Long-term variability of Atlantic water temperature in the Svalbard fjords in conditions of past and recent global warming

Daniil I. Tislenko[1,2], Boris V. Ivanov[2,1*]

[1]*Saint-Petersburg State University, Russia*
[2]*Arctic and Antarctic Research Institute, Saint-Petersburg, Russia*

Abstract
Within last decades, the climate of our planet has underwent remarkable changes. The most notable are those called "Arctic amplification." is the changes comprise a decrease in the area of multi-years ice in 2007 and 2012 in polar regions of the Northern hemisphere, accompanied by the temperature rise of intermediate Atlantic waters, increasing surface temperature. In this paper, an analysis of long-term variability of temperature transformed Atlantic waters (TAW) in the fjords of the West-Spitsbergen island (Isfjorden, Grønfjorden, Hornsund and Kongsfjorden) in the first period (1920–1940) and modern (1990–2009) warming in the Arctic is reported. It is shown that the instrumental observation data corresponds to the periods of rise in temperature in the layer of the TAW and surface air temperature (SAT) for the area of the Svalbard.

Key words: Arctic, Svalbard, climate variability, Atlantic waters

Abbreviations: AW – Atlantic water, AB – Arctic basin, TAW – Temperature of transformed Atlantic water, SAT – Surface atmosphere temperature, WSC – West Spitsbergen current, ESC – East Spitsbergen current, CC – Coastal current, SCC – South cape current

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[*]Corresponding author: Boris V. Ivanov <b_ivanov@aari.ru>
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Introduction

The Arctic region makes up an important part of the Earth's climate system connected with the other Earth's regions by the transport of heat and moisture in the atmosphere and the ocean. Formation and transport of desalinated surface water from the central part of the Arctic Basin exercise significant influence over the sea ice distribution, thermohaline circulation in the neighboring regions of the North Atlantic, as well as the regional and global climate (Alekseev 2003, Nikiforov et Speicher 1980).

In the 20th century and in the first decade of 21st century, the two period of significant warming are observed at Arctic region. The first warming period in the Arctic is considered within the interval of 1920-1940, while the second one fits to 1980-2009 (Alekseev et al. 1998, Alekseev et Ivanov 2003, Polyakov et al. 2002, 2003, 2004). The first warming in the Arctic (1920-1940) got attention of researchers in the first half of the 20th century (Vise 1937). In his article described the Arctic warming in 1920-1930 as the most severe climatic fluctuation registered at that time by means of regular meteorological observations.

Warm and saline AW enters into the central part of Arctic Basin AB near the Svalbard area (the Fram Strait, fjords of West Spitsbergen Island). Data from West Spitsbergen Island therefore allows estimate the cyclic recurrence of water entry into the internal regions of the AB. The average annual water temperature in the AW layer which enters into the archipelago gulfs may be regarded as a convenient indicator of changes observed.

The present study aims to evaluate the long-term variability of AW temperature in the fjords of the West Spitsbergen Island (Isfjorden, Grønfjorden, Hornsund, Kongsfjorden) during the first (from 1920 to 1940) and contemporary (from 1990 to the present day) periods of warming in the Arctic.

Material and Methods

Research area

The Svalbard is a vast polar archipelago that lies in the Arctic Ocean and ranges from 74° to 81° north latitude, and from 10° to 35° east longitude. Circulation of waters that sweep the coasts of archipelago is mainly determined by the four main currents: (1) - WSC, (2) - ESC, (3) - CC, and (4) – SCC (*see* Fig. 1). Oceanology conditions in the fjords (Isfjorden, Grønfjorden, Kongsfjorden, and Belsund) are related to the features of currents around the Svalbard. These fjords were selected due to their geographical location (direct contact with WSC waters) and due to the fact that these fjords, in compare with all others, are better provided by oceanographic observations. Warm and saline waters come to fjords from WSC which is the north branch of the Norwegian Coastal Current (Hanzlick 1993, Rudels et al. 2000, Cottier et al. 2005). In our study, we selected oceanographic stations located in the above-specified four main fjords for analysis of the long-term variability of water temperature in the fjords of the Svalbard.

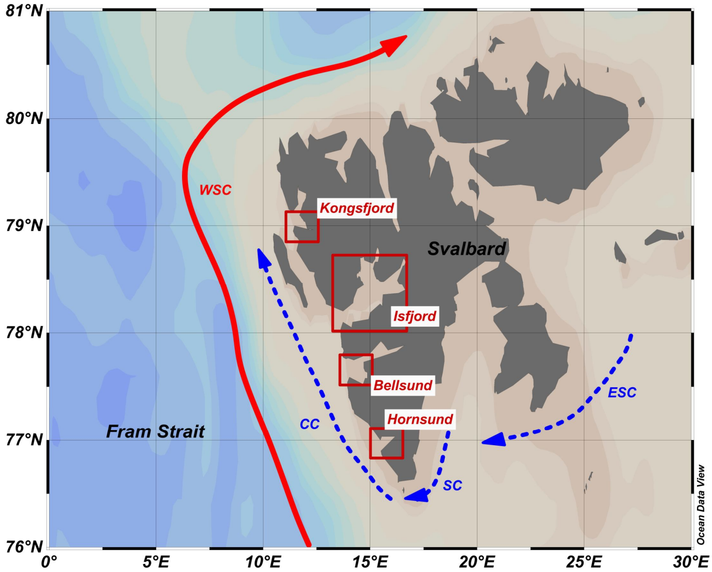

Fig. 1. The map was made using the Ocean Data View package (Schlitzer 2015).

Specification of data sets

Oceanographic measurements in these fjords started at the end of the 19th century. At the initial stage, the data involved a series of oceanographic stations (over 900) established from 1876 to 2012. The station records, however, differed in number of measured parameters and the intervals of observations. For most stations, the data were available on the following oceanographic parameters: standard depths, temperature and salinity. Moreover, the data come from different sources: (1) Archive of the All-Russia Research Institute Hydrometeorological Information – World Data Center, (Obninsk) and (2) the Nordic Seas Database created at Arctic and Antarctic Research Institute, Saint-Petersburg (Korablev et al. 2007).

Since majority of observations were carried out during summer (July – September), we used the stations operating during this period of year to analyze variability of thermohaline structure of water. Consequently, 317 oceanographic stations were selected for the 1901–2009 (Fig. 2).

Moreover, we used data from surface air temperature observations collected by the Norwegian Meteorological Institute in this study as well. The time series covered the period from 1898 to 2013 (Nordli et al. 2014). It was obtained by combining observations made at the Longyearbyen settlement (the administrative center of Svalbard) and at temporary observation points (expeditions of hunters, geologists, *etc.*) in this part of Svalbard (www.met.no). The time series was created using a special interpolation for filling the existing gaps (Nordli et al. 2014). The mean monthly data of SAT were used for joint analysis for the above-mentioned period of time.

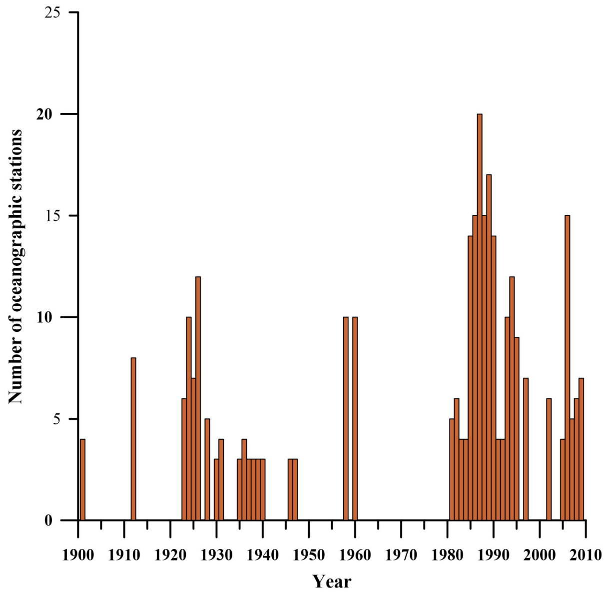

Fig. 2. Distribution of oceanograhic station (quantity) operating during the period of 1901-2009.

Data processing

We used various below-specified data processing methods during this work. Prior the data processing, we had to specify criteria for distinguishing of AW. In our study, we considered AW has the following features: temperature >3°C, and salinity >34.9‰. The TAW has temperature and salinity within 1 – 3°C and 34.7 – 34.9‰. TAW is the product of interaction of AW with local surface water masses of particular fjords that are formed during various seasons (Cottier et al. 2005).

The first stage involved the selection of oceanographic stations with simultaneous measurements of temperature and salinity were operating within the July-September period. The second stage involved calculation of average temperatures in TAW layer. Averaging of data was conducted for each separate station within a specific year and above range of salinity (34.7 – 34.9‰).

To analyze variability of average annual temperature in a TAW layer, we also calculated anomalies of these values in relation to average temperature value for the whole time series (from 1901 to 2009). We used normalized deviations which represent the relation of anomaly calculated for every year to a mean square deviation of the respective parameter during comparative analysis of long-term variability of temperature in a TAW layer and surface air temperature. Therefore, we obtained non-dimensional quantities that can be compared between themselves. This method was first used to analyze the long-period variability of the AW temperature (*see* e.g. Alekseev 2003).

The analysis of long-term variability of characteristics of TAW was carried out by calculating linear trends (linear regression) and determination factors that characterized the proportion of variance described by the obtained equation. Consequently, we tested the hypothesis of normality of distribution of average annual water temperatures in a TAW layer, and evaluated the statistical significance of correlation coefficient and linear trends (Rozhkov 2002).

The hypothesis on normality of distribution of values of the TAW time series was tested by the "W-test" (Rozhkov 2002). The test results suggested that the analyzed distribution did not differ from the normal. All equations of linear regression obtained during the study were statistically significant at the level of $P < 0.05$. The exception was found for SAT trends in January and December that are statistically significant at the level of $P < 0.15$.

Results and Discussion

The long-period variability of TAW temperature

Primary analysis indicates a general increase in average summer temperature in TAW layer over the whole studied period (Fig. 3a). In terms of linear trend (*see* the equation of linear regression, statistically significant at the level of $P < 0.05$), the water temperature increase makes 0.15 degrees over a decade. The determination coefficient is 0.37; *i. e.* the linear trend describes no more than 37% of the total variance of the analyzed time series. This could presumably be explained by a considerable year to year variability of TAW characteristics.

The average long-term water temperature in TAW layer during the period of 1901-2009 is 2.0°C. The water temperature deviations from average long-term values (Fig. 3a) demonstrate the two periods with positive temperature anomalies in TAW layer. The first one coincides with 1920-1940 (well-known "*first warming*" in the Arctic region). The second one coincides with the period of 1983-2009. The latter period is known as a phenomenon of fast warming in the Arctic - "*Arctic amplification*" (Polyakov et al. 2002). The absolute peak of average annual water temperature in TAW layer (3.7°C) coincides with the second period and the contemporary warming is more pronounced in terms of deviations from average values.

As a part of the analysis of long-period variability of TAW in fjords of the West Spitsbergen Island, we calculated anomalies of average annual water temperature in the TAW distribution layer. Based on the data shown in Figs. 3a, b the following conclusions can be postulated: (1) two periods with positive anomalies of average annual water temperature in TAW layer. The first period coincides with 1920-1940, and the second coincides with 1983-2009. Then (2) the contemporary warming is more powerful in comparison with the first one, in terms of deviations from mean values. Maximum deviation values during the contemporary warming made 1.8°C and 1.6°C and were observed in 2006 and 2007, respectively.

Long-period variability of surface air temperature

In agreement with fundamental methodological principles (Alekseev 2003, Vise 1937), which are based on a joint analysis of the thermal regime of the ocean and atmosphere, we studied the features of long-period variability of SAT, as one of the most important characteristics of the atmospheric thermal condition for Svalbard area. The time series of average monthly SAT values covers the period from 1898 to 2013 (Nordli et al. 2014). The total linear trend shows a 2.6 degrees increase in SAT for the above mentioned period. Atmospheric warming in Svalbard area for separate months is presented in Table 1 as linear trend coefficients defining an average rate of change in SAT for the considered time period. Linear trends of average monthly SATs are positive for all months, and the biggest warming was observed in February, March, April and November (0.4-0.5°C/10 years).

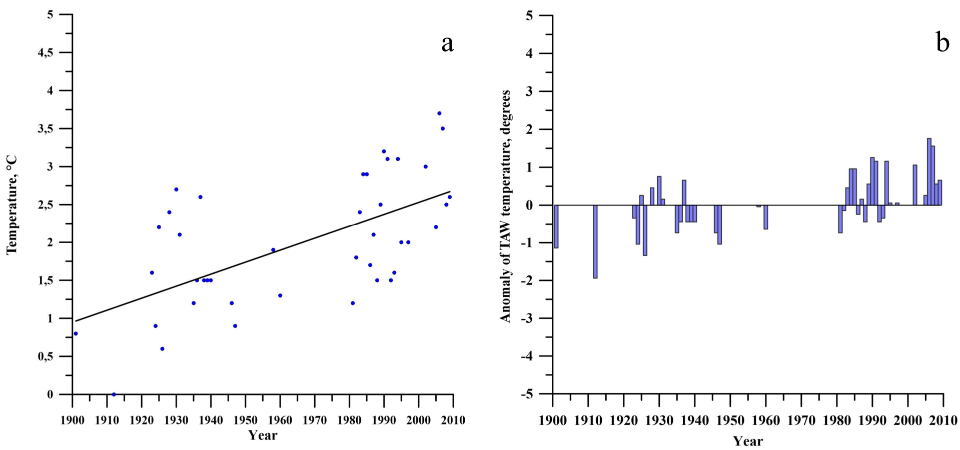

Fig. 3. The time variability of mean year (summer) values of TAW temperature (blue dots, black line – linear trend, Y = 0.016 * X - 29.016) in Svalbard fjords (a); the time variability of anomaly (blue column) of mean year TAW temperature in Svalbard fjords (b).

Month	**Trend coefficient (degrees per 10 years)**	**Month**	**Trend coefficient (degrees per 10 years)**
January	*0.207*	July	0.149
February	0.522	August	0.109
March	0.475	September	0.198
April	0.377	October	0.160
May	0.286	November	0.401
June	0.087	*December*	*0.194*
Year		**0.260**	

Table 1. The average evaluation of SAT line trend for individual month and year.
Note: The values given in *italics* indicate the months for which the linear regression equations are not statistically significant at $P < 0.05$.

Comparative analysis of long-period variability of TAW layer temperature and SAT

We compared normalized anomalies of TAW layer temperature and SAT in frame of comparative study of the long-period variability these characteristics (Alekseev 2003). Due to high year-to-year variability, the long-term variability of normalized anomalies of SAT is represented as curves obtained by filters of 5- and 11-year moving average (*see* Fig. 4).

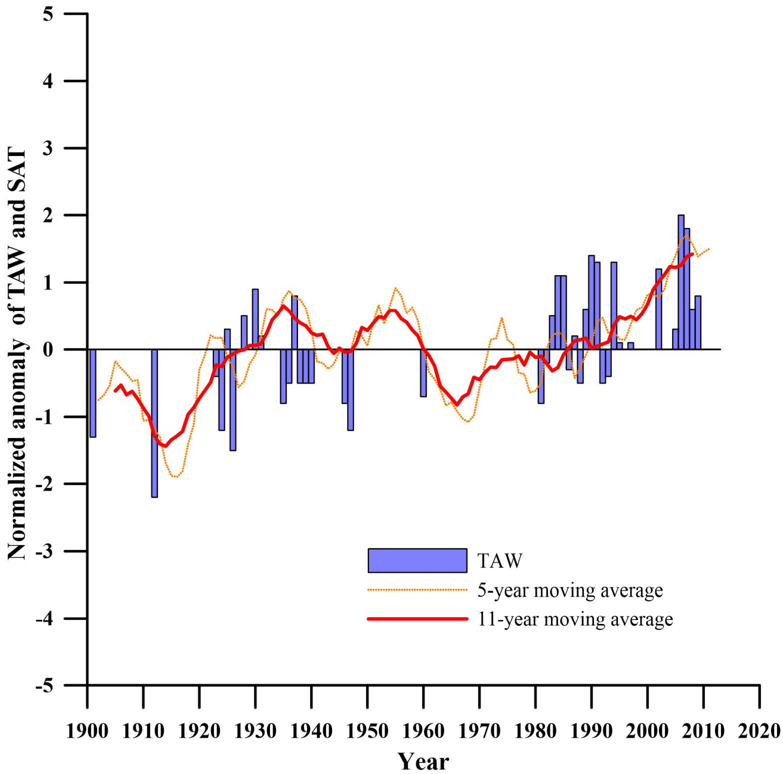

Fig. 4. The normalized anomaly of TAW layer temperature and SAT in Svalbard area (blue column – TAW layer temperature, orange curve – 5-year moving average, red curve – 11-year moving average of SAT anomaly).

During the first Arctic warming period (1920-1940), positive TAW temperature anomalies were observed in 1925-1930 and positive SAT anomalies were moved to the interval from 1930 to 1940. Contemporary warming was characterized by significant positive normalized temperature deviations in TAW layer over the period from 1980 to 2009. The SAT time series represented as 5- and 11-years moving average for this period showed that no noticeable anomalies (positive or negative) were observed from 1980 to 1990. Moreover, significant normalized anomalies of air temperature were only observed from the mid-1990s.

It should be noted that big gaps in time series for average annual temperatures in TAW layer make it impossible to instead the exact degree of correlation (interrelation) between the presented features. However, a general variability trend exists, especially for the contemporary period, *i.e.* an increase in water temperature in TAW layer and SAT. Presumably, there is a common external source of observed changes in both parameters. Taking into account the nonhomogeneous time data available for this study, it is difficult to identify the signs of lag of one process from another.

Concluding Remarks

The analysis of long-term temperature variability in TAW layer in the fjords of West Spitsbergen Island and SAT has brought the following conclusions. The increase in mean year temperatures for the period from 1901 to 2009 is 0.15°C per 10 years.

There are two separate time intervals of warming: first from 1920 to1940, and the other from 1980 to the present day.

Contemporary warming (from 1980 to the present day) is more intense in comparison with the first Arctic warming (considering duration, speed of warming and maximum temperatures). An increase in the average annual SAT found for the period of 1898-2013 reached 0.26°C per 10 years. Maximum warming of SAT was observed in February, March, April, and November. It is consistent with the reports on intensification and warming of the WSC core in the last decades of 20 century and first decades of 21 century (Walczowski et Piechura 2007, Schauer et al. 2008, Pavlov et al. 2010, 2013, Zhuravskiy et al. 2012, Marszs et Styszinska 2013).

Comparative analysis of the time series of normalized anomalies of water temperature in TAW layer and SAT in the Svalbard area showed the existence of quasi-synchronous variability of the characteristics. Presumably the reason for this phenomenon can be considered as an external source.

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