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Seasonal variability of Atlantic water on the continental slope of the Laptev Sea during 2002–2004

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Dedicated to Russian polar oceanographer Prof. Zalman Gudkovich on the occasion of his 80th birthday

Abstract

2002–04 observations carried out on the Laptev Sea continental slope as part of the Nansen and Amundsen Basins Observational System (NABOS) project are used to study variations of the intermediate (150–800 m) Atlantic water (AW) layer of the Arctic Ocean. At the mooring site, AW exhibits seasonal changes, with higher/lower temperature and salinity in winter/summer. This variability is attributed to the shift of the AW core toward the slope in winter and away from the slope in summer. Seasonal variation of wind is among the possible factors governing seasonal changes of the AW layer.

Keywords: Atlantic water layer; seasonal temperature variations; wind

1. Introduction

The warm and salty Atlantic water (AW) plays a special role in the thermal balance of the Arctic Ocean. It enters the Arctic Ocean through Fram Strait and the Barents Sea shelf, sinks to intermediate (150–800 m) levels, and flows cyclonically into the Arctic Ocean interior along the basin margins [1,2] with a warm core from 50 to 300 km off the Siberian slope [3]. Due to a scarcity of observations, little is known about AW seasonal variability in the Arctic Ocean interior. Kupetsky [4] suggested AW transformation occurs on the Siberian shelf slope in response to seasonal changes in atmospheric circulation patterns. However, year-long mooring-based observations from three sites at the junction of the Lomonosov Ridge with the Siberian slope provided no evidence of AW seasonal variability [5]. Here, new data from the Laptev Sea continental slope (Fig. 1) taken between 2002 and 2004 are used to analyze AW seasonal time-scale variability.

2. Data

The unique data used in this study were collected from a mooring deployed offshore of the Laptev Sea continental slope (Fig. 1) for two consecutive years (2002–03 and 2003–04). The mooring was equipped

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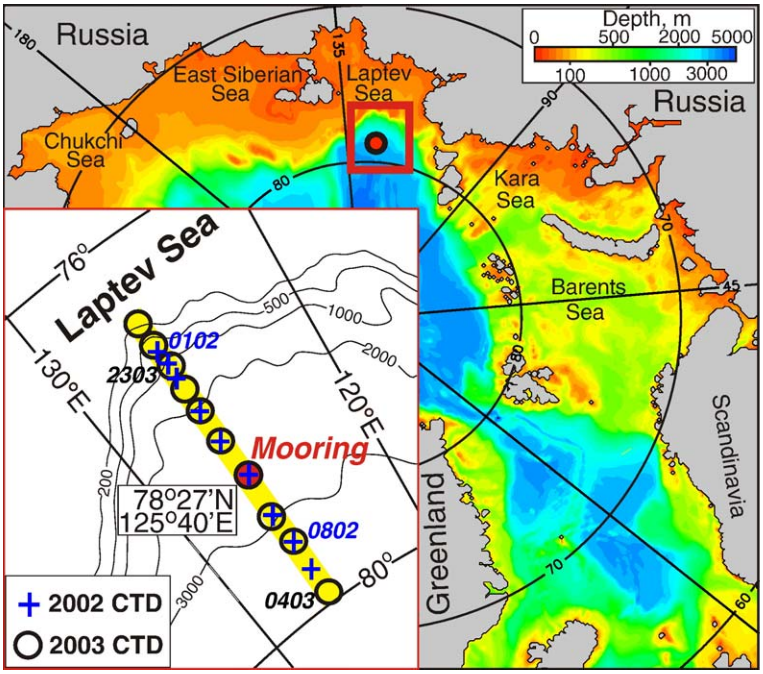

Fig. 1. A map of the Arctic Ocean with inset showing an enlarged view of the northern Laptev Sea region (red square). A red circle marks the mooring position; the inset shows a CTD section occupied during two cruises.

with a "McLane Moored Profiler" (MMP), an instrument which profiles vertically along a mooring line at a speed of about 25 cm/s, with a sampling period of 0.5 s. The MMP is equipped with a CTD (conductivity, temperature, and depth) and an ACM (acoustic current meter), giving measurements of temperature, salinity, and velocity. During the first year the profiler was programmed to profile between target depths of 164 and 2607 db. Drive-motor spring failure and ballasting problems resulted in a gradual decrease in profiling range over the year. The MMP finally stopped profiling in February 2003 at a depth of 435 db (it did continue recording, however). Due to technical problems no reliable current records were obtained during the first year. The second-year deployment provided year-long CTD and velocity records between 105 and 1509 db.

2002–03 temperature and salinity observations from an SBE-37 CTD deployed at 136 db, and an SBE-16 CT

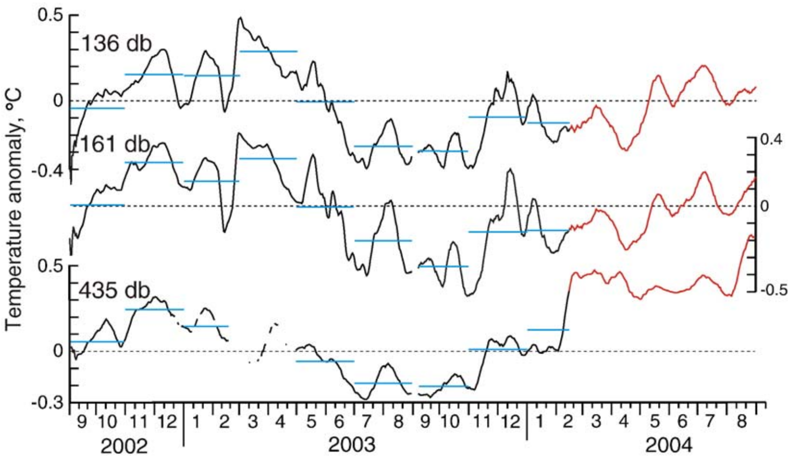

Fig. 2. Time series of 15-day running mean water temperature anomalies (°C). Blue horizontal lines show two-month means. Gaps in the records are due to missing data. Portion of data shown by red is associated with horizontal advection and therefore was eliminated from present analysis.

(conductivity and temperature) meter deployed at 161 db provided year-long records at fixed depths with a sampling period of 15 min. The shallowest CTD at 136 db was near the upper boundary of the AW layer (defined by the 0 °C isotherm), while the CTD at 161 db measured positive temperatures throughout the year. Fixed-depth year-long records were expanded for 1.5 years using MMP observations from 2003–2004. Composite 2002–04 time series are shown in Fig. 2.

Mooring observations were complemented by oceanographic surveys done in September 2002 and September 2003 using a shipboard SBE19+ CTD. Accuracies of individual temperature and conductivity measurements from the SBE-37 are 0.002 °C and 0.0003 S/m, respectively. Corresponding accuracies for the SBE-16 and SBE-19+ are 0.005 °C and 0.0005 S/m, and for the FSI micro-CTD on the MMP accuracies are 0.002 °C and 0.0002 S/m. The MMP Falmouth Scientific, Inc. ACM current velocity precision and resolution are reported to be ±3% of reading and ±0.01 cm/s, respectively. Compass accuracy is ±2°.

3. Results

Before February 2004 the temperature records from 136, 161, and 435 db levels are dominated by variability which may be attributed to a seasonal cycle with a background cooling trend (Fig. 2). A striking feature of these variations is that winter temperatures are generally higher than summer temperatures (Fig. 2). Two-month means corroborate this conclusion showing that during winter the upper AW boundary temperatures (136 and 161 db) are 0.2–0.6 °C higher than summer temperatures whereas at 435 db (below the AW temperature maximum) the range of winter–summer variations is lower, between 0.2 and 0.4 °C. The seasonal temperature contrast at 136 and 161 db is higher in 2002–03 than in 2003–04; at 435 db this difference between the two years is lower. Winter–summer temperature changes at all depths are in phase.

After February 2004 this seasonal pattern was disrupted by warming event clearly seen in the MMP record (Fig. 3), when the MMP captured an exceptionally strong warming with an AW temperature increase of about 0.4 °C. Following this event the AW layer equilibrated at a new warmer state for almost seven months, continuing until the end of the observational period in September 2004, and masking all other modes of variability. Therefore the present analysis of the AW seasonal variability extends only through this warming event that is associated with downstream propagation of the AW warm anomaly recorded in the Fram Strait in 1999 [6].

For the period of time between September and February the MMP temperature records from both 2002–03 and 2003–04 demonstrate a similar pattern of AW variability, with generally higher temperatures in winter and lower temperatures in summer (Fig. 3). For example, AW temperature averaged over the 160–530 db pressure range in September 2003 was 0.62 °C, 0.22 °C lower than the January 2004 temperature. The corresponding increase of the AW layer heat content from September 2003 to January 2004 was 33%, 89% of which was caused by an increase of water temperature (with an insignificant contribution from AW layer thickening). Similarity between temperature changes in 2002–03 and 2003–04 is supported by their relatively high correlation. For example, at 260 db (the AW temperature maximum) the temperature changes in 2002–03 and 2003–04 were correlated with correlation coefficient $R = 0.50$ (this and other presented statistical

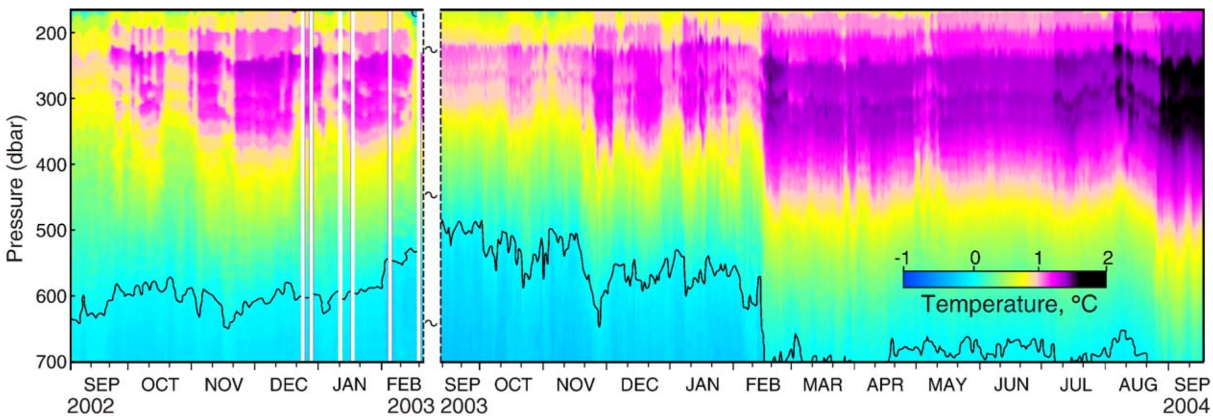

Fig. 3. Water temperature from the MMP profiler. The 0 °C isotherm (black line) traces the lower boundary of the AW layer. Blank areas represent missing data. 10-m vertical binning is used.

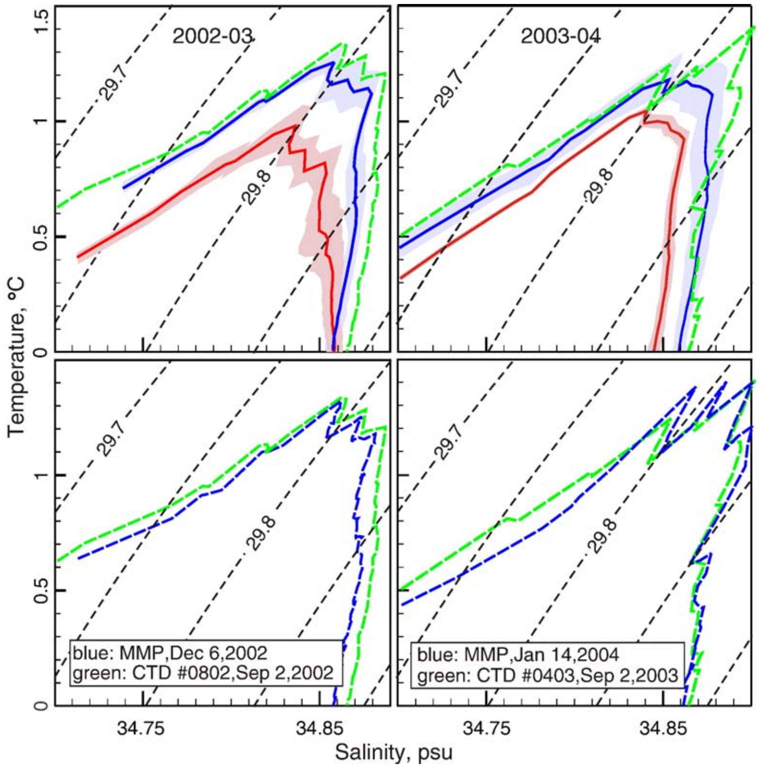

Fig. 4. (Top) Solid lines and shades show monthly mean T–S diagrams for September (red) and December 2002/January 2004 (blue) and their standard deviations (σ). (Bottom) T–S curves derived from individual winter MMP profiles (blue), and September CTD survey profiles taken from the AW core (green, also added to the top panels for comparison purposes). 10-m vertical binning is used. Dashed black lines are isopycnals referenced to 300 db.

estimates are significant at the 95% confidence level). The AW salinity variations (not shown) also demonstrate the seasonal pattern, with generally higher salinity in winter and lower salinity in summer, and an average difference of 0.02; in this temperature and salinity changes are highly correlated ($R=0.88$).

An additional perspective on the seasonality comes from a comparison of T–S diagrams for 2002–03 and 2003–04. The winter and summer T/S relation is distinct with saltier and warmer water in December 2002/January 2004 compared with September 2002–03 (Fig. 4, top). It is noteworthy that the standard deviation of the two season's T/S relation shows essentially no overlap. No significant winter–summer temperature and salinity variations were found below 1000 db (not shown).

Fig. 5 shows a distinct difference in AW flow between September 2003 and October 2003–February 2004. In September at 260 db (AW temperature maximum) the flow was dominated by relatively strong northwest (i.e., off-slope) current. Afterward the flow became southeast (i.e., dominated by along-slope current). In September the cross-slope current component of 2.1 ± 0.8 cm/s was off-slope, while in October–February it changed its sign and became on-slope with a speed of 0.6 ± 0.4 cm/s.

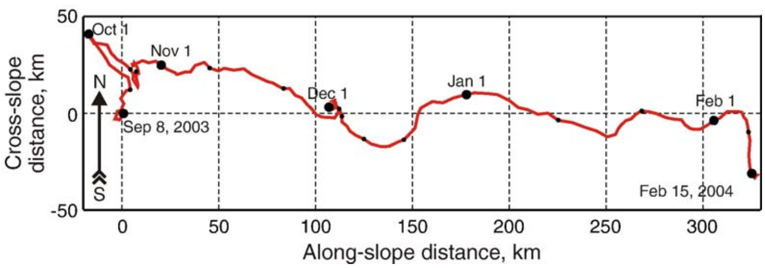

Fig. 5. Progressive vector diagram for the MMP 10-m binned current record at 260 db.

4. Discussion

We argue that winter/summer differences discussed above are due to the seasonal cycle. Strong seasonal variations of the temperature signal in Fram Strait were described by Quadfasel et al. [7]. Thus, it should be no surprise that a seasonal modulation of the AW temperature occurs downstream from Fram Strait in the eastern Eurasian Basin. Indeed, our data provide evidence that the seasonal cycle exists. However, we suggest that the observed decrease/increase in AW temperature and salinity over the Laptev Sea continental slope is governed not only by a change of the AW thermodynamic state, but is also controlled by dynamically driven shift of the AW core relative to the continental slope (Fig. 6). There are several pieces of evidence supporting our hypothesis. First, the MMP record of the AW cross-slope current component showed that currents were off-slope in September 2003 and on-slope during October 2003–February 2004 (Fig. 5). This current would be sufficient to advect the AW core onshore by 70 km in 4.5 months. This is in reasonable agreement with the observed summer position of the AW core relative to the mooring location. The 2002 and 2003 summer oceanographic surveys show the location of the AW core 250–300 km off the slope, and 80–120 km off the mooring site (Fig. 7). Based on our current observations we propose that a shift of the AW core closer to the slope (and the mooring) during winter caused temperature and salinity to increase at the mooring location.

A second piece of evidence for an on-slope/off-slope migration of the AW core comes from comparison of *T*–*S* curves derived from winter MMP profiles and CTD profiles obtained during summer surveys (Fig. 4). CTD casts #0802 and 0403 taken in the AW core 100 km and 150 km offshore of the mooring in September 2002 and 2003 (Fig. 7) look similar to MMP profiles from December 6, 2002 and January 14, 2004 (Fig. 4 bottom). This suggests off-shore waters sampled by the CTD were advected on-shore during fall/winter. The well-defined *T*–*S* structure of thermohaline intrusions may be considered to be a “marker” for the AW core. These intrusive features are coherent in the *T*–*S* plane over distances greater than 2000 km along AW pathways [8]. Similarity between intrusion *T*–*S* structure in winter MMP and summer CTD profiles indicate a near-isopycnal shift of the AW core toward the mooring site in winter. Fig. 4 also shows that *T*–*S* characteristics of the AW core obtained from summer surveys were similar to winter and different from summer thermohaline structure measured at the mooring site by the MMP. Thus, on-slope advection of the AW core suggested by the velocity record and confirmed by *TS* diagrams are highly suggestive of an on-shore advective mechanism as an explanation for the observed winter warming recorded by the MMP. It must be noted that the predominant current at the mooring site is along-shore (Fig. 5), so implicit in our concept of on-shore advection explaining *T*/*S* evolution at the mooring site is the requirement that the cross-shelf *T*/*S* gradients are much larger than along-shore gradients.

Shifts of the AW core relative to the continental slope may be explained by several mechanisms. Among them, the AW core may shift in response to wind variations. Nikiforov and Shpaikher [9] suggested that in response to off-shore wind surface currents would have a prevailing off-shore direction. They argued that this would result in compensating on-shore subsurface flow, moving the AW core closer to the slope. Over the Laptev Sea wind patterns are governed by seasonal shifts of the large-scale atmospheric circulation, with a predominance of the anticyclonic mode in winter and the cyclonic in summer [10]. Winter winds have an off-shore component from October to April, while prevailing summer winds are weaker, turning along-shore towards the east in May–September (Fig. 6). Wind seasonality suggests that the scheme proposed by Nikiforov and Shpaikher [9] may take place at seasonal scales (Fig. 6). This hypothesis is also supported by historical data from the Laptev Sea, which show the winter movement of relatively warmer water toward the shelf [11].

Seasonal wind tendencies described above were typical for 2002–04 (Fig. 8, right bottom). Analysis of 2002–04 temperature records and wind shows that

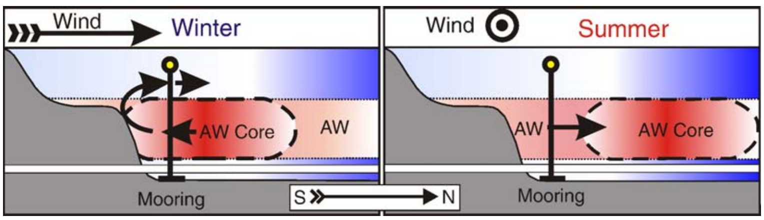

Fig. 6. Sketch of proposed seasonal shift of the AW core. Cross-slope winter wind causes off-shore surface current, which moves the AW core toward the shelf (left). In summer, the AW core relaxes back to its initial position (right).

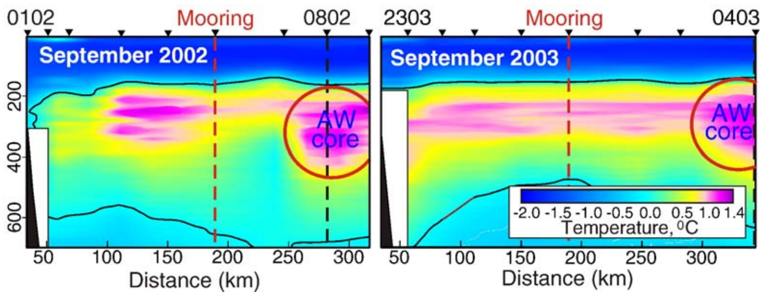

Fig. 7. 10-m binned temperature sections (°C) taken in 2002 and 2003 across the continental slope. The 0 °C isotherm (black solid line) traces the boundaries of the AW layer.

northward off-shore winter winds are generally associated with higher temperatures, whereas southward summer winds are associated with lower temperatures (Fig. 8). The average rate of temperature anomalies related to seasonal change in wind patterns is estimated at between ±0.3 °C for the upper boundary of the AW layer (136 and 161 db) and between ±0.2 °C at 435 db (Fig. 8), consistent with previous results.

Although our results generally support earlier findings by Kupetsky [4], and Nikiforov and Shpaikher [9], seasonal shift of the AW core relative to the slope caused by wind is not intuitive. It motivated us to make a series of numerical modeling experiments (see Appendix for more details on model and experiment design) to evaluate how the AW core responds to the seasonal change of wind forcing. A simple possible model configuration (ocean-alone model with simplified model domain initiating the basic features of the Siberian continental slope) has been employed. The initial temperature distribution with a clearly defined AW core (Fig. 9, top) is typical for the Laptev Sea continental slope.

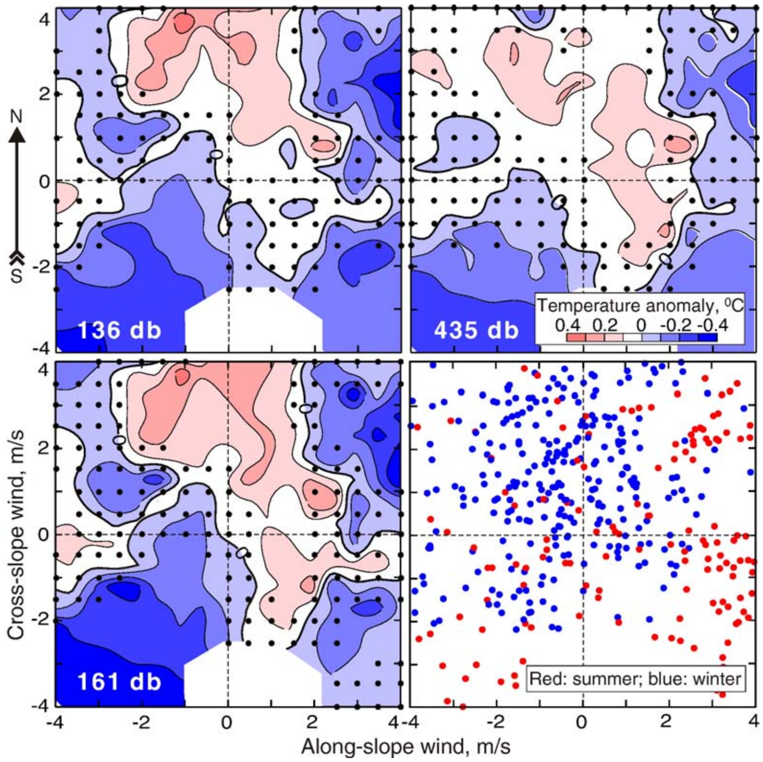

Fig. 8. (Top and bottom left) September 2002–February 2004 15-day running mean temperature anomalies (°C, color) at 3 depth levels versus 15-day running mean NCEP wind. Temperature anomalies not exceeding standard errors are statistically insignificant and marked by black dots. (Bottom right) Summer (May–September, red) and winter (October–April, blue) daily wind.

Fig. 9 shows cross-sections with the simulated water temperature and circulation (note that the latter is shown schematically to avoid making the figure too busy). Off-shore (winter) wind causes off-shore surface currents and fall of sea level near the coast (not shown). Along-shore (summer) wind results in on-shore surface currents and near-coast sea level rise. In both cases, at ~200–300 m (i.e., at the depth of the AW core) the circulation is opposite to the surface one. Note however that the "summer" off-slope under-surface current is much (~3 times) weaker as compared to the "winter" on-slope under-surface current. The different winter/summer circulation patterns result in strong on-slope shift of the AW core in winter and rather moderate off-slope shift in summer. This analysis strongly supports the available observational evidence of the seasonal migration of the AW core relative to the Laptev Sea slope. We found that the balance of forces in this idealized experiment with steep bottom topography is very simple. In the upper ocean the vertical friction (wind forcing) is balanced by the Coriolis force and sea-level slope whereas at the depths of the AW core and deeper the balance of forces of the on- and off-slope circulation is governed by the Coriolis force, sea-level tilt and, to a lesser degree, horizontal density gradients (not shown). This simple geostrophic balance of forces likely explains why our results are so robust to dramatic changes in vertical and horizontal viscosity formulations.

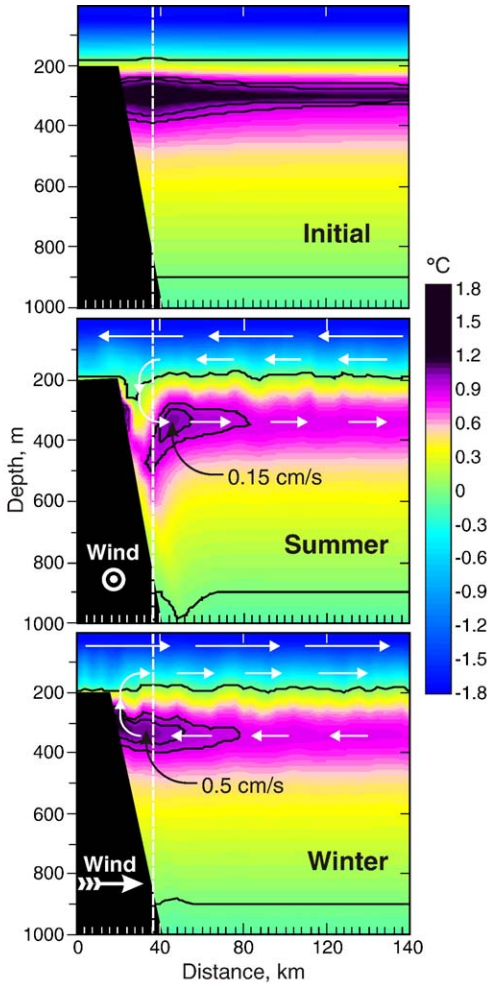

Fig. 9. Schematic showing the initial water temperature distribution within a part of model domain (top), and the AW core redistribution in response to the different wind forcing. The 0 °C isotherm (black line) traces the boundaries of the AW layer. White dashed line shows the initial position of the AW core relatively the continental slope. Water circulation is shown schematically by white arrows. Cross-slope off-shore wind causes an off-shore surface current, which moves the AW core toward the shelf (bottom panel). Along-shore wind results in on-shore surface current which shifts the AW core off-shore (central panel).

5. Concluding remarks

Observational data collected in the eastern Eurasian Basin at the Laptev Sea slope suggest the existence of a seasonal signal, with generally higher AW temperature and salinity in winter and lower values in summer. This variability may be attributed to the seasonal shift of the AW core towards the slope in winter and away from the slope in summer. Current measurements and numerical modeling corroborate this interpretation. Cross-slope mooring velocity measurements show mean summer off-slope and winter on-slope flow. Modeling results demonstrate on-slope shift of the AW core in response to off-slope (winter) wind, while the along-slope (summer) wind results in off-slope AW core movement. Our interpretation is also supported by similarity between profiles taken at the mooring site during winter with summer CTD profiles, taken 100–150 km offshore of the mooring site in the AW core. Seasonality of the wind is the hypothesized cause of the AW shifts, but probably does not provide a complete explanation. Several other mechanisms, including dynamical instabilities of the boundary current, or seasonal changes in sea level causing density-driven surface currents [14] may contribute to the shift of the AW core relative to the Siberian continental slope. Ongoing and future observations in this region will help clarify our findings.

Our results are also important in terms of detection of long-term trends in AW temperature. Seasonal shifting of the AW core produces "noise", and large-scale thermodynamic warming would need to rise above this level to be detected by a single mooring.

Acknowledgments

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Appendix A

The model used here is a three-dimensional Boussinesq, hydrostatic, nonlinear ocean model described in [12], and was also used to simulate processes in ice-covered sea [13]. It incorporates a turbulent closure model, which follows from the equation of turbulent kinetic energy and is a relation between the eddy viscosity coefficient, vertical shear of the horizontal velocity, and buoyancy. Coefficients of horizontal turbulent viscosity and diffusivity are taken as $2*10^6$ and $1.1*10^5$ cm^2/s.

The model domain is an idealized infinite-width channel, extending 400 km zonally across the continental slope with an open northern boundary, and a vertical wall along the southern boundary. A meridional linear 40 km wide slope separates a 1500 m deep abyssal basin and 200 m deep, 60 km wide shelf. This domain configuration aims to imitate the basic features of the Siberian continental slope. There are 50 vertical levels, with vertical spacing increasing from 2.5 m at the uppermost level to 100 m at depth. The horizontal resolution is 4 km. The model is initialized with the temperature and salinity distributions typical for the Laptev Sea continental slope. The initial temperature distribution, with a clearly defined AW core, is shown in Fig. 9, top. Initial salinity is vertically stratified and horizontally uniform. The initial condition for the current velocities and sea-level heights is rest. Cyclic boundary conditions are used at lateral along-slope boundaries for the temperature, salinity, sea level, and currents. At open (deep) boundary the zero heat/salt and momentum fluxes, and a slip condition for the along-boundary velocity component are specified. At the shallow boundary zero normal fluxes of heat and salt, and zero meridional component of current are used. Zero heat and salt fluxes are specified as surface boundary conditions. The model is forced by an idealized horizontally uniform cross-slope (off-shore) or along-slope (shallow-to-right) wind of 0.2 N/m^2. These wind stresses suppose to imitate seasonal changes of wind direction observed over the Laptev Sea margin.

The model was run for a 30-day period for each wind direction (along- and cross-slope). Results presented in Fig. 9 are averages over the last five days of the model integration. This time interval is not enough to equilibrate the model but is sufficient to exhibit tendencies resulting from the forcing fields. A series of test experiments were conducted to show the robustness of our analysis. For example, reduction of horizontal viscosity coefficients by an order of magnitude or use of constant vertical viscosity/diffusivity coefficient of 1 cm^2/s did not change our results qualitatively. To keep our analysis as simple as possible, the model used in these experiments was not coupled with an ice model. However, we estimated the sensitivity of our results to change of wind stresses by ice. For this purpose we ran the ocean model coupled with an ice dynamical model [13] neglecting thermodynamical processes associated with ice growth/decay and related heat/salt fluxes into the water. Initial horizontally homogeneous ice concentration and thickness were 0.95 and 1.6 m, respectively, and were kept unchanged over time. Thus, the ice model provided ice-ocean stresses to the ocean model only. The results of these model runs with off-shore and along-slope winds were only slightly different than results from the basic experiments described here (not shown).

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