# Changes in thermohaline system on the west Spitsbergen shelf since 1950 to present time

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## Abstract
The west Spitsbergen shelf is the principal region for the Atlantic water pass and it is very dynamic area, which has been changing a lot in the last two centuries. Herein, the analysis results of long-term variability of thermohaline characteristics of West-Spitsbergen current (WSC) and Coastal current (CC) are presented for the period from 1950 to present time based on the *in-situ* oceanographic data from the "Nordic Seas" database created in the Arctic and Antarctic Research Institute (AARI). Water temperature and salinity of WSC and CC were measured at 10 points and analyzed. It was concluded that the temperature and salinity in the study region were exposed to quasi-cyclic changes with common periods of about 5-6 and 10 years. Positive trends of water temperature for all points in the both currents were estimated (1.2°C per 60 years for WSC, and 2°C for CC, respectively). Correlation coefficients were calculated to describe the linear relationship between air temperature, atmospheric circulation indexes, the Atlantic multidecadal oscillation index, and water temperature in the region of the western shelf of the Spitsbergen.

***Key words:*** West-Spitsbergen current, Coastal current, Atlantic Water, long-term variability

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**List of Abbreviations:** AARI – Arctic and Antarctic Research Institute, AMO – Atlantic Multidecadal Oscillation, AO - Arctic Oscillation, ArW – Arctic waters, AW – Atlantic, C – meridional type of atmospheric circulation, CC – Coastal current, E – eastern type of atmospheric circulation, EGC – East Greenland current, ESC – East-Spitsbergen current, ESOP – European Subpolar Ocean Programme, ESP - elementary synoptic process, ICES - International Counsel Exploration of the Sea, Denmark, IMR - Institute of the Marine Research, Norway, NAO - North Atlantic Oscillation, NOAA – National Oceanic and Atmospheric Administration, NS – Nordic Seas, SST – sea surface temperature,

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TAW - transformed Atlantic waters, TRACTOR – Tracer and circulation in the Nordic Seas project, TS – temperature - salinity, US – United States, USSR - Union of Soviet Socialist Republics, VEINS – Variability of Exchanges in the Nordic Seas project, W – western type of atmospheric circulation, WM –water mass, WSC – West Spitsbergen Current

## Introduction

Arctic region has undergone significant changes in 20th and 21st centuries. Among them, an increase in air and water temperature, changes in ice conditions are of major importance. Changes in the Arctic are caused by a large-scale interaction between the ocean and the atmosphere. Some studies, however, show that the supply of heat with Atlantic waters (AW) is another important factor (Piechura et Walczowski 2009, Tverberg et al. 2014, Carmack et al. 2015). The only deep gateway, which connects the Arctic basin with other oceans, is the Fram strait (Rudels 1987). Through the Fram strait, the main heat and water exchange occurs (Schauer et al. 2004, Rudels 2015). In this region two main currents can be highlighted: (1) East Greenland current (EGC) which carries the colder and fresher Arctic waters (ArW) and sea ice out of the Arctic basin (Saloranta et Haugan 2001), and (2) West Spitsbergen current (WSC) which provides the largest part of warm and saline AW inflow into the Arctic basin (typical winter temperature 3-4°C and salinity about 35.1‰) (Beszczynska-Moller et al. 2012, Rudels 2015, Tverberg et al. 2014). WSC has a very complex structure with several brunches and recirculation features (Aagaard et al. 1987, Gascard et al. 1995). However, two main paths following bottom topography can be distinguished: the Svalbard branch follows the upper slope along 400 m isobaths, and the Yermak branch follows lower continental slope along the western flank of the Yermak Plateau (Saloranta et Haugan 2001, Cokelet et al. 2008). Less saline and colder Coastal current (CC) goes northward along the west Spitsbergen coast and separates WSC from Spitsbergen's fjords. CC is a continuation of East-Spitsbergen current, which is less studied, but known to be carrying colder and fresher Arctic waters with salinity about 34.3 – 34.7‰ and temperature close to freezing point during winter (Loeng 1991, Pfirman et al. 2013, Tverberg et al. 2014). Variability of the oceanographic and atmospheric param is determined by cycles and tendencies. The studies of polar and subpolar regions from last two decades (Proshutinsky et al. 2015, Venegas et Mysak 2000, Madhusoodanan et Thompson 2011) show cycles about 6-7, 9-10 and 16-20 years in the variability of sea ice concentration, outflow of sea ice through the Fram strait, heat content and atmosphere circulation patterns. Another common periodicity in atmospheric processes is quasi-two years cycle which can be observed in air temperature, wind speed and atmospheric pressure (Yakovleva 1976, Khairullina et Astafieva 2011). Changes observed in the study region and their connection with atmosphere circulation indexes were previously analyzed in different studies. Blindheim et al. 2000, Dickson at al. (2000) shows significant correlation between WSC temperature and NAO index (winter) while Saloranta et Haugan (2001) show low correlation coefficients (0.4). Main goal of this study was to distinguish main variability periods and their likely connection with atmosphere circulation. Many studies that had been carried out for this region showed significant changes, but most of them were based on shorter datasets (Walczowski et al. 2012 use period 2000 - 2010, Walczowski et Piechura 2011 – summer 2000 - 2007; Cottier et al. 2007 - winter

2005-2006; Beszczynska-Möller et al. 2012 – 1997-2010; research of the Saloranta et Haugan 2001 is based on the longest dataset 1910-1997 but it lacks the modern data). For this study, dataset containing data since 1950 to 2014 is used.

## Material and Methods

*Oceanographic data*

Temperature and salinity data for the analysis of thermohaline system of WSC and CC were obtained from the "Nordic Seas" database. The "Nordic Seas" (NS) is composite database that combines data for the North European Basin from all available sources (Korablev et al. 2007). Most part of the data came from the ICES (International Counsel Exploration of the Sea, Denmark) and the IMR (Institute of the Marine Research, Norway) as well as from a number of international projects (ESOP, VEINS, TRACTOR, CONVECTION *etc.*). A main feature of the database is availability of historical data from the USSR expeditions, which makes it particularly useful tool for the study of long-term variability in the Arctic, database contains measurements since 1900$^{th}$, but constant data without large gaps can be found since 1950$^{th}$.

Location of the points was chosen along the currents stream based on the amount of available data. The number of available data was analyzed using a NS database, mainly the points are located in the areas of the most frequently performed oceanographic sections. The data for this study were considered starting from the 50-ies of the 20$^{th}$ century up to the present time. In the WSC area, four most representative points were selected: near south tip of Spitsbergen, Bellsund fjord, Isfjorden and the northern part of Spitsbergen shelf. In the CC area: near south tip of Spitsbergen, Bellsund fjord, Isfjorden, Prins Karls Forland and the northern tip of Spitsbergen accordingly (*see* Fig. 1). Temperature or salinity values for each point were obtained by averaging of all available data by the "punctual kriging" method realized in NS database module (Korablev et al. 2007) within a radius of 30 km. Data were characterized by extreme inhomogeneity: in the winter months, data were often absent or very few and inclusion of such measurements in the analysis makes the time series was less reliable. Therefore, the data were selected for averaging only during the "summer" period (June-September). Thus, a dataset containing mean "summer" values for the time period since 1950 up to last available measurement date (2012 – 2014, end of the period differs for the points) was derived.

On the west shelf of Spitsbergen, several main water masses (WM) can be defined: Atlantic water mass (AW), which is associated with WSC with temperature >3°C and salinity >34.9‰ (Swift et Aagard 1981), Transformed AW (TAW) with temperature 1-3°C and salinity 34.7-34.9‰, which is produced by mixing between AW and ArW, this is the most common water mass in the west Spitsbergen fjords and it travels to the north with CC, in some years there can be found a surface water mass produced by river runoff and sea ice and glaciers melting, it is defined by salinity <34‰ and temperature >1°C (Pavlov et al. 2013).

In this study, we focused on the interaction between AW and CC waters and their variability so to analyze trends and find patterns in WSC area were separately selected AW layers and upper more variable and less saline layer. Thus, we consider three layers in the WSC area: 0-100 m, 100-200 and 200-300 m. TS clusters show that the layers 100-200 and 200-300 refer to AW while the 0-100 layer and CC refers to the TAW or surface water mass (Fig. 2).

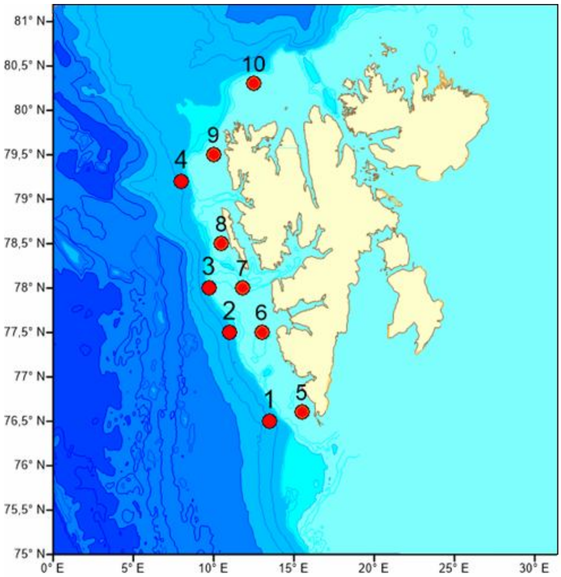


**Fig. 1.** Position of the points selected for analysis: 1-4 corresponds to WSC area, 5-8 – CC, 9-10 – northern part of the shelf.


**Fig. 2.** TS-clusters corresponding to selected points and layers (circles – layers 100-200, 200-300 m of WSC, triangles – 0-100 m of WSC, crosses – CC area).

*Air temperature*

Air temperature time series were derived from Barentsburg meteorological station and available in the Roshydromet archive, prepared in the Voeikov Main Geophysical Observatory. Dataset is regularly updated, controlled and errors in data are corrected (Bulygina et al. 2014 - [1]).

*Atmospheric circulation indexes*

The NAO index is based on the difference in surface pressure between the Subtropical (Azores) maximum and the Subpolar minimum. The positive phase of NAO reflects pressures below normal in the high latitudes of the North Atlantic and pressures above normal in the central part of the North Atlantic (eastern US, western Europe). The negative phase reflects the reverse location of the low and high pressure in these regions. Both NAO phases are associated with changes throughout the Atlantic Ocean basin: the position and intensity of the North Atlantic Current and the trajectory of storms, large-scale modulation of the normal model of zonal and meridional heat distribution and moisture transfer, which causes changes in temperature and precipitation from the northeast of North America to western and central Europe. The influence of North Atlantic Oscillation on the climate and weather is observed on a time scale ranging from 2-3 years to several tens of years and determines the temporal and spatial patterns of fluctuations in this region (Smirnov et al. 1998). AO is a climate model characterizing the anticyclonic movement of wind around the Arctic at 55° N. When the AO is in the positive phase, the ring of strong wind circulation around the northern polar region acts as a natural boundary for cold arctic air masses. When the AO is in the negative phase, this circulation becomes weaker, which makes it easier for cold air masses to penetrate into the middle latitudes (Smirnov et al. 2003). The average monthly data of NAO since 1950 was obtained from the historical archives of NOAA and averaged for further analysis[3].

In 1933, Vangengeim suggested a set of indexes characterizing atmospheric circulation. He introduced the concept of an elementary synoptic process (ESP). ESP is a process during which the character of pressure distribution and the direction of the main air transfer persists over the Atlantic-European sector of the northern hemisphere (Vangengeim 1933). As a result of this work, the whole variety of macroprocesses were successfully combined into 26 types. Analysis of typical maps and graphs of these 26 types has shown that, despite their fundamental differences from each other, a number of these types have similarities among themselves over more general characteristics of the processes. As a result, it turned out that all 26 types of ESP could be generalized in three types of atmospheric circulation: - the western (W), - the eastern (E) and meridional (C) (Girs 1978,Prokhorova et Svyashchennikov 2016). In the W form zonal components of the circulation are maximally strengthened at the ground and at altitudes, and the meridional components are weakened. This situation results in a considerably weakened inter-latitude exchange of air masses. The processes of the form C practically lack Icelandic and Aleutian centers of atmosphere circulation. In this case, the crest of a powerful Siberian anticyclone, the southern part of which is located in the subtropical zone, is connected to the polar anticyclone. The processes of the form E are close to the form C, however, the localization of the main crests and troughs in the hemisphere are reversed. In such case, the Icelandic and Aleutian depressions are well developed, stationary anticyclones and their crests are observed over Europe and Western America, the Siberian anticyclone is weakened and displaced (Bezuglova et Zinchenko 2009). It is known that there are periods with a prolonged anomalous development of a particular macroprocess - the so-called circulation epochs in the large-scale circulation of the atmosphere (Demin et Beloglazov 2011, Prokhorova et Svyashchennikov 2016).

*Atlantic multidecadal oscillation*

Cycle of about 60-years is observed in variability of the North Atlantic sea surface temperature (SST). This cycle was called Atlantic multidecadal oscillation (AMO) by (Kerr 2000). AMO warm phases occurred during 1860-1880 and 1940-1960, and cool phases during 1905-1925 and 1970-1990 (Enfield et al. 2001). AMO is related to the amount of precipitation, river runoff, hurricane activity and variations in the strength of the overturning circulation in the Atlantic Ocean (Enfield et al. 2001, Knight et al. 2006). In this study, NOAA archive of the AMO index values was used[4].

## Results and Discussion

During a compilation of the time series, all points for the WSC region were selected on the continental slope and it was controlled that in each year all of the points have been lying in a region of AW propagation. Therefore, the possibility of reducing the temperature or salinity associated with changes in WSC position were eliminated.

The main feature of the thermal structure of all points is quasi-periodic changes with the period of about 10 years. During these events water temperature and depth of AW propagation increases. Example of this features presented on the Fig. 3.

For the most southern part of the WSC area (point 1), the temperature of the upper layer is about 4-4.5°C in the beginning of the time series (1954-1958). In the early 1960-ies, temperature increased to 5.5°C. Similar events of increased water temperature were also found in the1970-ies and the 1980-ies but less pronounced. In the time series of the 0-100 m layer temperature, several peaks were observed (1970-71, 1975-76, 1983-84). In these periods, 3°C isotherm reached 300 m depth (from 200 m in the end of the 1960-ies). The most pronounced warming started in 1990-ies with a peak in 1992. The temperature in the 0-100 m layer temperature reached the values of about 6.5°C. Similarly, 3°C isotherm moved from 200 m in the end of 1980-ies to more than 400 m. After a slight decrease in water temperature in the late 1990-ies, the most intensive and prolonged warming of the early 2000's followed, with the maximum temperature observed in 2006 (up to 7.4°C). In 2006, the 3° isotherm decreased to a depth of 500 m. Relatively long duration and (more than 10 years) and intensity of the temperature increase are distinctive features of the latest warming period. The haline structure of the region is more homogeneous, but the strongest temperature changes are associated with an increase in salinity. In our study, the main changes in salinity were observed in the layer deeper than 100 m, where the salinity values periodically increased up to 35.1‰. Ordinarily salinity > 35‰ is found in the depths from 50-100 to 400-650 m, depending on the year of observation.

Changes in the structure of the WSC had a significant effect on the structure of the CC. CC was characterized by the lower values of temperature and salinity, then during the periods of the strongest warming in the region of the WSC, temperature of the CC changed by several degrees. These changes were, however, observed with some delay. They were found in the period of 1955-1962 (peak - 1960), 1972-1977, 1985, 1992, 1997, 2001, and 2004-2010. The last two peaks belong to a single warming period, with maxima in 2007-2008 (to 6.6°C). Most of the time, the layer from 0 to 150 m were occupied by water with salinity < 34.9‰, with rare increases in the 1960-ies, 1972, 2003-2009. Salinity at a depth of about 200 m increased to 35.1‰ in the corresponding periods.

Slightly more complicated structure with less pronounced periodicity was observed at points 2-6 (WSC and CC area close to Bellsund fjord). Water temperature maxima were observed in 1961, 1973, 1984, 1992 and the corresponding period of increasing water temperature since 1997 with a maxima in 2003 and 2006. An isotherm of 3°C layed at a depth of 100 m in colder periods and moved deeper to 350 m (even to 550 m in 2012) in the warmer periods. Also, the area of point 2 differed from point 1 by the presence of a more freshened surface (0-50 m) layer – salinity values drops to 33‰. In the years corresponding to the maxima in the temperature time series, a salinity increase up to 35.1‰ was observed at the depths of 100-300 m. The impact of changes in WSC on the CC is clearly traced in this area as well. The most pronounced warming events were observed in 1954-61 (maxima in 1954 T≈+55°C), 1971-1977 (maxima in 1973-1974 T≈+4-4.5°C), twin peaks in 1980$^{th}$-90$^{th}$ and temperature increase since 1999 with maximum in 2003, 2008 up to +5.5 - 6°C. A layer of 0-50 m is occupied by water with salinity below 34.5‰ with pronounced minima in 1961, 1996 and less pronounced in 1976, 1983, 1989. At the depths of more than 100-150 m salinity > 34.9‰ is observed.

A similar picture is observed around the points 3-7. The most pronounced maximums can be highlighted in the temperature and salinity time series in the following years: 1956, 1964, 1971, 1986, 1992, 2000-2001, 2006-2007. The temperature of the layer from 0 to 100 m rises up to 6-6.5°C in the years of strongest warming, in average up to ~ 4.5°C. The 3°C isotherm changes its position from 50 m (for example, in 1953, 1978) to 300-450 m in 2000-ies. Point 7 is characterized by a higher temperature than points 5 and 6. Periods of temperature increase are well pronounced, the temperature rises in the whole layer from 0 to 200 m. On average, from 2-3°C to 4°C and up to 5°C in 2007. Salinity corresponding to AW (> 34.9‰) is observed from depths of 50 m in the warmer years to depths of 150 m at the beginning of the 60-ies and total absence in 1978 and 1990.

Because of the lack of data, it is difficult to estimate the changes occurring in the 1950-ies and 1960-ies, but nevertheless it can be concluded that here presents a similar structure as in the vicinity of other points. A joint increase in temperature and salinity near the points 4-8 was observed with peaks in 1961, 1972, 1981, 1984-85, 1992. The warmimg in the 2000 in the point 4 does not correspond to the temperature rise in the CC region, however, this may be due to a lack of data. These results are consistent with results of (Saloranta et Haugan 2001), who highlighted temperature maxima around 1970, 1984 and 1992 in the region close to points 4, 8 and 9.

The periodicity in the time series was analyzed using a wavelet analysis (Torrence et Compo 1998). The Morlet wavelet was used as the mother wavelet. Because of missing data, for this type of analysis, the points with the minimum number of gaps were selected, and, consequently, the gaps were filled using a simple interpolation. Based on the results of the wavelet analysis, it can be concluded that for a 0-100 m layer in the region of the WSC, there is no clear periodicity. The maximum energy of process variability corresponded to small periods of the order of 2-3 years, a weak peak is visible on periods about 8-10 years, for depths of 100-200 m, characteristic periods of variability are 8-10 years and 5-6 years. An example of the results of wavelet analysis is shown in the Fig. 4. Positive trends of water temperature were found for all points in the both currents (1.2°C per 60 years for WSC and about 2°C for CC).

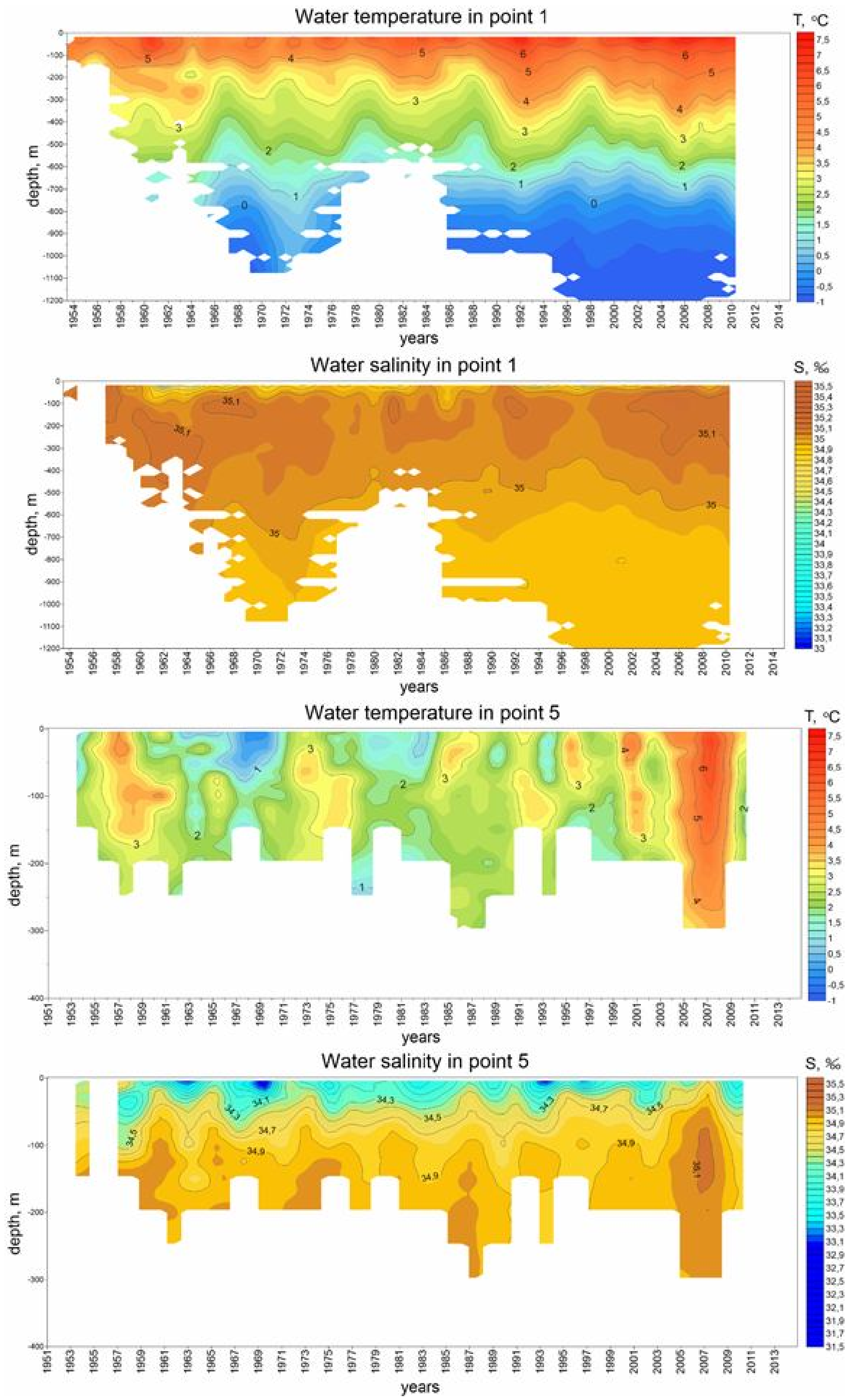


**Fig. 3.** Examples of water temperature and salinity timeseries for most southern points (1 and 5).

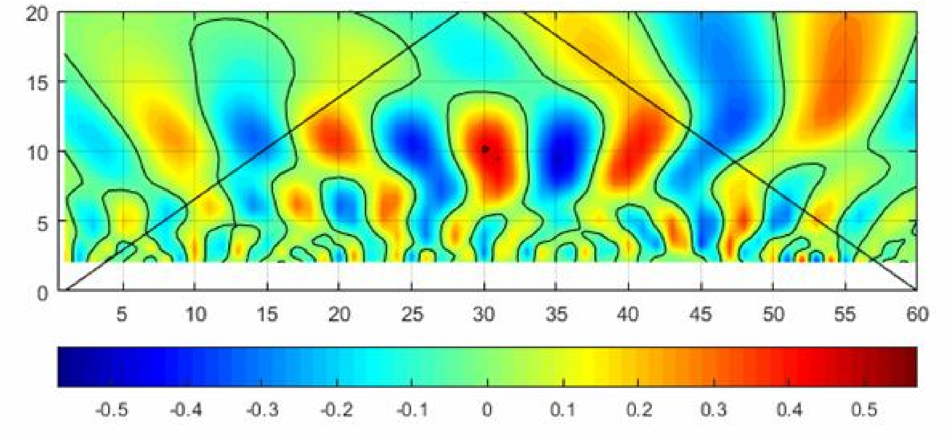


**Fig. 4.** Example of wavelet analysis results for the 100-200 m layer at point 1.

Another interesting feature of the thermohaline system of the western shelf area of the Spitsbergen archipelago was the dramatic decrease in salinity (to <33‰, at point 7 to 31.5‰). Such phenomena were especially pronounced in the early 1960-ies, during the period 1995-98 with a minimum of salinity in 1996 and at point 7 in 2004-2005 (Figure 5). The decrease in salinity may occur due to several factors: the action of a freshened AW, the increased flow of ArW through ESC and its further propagation northward with CC; and the local formation of a freshened water mass due to an active melting of glaciers and continental runoff. Belkin (2004) stated that the low salinity in the Sørkapp section found in 1996 was associated with the arrival of the great salinity anomaly of the 90-ies (GSA' 90). It can be possible explanation of the low values of salinity in this period at all points of the CC. However, salinity decrease in 2003-2005 is only present at the point 7 (the maximum freshening) and more northern points (less pronounced), which corresponds to the exit from Isfjorden. Salinity data from the mooring station installed in the Grønfjord (Zhuravskiy et al. 2012) also show a strong water freshening in 2004 (up to 19‰ by average monthly data and up to 26‰ annual). Presumably, such a strong salinity anomaly can be associated with a strong negative mass balance of glaciers on Spitsbergen and a corresponding high freshwater runoff. A negative mass balance was detected for various glaciers of Spitsbergen in 2004 (MOSJ - [2], Aas et al. 2016). On the other hand, due to the lack of data on the fresh water discharge through ESC, it is difficult to estimate the effect of ArW on the variability of the CC's salinity. Studies (Kwok et al. 2004, Spreen et al. 2009 and Vinje et al. 1998) show that during the periods 1994-1995 and 2004-2005, the outflow of sea ice with EGC was the most intensive. Assuming that intensifying of the ESC outflow was happening in the same years as the intensifying of the EGC, it is possible to connect changes in CC salinity and intensity of ArW flux. These dramatic changes in CC salinity is ambiguous question, thus, this issue requires further investigation.

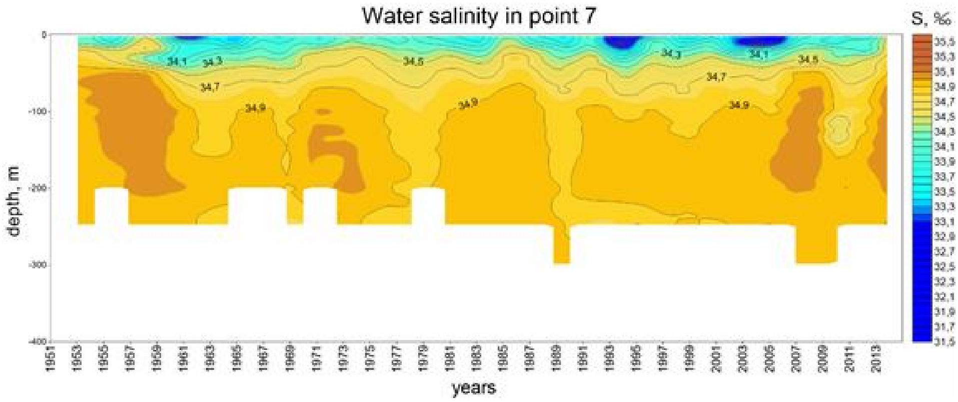


**Fig. 5.** Changes in water salinity at point 7.

## Concluding remarks

It was suggested that the atmospheric processes could significantly affect the thermohaline structure in the region of the western shelf of the Spitsbergen archipelago. Correlation coefficients were calculated to describe the linear relationship between air temperature, atmospheric circulation indexes, and the Atlantic multidecadal oscillation index. All significant coefficients (at the level of $p<0.05$) are rather low (from 0.33 to 0.68). The maximum coefficients were found for pairs of air temperature and points 5 and 7 (CC), the relationship between water temperature and air temperature is described by coefficients of the order of 0.5-0.6, with the exception of points 9 and 4. The relationship between the NAO, AO indexes and water temperature was not detected. The coefficient of order 0.4-0.5 describes the relationship between the zonal type of atmospheric circulation and the water temperature, ≈ -0.4 for the eastern type of circulation and the water temperature, the relationship between the meridional circulation type and temperature was not found. These results have a good agreement with the results of (Saloranta et Haugan 2001).

## References

AAGAARD, K., FOLDVIK, A. and HILLMAN, S. R. (1987): The West Spitsbergen Current: Disposition and water mass transformation. *Journal of Geophysical Research*, 92 (C4): p.3778.

AAS, K.S., DUNSE, T., COLLIER, E., SCHULER, T. V., BERNTSEN, T. K., KOHLER, J. and LUKS, B. (2016): The climatic mass balance of Svalbard glaciers: a 10-year simulation with a coupled atmosphere–glacier mass balance model. *The Cryosphere*, 10: 1089-1104.

BELKIN, I. M. (2004): Propagation of the “Great Salinity Anomaly” of the 1990-ies around the northern North Atlantic. *Geophysical Research Letters*, 31 (8): L08306.

BESZCZYNSKA-MOLLER, A. FAHRBACH, E., SCHAUER, U. and HANSEN, E. (2012): Variability in Atlantic water temperature and transport at the entrance to the Arctic Ocean, 1997-2010. *ICES Journal of Marine Science*, 69 (5): 852-863.

BEZUGLOVA, N. N., ZINCHENKO, G. S. (2009): Regional climatic manifestations of the global atmospheric circulation in the south of Western Siberia. *Journal of Geography and natural resources*, 3: 83-87 (In Russian).

BLINDHEIM, J., BOROVKOV, V., HANSEN, B., MALMBERG, S.-AA., TURRELL, W. R. and ØSTERHUS, S. (2000): Upper layer cooling and freshening in the Norwegian Sea in relation to atmospheric forcing. *Deep Sea Research Part I: Oceanographic Research Papers*, 47 (4): 655-680.

CARMACK, E., POLYAKOV, I., PADMAN, L., FER, I., HUNKE, E., HUTCHICHICHINGS, J., JACKSON, J., KELLEY, D., KWOK, R., LAYTON, C., MELLING, H., PEROVICHICHICH, D., PERSSON, O., RUDDICICK, B., TIMMERMANS, M.-L., TOOLE, J., ROSS, T., VAVRUS, S. and WINSOR, P. (2015): Toward Quantifying the Increasing Role of Oceanic Heat in Sea Ice Loss in the New Arctic. *Bulletin of the American Meteorological Society*, 96 (12): 2079-2105.

COKELET, E. D., TERVALON, N. and BELLINGHAM, J. G. (2008). Hydrography of the West Spitsbergen Current, Svalbard Branch: Autumn 2001. *Journal of Geophysical Research*, 113 (C1), p.C01006.

COTTIER, F. R., NILSEN, F., INALL, M. E., GERLAND, S., TVERBERG, V. and SVENDSEN, H. (2007): Wintertime warming of an Arctic shelf in response to large-scale atmospheric circulation. *Geophysical Research Letters*, 34 (10), p.L10607, doi:10.1029/2007GL029948.

DEMIN, V. I., BELOGLAZOV, M. I. (2011): Large-scale atmospheric circulation and near-surface ozone concentration on the north of Scandinavian peninsula. *Physics of Auroral Phenomena*. Proc. XXXIV Annual Seminar, Apatity, pp. 201-204 (In Russian).

DICKSON, R. R., OSBORN, T. J., HURRELL, J. W., MEINCKE, J., BLINDHEIM, J., ADLANDSVIK, B., VINJE, T., ALEKSEEV, G. and MASLOWSKI, W. (2000): The Arctic Ocean Response to the North Atlantic Oscillation. *Journal of Climate*, 13 (15): 2671-2696.

ENFIELD, D. B., MESTAS-NUÑEZ, A. M. and TRIMBLE, P. J. (2001): The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters*, 28 (10): 2077-2080.

GASCARD, J.-C., RICHEZ, C. and ROUAULT, C. (1995): New insights on large-scale oceanography in Fram Strait: The West Spitsbergen Current. pp. 131-182.

GIRS, A. A., KONDRATOVICH, K.V. (1978): Methods of long term weather forecasts. Leningrad, Gidrometeoizdat, 343 p. (In Russian).

KERR, R. A. (2000): A North Atlantic Climate Pacemaker for the Centuries. *Science*, 288(5473).

KHAIRULLINA, G. R., ASTAFIEVA, N. M. (2011): Quasi-two-year oscillations in the Earth's atmosphere. Review: Observation and formation mechanisms. Space Research Institute of the Russian Academy of Sciences (IKI RAS), Moscow (In Russian), 2163. 60 p.

KNIGHT, J.R., FOLLAND, C.K. and SCAIFE, A. A. (2006): Climate impacts of the Atlantic Multidecadal Oscillation. *Geophysical Research Letters*, 33(17), p.L17706.

KORABLEV, A., PNYUSHKOV, A. and SMIRNOV, A. (2007): Compiling of the oceanographic database for climate monitoring in the Nordic Seas, Trudy AARI (In Russian), 447, pp. 85-108.

KWOK, R., CUNNINGHAM, G. F. and PANG, S. S. (2004). Fram Strait sea ice outflow. *Journal of Geophysical Research*, 109(C1), p.C01009.

LOENG, H. L. (1991): Features of the physical oceanographic conditions of the Barents Sea. *Polar Research*, 10 (1): 5-18.

MADHUSOODANAN, M.S., THOMPSON, B. (2011): Decadal variability of the Arctic Ocean thermal structure. *Ocean Dynamics*, 61 (7): 873-880.

PAVLOV, A.K., TVERBERG, V., IVANOV, B. V., NILSEN, F., FALK-PETERSEN, S. and GRANSKOG, M. A. (2013): Warming of Atlantic Water in two west Spitsbergen fjords over the last century (1912-2009). *Polar Research*, 32, 11206, http://dx.doi.org/10.3402/polar.v32i0.11206.

PFIRMAN, S.L., BAUCH, D. and GAMMELSRØD, T. (2013): The Northern Barents Sea: Water Mass Distribution and Modification. In American Geophysical Union, pp. 77-94.

PIECHURA J.,WALCZOWSKI W. (2009 ): Warming of the West-Spitsbergen Current and sea ice north of Svalbard". *Oceanology* V., 51 (2): 149-164.

PROKHOROVA, U.V., SVYASHCHENNIKOV, P. N. (2016): Investigation spatio temporal variability of Atmospheric processes in Arctic regions. Conf. paper, International conference: Study of climate change using classification methods Atmospheric circulation regimes, 4 pp. (In Russian)

PROSHUTINSKY, A., , DUKHOVSKOY, D., TIMMERMANS, M-L., KRISHFIELD, R. and BAMBER, J. L. (2015): Arctic circulation regimes. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 373 (2052): 20140160.

RUDELS, B. (1987): On the mass balance of the Polar Ocean, with special emphasis on the Fram Strait, Norsk Polarinst, Skrifter, 188, 53 p.
RUDELS, B. (2015): Arctic Ocean circulation, processes and water masses: A description of observations and ideas with focus on the period prior to the International Polar Year 2007–2009. *Progress in Oceanography*, 132: 22-67.
SALORANTA, T. M., HAUGAN, P. M. (2001): Interannual variability in the hydrography of Atlantic water northwest of Svalbard. *Journal of Geophysical Research: Oceans*, 106 (C7): 13931-13943.
SCHAUER, U., FAHRBACH, E., OSTERHUS, S. and ROHARDT, G. (2004): Arctic warming through the Fram Strait: Oceanic heat transport from 3 years of measurements. *Journal of Geophysical Research*, 109 (C6): p.C06026, doi:10.1029/2003JC001823.
SMIRNOV, N. P., VOROBIEV, V. N. and KOCHANOV, S. YU. (1998): North Atlantic Oscillation and Climate. RSHU, St. Petersburg, 122 pp. (In Russian).
SMIRNOV, N. P., VOROBIEV, V. N. and KOCHANOV, S. YU. (2003). Arctic anticyclone and climate dynamics of the northern polar region. RSHU, St. Petersburg, 81 pp. (In Russian)
SPREEN, G., Kern, S., Stammer, D. and Hansen, E. (2009): Fram Strait sea ice volume export estimated between 2003 and 2008 from satellite data. *Geophysical Research Letters*, 36 (19): p.L19502, doi:10.1029/2009GL039591.
SWIFT, J. H., AAGAARD, K. (1981): Seasonal transitions and water mass formation in the Iceland and Greenland seas. Deep Sea Research Part A. *Oceanographic Research Papers*, 28(10): 1107-1129.
Torrence, C., Compo, G. P. (1998): A Practical Guide to Wavelet Analysis. *Bulletin of the American Meteorological Society*, 79 (1): 61-78.
TVERBERG, V., NØST, O. A., LYDERSEN, C. and KOVACS, K. M. (2014): Winter sea ice melting in the Atlantic Water subduction area, Svalbard Norway. *Journal of Geophysical Research: Oceans*, 119 (9): 5945-5967, doi:10.1002/2014JC010013.
VANGENGEIM, G. A. (1933): Experience of using synoptic methods to study and characterize climate. *Izvestiya GGO*, vol. 2 - 3: 3-16 (In Russian).
VENEGAS, S. A., MYSAK, L. A. (2000): Is There a Dominant Timescale of Natural Climate Variability in the Arctic? *Journal of Climate*, 13(19): 3412-3434.
VINJE, T., NORDLUND, N. and KVAMBEKK, Å. (1998): Monitoring ice thickness in Fram Strait. *Journal of Geophysical Research: Oceans*, 103(C5): 10437-10449.
WALCZOWSKI, W., PIECHURA, J., GOSZCZKO, I. and WIECZOREK, P. (2012): Changes in Atlantic water properties: an important factor in the European Arctic marine climate. *ICES Journal of Marine Science*, 69 (5): 864-869, doi: https://doi.org/10.1093/icesjms/fss068.
WALCZOWSKI, W., PIECHURA, J. (2011): Influence of the West Spitsbergen Current on the local climate. *International Journal of Climatology*, 31 (7): 1088-1093.
YAKOVLEVA, N. I. (1976): About a quasi-two-year cycle in air pressure and temperature oscillations over the northern hemisphere. *Trudy Glavnoy geofizicheskoy observatorii*, 380: 63-68 (In Russian).
ZHURAVSKIY, D., IVANOV, B. and PAVLOV, A. (2012): Ice conditions at Gronfjorden Bay, Svalbard, from 1974 to 2008. *Polar Geography*, 35 (2): 169-176.

**Other sources**

[1] Bulygina O.N., Razuvaev V.N., Trofimenko L.T., Shvets N.V. (2014): "Description of database of the average monthly air temperature at Russian Meteorological Stations" Certificate of state registration of the database № 2014621485 - http://meteo.ru/data/156-temperature#description of the mass-data
[2] Mass balance for glaciers in Svalbard - MOSJ (Environmental Monitoring of Svalbard and Jan Mayen) - http://www.mosj.no/en/
[3] NAO, AO - http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml
[4] AMO data - http://www.esrl.noaa.gov/psd/data/timeseries/AMO/