A comparative analysis of coastal environmental conditions in the eastern Norwegian Sea and southern Barents Sea by means of *Arctica islandica* growth records

Tamara Trofimova

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Scientific supervisors

Prof. Dr. Thomas Brey, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany

Dr. Alexey Sukhotin, White Sea Biological Station, Zoological Institute of Russian Academy of Sciences, St. Petersburg, Russia

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Abstract

Since the 1970s tremendous changes have been observed in the Arctic region. As such, the surface air temperature within this region has increased twice the global average and according to existing climate model predictions, this trend will continue in the future (IPCC, 2007). However, interpretation of such transformation, which results from greenhouse warming, is still difficult. This is due to a lack of knowledge about the influence of multi-annual to decadal climate variations and the fact that climatic data from this region are usually temporally and spatially biased. Therefore, a better understanding and further research on the effects and predictability of climate variability is needed.

We examined the growth variability in shells of the bivalve mollusc *Arctica islandica L.* which is affected by environmental factors, mainly temperature and food supply. The prime objective of the project was to compare the shell growth of molluscs from two distinct populations in European Arctic and to determine the external factors influenced on the annual shell growth variability in *A. islandica*. We compared shells from two sampling sites: the northern Norwegian coast and the Kola Peninsula coast (SW Barents Sea). Both localities are in the realm of the Norwegian Coastal Current (after crossing the border to Russia it is called the Murman Coastal Current). For the investigation of the annual and inter-annual growth variability all collected shells were cut, 3 mm thick-sections were attached to a glass slide, grinded, polished and stained. Annual growth bands were identified and measured. Samples for the stable isotope ($\delta^{18}O$, $\delta^{13}C$) analysis and the seasonality approach were taken using a hand drill and the milling technique.

Based on increments measurements of 62 specimens, we found significant difference in growth rates between these two locations, which presumably resulted from a difference in thermal regime in the two sites and in the depth of collection of the molluscs. By comparison of growth chronologies with the time series of environmental and climatic parameters, we indicated a growth response of a specimen from the Norwegian coast to seawater temperature variability in the study area and found a similarity in a pattern with NAO-index. The molluscs from the Barents Sea responded to variation in air temperature, especially during colder periods.

Analyzed stable isotope ratio ($\delta^{18}O$, $\delta^{13}C$) profiles showed cyclic patterns within annual growth lines related to seasonal changes in temperature and primary production. The obtained values of stable oxygen isotope ratio allowed a reconstruction of seasonal changes of water temperature, but for the precise results accurate data on salinity or $\delta^{18}O$ ratio of seawater is needed.

Аннотация

Начиная с 1970х, в Арктике наблюдаются значительные климатические изменения. Так, к примеру, приземная температура воздуха в этом регионе возросла двукратно по отношению к мировому уровню, и, в соответствии с существующими климатическими моделями, этот рост продолжится и в будущем (IPCC, 2007). Однако, считать подобные изменения следствием глобального потепления, вызванного парниковыми газами, недостаточно обоснованно. Это связано с отсутствием знаний о многолетних климатических колебаниях и временной и пространственной разнородностью климатических данных в этом регионе. Поэтому, требуются дальнейшие исследования климатических изменений и анализ их влияния на морские экосистемы.

Мы изучили изменчивости линейного роста двустворчатых моллюсков *Arctica islandica* L.*,* который зависит от факторов окружающей среды, преимущественно температуры и пищевых ресурсов. Целью работы было сравнение роста раковин моллюсков из двух популяции, а также оценка факторов, влияющих на изменчивость годового прироста *A.islandica*. Мы сравнивали раковины, отобранные на северном побережье Норвегии и на берегу Кольского полуострова (юго-запад Баренцева моря). Обе точки связаны Норвежским прибрежным течением, которое в Российских водах называется Мурманским прибрежным течением. Для изучения годовых и межгодовых изменений роста, все отобранные раковины были распилены вдоль линии максимального роста и, полученные срезы были прикреплены к предметным стеклам. После полировки, все срезы были окрашены, линии ежегодной остановки роста были определены и расстояние между ними измерено. Пробы для анализа стабильных изотопов кислорода и углерода были отобраны с помощью ручной дрели.

Основываясь на измерениях 62 раковин, были обнаружены достоверные различия в росте между моллюсками из двух исследуемых популяций, которые предположительно связаны с различиями в температурном режиме и с глубиной отборы раковин в обеих точках. Сравнивая ряды стандартизованных годовых приростов с временными рядами климатических параметров, мы обнаружили статистически достоверную положительную корреляцию между ростом раковин с норвежского побережья и межгодовыми вариациями температуры воды

Мурманского течения, а также с межгодовыми колебаниями значения NAO-индекса. Рост раковин из Баренцева моря, в свою очередь, коррелирует с колебаниями среднегодовой температуры воздуха, в особенности в холодный период года.

Изменения в соотношениях изотопов кислорода и углерода ($\delta^{18}O$, $\delta^{13}C$) в анализируемых раковинах, носят циклический характер, в соответствии с линиями годового прироста, и обусловлены сезонными изменениями в температуре и первичной продукции. Полученные значения $\delta^{18}O$ в карбонате раковин позволяют восстановить температурные условия окружающей среды, однако, для получения абсолютных величин необходимы точные данные о солености или $\delta^{18}O$ окружающей морской воды.

1 Introduction

The problem of global climate change is not a new one in science. In a variety of investigations it has been shown that the Arctic is the most sensitive region in the Northern hemisphere (e.g., Walsh, 2008). Additionally, the increasing industrialization and commercial use of Arctic create necessity of a better understanding of all on-going processes. This will be essential to predict the future of the natural systems.

Since the 1970s tremendous changes have been observed in the Arctic region. The surface air temperature within this region has increased twice the global rate (IPCC, 2007). According to existing climate model predictions this trend will continue in the future (IPCC, 2007; Wassmann et al., 2011). Other evidences of warming processes are the decreasing of sea ice, an increasing precipitation rate and changes in the thermohaline circulation of the Arctic Ocean (Gordeev et al., 2001). These changes modify various biological components of the ecosystems (reviewed in Wassmann et al., 2011), which combined create a coherent picture of transformation. However, interpretation of such transformations, which result from greenhouse warming, is still difficult. This is due to a lack of knowledge about the influence of multi-annual to decadal climate variations, such as the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) (Serreze et al., 2000). Consequently, the increasing concerns about the global climate change have led to an increased interest in the processes of climate variability and the effect on marine ecosystems in the recent decades. Therefore, a better understanding and further research on the effects and predictability of climate variability is needed.

One way to address the predictability of climate change is by using climatic information from the past. Unfortunately, high-resolution instrumental measurements of environmental parameters are only available for the last century. Another complication, related to the Arctic, is the harsh natural conditions. These make continuously recorded environmental observations difficult. For this reason, climatic data from this region are usually temporally and spatially biased. To fill this gap we can utilize biological proxies.

It is well known that the seasonal and annual variability of environmental conditions has a strong influence on the different physiological processes in living organisms (e.g., growth) (Jones, 1980; Brockington and Clarke, 2001; Richardson, 2001). One of the visible results of such dependence is growth periodicity, which occurs in a wide taxonomic range of organisms and manifested in the formation of annual and sub-annual growth bands (increments) in hard structures of animals and plants. Widely known (non-marine) examples of such structures are tree rings, which have successfully been used for the reconstruction of climatic condition in the past (García-Suárez et al., 2009; Helama et al., 2010). Within the aquatic habitats, growth bands, similar to the tree rings, can be found in the accreted hard parts and skeletons of molluscs, corals, sclerosponges, brachiopods, fish and coralline algae (Hemle and Dodge, 2011). The physical and chemical properties of these structures are an object for sclerochronological studies. By measuring and counting annual increments, information about growth rates and ontogenetic ages can be obtained. Furthermore, it is possible to reconstruct environmental parameters of the past.

Bivalve molluscs are one of the most commonly used taxonomic groups in sclerochronology. These organisms are widely distributed in different aquatic habitats all over the world. Since the process of shell growth and shell formation is sensitive to the changes in ambient conditions, bivalves are unique bio-archives of the environment. By using sclerochronological techniques we can obtain data by analysing the stable isotopic composition of the shell and the relative width of growth increments. This information can be used for the reconstruction of different environmental parameters, such as water temperature (Jones et al., 1989; Schöne et al., 2004b; Schöne et al., 2005b; Stott et al., 2010), air temperature (Schöne et al., 2004a) and the amount of precipitation (Schöne et al., 2007). Moreover, annual growth increments can be used for the construction of long-term (even multicentennial) shell-based chronologies for the marine environment (Butler et al., 2011).

The ocean quahog, *Arctica islandica* is a boreal species and one of the biggest bivalve species inhabiting the marine waters of the North Atlantic (Zatsepin and Filatova, 1961; Thórarinsdóttir and Einarsson, 1996). It is considered as an ideal organism for the sclerochronological studies and the construction of long-term chronologies of growth variation (Marcitto et al., 2000; Schöne et al., 2003; Wanamaker et al., 2008; Butler et al., 2011). At the one hand, *A. islandica* has a wide geographical distribution (the fossil records show even bigger range) (Fig.1) and it can be found in a variety of different habitats (Nicol, 1951; Zatsepin and Filatova, 1961; Merrill and Ropes, 1969; Dahlgren et al., 2000). On the other hand, it is the longest lived, non-colonial animal known to science, with a maximum life span potential which exceeds 400 years (Wanamaker et al., 2008). Therefore, the shells of *A. islandica* might contain information about the climate variability for centuries. By applying a cross-dating approach this peculiarity has already successfully been used for the construction of a multicentennial shell-based master chronology in the marine environment (Butler, 2011). Moreover, *A. islandica* shows variations in growth according to different environmental factors, such as temperature (Marcitto et al., 2000; Schöne et al., 2005b) or food supply (Witbaard, 1996). Furthermore, the correlation between annual growth and climate events, such as the North Atlantic Oscillation (NAO) has been proven for shells from the North Sea (Schöne et al., 2003).

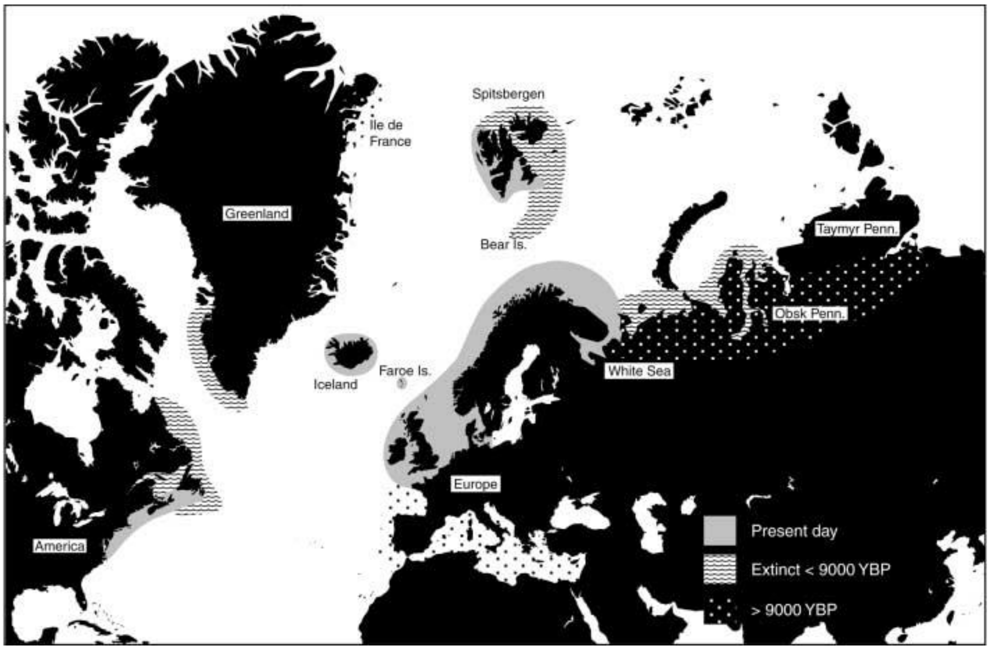

Figure 1 The past and present day distribution of *Arctica islandica* in the North Atlantic (from Dahlgren et al., 2000).

In the present study we examined the growth variability of *A. islandica*. Our prime objective is to identify the main environmental factors which influence the shell growth formation from the sub-annual to the decadal time level. One of our sampling points is located along the Norwegian coast, another one is on the south coast of the Barents Sea. Both localities are exposed to the same ocean current. It is expected that similarities in the oceanographic conditions are reflected in the shell, possibly occurring with certain time lag.

All laboratory work for the present investigation was carried out at the Bioscience/Functional ecology division of Alfred-Wegener-Institute for Polar and Marine Research (AWI) at Bremerhaven.

1.2 Objectives

The main aims of this research project were:

- To analyse the growth variability of *Arctica islandica* and to compare the results from the Norwegian and the Russian populations.
- To determine the external factors controlling the annual shell growth variability in *A. islandica*.
- To check for decadal oscillations (NAO?) within the growth patterns of *A. islandica.*
- To use stable oxygen isotopes ($\delta^{18}O$) to reconstruct seasonalities and water temperatures on a sub-annual level.

2 Materials and Methods

2.1 Study area

The area of investigation includes the east coast of the Norwegian Sea north of the Arctic Circle and the south coast of the Barents Sea. The feature of this region is subarctic climate with long and relatively cold winter season and mild and short summers.

Climate in the study area is strongly influenced by general ocean circulation patterns, particularly by the properties and activity of the inflowing Atlantic water from the North Atlantic Current (Edlandsvik and Loeng, 1991). This relatively warm water mass characterized by salinity >35‰ (Helland-Hansen and Nansen, 1909), has a winter temperature exceeding 6 °C (Gyory et al., 2009). The North Atlantic current has an eastern boundary formed by Norwegian Coastal Current (NCC) (Fig.2), which flows along the western and northern coast of Norway and after crossing the border to Russia it is called the Murman Coastal Current (Loeng, 1991). Both of our sampling points are exposed to this current. During winter time NCC is deep and narrow, while during summer season it is wide and shallow (Loeng, 1991). In comparison with Atlantic water, Coastal Water has almost the same temperature but with stronger seasonal signal (ICES, 2009; Loeng, 1991). The main parameter that distinguishes these two water masses is salinity. The NCC is fresher (<34.7‰); it includes a flow of brackish water from the Baltic Sea and Skagerrak, which enlarged by inflow from fjords and rivers along the coast (James, 1991).

The North Atlantic Current together with Norwegian Coastal Current play an important role in climate of the coastal zone due to a mechanism of exchange of energy between the surface water and atmosphere, which result in moderating effect on temperature extremes along the coast. Thus, the heat release during the winter time causes the warming of overlaying air mass. During summer the process of exchange is reversed, warm air mass transfer the heat to underlying ocean (Helland-Hansen and Nansen, 1909).

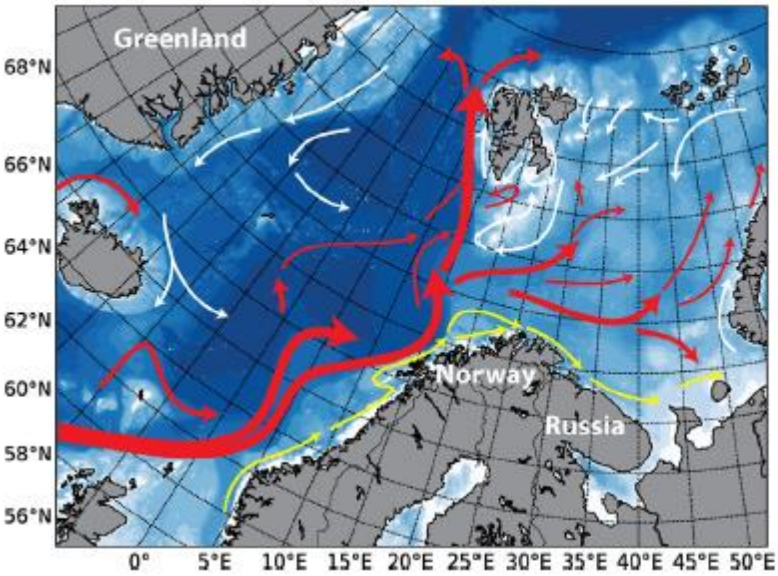

Figure 2 The Norwegian and Barents Sea surface water circulation. Arrows show the distribution of the currents, in red: Atlantic current, white: Arctic current, yellow: Coastal current (Norwegian, Murman) (Map from Drinkwater, 2011).

2.2 Time series of environmental and climatic parameters

In order to characterize environmental and climatic conditions of the area of investigation we analysed different environmental and climatic parameters from a number of data sources. We selected only those of them that based on monitoring observation in area close to sampling sites.

Due to the lack of regular observation that covers the period equivalent to our master chronologies, we selected the possible longest time series.

2.2.1 Seawater temperature

Source: Bochkov, 2005; http://www.pinro.ru.

For the present study the temperature series from the Russian records on the Kola section along the 33^{o}30`E were selected. This section is located in the Murman Current and representative for the portion of Atlantic Water inflow from the Norwegian coast to the Barents Sea. The variation of seawater temperature that recorded in this section coincides with those on the coast Barents Sea as well as whole Norwegian coast (Loeng, 1989). The distribution of monitoring stations is shown on the map (Fig.3). The Kola section temperature time series presented as means of seawater temperature in 0-200m layer from 1900 to the 2010. To our knowledge it is the longest time series in the region, which have only a few gaps from 1906 to 1920 and from 1940 to 1945. These gaps were filled by the model data (Bochkov, 2005). For this study historical data were taken from Bochkov (2005) and supplemented by resent data from PINRO (http://www.pinro.ru).

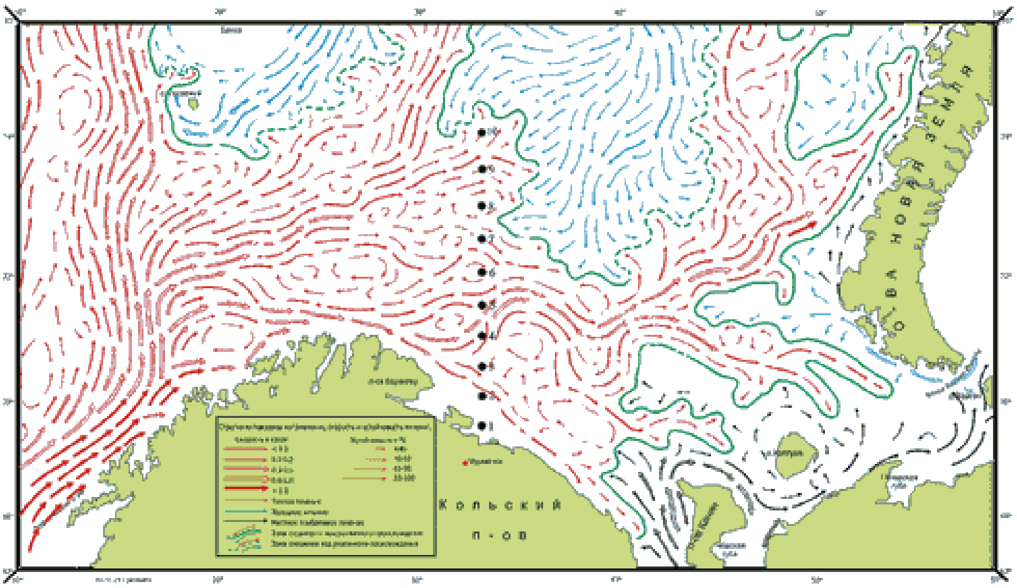

Figure 3 The map of distribution of a monitoring station of Kola section. The black dots corresponds to the stations, red arrows denotes a distribution of Atlantic Water Mass in the area of investigation. (Map from http://www.pinro.ru)

According to existing data the annual values of water temperature in this area varied between years and ranged from 2,83°C to 5,08°C. During the observation period of 111 years, the minimum value of this parameter was observed in 1966, then, with exception of few cold years, the temperature increased up to a maximum value in 2006 (Fig.4).

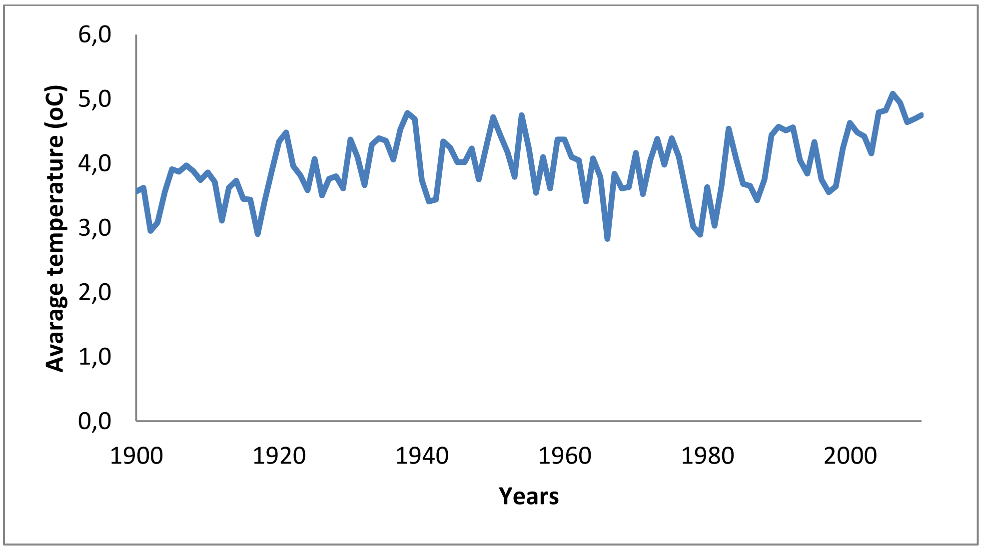

Figure 4 Times series of annual mean of seawater temperature from the Kola section from 1900-2010.

2.2.2 Air temperature

Source: iridl.ldeo.columbia.edu

The air temperature time series were constructed using the annual means of air temperature, which were calculated on a base of monthly mean temperature observations from two meteorological stations the closest to our sampling points. The first one is located in Tromsø (69°68'N 18°92'E) (WMO Station ID – 102500). The air temperature data from this station covers a time interval from 1921 to 1993. The data from the second station, which is located in Murmansk (68°97'N 33°05'E) (WMO Station ID – 2211300) corresponds to the period 1919-1993.

The data from the both stations shows similar variation between years, but the temperature in Murmansk is usually on a few degrees less than average in Tromsø (Fig.5)

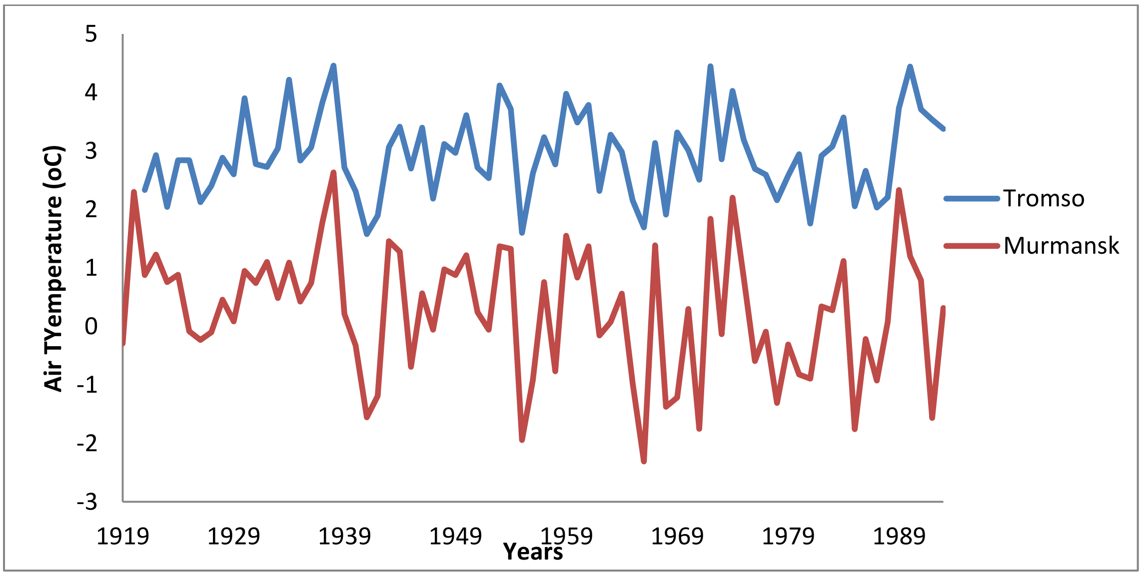

Figure 5 Time series of annual average air temperature in Murmansk (red line) and Tromsø (blue line).

2.2.3 North Atlantic oscillation index (NAO index)

The NAO is a recurrent climatic phenomenon, which affecting climatic variability from Arctic to subtropical Atlantic and from North America seaboard to Siberia, especially during boreal winter (Hurrel et al., 2003). Hurrell (1995) calculated a NAO index as a mean normalized pressure difference between Stykkisholmur (Iceland) and Lisbon (Portugal).

The positive phase of the NAO corresponds to a large pressure difference between two mentioned locations. When the difference is low, it is considered as a negative state.

The positive values of NAO index associated with wet and mild weather across the Northern Europe, while during negative phase opposite patterns in a temperature and precipitation are typically observed.

Source: climatedataguide.ucar.edu

In this study we used the station-based winter (December-March) Hurrell North Atlantic Oscillation Index, because the signal is stronger during this period and these months are prior to the period of active growth of molluscs in the area of study. Time series of NAO index cover a period from 1864 to 2010.

Besides year-to-year variability, the NAO index exhibited significant multi-decadal variability. For example, one of prominent periods starts in 1940s. Since that time until 1970s the negative phase of NAO was dominant (Hurrell, 1995). During the past 30 years the values of this index tend to be more positive with maximum recorded in winters of 1983, 1989 and 1990 (Fig. 6).

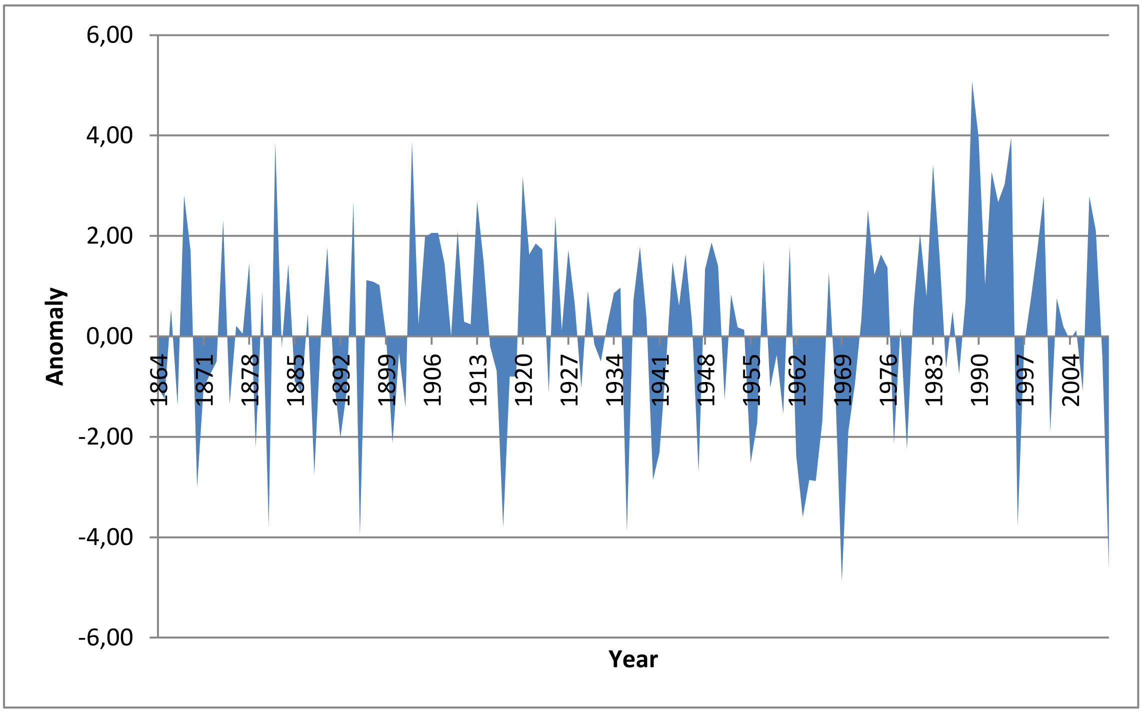

Figure 6 Time series of WNAO index 1864-2010

2.2.4 Arctic oscillation index (AO)

The Arctic Oscillation (AO), also referred to as a Northern Hemisphere Annual Mode, is defined as main pattern of sea level pressure field in Northern Hemisphere (20°-90°) (Thompson and Wallace, 2001). The AO is characterized by two centers of a sea-level pressure anomalies with opposite sign, one is over the polar region and the other one centered about 37-45°N.

The positive phase of this pattern associated with below normal sea-level pressure over the Arctic, enhanced surface westerlies in North Atlantic, bringing a wetter weather to Scotland and Scandinavia. During the negative phase the situation is reversed.

Within the Atlantic sector the AO dominated by NAO structure. Despite the common features, the AO has an additional center of action in the North Pacific, that gives the AO more zonally symmetric structure (Tremblay, 2001).

Source: climatedataguide.ucar.edu

In this study we used a normalized Hurrel SPL-based winter AO index for the period 1899-2011 (Fig.7).

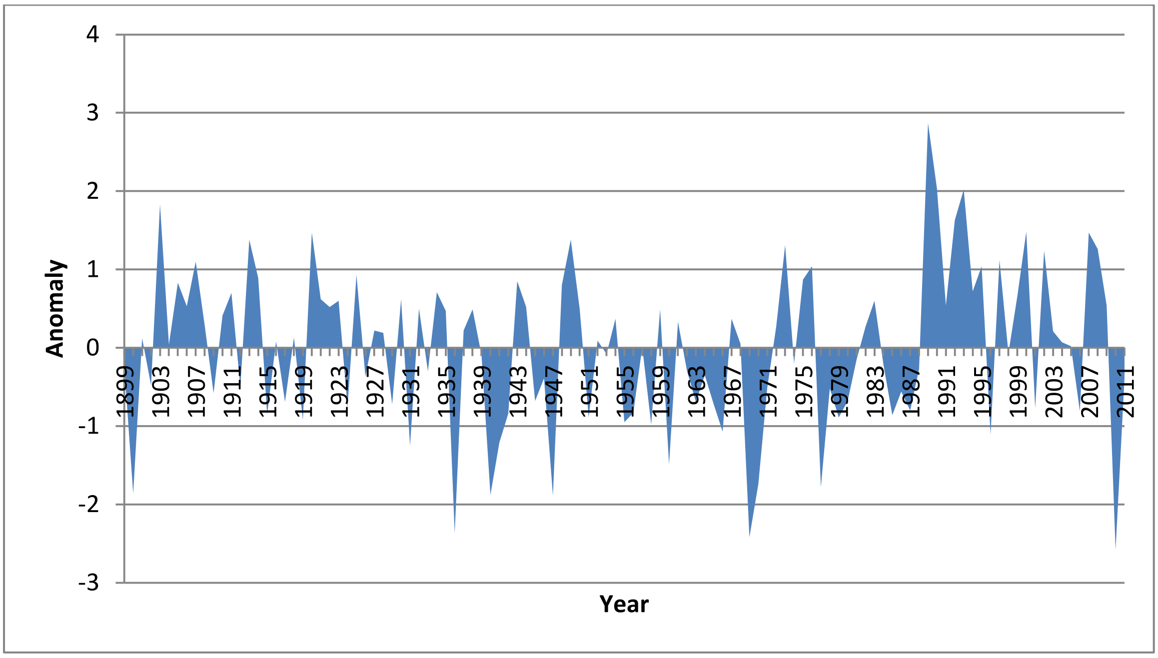

Figure 7 Time series of AO index 1899-2011

2.3 Collection of a shells and processing

The shell material for this study has been collected from three different localities. It comprises 30, 32 and 18 specimens of *A. islandica* from the Norwegian Sea (69°39'N 18°57'E), Russian coast of the Barents Sea (69°11'N 36°05'E) and the White Sea respectively (66°20'N 33°38'E) (Fig.8). The molluscs from the Norwegian Sea have been collected in 2006 at depths 10-30 m and dissected by Salma Begum (AWI Bremerhaven). The specimens from the Barents Sea were sampled in 2011 at depth 5-7 m by Larisa Basova (St-Petersburg State University), while those from the White Sea were collected in 2006, 2007 and 2008 by Vladimir Krapivin (St-Petersburg State University). The White Sea specimens were used only for the comparison of shell morphometric parameters. All molluscs were collected alive, dissected and the soft tissue parts were removed immediately after collection. For the investigation we used only one valve from each specimen.

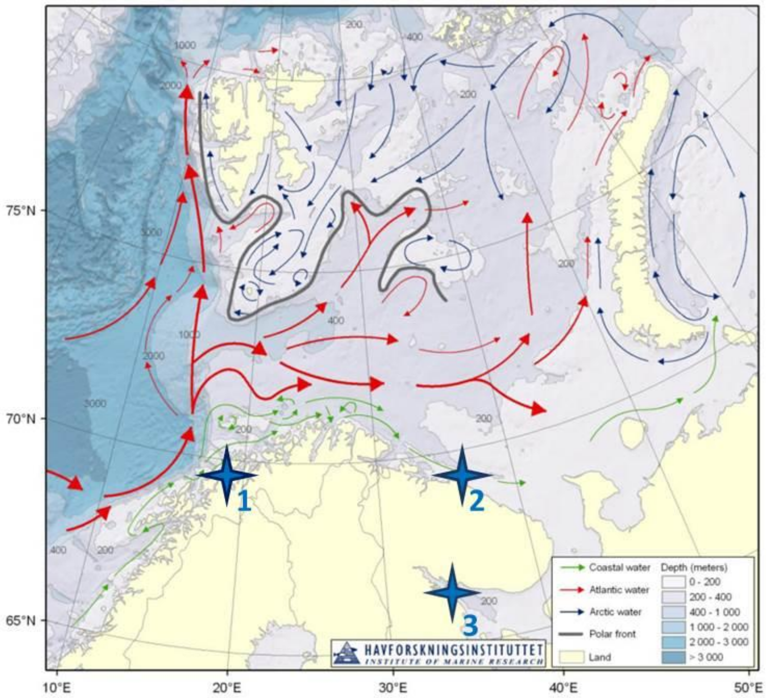

Figure 8 The map of the study area showing the main ocean circulations (arrows). Blue stars showing the three locations of the sampling points, 1: Norwegian coast, 2: Barents Sea coast, 3: White Sea coast. Arrows show the distribution of the currents, in red: Atlantic current, blue: Arctic current, green: Coastal current (Norwegian, Murman) (Map from Stiansen et al., 2005).

2.4 Shell morphology

In order to analyse morphological features of the shells, specimens from all three locations have been used. Firstly, all shells were weighted to the nearest 0.1 g using an electronic balance. Length (L; the greatest distance between anterior and posterior shell margins), width (W; the longest distance of the valve in a lateral plane across the valve) and height (H; measured along the line of the strongest growth) of the shells were measured using digital callipers to the nearest 0.01 mm (Fig.9).

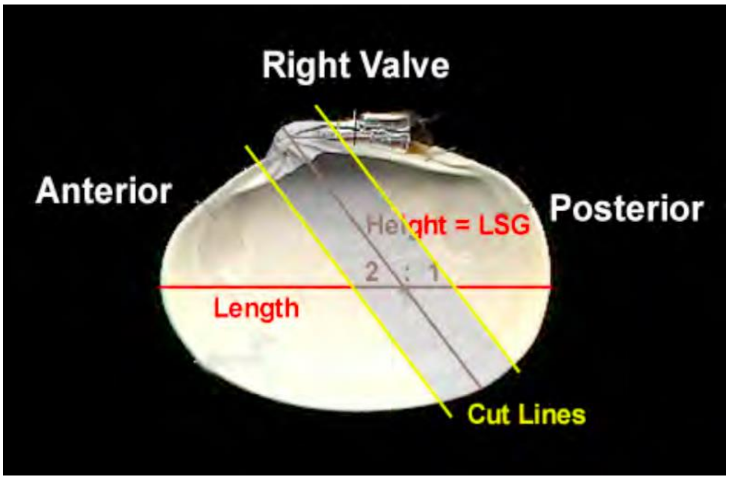

Figure 9 Right valve of *A. islandica* with length, height (line of the strongest growth, LSG) and cut lines parallel to LSG (from Müller-Wiegmann, 2006).

Individually, all of these parameters do not allow describing the features of shell shape and cannot be used separately for the comparison of the shell morphometry, because of the difference of size classes of existing shell material. Thus, three descriptors of a shell shape (Caill-Milly et. al, 2012) and one that links the shell mass (M, in mg) with the volume were selected in order to compare the general morphological tendencies (Tab. 1) between the locations.

Table 1 Descriptors of morphometric parameters

Descriptor	**Formula**
Elongation index	H/L
Compacity index	W/L
Convexity index	W/H
Mass to volume relation	M/(L*H*W)

The calculated values of the descriptors were tested by one-way analysis of variance (ANOVA) and the Tukey`s honest significance test (HSD) test for *a posteriori* comparison among sampling sites. The critical level of statistical significance was taken as P = 0.05.

In order to compare the morphology of a young individuals with older ones, the shells from the Barents Sea were divided on a two groups by age 30 (for the details of age determination see 2.6) The same analysis, as described above, was performed for comparison of a shell shape descriptors between two these groups.

2.5 Cross-section preparation

For the sclerochronological analyses, the shell from the Barents Sea and the Norwegian coast were used. Each valve has been coated twice with EPO-TEK® 302-3M epoxy resin for protection during sawing. Then, the shells have been cut parallel to the line of strongest growth (LSG; Fig.) and were attached to a glass slide with quick-drying metal epoxy. The 3-mm thick-sections (one for the each specimen) were cut along the LSG and through the umbo with a 0.4 mm diamond-coated saw blade using a low speed precision saw (Buehler®, IsoMet™). The section was then mounted on glass slides with EPO-TEK® 302-3M epoxy and grinded with Buehler® 2 speed grinder-polisher with 1200, 2500 and 4000 SiC grinding paper. Finally, samples were etched in Mutvei`s solution for 20 minutes at around 39°C (for the details see Schöne et al. 2005a).

For the stable isotope measurements, one specimen from the Barents Sea and one from the Norwegian coast were selected. From each of these shells 5-mm thick-section had been made and remained unetched.

2.6 Growth increment measurements

In order to analyse a growth variability of the shells from the Barents Sea and the Norwegian coast, in each etched cross-section growth increments had been identified (Fig.10) and measured under a microscope (Olympus SZX12) at magnifications ranging from x10 to x63. The measurements of annual growth rings were conducted in the outer shell layer using analySIS docu software (Olympus Soft Imaging Solutions). Ontogenetic ages of studied specimens were determined by counting the annual increments.

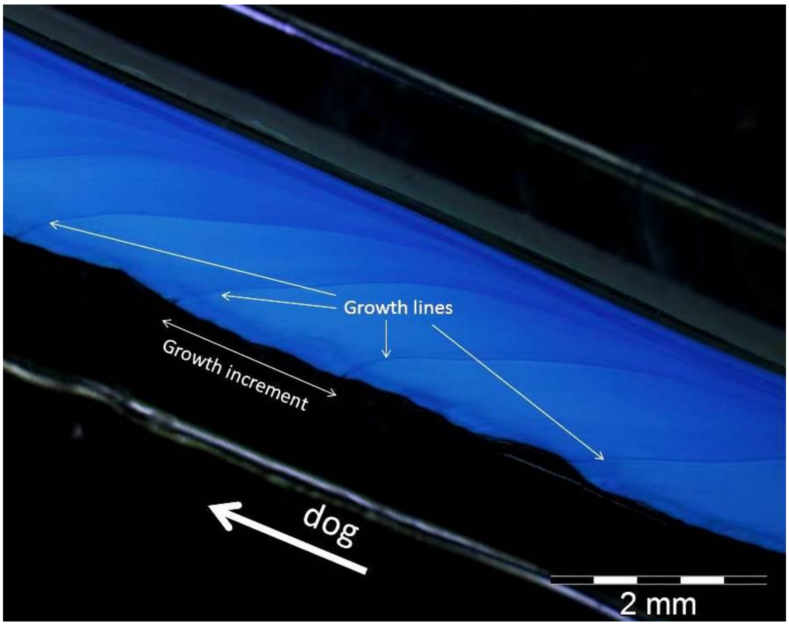

Figure 10 Cross-section of *A. islandica* shell (specimen from the Norwegian Sea) etched with Mutvei`s solution. Image was taken with 10x magnification and clearly shows annual growth lines. DOG indicates the direction of growth.

2.7 Growth

By using the cumulative width of the increments, the length of the shell surface along the LSG at a certain ontogenetic age was calculated. Growth of the shells was modelled by fitting a von Bertalanffy growth function (VBGF) to the obtained data. This function is described by the equation:

$$S_t = S_\infty \left(1 - e^{\left(-k(t-t_0)\right)}\right)$$

where S_t is shell size at age t, calculated as sum of the widths of all prior increments , S_∞ is the physiologically possible maximum shell size, k is the growth coefficient, and t_0 is the theoretical age at $S_t = 0$.

A VBGF model was fitted to data iteratively by a nonlinear Newton algorithm (Brey, 2001) with fixed parameter S_∞ derived by the “Gulland-and-Holt plot” method (following the procedure described by Pauly et al., 1993). The difference in growth between the locations was determined by analysis of covariance (ANCOVA) (size of the increment (ΔS) vs. location and covariate the size of a shell in the middle of this increment ($\bar{S}$)).

2.8 Growth chronology construction

Since all of the molluscs were collected alive, each growth increment was measured and assigned to the particular calendar year in which it has been deposited. This was performed by counting backwards from the last formed growth band on the outer shell margin.

Before the resulting increment-width series can be used for the construction a chronology the data needs to be standardized. During life the bivalves experience a decline in annual growth, resulting in decreasing increment widths, which become less variable with age (Jones 1981; Marchitto et al., 2000; Schöne et al., 2004). Such age-related trends must be removed from the data.

The growth of *A. islandica* is often characterized by rapid increase in increment width during the first years of life (5-7 years) then after reaching the maximum value the growth rate declines (Butler et al., 2010). This leads to the fitting problem during detrending (Butler et al., 2010). Moreover, the shape of the first increments is more curved resulting in an increased measurement error. That is why the first five increments were excluded from the time series. In order to remove the trend of variance from the raw increment-width series, an adaptive power transformation was applied to the data of each series, prior to the growth trend removal (Cook and Peters, 1997).

The average growth trends have been modeled for each individual specimen by applying a cubic smoothing spline (λ=10000) (SAS-institute, 2007) (Fig.10). Hereafter, growth indices (GI) were calculated for the each series by subtracting the modeled values from the powered-transformed increments widths (Cook and Peters, 1997). In order to remove the correlation between the mean and variance from the data, the calculated GI values were standardized by subtracting the mean and dividing it by the standard deviation of the GI time series (Schöne et al., 2005b). The resulting standardized growth index (SGI) is a dimensionless parameter, which explains how the shell growth in the particular year deviates from the predicted value. So, in general, wider increments tend to have positive values of SGI, the narrower- negative (for the details see Schöne et al., 2003).

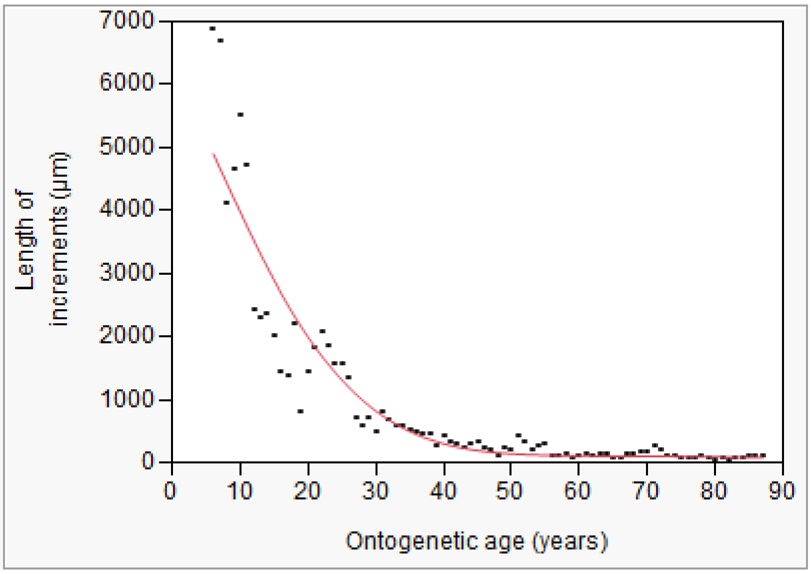

Figure 11 Annual growth of shell YaBa-A09 (Barents Sea). Dots correspond to values of increment width. The age- related growth trend was removed by using cubic smoothing spline (red line).

For the construction of a growth chronology SGI time series of molluscs older than 30 years were used. The synchrony among the SGI time series was analyzed by computation of correlation coefficients for the each individual series and the mean of the other series from the same location. Time-series with correlation coefficient higher than 0.2 were assembled into a chronology.

2.9 Relationship between *Arctica islandica* growth chronology and environmental data

For homogenization of signal amplitudes, before the comparison with growth chronologies, all environmental time series were standardized by applying the same procedure as it was done for the growth indexes. In order to remove the noise of a small frequency, prior to the comparison, the SGI chronologies, as well as, environmental data series were transformed by weighted moving average over three consecutive years (with weights 1:4:1) (Fig.12).

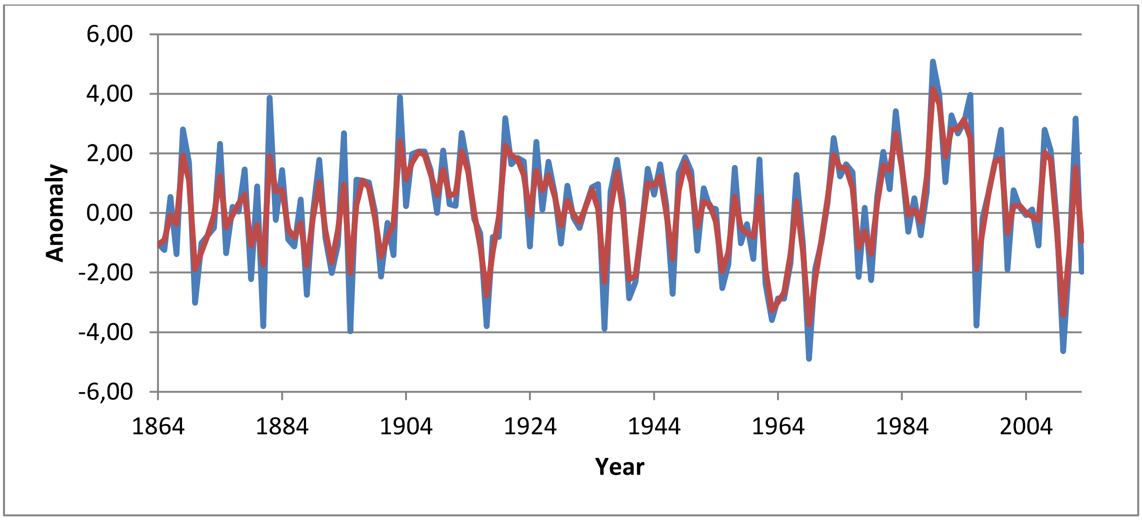

Figure 12 Standardized WNAO index (blue line), together with 3 year weighted moving average (1:4:1) (red line).

The relation between environmental data time series and SGI chronologies were estimated using Spearman`s rank correlation coefficient. Due to the fact that both of locations are exposed to the same ocean current, it is expected that similarities in the oceanographic conditions are reflected in the shell, possibly occurring with certain time lag. Thus, according to the observations of Helland-Hansen and Nansen (1909) there is a delay of two years in the temperature signal from the Norwegian west coast (61°N) to the Russian Kola section. That is why possible time lags of one and two years were considered.

2.10 Stable isotope analysis

Two unetched polished cross-section, 24568-L from the Norwegian Sea and YaBa-A03-L from the Barents Sea, were selected for the analysis of stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes. For the sample preparation, in both specimens ontogenetically identical years were chosen in order to guarantee a comparability of the results.

On the prepared cross-sections, epoxy coating, as well as periostracum, was removed from the outer shell surface. Then, under the binocular microscope at 7x to 20x magnification within each growth increment carbonate samples were extracted by milling parallel to the growth lines Using a cylindrical drill bit (700µm diameter) mounted onto a dental drill device (Minimo 1, Minitor Co., LTD.) (for details see Schöne et al., 2005b). A total of 90 carbonate powder samples have been obtained from the Barents Sea shell, while 124 individual samples from the Norwegian Sea specimen were taken. Average sample weight varied between 40 and 100 µg.

The samples were analyzed with a Thermo Finnigan MAT 253 mass spectrometer with an automated preparation device Kiel IV at the Geology department of Alfred-Wegener-Institute for Polar and Marine Research (AWI) in Bremerhaven.

Isotopic composition of oxygen and carbon were expressed by "δ", which shows a relative concentration of rare (heavier) isotope in a sample. The values of $\delta^{18}O$ and $\delta^{13}C$ were calculated as a difference in proportion of heavier and lighter isotopes (‰) between the measured sample and a standard:

$\delta^{18}O = [(^{18}O/\,^{16}O)_{sample}/(^{18}O/\,^{16}O)_{standard} - 1] * 1000$,

$\delta^{13}C = [(^{13}C/\,^{12}C)_{sample} /(^{13}C/\,^{12}C)_{standard} - 1] * 1000$.

The isotope values were calibrated against the NBS-19 standard, and all data are reported as ‰ VPDB. The average errors of individual measurements are ±0,08‰ for $\delta^{18}O$ and ±0,06‰ for $\delta^{13}C$.

2.10.1 Reconstruction of absolute water temperatures from carbonate stable oxygen isotopes

In equilibrium conditions during deposition, stable oxygen isotope ratio in a calcium carbonate (calcite, aragonite) differs from isotope composition of oxygen in surrounding water due to isotopic exchange in a system carbonate-water according to following reaction (Zakharov et al., 2006):

$1/3CaCO_3^{16}+H_2O^{18} = 1/3CaCO_3^{18}+H_2O^{16}$.

Isotope fractionation in this system is temperature dependent; that is why in equilibrium conditions with water, the stable oxygen isotope ratio in carbonates determines by water temperature. (Epstein and Mayeda, 1953; Beck et al., 2005)

Another factor that controls a stable oxygen isotope ratio in a carbonates is $\delta^{18}O$ of ambient water which prevailed during the shell formation. Thus, Epstein and Mayeda (1953) formulated the isotopic temperature scale as following:

$T^{o}C = 16.5 - 4.3 *(\delta^{18}O_{carbonate} - \delta^{18}O_{water}) + 0.14 *(\delta^{18}O_{carbonate} - \delta^{18}O_{water})^2$.

Mineral composition of biogenic carbonates also significantly affects the relationship between $\delta^{18}O$ in carbonates and temperature. This fact was proven by Horiba and Oba

(1972) and later by Grossman and Ku (1986) formulated the isotopic temperature scale for aragonite:

$T^{o}C = 20.6 - 4.34*(\delta^{18}O_{aragonite} - \delta^{18}O_{seawater})$

So, knowing the $\delta^{18}O_{seawater}$, it is possible to reconstruct the water temperature from aragonite shells mollusk. *A.islandica* were successfully used as an object for such reconstruction (Weidman et al., 1994; Schöne et al., 2003b; Schöne et al., 2005c)

In present study water temperature were reconstructed using the equation established by Grossman and Ku (1986) in the corrected version as follows (Dettman et al., 1999)

$T_{\delta 18O}$ $(^{o}C) = 20{,}60 - 4{,}34*(\delta^{18}O_{aragonite} - (\delta^{18}O_{seawater} - 0{,}27))$

where $\delta^{18}O$ $_{aragonite}$ is measured relative to the VPDB scale and $\delta^{18}O$ $_{seawater}$ is relative to the SMOW scale.

For the water temperature reconstruction we used the $\delta^{18}O_{seawater}$ according to the gridded surface dataset described by LeGrande and Schmidt (2006). Therefore, the surface water at the Norwegian coast is assumed to be characterized by an average $\delta^{18}O_{seawater}$ values close to 0.0‰ (SMOW), while the Barents Sea surface at the Kola Peninsula coast is associated with an average $\delta^{18}O_{seawater}$ value of -0.3‰ (SMOW).

3 Results

3.1 Shell morphology

The morphometric parameters were measured for the shells from the Barents Sea, the Norwegian Sea and the White Sea. The shells from the White Sea were represented by relatively small specimens with a maximum length 51,2 mm (at height 49,8 and width 13,3 mm), while the material from Norwegian coast consisted of only bigger molluscs, where the minimum length was 73,1 mm (at height 67,6 and width 20,5 mm). The material from Barents Sea included shells of all size groups. The range of variation of these morphometric parameters within the locations are presented on a scatterplot (Fig. 13)

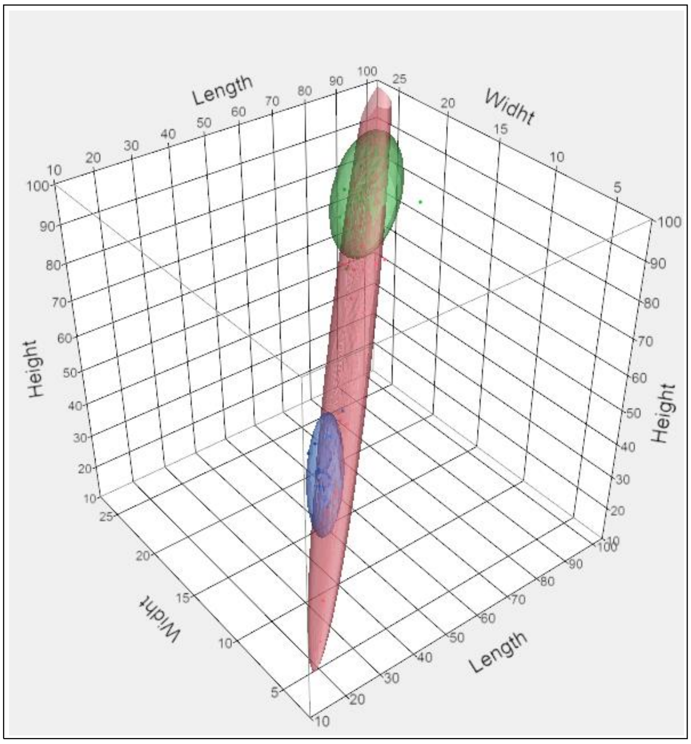

Figure 13 A three dimensional scatterplot of the morphometric parameters (Height, Length, and Width in mm) in relation to each other. The data points are grouped by normal contour ellipsoids (showing 90% of the point distribution) into locations. Blue color corresponds to the White Sea shells; pink denotes the Barents Sea, while green ellipse shows the data points related to the shells from Norwegian coast.

Analyses of variance of the main morphometric descriptors indicate a significant difference among the sampling sites (Tab. 2). Further comparison with Tukey`s HSD test determine that the White Sea shells significantly differ from the shells from other locations in terms of all the descriptors, with one exception. In case of Convexity indexes (Fig. 14, C), the shells from White Sea have no significant difference from the Norwegian shells.

Table 2 ANOVA results of a shell shape descriptors

Source	*DF*	*Sum of squares*	*Mean squares*	*F ratio*	*F probability*
Elongation index					
Between groups	2	0,073	0,010	12,138	<0,0001*
Within groups	77	0,066	0,001		
Total	79	0,086			
Compacity index					
Between groups	2	0,006	0,003	13,155	<0,0001*
Within groups	77	0,018	0,0002		
Total	79	0,024			
Convexity index					
Between groups	2	0,002	0,001	3,231	0,0450*
Within groups	77	0,024	0,0003		
Total	79	0,026			
Mass to volume relation					
Between groups	2	0,138	0,069	61,699	<0,0001*
Within groups	77	0,086	0,001		
Total	79	0,244			

*Significantly different at α=0,05 level

The only descriptor that discriminates between all of the locations is mass to volume relation. According to this parameter the Barents Sea shells are significantly heavier than the shells form other locations, while the specimens from the White Sea are characterized by the lowest values of mass per unit of volume.

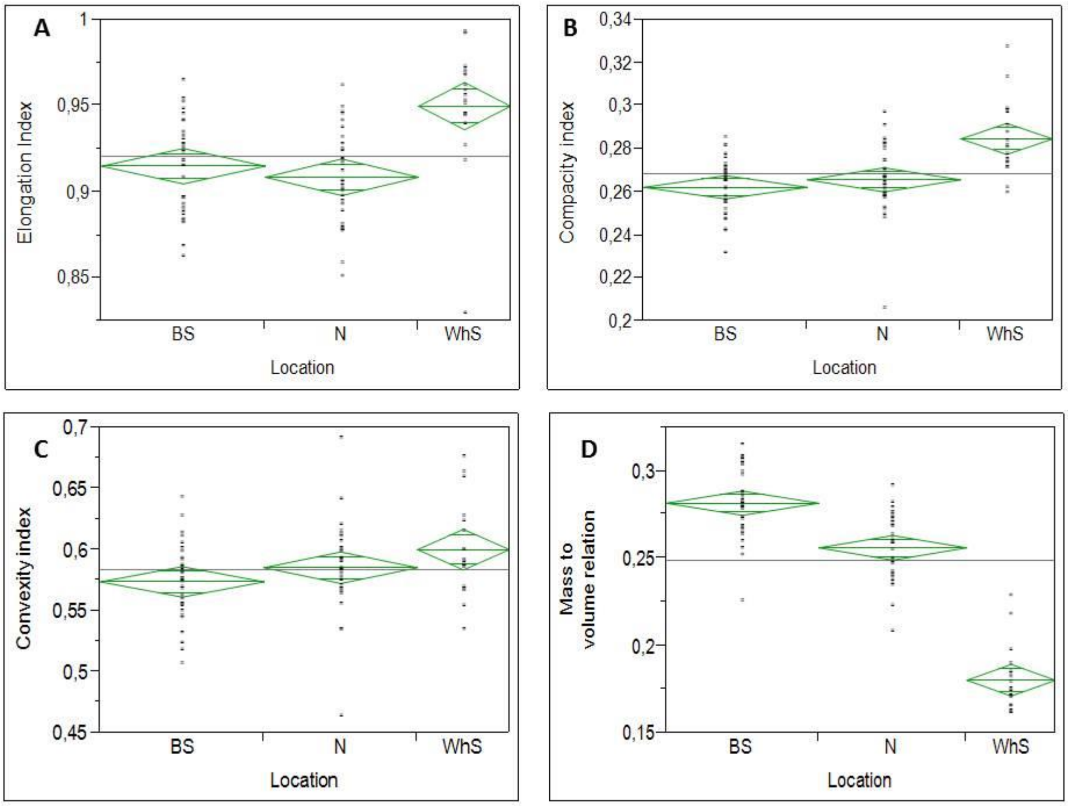

Figure 14 Analysis of variance (ANOVA) for calculated descriptors (A - Elongation index, B - Compacity index, C – Convexity index, D – Mass to volume relation) versus location. Dots represent individual values of descriptors. The top and bottom of each diamond represent a 95% confidence interval, the width is proportional to a sample size for each group of locations.

In order to analyse the difference in shell morphology within the populations the values of shell descriptors of young individuals from Barents Sea (11 specimens) were compared to those of older ones (21 specimens). No significant differences were detected.

3.2 Growth

A total of 1999 annual growth increments were measured in the shells of *A. Islandica* from the Barents Sea and 1893 single increment measurements were made for shells from the Norwegian coast. The maximum determined ages of the molluscs are 118 and 82 years respectively. The von Bertalanffy growth curves were constructed for the shell from both locations. (Fig. 15). Applying a ‘Gulland-and-Holt’ method together with nonlinear iterative fitting algorithm to the data from the Norwegian Sea (N) and the Barents Sea (BS) resulted in following equations:

N: $S_t= 93.81*(1-e^{-0.07*(t+2.87)})$, $R^2= 0.85$

BS: $S_t= 86.58*(1-e^{-0.08*(t-0.44)})$, $R^2= 0.98$

It was noticed that the growth rate was relatively rapid during the first 30 years of life in both populations and then started to decrease. As the values of growth coefficients (k) obtained for both locations are almost the same, the shape of the curves is similar, but the shells from the Norwegian coast tend to be bigger at the same age than those from the Barents Sea.

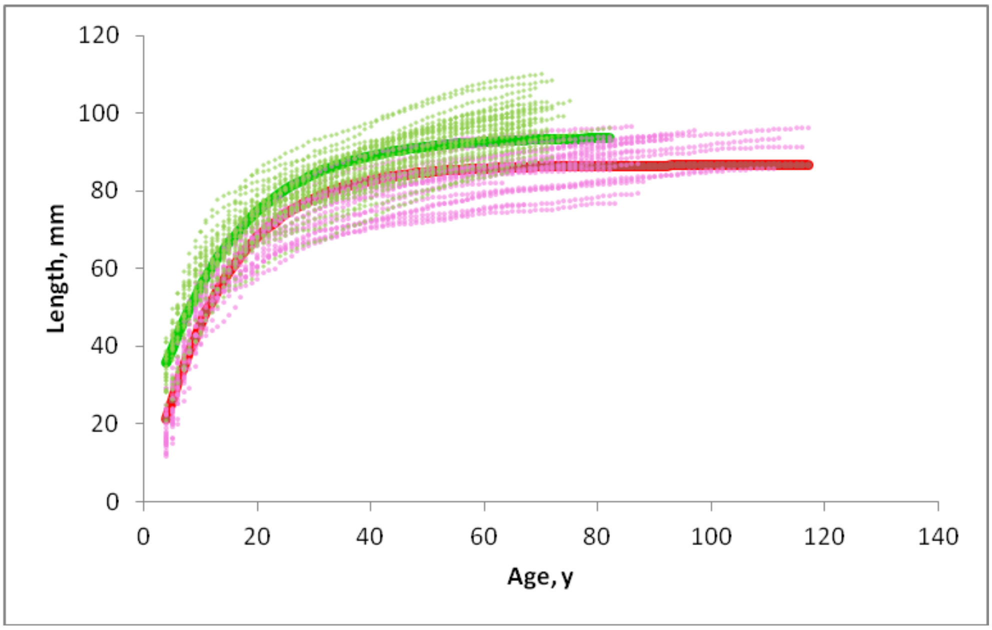

Figure 15 Von Bertalanffy growth curves of A*rctica .islandics* and measured size-at-age data for two locations. Green color corresponds to Norwegian coast (S_∞ = 93.81; *k* =0.07), red color denotes the Barents Sea (S_∞ = 86.58; *k* =0.08) .

For the test of a difference in growth between the shells from the Norwegian coast and the Barents Sea we performed full factorial ANCOVA (size of the increment (ΔS) vs. location and covariate the size of a shell in a middle of this increment ($\bar{S}$)). As the ANCOVA model is a linear model (Quinn & Keough, 2002), the analysis was computed using multiple regressions. Due to the fact that the changing of a size of increments with size of the shell is not a strictly linear processes it cause a problem with fitting of a regression line to the whole range of data points and could be noticed in a graphical representation as a decrease in slope with increasing of size (Fig.16). In order to avoid this problem and perform the analysis, the datasets for the each location were divided into two groups by the value of mean size of 80mm.

The full factorial ANCOVA for the data, which belongs to the group with size less than 80 mm indicates that the growth differed significantly between the locations (P< 0.0001) (Fig. 17)

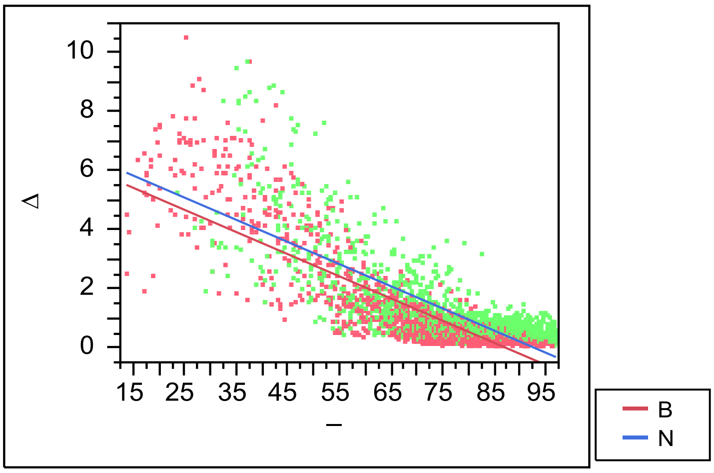

Figure 16 Annual growth of *A.islandica* from the Barents Sea (pink) and the Norwegian Sea (green). Regression lines show the locations (red- Barents Sea, blue- Norwegian coast) (R^2= 0,7; P<0,0001)

The prior to ANCOVA, test of homogeneity among the slopes for the second group were performed by including an interaction term ($\bar{S}$ * location) in the model. A recorded significant interaction effect indicates that relation between the covariate ($\bar{S}$) and the response variable (ΔS) differs between groups (Engqvist, 2005)

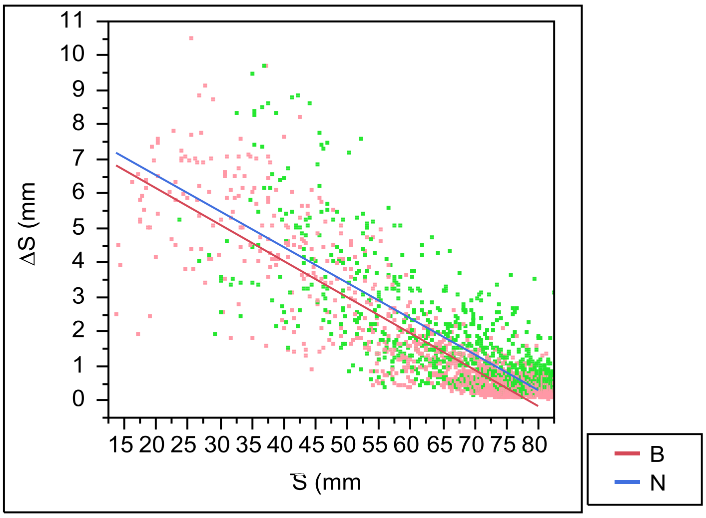

Figure 17 Annual growth of *A.islandica* (for the size less than 80 mm) from the Barents Sea (pink) and the Norwegian coast (blue; green). Regression lines show the locations (R^2= 0,7; P<0,0001)

3.3 Shell growth chronologies

For all individual time series of the shells older than 30 years, that is total of 30 specimens from the Norwegian Sea and 21 from the Barents Sea, the correlation with mean of the other time series from the same location were calculated. Those of them with correlation less than 0.2 were not used for the chronology construction.

A total of 19 individual SGI time series of shells from the Norwegian Sea and 11 from the Barents Sea were assembled to shell chronologies separately by locations. The average correlation of each SGI series with the mean of resulted chronologies comprises 0,42 for the Norwegian Sea shell growth chronology and 0,28 for the Barents Sea.

The length of constructed shell chronology for the Barents Sea is 113 years, which covers a period from 1898 to 2010 (Fig.18). The shell growth chronology for the Norwegian coast comprises a 71-years of period from 1935 to 2005 (Fig.19).

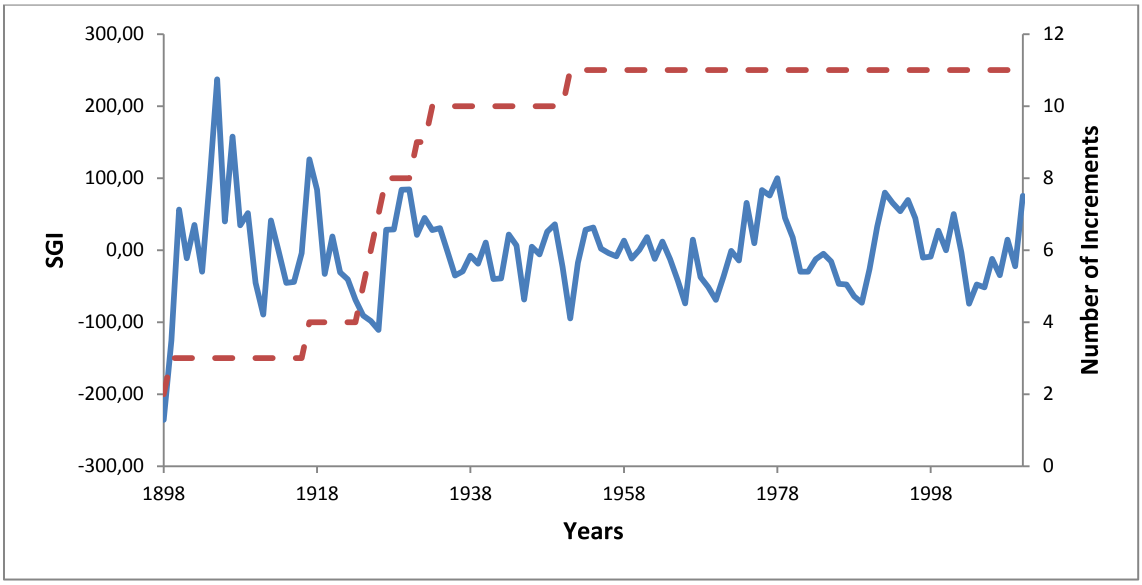

Figure 18 Barents Sea shell growth chronology

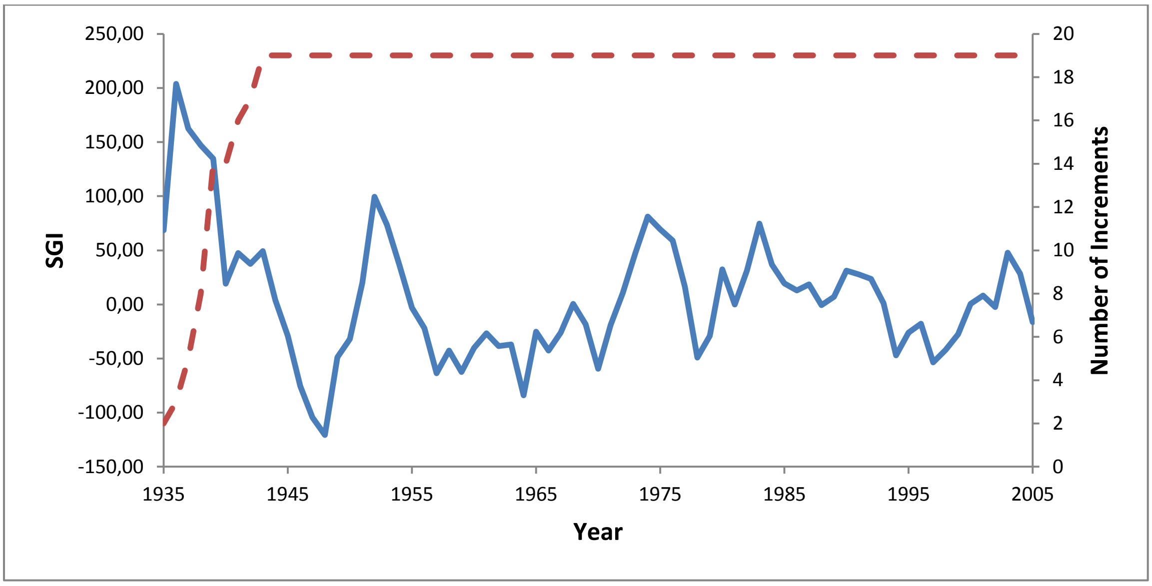

Figure 19 Norwegian Sea shell growth chronology

3.4 Correlation of master chronologies with environmental and climatic parameters

Statistical relation between environmental and climate time series and *A.islandica* growth chronologies from the Barents Sea (BS) and the Norwegian Sea (NS) were tested with the Spearman`s rank correlation. The comparison of the BS- chronology with those from the Norwegian coast did not indicate statistically significant correlation, even considering possible time lags.

Similar patterns and significant positive correlation has been founded between the Norwegian Sea (NS) growth chronology and seawater temperature of 0-200m layer in the Kola Section (Fig.20; Tab.3), while the correlation with air temperature data is not significant. The NS-SGI-chronology is also positively correlated with North Atlantic Oscillation index time series (Tab.3) with a maximum correlation in a period of about 25 years from 1960 (rho= 0.79; p<0.0001) (Fig.21). Despite the absence of significant correlation between Arctic Oscillation and NS-SGI-chronology on the whole overlapping period (1935-2005), for the period 1960-1985 correlation coefficient is 0.622 (p=0.0007).

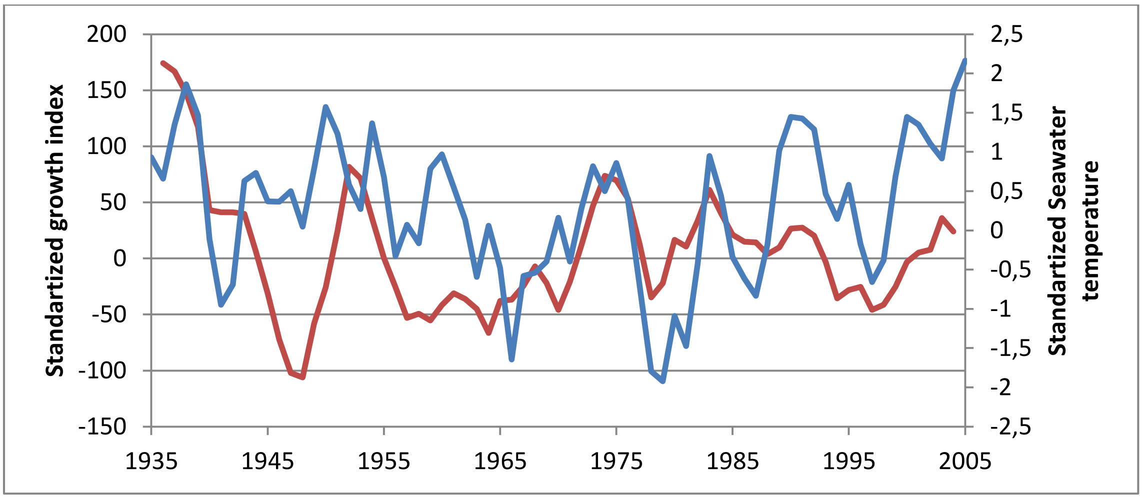

Figure 20 Seawater temperature time series (blue line) and Norwegian Sea growth chronology (red line). To the both time series WMA3- filtering was applied.

No significant correlation was detected between the Barents Sea growth chronology and climate indexes (NAO, AO) on the whole overlapping period (1898-2010), as well as with the seawater temperature, while the air temperature data from Tromsø is positively correlated with obtained SGI-chronology from the Barents Sea with maximum of correlation on the period 1940-1975 (rho=0,569; p=0.0003).

Table 3. Correlation between chronologies of standardized growth indexes SGI and environmental data (Seawater temperature, Air temperature, WNAO, AO). Indicated Sperman`s correlation coefficient and the probability of error (in brackets). Abbreviations: BS - Barents Sea; NS – Norwegian Sea, ns- no statistically significant correlation.

	Period	**BS-SGI-chronology** **1898-2010**	**NS-SGI-chronology** **1935-2005**
Seawater T^o	1900-2011	ns	0.301 (p=0.012)
Air T^o Tromsø	1921-1993	0.281 (p=0.018)	ns
Air T^o Murmansk	1919-1993	ns	ns
WNAO	1864-2011	ns	0,255 (p=0.035)
AO	1899-2011	ns	ns

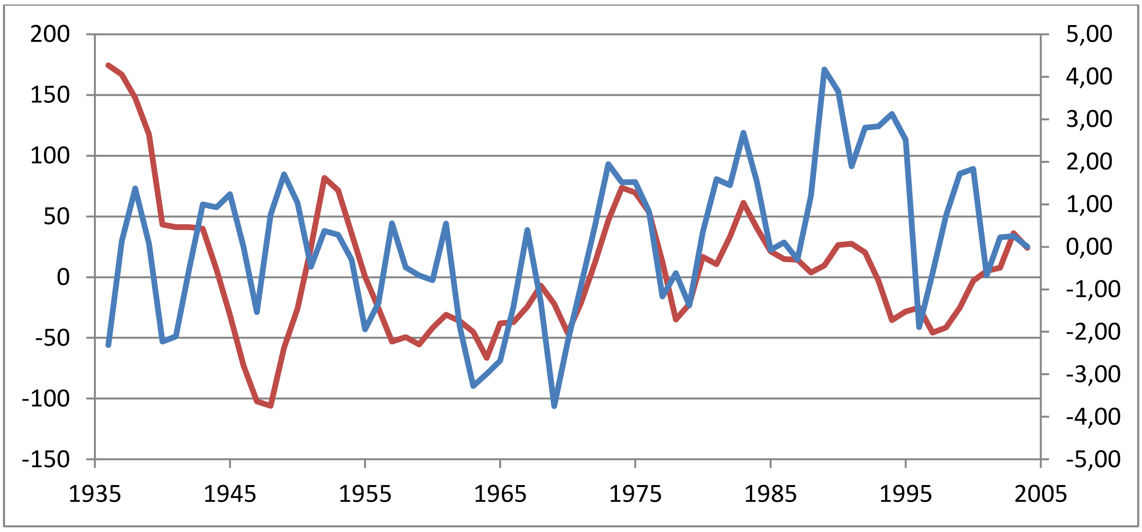

Figure 21 NAO time series (blue line) and Norwegian Sea growth chronology (red line). To the both time series WMA3- filtering was applied.

Despite the fact that the correlation of BS-growth chronology with air temperature data from Murmansk during a whole investigated period is not significant, the observed patterns of these two time series have a similarity (Fig.22) and the value of correlation coefficient for the period from 1940 to 1970 is even higher than those for the Barents Sea chronology and air temperature in Tromsø (rho=0,503; p=0,004). Taking into account the high dependence of environmental and climatic parameters in this region (Ottersen et al., 2001), we compare BS-SGI-chronology with analysed climatic time series on this particular time interval and found significant positive correlation with NAO (rho=0.414; p=0.012) and AO (rho=0.519; p=0.001).

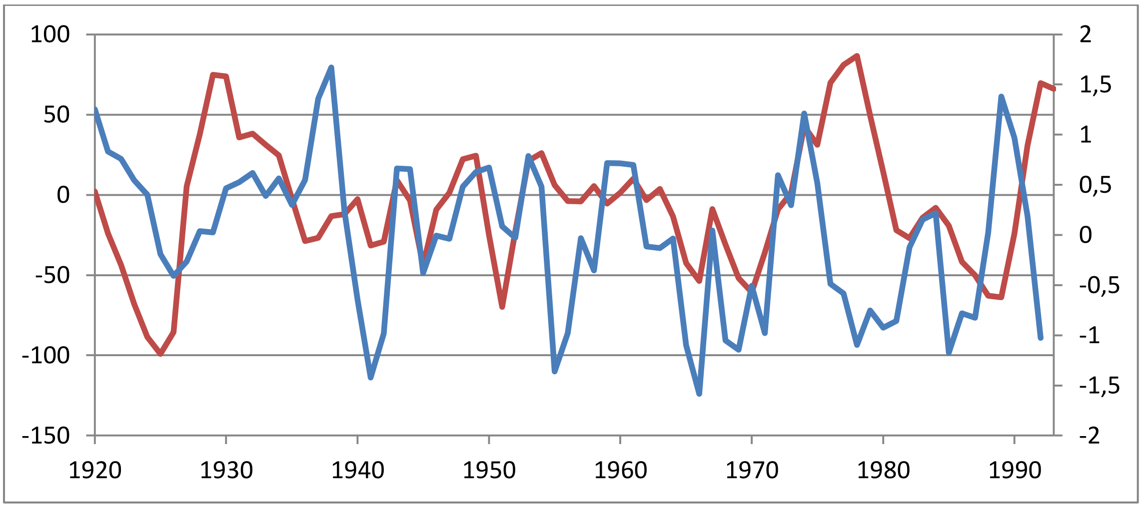

Figure 22 Air temperature time series form Murmansk (blue line) and BS-SGI-chronology (red line). To the both time series WMA3- filtering was applied.

3.5 Stable oxygen isotope analysis

The stable oxygen isotope profiles of both investigated specimens characterized by seasonal cycles were the peak values of a δ^{18}O after the growth line (Fig. 23, 24) The values of δ^{18}O ranged from 1.019±0.013‰ to 3.023±0.032‰ for the Norwegian Sea specimen and from 1.068±0.067‰ to 3.648±0.011‰ for the Barents Sea.

The carbon stable isotope profiles for both shells also showing the seasonality, but the peak values shifted relatively to those of oxygen (Fig. 23, 24) The range of variation of a δ^{13}C for the Norwegian Sea specimen is 2.077±0.007‰ - 3.211±0.007‰ and 2.11±0.024‰ - 3.228±0.004‰ for the Barents Sea.

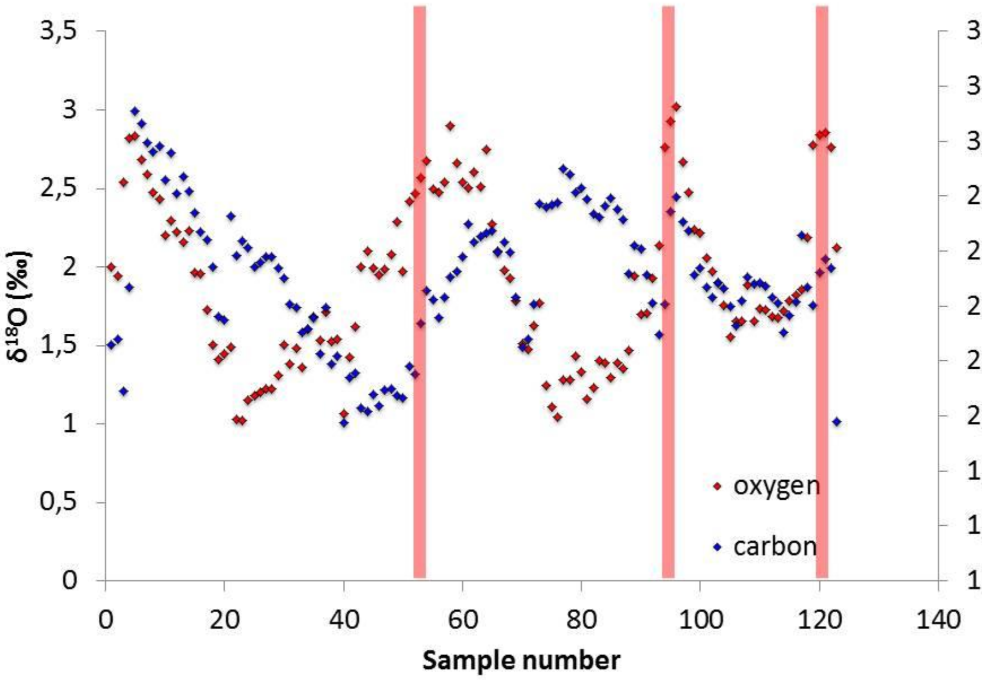

Figure 23 Stable oxygen and carbon isotope profile of *A.islandica* specimen from Norwegian Sea (24568-L). The pink lines indicate a location of observed annual bands.

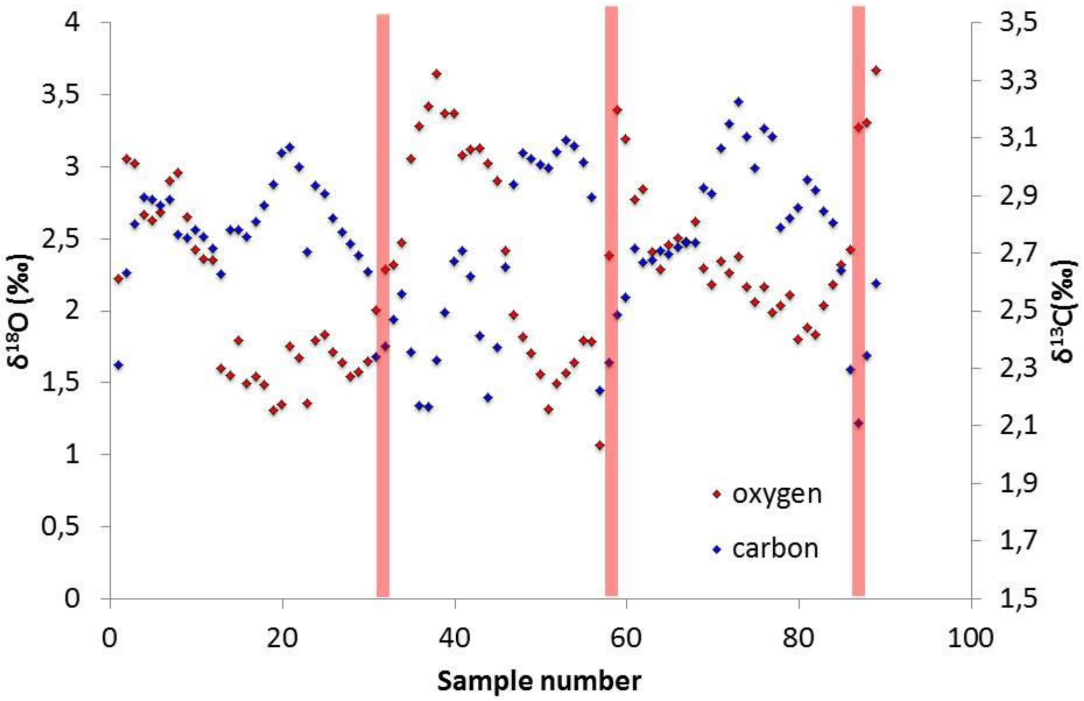

Figure 24 Stable oxygen and carbon isotope profile of *A.islandica* specimen from the Barents Sea (YaBa-03L). The pink lines indicate a location of observed annual bands.

4 Discussion

4.1 Morphology and shell growth

Obtained values of measured morphometric parameters, as well as values of shell shape descriptors, agree with previous investigations (Witbaard, 1997). However, the maximum values are slightly higher (L=87.89; H= 78.2) than reported by Zacepin and Filatova, (1961) (L=85.5; H=74). They also mentioned that in Barents Sea the young molluscs tended to have a lower Compacity index values (0.47-0.50). This cannot be confirmed in the present study (see Chapter 3.1).

Despite the fact that the values of shell shape descriptors are highly variable within each population, the shells from the White Sea are significantly different from the others. This morphological difference could be a reflection of genotypic differences (Holmes et al., 2003), due to the reproductive isolation of this population coupled with an influence of “stress” environmental conditions in this area (Begum et al., 2010). These distinctive features of morphology of White Sea shells have been reported in a previous study (reference). Thus, Zacepin and Filatova (1961) reported the existence of a specific form *Cyprina (=Arctica) islandica maris-albae* ssp., which is morphologically distinct from other North Atlantic subspecies. It is characterized by a slightly different shape ventral margin of the shell is straitened and from the umbo to the ventral margin occurs a radial prominence) and a thinner, lighter shell. The same tendency was founded in our investigations. Thus, according to our data, the shells from the White Sea have the lowest values for the mass to volume relation descriptor.

The mass to volume relation is the only descriptor that distinguishes the Barents Sea from the Norwegian population. The average values of this parameter (0.29±0.05) are significantly higher for the specimens from the Barents Sea. The simplest explanation of this difference is related to differences in the specific growth rates. Taking into account that the Barents Sea shells of comparable size are ontogenetically older than the Norwegian Sea specimens, i.e. having a larger number of growth increments, it is possible that the thickness of a shell, as well as the shell mass, is bigger for those specimens. In the present study, the shell thickness was not measured, that is why we could not prove this statement.

As mentioned before, the population specific growth rates from Barents Sea and Norway are different. Based on increments measurements (see Chapter 3.2) we could prove that the shell from the Norwegian coast grow faster as it can be seen from our model (Fig.15). Despite the genetic variability between individuals, such difference is likely to be a result of dissimilarity of environmental conditions in both locations (Witbaard, 1997). Water temperatures are considered to be one of the main factors controlling shell growth in bivalves (e.g., Nichols and Thompson, 1982, Lutz et al., 1983, Reis et al., 2012). The values of water temperature in both locations vary seasonally (Fig. 25). In general, water temperatures at the Norwegian coast are a few degrees higher, it could results in a prolongation of a growing season. This fact might be considered to be one possible explanation for observed differences in population growth rates. Thus, for instance, Nichols and Thompson (1982) reported a difference in a growth rate of the bivalve *Macoma baltica* depending on latitude distribution. They founded a maximum growth rate in the southern population and decreasing of this parameter northwards. Such feature was related to a temperature controlling growth season of the molluscs.

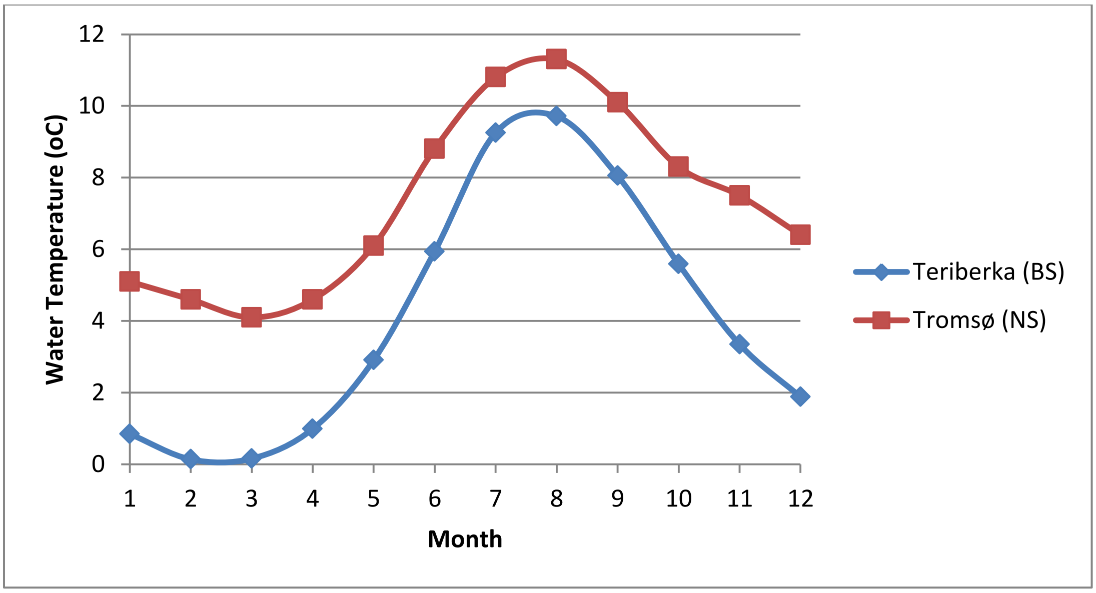

Figure 25 Monthly mean water temperatures in areas close to sampling locations. The red line indicates monthly mean for the Norwegian coast (Tromsø; 69°68'N 18°92'E). Blue line corresponds to monthly mean temperatures for the Barents Sea coast (Teriberka; 69°20'N 35°10'E). Data sources: data.oceaninfo.info; www.seatemperature.org.

Our growth model based on cumulative increment values cannot directly be compared to other models, which are based on actual shell length-at-age data. Due to the curved shape of a shell, our measured values are bigger than the corresponding distance from umbo to the ventral shell margin. However, according to our model, the molluscs from both locations reach more than two thirds of their infinitive size during the first 25 years of ontogeny. Afterwards, their growth rates decrease rapidly. Similar growth features for *A. islandica* have been observed in populations from Kattegat, German Bight, Iceland and Kiel Bay (Begum et al., 2010).

4.2 Shell growth chronologies

For the construction of site specific master chronologies we used individual SGI time series (Chapter 2.8), which had correlation factors higher than 0.2 (compared to the mean of the remaining time series). We made this restriction in order to remove those time series not showing the same signals. Even if all molluscs (at a specific site) were collected in the same area, they might be influenced by several different factors that do not control the growth of a whole population, but can have a big influence on individuals, for example, disturbance by trawling (Henderson and Richardson, 1998; Ramsay et al., 2000) or predators (Nakaoka, 2000).

The inner-population growth synchrony is poor for both locations, as evidenced by low values of correlation (Chapter 3.3). Only 19 (from 30) individual SGI-time series from the Norwegian coast and 11 (from 21) from the Barents Sea were assembled into the site-specific master chronology. After removal of those shells the average correlation values increased slightly (0.42 for the Norwegian Sea and 0.28 for the Barents Sea). The relatively low growth synchrony of *A. islandica* has also been reported by Epplé et al. (2006) for specimens from the coastal zone inside German Bight. By comparison with previous investigations on *A. islandica* shells from offshore sites, the authors concluded that the reason for a poor synchrony in shell growth is a high variability in environmental conditions in coastal areas. Our study confirms this observation. Both sampling sites are located in coastal areas, which are characterized by highly dynamic fluctuations in water temperature, salinity, tidal dynamics and other parameters (Treiziev et al., 1990). For example, the salinity of surface water layer (1.5m) in the Yarnyshnaya Bay (the sampling sites for the Barents Sea shells) varies in a range 0-32‰ (IPY, 2008), while the tides in that area could reach 3 meters (http://www.aari.nw.ru). Combined they contribute strong 'random components' to the shell growth pattern. By considering many individual time series from one location and calculating a population specific mean value for shell growth, the external influences may be reduced and single major signals might become visible.

4.3 Correlation of master chronologies and environmental parameters

Using a Spearman`s rank correlation we compared the growth chronologies from the Barents Sea and the Norwegian coast. We could not detect a statistically significant correlation between these two chronologies, even when considering possible time lags (Chapter 2.9). Taking into account that shell growth is controlled by environmental factors, we suggest that the reason for the observed shell growth dissimilarity might a difference in prevailed local environmental conditions at the two sampling sites.

In order to identify the factors controlling the growth we compared our two SGI master chronologies to the several (standardized) environmental parameters (air and water temperature) and climate indices (NAO, AO) (Chapter 3.4). Results will be discussed in the following.

Seawater temperature

Temperature has a great influence on the metabolism of bivalves, as poikiloterms (Newell, 1966). Also, water temperature is one of the main factors determining shell growth (Reis et al., 2012). In addition, water temperature influences primary production within the ambient water (Skogen et al., 2007), and thus indirectly controls the food supply for the bivalves. In the present study we detected a statistically significant correlation (rho= 0.301; p=0.012) between seawater temperature and the Norwegian Sea (NS) SGI- master chronology, indicating an influence of this factor on shell growth.

We could not detect a statistically significant correlation between Barents Sea (BS) SGI master chronology and water temperature from the Kola Section. Taking into account that there is no evidence that this time series is not representative for our location, the lack of correlation may be caused by the specific dynamics of local environmental conditions at the sampling site, which also resulted in a poor synchrony in chronology (Chapter 4.2).

Air temperature

Air temperature can have an effect on the shell growth of bivalves. Schöne et al. (2005) reported on a significant positive correlation between shell growth of freshwater pearl mussels and air temperatures in Scandinavia.

In this study, shell growth of *A. islandica* specimens from the Barents Sea coast correlates significantly with air temperatures at Tromsø for the period 1921-1993 (rho=0.281; p=0.018) with a maximum (rho=0.460; p=0.0048) on the time interval 1940–1975. We could not detect a correlation between BS-SGI master chronology and air temperatures from Murmansk for the whole overlapping interval (1919-1993). However, for the 1940–1975 period the correlation is highly significant (rho=0.569; p=0.0003). The lack of the correlation on the prior period might partially be explained by the SGI-chronology itself. The number of increments, which were included in chronology for the covering the period from 1898 to 1932 varies from 2 to 9 (Fig. 18). This may cause a more biased signal for the beginning of the master chronology. Nevertheless, it does not explain the lack of significant correlation for the period after 1970. One possible explanation would be that due to some unknown events during the period around 1940–1970 might have increased the shell growth response to variations in air temperature. From the early 1940s to the early 1970s, when the NAO index exhibited downward trend, European winters were characterized by lower than normal temperatures (Hurrell, 1995). The same trend in temperature has been reported for the remaining seasons, but to a smaller extent (Williams and von Loon, 1976a; Williams and von Loon, 1976b). Such temperature anomaly during this period might have great influence on a growth of molluscs, but we could not conclude that is a reason of correlation only on given time interval. For answering this question, further research is needed.

While the growth of shells from the Barents Sea responds to air temperature fluctuations, we could not detect a significant correlation between this parameter and the NS- master chronology.

North Atlantic Oscillation and Arctic Oscillation

In previous studies, highly significant positive linear correlations of shell growth in *A. islandica* and NAO have been reported for the specimens from the North Sea and Norwegian Sea (Schöne et al., 2003; Schöne et al., 2005). For the Barents Sea area a strong linkage between shell growth in *Clinocardium ciliatum* and *Serripes groenlandicus* with NAO has been found (Carrol et al., 2009; Carrol et al., 2011).

In the present study a relatively weak positive correlation (rho=0.255; p=0.035) between the NS-SGI master chronology and the winter NAO index has been found for the overlapping period 1935-2005, with maximum at interval 1960-1985 (rho= 0.79; p<0.0001). Taking into account that the AO and NAO are usually closely linked in the artic realm (climatedataguide.ucar.edu), it is not surprising that we could detect a significant positive correlation between the NS-SGI master chronology and the AO index at this particular interval, while the correlation for the whole overlapping (1935-2005) period was not significant.

The growth of the shells from the Barents Sea did not correlate with the NAO and AO indexes on a whole overlapping period (1989-2010), but we found significant positive correlation on interval 1940-1970 (with NAO: rho= 0.414, p=0.012; AO: rho= 0.519; p=0.001).

Despite the fact that we found a highly significant positive correlation between our chronologies and climatic parameters on some intervals, the correlation for the whole overlapping periods is not significant or relatively poor. One possible explanation for both locations could be the highly dynamical shallow water environment the molluscs have been found in. In general, living close to the coast bivalves might experience a dynamic fluctuation of environmental parameters (Chapter 4.2). Besides the poor growth synchrony within the population, it leads to difficulties in the detection of 'superior' climatic events (such as NAO or AO) inside the shell growth record.

4.4 Stable isotopes

The cyclic periodicity in both the $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ profiles derived from the shell carbonate, indicate seasonal changes in the ambient water conditions (in terms of primary production, water temperature and/or salinity). This confirms the results of previous studies on *A. islandica* (Witbaard et.al., 1994; Schöne B.R. et al., 2005b; Schöne B.R. et al., 2005c).

The $\delta^{18}O_{shell}$ ratio within the shell carbonate is controlled by the $\delta^{18}O_{water}$ composition of the ambient water and the water temperature during the period of shell formation. Due to missing data on the variation of $\delta^{18}O_{water}$ at both sampling sites, we could not evaluate the role of this parameter within the $\delta^{18}O_{shell}$ signal in shells.

In the present study we found distinct seasonal fluctuations in the $\delta^{18}O_{shell}$ aragonite with most positive values coinciding with the annual winter lines (Fig.23,24). This line forms during winter time (December-February), when the growth slows down or stops, due to food availability (Schöne B.R. et al., 2005d). The slight shifts of the peaks are most probably due to the applied milling procedure.

The same patterns of seasonal changes in $\delta^{18}O_{shell}$ were found in all six analysed shell increments with the exception of the first measured year in shell YaBa-03L (Barents Sea, Fig.25). Here, the winter line is located in the middle between the minimum and maximum values of $\delta^{18}O$. It might be assumed that this line was mistakenly classified as an annual winter line in the first place. Thus, the following line, which has been not considered being an annual line, and coinciding positive peak values of $\delta^{18}O$ in the first place, must be considered being the 'real' winter growth line (Fig. 26).

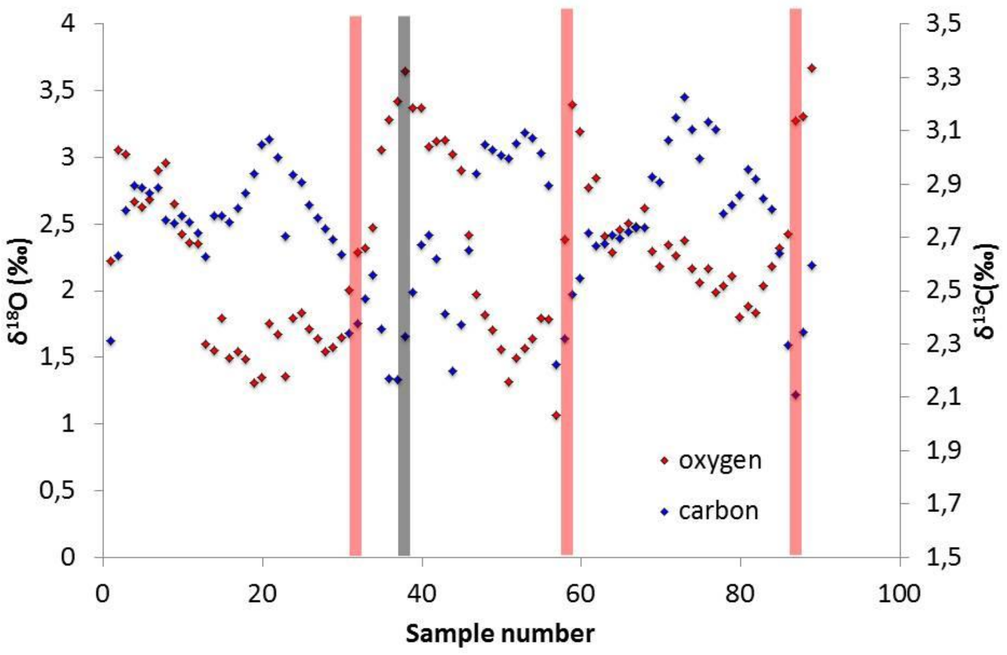

Figure 26 Stable oxygen and carbon isotope profiles of *A. islandica* specimens from the Barents Sea (YaBa-03L). The red line indicates the location of visually observed annual (winter growth) bands. The grey line corresponds to a growth line, which initially has not been considered an annual line.

The interpretation of seasonal variation in δ^{13}C is more difficult than for δ^{18}O. Shell δ^{13}C is determined by metabolic carbon and ambient water DIS (Dissolved Inorganic Carbon) (McConnaughey and Gillikin, 2008, Beirne et al., 2012).

In the present study we found that the maximum values of δ^{13}C did not coincide with those of δ^{18}O. The most positive δ^{13}C values occur just before the minimum values of δ^{18}O, which corresponds to maximum water temperatures during the growing season. However, the lowest δ^{13}C values matched the annual growth lines (Fig. 23, 24). This observation might most probably be connected and explained by the abundance of phytoplankton in the ambient waters (Witbaard et al., 1994). Taking into account that *A. islandica* deposits its shell carbonate in equilibrium with DIC of ambient water (Witbaard et al., 1994), the relative enrichment of seawater in ^{13}C (due to a phytoplankton bloom) may be seen as an explanation for increased δ^{13}C values in the shells. After the collapse of such blooms the DIC composition of the water reverts to normal values and causes a decrease of δ^{13}C in the shell aragonite (Witbaaed et al.,

1994) In the study area the phytoplankton blooms starts at March (Naustvoll, 2013), when the lowest values of water temperature usually observed (Fig.25).

Reconstruction of seawater temperatures

Numerous studies showed that $\delta^{18}O$ ratios in shells of *A. islandica* could be used for the reconstruction of the water temperatures (Weidmann et al., 1994; Epplé, 2004; Schöne B.R. et al.,2004b;). However, the shells cannot provide records of the whole annual temperature amplitude, as they record environmental conditions only during their growing season (February- December).

Due to the lack of the actual data on the $\delta^{18}O_{water}$ values, as well as on salinity data at both sampling sites, we could not reconstruct water temperatures, that were not also influenced by annual salinity changes. Using the equation by Grossman and Ku (1986) in modification by Dettman et al., (1999) and average values for $\delta^{18}O_{water}$ based on LeGrande and Schmidt (2006), we calculated approximate values of the water temperature.

For the specimens from the Norwegian Sea the calculated water temperatures vary between 6.03^{o}C and 14.97^{o}C (Fig. 26). The obtained range of 8.94^{o}C corresponds well to the existing data for water temperatures at Tromsø, while the maximum values of 14.97^{o}C exceeds the upper limit of temperature by 1.2°C. One of the reasons for this discrepancy between estimated and observed data is most likely our assumption of the $\delta^{18}O$ ratio of seawater. Taking into account that the $\delta^{18}O$ of seawater depends on salinity and the fact that our sampling sites are located close to the coast and in realm Norwegian Coastal Current, our signals will be (to an unknown degree) most likely be influenced by freshwater inflow (Loeng, 1991).

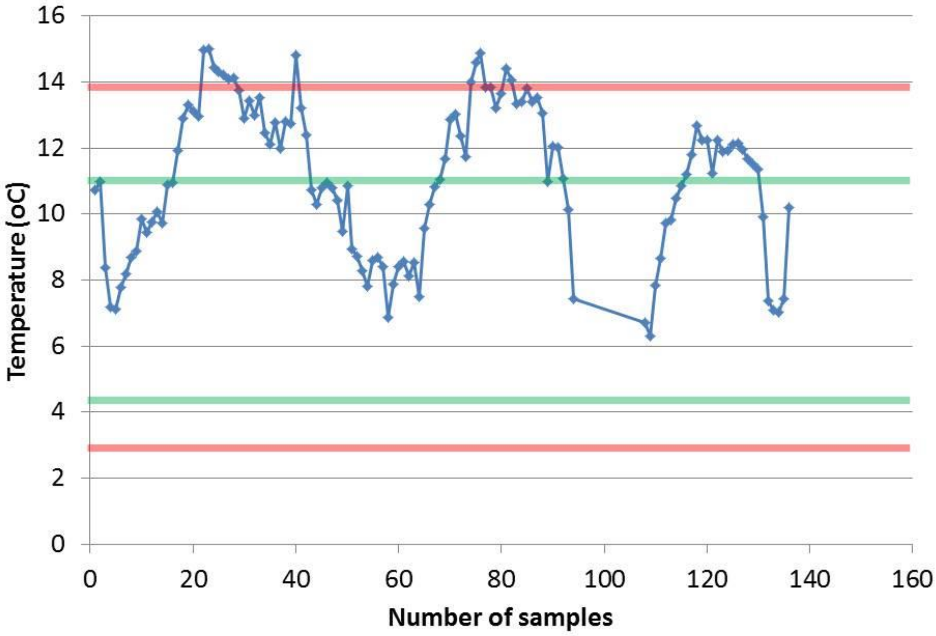

Figure 26 Shell oxygen isotope derived water temperature reconstructions from the specimen 24568- L (Norwegian Sea). The green lines indicate limits of monthly average water temperatures observed in Tromsø (69°68'N 18°92'E). Red lines correspond to reported extremes of temperatures. (Datasource: www.seatemperature.org.)

The calculated range in water temperature variation for the Barents Sea coast coincides with the seasonal temperature range observed in that area. Moreover, the maximum value of a calculated temperature does not exceed the upper limit in the observational data, although it is slightly higher than the average values for the warmest month (August). We cannot compare the lower limits of temperature, because the coldest periods are not recorded due to the winter growth cessation.

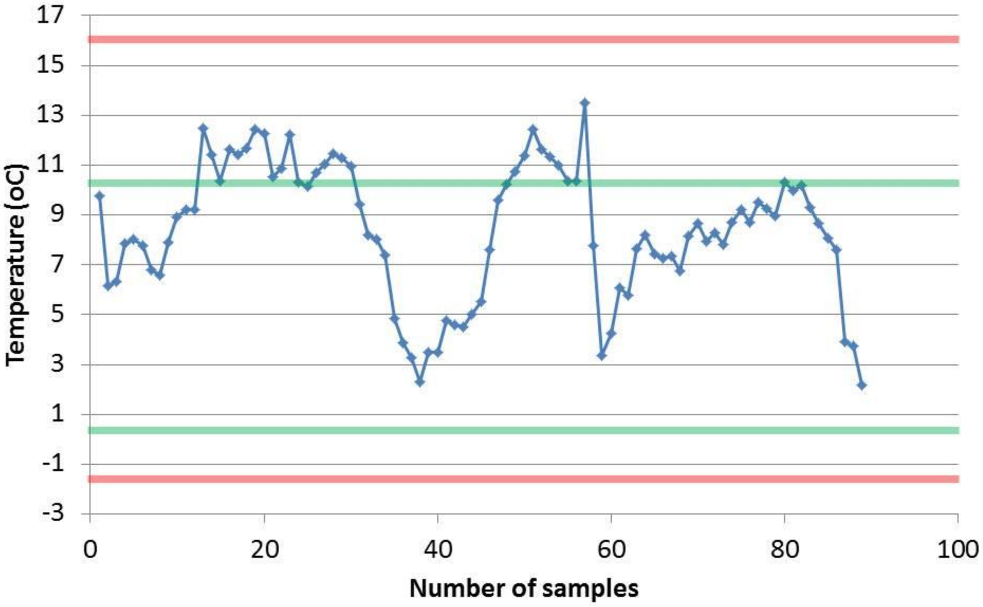

Figure 26. Shell oxygen isotope derived temperature from the specimen YaBa-03L (Barents Sea). The green lines indicate limits of monthly average water temperatures observed in Teriberka (69°20'N 35°10'E). Red lines correspond to reported extremes of temperatures. (Datasource: data.oceaninfo.info).

Based on the results for the both specimens, we conclude that *A.islandica* from both study areas could be used for the reconstruction of absolute water temperature values. For more precise results in potential future studies, more accurate data about the $\delta^{18}O$ ratio of seawater is needed.

5 Conclusions

Present investigation demonstrates distinct difference in growth of *Arctica islandica* form the Barents Sea and the Norwegian coast. Due to the difference in thermal regime, molluscs from the Norwegian Sea grew faster and attained a larger size at the same age, while the morphological characteristics remained stable.

Highly variable environmental conditions of coastal zone resulted in a poor synchrony of growth between the specimens in both populations. By joint consideration of many individual time series in master-chronologies, it was possible to determine growth response of population on variability of environmental and climatic parameters. Thus, the growth of molluscs from the Norwegian coast correlated with seawater temperature in that area and showed similarity in a long-term dynamics with NAO-index time course. Growth of animals from the Barents Sea responded to variation in air temperature, especially during colder periods.

Stable isotope analysis indicated cyclic patterns in carbonate deposition, which reflected seasonal changes in environmental conditions. A comparison of reconstructed water temperature range with existing data on seasonal variability of this parameter demonstrated a suitability of *A. islandica* shells as a proxy for the water temperature reconstruction in the study area. However, in order to obtain precise results more accurate data on $\delta^{18}O$ ratio of seawater are needed.

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Appendix

Please, find Table 4-5 attached on the disk.

Table 1 Morphometric parameters of Barents Sea shells

Table 2 Morphometric parameters of Norwegian Sea shells

Table 3 Morphometric parameters of White Sea shells

Table 4 Increment measurements, Barents Sea

Table 5 Increment measurements, Norwegian Sea

Table 1 Morphometric parameters of Barents Sea shells

Code	**Date**	**Valve (R or L)**	**Width 1 Valve**	**Length (mm)**	**Height (mm)**	**Mass 1 Valve (mg)**	**Growth rings Valve**
TT-YaBa-A01-L	Aug.2011	L	21,04	79,05	73,18	33300	94
TT-YaBa-A02-L	Aug.2011	L	21,41	75	66,54	30000	116
TT-YaBa A03-L	Aug.2011	L	22,15	82,81	73,09	30300	88
TT-YaBa A04-L	Aug.2011	L	22,45	82,1	73,14	35700	117
TT-YaBa A05-L	Aug.2011	L	19,16	74,66	68,94	51800	90
TT-YaBa A06-L	Aug.2011	L	21,72	81,92	75,7	37700	92
TT-YaBa A07-L	Aug.2011	L	22,31	79,29	75,48	40800	95
TT-YaBa-A08-L	Aug.2011	L	20,24	77,33	72,79	35100	90
TT-YaBa-A09-L	Aug.2011	L	21,74	87,89	83,08	41200	91
TT-YaBa-A10-L	Aug.2011	L	18,28	78,76	72,07	26200	64
TT-YaBa-A11-L	Aug.2011	L	21,78	87,08	77,74	44200	117
TT-YaBa-A12-L	Aug.2011	L	18,75	77,53	70,42	31200	89
TT-YaBa-A13-L	Aug.2011	L	19,87	73,62	68,3	26600	90
TT-YaBa-A14-L	Aug.2011	L	22,17	81,61	76,88	39300	82
TT-YaBa-A15-L	Aug.2011	L	22,54	83,68	78,2	42500	98
TT-YaBa-A16-L	Aug.2011	L	18,12	67,79	65,42	21600	68
TT-YaBa-A17-L	Aug.2011	L	19,7	76,24	72,29	31300	74
TT-YaBa-A18-L	Aug.2011	L	21,89	85,49	75,48	43500	118
TT-YaBa-A19-L	Aug.2011	L	20,54	74,32	69,19	28300	84
TT-YaBa-A20-L	Aug.2011	L	20,44	73,62	68,32	28000	104
TT-YaBa-A21-L	Aug.2011	L	13,94	51,84	47,62	9600	21
TT-YaBa-A22-L	Aug.2011	L	13,38	50,47	47,09	8400	18
TT-YaBa-A23-L	Aug.2011	L	16,67	67,35	64,28	20100	85
TT-YaBa-A24-L	Aug.2011	L	12,02	42,7	38,3	5500	9
TT-YaBa-A25-L	Aug.2011	L	11,35	42,71	37,76	5200	8
TT-YaBa-A26-L	Aug.2011	L	12,89	51,05	46,86	7900	10
TT-YaBa-A27-L	Aug.2011	L	10,64	41,65	37,37	5100	8
TT-YaBa-A28-L	Aug.2011	L	10,24	37,69	33,52	3700	10
TT-YaBa-A29-L	Aug.2011	L	10,58	40,33	36,18	4600	7
TT-YaBa-A30-L	Aug.2011	L	10,13	40,55	37,13	4300	9
TT-YaBa-A31-L	Aug.2011	L	6,67	26,13	22,69	1200	6
TT-YaBa-A32-L	Aug.2011	L	5,06	20,86	18,01	600	6

Table 2 Morphometric parameters of Norwegian Sea shells

Code	**Date**	**Valve (R or L)**	**Width 1 valve (mm)**	**Length (mm)**	**Height (mm)**	**Mass 1 Valve (mg)**	**Growth rings Valve**
N2	2006	R	25,69	96,25	86,73	57700	71
N3	2006	R	19,02	92,25	82,03	34500	72
N4	2006	L	22,8	90,31	76,92	43300	82
N11	2006	R	25,63	90,74	83,35	52000	71
N17	2006	L	22,5	86,82	76,16	40800	71
N18	2006	L	20,38	81,65	73,31	31600	71
N19	2006	R	23,8	83,6	77,94	45200	74
N20	2006	L	22,72	86,82	78,48	38300	68
24564	2006	L	23,29	86,08	77,61	42300	68
24565	2006	R	24,65	84,63	79,34	43200	68
24567	2006	R	24,95	96,86	85,39	53400	71
24568	2006	L	23,15	86,66	82,04	45500	75
245611	2006	R	23,61	83,3	77,04	42300	67
245612	2006	L	22,92	90,68	79,73	39400	69
245615	2006	L	24,07	91,59	80,49	49100	72
245616	2006	L	22,86	85,53	78,4	38200	71
245620	2006	R	23,09	82,01	72,02	35300	76
245624	2006	R	24,79	83,46	71,69	35900	71
245626	2006	R	24,63	95,11	86,27	48500	67
245632	2006	L	22,55	90,95	84,43	44100	69
245634	2006	L	23,13	84,11	79,52	32200	68
245636	2006	R	22,23	86,11	77,06	36400	64
245637	2006	R	22,95	85,06	80,8	42600	73
245638	2006	L	23,18	86,54	81,52	43100	69
245639	2006	R	22,76	88,44	85,07	38200	74
245640	2006	L	25,045	91,24	83,29	44800	73
245643	2006	R	22,62	85,66	76,5	34700	72
245644	2006	R	23,9	90,26	81,77	42500	71
245647	2006	L	23,64	91,04	83,72	45000	67
245648	2006	L	20,51	73,12	67,58	28600	64

Table 3 Morphometric parameters of White Sea shells

Code	**Date**	**Valve (R or L)**	**Width 1 valve (mm)**	**Length (mm)**	**Height (mm)**	**Mass 1 Valve (mg)**
TT-KaBa-A01-L	2006	L	10,81	38,52	36,66	2600
TT-KaBa-A02-L	2006	L	12,94	45,99	45,65	4500
TT-KaBa-A03-L	2006	L	12,25	40,99	39,8	3300
TT-KaBa-A04-R	2006	R	13,31	51,18	49,8	5900
TT-KaBa-A05-L	2006	L	12,17	41,81	38,76	3200
TT-KaBa-A06-R	2006	R	10,66	38,38	36,3	2600
TT-KaBa-A07-L	2007	L	11,98	40,2	39,94	3800
TT-KaBa-A08-R	2007	R	13,75	41,96	40,64	3800
TT-KaBa-A09-L	2007	L	11,3	39,27	37,67	2700
TT-KaBa-A10-L	2008	L	11,62	39,14	37,3	2900
TT-KaBa-A11-L	2008	L	10,74	40,99	38,74	3100
TT-KaBa-A12-L	2008	L	13,92	44,41	41,96	4800
TT-KaBa-A13-L	2008	L	11,07	39	37,73	3000
TT-KaBa-A14-L	2008	L	11,29	41,22	39,65	3300
TT-KaBa-A15-L	2008	L	10,98	40,12	33,3	3200
TT-KaBa-A16-L	2008	L	12,15	44,09	41,43	3800
TT-KaBa-A17-L	2008	L	11,19	41,16	37,8	3300
TT-KaBa-A18-L	2008	L	10,14	37,35	35,73	3100

Statement on the thesis’ originality

Herewith I, Tamara Trofimova, declare that I wrote the thesis independently and did not use any other resources than those named in the bibliography, and, in particular, did not use any internet resources except for those named in the bibliography. The master thesis has not been used previously as part of an examination. The master thesis has not been previously published.