



Barents Sea multidecadal variability

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Received 1 July 2009; revised 20 August 2009; accepted 8 September 2009; published 9 October 2009.

[1] We present area-averaged time series of temperature for the 100–150 m depth layer of the Barents Sea from 1900 through 2006. This record is dominated by multidecadal variability on the order of 4°C which is correlated with the Atlantic Multidecadal Oscillation Index.

Citation: Levitus, S., G. Matishov, D. Seidov, and I. Smolyar (2009), Barents Sea multidecadal variability, *Geophys. Res. Lett.*, 36, L19604, doi:10.1029/2009GL039847.

1. Introduction

[2] The thermohaline regime of the Arctic Ocean is determined by several key processes—the inflow of Atlantic Water (AW) through two gateways—the Fram Strait [Schauer *et al.*, 2004; Walczowski and Piechura, 2006] and the Barents Sea (BS) [Furevik, 2001], air-sea interaction in the Arctic, river runoff [Peterson *et al.*, 2002], and Pacific water inflow through the Bering Strait [Jones *et al.*, 2008; Woodgate and Aagaard, 2005; Woodgate *et al.*, 2006]. If the BS, as one of the gateways to the Arctic, is warming, there is a possibility that this warming may be amplified in the Siberian Arctic Seas due to reduced seasonal sea ice cover resulting from the ice-albedo feedback effect. Temperature-salinity anomalies of the water comprising the boundary currents of the Arctic may propagate towards the interior of the Arctic as thermohaline intrusions [Carmack *et al.*, 1997; McLaughlin *et al.*, 2009]. Recent analyses emphasize strong interannual to decadal variability of the Arctic Ocean [e.g., Dmitrenko *et al.*, 2008a, 2008b; Polyakov *et al.*, 2008] that depend or may depend on the interplay of the above-mentioned climatic elements. Alekseev *et al.* [2003] provide a detailed review of Arctic Ocean variability.

[3] Observations and climate models suggest that certain teleconnections and feedbacks link interannual to decadal variability between the Arctic Ocean and other geographic regions. The most prominent feedbacks identified so far are the linkages between Arctic climate variability and the North Atlantic Oscillation (NAO)/Arctic Oscillation (AO). Both the NAO and AO are characterized by vacillations of the atmospheric pressure systems of mid-latitude highs and high-latitude lows, with the ocean-atmosphere interactions in the northern North Atlantic being the lead factor in the NAO [Visbeck *et al.*, 2001]. There is evidence of links between the NAO and the circulation patterns of the Arctic Ocean characterized by multidecadal oscillations with periods of 10 to 40–60 years [Mysak, 2001]. A discussion of the robustness of correlations between the NAO and other

effects with BS climate dynamics was given by Goosse and Holland [2005]. Using the Community Climate System Model, version 2 (CCSM-2), they found a persistent correlation between the thermal history of the model BS and the history of model AW inflow. Their model runs showed that variability in air-sea exchange and heat transport in the BS dominate in forcing Arctic surface air temperature variability suggesting an important role of the BS in Arctic climate dynamics. In addition to the recent multidecadal decrease in the extent of Arctic sea ice cover there has been a dramatic drop during 2007. This sudden decrease does not appear to be directly related to the NAO or AO [Zhang *et al.*, 2008; Overland *et al.*, 2008].

[4] The BS is perhaps the only Arctic sea where presently available *in situ* observations are sufficient for unambiguous detection and analysis of long-term ocean climate variability. Because it remains ice-free almost throughout the year, the BS is covered by a well-developed observational network of standard sections [Matishov *et al.*, 1998] (Figure 1a) accompanied by a large number of historical and recent ocean profiles that are not part of this network (Figure 1b) that are available in the *World Ocean Database* (WOD) [Boyer *et al.*, 2006] (data available at www.nodc.noaa.gov). The BS serves as a transit zone between the upper layer warm water masses of the Atlantic Ocean and cold waters of the Eastern and inner Arctic. Therefore ocean conditions and long-term climatic trends in the BS may be indicative of the overall climate change in the Arctic Ocean, or at least in its eastern half. Our goal is to document the long-term thermohaline history of the BS that may be important for better understanding and prediction of possible changes in the Arctic Ocean.

2. Data and Processing

[5] The BS portion of WOD includes archived temperature and salinity for a time period exceeding 120 years. Recently there has been a large increase of the number of ocean profile data in WOD. The atlas of the BS by Matishov *et al.* [1998] contained about 74,000 temperature profiles. The online version of WOD we use in our present analysis includes more than 230,000 profiles for the BS as shown in Figure 1b. Because of the relatively large volume of available data in a geographically small area, we used a simple approach to data analysis. Most parts of the BS are well-represented with data for most years making it possible to consider these data as random sampling ensembles. To address the inhomogeneity of the observational network (Figures 1a and 1b), temperature and salinity data extracted from the WOD were averaged on a regular grid with 1° × 1° resolution in the region 11–57°E, 69–78°N for individual months. Such gridding reduces the geographic bias of the data. Vertically, we divided the BS into 4 layers defined as 0–50 m, 50–100 m, 100–150 m, and 150 m–bottom.

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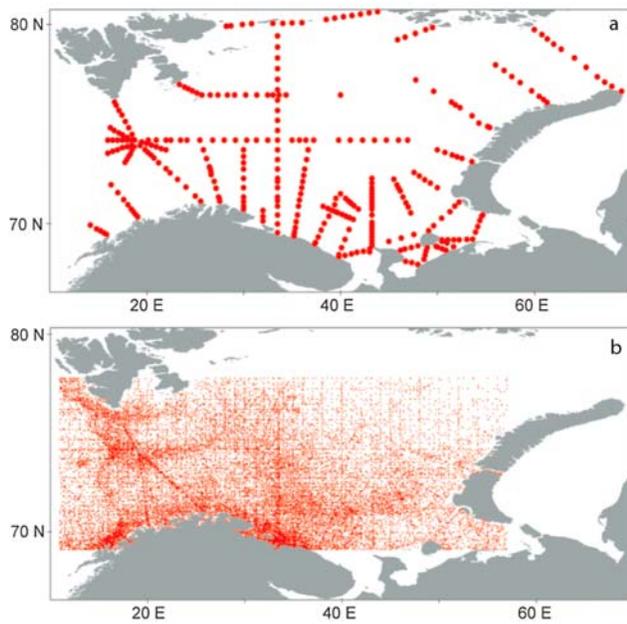


Figure 1. (a) Observational network on standard quasi-regularly repeated hydrographical stations in the Barents Sea [from Matishov *et al.*, 1998]. (b) Total data coverage in the Barents Sea (WOD select; see text). In Figure 1b, one dot represents three stations.

Data within each layer were averaged over the entire layer and assigned to the middle depth of each layer; if the bottom was within the chosen depth interval it entered this layer as its lower boundary. Obviously erroneous temperature and salinity profiles were excluded from the BS data subset. Additionally, in our gridded data arrays all grid cells with less than 3 observation points were considered empty. After gridding, all $1^\circ \times 1^\circ$ cells were considered equal, although the observational error is different for different cells—lower for the heavily populated cells and higher for the less

populated ones. In the best sampled years, approximately 60% of the gridboxes in Figure 1 is covered by $1^\circ \times 1^\circ$ boxes with temperature data. Usually coverage was between 40 and 50%. The years with less than 20% coverage were excluded from our analysis. The standard error (computed as a standard deviation divided by $N^{1/2}$ where N is the number of observations) in annually and spatially averaged temperature is about $\pm 0.2^\circ\text{C}$ (average temperature was calculated by averaging all cell-averaged temperatures for each month and annually averaging over the twelve months).

3. Results

[6] Figure 2 depicts the Barents Sea average monthly mean water temperature for the 100–150 m layer for 1900–2006. Interannual to interdecadal variability is evident in Figure 2. The difference between the most recent cold (1978–1982) and warm periods (2002–2006) exceeds 4°C . A similar temperature difference occurs between an earlier cold period (occurring around 1925) and an earlier warm period (occurring around 1950). In the North Atlantic sector of the Arctic, Venegas and Mysak [2000] found several dominant periods in sea ice and surface air pressure variability: from 6–7 years at the shortest to 50–60 years at the longest. Polyakov *et al.* [2004] found long-term variability of order 50–80 years in the temperature of the AW of the Arctic which in the central Arctic occurs at intermediate depths. There is a positive linear trend during the 1930s to the 1950s followed by a negative trend to the late 1970s. A positive trend follows. The warming accelerates after the early 1980s. The annual mean temperature of the 100–150 m layer rises at a rate of almost 0.2°C a year. The most important feature of this series is the multidecadal variability with a range on the order of 4°C . Based on a meridional line of stations known as the Kola Section (established in 1900 along $33^\circ 30'\text{E}$), Bochkov [1982], Yndestad [1999, 2006], and Yndestad *et al.* [2008] identified long-term variability similar to what we describe here. Skagseth *et*

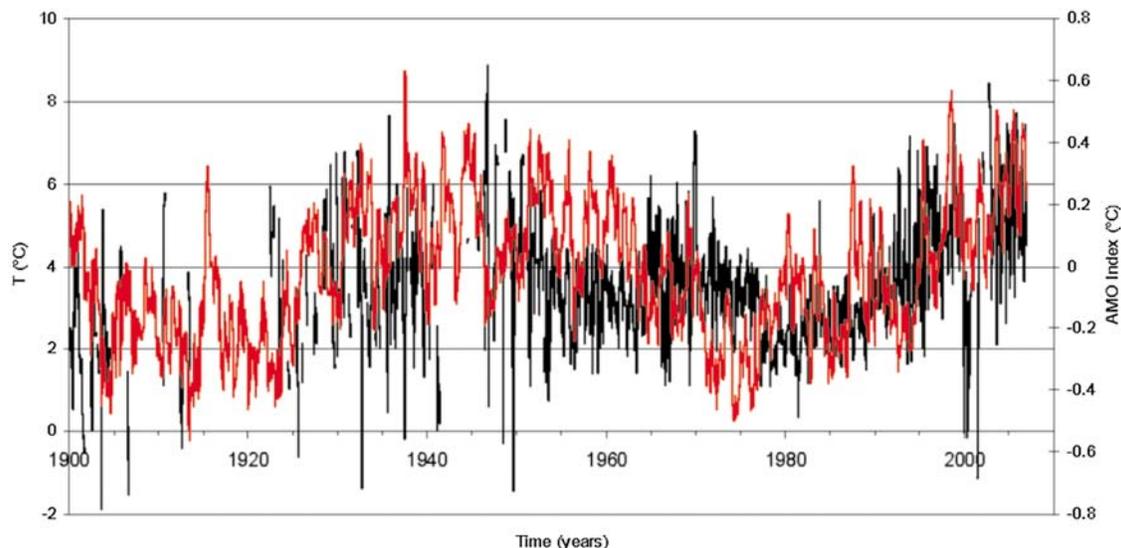


Figure 2. Monthly temperature ($^\circ\text{C}$) in the Barents Sea for the 100–150 m layer, from 1900 to 2006. Years without all 12 months of data are not plotted. The red line is the Atlantic Multidecadal Oscillation Index.

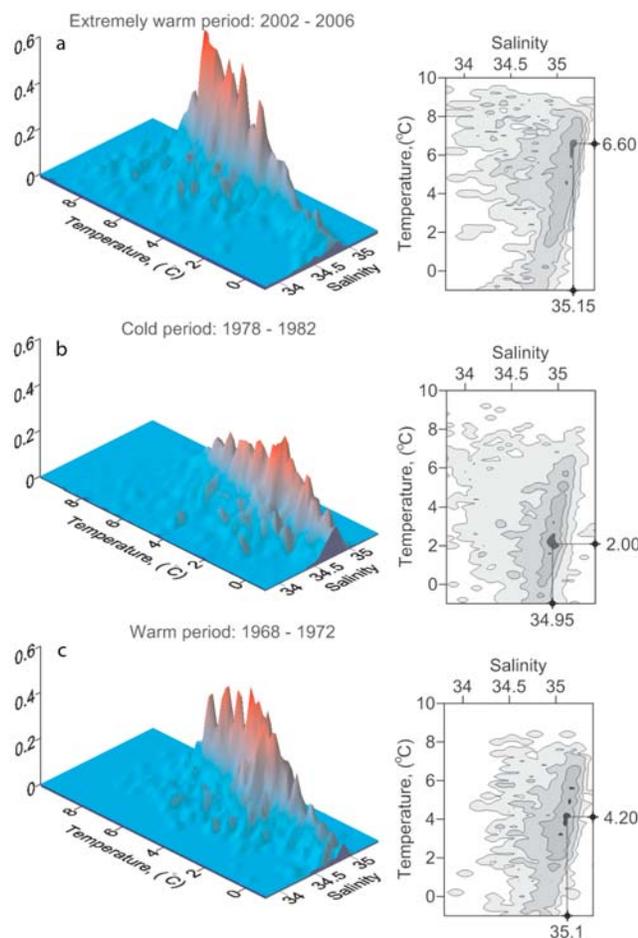


Figure 3. Shifts of the thermohaline characteristics of the Barents Sea between cold and warm periods. (left) A 3-D visualization of annual-mean T-S diagrams of water in the 100–150 m layer for three periods: (c) 1968–1972, (b) 1978–1982, and (a) 2002–2006. All T and S values within this layer are binned by units of 0.1°C and 0.1 . The vertical axis shows the number of observations with temperature and salinity within those intervals relative to the total number of observations in the layer. (right) The 2-D projections of the 3-D diagrams illustrating the shifts of thermohaline regime in the BS.

al. [2008] plotted the time series of the Kola Section mean temperature and the AMO index which we also plot here (based on Kaplan SST V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at <http://www.cdc.noaa.gov/>). The AMO index is defined as the average of sea surface temperature (SST) for the $0\text{--}70^{\circ}\text{N}$ region of the Atlantic Ocean. We find as Skagseth et al. found, a strong correlation between temperature and the AMO index. Skagseth et al. suggest, and we agree with, that the strong similarity between these temperature series and the AMO index indicate that the climatic variation in the BS region “is a local manifestation of a larger-scale climatic fluctuation covering at least the entire North Atlantic Ocean.” We note however that the correlation could be fortuitous because the record length is

relatively short. General circulation models and paleoclimatic data are necessary to study this phenomenon.

[7] To further document the variability of the subsurface water in the BS we plotted a frequency distribution of paired temperature and salinity observations in T-S space based on the original observations (Figure 3). Figure 3 shows the fraction of observations with T-S characteristics in the layer between 100 and 150 m depth, binned in $0.1^{\circ}\text{--}0.1^{\circ}\text{C}$ intervals in the T-S domain, out of the total number of stations for three key time periods: (a) the warm period of 2002–2006—the warmest period in BS thermal history so far, (b) the cold period of 1978–1982, and (c) the warm period of 1968–1972. The vertical axis in Figure 3 shows how often (in term of the fraction of the total number of observations) certain temperature and salinity values were found in the data. The frequency distributions in Figure 3 document that the water in this layer (and below, with similar T-S distributions) is mainly of North Atlantic origin, with the bulk of stations having T-S relationships close to those associated with AW [Smolyar and Adrov, 2003; O’Dwyer et al., 2001]. Increased AW inflow after the late 1980s–early 1990s explains the shift toward higher volume of AW in the BS in the last two decades [Zhang et al., 1998]. Thus, Figure 3 indicates that the ocean climate changes in the BS—cooling or warming—are due to the strength and thermohaline conditions of the AW incursion. In support of this hypothesis, we argue that the relative warmth or coldness of the central BS depends on how warm AW is and how effectively AW flushes modified BS water away from the central BS. The coherence between warm and salty water, attributed to each of the three chosen time intervals, imply that AW incursion is the dominant control of the T-S characteristics in subsurface waters of the BS. A recent shift toward a warmer BS (Figure 3a) is dramatic and may have important climatic consequences. A sharp increase in temperature without an accompanying equally sharp increase in salinity below the mixed surface layer leads to a weakened seasonal pycnocline. A weaker pycnocline means easier downward mixing of fresher but colder surface water in winter and therefore a substantial release of heat from sea to air.

[8] Although the salinity in subsurface layers is higher during warm periods (Figure 3), the surface salinity (not shown) does not closely follow this pattern. Warming and/or freshening of the surface water implies increased buoyancy of water in the upper layer and thus a sharper pycnocline shielding the atmosphere from the heat stored below the pycnocline (effectively the halocline in most places is below the upper ~ 50 m). With reduced winter sea ice cover heat is released to the near-surface atmosphere. At some point, because of this cooling, surface water loses its buoyancy and begins mixing with warmer AW beneath it and thus further warms the air over the BS. Balancing the alternations between buoyancy of warm and cold surface waters in the BS determines the heat loss of the AW throughflow and thus the climatic fate of the eastern Arctic. As suggested by Peterson et al. [2002], increased freshwater discharge from Eurasian arctic rivers may impose an additional strong control on this balance. However, in contrast with AW, the origins and intensity of freshwater impacts in the BS are difficult to localize. Moreover, freshwater events in the Nordic seas, including the Labrador Sea can increase the

buoyancy of AW [e.g., *Yashayaev et al.*, 2007]. Fresher subsurface AW means relatively less buoyant surface water and thus stronger vertical mixing in the BS when sea ice is absent.

4. Discussion

[9] Average BS temperature trends in the 100–150 m layer agree with previous findings that the Arctic has warmed during the past 30 years. These trends align closely with spectacular surface air temperature increase over the entire Arctic and with the rapid sea ice retreat [*Arguez et al.*, 2007]) since the end of the 1990s. Since the late 1970s the temperature of the 100–150 m layer of the BS increased by approximately 4°C as part of multidecadal variability that is correlated with the AMO Index for the past 100 years.

[10] However, despite good qualitative agreement between the BS oceanic climate trends and other climate tendencies in the Arctic, we must draw attention to some caveats inherent to our work. First, there is some uncertainty in “connecting the dots” between a warmer BS and reduced sea ice cover in the central Arctic—the presumed link between the two observables, which is yet to be explained. One of the plausible explanations would be to link AW throughflow in the BS to a lower rate of seasonal sea ice growth in winter in the BS [*Wu et al.*, 2004] and further downstream of the throughflow. However, AW sinks and thus may not have that much impact downstream on ice cover. Recent results suggest that the advection of warming near-surface water from the North Pacific Ocean to the Arctic Ocean through the Bering Strait may play a significant role in Arctic sea-ice retreat [*Woodgate et al.*, 2006]. Thermohaline intrusions of relatively warm water from the Arctic boundary currents into the Arctic interior [*McLaughlin et al.*, 2009] may play a role. Aerosols may also play a role [*Shindell*, 2007].

[11] Prior to about 1970, there was generally above-average sea ice cover, with the maximum extent observed in the late 1960s. Since the late 1970s sea ice extent has decreased substantially [*Comiso et al.*, 2008], whereas, simultaneously, AW has become warmer and perhaps more abundant in the BS. The warmer air and the gradual decrease of albedo of thinning ice in summer would cause melting from above. Additionally, the sea ice decrease may be due to heating from below, when the water mixing channels heat stored in subsurface layers toward the sea ice base. More and warmer AW may contribute to shortening or complete elimination of seasonal sea ice presence in some part of central and eastern Arctic. It is still not clear whether, or how much, subsurface AW has directly contributed to the substantial ice melting that has been observed during last 20 years in the central Arctic; another plausible explanation for an AW role in this process may be the BS impact on the Arctic climate via ocean-air interaction [*Goosse and Holland*, 2005]. (See also the comment on possible role of Bering Strait inflow above.)

[12] **Acknowledgments.** This work was supported by the NOAA Climate Change Data and Detection Program and the NOAA Climate Program Office. We thank the many scientists, technicians, data center staff, and data managers for their contributions of data to the IOC/IODE and ICSU/World Data Center systems, which has allowed us to compile the database used in this work. We also thank our colleagues at the Ocean Climate Laboratory for their work in constructing the *World Ocean*

Database, which made this work possible. We appreciate comments by Charles Sun and two anonymous reviewers on a draft version of this paper. The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official NOAA or U.S. Government position, policy, or decision.

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