–	–	–	–
2010s	–33	–16	–64	–33	–23	–51	36	45	22	–	–	–	–	–	–

0—50 m layer in both regions. Comparison of the FWC in these basins shows the excess of FWC in the Fram Basin almost two times in the 0—50 m layer and more than double in the 50—100 m layer. In the 2010s, the ratio slightly decreased for FWC in the 0—50 m layer and increased for a layer of 50—100 m.

In the Beaufort Gyre, the FWC during the 1950—1980s exceeded the FWC in the Nansen Basin 3—4 times. Later in the 1990—2010s, it was almost 5 times higher in the 0—50 m layer and 10—11 times in the 50—100 m. During these years, the most noticeable FWC increase in the gyre relative to the 1970s was registered in the 0—50 m layer (36 %).

3.3. Freshwater inflows into the Arctic seas and the Arctic Basin

Increased freshwater inflows with river runoff and precipitation served as the sources of FWC growth in the Amerasian sector of the Arctic Basin. On average, the inflow per year is determined primarily by the river runoff (42 %), then the inflow through the Bering Strait (32 %), and precipitation minus evaporation (26 %) [36]. Aagaard & Carmack (1989) [37] estimated the contribution of river flow to be 56 %, 28 % of the inflow through the Bering Strait, and 15 % of net precipitation. At the same time, half of the average annual river inflows come from the three largest Siberian rivers: Ob, Yenisei, and Lena [37]. The total runoff of the three main Siberian rivers and the largest North American Mackenzie River is about 60 % of the average annual volume of freshwater entering the Arctic seas [38,39]. There is an increase in the total average annual discharge of six rivers (Ob, Lena, Yenisei, Kolyma, Mackenzie, Indigirka), and each river average runoff (Table 5), significant in the 2000s and especially in the 2010s.

The decade average annual runoff increased in the 2000s, reaching 2113 km^3yr^{-1}, which is more than 150 km^3yr^{-1} more than in the previous two decades.

Precipitation was calculated for the water area of the Arctic Basin and the adjacent Arctic seas: the Kara, Laptev, East Siberian, Chukchi, and Beaufort seas, with an area of 8.881 million km^2 in total. The initial monthly data on precipitation was averaged over the entire region for each month, summed up over the year, and multiplied by the area of the water area, and then the average annual precipitation over the decade was derived. The results of the calculation are presented in Table 6.

The combined annual freshwater supply with river runoff and precipitation averaged over a decade is presented in Table 7.

Table 5

Mean decadal annual runoff of six rivers, km^3 $year^{-1}$

Years	Ob	Lena	Yenisei	Kolyma	Mackenzie	Indigirka	Total six rivers
1980–1989	376	548	582	98	273	53	1930
1990–1999	405	532	613	105	283	53	1991
2000–2009	417	590	641	106	304	55	2113
2010–2019	419	590	579	109	280	56	2033

Table 6

Mean decadal annual precipitation (km^3/year) at the Arctic Basin and Arctic seas water area based on three monthly precipitation data arrays

Decade	GPCC	ERA5	Observations
1980–89	2317	3010	2188
1990–99	2208	3056	2209
2000–09	2482	3094	2281
2010–19	2860	3217	2312

Table 7

Mean decadal annual river runoff (km^3/yr) of six largest rivers (Ob, Lena, Yenisei, Kolyma, Indigirka, Mackenzie), flowing into the Arctic seas, and annual precipitation (km^3/yr) at the water area of the Arctic Basin and Arctic seas, calculated by data of GPCC data array

Decade	Annual runoff	Annual precipitation — evaporation	Supply
1980–1989	1930	1483	3413
1990–1999	1991	1413	3404
2000–2009	2113	1588	3701
2010–2019	2033	1830	3863

The precipitation volume is reduced by the losses from evaporation. In the work of Serreze et al., 2006, precipitation is estimated at 3300 km^3/year, and evaporation is 1200 km^3/year. The evaporation / precipitation ratio is 0.36. Then (P-E) = 0.64 R. We used this ratio to calculate (P-E) in Table 7.

The contribution of sea ice melting is the difference between summer melting and winter freezing. This difference was calculated from the ice-cover parameters with the joint ocean-ice model AARI–IOCM [33, 40] and appeared to be negative for the entire Arctic Ocean, i.e. more ice freezes over a year than it melts. According to formula (3), the excess of the ice buildup is equal to the annual removal of ice minus the increase in summer ice melting. In a stable climate, the growth of melting is zero, and with warming, it increases.

Table 8 shows the calculation results of the average annual volumes (103 km^3) of ice melting in the Arctic Ocean over a decade.

Obviously, the average annual increase in ice melting over a decade in Table 8 is a small fraction of the annual ice removal through Fram Strait, equal to 2400 ± 640 km^3 according to the estimate [41].

For the Beaufort Gyre, the ice-melt contribution estimate to the desalination of the upper layer was 50% [42]. Our estimates of changes in ice volume in the area of the Beaufort Gyre (71–80°N, 130–160°W) based on the AARI–IOCM model did not show a noticeable excess of winter growth over summer melting.

Average for the 1980–2019s, the melting excess over freezing in the Beaufort Gyre averages 15 km^3 in the annual cycle. The maximum summer melting surplus of 420 km^3 was obtained for 2008. The estimates are calculated without accounting for the export of ice outside the gyre, which alternatively would raise the estimates of summer melting.

The accumulation of freshwater observed in the last two decades in the gyre is primarily supplied from external sources: from precipitation, river runoff (Tables 5–7), water from the Pacific Ocean, also ice melting in the Chukchi and East Siberian seas, where an excess of melting over freezing was simulated on the model.

4. Discussion

Estimates of FWC changes in the 2000–2010s relative to the 1970s in the 0–100 m layer in the Arctic Basin and its parts (Table 9) show a climatic shift in FWC from the cooling period in the 1970s to warming in the 2000–2010s.

Table 8

Mean decadal annual volumes (km^3) of ice melting rise $\left(V_{\min}^{g-1} - V_{\min}^{g}\right)$ in the Arctic Basin

	ΔV_{melt}
1981–1989	153
1990–1999	41
2000–2009	359
2010–2017	127

Table 9

Changes of mean fresh water content (ΔV_{fw}) in the layer 0–100 m of the Arctic Basin and its parts since 1970s till 2000–2010s

№	Arctic Basin region	Area, km^2	ΔV_{fw}, km^3	ΔV_{fw}, %
1	Arctic Basin	4194402	3356	10.3
2	Eurasian part	1626154	–2179	–29.6
3	Amerasian part	2568248	5162	21.0
4	Beaufort gyre	740412	2895	36.3

Changes in FWC between the 1950–1980s and the 2000–2010s are not associated with calculation errors of the decadal averages, which are small due to the large dataset (more than 10,000) of FWC values averaged in each decade at individual points. As a result, the standard deviation of the decadal averages (0.21) is an order of magnitude greater than the errors of the averages (0.011).

FWC in the upper 100 m layer of the Arctic basin in the 2000–2010s increased by 10 % compared to the 1970s. At the same time, in the Eurasian part of the basin, FWC decreased by 30 %, and in the Amerasian region, it increased by 21 %. On average, the growth of FWC prevailed in the entire basin due to the biggest FWC contribution from the Amerasian region, which occupies 61 % of the basin area. In the Beaufort gyre, FWC increased in the 2000–2010s by 36 % compared to the 1970s. In the study of Proshutinsky et al. [44], the FWC increase in the gyre from the 1970s to the 2003–2018s is estimated as 40 %.

The highest FWC in the entire basin was obtained in the 1960s, preceding the negative salinity anomaly in the North Atlantic in the 1960–1970s [34]. Moreover, the greatest decrease in salinity during this period was registered in the Eurasian Basin (Table 2).

The largest FWC drop (more than double compared to the 1970s) occurred in the 50–100 m layer of the Eurasian Basin in the 2000–2010s. The drop was caused by the salinity increase in the layer located above the AW (Fig. 5). The influence of the AW on the FWC decline in the 50–100 m layer is most noticeable in the Nansen Basin, through which the AW passes. Here FWC in the 2000–2010s decreased by more than 60 % (Table 4). In-situ observations during these years along a transect near the continental slope of the Nansen Basin reflected the rise of the upper boundary of the AW and an increase in salinity in the overlying layer (Fig. 8).

A gradual increase is apparent in the AW temperature and the rise of the upper and deepening of the lower 0-isotherms, demarcating the growing AW layer. The upper intermediate layer between AW and desalinated near-surface water becomes saltier. These changes were caused by an expanded inflow of saltier and warmer AW, which increased in the 1990s, concurrent the most noticeable increase in salinity at the 100 m, and the corresponding decrease in FWC (Fig. 4, 5, 7). Subsequently, the increased inflow of AW was retained, and heat and salt from the expanded AW layer gradually spread into the overlying layer, suggesting the “atlantification” of the upper layer in the Eurasian part of the Arctic basin [43, 44]. An increase in the AW volume also contributed to a reduction in the FWC in the upper layer resulting from a decrease in its thickness [26].

In the Fram Basin, to the north of the Nansen Basin, the reduction in FWC in the 50–100 m layer was 50 %. Initially, the FWC in the 0–50 m layer was more than 1.5 times higher in the Fram Basin, and in the 50–100 m layer, it was 2–2.5 times higher than in the Nansen Basin due to the difference in salinity. First, this salinity distribution feature in the upper layer of the Arctic Basin near the continental slope was described by N.N. Zubov (1944) [45], who explained its origin by winter mixing with the underlying Atlantic waters. Later A.F. Treshnikov (1959) [46] also noted, based on more complete data, high salinity values near the continental slope of the Kara and Laptev Seas. In the outermost part of the Fram Basin, near the North Pole, the upper intermediate layer also became slightly saltier, and the freshwater content in the 2000s and 2010s decreased relative to the 1970s. Most of all (46 %) FWC increased in BG during this period in the upper 50 m layer. The increase in the FWC in the gyre is associated with the anticyclonic effect of wind [35, 47], melting of sea ice [42], the runoff of the Mackenzie River [48], and the inflow of the Pacific Ocean [49, 50].

The data in Table 9 confirmed the decrease in FWC in the Eurasian Basin, despite the increase in precipitation and river runoff into the Arctic Basin resulting from the increased inflow of Atlantic water since the 1990s and salinization of the upper 100-meter layer. According to our estimates (Table 7), the freshwater inflow from runoff and precipitation increased in the 2010s compared to the 1980s by 450 km^3 per year (13 %) on average. Freshwater accumulates in the Beaufort Gyre and throughout the Amerasian Basin. In the 1960s, freshwater also accumulated in the same regions. The outflow of freshwater and ice through the Fram Strait caused the “great salinity anomaly” in the North Atlantic [34].

5. Conclusion

Decadal changes in the content and inflow of freshwater into the upper 100-meter layer of the Arctic Basin from the 1950s to the 2010s were evaluated for the first time.

The results show that the freshwater content (FWC) in the upper layer of the Arctic Basin by the 2000–2010s expanded relative to the 1970s by 10 %. At the same time, FWC decreased in the Eurasian and increased in the Amerasian regions of the basin. The growth prevailed due to the contribution of the Amerasian region, which occupies 61 % of the basin area. The highest freshwater content in the entire basin was registered in the 1960s, preceding the negative salinity anomaly in the North Atlantic in the 1960–1970s.

The decrease in FWC in the Eurasian Basin resulting from an increased inflow of Atlantic water since the 1990s and a related increase in temperature and salinization of the upper 100 meter layer, despite an increase in precipitation and river runoff into the Arctic Basin.

The rise in inflow and temperature of Atlantic water in the Arctic Basin begins in the tropical North Atlantic.

Freshwater accumulates in the Beaufort Gyre and throughout the Amerasian Basin. In the Beaufort Gyre, FWC in the 0–100 m layer increased in the 2000–2010s by 36 % compared to the 1970s. The most significant increase of FWC (46 %) occurred during this period in the upper 50 m layer.

The average annual inflow from six rivers (Ob, Lena, Yenisei, Kolyma, Mackenzie, Indigirka) was increasing, as is the inflow from precipitation- evaporation difference. The total average annual inflow increased from the 1980s to the 2010s by 450 km^3/year.

Based on the calculation of the ice cover parameters on the joint ocean-ice model AARI–IOCM, the contribution of sea ice melting to the freshwater balance of the Arctic Basin was estimated. In a year, ice freezing exceeds melting by the amount of annual ice removal from the basin minus the growth of summer ice melting. With a stable climate, the increase in melting is equal to zero. During the observed warming since 1980, it increased on average by 0.17 ± 0.14 km^3/year, and in the 2000–2010s by 0.24 ± 0.14 km^3/year.

6. Funding

This work was supported by the RFBR project 18–05–60107.

Литература

1. *Alekseev G.*, *Kuzmina S.*, *Bobylev L.*, *Urazgildeeva A.*, *Gnatiuk N.* Impact of atmospheric heat and moisture transport on the Arctic warming // Int. J. Climatol. 2019. V. 39, № 8. P. 1–11. doi: 10.1002/joc.6040
2. *Алексеев Г.В.*, *Кузьмина С.И.*, *Уразгильдеева А.В.*, *Бобылев Л.П.* Влияние атмосферных переносов тепла и влаги на усиление потепления в Арктике в зимний период // Фундаментальная и прикладная климатология. 2016. Т. 1. С. 43–63.
3. *Марчук Г.И.*, *Скиба Ю.Н.* Численный расчет сопряженной задачи для моделей термического взаимодействия атмосферы с океаном и континентом // Изв. АН СССР. ФАО. 1976. Т. 12, № 5. С. 16–24.
4. *Николаев Ю.В.* Крупномасштабное взаимодействие океана и атмосферы и формирование аномалий погоды. Л.: Гидрометеоиздат, 1981. 51 с.
5. *Kushnir Y.* Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions // J. Clim. 1994. V. 7, № 1. P. 141–157.
6. *Семенов В.А.* Влияние океанического притока в Баренцево море на изменчивость климата в Арктике // Доклады РАН. 2008. Т. 418, № 1. С. 106–109.
7. *Palmer M.D.*, *Haines K.*, *Tett S.F.B.*, *Ansell T.J.* Isolating the signal of ocean global warming // Geophys. Res. Lett. 2007. V. 34, № 23. P. 1–6.
8. IPCC: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change / eds. R.K. Pachauri, L.A. Meyer. Geneva, Switzerland, 2014. 151 p.
9. *Тимофеев В.Т.* Водные массы Арктического бассейна. Ленинград: Гидрометеоиздат, 1960. 190 с.
10. *Трешников А.Ф.*, *Баранов Г.И.* Структура циркуляции вод Арктического бассейна. Л.: Гидрометеоиздат, 1972. 158 с.
11. *Иванов В.В.*, *Тимохов Л.А.* Атлантические воды в арктической циркуляционной трансполярной системе // Метеорология и гидрология. 2019. V. 4. P. 36–53.
12. *Polyakov I.V.*, *Walsh J.E.*, *Kwok R.* Recent changes of Arctic multiyear sea ice coverage and the likely causes // Bull. Am. Meteorol. Soc. 2012. V. 93, N2. P. 145–151.

13. *Polyakov I.V.*, *Alekseev G.V.*, *Timokhov L.A.*, *Bhatt U.S.*, *Colony R.L.*, *Simmons H.L.*, *Walsh D.*, *Walsh J.E.*, *Zakharov V.F.* Variability of the intermediate Atlantic water of the Arctic Ocean over the last 100 years // J. Clim. 2004. V. 17, N 23. P. 4485–4497.

14. *Häkkinen S.*, *Proshutinsky A.* Freshwater content variability in the Arctic Ocean // J. Geophys. Res. Ocean. 2004. V. 109, N C3.

15. *Алексеев Г.В.*, *Фролов И.Е.*, *Соколов В.Т.* Наблюдения в Арктике не подтверждают ослабление термохалинной циркуляции в Северной Атлантике // Доклады Академии Наук. 2007. Т. 413, № 2. С. 277–280.

16. *Алексеев Г.В.*, *Булатов Л.В.*, *Захаров В.Ф.*, *Иванов В.В.* Тепловая экспансия атлантических вод в Арктическом бассейне // Метеорология и гидрология. 1998. Т. 7. С. 69–78.

17. *Carmack E.C.*, *Macdonald R.W.*, *Perkin R.G.*, *McLaughlin F.A.*, *Pearson R.J.* Evidence for warming of Atlantic water in the Southern Canadian Basin of the Arctic Ocean: Results from the Larsen-93 Expedition // Geophys. Res. Lett. 1995. V. 22, N 9. P. 1061–1064.

18. *Алексеев Г.В.*, *Булатов Л.В.*, *Захаров В.Ф.*, *Иванов В.В.* Поступление необычно теплых атлантических вод в Арктический бассейн // Доклады РАН. 1997. Т. 356. С. 401–403.

19. *Zhang X.*, *Sorteberg A.*, *Zhang J.*, *Gerdes R.*, *Comiso J.C.* Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system // Geophys. Res. Lett. 2008. V. 35, N 22. P. 1–7.

20. *Zhang X.*, *He J.*, *Zhang J.*, *Polyakov I.*, *Gerdes R.*, *Inoue J.*, *Wu P.* Enhanced poleward moisture transport and amplified northern high-latitude wetting trend // Nat. Clim. Chang. 2013. V. 3. P. 47–51.

21. *Prowse T.D.*, *Bring A.*, *Carmack E.C.*, *Holland M.M.*, *Instanes A.*, *Mard J.*, *Vihma T.*, *Wrona F.J.* Freshwater // Snow, Water, Ice and Permafrost in the Arctic (SWIPA). Oslo, 2017. P. 175–176.

22. *Polyakov I.V.*, *Alexeev V.A.*, *Ashik I.M.*, *Bacon S.*, *Beszczynska-Möller A.*, *Carmack E.C.*, *Dmitrenko I.A.*, *Fortier L.*, *Gascard J.*, *Hansen E.*, *Hölemann J.*, *Ivanov V.V.*, *Kikuchi T.*, *Kirillov S.*, *Lenn Y.*, *McLaughlin F.A.*, *Piechura J.*, *Repina I.*, *Timokhov L.A.*, *Walczowski W.*, *Woodgate R.* Fate of early 2000s arctic warm water pulse // Bull. Am. Meteorol Soc. 2011. V. 92, N 5. P. 561–566.

23. *Алексеев Г.В.*, *Пнюшков А.В.*, *Иванов Н.Е.*, *Ашик И.М.*, *Соколов В.Т.* Комплексная оценка климатических изменений в морской Арктике с использованием данных МПГ 200708 // Проблемы Арктики и Антарктики. 2009. Т. 1, № 81. С. 7–14.

24. *Алексеев Г.В.*, *Иванов Н.Е.*, *Пнюшков А.В.*, *Балакин А.А.* Изменения климата в морской Арктике в начале XXI века // Проблемы Арктики и Антарктики. 2010. Т. 3, № 86. С. 22–34.

25. *Алексеев Г.В.*, *Иванов Н.Е.*, *Пнюшков А.В.*, *Харланенкова Н.Е.* Климатические изменения в морской Арктике в начале XXI века // Метеорологические и геофизические исследования. Изд-во Paulsen, 2011. С. 7–28. doi: 10.13140/RG.2.1.2235.6009

26. *Алексеев Г.В.*, *Пнюшков А.В.*, *Смирнов А.В.*, *Вязилова А.Е.*, *Глок Н.И.* Влияние притока из Атлантики на содержание пресной воды в верхнем слое Арктического бассейна // Проблемы Арктики и Антарктики. 2019. Т. 4. С. 363–388. doi: 10.30758/0555–2648–2019–65–4–363–388

27. Environmental Working Group (EWG). Joint U.S. Russian Atlas of the Arctic Ocean: Oceanography Atlas for the Winter Period / National Snow and Ice Data Center. Boulder, CO, 1997. URL: http://ns.noaa.gov/atlas (дата обращения: 01.05.2020).

28. *Barth A.*, *Beckers J.-M.*, *Troupin C.*, *Alvera-Azcárate A.*, *Vandenbulcke L.* divand-1.0: n-dimensional variational data analysis for ocean observations // Geosci. Model Dev. 2014. V. 7, N 1. P. 225–241.

29. *Adler R.F.*, *Huffman G.J.*, *Chang A.*, *Ferraro R.*, *Xie P.P.*, *Janowiak J.*, *Rudolf B.*, *Schneider U.*, *Curtis S.*, *Bolvin D.*, *Gruber A.*, *Susskind J.*, *Arkin P.*, *Nelkin E.* The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present) // J. Hydrometeorol. 2003. V. 4, N 6. P. 1147–1167.

30. *Lammers R.B.*, *Shiklomanov A.I.*, *Vörösmarty C.J.*, *Fekete B.M.*, *Peterson B.J.* R-ArcticNet, A Regional Hydrographic Data Network for the Pan-Arctic Region (ISO-image of CD-ROM). PANGAEA. 2016. URL: https://doi.org/10.1594/PANGAEA.859422 (дата обращения: 14.04.2020).

31. *Shiklomanov A.I.*, *Holmes R.M.*, *McClelland J.W.*, *Tank S.E.*, *Spencer R.G.M.* Arctic Great Rivers Observatory. Discharge Dataset, Version 20190402. 2018. URL: https://www.arcticrivers.org/data (дата обращения: 14.04.2020).

32. *Карсаков А.Л.* Океанографические исследования на разрезе «Кольский меридиан» в Баренцевом море за период 1900–2008 гг. Мурманск: Изд-во ПИНРО, 2009. 139 с.

33. *Кулаков М.Ю.*, *Макштас А.П.*, *Шутилин С.В.* AARI–IOCM — совместная модель циркуляции вод и льдов Северного Ледовитого океана // Проблемы Арктики и Антарктики. 2012. Т. 2(97). С. 6–18.

34. *Dickson R.R.*, *Meincke J.*, *Malmberg S.A.*, *Lee A.J.* The “great salinity anomaly” in the Northern North Atlantic 1968–1982 // Prog. Oceanogr. 1988. V. 20, N 2. P. 103–151.

35. *Proshutinsky A.*, *Krishfield R.A.*, *Timmermans M.-L.*, *Toole J.M.*, *Carmack E.C.*, *McLaughlin F.A.*, *Williams W.J.*, *Zimmermann S.L.*, *Itoh M.*, *Shimada K.* Beaufort Gyre freshwater reservoir: State and variability from observations // J. Geophys. Res. 2009. V. 114, N C00A10. P. 1–25. doi: 10.1029/2008JC005104

36. *Serreze M.C.*, *Barrett A.P.*, *Slater A.G.*, *Woodgate R.A.*, *Aagaard K.*, *Lammers R.B.*, *Steele M.*, *Moritz R.E.*, *Meredith M.*, *Lee C.M.* The large-scale freshwater cycle of the Arctic // J. Geophys. Res. Ocean. 2006. V. 111, N C11010. P. 1–19. doi: 10.1029/2005JC003424
37. *Aagaard K.*, *Carmack E.C.* The role of sea ice and other fresh water in the Arctic circulation // J. Geophys. Res. 1989. V. 94, N C10. P. 14485–14498.
38. *Grabs W.E.*, *Portmann F.*, *Couet T.* Discharge Observation Networks in Arctic Regions: Computation of the River Runoff into the Arctic Ocean, Its Seasonality and Variability // The Freshwater Budget of the Arctic Ocean / ed. E.L. Lewis. Dordrecht, The Netherlands: Kluwer, 2000. P. 249–267.
39. *Ahmed R.*, *Prowse T.*, *Dibike Y.*, *Bonsal B.*, *O'Neil H.* Recent trends in freshwater influx to the arctic ocean from four major arctic-draining rivers // Water. 2020. V. 12, N 4. P. 1189.
40. *Кулаков М.Н.*, *Макштас А.П.*, *Шутилин С.В.* Модельные оценки чувствительности ледяного покрова Северного Ледовитого океана к изменениям форсингов // Проблемы Арктики и Антарктики. 2012. V. 3, N 93. P. 66–74.
41. *Spreen G.*, *Steur L. De*, *Divine D.*, *Gerland S.*, *Hansen E.*, *Kwok R.* Arctic Sea Ice Volume Export Through Fram Strait From 1992 to 2014 // J. Geophys. Res. Ocean. 2020. V. 125, N 6. P. e2019JC016039. doi: 10.1029/2019JC016039
42. *Wang Q.*, *Wekerle C.*, *Danilov S.*, *Koldunov N.*, *Sidorenko D.*, *Sein D.*, *Rabe B.*, *Jung T.* Arctic Sea Ice Decline Significantly Contributed to the Unprecedented Liquid Freshwater Accumulation in the Beaufort Gyre of the Arctic Ocean // Geophys. Res. Lett. 2018. V. 45, N 10. P. 4956–4964. doi: 10.1029/2018GL077901
43. *Polyakov I.V.*, *Pnyushkov A.V.*, *Alkire M.B.*, *Ashik I.M.*, *Baumann T.M.*, *Carmack E.C.*, *Goszczko I.*, *Guthrie J.*, *Ivanov V.V.*, *Kanzow T.*, *Krishfield R.*, *Kwok R.*, *Sundfjord A.*, *Morison J.*, *Rember R.*, *Yulin A.V.* Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean // Sci. 2017. V. 356, N 6335. P. 285–291. doi: 10.1126/science.aai8204
44. *Polyakov I.V.*, *Rippeth T.P.*, *Fer I.*, *Alkire M.B.*, *Baumann T.M.*, *Carmack E.C.*, *Ingvaldsen R.*, *Ivanov V.V.*, *Janout M.*, *Lind S.*, *Padman L.*, *Pnyushkov A.V.*, *Rember R.* Weakening of cold halocline layer exposes sea ice to oceanic heat in the eastern arctic ocean // J Clim. 2020. V. 33, N 18. P. 8107–8123. doi: 10.1175/jcli-d-19–0976.1
45. *Зубов Н.Н.* Льды Арктики. М.: Изд-во Главсевморпути, 1944. 360 с.
46. *Трешников А.Ф.* Поверхностные воды Арктического бассейна // Проблемы Арктики и Антарктики. 1959. Т. 7. С. 5–14.
47. *Proshutinsky A.*, *Krishfield R.*, *Toole J.M.*, *Timmermans M.-L.*, *Williams W.*, *Zimmermann S.*, *Yamamoto-Kawai M.*, *Armitage T.W.K.*, *Dukhovskoy D.*, *Golubeva E.N.*, *Manucharyan G.E.*, *Platov G.*, *Watanabe E.*, *Kikuchi T.*, *Nishino S.*, *Itoh M.*, *Kang S.-H.*, *Cho K.-H.*, *Tateyama K.* Analysis of the Beaufort Gyre Freshwater Content in 2003–2018 // J. Geophys. Res. Ocean. 2019. V. 124, N 12. P. 9658–9689. doi: 10.1029/2019JC015281
48. *Рябченко В.А.*, *Алексеев Г.В.*, *Неелов И.А.*, *Дворников А.Ю.* Распространение речных вод в Северном Ледовитом океане // Метеорология и гидрология. 2001. Т. 9. С. 61–69.
49. *Kelly S.J.*, *Proshutinsky A.*, *Popova E.K.*, *Aksenov Y.K.*, *Yool A.* On the origin of water masses in the Beaufort Gyre // J. Geophys. Res. Ocean. 2019. V. 124, № 7. P. 4696–4709.
doi: 10.1029/2019JC015022
50. *Woodgate R.A.* Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data // Prog. Oceanogr. 2018. V. 160. P. 124–154. doi: 10.1016/j.pocean.2017.12.007

References

1. *Alekseev G.*, *Kuzmina S.*, *Bobylev L.*, *Urazgildeeva A.*, *Gnatiuk N.* Impact of atmospheric heat and moisture transport on the Arctic warming. *Int. J. Climatol.* 2019, 39, 8, 1–11. doi: 10.1002/joc.6040
2. *Alekseev G.V.*, *Kuzmina S.I.*, *Urazgil'deeva A.V., Bobylev L.* Impact of atmospheric heat and moisture transport on Arctic warming in winter. *Fundamental and Applied Climatology*. 2016, 1, 43–63 (in Russian).
3. *Marchuk G.I.*, *Skiba Y.N.* Numerical Calculation of the Conjugate Problem for a Model of the Thermal Interaction of the Atmosphere with the Oceans and Continents. *Izv.Acad. Sci. USSR. Atmospheric and Oceanic Physics*. 1976, 12, 5, 16–24 (in Russian).
4. *Nikolaev Y.V.* Large scale ocean-air interaction and weather anomalies formation. *Leningrad*, *Gidrometeoizdat*, 1981. 51 p. (in Russian).
5. *Kushnir Y.* Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. *J. Clim*. 1994, 7, 1, 141–157.
6. *Semenov V.A.* Influence of oceanic inflow to the Barents Sea on climate variability in the Arctic region. *Doklady Earth Sciences*. 2008, 418, 1, 106–109.
7. *Palmer M.D.*, *Haines K.*, *Tett S.F.B.*, *Ansell T.J.* Isolating the signal of ocean global warming. *Geophys. Res. Lett.* 2007, 34, 23, 1–6.

8. IPCC: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change / eds. R.K. Pachauri, L.A. Meyer. *Geneva*, *Switzerland*, 2014. 151 p.
9. *Timofeev V.T.* Water Masses in the Arctic Basin. *Leningrad*, *Gidrometeoizdat*, 1960. 190 p. (in Russian).
10. *Treshnikov A.F.*, *Baranov G.I.* Structure and Circulation of Water in the Arctic Basin. *Leningrad*, *Gidrometeoizdat*, 1972. 158 p. (in Russian).
11. *Ivanov V.V.*, *Timokhov L.A.* Atlantic Water in the Arctic Circulation Transpolar System. *Russ. Meteorol. Hydrol*. 2019, 4, 36–53. doi: 10.3103/S1068373919040034
12. *Polyakov I.V., Walsh J.E.*, *Kwok R.* Recent changes of Arctic multiyear sea ice coverage and the likely causes. *Bull. Am. Meteorol. Soc*. 2012, 93, 2, 145–151.
13. *Polyakov I.V.*, *Alekseev G.V.*, *Timokhov L.A.*, *Bhatt U.S.*, *Colony R.L.*, *Simmons H.L.*, *Walsh D.*, *Walsh J.E.*, *Zakharov V.F.* Variability of the intermediate Atlantic water of the Arctic Ocean over the last 100 years. *J. Clim*. 2004, 17, 23, 4485–4497.
14. *Häkkinen S.*, *Proshutinsky A.* Freshwater content variability in the Arctic Ocean. *J. Geophys. Res. Ocean*. 2004, 109, C3.
15. *Alekseev G.V.*, *Frolov I.E.*, *Sokolov V.T.* Observations in the Arctic Ocean do not confirm weakening of thermohaline circulation in the North Atlantic. *Doklady Earth Sciences*. 2007, 413, 2, 277–280 (in Russian).
16. *Alekseev G.V.*, *Bulatov L.V.*, *Zakharov V.F.*, *Ivanov V.V.* Thermal expansion of Atlantic water in the Arctic Basin. *Russian Meteorology and Hydrology*. 1998, 7, 54–61.
17. *Carmack E.C.*, *Macdonald R.W.*, *Perkin R.G.*, *McLaughlin F.A.*, *Pearson R.J.* Evidence for warming of Atlantic water in the Southern Canadian Basin of the Arctic Ocean: Results from the Larsen-93 Expedition. *Geophys. Res. Lett*. 1995, 22, 9, 1061–1064.
18. *Alekseev G.V.*, *Bulatov L.V.*, *Zakharov V.F.*, *Ivanov V.V.* Advection of unusual warm atlantic water into the arctic basin. *Doklady Akademii Nauk SSSR*. 1997, 356, 401–403 (in Russian).
19. *Zhang X.*, *Sorteberg A.*, *Zhang J.*, *Gerdes R.*, *Comiso J.C.* Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system. *Geophys. Res. Lett*. 2008, 35, 22, 1–7.
20. *Zhang X.*, *He J.*, *Zhang J.*, *Polyakov I.*, *Gerdes R.*, *Inoue J.*, *Wu P.* Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. *Nat. Clim. Chang*. 2013, 3, 47–51.
21. *Prowse T.D.*, *Bring A.*, *Carmack E.C.*, *Holland M.M.*, *Instanes A.*, *Mard J.*, *Vihma T.*, *Wrona F.J.* Freshwater. *Snow*, *Water*, *Ice and Permafrost in the Arctic* (*SWIPA*). Oslo, 2017. P. 175–176.
22. *Polyakov I.V.*, *Alexeev V.A.*, *Ashik I.M.*, *Bacon S.*, *Beszczynska-Möller A.*, *Carmack E.C.*, *Dmitrenko I.A.*, *Fortier L.*, *Gascard J.*, *Hansen E.*, *Hölemann J.*, *Ivanov V.V.*, *Kikuchi T.*, *Kirillov S.*, *Lenn Y.*, *McLaughlin F.A.*, *Piechura J.*, *Repina I.*, *Timokhov L.A.*, *Walczowski W.*, *Woodgate R.* Fate of early 2000s arctic warm water pulse. *Bull. Am. Meteorol. Soc*. 2011, 92, 5, 561–566.
23. *Alekseev G.V.*, *Pnyushkov A.V.*, *Ivanov N.E.*, *Ashik I.M.*, *Sokolov V.T.* The complex estimation of climatic change in the sea Arctic according to IPY2007/08 data // Arctic and Antarctic Research. 2009. V. 1, № 81. P. 7–14 (in Russian).
24. *Alekseev G.V.*, *Ivanov N.E.*, *Pnyushkov A.V.*, *Balakin A.A.* Climate change in the marine Arctic in the early 21st century // Arctic and Antarctic Research. 2010. V. 3, № 86. P. 22–34. (in Russian).
25. *Alekseev G.V.*, *Ivanov N.E.*, *Pnyushkov A.V.*, *Kharlanenkova N.E.* Climate change in the marine Arctic in the beginning of 21s Century. In book: Contribution of Russia to International Polar Year 2007/08: *Meteorological and geophysical researches*, *Paulsen Editions*, 2011, 7–28. doi: 10.13140/RG.2.1.2235.6009 (in Russian).
26. *Alekseev G.V.*, *Pnyushkov A.V.*, *Smirnov A.V.*, *Vyazilova A.E.*, *Glok N.I.* Influence of Atlantic inflow on the freshwater content in the upper layer of the Arctic Basin. *Arctic and Antarctic Research*. 2019, 65(4), 363–388 (in Russian). doi: 10.30758/0555–2648–2019–65–4–363–388
27. Environmental Working Group (EWG). Joint U.S. Russian Atlas of the Arctic Ocean: Oceanography Atlas for the Winter Period / National Snow and Ice Data Center. Boulder, CO, 1997. URL: http://ns.noaa.gov/atlas (date of access: 01.05.2020).
28. *Barth A.*, *Beckers J.-M.*, *Troupin C.*, *Alvera-Azcárate A.*, *Vandenbulcke L.* divand-1.0: n-dimensional variational data analysis for ocean observations. *Geosci. Model Dev*. 2014, 7, 1, 225–241.
29. *Adler R.F.*, *Huffman G.J.*, *Chang A.*, *Ferraro R.*, *Xie P.P.*, *Janowiak J.*, *Rudolf B.*, *Schneider U.*, *Curtis S.*, *Bolvin D.*, *Gruber A.*, *Susskind J., Arkin P.*, *Nelkin E.* The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present). *J Hydrometeorol*. 2003, 4, 6, 1147–1167.
30. *Lammers R.B.*, *Shiklomanov A.I.*, *Vörösmarty C.J.*, *Fekete B.M.*, *Peterson B.J.* R-ArcticNet, A Regional Hydrographic Data Network for the Pan-Arctic Region (ISO-image of CD-ROM). PANGAEA. 2016. doi: 10.1594/PANGAEA.859422
31. *Shiklomanov A.I.*, *Holmes R.M.*, *McClelland J.W.*, *Tank S.E.*, *Spencer R.G.M.* Arctic Great Rivers Observatory. Discharge Dataset, Version 20190402. 2018. https://www.arcticrivers.org/data (date of access: 14.04.2020).

32. *Karsakov A.L.* Oceanographic investigations along the "Kola Meridian" section in the Barents Sea in 1900–2008. *Murmansk*, *PINRO Press*, 2009. 139 p. (in Russian).
33. *Kulakov M.U.*, *Makshtas A.P.*, *Shutilin S.V.* AARI–IOCM — coupled ice and circulation model for the Arctic region. *Arctic and Antarctic Research*. 2012, 2(97), 6–18 (in Russian).
34. *Dickson R.R.*, *Meincke J.*, *Malmberg S.A.*, *Lee A.J.* The "great salinity anomaly" in the Northern North Atlantic 1968–1982. *Prog. Oceanogr*. 1988, 20, 2, 103–151.
35. *Proshutinsky A.*, *Krishfield R.A.*, *Timmermans M.-L.*, *Toole J.M.*, *Carmack E.C.*, *McLaughlin F.A.*, *Williams W.J.*, *Zimmermann S.L.*, *Itoh M.*, *Shimada K.* Beaufort Gyre freshwater reservoir: State and variability from observations. *J Geophys Res*. 2009, 114, C00A10, 1–25. doi: 10.1029/2008JC005104
36. *Serreze M.C.*, *Barrett A.P.*, *Slater A.G.*, *Woodgate R.A.*, *Aagaard K.*, *Lammers R.B.*, *Steele M.*, *Moritz R.E.*, *Meredith M.*, *Lee C.M.* The large-scale freshwater cycle of the Arctic. *J. Geophys. Res. Ocean*. 2006, 111, C11010, 1–19. doi: 10.1029/2005JC003424
37. *Aagaard K.*, *Carmack E.C.* The role of sea ice and other fresh water in the Arctic circulation. *J. Geophys. Res*. 1989, 94, C10, 14485–14498.
38. *Grabs W.E.*, *Portmann F.*, *Couet T.* Discharge Observation Networks in Arctic Regions: Computation of the River Runoff into the Arctic Ocean, Its Seasonality and Variability. *The Freshwater Budget of the Arctic Ocean* / Ed. E.L. Lewis. *Dordrecht*, *The Netherlands*, *Kluwer*, 2000, 249–267.
39. *Ahmed R.*, *Prowse T.*, *Dibike Y.*, *Bonsal B.*, *O'Neil H.* Recent trends in freshwater influx to the arctic ocean from four major arctic-draining rivers. *Water* (*Switzerland*). 2020, 12, 4, 1189.
40. *Kulakov M. Yu.*, *Makshtas A.P.*, *Shutilin S.V.* Modelling estimations of sensitivity of the Arctic ocean ice cover to changes of forcings. *Arctic and Antarctic Research*. 2012, 3, 93, 66–74 (in Russian).
41. *Spreen G.*, *Steur L. De*, *Divine D.*, *Gerland S.*, *Hansen E.*, *Kwok R.* Arctic Sea Ice Volume Export Through Fram Strait From 1992 to 2014. *J. Geophys. Res. Ocean*. 2020, 125, 6, e2019JC016039. doi: 10.1029/2019JC016039
42. *Wang Q.*, *Wekerle C.*, *Danilov S.*, *Koldunov N.*, *Sidorenko D.*, *Sein D.*, *Rabe B.*, *Jung T.* Arctic Sea Ice Decline Significantly Contributed to the Unprecedented Liquid Freshwater Accumulation in the Beaufort Gyre of the Arctic Ocean. *Geophys. Res. Lett*. 2018, 45, 10, 4956–4964. doi: 10.1029/2018GL077901
43. *Polyakov I.V.*, *Pnyushkov A.V.*, *Alkire M.B.*, *Ashik I.M.*, *Baumann T.M.*, *Carmack E.C.*, *Goszczko I.*, *Guthrie J.*, *Ivanov V.V.*, *Kanzow T.*, *Krishfield R.*, *Kwok R.*, *Sundfjord A.*, *Morison J.*, *Rember R.*, *Yulin A.V.* Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. *Science*. 2017, 356, 6335, 285–291. doi: 10.1126/science.aai8204
44. *Polyakov I.V.*, *Rippeth T.P.*, *Fer I.*, *Alkire M.B.*, *Baumann T.M.*, *Carmack E.C.*, *Ingvaldsen R.*, *Ivanov V.V.*, *Janout M.*, *Lind S.*, *Padman L.*, *Pnyushkov A.V.*, *Rember R.* Weakening of cold halocline layer exposes sea ice to oceanic heat in the eastern arctic ocean. *J. Clim*. 2020, 33, 18, 8107–8123. doi: 10.1175/jcli-d-19–0976.1
45. *Zubov N.N.* Arctic ice. *Moscow*, *Izdatel'stvo Glavsermorputi*, 1944. 360 p. (in Russian).
46. *Treshnikov A.F.* Arctic Ocean surface waters. *Arctic and Antarctic Research*. 1959, 7, 5–14 (in Russian).
47. *Proshutinsky A.*, *Krishfield R.*, *Toole J.M.*, *Timmermans M.-L.*, *Williams W.*, *Zimmermann S.*, *Yamamoto-Kawai M.*, *Armitage T.W.K.*, *Dukhovskoy D.*, *Golubeva E.N.*, *Manucharyan G.E.*, *Platov G.*, *Watanabe E.*, *Kikuchi T.*, *Nishino S.*, *Itoh M.*, *Kang S.-H.*, *Cho K.-H.*, *Tateyama K.* Analysis of the Beaufort Gyre Freshwater Content in 2003–2018. *J. Geophys. Res. Ocean*. 2019, 124, 12, 9658–9689. doi: 10.1029/2019JC015281
48. *Ryabchenko V.A.*, *Alekseev G.V.*, *Neelov I.A.*, *Dvornikov A.Y.* Distribution of River Waters in the Arctic Ocean. *Russian Meteorology and Hydrology*. 2001, 9, 61–69 (in Russian).
49. *Kelly S.J.*, *Proshutinsky A.*, *Popova E.K.*, *Aksenov Y.K.*, *Yool A.* On the origin of water masses in the Beaufort Gyre. *J. Geophys.Res. Ocean*. 2019, 124, 7, 4696–4709. doi: 10.1029/2019JC015022
50. *Woodgate R.A.* Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data. *Prog. Oceanogr*. 2018, 160, 124–154. doi: 10.1016/j.pocean.2017.12.007

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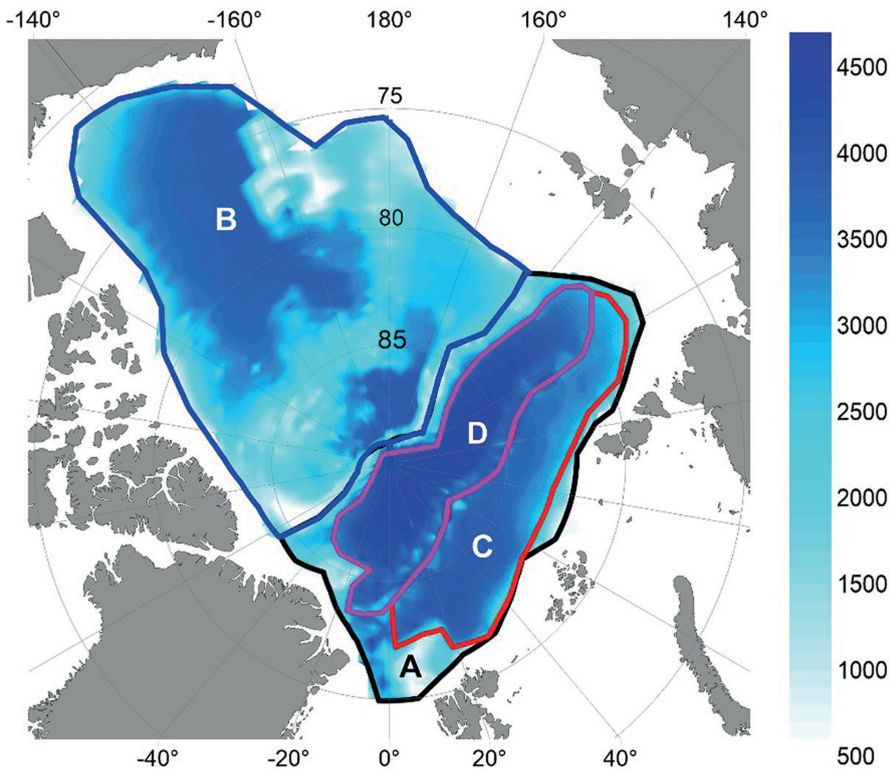

Fig. 2. Geographical areas of the Arctic Basin: *a* — Eurasian part, *b* —Amerasian part, *c* — Nansen Basin, *d* — Fram Basin.

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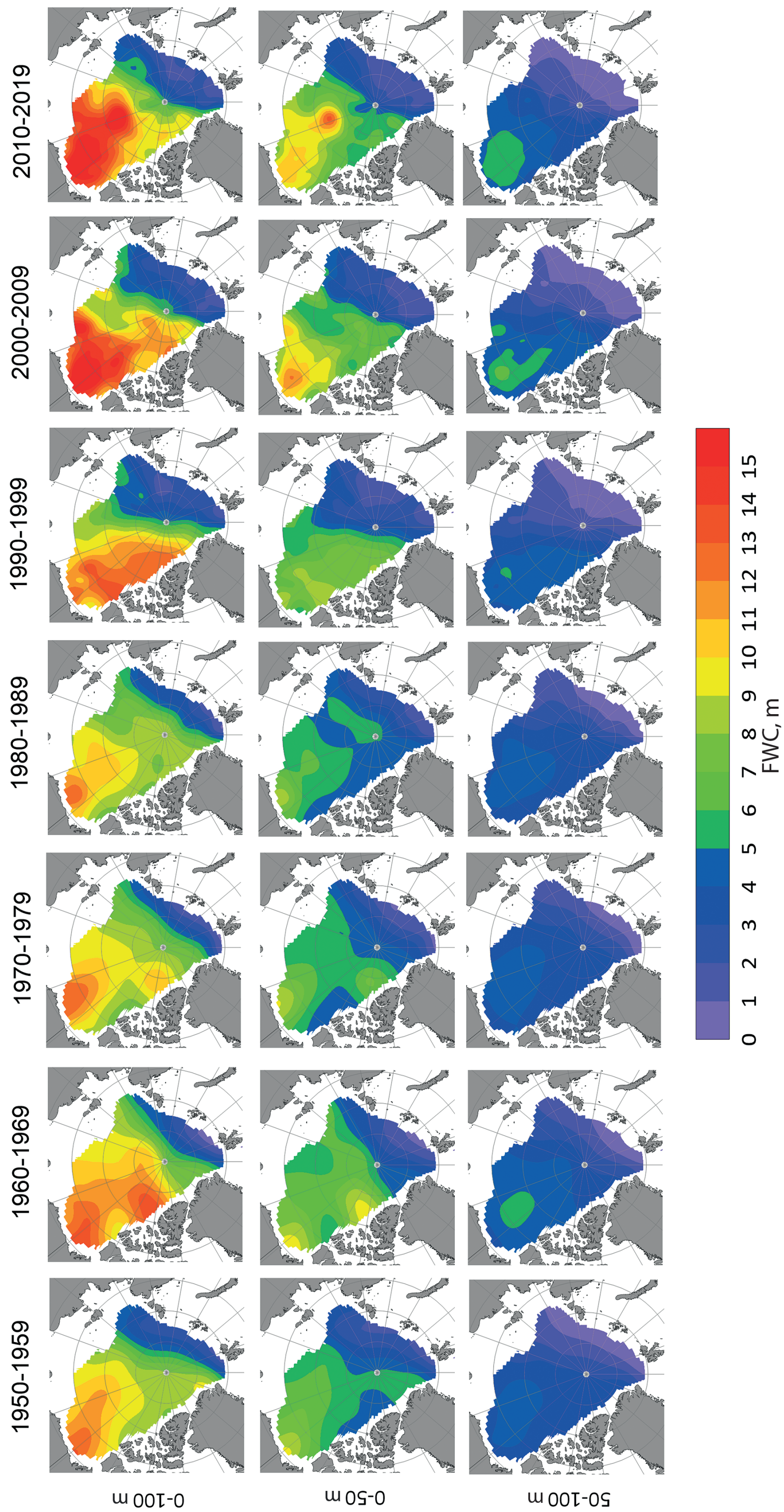

Fig. 4. Fresh water content in the upper layer of the Arctic Basin in 1950–2010s. Top panel — in the layer 0–100 m, middle panel — in the layer 0–50 m, bottom panel — in the layer 50–100 m.

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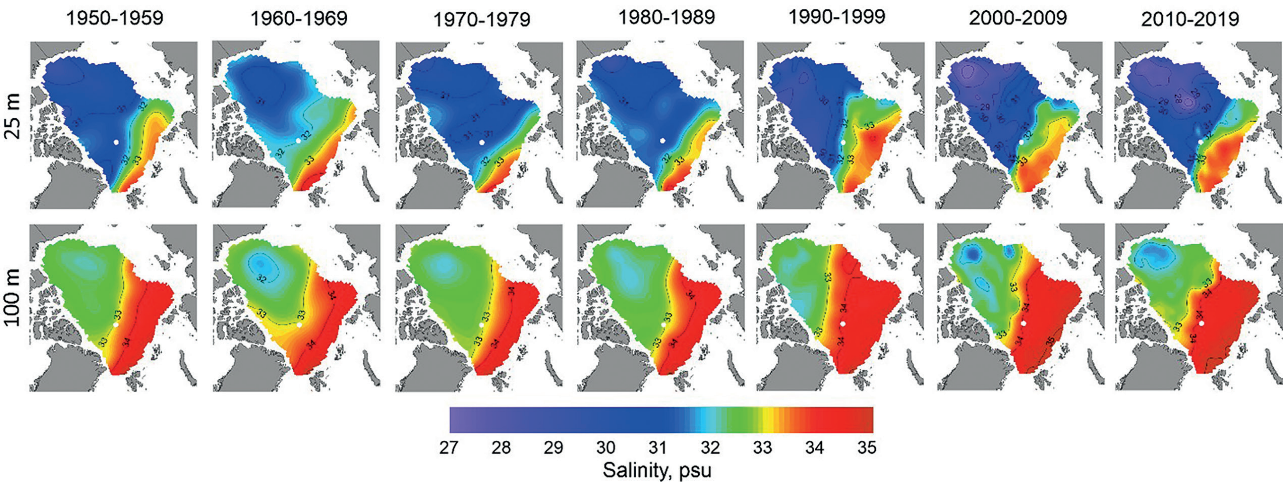

Fig. 5. Water salinity in the Arctic Basin in the decades 1950–2010s at the layers of 25 and 100 m.

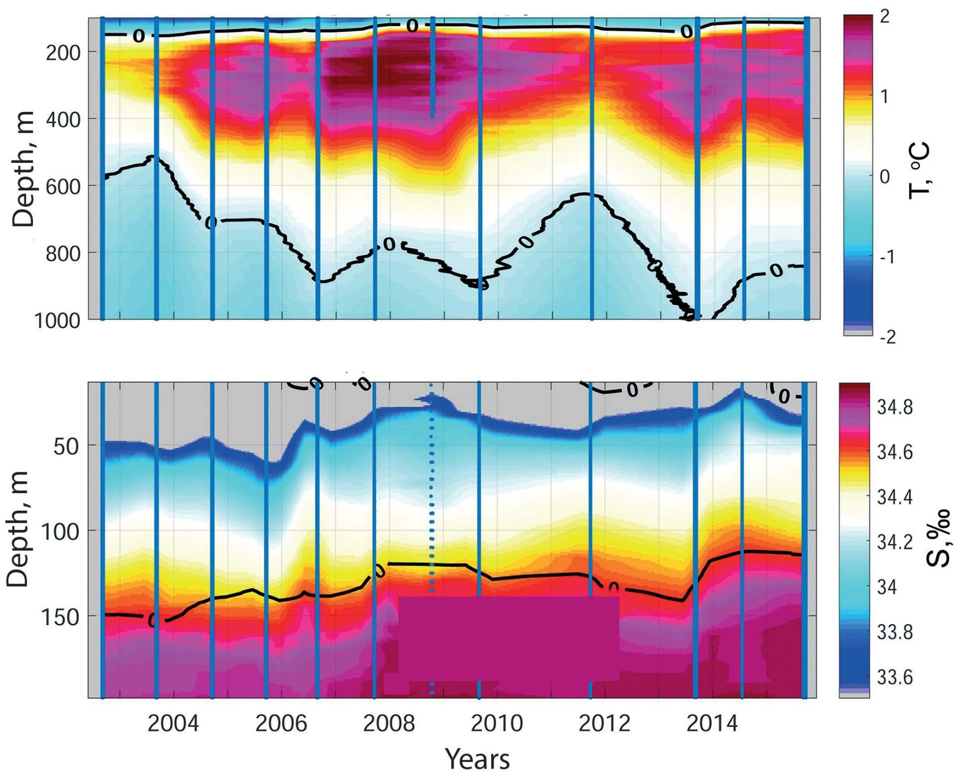

Fig. 8. Water temperature and salinity based on CTD measurements on the continental slope of Nansen Basin in the area of 125° E in 2002–2016.